STUDIES FOR IMPROVED VAPOUR-LIQUID CONTACTING

by

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SUMMARY.

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The object of the work was to attempt to propose an improvement in the process of vapour-liquid contacting with particular reference to commercial distillation.

The literature was reviewed by considering both the overall performance data of the methods and devices used for contacting and the more fundamental studies of the mechanisms and effects taking place in them. It was concluded that the cross-flow Sieve tray with a high free area and many small holes would offer the best performance. This solution, however, is not commercially viable as the cost of producing a device to these specifications by conventional means would be excessive. To overcome this economic restraint and to retain the improved performance, a cheaper method of tray floor construction was proposed in which the material used was inherently porous.

Many materials satisfy the requirements for use as a tray floor, for example, open cloths, meshes and gauzes and open cell foam and sintered materials. Sorting tests were, therefore, performed on a small scale, using an air-water system, to eliminate those materials which gave unsatisfactory hydraulic performance.

A 68" x 14" column, also using an air-water system, was employed to test the feasibility and the hydraulic performance of the proposed tray floors on a large scale. The same apparatus was then used to determine the liquid mixing

characteristics of the most promising material.

To discover the performance of the new trays under actual vapour-liquid conditions, a 12" diameter, three tray distillation column was built and used experimentally. The separation efficiencies and tray pressure drops were evaluated for total reflux conditions at various vapour rates and outlet weir heights using the systems toluene n-heptane and toluene methyl-cyclo-hexane. The results for the new glass cloth trays showed that better performance could be obtained than conventional trays, particularly with regard to the flexibility.

Various interesting phenomena manifested themselves in marked differences between the results obtained for the same material using the air-water and the hydrocarbon systems. The factors and their effects which produce these phenomena were, therefore, studied using various systems and glass cloths in a 3" diameter column.

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FORWORD.

The volume of published literature on vapour-liquid contacting and related topics is enormous. This study, therefore, only includes those of immediate relevance and those which can be applied directly to it. That is, the literature cited in this work tends to concentrate more on the effects of the changes in design on device performance and only briefly includes more general and theoretical considerations.

The majority of the experimental and derived data obtained in this work are tabulated in the Appendix to the thesis. Only the graphs of the relevant results are included in the body of the text. Also for ease of comparison the graphs of the results are presented together at the end of their corresponding study.

The meanings and units of all the symbols used, if not defined immediately preceding or following the reference to them, can be found in a list of nomenclature at the end of the thesis.

The experimental work presented in this thesis was not carried out in the order in which it appears. Closely related groups of work have been collected together into larger studies for continuity of ideas and for convenience of comparison. However, the general chronological order of the work has been maintained.

SECTION 1

INTRODUCTION.

SECTION 1 INTRODUCTION.

In this work it is proposed to study the process of separation with particular reference to improving vapour-liquid contacting operations.

Many separations are carried out using this means but by far the largest examples of this type are distillation and gas absorption. These two processes are used in the separations and purifications required to produce many of our bulk commodities, the best example being petroleum products. Capital expenditure on distillation equipment alone reaches many millions of pounds per year and so improvements in a field of this size could yield great savings and would, therefore, be most welcome. (1,2).

Very many devices have been used since vapour-liquid contacting was introduced as a commercial operation in about 1815. In the main, however, new devices have been proposed from arbitrary considerations or empirically from overall performance studies on existing devices. In more recent times interest has turned to the more fundamental study of the processes and mechanisms involved in the mass, heat and momentum transfer taking place in the devices. From studies of this sort, carried out during and shortly after World War II, Sieve trays regained the popularity they have today, after

being out of favour for very many years. Since that time much work has been carried out both on the more fundamental aspects of vapour-liquid contacting and in the overall performance of old and new devices. It has, therefore, been the object of the work presented in this thesis to review the present knowledge considering both these aspects and from this study to propose a device incorporating possible improvements for vapour-liquid contacting.

Once the specification for the new device has been laid down, its operation must be studied and its performance evaluated. From these studies the validity of the conclusions and the feasibility of the approach can be verified and the basic knowledge for future work obtained.

SECTION 2 THE CONTACTING DEVICE.

(A Review of Present Devices and their Performance)

Vapour-liquid contacting devices can bring the two phases together in one or more of three ways. Either phase may be continuous whilst the other is discontinuous or both phases can be continuous. This means that the interfacial area between the phases is in the form of the surface of a liquid droplet, a vapour bubble or a liquid film respectively. Most practical devices use all three methods of contact but generally one method accounts for the vast majority of the mass transfer. For example, in a bubble-tray column most of the mass transfer takes place in the frothy dispersion but some takes place between entrained droplets of liquid and the vapour above its surface.

As so many devices have been proposed since the advent of modern commercial distillation in about 1815 it is convenient to study them in groups based on the method of contact by which the majority of the mass transfer is achieved. That is, having i) The vapour as the continuous phase and the liquid as the discontinuous phase. Venturi atomisers, shower and spray type contactors fall into this category by producing droplets of liquid in the vapour.

ii) Both phases continuous. For example, a contactor in which the vapour stream flows over a liquid film as in wetted wall columns or packed towers.

or iii) The liquid phase continuous and the vapour phase discontinuous as in bubble trays where froths and foams are produced.

It is, therefore, proposed to study the performance and potential for improvement of each method of contact in turn. Then, from this study recommend the ways by which improvements in vapour-liquid contacting can be achieved.

2.1 Droplet type Contactors.

(Vapour continous - Liquid discontinuous).

Before contact can be achieved in this way the liquid must be broken up into fine droplets and distributed in the vapour stream. It is, therefore, possible to achieve contact either counter or co-currently within each stage. Each method may be used to give a series of contacts which are countercurrent overall. The limiation of co-current contact to one theoretical stage is thus removed.

Counter-Current Contactors.

Examples of devices using true countercurrent contacting throughout are Showerdecks and Gulf Perforated trays. Each is similar in design and contains a Sieve type tray with many holes in its floor. The Showerdeck uses segmental vapour risers whilst the Gulf Tray uses conventional liquid downcomers. In the case of the showerdeck this arrangement allows the liquid to fall through the holes and thus produce a stream of liquid droplets falling to the tray below. The vapour flows at right angles to the falling liquid across the space between the trays to the riser segment at the opposite wall.

Zuiderweg (6) found that the performance of showerdecks was not outstanding when compared with conventional Sieve

trays. Under the correct operating conditions, that is, when the liquid was raining from the trays, the separation efficiency was very low. In the higher part of the capacity range, when the liquid was stripped from the underside of the trays and thrown to the opposite wall by the vapour flow, the efficiency rose markedly. However, not only is the efficiency low, but the operational flexibility is low also. These findings have been verified by other workers (7,8). Nevertheless Ross suggested that showerdecks could be useful if a packed tower would not satisfy the process requirements where a short tower with high liquid loading was needed.

Gulf perforated trays (9) are used as high tray spacing, Sieve trays with no outlet weirs. The small amount of liquid on the tray is, therefore, thrown into the space between the trays by the high vapour rates employed in this device. Unfortunately this arrangement gives columns which are tall due to the large tray spacing needed to overcome entrainment and of small diameters due to the large vapour capacity of the trays. Columns of these dimensions lead to more difficult mechanical design of the column shell, its supports and foundations. However, very limited data is available on both these types

of trays in industrial applications and little popularity has been achieved as neither have outstandingly better performance than conventional trays. Furthermore, there does not seem to be much potential for great improvements (10).

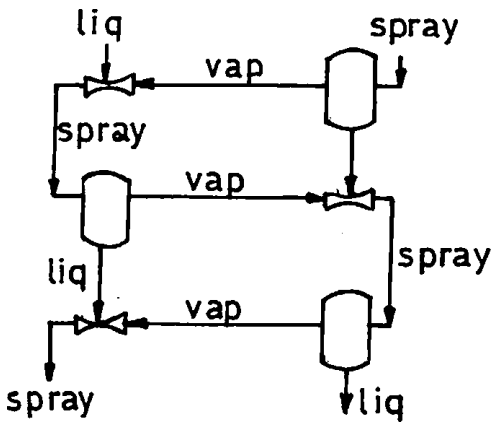
Co-Current Contactors.

It has been found (11) that whilst the "height" of a theoretical unit increases with vapour rate for counter-current flow, it remains almost constant for co-current flow. For this reason cocurrent contactors have been usefully investigated as elements in an overall countercurrent system.

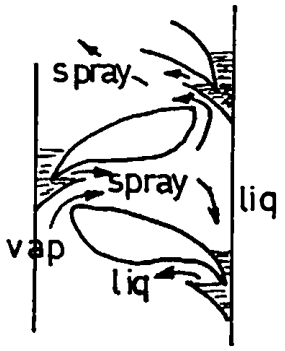
As previously mentioned the liquid must be atomised within the vapour stream and unless mechanical means are used the droplets must be generated by a high velocity vapour stream. High velocities can give two advantages. Firstly, they permit higher column velosities to be used leading to more compact equipment, and secondly high rates of shear can be obtained promoting high heat and mass transfer coefficients.

It is of historical interest to mention two inventions that employed the cocurrent method of vapour liquid contacting. In the first, by Underwood (12) in 1934, a pot still was used in conjunction with perforated tray type atomisers and cyclones to separate the phases after contact. In the second, by Ravier (13), a series of venturi elements and

cyclones were arranged so that the liquid was fed back from a cyclone to the throat of the previous venturi-cyclone pair whilst the vapour passed on to the next venturi, (see fig. 2.1) Neither of these inventions achieved any commercial success, but interest has been revived in this method of contact in recent years. Berry (14) described an apparatus in which horizontal venturi elements were placed vertically above each other in a rectangular column, (see fig.2.1). The liquid flowed down from stage to stage and was atomised at the venturi throat by the vapour stream. Separation of the phases took place at the column wall where the vapour flow turned through about 180° to the stage above. Another recent device proposed by Poplavasky and intended for Soviet oil refineries and petrochemical plants used many concentric pipe elements fastened vertically through the trays in the tower (15,16,17,18), See fig. 2.1. Liquid from a down pipe was carried upwards in the surrounding annular space by the vapour from the floor below. A cup was attached to the lower end of the down pipe to give a hydraulic seal. The liquid spray in the vapour leaving the annular pipe impinged on the bottom of the tray above and the phases separated. The liquid passed down the next lower

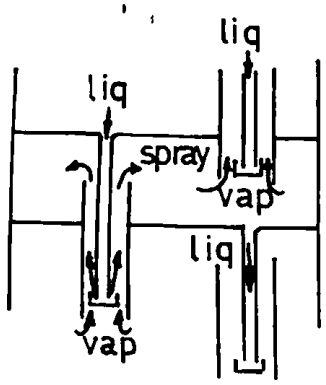


RAVIER'S SYSTEM[13]

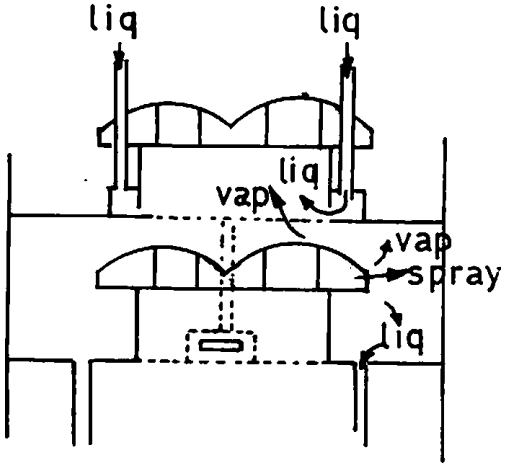


BERRY'S CONTACTOR[14]

FIGURE 2·1 SPRAY TYPE DEVICES



POPLAVASKY'S CONCENTRIC TUBES[15,16,17,18.]



AKKERMAN'S CONTACTOR[24,25]

down pipe whilst the liquid flowed up into the next higher contacting tube.

Unfortunately no information is available on these contactors so their performance cannot be studied.

Venturi Atomisers.

Fundamental mass transfer studies have been carried out using venturi contactors (19-23). Although the efficiency obtained approaches 100% the pressure drop across the venturi is high, (9" W.G.), when the vapour rate is high (150ft/sec.). However, this pressure drop does not compare favourably with conventional trays and the liquid loadings are small when compared to vapour loadings. Similar liquid vapour ratios are encountered in vacuum distillation, but for this service the pressure drop must be extremely small.

Lower throat velocities have been used to achieve lower pressure drops, but in general there is a large fall in efficiency (17), (See fig. 2.2). At low vapour rates (up to 25ft/sec.) the liquid remains in an unbroken jet from the tip of the inlet nozzle. As the velocity increases the efficiency increases slowly from about 40% to 50% due to the jet beginning to oscillate. At about 50ft/sec. the jet begins to break up accompanied by a rapid increase in efficiency to about 80%. Once the transition region is left the droplets become smaller and the efficiency

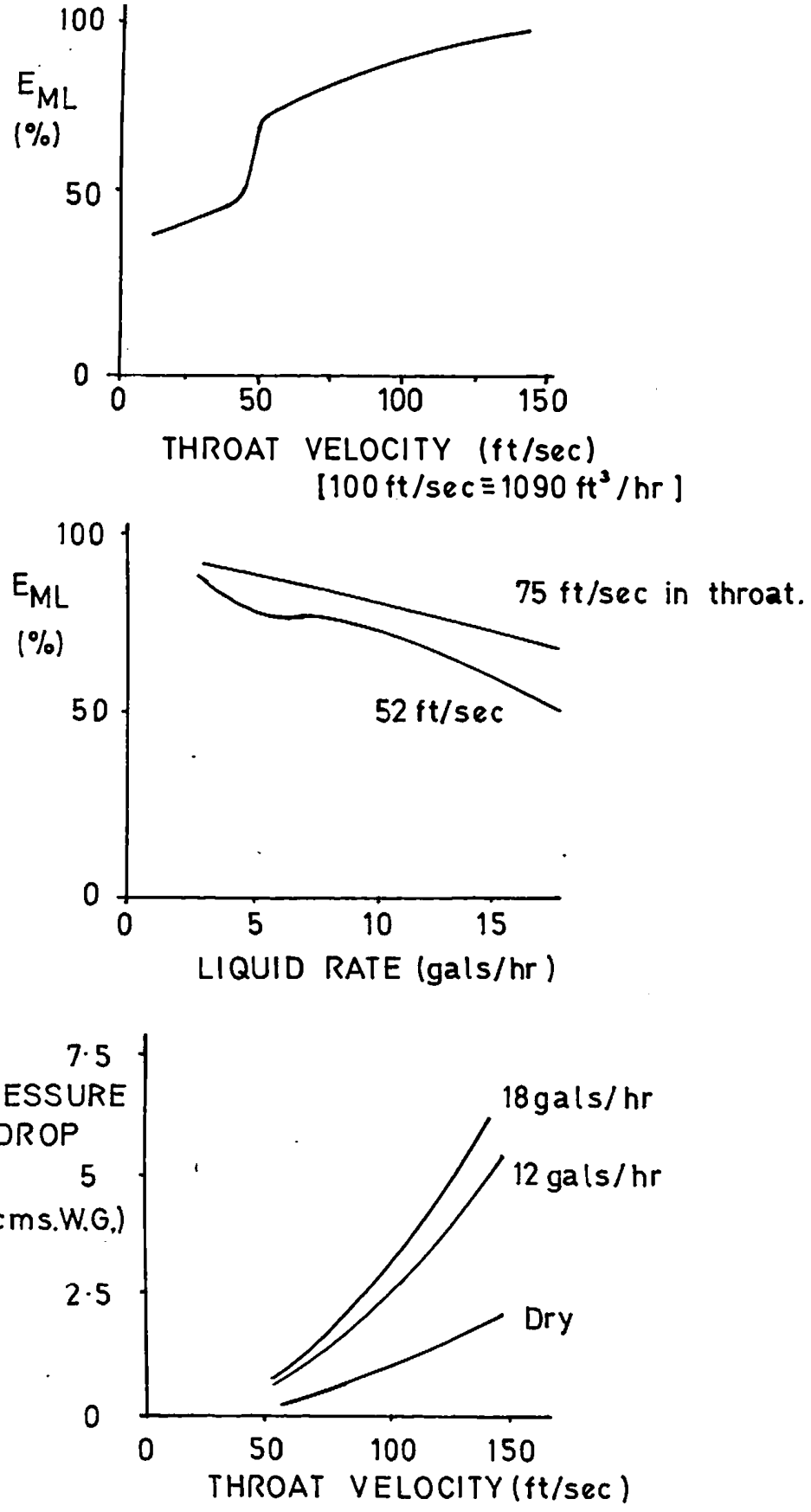


FIGURE 2·2 VENTURI ATOMISER PERFORMANCE[17].

shows a corresponding slight increase to about 90% at 150 ft/sec. This work also verifies that the majority of mass transfer takes place immediately after formation of the droplets. Johnson (19) found that equilibrium was almost reached in less than one millisecond in a vapour velocity of 200ft/sec. The inherent disadvantage of high velocity streams giving short contact times is, therefore, much reduced in effect.

However, the efficiency falls with liquid rate at constant vapour rate because of the poor dispersion of the jet resulting in the formation of larger droplets. At higher vapour velocities much better atomisation takes place and higher liquid rates can be used without loss in efficiency. Unfortunately the pressure drop also increases with liquid rate, but on the combined counts of efficiency and pressure drop the venturi atomiser is a reasonably attractive device for mass transfer if operated at lower velocities. The pressure drop and efficiency are reasonable in this operating region, but the flexibility is very limited especially if the vapour load has to be reduced. Furthermore, the advantages of this type of device tend to be more than offset by the volume of the device for its liquid flow rates. This is mainly due to the large vapour to liquid ratios need to achieve satisfactory atomisation, and the large spaces needed for separation of

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the phases after contact.

Akkerman (24,25) suggested a solution to the latter problem by using centrifugal force to aid the separation of the phases, (see fig. 2.1). This unit consisted of a stationary impellor from a centrifugal fan placed above a sieve tray type contactor. The liquid flowed onto the perforated tray floor and was carried upwards in the vapour stream. Both phases flow through the blades of the impellor whence the liquid is separated to the walls of the column. The vapour flows through the sieve holes of the tray above whilst the liquid flows down the pipe to the next lower tray. No details of the performance are available except that a higher capacity per unit volume than Poplavasky's concentric tubes (15,16) can be obtained. Other devices using centrifugal force to separate the two phases after contact have been suggested, but information on their performance is also very limited. (22,23,26,27).

In conclusion it can be said that this method of operation will not produce as good a device as conventional bubble trays which out-perform it in almost every way.

Showerdecks lack the high flexibility and efficiency of conventional trays whilst spray type trays lead to tall thin towers which give extra difficulties in mechanical specification with no corresponding increase in performance.

Venturi type contactors can give very high mass transfer efficiencies, but when allied with unacceptably high pressure drops at high vapour rates and the need for large disentrainment spaces they are not commercially feasible. Venturi type devices can be run at lower vapour velocities to reduce the pressure drop, but the mass transfer flexibility falls off drastically and very low liquid to vapour ratios must be used. Their only possible field of application using these loadings is vacuum distillation, but in that case the pressure drop should be exceptionally low.

The most promising designs using this method of contact would use multiple banks of concentric tubes and centrifugal separation. Although much work has been done in Russia on this type of device, little useful information is available, and it is probably best to note their progress (10)

On the whole, therefore, it does not appear that any device using this method of contact can achieve the all round good performance of more conventional devices. For the purpose of this study it is, therefore, irrelevant to consider the present group of devices in more detail.

2.2 Liquid Film Type Contactors.

(Both phases continuous).

The basic element of this type of device is a surface over which the liquid flows in a thin film. There have been many proposals for methods of producing a liquid film, but the most successful are undoubtedly columns filled with small packing pieces. For general performance and low cost randomly packed beds are best (28-32). There are many types of packing pieces used for this purpose but in general they range in size from $\frac{1}{2}$" to 3" (28-34). Although smaller pieces will give a higher surface area per unit volume of packing the flow path for the vapour is more tortuous and the pressure drop is, therefore, higher. Also the whole of the packing surface is not wetted by the liquid and, therefore, the amount of mass transfer taking place in a given volume of packing is much reduced (28-32,35). The fraction of the available surface area that is wetted increases with better design of packing pieces and with an increase in packing size but never reaches unity. However, as the packing size is increased the amount of channelling through the bed increases. In small columns maldistribution occurs both by channelling through the bed and by preferential liquid flow down the column (36,37). This maldistribution drastically reduces the mass transfer performance of all packed columns, (6,28-32,38) but is most

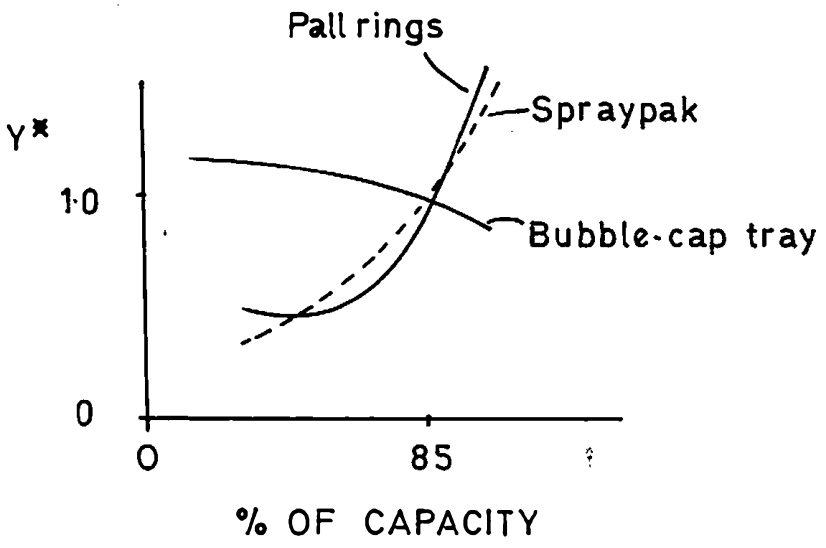
marked where the ratio of the column diameter to the packing diameter is less than about thirty. (36,37). For this reason it is much more difficult to scale up packed columns from small scale apparatus than to do the same for tray columns. Also due to their tendency to maldistribution packed columns are particularly sensitive to the initial distribution of the feed or reflux liquid streams. Moreover they must be provided with redistributors at frequent intervals so that the loss of efficiency due to maldistribution is reduced to a minimum. The provision for adequate redistribution can markedly increase the cost of a packed column for a given service.

The efficiency of packed columns is affected in two different ways at each end of their operating range. If the vapour rate and liquid rates are reduced less of the packing is wetted and the efficiency falls. The effect on large packings is greatest at low liquid loadings but at high liquid loadings the bed floods most easily with small packings. These limitations make the range of flow rates available for use from a given packing narrower thus giving packed columns a lower flexibility than conventional tray columns (1,38-41),(See fig.2.3).

Randomly packed columns tend to have a few advantages over tray columns. In general the pressue drop for a given duty is marginally lower (39,42). Also packed columns

FIGURE 2·3

COMPARISON OF FLEXIBILITY OF PACKED COLUMNS WITH BUBBLE-CAP TRAYS[6]



* [Y = RATIO OF EFFICIENCY AT A GIVEN PERCENTAGE OF THE COLUMN CAPACITY WITH THAT AT 85% OF THE COLUMN CAPACITY]

tend to be the better choice when considering corrosive service, but cannot be used so well for foaming systems or those containing sludges or suspended solids (39).

However, packed columns do have many disadvantages not encountered when using tray columns. It is more difficult to introduce or remove feed or side streams without being involved in the extra expense of redistribution plates. Also when removing or adding heat, as in an absorption column, it is usually necessary to pass some of the liquid from the column through an external heat exchanger instead of using internal coils as can be used on bubble trays (39).

If a column is subject to loading changes or to frequent shut down, packed columns are not so good as plate columns as the packing pieces are much more easily damaged by thermal and mechanical shocks.

Although a packed column tends to be shorter and greater in diameter than a tray column for the same duty its total weight is generally much greater. Even though packing supports can be used to prevent the packing pieces being crushed at the bottom of the column, a more serious problem is the greatly increased expense of the more substantial foundations needed for a packed column. However, newer plastic packings can drastically reduce the weight of

a column, but unfortunately they can only be used for moderate temperature duties. (39,43).

In some cases where high liquid or vapour rates are to be used stacked packing pieces, generally bigger than 3", can be considered, but little data is available on their performance. It has been found that the simpler designs of packing, such as Lessing rings, give better performance than more complex designs using fluted or twisted packing pieces. In general, however, the extra performance gained is more than counterbalanced by the extra cost of stacking the pieces in the column (32).

One duty where liquid film devices come into their own is vacuum distillation. Very low pressure drops are essential to protect the product from heat damage or to gain a product at all. Many devices have been proposed and they fall into two groups. One group uses vertical flow surfaces such as multiple wetted wall columns whilst the other group uses moving ports to produce and maintain a liquid film and to keep the pressure in the still low. (5,44-49).

However, this is a specialised application for very high vapour volumes and low liquid loads and is not relevant to general distillation as carried out at higher pressures where the performance of these devices is very poor.

Most Authors agree that packing pieces have been improved considerably since Raschig rings were first introduced, and there are many applications where packed columns can be used to advantage. However, for general distillation packed columns are not considered a practical proposition for column diameters greater than about 2 feet as plate columns can give better performance at a cheaper cost (36,39,43,50-52).

Nevertheless, it is certain that a very useful gain could be achieved if the surface of each packing piece could be fully wetted and if maldistribution in the column could be reduced. The most elegant solution to these problems would be an improvement in the design of the individual packing pieces. Attempts have been made to design theoretically sound packing pieces, but at present insufficient basic knowledge and understanding of the mechanisms and flow pattern phenomena is available for this purpose.

2.3 Bubble Type Contactors.

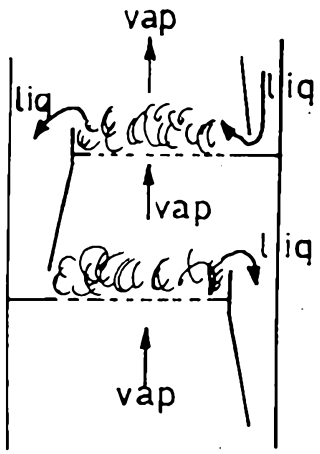
(Liquid continuous - Vapour discontinuous.)

All devices considered so far have been compared with conventional bubble-trays and it has been found that these trays offer more advantages than the two previous methods of contact. It is, therefore, proposed to consider various bubble-tray devices and to study their operation and performance in more detail.

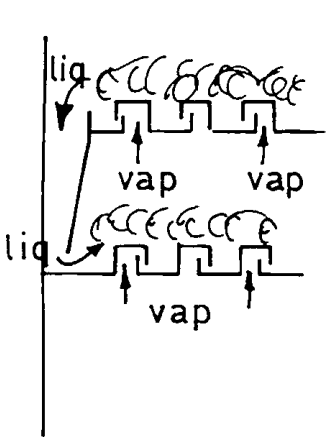
The vast majority of devices using the surface of bubbles as the contacting interface use trays upon which the liquid and the vapour are contacted in a frothy dispersion. The liquid flows onto the tray whilst the vapour flows through the tray from the underside and thus maintains the dispersion. In general these trays are arranged substantially one above the other so that the liquid and vapour streams may be brought into contact more than once and that the flow of the two phases is essentially counter-current. The liquid, however, may flow either in a truly countercurrent manner with the vapour or it may flow across the trays at right angles to the vapour flow through the tray. The liquid is then passed onto the tray below via a liquid downpipe or downcomer. The pattern of liquid flow gives a ready method of classification of trays into counterflow and cross-flow types, (See Fig. 2.4).

FIGURE 2·4 BUBBLE TRAY CLASSIFICATION

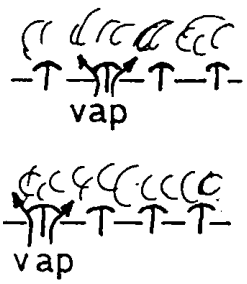
CROSS-FLOW TRAYS



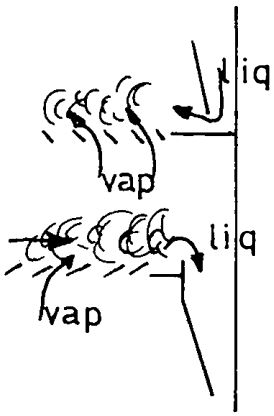
SIEVE TRAY



UNIFLEX TRAY

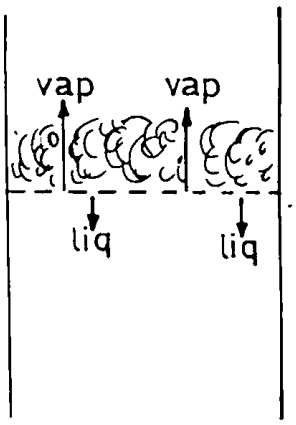


VALVE TRAY

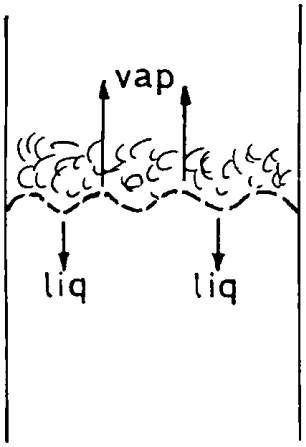


JET TRAY

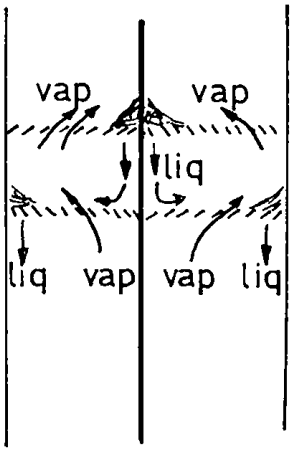
COUNTER-FLOW TRAYS



TURBOGRID



RIPPLE TRAY



KITTEL TRAY

The crossflow type tray has been used from the advent of commercial distillation. In fact the two trays which gained immediate acceptance, namely Bubble cap and Sieve trays, are, after many modifications, still in widespread use today. These two trays illustrate the principle methods by which the liquid is kept on the trays. The Bubble-cap tray and its many modifications and improvements, the Tunnel cap tray and the Uniflex tray (53-56), use a mechanical seal to prevent the flow of liquid bypassing the tray by falling down the holes intended for vapour flow. The Sieve tray (56,57) and other similar devices, such as the Protruded Sieve tray (58-60) and the Jet tray, (2,61-63), use the kinetic energy of the vapour stream to preserve its own flow path through the holes in the tray floor. However, it is possible to use a combination of these methods by using a tray construction which allows the free area for vapour flow to change such that the kinetic energy of each vapour stream is sufficiently high even at low vapour loadings. The vapour flow area may be changed mechanically by an arrangement such as a flap valve, as in the Valve, Ballast or Flexitrays (54,56,64,65), or by a liquid seal held between two plates as in the A.P.V. West (66) Monticatini (67), Nagbarth (68,69) or other similar trays. (70-72). A.P.V. West trays also use

a bubble-cap arrangement to complement this system.

Counterflow trays received an increase in interest during the early 1950's due to the publicity given by Shell to its Turbogrid tray (56,73-77). About the same time many other counterflow trays appeared on the market and were advertised by many manufacturers, for example Ripple Trays (78-80) and Kittel trays (81-84).

The basic principle of this type of operation is that the liquid and vapour are not provided with separate flow paths through the tray. Both phases are allowed to flow through the holes in the tray floor and so downcomers are eliminated. The froth produced on these trays is similar to that produced on cross-flow trays except that the overall liquid flow direction is vertically downwards, in counterflow with the vapour. In normal operation the liquid flows through the holes in the tray floor due to the production of local hydraulic gradients. That is, where the head of liquid over a hole is greater than the pressure difference across the tray floor, that hole will be used for liquid flow. Conversely the vapour will flow through the holes under a lower liquid head. In its usual form the Turbogrid tray is constructed from parallel bars held in position by a retaining ring. The local hydraulic gradients are, therefore, produced in a random but changing position on the

tray. (73-76). On the other hand the construction of Ripple and Kittel trays allows the build up of liquid at certain points on the tray thus ensuring liquid downflow at these points. Ripple trays are constructed from thin perforated sheet pressed into a sinusoidal wave form which gives a liquid build-up at the bottom of each trough. So that the liquid cannot fall straight down the column from one tray to the next, the direction of the waves in the tray floors are set at right angles on alternate trays (78-80).

Kittel trays are made from expanded metal sheets arranged in such a way that the liquid is thrown by the kinetic energy of the vapour stream to the centre or to the walls of the column on alternate trays. The build-up of the liquid at these points gives the hydraulic head for liquid downflow (81-83).

Contactors other than bubble trays, yet falling into this general classification by using the surface of bubbles as the contacting interface have been proposed, but never received any popularity due to their inferior performance. For example a liquid filled venturi contactor was proposed by Bauer (85), but its pressure drop was in the region of 500 mm.Hg. as opposed to about 5 mm.Hg. for normal bubble trays.

It is, therefore, intended to study the properties of the bubble tray devices which are in widespread use at present.

Also by considering the factors and their effects on the operation and performance of these trays it should be possible to specify an improved device which will exploit this method of contact by increasing the advantages and decreasing the disadvantages of conventional trays.

In a study of this sort the properties of most interest are those associated with that particular design which govern the cost to achieve a given duty of throughput and separation. They fall into three general groups. Those properties which affect the size of equipment, namely the capacity and the separation efficiency. Operational considerations are the mass transfer flexibility, the controlability and the pressure drop whilst the cost of the equipment will depend on the tray cost itself and the maintenance costs.

Before considering the factors which affect the tray properties it is of interest to compare the performance of each group of bubble tray devices in use at present. Many comparisons have been made in the past and in general it has been useful to present the performance not in absolute terms, but compared with a standard. As Bubblecap trays have been used so extensively in the past it has been general practice to use these trays as a base from which to measure the performance of others. In comparing performance of a device a Bubblecap column of the same dimensions has been used. In some cases the cost has been measured against that of a

Table 2.1 Tray Performance Compared with Bubble cap trays.

Property / Tray	Equipment Size		Operational Considerations		Equipment Cost	
	Capacity	Optimum Eff.	Flexibility	Pressure drop	Tray Cost	Corrosive or dirty Service
Tunnel cap	Similar	Similar	Similar	Similar	0.8 - 0.5	Similar
Uniflex						
Valve	20-50% higher	5-10% higher	higher	slightly lower	0.67	better
Sieve	20-40% higher	10% higher	slightly lower	much lower	0.6	worse
Turbo grid	20-40% higher	slightly lower	much lower	much lower	0.7-0.5	better
Ripple						

Bubblecap column needed to perform the same duty, but this cost includes such factors as increased capacity, and if possible, we want to study each factor separately.

Table 2.1 gives an average comparison of the principle tray properties. (1,2,6,53-57,61,64,66,77,86-100).

2.3.1 Capacity.

The vapour and liquid handling capacities of a device correspond to the maximum loadings that can be used before the separation efficiency falls off drastically. This property is highly important as it governs the column dimensions. The tray diameter will be determined by the maximum liquid and vapour tray loadings and as the capacity also depends on the tray spacing the column height will be affected.

At higher operating conditions the efficiency and thus the capacity can be affected by three major phenomena, namely entrainment, priming and flooding.

The entrainment of the liquid by the vapour stream can affect the separation efficiency of the device in two ways. By holding droplets of liquid above the surface of the froth on the tray, the contact time and the interfacial area can be increased thus enhancing the separation (2,101,102). However, if the liquid droplets do not separate from the

vapour but are carried to the tray above, and then mixed with the liquid on that tray, the effective separation will be reduced. As the vapour velocity is increased the latter effect becomes more and more marked until it causes a substantial loss in the separation achieved by the tray.

Very many studies have been carried out to find the extent and mechanism of entrainment on all types of bubble trays (1,2,6,56,58,75,76,86,89,90,92,97,98,102-121). All have found that the entrainment increases with vapour rate and decreases less markedly with an increase in the liquid loading. Also the smaller the tray spacing the greater the detrimental effect of entrainment.

The froth on all trays is similar but Bubble-cap and Tunnel trays produce the greatest amount of entrainment. Sieve trays give about one third this amount whilst Protruded Sieve trays are able to reduce the entrainment produced by half again (58,60). Grid trays and Valve trays give values for entrainment in the same range as Sieve trays.

Many empirical relationships have been proposed to predict the entrainment but in general they use different constants and variables for different types of devices (107,122-126). For example, the Souders-Brown equation (123,127) has been used to find the maximum allowable vapour rate before entrainment becomes excessive.

$$U = K \cdot \sqrt{\frac{(d_L - d_V)}{d_V}}$$

This is given in terms of the liquid and vapour densities (d) but K depends on other physical properties and the type and geometry of the equipment. However, the main function of equations of this type is to predict tray spacing and so they are of little use in this study where the interest is centred round the effects and mechanisms of the operation of trays rather than the design techniques .

Many mechanisms have attempted to explain the varying amounts of entrainment produced at different loadings and by different devices. Teller (119) and others (116-117) suggested that when the bubbles in the froth burst or coalesce droplets are formed which are carried away by the vapour stream. Also they explain the increase of entrainment with vapour rate due to the production of larger bubbles. To support this contention many workers found that the entrainment was a function of liquid surface tension. This physical property has an effect due to the loss of the excess energy when the bubble bursts (107,111,120).

However, Bakowski (114) and others (127,219) have shown that for bubble trays bubbles are not formed discreetly but that the majority of the vapour flows in channels through

the froth. Also Mayfield (109) and others (107,110-112) have explained that entrainment is reduced for sieve trays due to the more uniform vapour distribution and less tendency to jetting than bubble-cap trays. To support this explanation it ~~has~~ was found that entrainment is much higher for sieve trays with larger holes than smaller ones. (102,109-112,121). Moreover Protruded Sieve trays are explained to give less entrainment due to the vapour being introduced smoothly into the froth. In most cases the kinetic energy of the vapour stream is sufficient to tear off droplets of liquid lying adjacent to the vapour flow path. If the kinetic energy of the vapour stream is higher as in bubble cap trays or large hole Sieve trays then so is the amount of liquid entrained. Similarly if the vapour rate is increased so is the entrainment but as the liquid holdup on the tray is increased more of the kinetic energy is absorbed by the bulk of the liquid and the entrainment is reduced.

This explanation is supported by the low amounts of entrainment produced by valve or jet trays in which the vapour is introduced into the froth almost parallel to the tray floor (2,61,65).

Also when the dispersion on the trays changes from a cellular foam to a turbulent froth there is a marked increase

in entrainment (106,118). This phenomenon cannot be explained satisfactorily by bubble bursting but is consistent with the kinetic energy proposals. The effect of surface tension on entrainment can be explained by the energy needed to detach the droplets from the surface of the liquid.

Therefore, if the amount of entrainment is to be reduced by tray design, a good vapour distribution is required by which the kinetic energy of each vapour stream can be kept low. That is, a high free area and a small hole diameter are needed and, if possible, the vapour stream should be introduced into the froth smoothly or parallel to the tray floor. It is also an advantage to have a high liquid hold up to reduce the amount of entrainment.

Priming occurs when the froth on one tray reaches the tray above. This condition causes a drastic loss in separation as well as a large increase in the pressure drop of the column. However, priming usually occurs when a low liquid hold-up and low vapour rates are used for a foaming system. Under these conditions a cellular foam is produced and priming ensues if the tray spacing is not large enough. In general contacting devices are not operated in this flow regime and entrainment is usually excessive before the dispersion reaches the tray above.

Flooding can occur for two different reasons depending

on the type of tray used, but in each case there is an excessive liquid build-up on the trays. This condition obviously causes the column to cease operating correctly.

For cross flow trays, flooding ensues when the liquid downcomers are unable to handle the high liquid flow rates demanded of them. Starting at the top tray in the column, the liquid builds up as the liquid flow rate onto the trays is greater than that from them. The liquid flow rate in the downcomers can be increased by increasing the available liquid head in them or by increasing their size.

The available head in the downcomers depends on the pressure drop across the trays and the tray spacing. The pressure drop of trays is discussed more fully later but at present it is sufficient to note that the pressure drop increases with liquid hold-up and is affected by tray design. The liquid hold-up can be reduced by increasing the liquid flow from the trays by using different flow patterns. Huang and Hobson (127) give the wide range of liquid to vapour flow rates which can be handled by a normal cross flow pattern. They advise split or radial flow for high liquid loadings and reverse flow for low liquid loadings.

The maximum head in the downcomers can be increased by increasing the tray spacing but this is not a very useful

solution as it also increases the column height and thus cost.

The liquid flow rate through the downcomers can be increased by increasing their size but many modern workers (127-135) have found that liquid loads as high as two to three times the conventional design ratings can be handled without difficulty.

Flooding in counterflow tray columns will occur when the kinetic energy of the vapour flow through the holes is sufficient to hold back the liquid in such amounts that more flows onto the tray than flows through it. However, for a reasonably designed tray entrainment is excessive before this situation is reached (103). If higher liquid loads are anticipated the free area of the tray is increased at the design stage.

In conclusion, therefore, it can be seen that the capacity of bubble trays is governed by the amount of entrainment produced at high vapour rates. The entrainment can be reduced by providing good vapour distribution where the kinetic energy of each vapour stream is low or by introducing the vapour into the frothy dispersion either smoothly or parallel to the tray floor. Each of these factors may be enhanced by increasing the liquid hold-up

on the tray. However, if this is done excessively the pressure drop and thus the chance of flooding will be increased. Although flooding is not generally a major limitation on the capacity of bubble trays it can become dominant unless adequate precautions are taken at the design stage of a tray.

By taking advantage of one or more of the above factors most modern trays have capacities greater than conventional Bubble-cap trays. Various claims have been made but on average each type of trays has a capacity 20% to 40% higher than Bubble-cap trays. Tunnel-cap and Uniflex trays have about the same capacity as Bubble-cap trays as they are very similar and do not exploit more of the advantages than Bubble-cap trays.

2.3.2 Separation Efficiency.

An obvious requirement for a bubble tray is that the maximum amount of mass transfer possible should take place on it. The tray efficiency should, therefore, be as high as possible as this will determine the number of actual trays in a column for a given separation. We must consider, therefore, the separation efficiency of the trays at their optimum loadings.

Many definitions of efficiency have been proposed from Lewis' (137) and Murphree's (136) to more modern ones such

as Standart's (138,139). All have disadvantages but the Standart definition seems to offer more advantages than draw backs (140). Most authors agree that the overall tray efficiency is needed and this can be found by considering the point efficiency in the froth on the bubble tray. The point efficiency is governed by the amount of mass transfer which takes place and this in turn is affected by the conditions in the froth on the tray. Geddes (148) and others (177) have considered the mass transfer taking place in the froth and found that the point efficiency (Ep) is given by:-

$$-\ln (1 - E_p) = K_c . a . t$$

The amount of mass transfer between the two phases will, therefore, depend on the mass transfer coefficiency (Kg), the interfacial area (a), and the contact time (t). Once the point efficiency is known the overall tray efficiency can be found by considering the mixing on the tray.

The mass transfer coefficients have been determined for both liquid and gas film controlled conditions and empirical relations produced by the investigators in the Universities of Delaware, Michigan and N. Carolina. The American Institution of Chemical Engineers used this work for its 'Bubble Tray Design Manual' (122,141-143). It was found that the mass transfer coefficients were affected only by the physical properties of the system being distilled.

Most published work both before and afterwards has agreed with these findings but has disagreed on the physical properties to be used in the determination of the coefficients (137,144-150). However, it has been found that the mass transfer coefficient is enhanced by internal circulation in bubbles, but that this depends on the size of the bubble and the physical properties of the system (141,151).

The interfacial area between the two phases is governed by many factors, the physical properties of the system; the hydraulic conditions on the tray, the tray itself and combinations of these. The largest changes in interfacial area occur between the two stable regimes of liquid vapour dispersions namely foaming and frothing conditions on the tray. The existance of a surface tension gradient at the interface can either aid or hinder the stabilisation of a cellular foam (152-159) and produce a marked increase in the interfacial area. However, for advantage to be taken of these physical phenomena the conditions on the tray must be favourable to the formation of a cellular foam (106,140,160-162). However, Bainbridge and Sowistowski (153) point out that bubble trays are generally operated under conditions unfavourable to the formation of cellular foams but favourable to the production

of turbulent froths. Under frothing conditions the interfacial area depends on the absolute value of the surface tension as well as the surface tension gradients (163,164). Nevertheless Zuiderweg (6) and others (92,102,162) noted that devices with small orifices derived greater advantages from a given system than those with larger holes. With large holes the vapour channels through the dispersion and thus reduces the interfacial area (114,127) whereas smaller holes give a better vapour distribution and favour the formation of foam with a higher interfacial area.

Many other physical properties affect the interfacial area in the dispersion (95,106,140,145,165,166) but those not dependent on the tray itself are of little interest in this study. Heckman found that all types of bubble trays behave similarly with respect to these properties (95).

Garner and Porter (167) have pointed out that there are three distinct regions distinguishable in the dispersion on a bubble tray. Next to the tray floor there can be seen a clear liquid layer which gives little interfacial area as the bubbles pass through it at high velocity. The thickness of this layer depends on the design of the tray, being thickest for Bubble-cap trays. Valve and Sieve trays give a thinner layer, in the case of Sieve trays due to the

better vapour distribution at the tray floor and due to the vapour flowing parallel to the tray floor in the case of valve trays (65).

Above the froth on the tray is a spray of entrained liquid which can enhance the enrichment achieved by the tray but does not generally represent a major fraction of the interfacial area until very high vapour velocities. The majority of the interfacial area on a bubble-tray in its normal operating range is produced in the froth and it is this region which has attracted most study.

The effect of the bubble size in the froth on the interfacial area has been studied by many workers but most of the work cannot be applied to distillation studies as it is either in the wrong flow regimes or under the wrong conditions (168,169). In commercial distillation chain bubbling at constant pressure of formation occurs (168-171). For multiple orifices over a wide range of hole sizes the bubbling rate is constant at about 15-20 per second once a critical low vapour velocity has been exceeded. In this case the surface area of the bubbles depends only on the number of orifices and the vapour rate (170-172).

The effects of the various hydraulic conditions, liquid and vapour hold-ups (144,173-177) and the vapour and liquid rates (92,102,178,179), on the interfacial area have been

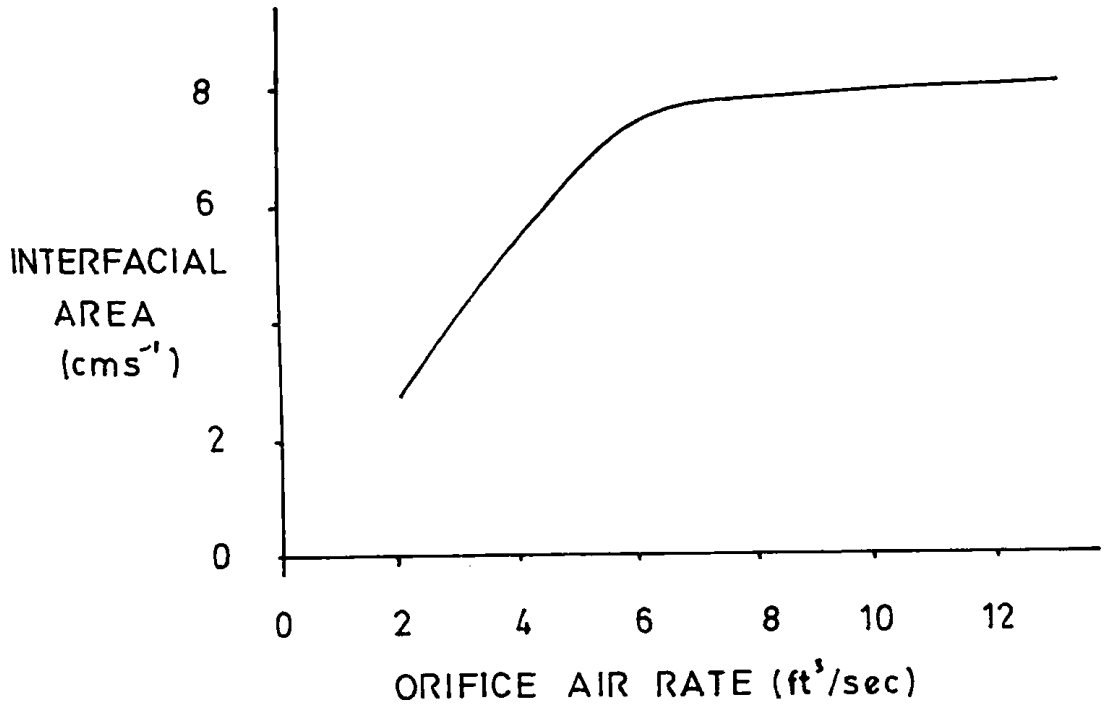
studied but it has been found that the effect of each one cancels the others and the interfacial area remains almost constant. Therefore, when studying the interfacial area produced on a Sieve tray, Calderbank and others (166,170-177, 180) found that after an initial increase with vapour velocity the interfacial area remained virtually constant for the rest of the range (See Fig.2.5). Even though Porter (181) and Sargent (182) disagree with the values of the interfacial area found in these studies, as they are confined to the region near the wall of the column, they nevertheless both confirmed that the interfacial areas produced by bubble trays are virtually independent of most of the operational variables associated with the tray.

Contact Time.

Many early workers supported the theory that the bubbles in a froth rose with the terminal velocity of a free bubble and therefore, the contact time was independent of vapour rate (183,184). However, more modern workers have found that bubbles tend to push each other through the froth at a rate proportional to the vapour velocity (114,127,141,177). This proposition is supported by others who found that even though the froth height increases with vapour rate the contact time appears virtually

FIGURE 2·5

THE EFFECT OF AIR RATE ON INTERFACIAL AREA[172].



unchanged (102,112,144).

The contact time can be increased if the froth height on the tray is increased by increasing the liquid hold up either by changing the liquid rate or the weir heights.

Obviously the contact time can also be changed by the physical properties of the system being distilled. For example, high viscosity liquids tend to retard bubble rise (145,165), but this is of little interest in this study as these effects are not modified by the tray.

It is also relevant to consider the layer of stagnant clear liquid next to the tray floor as the bubbles rise through it much more rapidly than through the bulk of the froth. By reducing this layer and replacing it with froth the contact time can be increased. As explained previously Sieve trays and Valve trays have thinner stagnant clear liquid layers than Bubble-cap trays. (65,167).

As the interfacial area can be increased by the presence of entrained liquid droplets in the vapour so can the contact time. Moreover the vapour entrained in the downcomers can also increase the average contact time between the phases. Under normal conditions an increase of 5% to 10% in the efficiency can be obtained by using downcomers (102,115). However, if either of these effects becomes excessive the

efficiency will fall markedly.

Mixing effects had been mentioned previously but Lewis (186) was the first to set out the various combinations of mixing that could be achieved using cross flow trays. He considered the effects of complete mixing or complete unmixing in both vapour and liquid streams.

Lewis found that a lack of mixing in the vapour could be advantageous if the liquid flow was in the same direction on successive trays. This flow technique has been used with success in the distillation of liquid air where very close tray spacings are used to reduce loss of cold (121). However, it has been shown that in conventional distillation columns vapour mixing is almost complete and any variation in the vapour is due to entrained liquid droplets. At optimum operating conditions the entrainment reaching the tray above is low and so the vapour can be considered completely mixed (186-190).

Advantage can be gained if the liquid is not completely mixed but the extent of the advantage depends on the degree of the lack of mixing. However, the circulation on a bubble tray is highly complex and renders the postulation of an accurate and useful mechanism for predicting the mixing from fundamental hydrodynamic considerations impossible.

As the flow patterns on bubble-trays cannot be analysed

rigidly various simplified models have been proposed. Kirschbaum (189) and others (191) have used a model in which the tray is divided into a number of pools, completely mixed within themselves but completely unmixed with the surrounding pools. Oliver (187,188) and others considered that a certain fraction of the liquid stream flowed from the outlet weir back to the inlet weir whereas Johnson (192) suggested that the majority of the mixing took place by splashing back upstream. Gerster (193) and many others (194-197) have used the frequency response and the residence time distribution on the tray to characterise the degree of mixing. Dankwerts (198) proposed that liquid mixing could be represented by the simple laws of diffusion and many others have used this model (144,199-202). However, even though these concepts are useful in the prediction of tray efficiencies they contain empirical constants which have to be determined for each type of tray and cannot, therefore, be used directly in this study. Nonetheless it has been noticed from these empirical constants that Sieve trays give froths which are not as well mixed as those on Bubble-cap trays (199-201). This is probably due to the froth being less turbulent and having less tendency to jetting. This assumption is confirmed by Sieve trays with small holes and low free area giving less

mixed froths (203).

The amount of mixing on a tray can be altered by the operating conditions such as vapour and liquid rate and weir height but all trays seem to be affected in a similar way so no type of cross flow tray seems to gain any advantage.

Counterflow trays give froths which are almost completely mixed and a liquid path which cannot be increased in length as the tray size increases. The value of their tray efficiency is limited to the point efficiency. This limitation can be a considerable disadvantage (65) as tray efficiencies on cross flow trays can be enhanced to values well over 100% if the liquid is unmixed over a long flow path (187,188).

It can be seen that for general distillation the separation efficiency of all bubble trays when operated at their optimum loadings is high, in the range 70% to 90% (6,56,66,86,89-92,95,100). This would appear to be due to the major effects on the efficiency being dependent on the physical properties of the system being distilled and independent of the tray itself. However, comparatively small advantages can be gained by tray design;- i) By increasing the foaming tendency of the dispersion by using small holes and a good vapour distribution. ii) By decreasing the thickness of the clear liquid layer next

to the tray floor by using a good vapour distribution at the tray floor or by introducing the vapour parallel to the tray floor.

iii) By using cross flow liquid patterns in long unmixed liquid flow paths to enhance the tray efficiency over the point efficiency. The most unmixed froth can be obtained by using small holes or low free areas.

Comparisons of commercial bubble trays confirm the results obtained under laboratory conditions. Tunnel trays have similar efficiencies to Bubble cap trays as only the same cross flow advantage is gained. Valve trays gain about 5% to 10% on their efficiency by using vapour flow parallel to the tray floor and liquid downcomers whilst sieve trays gain about 10% by exploiting all three advantages. On the other hand counterflow trays have efficiencies lower than Bubble cap trays by losing the advantage inherent in the cross flow arrangement.

2.3.3 Operational Flexibility.

A tray may perform well at its design loadings but in general distillation columns are subject to a range of operational loadings. The width of the range will depend on the type of plant in which the column is operated. So that the column will produce on specification product at various loadings, without an excess of spare trays, each tray should have a wide high efficiency operating range.

They should also be amenable to automatic control.

Many authors have compared the mass transfer flexibility of the most popular bubble trays and found that those with downcomers are better than those without and that those which use a mechanical seal to prevent the liquid falling through the tray floor have the highest flexibility of all (1,6,54,56,65,66,86,89,90,99-112), (See Fig.2.6). To understand the reasons for this we must consider the factors which reduce the efficiency at loadings higher and lower than the optimum.

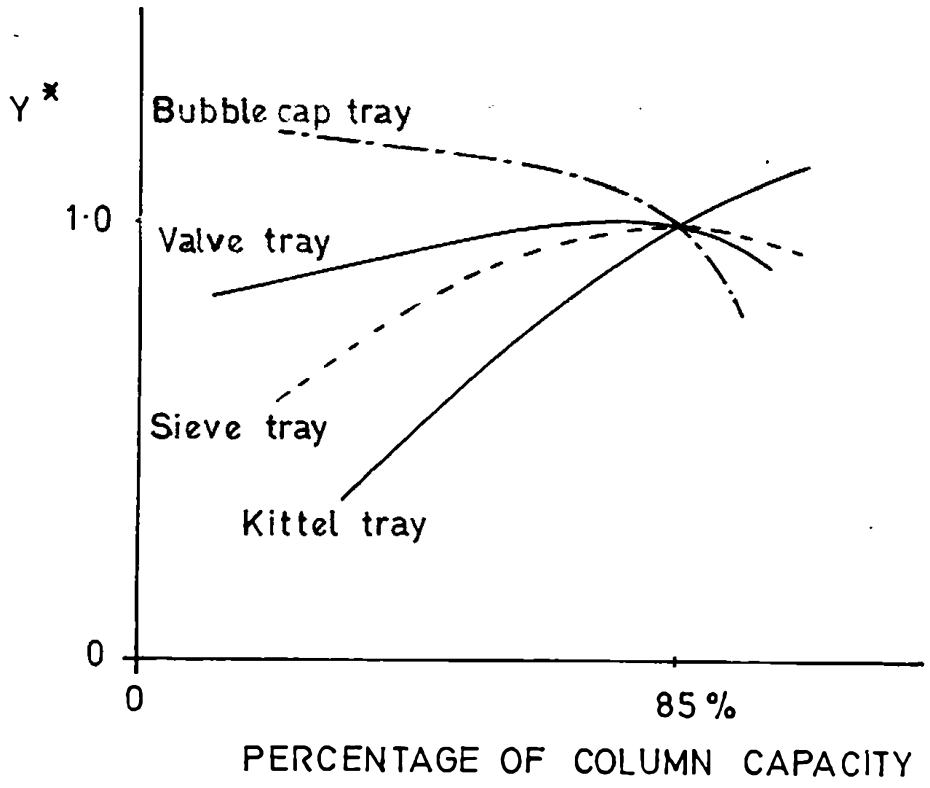
The effects at higher loadings were considered when studying the capacity of bubble trays (2.3.1) and it was concluded that the limiting factor in general was entrainment.

Cross Flow Trays.

The conditions which affect the efficiency at low vapour loadings give reduced contact due to liquid and vapour by-passing of the tray. That is, portions of the tray are not aerated by the vapour whilst the clear liquid falls to the tray below. On bubble-cap and Tunnel trays this condition is caused by a high liquid gradient on the tray. At low vapour rates an insufficient vapour head exists to cause all the orifices to operate and only those under the least liquid head will do so. (204). The tray

FIGURE 2·6

RELATIVE FLEXIBILITY OF TRAY DEVICES[6].



* [Y = RATIO OF EFFICIENCY AT A GIVEN PERCENTAGE OF THE COLUMN CAPACITY WITH THAT AT 85%]

will then produce a frothy dispersion at the outlet weir and a region of clear liquid at the inlet weir. When the head of clear liquid is greater than the pressure drop the liquid will run down the vapour risers and bypass the tray. This condition can be reduced by reducing the liquid gradient by removing the obstructions in the liquid flow path.

Using Sieve trays the obstructions are reduced to a minimum but in this case the liquid falls through the sieve holes due to the vapour stream having insufficient kinetic energy to hold it back. The liquid gradient on sieve trays is very low and so when the liquid dumps most of the holes dump together. Below this vapour rate the tray will not operate as a bubble tray. There is also another phenomenon associated with Sieve trays, namely weeping. In this case some holes weep in a random manner due to transient excess liquid heads existing over them. Weeping does, of course, reduce the efficiency of the tray more markedly as its intensity increases. Weeping can be reduced by using smaller holes and the onset of dumping can be held back by reducing the free area of the tray or to a less extent by reducing the hole size. (1,99-112,205,206). The situation is not, however, simple for sieve trays as the free area can affect the flexibility at both ends of its useful range.

(86,107,121,207). Using low free areas (5%) weeping is small and the dump point is low but at high vapour rates the pressure drop is high and thus the capacity is low. Moreover, using high free areas (20%) the dump point is very high, but capacity is reduced by excessive entrainment. Within the useful range of free areas the flexibility can be increased by making the above changes, namely smaller holes and higher free area.

To overcome this situation variable geometry trays, for example Valve trays, were introduced to give high flexibilities by continuously changing the free area and hole sizes to suit the vapour loadings. At high vapour loading the holes are completely open, at low vapour loadings the holes are almost closed and at intermediate loadings the holes are partially open. By this means an almost constant vapour velocity can be produced by each hole and a good vapour distribution, with its attendant advantages, achieved throughout the vapour loading range. This ideal has not been realised as the holes are not all partially open at intermediate loadings, but some are open, some are closed and some oscillate between the two positions. (6,65,66,208-211). Designs of valves have been proposed to overcome this failure (210-211), but without modification this type of tray still has a higher flexibility than Bubble-cap trays.

Counterflow Trays.

From their earliest introduction into commercial distillation, counterflow trays have never been advocated for duties which require high flexibility (73-76,78,113,212). The free area and hole dimensions of a counterflow tray are designed for a particular liquid to vapour loading ratio and when the actual ratio deviates from the design ratio the tray ceases to function. If the vapour rate is too low the liquid is not held on the tray and little interfacial area is produced. Alternatively if the vapour rate is too high excessive entrainment results or the liquid hold-up on the trays increases and the column floods.

To add to this difficulty counterflow trays also suffer from the effects of maldistribution. Zuiderweg (6) found that a Turbogrid column lost half its separation at 65% maximum loadings when either the liquid or the vapour was fed to only half its feed plate.

Majewski (212) suggested that the only way to improve the flexibility of counterflow trays was to break the vapour and liquid loading interdependence by using liquid downcomers. This solution in effect changes the counterflow tray into a crossflow tray.

In general, therefore, variable geometry trays can give the highest flexibility by providing a better vapour distribution to the tray over a wider range of operating

conditions. However, due to their valves not operating ideally they are not far superior to Bubble-cap trays. Sieve trays with smaller holes but a free area in the range 5% to 20% can give good flexibility, but counterflow trays as such cannot be markedly improved and remain with the lowest flexibility of all.

Controlability.

With regard to the controlability of trays much less is written, but in general trays with low vapour and liquid hold up and which can absorb surges in loadings will give better results (73-76,220-221). Counterflow trays are usually mentioned as having good characteristics from this point of view. Even so the time to come to equilibrium is still measured in hours. It should also be noted that the flexibility of counterflow trays is much lower than cross flow trays. They, therefore, must be controlled more precisely near to their optimum flow conditions to be efficient at all. However, the cost of extra elaborate measurement and control systems for counterflow trays far out-weighs their inherent controlability. (212).

In conclusion not much is known about the design factors affecting the controlability of a bubble tray. However, it would appear that the provision for high mass transfer flexibility is a much more important requirement

in tray design.

2.3.4 Tray Pressure Drop.

The tray pressure drop can affect the cost of a given separation by increasing the temperature required in the still and thus the heat load or by lowering the onset of flooding can increase the column size needed. An ideal tray should, therefore, give not only a low pressure drop, but one which increases as little as possible with vapour rate.

The total pressure drop across an operational tray can be compounded from that due to the tray itself and that due to the hydraulic head of the frothy dispersion on the tray. Many workers have found a slight discrepancy in the pressure drop predicted in this way but have explained it by the excess pressure needed in bubble formation (111,127,213). This effect is greater as the bubble size is reduced but on conventional bubble trays is not very great even when such a high surface tension liquid as water is used.

The hydraulic head on the tray depends on the liquid hold-up on the tray and this effect is similar for all cross flow trays.

The most important factor, therefore, is the nature of the tray itself and the vapour flow path through it as the pressure drop through the tray itself is produced by the

various resistances to flow. For example, in the case of a Bubble-cap tray the vapour has to contract into the riser, turn 180° and expand into the cap, turn 90° and contract to flow out of the slots in the cap (214). This tortuous flow path gives Bubble-cap trays a higher pressure drop than any other tray. The vapour flow path for Valve trays and other variable geometry trays is simpler but not as straight forward as that through Sieve and counterflow trays. However, Protruded Sieve trays offer the smoothest flow path and thus have the lowest pressure drop.

The most important design variable for sieve tray pressure drops is the free area for vapour flow followed by the hole size and the tray thickness. Very many empirical and semi-empirical correlations have been proposed for the calculation of the dry plate pressure drop (111,134,135). For example, Hughmark and O'Connell (135) found that the pressure drop, P, for a given F factor through the holes of a Sieve tray with a fractional free area, f, was given by:-

$$P = k . F^2 . (1-f)^2$$

where K depends on the hole size and tray thickness. This shows that Sieve trays gain more advantage in lower pressure drops by using larger free areas. The above equation and others also indicate that for a given free area Sieve tray the pressure drop increases approximately with the square

of the velocity in the orifices. This means that the pressure drop of a low free area Sieve tray will increase much faster than that for a higher free area tray. This difference is highly important when considering the onset of flooding in the column. In general, the hole size and the tray thickness have been accounted for in empirical constants but some work has been done to find their effect.

Arnold (213) carried out a comprehensive study of Sieve tray pressure drop which confirm that the free area affected the pressure drop as discussed above. He also found that for a given free area the pressure drop decreased with the hole size.

The higher parasitic pressure drop of variable geometry trays gives them a higher pressure drop than plain Sieve trays for the same free area, but as the free area changes with vapour rate the rate of change of pressure drop is not so high.

Counterflow trays on the other hand produce very low pressure drops at their design loadings as their free area is high and the vapour has an unobstructed flow path. However, at higher loadings, particularly at high liquid rates the effective area for vapour flow is reduced by the countercurrent liquid flow (6,73-78,82,83). The pressure

Table 2.2

Comparison of the Cost and Weight of Various Conventional Trays with Bubble cap Trays.

Tray Type	Comparative Cost	Weight
Tunnel	0.8	0.87
Uniflex	0.5	0.48
Valve	0.67	0.48
Sieve	0.57	0.30
Turbogrid	0.5	0.48
Ripple	0.67	0.3

drop, therefore, increases very sharply.

In conclusion the tray with the best properties would have as low a pressure drop as possible with the minimum increase with vapour flow rates. These properties can be obtained by using a cross flow tray with smooth vapour flow path, large free area combined with small holes or a larger free area and variable geometry and small holes.

2.3.5. Equipment Costs.

The cost for a given separation will depend on many factors but the cost of the trays themselves will make an important contribution. Table 2.2 gives the cost of various trays compared with that of a Bubble-cap tray of the same diameter. (1,86,89,90,215,216).

All other factors being equal and as similar thickness metal is used for all trays the cost will depend on the simplicity of the tray and its ease of construction. For example, compared to Sieve trays and Grid trays, Bubble cap trays have many complex parts. Ripple trays, even though lacking downcomers, tend to be comparatively expensive as the sheets have to be pressed into wave form after the holes have been punched in them. Valve trays although comparatively complex use fewer and larger holes than Sieve trays and use simple pressings which reduce their fabrication cost.

From performance considerations it has been evident that sieve trays can give better results when their floor is highly perforated with small holes. Serious economic difficulties are encountered if this proposal is considered. As the holes are reduced in size their number must be increased to achieve the same free area. That is, if the hole size is reduced to half its former value the number of holes must be increased four times. The cost of punching the extra holes would increase the cost of the tray considerably. Also the limitation generally used when punching is that the sheet thickness can be no thicker than half the hole diameter. The tray thickness is generally governed by mechanical considerations so if smaller holes are required they must be drilled. Drilling, however, is much more expensive than punching (206,222).

Tray weight can have a marked effect on the cost of large columns as the tray supports and column foundations can increase the total cost drastically. Ridgeway (3) gave an example of the savings achieved when a column diameter was reduced from 10ft. to 9ft. A considerable saving was made but only 25% was due to the trays themselves, the majority was saved in the foundations for the column.

In considering the weight of the tray itself it must be remembered that the tray must be supported and stiffened

within the column so that the lighter the tray the less support will be needed.

Table 2.2 gives a list of the weights of various trays compared to the same size Bubble-cap tray. (89,90) It can be seen that the cost and weight have a close relationship as the principle factor in each is the simplicity of the construction. Ripple trays are a marked exception as thin metal sheet can be used because the waves in the tray give it high rigidity. Valve trays also show a deviation but this is due to relative complexity of the light weight valve caps and their retainers.

All in all the prime virtue when considering the cost of a tray is simplicity. It reducing the cost of the tray itself and that of the column and foundations.

Although maintenance costs are considered as part of the running costs of a process they can affect the choice of device and thus in the overall cost that of the tray itself and the maintenance costs are interdependent.

For a corrosive service there is generally an economic balance between using a highly expensive corrosion resistant material or using a cheap material and replacing it frequently. Thin or more complicated parts such as screw threads should be avoided as, in general, these corrode most easily and are

difficult to remove when being replaced. Simple designs from thicker materials tend to be favoured as these can be not only cheaper to install but can last longer and be cheaper and easier to replace.

Sieve trays and Grid trays are the simplest but tend to be less favoured as the free area and thus the operational stability can be affected by the corrosive action round the holes. Smaller holes tend to suffer a greater change in free area than large holes (206,56), but larger holes must be designed more precisely so the advantage of larger holes is not so great as at first appears. For fouling or dirty service the main requirement is that the tray lacks inactive areas where the suspended solids can be deposited and accumulate. The turbulent froth of Turbogrids and the movement of the valves on Ballast trays is claimed to account for their good performance in dirty service (86,56). However, opinions differ concerning the performance of Sieve trays. Some authors say that good vapour distribution using high free areas and small holes gives good performance under these conditions whilst others say that small holes get blocked and that large holes should be used.

As corrosive and dirty service are difficult and expensive to simulate experimentally little published data is available and the choice of tray seems to be governed

by opinion and the weight of other considerations.

Table 2.3 Factors for Improving Bubble Tray Performance.

Capacity	Separation Efficiency	Flexibility	Pressure Drop	Tray Cost
Entrainment i) good vapour distribution ii) small holes iii) smooth vapour introduction iv) vapour flow parallel to tray floor Flooding i) low pressure drop at high loadings	Foaming Tendency i) good vapour distribution ii) small holes Clear Liquid Layer i) good vapour distribution ii) Vapour flow parallel to tray floor Mixing i) cross flow tray with long liquid path. ii) small holes iii) low free area	i) liquid cross flow ii) variable geometry tray iii) small holes	Optimum Loadings i) minimum obstruction in vapour path ii) high free area iii) small holes At higher Loadings i) as above ii) higher free area and variable geometry tray iii) Liquid cross flow	i) simple construction ii) minimum of simple manufacturing operations

2.4. Conclusions.

Most authors agree that there is no single contacting device which is best for all distillation duties (6,87,88,92, 217,218). All have their advantages and disadvantages but for particular duties the importance of each varies. However, for the majority of commercial applications bubble tray devices offer the most advantages and of this type Sieve trays give the best all-round performance for the least cost.

Table 2.3 gives a summary of the factors for improving the performance of bubble trays. Many factors cancel each other. For example, to decrease the entrainment it is advantageous to arrange the vapour flow to be parallel to the tray floor but this change will increase the pressure drop which is disadvantageous. Some factors have been cancelled out in the body of study. For example, if the liquid hold up is increased the contact time and the entrainment will be improved whilst the effect on flooding, mixing, flexibility and pressure drop will be to reduce the performance.

Nevertheless it can easily be seen that a cross flow tray with good vapour distribution and small holes with a smooth vapour flow path is required. This specification corresponds to a Sieve tray with high free area and small

SECTION 3

TRAY FLOOR MATERIAL SELECTION.

Section 3 Tray Floor Material Selection.

3.1 Material Specification and Requirements.

It has been noted from the conclusions of the previous section that the proposition of an improved vapour-liquid contacting device demands the discovery of an economic method of production for the floor of its trays. These tray floors should have a high free area, up to 20%, and small holes, up to $\frac{1}{8}$" diameter. Also to gain full advantage the holes should have a protruded nature or for a higher free area should have variable geometry.

The ideal can be achieved by using materials for the tray floor which are inherently porous. That is, they have passages for vapour flow preformed through their bulk. There are three types of material which satisfy this requirement in general use today. They are of sintered, open cell foam or fabric type construction. In all these materials the free area and hole size are independent of each other and the cost of the material. The best combinations of properties can, therefore, be chosen.

As the holes through these materials tend not to have parallel sides a protruded effect is included in their construction. Also in the case of open cloths the possibility exists that the free fibre on the yarn may produce a variable geometry effect.

However, for any material to be useful as a tray floor

it must give a tray with better hydraulic and mass transfer performance than conventional trays. Not only this but the tray must satisfy many other mechanical, operational and economic requirements (223). Above all the cost of performing the same duty with the new tray must be less than that for conventional trays. Alternatively for the same cost a higher throughput or quality product must be obtained when using the new tray.

The tray floor material should be light in weight so that the minimum amount of supporting members are needed. The floor should also be stiff or rigid so that it can cantilever across long distances between supporting members and can also handle changes in liquid and vapour loadings without undue distortion.

In addition to the purely mechanical requirements needed in the operation of the tray there are constructional and maintenance considerations. During transport from the manufacturer's works to the construction site and on the site itself, the trays could be subjected to mechanical loads and blows much greater than those encountered in normal service.

Large trays are usually manufactured in subsections and then fastened to grids in the tower when it has been erected. The subsections should be of such a size and strength that they need the minimum amount of jigs and strong packing to

prevent distortion and damage in transit. Also the weight should be kept low so that heavy lifting gear is not required for on and off-loading. However, the larger the permissible size the fewer grids and subsections will be needed and the cheaper the cost of construction. This type of construction allows easy access from tray to tray for construction and maintenance personnel. Apart from the load imposed by the weight of the tray itself and the liquid and vapour loads one must not forget the load due to construction and maintenance workers. To satisfy this consideration it is preferable that the tray floor as well as the supporting grids be mechanically strong.

In dirty or corrosive service the tray should be self or easily cleaned or replaced. Also the material should have a long life or be so cheap as to be replacable. Another consideration under these conditions is the need to avoid screw threaded parts and to use wedges for fastening.

The material should ideally suffer the minimum of thermal distortion so that expensive compensating devices can be eliminated.

Obviously the choice of the material for practical trays requires a compromise of the properties available from any one given material.

For the purpose of these studies it is considered that the detailed mechanical design of a commercial tray should be left to those practiced in that discipline and to concentrate more on the search for and the study of a tray floor material which will conform to the general requirements.

In brief the general requirements are that the tray floor material must:-

i) Have holes preformed through its bulk in such a way that improved hydraulic and mass transfer operation is achieved.

ii) Be cheaper than conventional trays for the same duty.

iii) Be light in weight yet strong and rigid.

iv) Suffer the minimum of thermal distortion.

v) Have a long life in corrosive or abrasive service.

vi) Be self or easily cleaned or replaced.

3.2 Material Proposals and Studies.

Many materials can be proposed which will satisfy the requirements that have been laid down for the tray floor. The properties of the various materials are only known to a greater or less extent but the ones with the most suitable physical and mechanical properties can be chosen. However, their ability to satisfy the requirements relating to the hydraulic and mass transfer performance is completely unknown and it is the knowledge of this performance data which is essential to the proposition of a new tray floor. This performance data can only be obtained by studying the proposed material in vapour-liquid contacting operation. All the materials proposed for this duty cannot be tested thoroughly so a quick, easy and cheap method must be devised so that a small number of the most promising materials can be selected for further study. That is, the proposed material should first be tested to see if it will act as a bubble tray floor. If so, its hydraulic performance, (pressure drop and froth height dependence on vapour flow rate and liquid hold-up) can then be studied. For this purpose a small scale glass column was designed and built.

For the proposed material to be considered for further studies its performance must compare favourably with that of conventional trays. For comparison purposes the work

of D.S. Arnold et al (213) was chosen for the wide range of Sieve tray geometry studied. The results of Arnold's work is plotted in figure 3.4. It should be noted, however, that the results are given in terms of weir height and not clear liquid height.

It is, therefore, intended to choose the most suitable samples from each type of material and study their hydraulic performance so that only the most promising materials need be studied even more thoroughly.

3.2.1 Apparatus.

The apparatus, which can be seen in figures 3.1,3.2 and 3.3, consisted of a glass column with the test sample held between the flanges of two of its sections. The column sections had an internal diameter of four inches. An air-water system was used because of its cheapness and availability. Many other advantages are also gained by using this system in a small scale apparatus that is to be dismantled frequently.

The air was supplied by a centrifugal blower driven by a six horse power electric motor. The air rate was measured by directing the flow through one of two rotameters calibrated from 1-10 and 2.5-25 standard cubic feet per minute. The blower could deliver a maximum air velocity in the column of six feet per second. The air flow to the column was

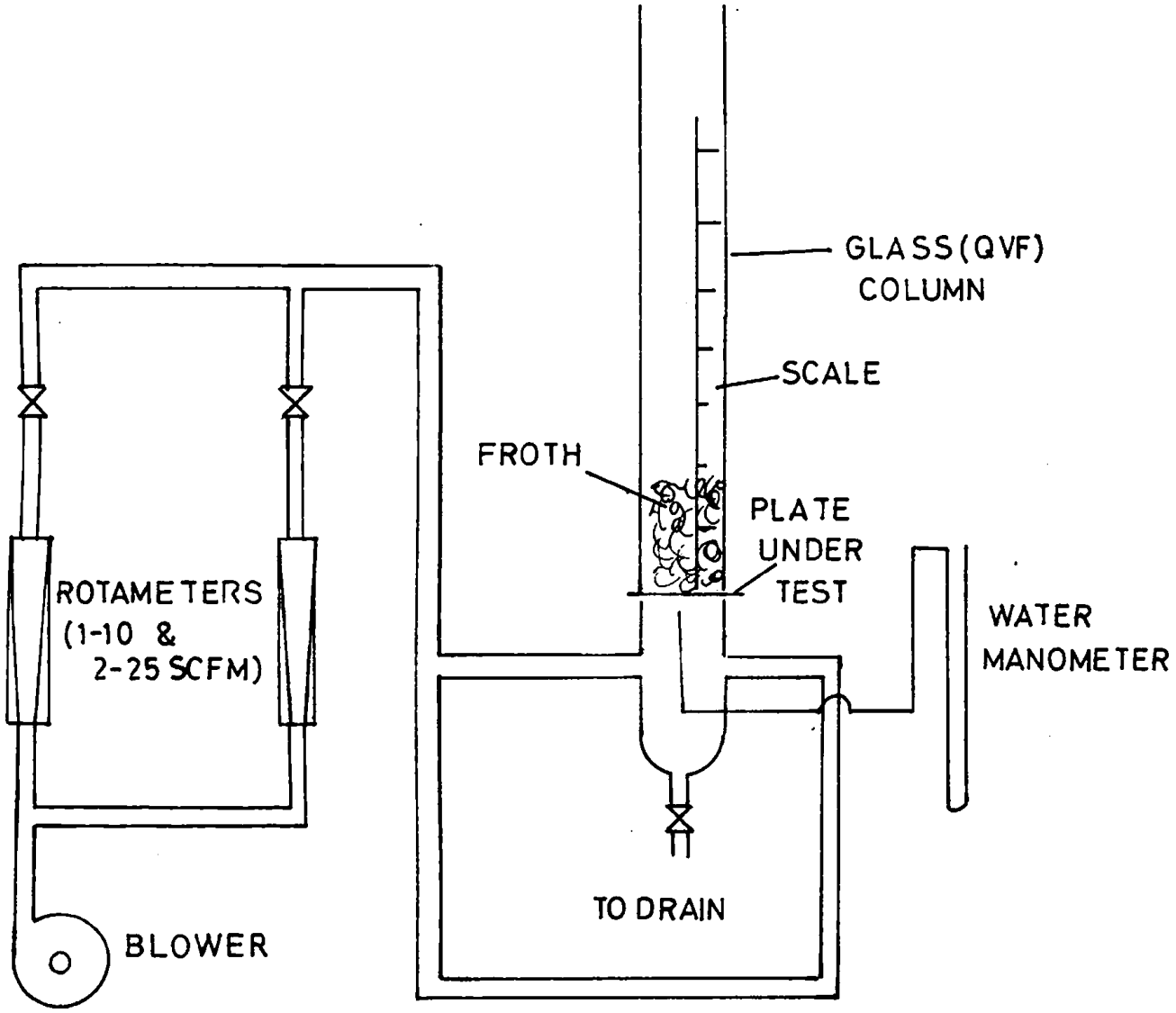
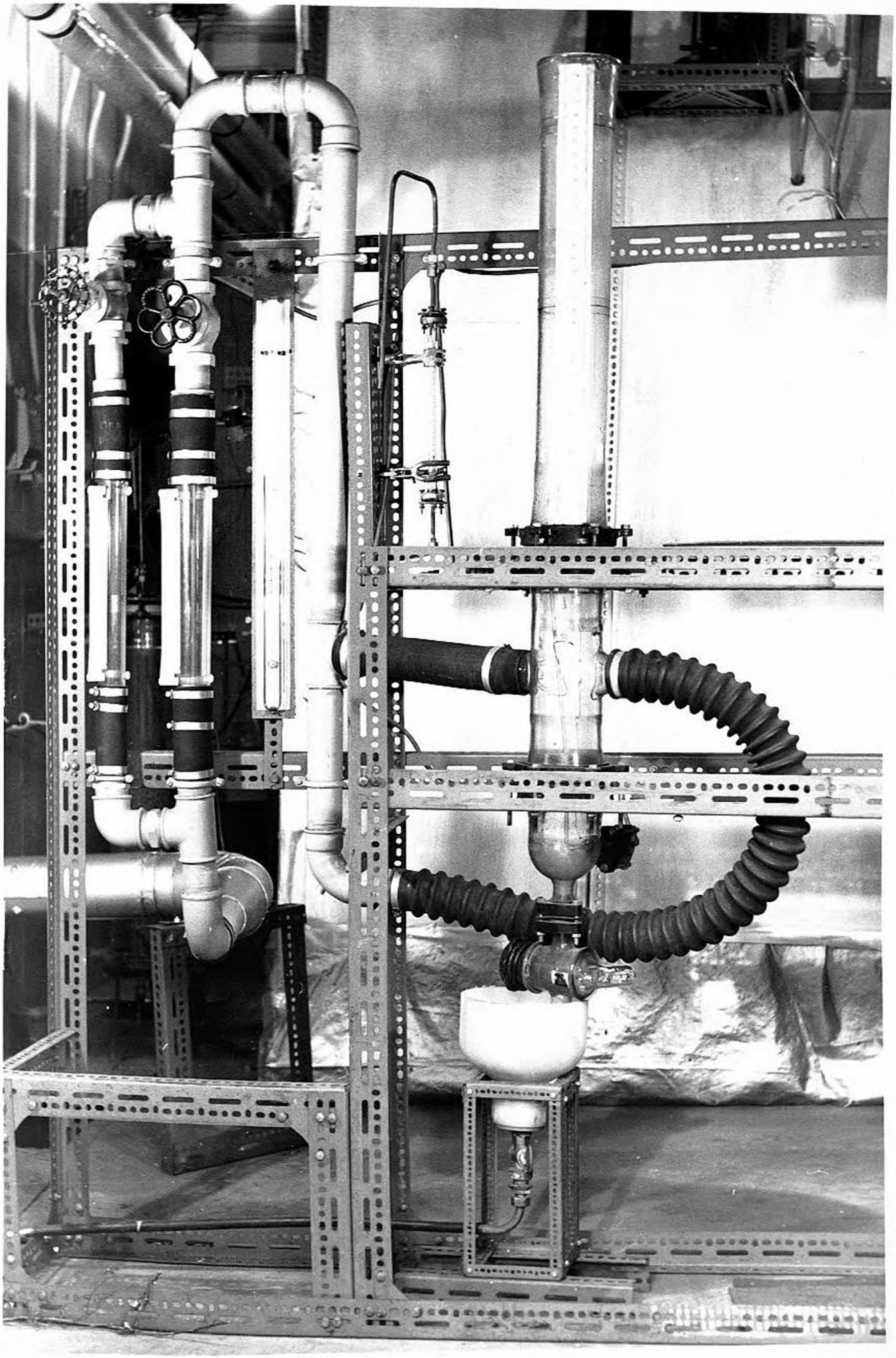


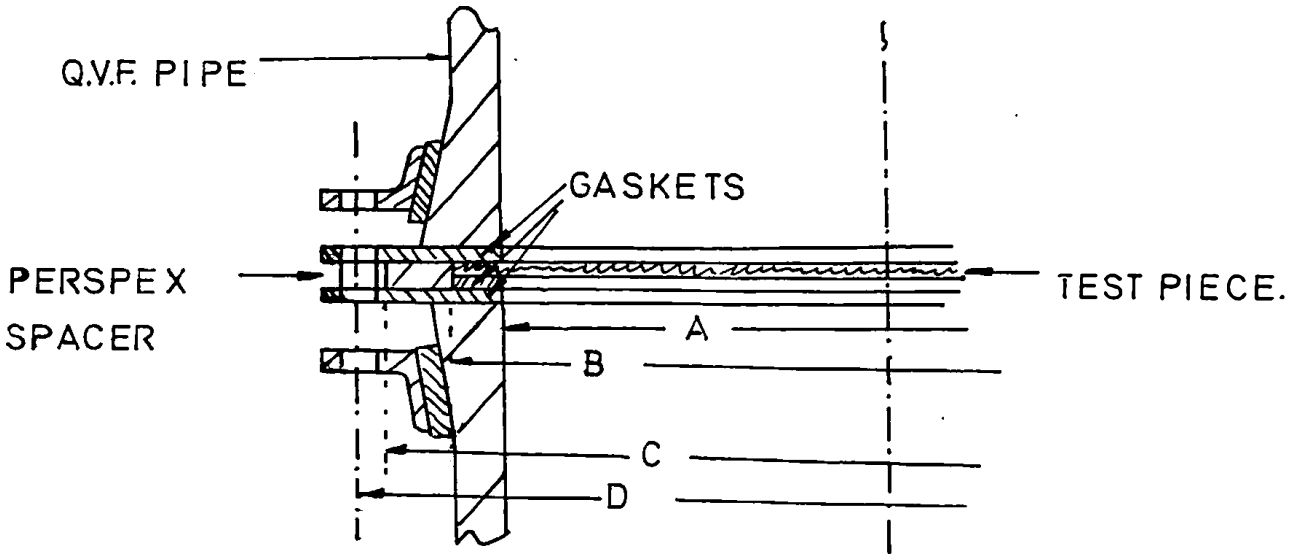
DIAGRAM OF SMALL SCALE TEST RIG FIG. 3·1

FIGURE 3.2

SMALL SCALE APPARATUS WITH

4" COLUMN.





DIMENSIONS	3"	4" C.OLUMN
A	3·0	4·25
B	3·5	5·125
C	4·75	6·625
D	5·375	7·0

FIG. 3·3
DETAIL OF FASTENING TEST PIECE
IN 3" & 4" COLUMNS

controlled by a valve above each rotameter. After flowing up through the sample in the column the air was exhausted to atmosphere.

No provision was made for liquid flow across the tray but water was poured onto the tray at the beginning of a run and dumped through the tray at the end of the run.

The pressure drop across the tray was found using a water manometer and the froth height measured using a scale fastened to the outside of the column.

3.2.2 Procedure.

The sample to be tested was fastened in the position and the column reassembled. The blower was switched on and the air velocity adjusted to about two feet per second. A measured amount of water equivalent to the chosen clear liquid height (1" = 232 ccs) was carefully poured onto the tray. The pressure drop and froth height readings were recorded at various air rates. After the run water was dumped through the tray by stopping the air flow. The experiment was repeated for the same sample using different clear liquid heights.

3.2.3 Sintered Materials.

Sintered materials can be made from metals, plastics or ceramics but metals offer the best mechanical properties. Two types of sintered construction are available. One

type uses powdered metal and thus gives a nonuniform pore size; the other uses sintered wires and thus has a more uniform character. In the first type powder of the desired particle size is subjected to heat and pressure to produce the finished material. Sintered wire meshes consist of one or more layers of woven wire meshes sintered together. This process makes the mesh rigid and improves the overall strength whilst maintaining the original uniformity of the weave.

However, as the flow path through sintered materials is comparatively tortuous high free areas should be used to obtain a low pressure drop.

Results and Discussion.

Two samples of sintered powder discs and three samples of rigid mesh were obtained and tested in the column. Their specification is given in appendices A.3.1.1 and A.3.1.2 respectively.

Except for the sample of rigid mesh with a free area of 56% the pressure drop incurred with an air rate of one foot per second and a clear liquid height of one inch was greater than 20 inches of water gauge. As the dry pressure drop was comparatively low, the high wet pressure drop must be attributed to the effect of the surface tension on the small holes (less than 1/16" diameter). However, the

pressure drop was considered excessive so further study of these samples was abandoned.

The hydraulic results for the 56% free area sample are given in Appendix A.3.1.3. and figure 3.5 Comparing the pressure drop results with conventional Sieve trays (fig.3.4), it can easily be seen that those for the rigid mesh sample are far higher under all conditions.

However, the air-water dispersion formed above the tray of the 56% free area sample was of comparable appearance to that on Sieve trays. Therefore, if the pressure drop were unimportant trays of this material would probably be feasible.

3.2.4 Open Cell Foam Materials.

To use foam or cellular materials as tray floor materials the most important requirement is that they should be porous. It is also desirable that they should be rigid. These two requirements alone unfortunately eliminate all foam materials known at present. Even though most resins and plastic melts can be formed into cellular structures, by proper introduction of a dispersed gas, they most easily give impervious monocellular materials. The plastics which do form open cell materials tend to be flexible, rather than rigid, but fortunately are still quite strong. (224,225). The best choice available at present, to satisfy our requirements, is polyurethane foam as can easily be seen from Table 3.1.

Table 3.1 Properties of Foam Plastics (224,225).

	Poly-styrene	P.V.C.	Poly-urethane	Phenol-formaldehyde	Phenol-urea-formaldehyde
Softening Temperature (°C)	85-100	65-90	150-185	150-200	60-200
Tensile Strength (psi)	5000-8000	6000-10,000	6500-12,000	6000	6000
Density	—— between 0.5 & 20 lbs/ft.^{3} depending on production technique ——				
Effect of Water	-*	softens	slight absorption	-	-
" Acids	Oxidising acids attack	—— attacked by concentrated acids ——			
" Alkalis	-	-	-	attacked by weak alkalis	attacked by conc. alkalis
" Organic Solvents	attacked by many alchols, ketones etc.		-	-	-
Effect of Oils	-	-	-	-	-
" Light	slow degradation	very slight degradation	-	slight darkening	-
" Ageing	very slight	slow hard-ening	-	-	slow shrinkage
Inflammability	slow burning	non-inflam-mable	slow burning	very slow burning	non-inflam-mable.

* - denotes no effect.

Results and Discussion.

Samples of polyurethane foam were, therefore, obtained and tested. The five samples chosen had 10,30,45,60 and 100 pores per lineal inch. (A fuller specification is given in appendix A.3.2.1.)

It was found that only the 60 & 100 p.p.i. samples actually behaved as bubble trays and held the water above themselves. The froth formed on these two samples compared well with that produced by Sieve Trays. When in operation, it was noticed that the samples of foam, being non-rigid, bowed upwards. A wide wire grid was, therefore, put on the top and underneath the sample to keep it flat. The hydraulic results from samples with 60 & 100 p.p.i. can be seen in figure 3.6 and in Appendix A.3.2.2.

The other samples, namely those having 10,20 and 45 p.p.i. let the water fall through them even at air velocities in excess of ten feet per second. Hydraulic properties were, therefore, unobtainable for these three samples.

It can be seen by comparing the results obtained using the 60 & 100 p.p.i. samples that, as expected, the foam with the tighter construction, 100 p.p.i., gave a higher pressure drop for a given air velocity and clear liquid height. Comparing the pressure drop results with those for sieve trays, it can be seen the curves obtained using plastic trays

are much flatter than for low free area sieve trays and have a much wider operating range than both low and high free area sieve trays. (figures 3.4 & 3.6). It should be noted that for each of these two samples the weep point was found to be below 1/6 foot per second, the lowest measurable air flow rate. Another interesting observation is the exceptionally low dry plate pressure drop combined with a comparatively high loaded pressure drop.

3.2.5 Fabric Materials.

Even though foam plastics had been proved feasible as bubble trays another group of materials exists, namely fabrics, which can give better temperature and chemical resistance. Fabrics can be woven, knitted or made in a random manner from metallic wires or fibrous yarns. The former two methods of manufacture are of more interest in this study as the hole size and free area have more predictable and uniform qualities.

Metallic construction is the first choice for many reasons but it has been found impossible to produce porous materials from wires which are suitable for this duty. In a mesh the wire used is comparatively thick but the free area and hole size are too large. The wires cannot be moved closer together as they are too thick to bend

sufficiently in manufacture. If the free area and hole size are correct the material must be woven into a gauge using fine wires but then the bulk strength of the material is low. Also when using fine wires the corrosion resistance is generally reduced.

Fortunately a useful alternative exists in the form of fabrics made from fibrous yarns. Yarns can be made in various weights and due to their flexibility can be made up into fabrics with the correct range of free area and hole size.

Many fibrous yarns are available for this purpose but the most suitable are those made from glass fibres. Glass yarns are light and strong and give good corrosion and heat resistance. Poor performance under the latter two conditions eliminates most yarns whilst the low cost of glass gives it great advantage over the remainder of the materials.

Three types of glass yarn are available, their properties depending on the method of manufacture. Continuous filament yarns are made from long unbroken fibres with little twist in the yarn. This gives the highest tensile strength with virtually no extension under

load. However, the abrasion resistance is poor.

Staple fibre yarns have a much thicker appearance due to the free fibre on the surface as they are made from much shorter fibres. This construction leads to a fuller fabric with greater abrasion resistance, but lower overall strength.

Taslaned fibre yarns have properties between the previous two types as the amount of free fibre can be controlled in manufacture. The fullness of the cloth, and thus the free area and hole size, can thus be adjusted with only a small change in weight during the manufacture of the yarn.

Results and Discussion

Various combinations of yarns and make-ups were studied and five cloths were chosen and tested in the column. A full specification of the cloths is given in appendix A.3.3.1.

As with mechanically flexible foam plastics a wide wire mesh was put on the top and bottom of the sample to prevent it from bowing in operation.

The monofilament cloth, AD234, proved to have too high a weep point and so could not be studied. The four remaining samples all acted as bubble trays and had weep points below 1/6 foot per second. As with plastic foam

and rigid mesh a froth not unlike that produced by conventional trays was observed. Further studies were carried out to find the hydraulic characteristics of the glass cloths and the results are given in figs. 3.7 & 3.8 and in appendix A.3.3.2.

In the case of the knitted cloths the natural tendency of the material to stretch under load led to considerable sagging at low air velocities. At higher air velocities the knitted cloths bowed upwards between the strands of the containing grid and produced a maldistribution of air bubbles in the water dispersion. The bubbles tended to form at the top of the bowed sections where the holes are larger and the hydraulic head was less.

It can be seen from figures 3.6, 3.7,& 3.8 that the glass cloths exhibit similar curves to those of plastic foams when used as trays, but tend to be slightly steeper. Also the glass cloth trays show similar very low dry plate pressure drop curves. The curves of the two porous types of materials differ from those of conventional Sieve trays, (fig. 3.4), by being flatter than those with low free areas and having a much wider operating range than those with high free areas.

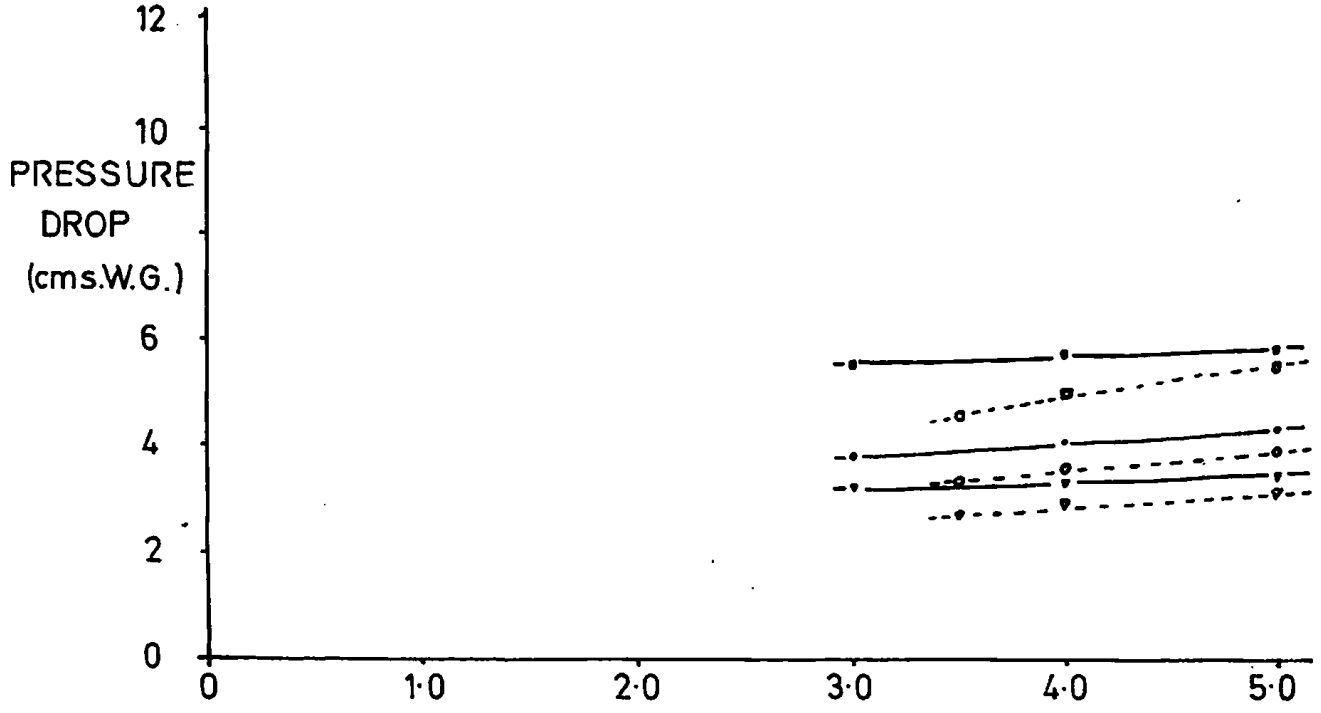
The pressure drops across the cloth trays seem to be consistent with the tightness of their construction, the

tighter the make-up the higher the pressure drop under given conditions and the steeper the curve. The knitted samples tend to give lower pressure drops than the woven samples even though the cloth looks tighter and heavier. In fact the holes through a knitted material are larger and more numerous than a plain weave material of the same weight. However, the holes are not perpendicular to the air flow so all of them cannot be seen at once. This factor coupled with the stretching and bowing of the knitted materials could account for their lower pressure drops.

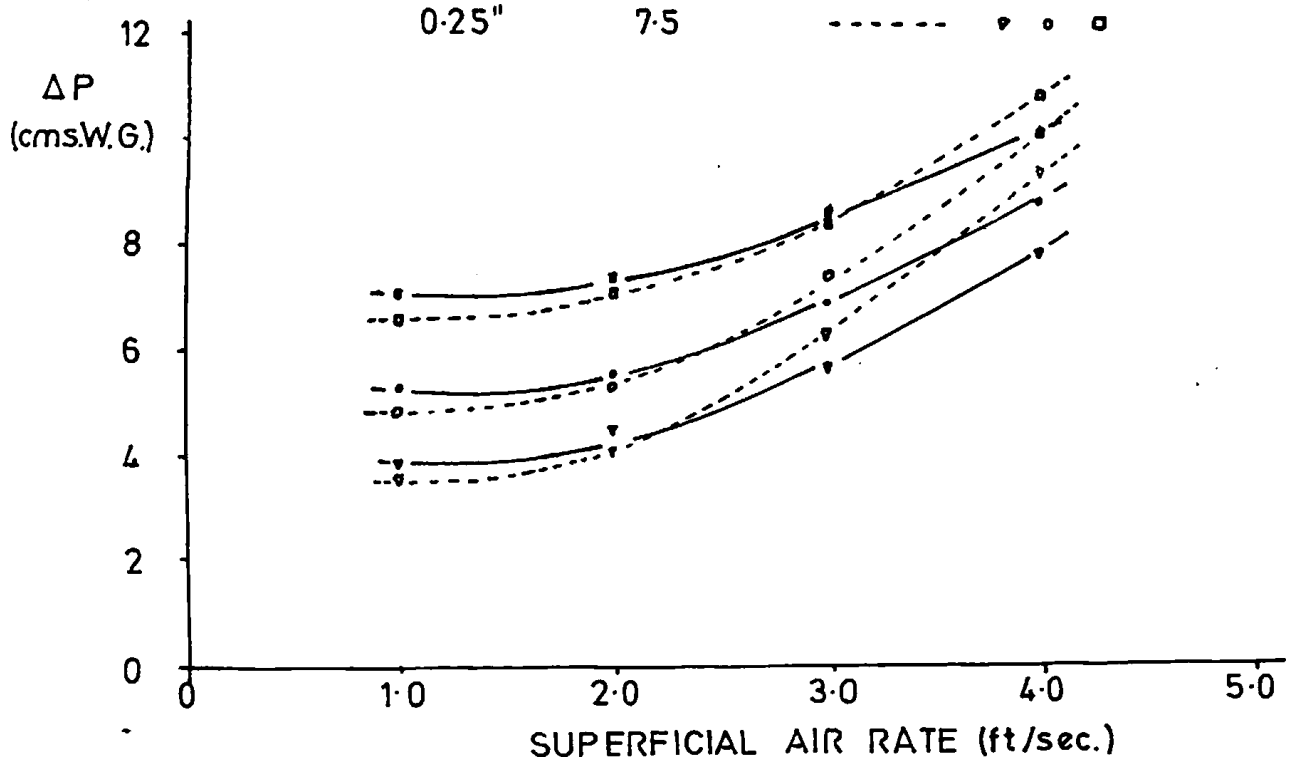
D.S. ARNOLD et al (213) FIG 3·4

15" DIA. GLASS COLUMN. AIR/WATER SYSTEM.
SIEVE TRAYS

Hole dia	Free area	Weir height	½"	1"	2"
0·083"	17·7 %	———	▼	●	■
0·376"	19·4 %	- - - - - - -	▽	○	□



Hole dia	Free area	Weir height	½"	1"	2"
0·059"	6·6	———	▼	●	■
0·25"	7·5	- - - - - -	▽	○	□

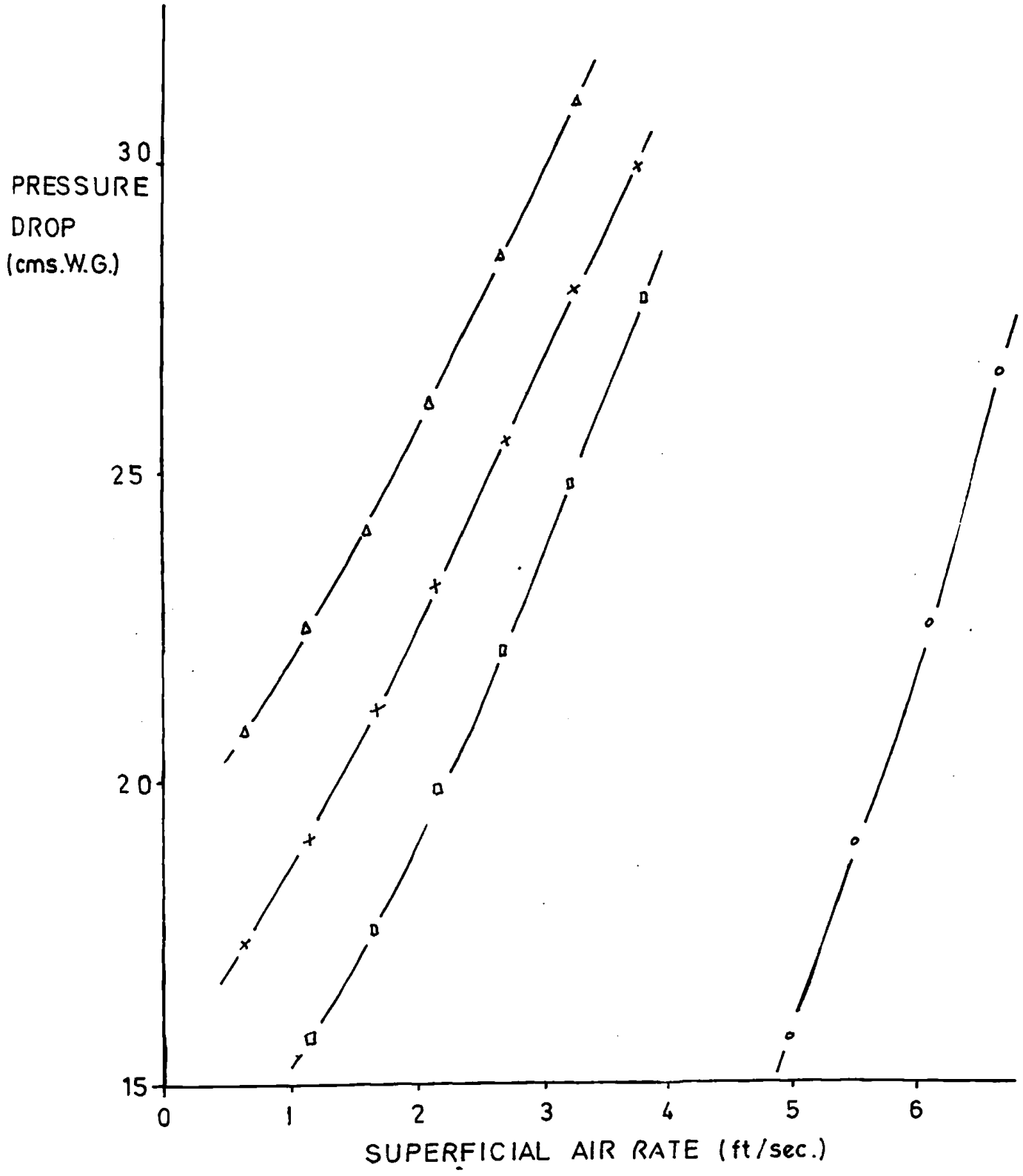


PRESENT WORK FIG 3·5

56% FREE AREA RIGID MESH

4" Q.V.F. COLUMN AIR / WATER SYSTEM

C.L.H. DRY 1" 2" 3"

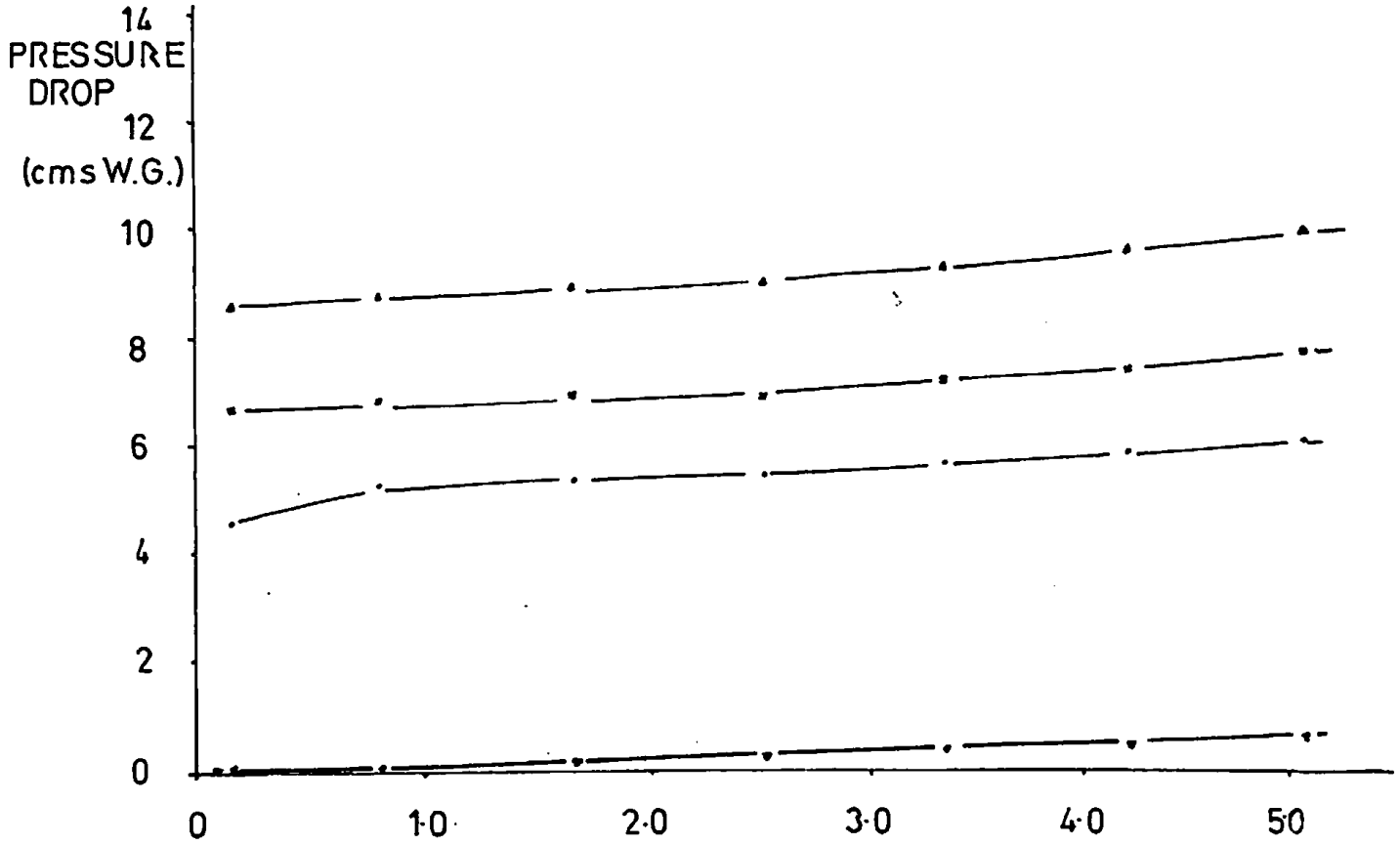


PRESENT WORK FIG 3·6

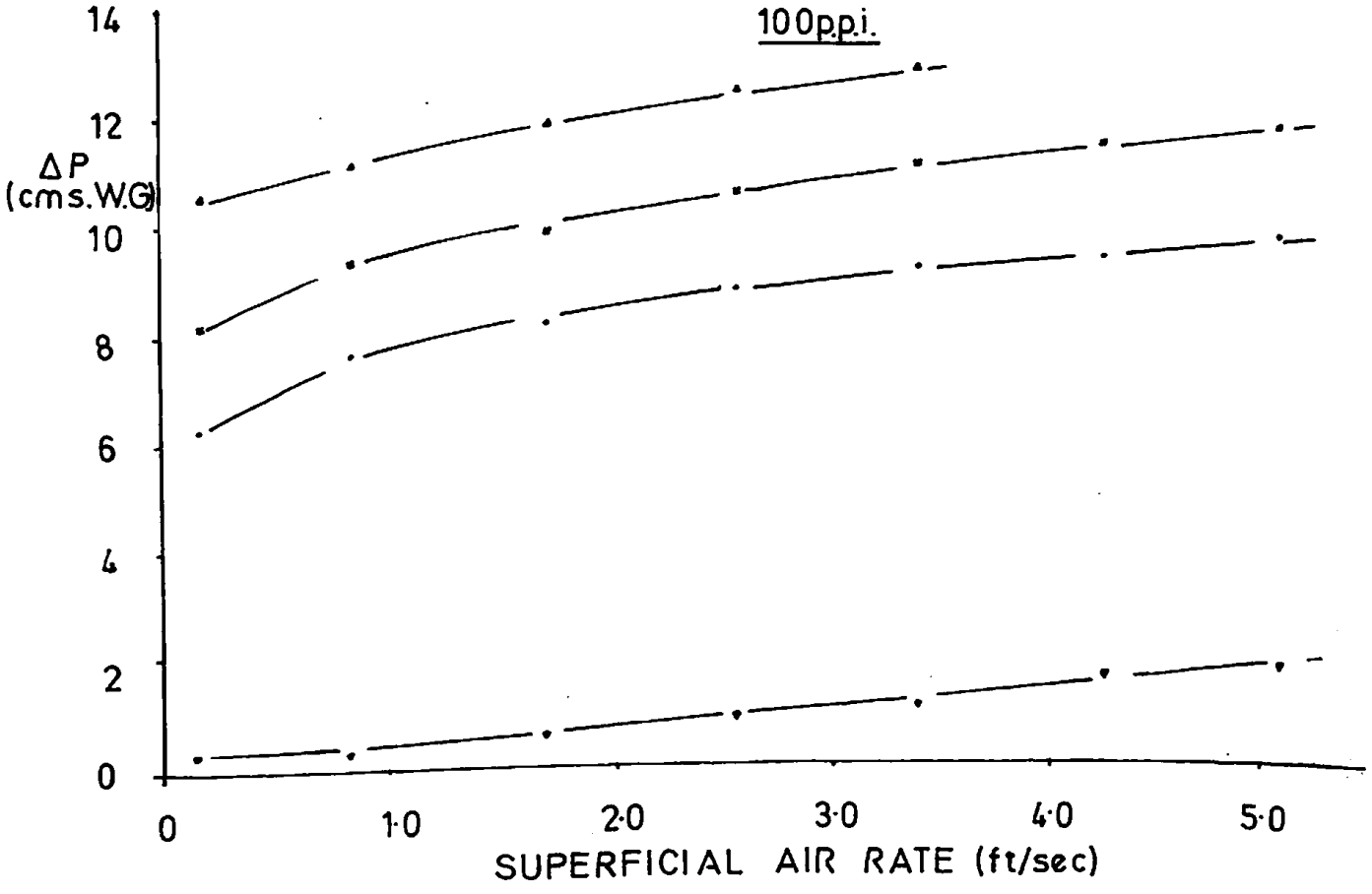
4" DIA. QVF COLUMN AIR/WATER SYSTEM

CLEAR LIQUID HEIGHT dry ▽ 1" ○ 2" × 3" △

PLASTIC FOAMS:- 60p.p.i.



100p.p.i.

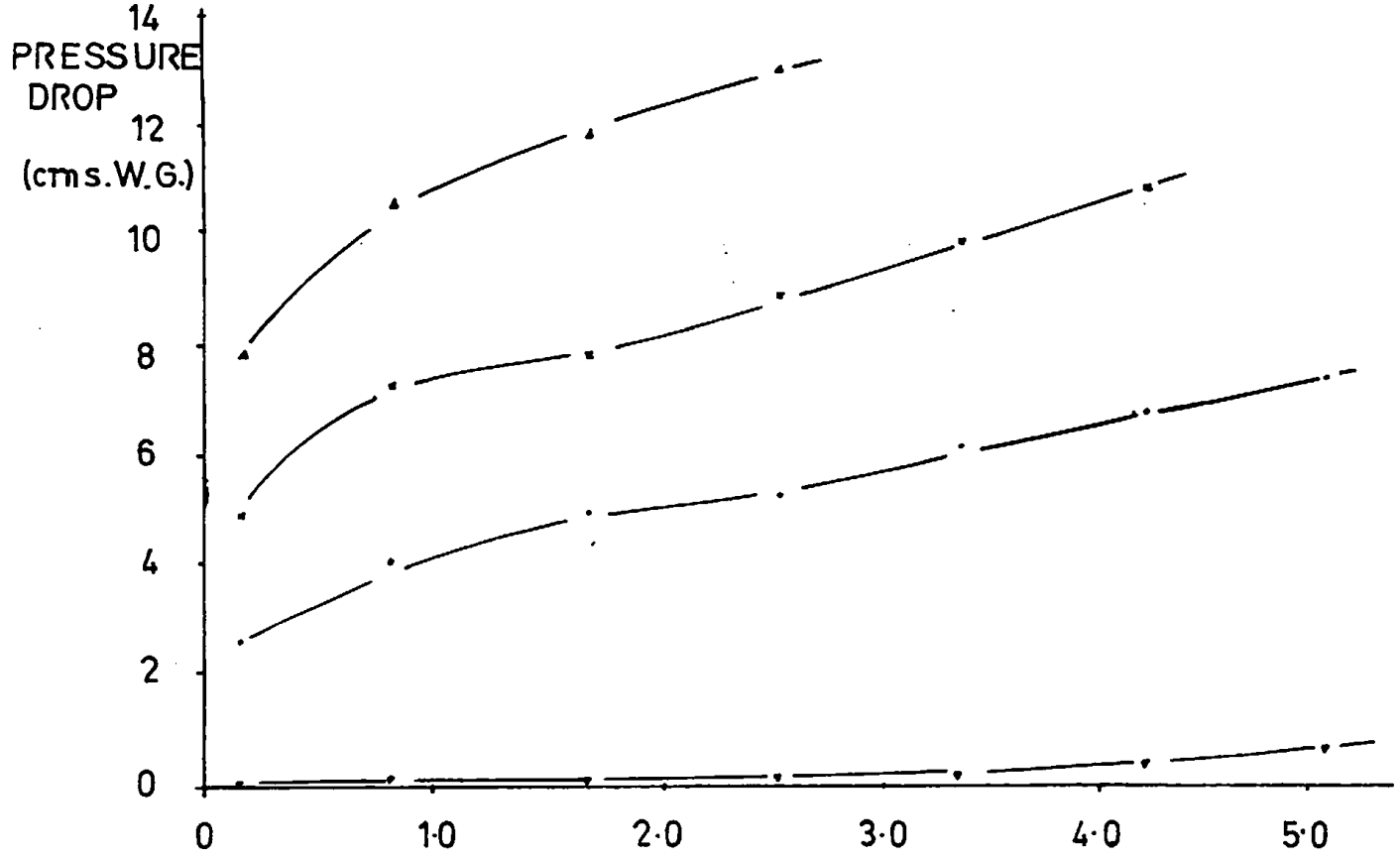


PRESENT WORK FIG 3'7

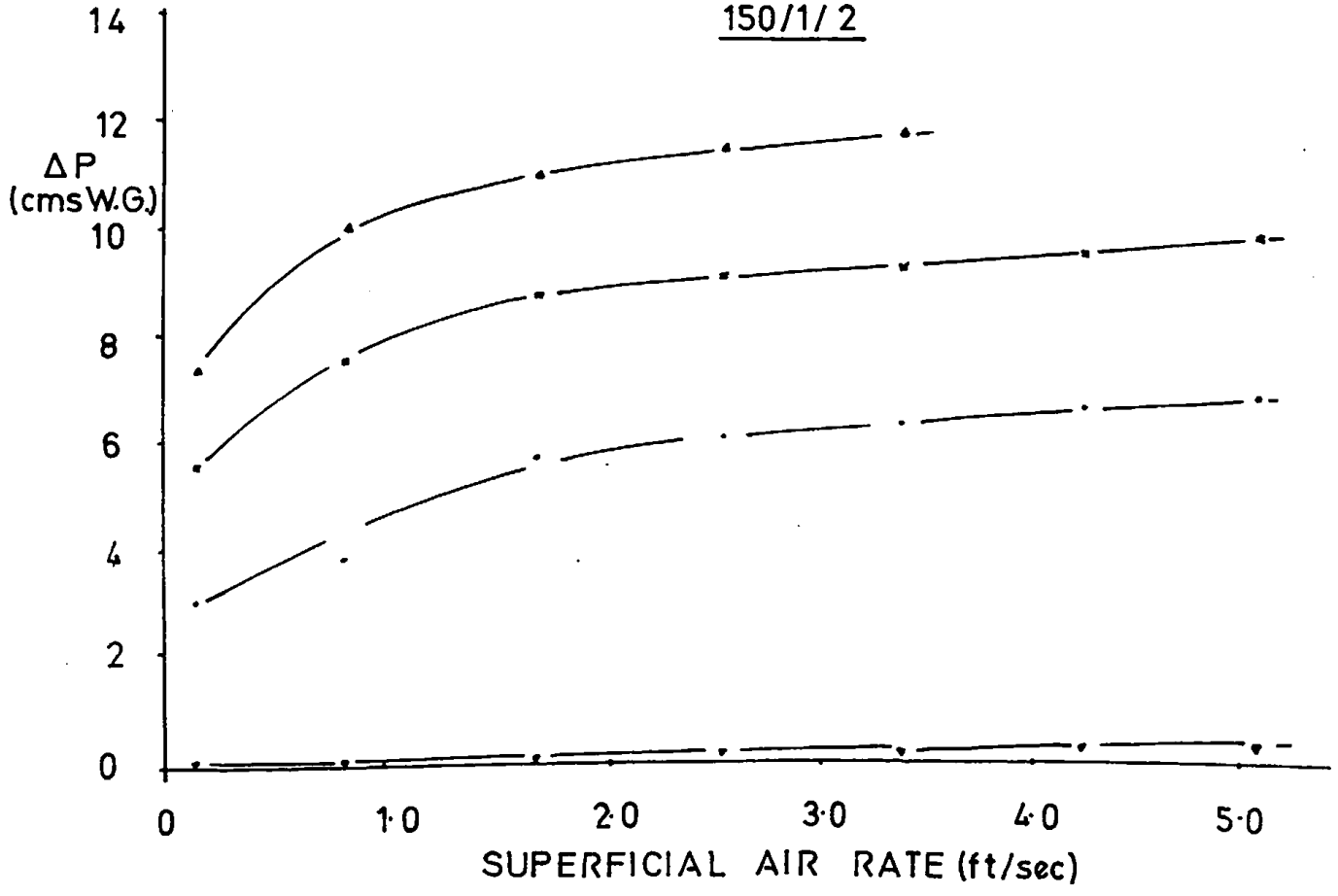
4"DIA. QVF COLUMN AIR/WATER SYSTEM

CLEAR LIQUID HEIGHT dry 1" 2" 3"

KNITTED GLASS CLOTHS :- 150/2/2



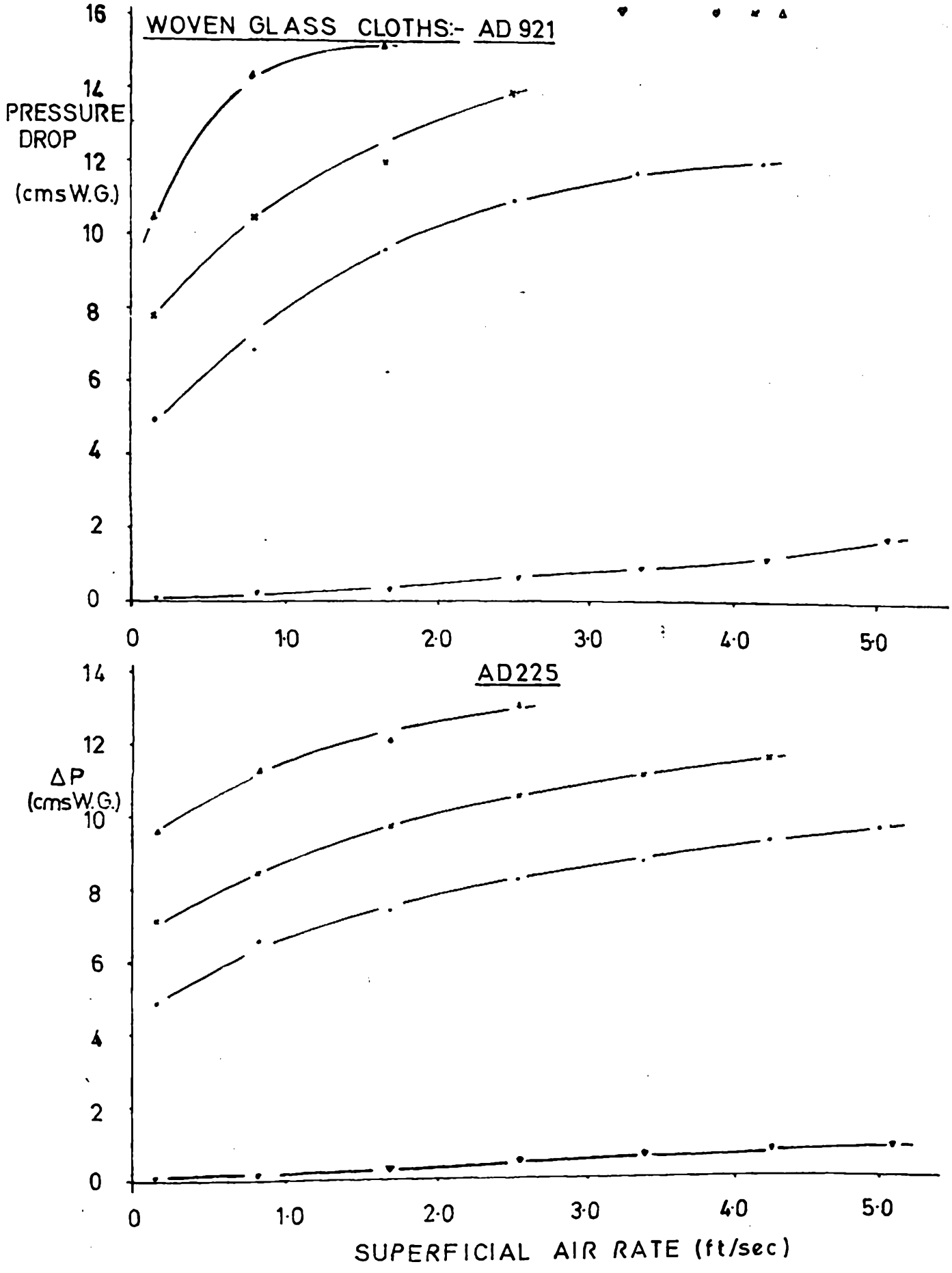
150/1/2



PRESENT WORK FIG 3·8

4"DIA. Q.V.F. COLUMN AIR/WATER SYSTEM

CLEAR LIQUID HEIGHT dry 1" 2" 3"



3.3 Extension of Hydraulic Data.

The results obtained in the four inch diameter column using polyurethane foams and glass cloths showed a marked difference in hydraulic behaviour from that of conventional sieve trays. It was, therefore, decided to modify the column to extend the hydraulic data by using a higher range of air velocities in the column. If the pressure drop curves of these porous materials remain flat instead of following the more exponential trend of Sieve trays a decided advantage would be gained. The possibility exists that using these trays a column could operate at higher vapour velocities and thus achieve a higher throughput for only a small increase in pressure drop.

3.3.1 Apparatus.

The apparatus was basically the same as the four inch diameter column except that the internal cross sectional area and thus the tray floor area was decreased by reducing the internal column diameter to 3 inches. The air now passed through a reducing section before passing through the sample held between the flanges of two 3 inch diameter sections. This modification allowed the blower to deliver a maximum air velocity of 12 feet per second in the column. Also the 3" diameter column was fitted with a side-arm and a funnel so that the feed liquid could be

directed against the wall near to the tray so that the liquid would not fall through the tray on impact.

A photograph of the apparatus is given in figure 3.9 and details of the method of fastening the test sample in the column are given in figure 3.3.

3.3.2 Procedure.

The experimental procedure was identical to that used for the 4" diameter column except that a clear liquid height of 1" was obtained by pouring 116ccs of water onto the tray.

3.3.3 Results and Discussion.

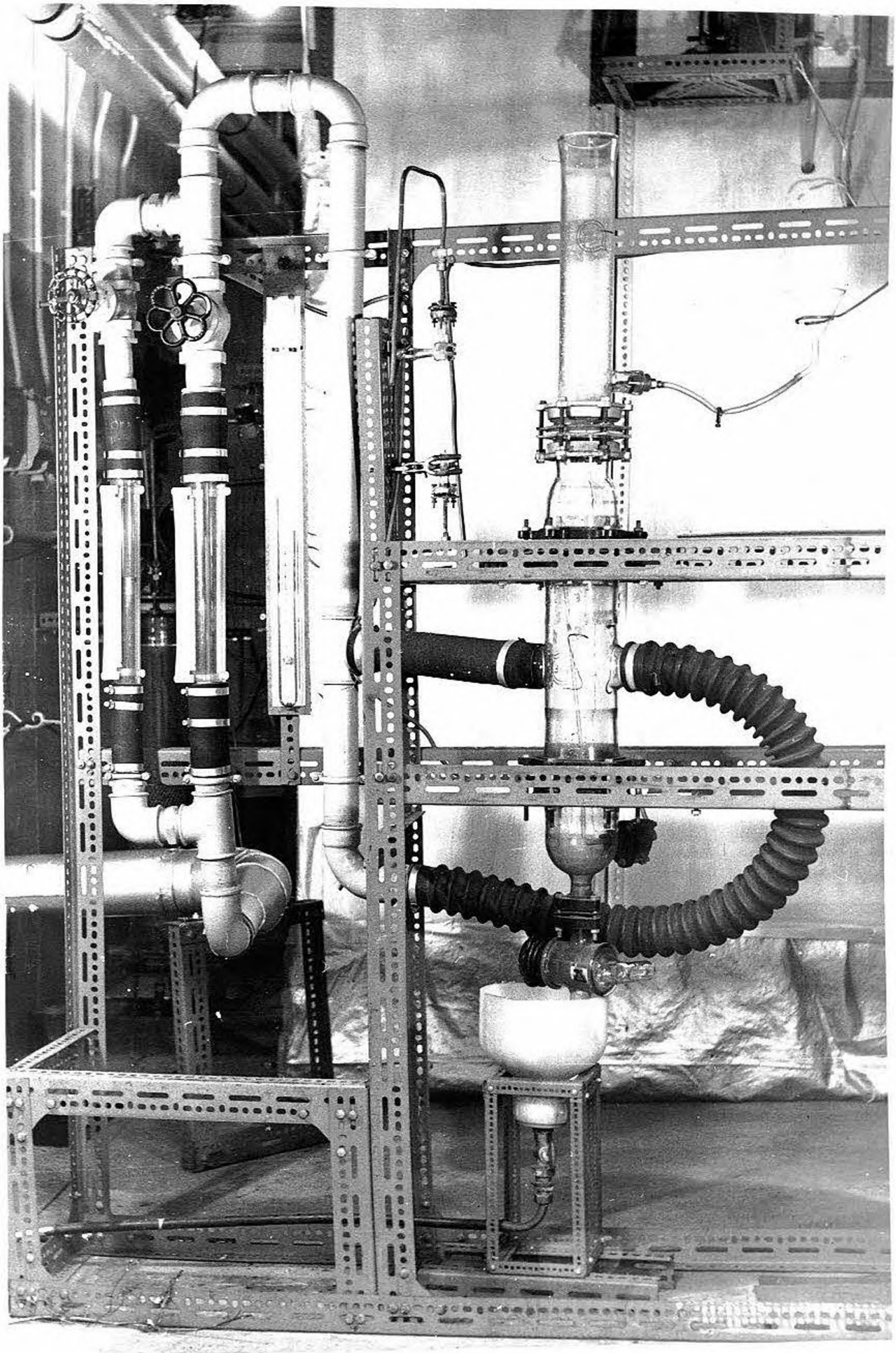
For these studies the samples chosen were those which gave the most promising performance in the previous study, namely, 60 p.p.i. polyurethane foam and woven glass cloth AD225.

The results of the present study is given in appendix A.3.4. Comparing the results obtained with those from the 4" diameter column, given in figures 3.10 & 3.11, it can be seen that the dry plate pressure drop results compare very well. However, though the results for the glass cloth in operation are reasonably consistant, those for the plastic foam are not. It was noticed that when in operation the underside of the plastic foam tray was wetted near to the walls of the column. However, no

FIGURE 3.9

SMALL SCALE APPARATUS WITH

3" COLUMN.



liquid wept through the tray. This wetting effect at the walls is probably due to the clear liquid height, being artificially increased by the walls of the column (239), increasing the tendency of the liquid to flow down into the pores of the plastic foam. The wetting effect would reduce the free area available for air flow by closing some of the pores and thus increase the pressure drop.

The increase in the pressure drop should be more pronounced at greater clear liquid heights as the tendency to wetting should be greater due to the increased liquid head at the tray floor. This tendency should have a greater effect on the smaller column as a larger proportional reduction in the free area will occur when one extra pore becomes obstructed by the liquid.

At lower liquid hold-ups there will be a reduced tendency for the liquid to flow into the pores of the plastic foam. The air flow will thus remove some of the liquid from the pores. As in the previous conditions, but having the opposite effect, the release of one extra pore for air flow will reduce the pressure drop in the smaller column by a greater amount.

At higher air rates the air flow will force out more liquid from the pores and the effective free area will be increased. However, the pressure drop of the sample in

the smaller column will be higher as the small amount of residual liquid in the pores at the walls of the column will cause the effective free area to be proportionally less.

Similar effects take place when the glass cloth tray is used but the difference between the results from the two columns is not so great as there is a much smaller volume within the cloth for the liquid to lodge and the air to flow. These effects on the pressure drop and effective free area of a glass cloth tray floor are studied more closely in Section 6.

Nevertheless the results from the present studies do show that the flatter pressure drop curves of the chosen materials extend to higher air flow rates and do not suddenly increase rapidly.

PRESENT WORK FIG 3·10

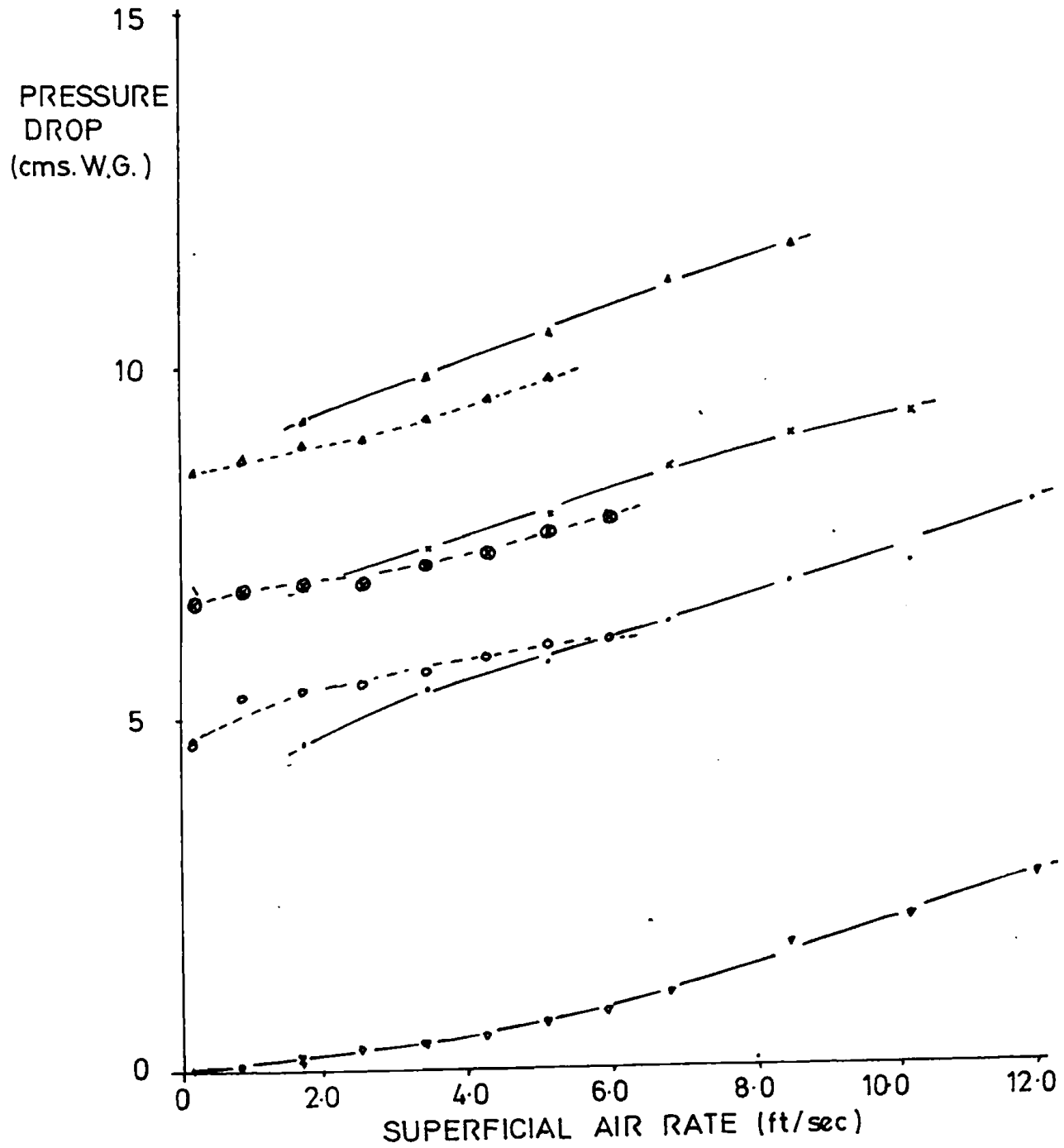
PLASTIC FOAM 60ppi

AIR/WATER SYSTEM

CLEAR LIQUID HEIGHT :- dry 1" 2" 3"

3" Q.V.F. COLUMN :- ——

4" Q.V.F. COLUMN :- - - - -



PRESENT WORK FIG 3·11

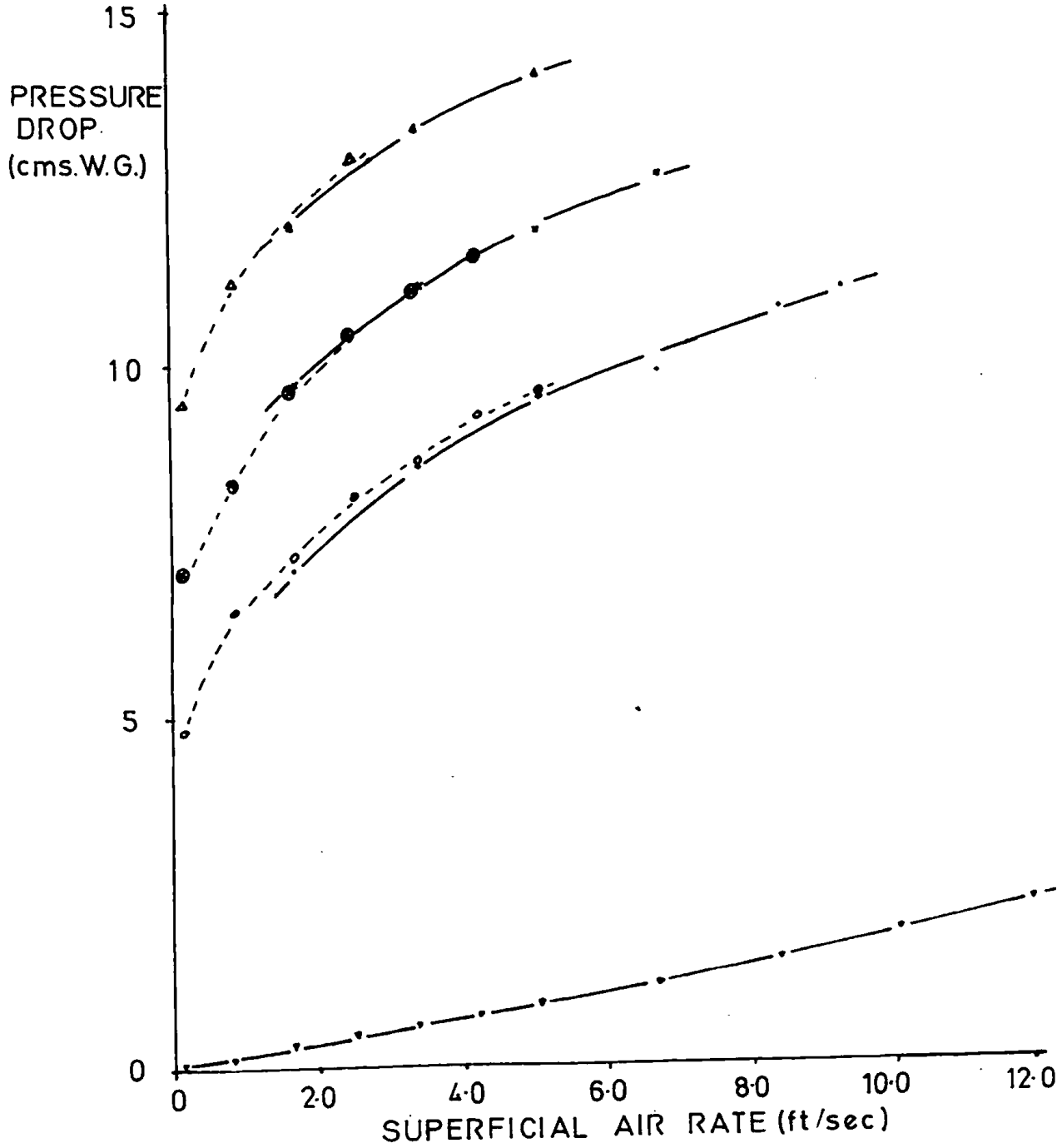
GLASS CLOTH AD225

AIR/WATER SYSTEM

CLEAR LIQUID HEIGHT :- dry 1" 2" 3"

3" Q.V.F. COLUMN :- ——— • x ▲

4" Q.V.F. COLUMN :- - - - - ○ ⊗ △



3.4 Choice of Materials for Further Studies.

It is not the object of this present study to develop the best material for tray floors but to take an example of a material which performs reasonably well, study its operation and characteristics and demonstrate the feasibility of this approach to improved vapour-liquid contact. At present no preformed porous material is specifically made for use as a bubble tray floor, but it is felt that with commercial experience and incentive Industry will develop materials which will have the optimum properties for any given duty.

The materials which have been tested have many advantages and disadvantages and there are many other materials which will give better or worse results. However, it is intended to restrict the choice from the range of materials that have already been tested and not to investigate any further variations along similar lines.

Of the materials chosen all could quite easily be improved to a greater or less extent by changing the various parameters of manufacture. Sintered materials could no doubt be made to have a much lower pressure drop by increasing the pore size and free area for vapour flow. One powerful argument in their favour is their metallic construction, implying great mechanical strength.

Also Industry's familiarity with metallic constructions

is another great asset. However to weigh against these advantages are their comparatively high cost and weight.

Plastic trays could be improved upon by increasing their rigidity, temperature and chemical resistance. High temperature and chemical resisting plastics do exist at present, but it has not been possible to make them as open cell foams. In the future the ideal plastic may be produced, but it is not available at present. The chemical resistance of polyurethane is reasonable but its temperature resistance is poor (softening pt. 150-185°C).

The rigidity of a foam plastic tray floor could be greatly improved by moulding the foam round a supporting grid. However, this compromise solution would increase the cost of the tray.

The foams used in the present study all had voidages of 97% but by changing the voidage and pore size the pressure drop curves could be altered and a series of foams useful for bubble tray floors could be produced.

Glass cloths seem the most suitable for immediate application but their relatively high pressure drop and lack of rigidity must be improved. Woven cloths have the advantage over knitted cloths in that they are mechanically more stable. The pressure drop characteristics of woven cloths could be improved by changing the weave geometry and the weight of the yarn used. A lower pressure drop could

also be achieved by using, say, a twill weave. This weave would also give a stronger cloth for a given hole size and yarn weight. The mechanical strength and the rigidity of any weave can be improved considerably by incorporating wire into the yarn before weaving. This solution would be much cheaper than using a retaining grid in conjunction with the cloth.

In conclusion to the series of studies to find possible tray floor constructions, two materials have been proved worthy of further study. They are woven glass cloth AD225 and 60 pores per inch polyurethane foam.

At this point it is relevant to enumerate the advantages and disadvantages of the two materials chosen for further study in the light of the requirements specified at the beginning of the section.

i) The materials have holes preformed through their bulk, thus pore size and free area are virtually independent of each other and most of all of the cost. Experimental work has manifested a very wide hydraulic flexibility by finding a very low weep point and a low dependence of pressure drop on air velocity. This should lead to a highly flexible performance with a high turn-down ratio. The possibility exists that columns could be run at higher velocities and thus save capital in requiring smaller cross

sectional areas or increase the throughput when replacing the trays in the column.

ii) The tray floor materials are cheap (5/- to 10/- per ft.^{2}) compared with the cheapest perforated plates (15/- to 20/- per ft.^{2} for mild steel). Moreover glass cloths can give very cheap corrosion resistance as the cost of stainless steel perforated plates is 5 to 6 times that of mild steel. However, the trays need conventionally constructed downcomers whose cost will be similar to those of present trays. If high temperature and chemical resisting plastics become available, it will be possible to make the tray floor out of a porous plastic and the downcomers out of an impervious variety.

iii) The materials are light in weight and strong, but are not very rigid. In operation tray floors of these materials are self-supporting but wires woven into the cloths or grids moulded into the plastics could provide sufficient strength for the loads encountered in transport and imposed by maintenance personnel. Also if rigid and strong porous plastics become available the need for their internal grid structure will be greatly reduced. Nevertheless the whole tray floors will be considerably lighter than those of conventional construction and so fewer and lighter supporting members will be needed.

Due to the fragile appearance of glass cloth it was decided to test a sample to destruction. The details of this test are given in Appendix A3.5.

iv) Thermal expansion is no problem with either glass cloths or plastic foams as these materials could absorb small changes within their bulk.

However, plastics, in their resistance to high temperature deformation, and glass, in its failure at low temperatures, leave much to be desired. New glasses and plastics are being developed rapidly and it may not be long before these temperature limitations are removed.

v) Glass, in general, has excellent corrosion resistance but plastics are only fair.

vi) Using a tray floor of a material with small evenly spaced holes will virtually eliminate 'dead' areas. This will probably make the trays self cleaning. However, as the material is cheap and at present mechanically flexible it will be a relatively cheap and easy job to remove and replace it. With regard to the removal through manholes the material can be rolled up and thus larger sections can be used in the construction of the tray.

SECTION 4.

LARGE SCALE PERFORMANCE STUDIES.

Section 4 Large Scale Performance Studies.

4.1 Feasibility and Hydraulic Studies.

Two materials have been chosen for further studies of their performance as bubble tray floors for vapour-liquid contacting devices. The materials satisfy the specifications laid down at the beginning of Section Three and perform well on a small scale. However, the object of the work is to propose and study an improved device which could find a commercial application. The proposed device must, therefore, be shown to be effective on a large scale for the study's aim to be fully realised.

It is general practice to manufacture and transport large bubble tray floors in smaller subsections. The size of the subsections depends on many factors, but if they are to be passed through manholes their maximum width cannot exceed 18".

A rectangular air/water simulator for bubble trays had been used by many previous workers in the Department (203,227,228) and was available for use for the present study. As the tray floor dimensions of the simulator were 68" x 14", it would adequately represent a large subsection of a bubble tray floor in a commercial column. If the proposed tray floors proved feasible on this scale then it is reasonable to suppose that a

commercial tray made from many similar sized subsections would be equally feasible.

4.1.1 Apparatus.

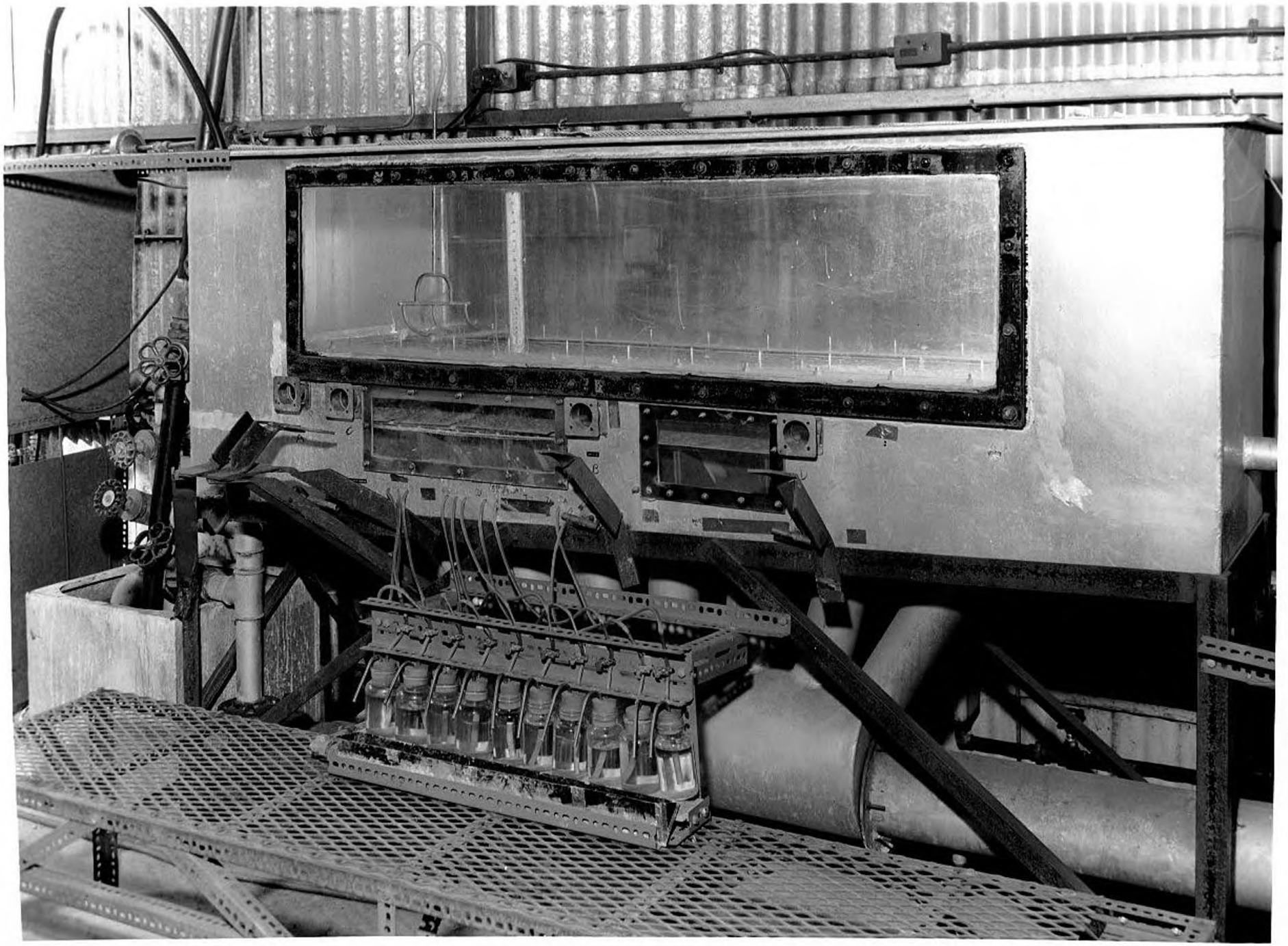
The apparatus is shown photographically in figure 4.1 and diagramatically in figure 4.2. Essentially the apparatus consisted of an aluminium chest 88" long, 20" wide and 30" deep. An internal flange, 3" wide, for securing the bubble tray floors, was welded 18" from the top of the chest. Water was introduced and withdrawn 10" from each end of the chest over inlet and outlet weirs. Above and below the internal flange were large perspex windows so that both the air-water dispersion above the tray and the extent of weeping, if any, could be observed.

To eliminate channelling in the dispersion along the walls of the chest above the internal flange, a set of perspex walls, running the length of the chest were fastened to the top of the tray 3" from the walls of the chest. Due to the corrosive action of the air-water dispersion it was found necessary to use stainless steel or brass nuts and bolts throughout.

Air was supplied by a centrifugal blower capable of delivering 2100 s.c.f.m. against 10" water gauge, (giving a maximum air velocity through the tray of about 5 ft/sec.). The air flow rate was controlled by a damper

FIGURE 4.1

LARGE SCALE APPARATUS.



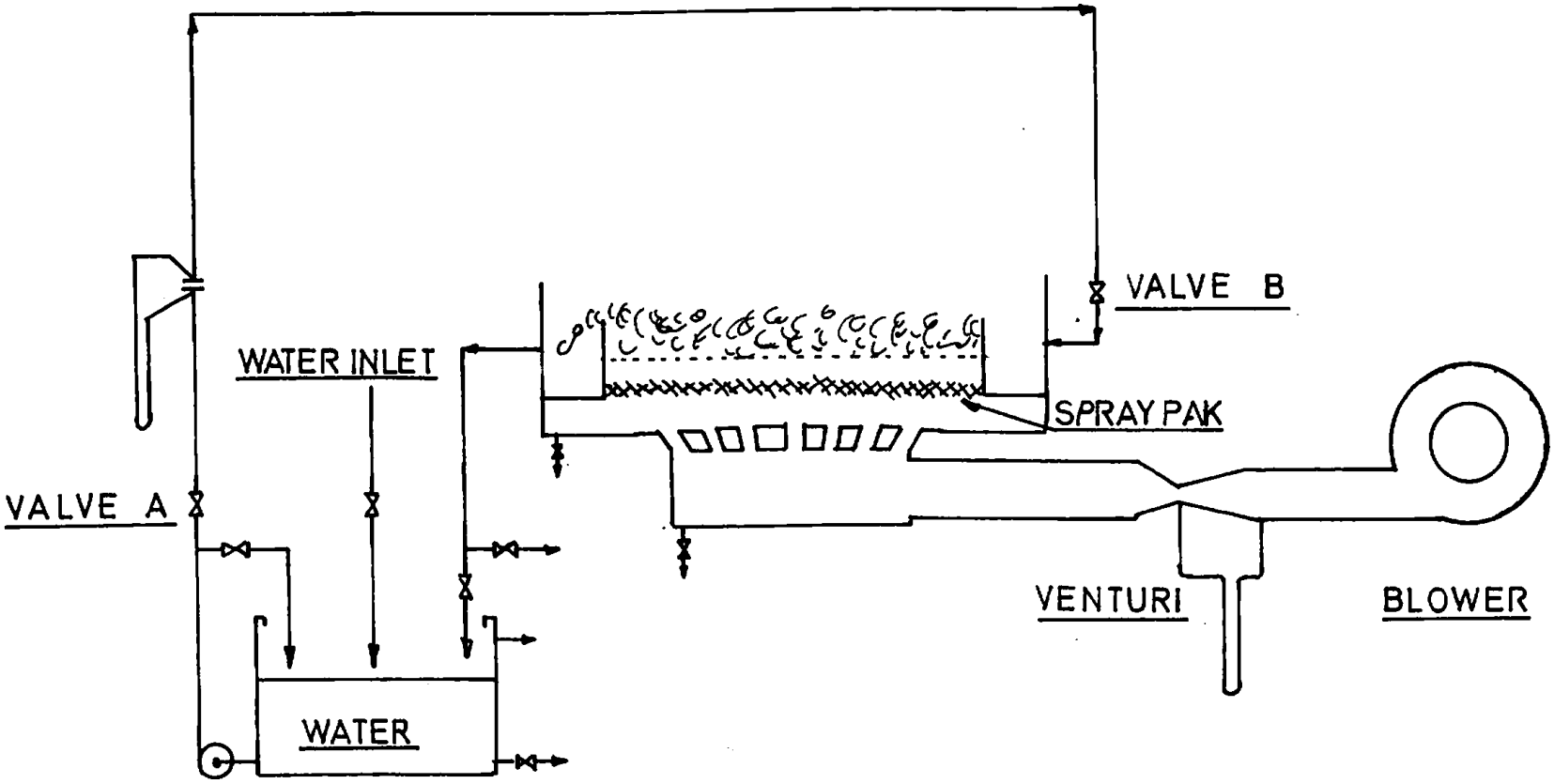


DIAGRAM OF LARGE SCALE APPARATUS FIG.4·2

which throttled the inlet air stream to the blower. The outlet air stream from the blower was connected to the chest by about 18 ft of 7" diameter steel ducting.

The air flow meter consisted of a venturi, in the air line 13 ft. from the blower, with its pressure difference read from a water filled manometer. The dimensions of the venturi are given in figure A 4.1a and its calibration is given in Appendix A4.1.

The air was directed into the chest below the tray through seven 4" diameter pipes from a 12" diameter, 36" long manifold. Under the tray there was a distribution grid of many layers of "spray-paking".

The water supply was obtained from the mains and was fed into a 30 gallon storage tank from where it was circulated to and from the tray through 2" B.S.P. pipes. A centrifugal pump, capable of delivering 80 gallons per minute against a head of 14 feet of water was used, the flow from which was controlled by two gate valves, A & B, the one, A, in the line immediately after the pump and the other, B, immediately before the entrance to the tray. In operation valve A was left completely opened and valve B used for controlling the flow rate. The valve nearer the pump, A, was used only at start up and shut down to prevent draining the pressure tapping lines of an orifice plate which was situated between the two valves. The

calibration of the orifice plate is given in Appendix A.4.2.

The inlet weir was of fixed height but had many small holes ($\frac{1}{8}$") through it to ensure that the liquid entered the tray evenly. The outlet weir height was adjustable to heights of 1" and $2\frac{1}{2}$". After flowing across the tray the water could either be returned to the storage tank or run to waste.

For drainage purposes the chest and air manifold were slightly inclined and had drain taps at their lowest points.

4.1.2 Procedure.

The tray floors were secured to the internal flange of the chest, the apparatus reassembled and the outlet weir height set.

The blower was started and the air rate adjusted to about 3-4 feet per second. The water supply was checked and the circulating pump switched on. Valve A in the water line was opened and the water flow rate adjusted to the desired value using the other valve in that pipe, B.

Both the mechanical and hydraulic performance were observed at various flow conditions. The clear liquid height was measured using three water manometers fastened into the tray floor, one in the middle of the tray and one near to each end.

The experiments were repeated using all combinations

of outlet weir height, water and air rates.

After the experiment the water supply to the tray was stopped by closing valve A, and then switching off the circulating pump. The liquid remaining from the dispersion was then dumped through the tray by switching off the blower.

4.1.3. Results and Discussion.

4.1.3.1. 60 p.p.i. Plastic Foam.

A large sample of 60 pores per inch polyurethane foam was obtained and its performance evaluated. (for specification see Appendix A.3.2.1.)

The foam plastic, covered above and below by a steel mesh, was held in position by trapping it at the edges between the flanges of the column. Soft rubber gaskets were used between the steel mesh and the flanges.

At first chicken wire was used on the top and the bottom of the foam, but it was found to be too flexible over the length of the tray. It was also noticed that it was unnecessary to have a support under the foam. In operation the foam was self-supporting and at shut down it was found that the load imposed by the liquid was insufficient to cause undue sagging of the foam or the dislodge the foam from its fastenings.

Meshes made from flattened expanded metal were tried as upper retaining grids and the lightest grade found which

held the tray rigidly was Expanded Metal Ltd.'s No. FE.3404. This grid has a free area of 75.6% and, therefore, covers 24.4% of the bubbling area of the tray.

When the tray was shut down and the liquid allowed to dump through the foam, it was found that certain areas of the foam became wetted. These areas did not dry out when the tray was started up again, but held liquid in their pores. At very low air rates (less than $\frac{1}{2}$ft/sec.) this condition led to slight weeping from these points. At higher air rates the air eventually forced the water out of the pores back into the froth. This phenomenon was more marked towards the edges of the tray probably due to the wall effect giving an artificially high clear liquid height there (239). A similar effect had been noticed in the previous studies using the 4" and 3" diameter columns. It must be noted, however, that the thickness of the foam used was probably too great for this purpose. A thickness of $\frac{1}{4}$" or less would probably satisfy the hydraulic requirements for a tray floor. Also using a thinner foam the tray would not suffer this wetting effect as the air would not be able to pass round the wetted zone within the foam, but would have to flow through it and thus force out the water. This proposition could not be tried experimentally as thinner sheets of plastic foam were not readily available.

The full hydraulic results for the 60 ppi plastic foam tray are given in Appendix A 4.3.1 and are shown in figure 4.6. Comparing the clear liquid height curves with the pressure drop curves it can be seen that there is a considerable difference between the actual pressure drop and the total of the dry plate pressure drop and the clear liquid height. As the difference is much larger using higher liquid hold up, it would appear that the wetting effect could explain the situation. In this case the liquid in the foam effectively reduces the free area for air flow. This is shown by the differences between the pressure drop curves corresponding to the differences between the clear liquid height curves except at higher air rates where the air rate has a more profound effect on pressure drop.

The hydraulic performance of the material in the 4" and 3" columns, as shown in figures 3.6 & 3.10, cannot be compared directly with the large tray performance. However, as the results obtained are of the same order and follow the same trends it is reasonable to suppose that the trays are operating in a similar manner.

To compare the results directly it is convenient to take the results obtained by previous workers (201,203,227, 228) for Sieve tray floors of various free areas and hole sizes in the same apparatus. Hydraulic results for the various types of sieve trays are given in figures 4.3,4.4

and 4.5.

The pressure drop results for the plastic foam tray compare favourably with the 5½% free area Sieve trays so far as the magnitude of the pressure drop is concerned. Also the trend of pressure drop with increasing air flow rate is less for the ½" holes and much less than the 3/16" holes. However, compared with the 15% free area sieve tray the pressure drop is higher particularly for the higher outlet weir. Also the trend with increasing air rate is about the same, but the range of stable hydraulic operation of the 15% free area Sieve tray is much smaller.

The clear liquid height curves are much more constant than for the Sieve trays which tend to decrease sharply with increasing air rate. The much flatter clear liquid height and dry plate pressure drop curves account for the flat pressure drop curves particularly for the plastic foam and the 15% free area Sieve tray.

4.1.3.2 Woven Glass Cloth AD.225

The performance studies on the woven glass cloth AD225 were carried out in a similar manner to those on the plastic foam. The cloth was held in the column by trapping it at the edges between the bottom flange gasket and the retaining grid. Soft rubber gaskets were used on the top side of the lower flange, between that flange and the cloth, and between

the retaining grid and the bottom side of the upper flange. A good seal was thus obtained between the uneven materials trapped by the two flanges. The same grade flattened expanded metal, namely No. FE3404, was used as a retraining grid for the cloth tray.

It was found that the operation of the cloth tray was entirely satisfactory from a mechanical point of view. The cloth did not sag under load at low air rates nor did it bow unduly at high air rates.

The weep point was found to be very low indeed. In fact with a high weir height and a negligible air flow rate (the blower having been switched off and allowed to run down) the tray was able to support more than four inches of clear liquid without weeping. Also the cloth tray did not weep even when wetted after being previously dumped, as did the plastic foam tray.

Full hydraulic results for the woven glass cloth AD225, when used as a tray are given in Appendix A.4.3.2. and in figure 4.7.

The pressure drop curves are as expected from the previous section, namely flat curves with high valves. Also the pressure drop is much higher than the sum of the dry plate pressure drop and the clear liquid height. This phenomenon was also encountered in both the large and small

scale studies on plastic foam. In that case it was explained that the increased pressure drop was due to the reduction of effective free area by wetting of the foam. In the case of the glass cloth the effect is similar and is studied in more detail in Section 6.

Comparing the pressure drop results for the glass cloth tray with others, figures 4.3 to 4.7, it can be seen that all have lower valves except 3/16" x 5½% sieve trays at high air rates. Also as with plastic foam the stable operating range is much wider than the Sieve trays with comparable flat curves. These effects are expected both from the conclusions reached in Section 2 and the small scale hydraulic results in Section 3.

The clear liquid height results for the glass cloth tray show a different trend from the others at low air rates. This is particularly marked for a weir height of 2½" and a liquid flow rate of 10 gallons/minute/ft. weir width at low air rates. Under these conditions a highly cellular foam was produced on the tray with a corresponding decrease in the liquid hold-up. The tendency to produce cellular foams was discussed in Section 2 and the conclusions are borne out in this case where the small evenly spaced holes enhance the tendency under favourable operating conditions. Under other

conditions the foaming tendency is less marked but still accounts for the comparatively low clear liquid height results. At higher rates still the clear liquid height curves show similar tendencies to the other trays.

FIGURE 4·3 R.W. BOAZ (203)

68"x14" SIEVE TRAY. AIR/WATER SYSTEM.

3/16" DIA HOLES 5 1/2 % FREE AREA.

WEIR HEIGHT :- 1" ····· 2 1/2" ——

WATER RATE :- dry 10 20 40 galls/min. ft weir.

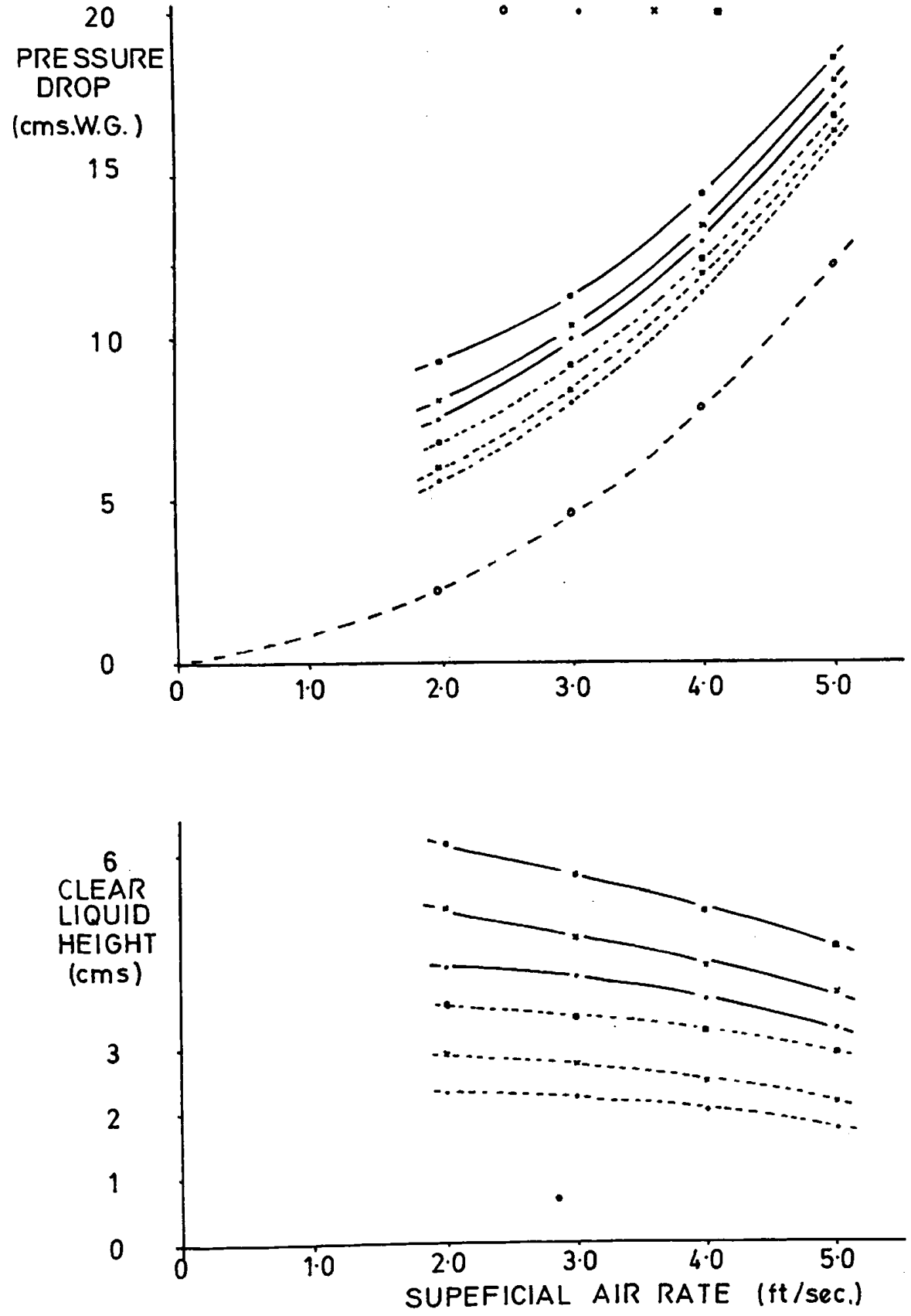


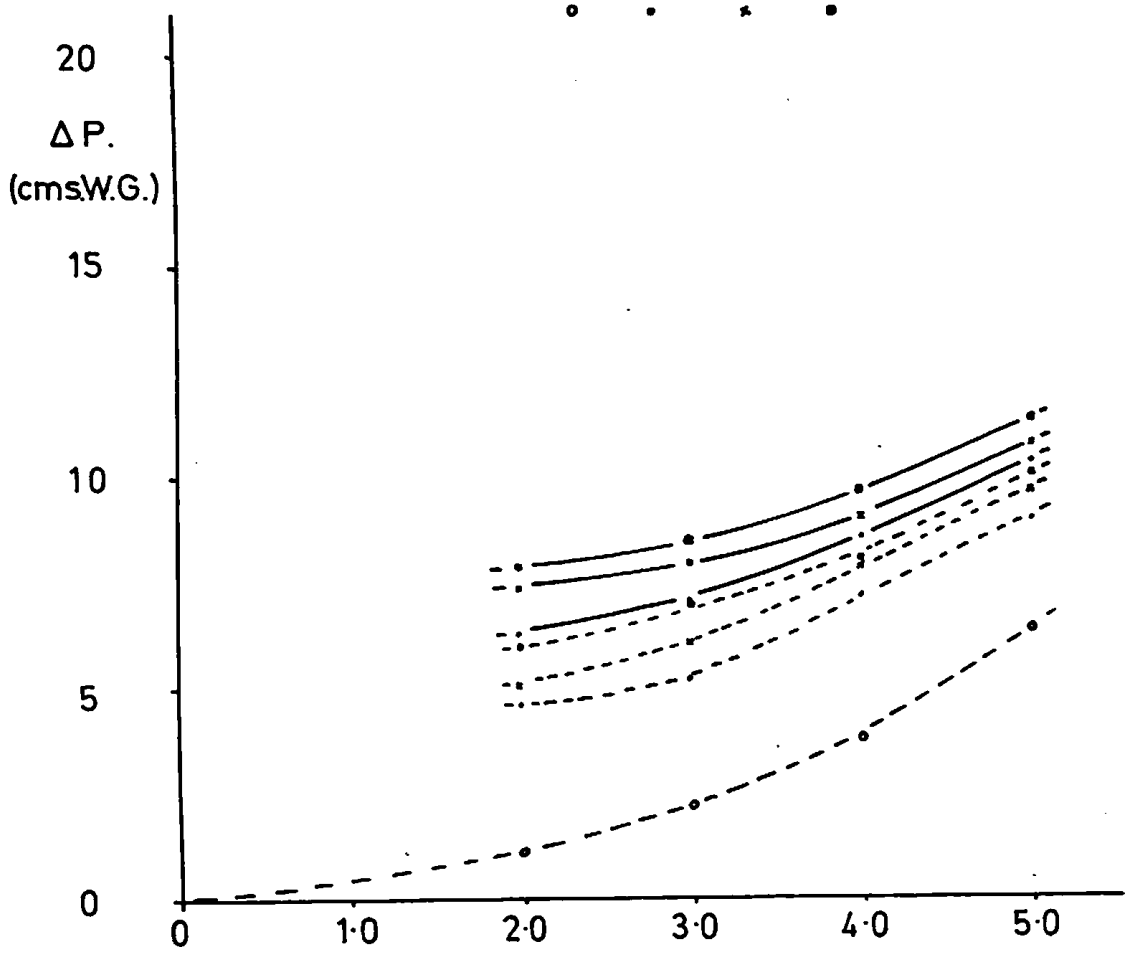
FIGURE 4·4 R.W.BOAZ[203]

68"x14" SIEVE TRAY. AIR/WATER SYSTEM.

$\frac{1}{8}$" DIA. HOLES. 5$\frac{1}{2}$% FREE AREA.

WEIR HEIGHT :- 1" ---- 2$\frac{1}{2}$" ——

WATER RATE :- dry 10 20 40 galls/min.ft weir.



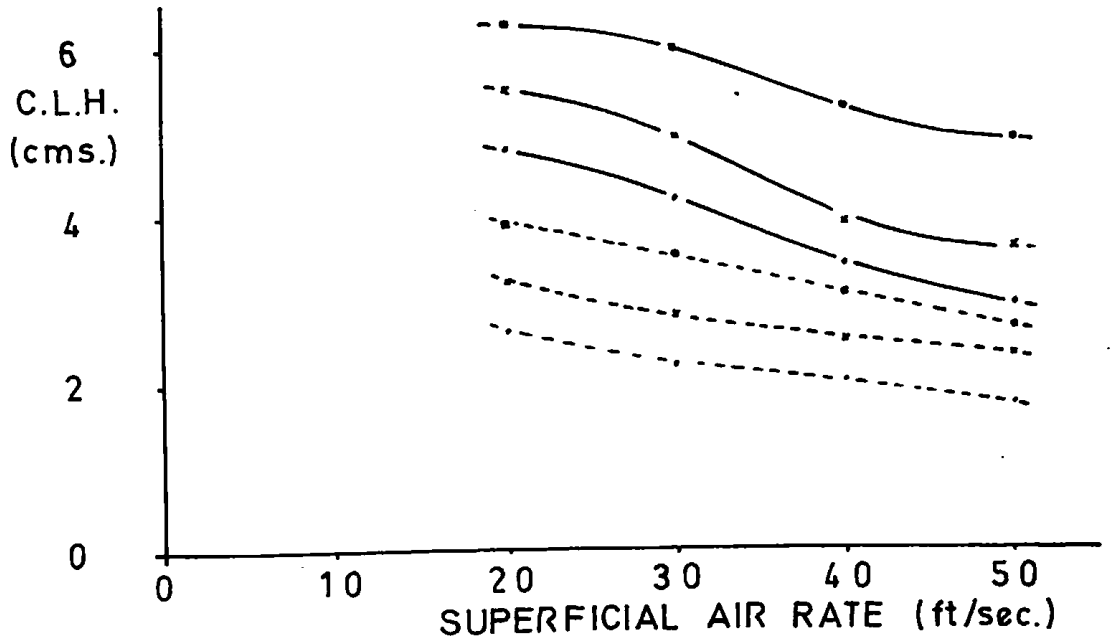


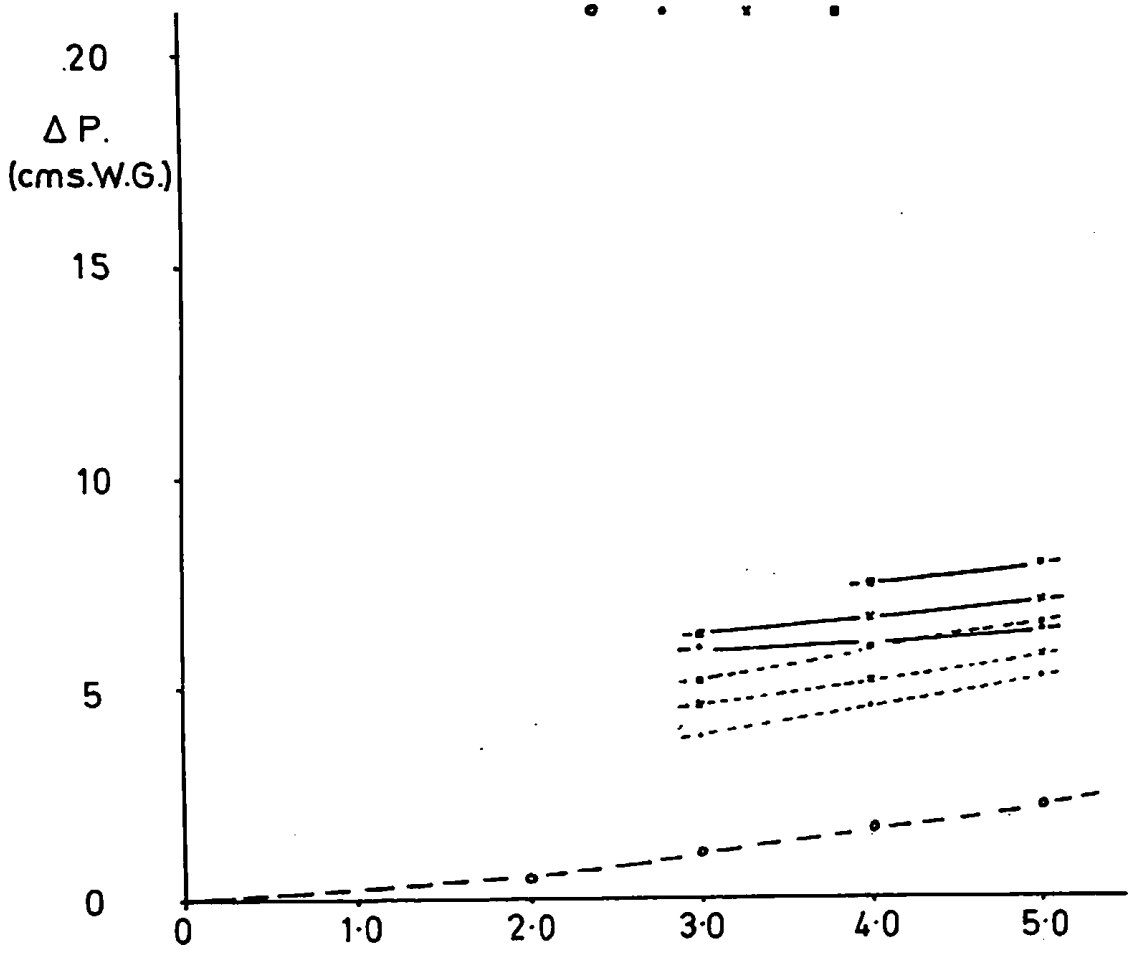
FIGURE 4·5 R.W. BOAZ[203]

68"x14" SIEVE TRAY. AIR/WATER SYSTEM.

$\frac{1}{2}$" DIA. HOLES. 15% FREE AREA.

WEIR HEIGHT:- 1"-----2$\frac{1}{2}$"——

WATER RATE :- dry 10 20 40 galls/min. ft weir.



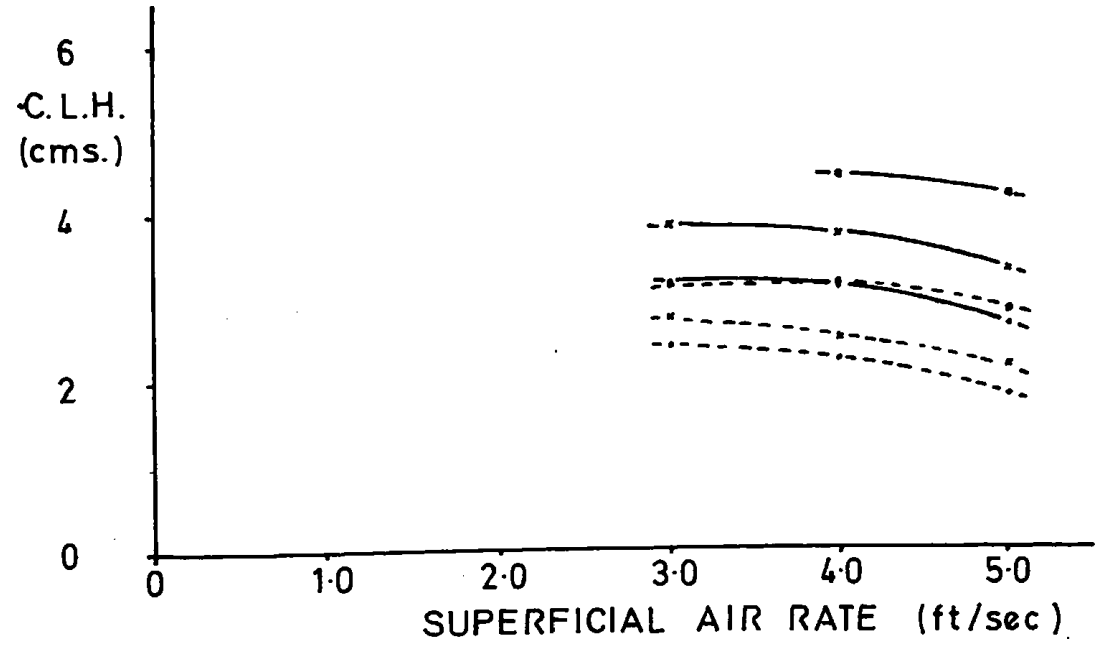


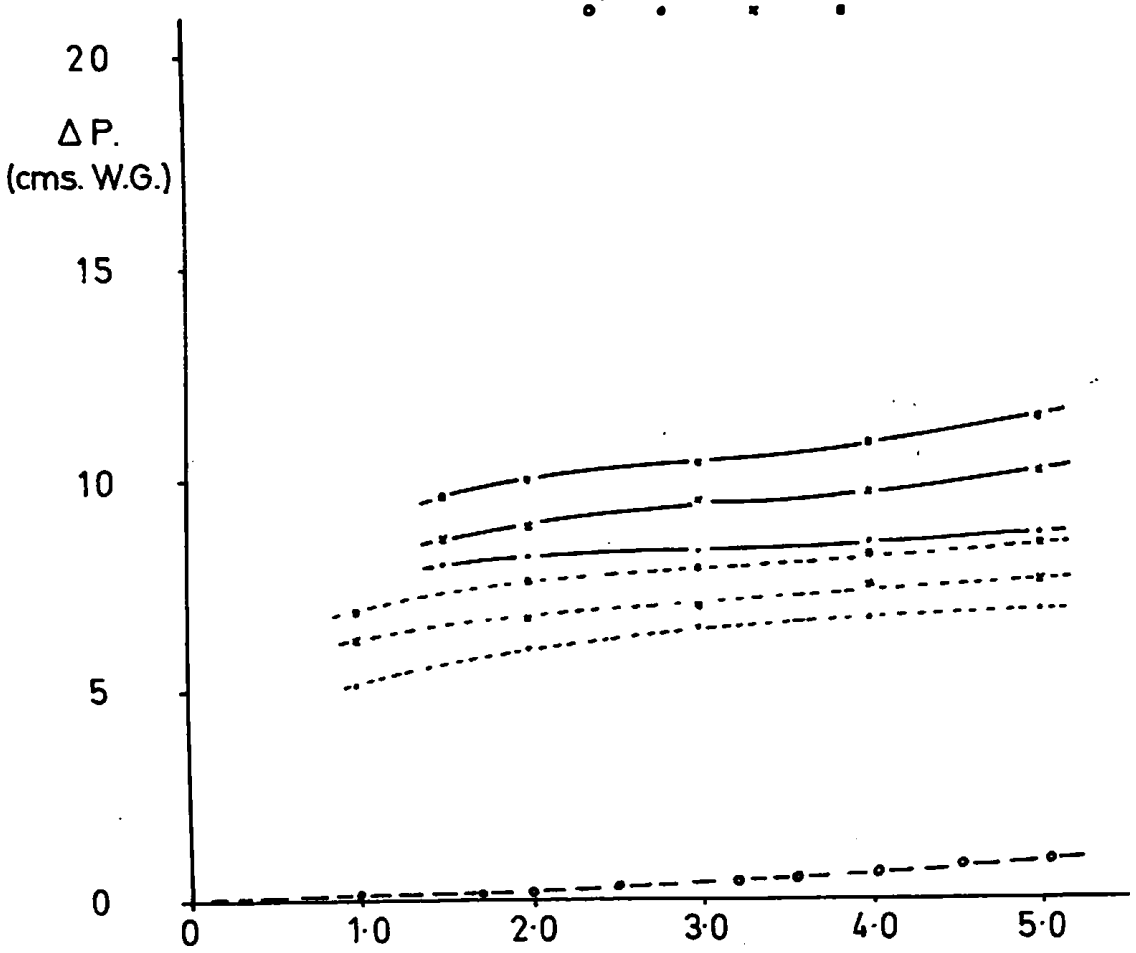
FIGURE 4·6 PRESENT WORK

68"x14" COLUMN. AIR/WATER SYSTEM.

60 ppi. PLASTIC FOAM.

WEIR HEIGHT:- 1"---- 2½"——

WATER RATE :- dry 10 20 40 galls/min.ft weir.



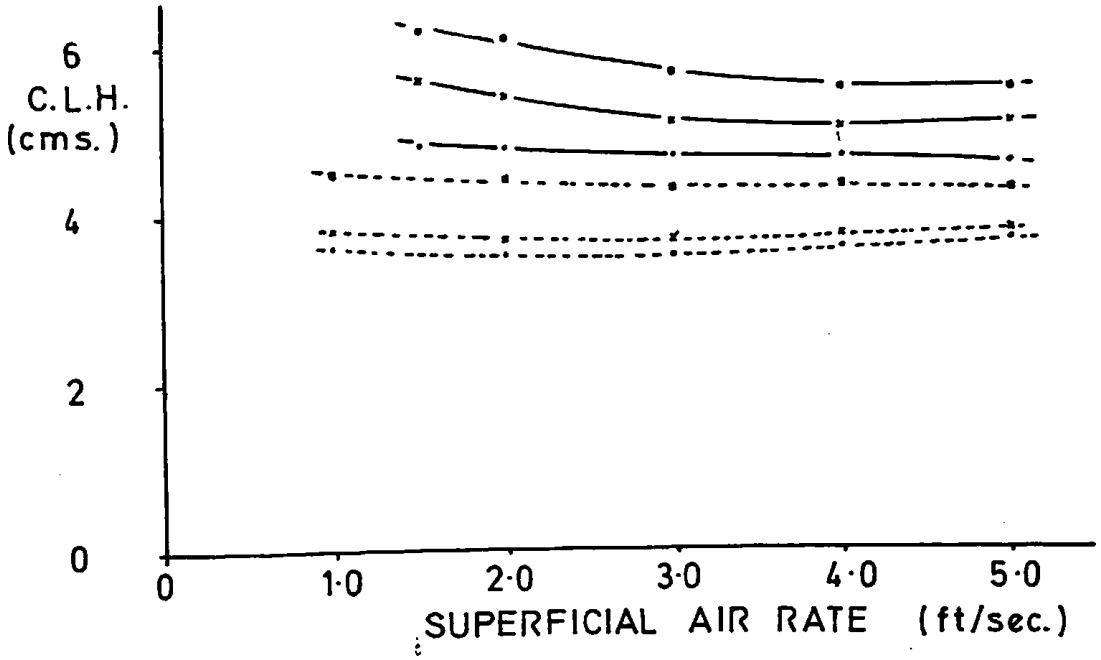


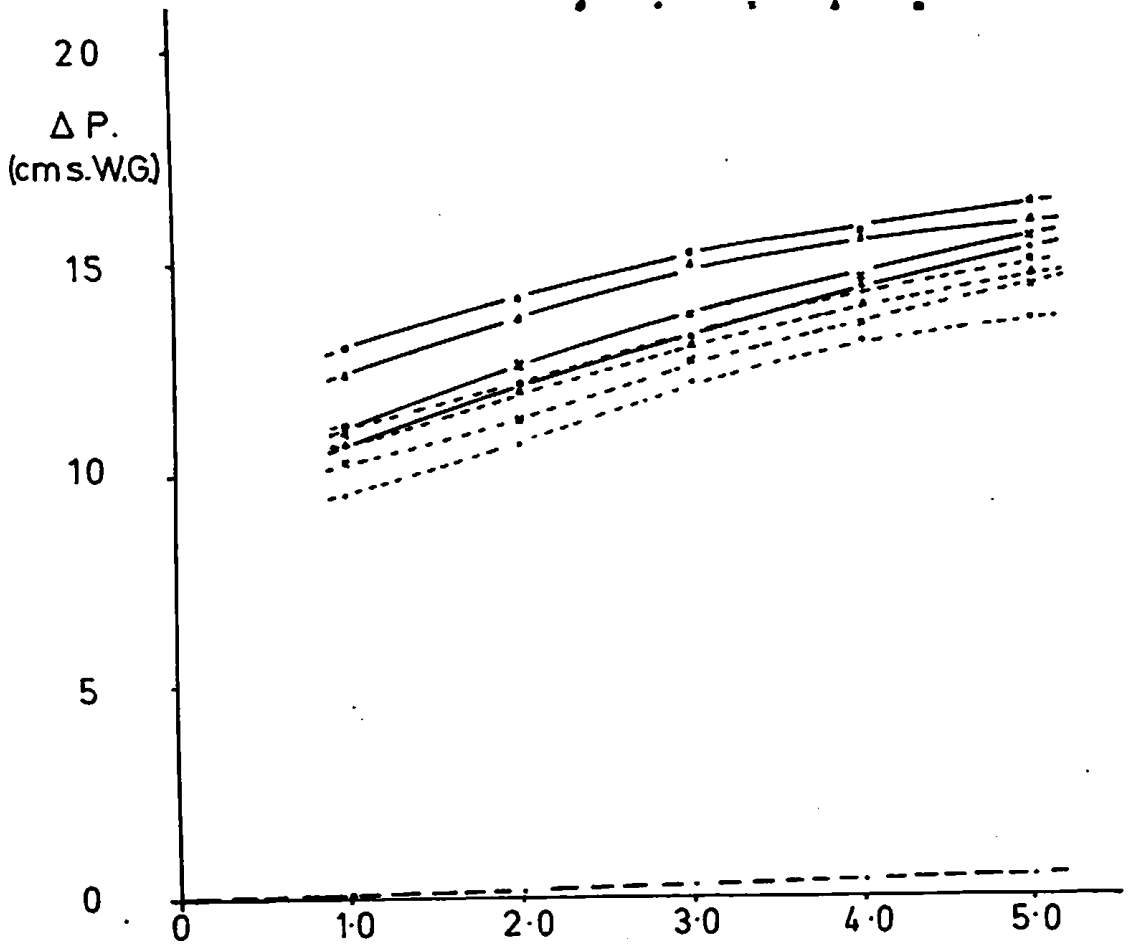
FIGURE 4·7 PRESENT WORK

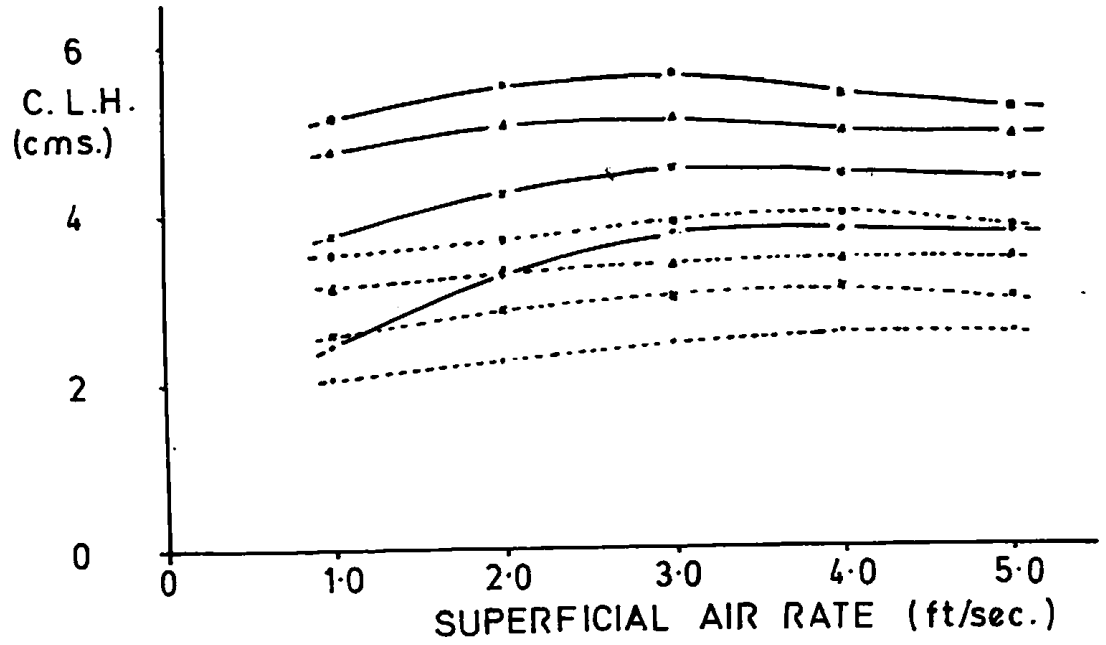
68"x14" COLUMN. AIR/WATER SYSTEM.

WOVEN GLASS CLOTH AD 225

WEIR HEIGHT :- 1"--- 2½"——

WATER RATE :- dry 10 20 30 40 galls/min.ft weir.





4.1.4 Conclusions.

It has been shown that it is feasible to use both materials as tray floors on a large scale. Glass cloths are more favourable, however, due to their inherently better physical and mechanical properties.

With regard to the flat pressure drop curves and the wide range of operation these materials exhibit very favourable hydraulic characteristics. Nevertheless the pressure drop incurred when using either of these materials as a bubble-tray floor must be reduced before this type of tray can achieve any importance.

The production of a cellular foam at low liquid and air rates and high weir heights could be beneficial to the use of glass cloth trays by producing an increased interfacial area for mass transfer. However, if this tendency were unchecked it could lead to priming with its resulting disadvantages.

4.2 Liquid Mixing Studies.

The use of the theoretical tray concept considerably simplifies the design of tray columns, but is only useful if the tray efficiency of practical trays can be accurately determined. Murphree (136) has proposed the most useful definition of efficiency to date, but he assumed complete mixing of the vapour and liquid streams into and out of each tray in the column. In such a case the overall tray efficiency and the point efficiency in the froth on the tray are equal. Although the vapour can be considered to be completely mixed for practical purposes (186-190), it is known that the liquid is not. Therefore, to find the overall tray efficiency it is necessary not only to know the point efficiency in the froth on the tray, but the relationship between the overall tray efficiency and the point efficiency.

Lewis (186) derived the increase of the value of the overall tray efficiency, Eo, over the point efficiency, Ep, when the liquid flowing across the tray was completely unmixed.

$$E_o = A \left[\exp (E_p/A) - 1 \right]$$

where A = 1/Mv, l and v are the liquid and vapour rates respectively, and M is the ratio of the slopes of the

equilibrium and operating lines.

However, it has been shown that the liquid is neither completely mixed nor completely unmixed, but partially mixed, the extent depending on many factors. Many attempts have, therefore, been made to accurately determine the extent of liquid mixing. Furthermore, theoretical concepts of the nature and mechanism of mixing have been proposed so that the amount of liquid mixing can be confidently predicted. However, as the flow patterns on the tray are exceptionally complex the situation has defied rigid hydrodynamic analysis and various simplified models have been suggested which can represent the mixing behaviour of the system. From these concepts it is possible to predict the extent of mixing and its effect on the relative values of the point and overall tray efficiencies.

Kirshbaum's (189) pool concept, later revived by Gautreaux and O'Connell (191), assumed that the tray could be divided into a number of equally sized pools in the direction of liquid flow. The pools were defined as perfectly mixed within themselves, but completely unmixed with the surrounding pools. The liquid flowed across the tray from one pool to the next in its path from the inlet to the outlet weir. If the number of unmixed pools on the tray is n then the following relationship can be used to find the value of the overall tray efficiency from point efficiency.

$$E_o = A\left[(1 - E_p/nA)^n - 1 \right]$$

When the tray is completely mixed the number of pools tends to one and the overall tray efficiency and point efficiency are equal as suggested by Murphree. Also it is pointed out that when the number of pools tends to infinity and the tray is completely unmixed the above equation tends to Lewis's equation.

However, the concept is not very realistic as a specific pool of mixed liquid on an actual tray is very difficult to define in practice and the mixing performance of actual trays can be better defined in terms of the degree of mixing.

The Recirculation Model.

Oliver and Watson (187,188) suggested that mixing could be represented by a certain fraction of the liquid stream from the outlet weir being recirculated and mixed with liquid at the inlet weir. The extent of the recirculation, and thus the mixing, is characterised by the value of the ratio of the differences of the liquid concentrations in the region of the inlet and outlet weirs. The concentration difference parameter, C, is defined as

follows:-

$$C = \frac{x_2 - x_0}{x_1 - x_0}$$

Where x_2, x_1 and x_0 are the liquid concentrations fed to the tray, immediately downstream of the inlet weir, and leaving the tray respectively. Using this parameter it is possible to establish a relationship between the overall and point efficiencies.

$$E_0 = (c/m)\left[\exp.(m.E_p/c) - 1\right]$$

As in the case of Kirshbaum's equation this relationship reduces to Murphree's and Lewis's values when the tray is fully mixed or fully unmixed.

Unfortunately the disadvantage of this method is that it is necessary to take samples from the unstable region near the inlet weir. It is, therefore, not so reliable as the basis for experimental studies.

The Liquid Splashing Model.

Johnson and Marangozi (192) proposed that the majority of the liquid mixing took place by liquid splashing along its flow path. By measuring the extent of the splashing they were able to suggest a relationship between the point and overall tray efficiencies in terms of a parameter, S, which was a function of the splashing factor and the length of the tray, Z.

$$E_o = \frac{E_p}{SZ} \cdot [1 - \exp(-SZ)]$$

However, except under hydraulic conditions where splashing is really significant the mixing factor is so small that there is little difference between the values obtained by the above equation and Lewis's. This concept can only be used at high vapour rates and low liquid rates and not at other conditions when any mixing is caused by turbulence on the tray rather than splashing (227).

The Residence Time Distribution Concept.

The degree of mixing has been well represented by Foss (193) and others using the residence time distribution of the liquid on the tray. To use this method it is necessary to introduce a known input of tracer, such as a step function, into the froth on the tray and analyse the disturbance downstream. Neglecting the need for complex apparatus this method gives a long and tedious calculation for the degree of mixing. Also a highly complex relationship is needed to predict the relative values of the overall tray and point efficiencies.

$$E_o = (1 - I)/mI$$

Where $I = \int_0^\infty [F(T) \exp.(-m.Ep.T)]dT$, and F (T) is the residence time distribution function in terms of the relative time, T. The relative time, T, is further defined

as the ratio of the actual and the average residence times of the liquid on the tray.

The Eddy Diffusion Model.

The model which has probably been most widely used is that in which the liquid mixing is represented by an eddy diffusion mechanism (141,198,201). This model supposes that, in addition to material transport by bulk flow across the tray, material flow takes place between points in the liquid by eddy diffusion. The rate of diffusion is proportional to the difference in concentration at those points and is characterised by an eddy diffusion coefficient, DE. The bulk and diffusion flows are then related by the dimensionless Peclet number, Pe.

By considering an element of liquid on the tray it is possible to derive a relationship between the overall tray and point efficiencies.

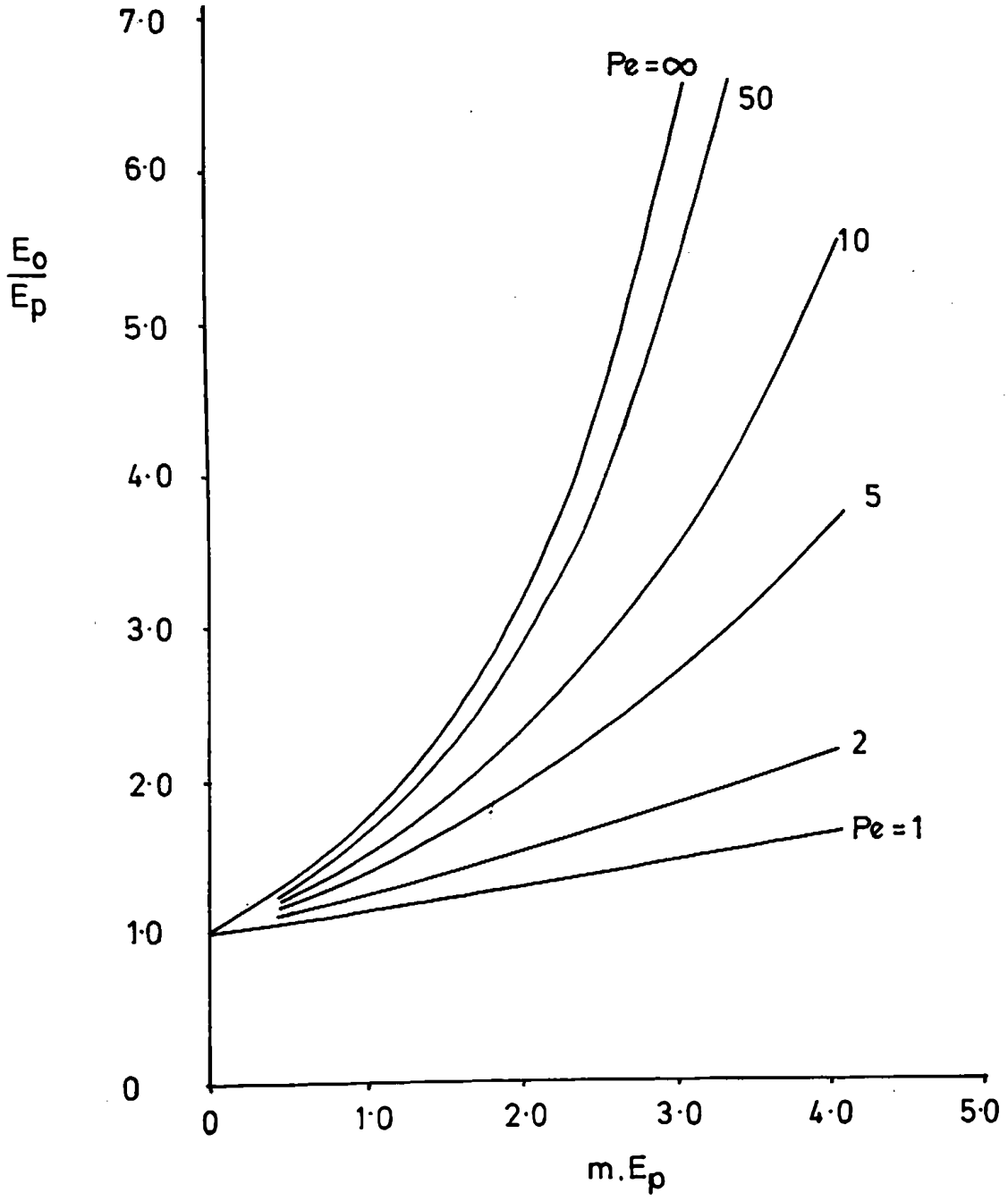
$$\frac{E_o}{E_p} = \frac{1}{E_p.m} \cdot \left[K_1 \exp(-k_2 Z) - K_2 \exp(-k_1 Z) \right]$$

Where K_1 and K_2 are the roots of the quadratic equation, of the second order differential equation, obtained in the derivation. From this $K_1 = k_1^1 / (k_1^1 - k_2^2)$ & $K_2 = k_2^2 / (k_1^2 - k_2^2)$

Although this expression appears complex it can be rearranged as a function of the Peclet number and the point efficiency. When rearranged in this way it is usual to give the graphical solution using the two terms containing

FIGURE 4·8

GRAPHICAL SOLUTION OF EDDY DIFFUSION EQUATION.
(141, 227, 229.)



efficiency as the coordinates and the Peclet number as the parameter (141,227,229) as shown in figure 4.8.

Furthermore it is possible to determine the Peclet number on an actual tray using a comparatively simple experimental technique. Moreover this technique is ideally suited to using an air-water system in conjunction with an involatile tracer. The latter system and tracer are generally very convenient and cheap to use for experimental purposes both from operational and analytical considerations.

Many workers, including those in this Department have, therefore, used the eddy diffusion model as the basis of their studies. It was decided that the study of the liquid mixing characteristics of the glass cloth tray should be carried out using both the same apparatus and experimental technique. In this way a direct comparison with the results for various Sieve trays can be made and an indirect comparison with the work in the AIChE Delaware Report (141).

The theoretical derivation of the equations used in this technique is given in Appendix A4.4. The relationships derived enabled the experimental evaluation of the Peclet number, which is dependent on the dimensions of the apparatus and hydraulic conditions on the tray. The Peclet number is found by continuously introducing a nonvolatile tracer into the froth on the tray near the outlet weir and measuring its concentration at points upstream. The value of the Peclet

Peclet number can be found from the gradient of the line obtained by plotting the results on semi-logarithmic axes as shown in Appendix A4.6.

The eddy diffusivity, which is characteristic of that type of tray, is required for a general design method. Its value can be derived from the Peclet number obtained from a particular tray as given in Appendix A.4.4 and in the sample calculation in Appendix A.4.6.

4.2.1. Apparatus.

The bulk of the apparatus used in this study was identical to that used for the large scale hydraulic studies and is described in section 4.1.1. The apparatus, which was originally designed for liquid mixing studies (227), can be considered as a section cut from a 7ft diameter tray. in the direction of liquid flow. Its advantages for liquid mixing studies are the provision of a long liquid path and a rectangular section to simplify the interpretation of the results.

For this study the apparatus was, modified to render the experimental work to be carried out more easily and quickly. A diagram of the apparatus is given in figure 4.9 and a photograph in figure 4.1. Both air and liquid flows have been described in section 4.1.1 so only the tracer flow remains undescribed. The tracer, a salt solution, was made

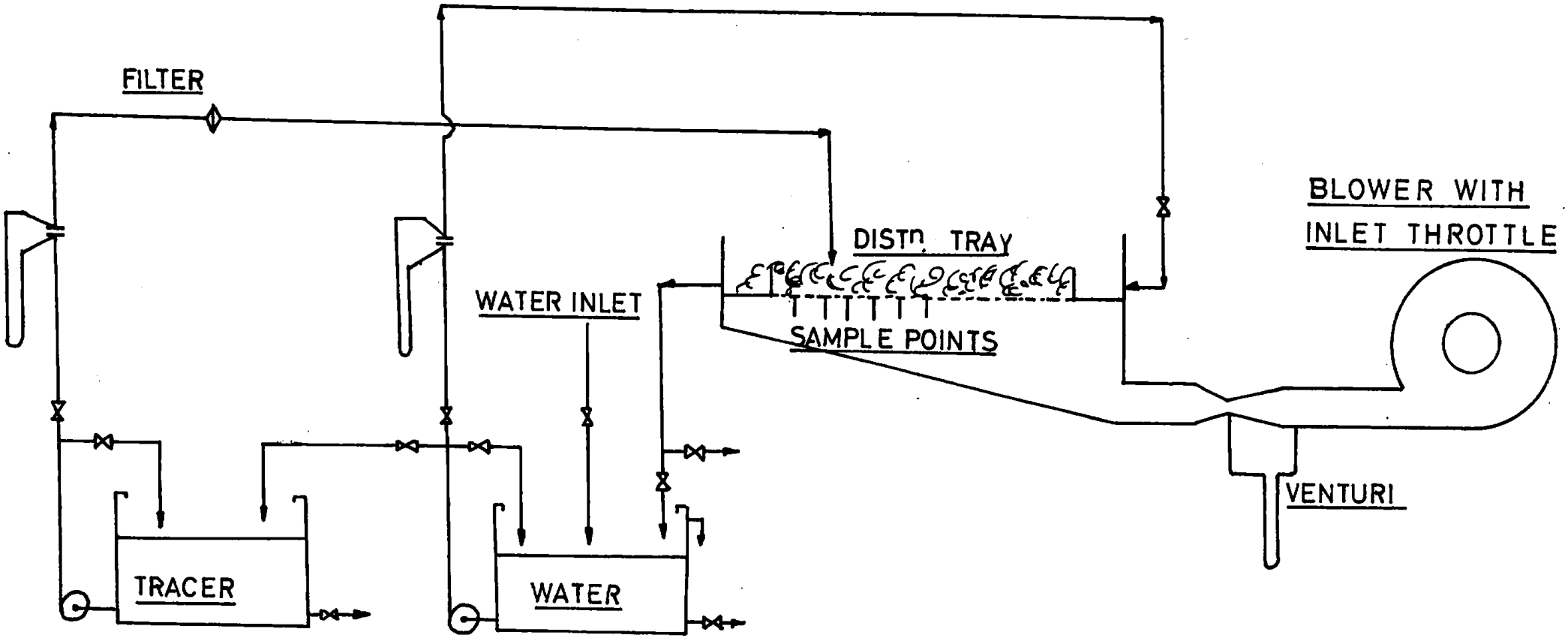


DIAGRAM OF LIQUID MIXING APPARATUS FIG.4·9

up in a 30 gallon storage tank and pumped to the injector which was immersed in the froth on the tray. The tracer flow was filtered so that the injection holes did not block and cause maldistribution. The flow of tracer was measured by an orifice plate and manometer and was regulated by a needle valve.

The tracer was injected across the full width of the tray in a vertical sheet through 1/32" holes drilled at $\frac{1}{2}$" intervals in the top and bottom of a $\frac{1}{2}$" copper tube which formed the bottom of the injector. This tube was located 51" downstream of the inlet weir and at about half the depth of the froth on the tray.

Sample points were put in the tray floor at distances of 55", 53", 51", 50", 49", 48", 47", 46", 36" and 6" from the inlet weir. Using the glass cloth tray the sample points were made from $\frac{1}{4}$" copper tube with one end belled out to form an anular disc and surrounded by a $\frac{3}{8}$" diameter rubber backing disc. The backing disc was necessary to mask off the surrounding holes in the cloth and thus create a comparatively bubble free zone immediately above the sample tube so that the liquid would flow down it.

The samples flowed from the points through polythene tubes out of the column into 250 ccs. sample jars and allowed to overflow continuously into a waste trough. Samples for

analysis were taken from the overflowing streams.

4.2.2 Procedure.

Between 5 and 40 lbs. of salt were dissolved in the tracer supply tank and the solution circulated for about 10 minutes. The tracer concentration and flow rate needed to give a reasonable concentration (approximately 5 gms/l) in the froth at the injection point was known from previous experience.

The tray was started up and operated at given hydraulic conditions as described in section 4.1.2. The water was used on open circuit, i.e. the water from the outlet weir was passed directly to waste.

The tracer flow was started and its rate adjusted to a rate known from previous experience, usually about 0.1 lbs/min. The sample flows were started and adjusted to about 100 ccs. per min.

All the flow rates were maintained constant for about 20 minutes and then the experimental conditions noted and samples of the overflow streams taken.

The salt concentration of each sample was found by measuring its electrical conductivity using a Mullard conductivity bridge. The calibration of the bridge is given in Appendix A.4.5. As the electrical conductivity changes with temperature the samples were put in a 25°C constant

temperature bath for about 10 minutes before their conductivities were measured.

The Peclet number and eddy diffusivity were calculated as shown in appendix A.4.6.

The experiment was repeated using all the combinations of water and air flow rates and outlet weir heights.

4.2.3 Results & Discussion.

The liquid mixing results for the glass cloth tray can be found in Appendix A.4.7 and are plotted in figure 4.10 using the liquid and vapour rates as the coordinates. It can be seen that the results fall into families of curves as expected from studying similar results of different trays. (141,201,203,227,228).

It can also be seen that an increase in the extent of mixing, characterised by a decrease in the Peclet number or an increase in the eddy diffusion coefficient, is apparent with both an increase in the air rate and liquid hold up. Similar effects have been noted by other workers and many empirical relationships have been proposed to predict the changes in the extent of the mixing. For example, the University of Delaware's Final Report (141) suggests that

$$D_E^{\dot{\epsilon}} = 0.0124 + 0.0171\,U + 0.00313\,L + 0.0150\,W$$

can be used for trays having 3" diameter bubble-caps, where U and L are the air and liquid rates respectively and W is the weir height.

Using the above relationship, values for the degree of mixing at corresponding operating conditions were calculated and then plotted in figure 4.11. It can easily be seen the results are of similar form, but the values are higher for trays using 3" diameter bubble-caps than glass cloths, for most conditions. The slope of the curves with air rate is similar but the effect of liquid rate is much more pronounced for the Bubble-cap tray. This latter effect is probably due to the liquid hold up having a greater damping effect on the turbulence produced by small, low momentum giving holes.

It is obvious that a relationship similar to that given above could be proposed for the glass cloth tray, but it is felt that as it is merely empirical the values of the constants would be affected by a change in the make-up of the cloth. Moreover as the cloth used in the present studies could not be used commercially the correlation of any empirical formulae for this particular cloth would be redundant.

Other workers in this Department (203,227,228) using Sieve trays with low ($5\frac{1}{2}\%$) and high (15%) free areas found results over the same range of operating conditions using the same apparatus (see fig. 4.12). At low air rates the values for the eddy diffusion coefficient are slightly higher for low free area Sieve trays than for the glass cloth tray using the same outlet weir height. However, at higher air

rates for the same Sieve trays the coefficient increases rapidly to values in the range 0.04 to 0.065 ft²/sec. In each case the tray with the largest holes gave the highest values for the same conditions. Also using a high free area Sieve tray with large holes ($\frac{1}{2}$") the coefficient was found to be larger than both the previous trays, that is, having a range of values from 0.04 to 0.08 ft²/sec.

All the above results are as expected from the considerations in section 2 from which it was concluded that the minimum liquid mixing would be obtained by using a tray which introduced the least momentum from the vapour stream into the liquid on the tray. This condition, it was proposed, could be obtained by using small holes or a low free area.

When considering the enhancement of the overall tray efficiency over the point efficiency the value of the Peclet number for that tray under those conditions is required. (See figure 4.8). In the present study and those of the previous workers in the Department (203,277,278) the value of the Peclet number for this apparatus was found experimentally, as an intermediate stage in the determination of the eddy diffusion coefficient. The values are given in figures 4.10 and 4.12 respectively.

It can be seen that in each case the Peclet number

increases with liquid rate, but to a less extent at higher rates. Also the Peclet number is higher for lower air rates and weir heights. These changes are consistent with eddy diffusion coefficient results.

Also it can be seen for corresponding flow conditions the glass cloth tray and the Sieve trays with low free areas have similar results, but the glass cloth tray tends to give slightly higher values. However, for the high free area Sieve trays the value of the Peclet number is much smaller and the enhancement will, therefore, be lower.

The Peclet numbers corresponding to the dimensions of the present apparatus were calculated from the eddy diffusion coefficients for a 3" Bubble-cap tray. The hydraulic data necessary for the conversion was obtained from the Delaware Report (141). The results thus obtained are given in figure 4.11. These results show a slightly different trend from that expected from the eddy diffusion coefficient results. For not only does the rise in the Peclet number level off at higher liquid rates, but it begins to fall again. This effect is caused by the clear liquid height increasing faster than the liquid flow rate at higher rates. This tendency and the higher values of the eddy diffusion coefficient gives values of Peclet number which are considerably lower than those for the glass cloth

tray under the same conditions. The corresponding enhancement of the value of the overall tray efficiency over the point efficiency will, therefore, be less for the Bubble-cap tray.

Oscillation of the froth on the trays has been discussed by some authors in conjunction with similar work (201,203,230), but the phenomenon was not observed in the range of operating conditions used in this study. It would appear, however, that the onset of oscillation occurs at higher air rates for trays with smaller holes, and so the range of air rates available using this apparatus was too low to encounter this effect for the glass cloth tray.

4.2.4 Conclusions.

Liquid mixing takes place on the glass cloth tray as on other cross-flow trays, and is affected in a similar manner by the air rate and the liquid hold-up. The degree of mixing is, however, lower than the other cross-flow trays for the same operating rates. This result should lead to greater enhancement of the overall tray efficiency over the point efficiency under favourable long liquid flow path conditions.

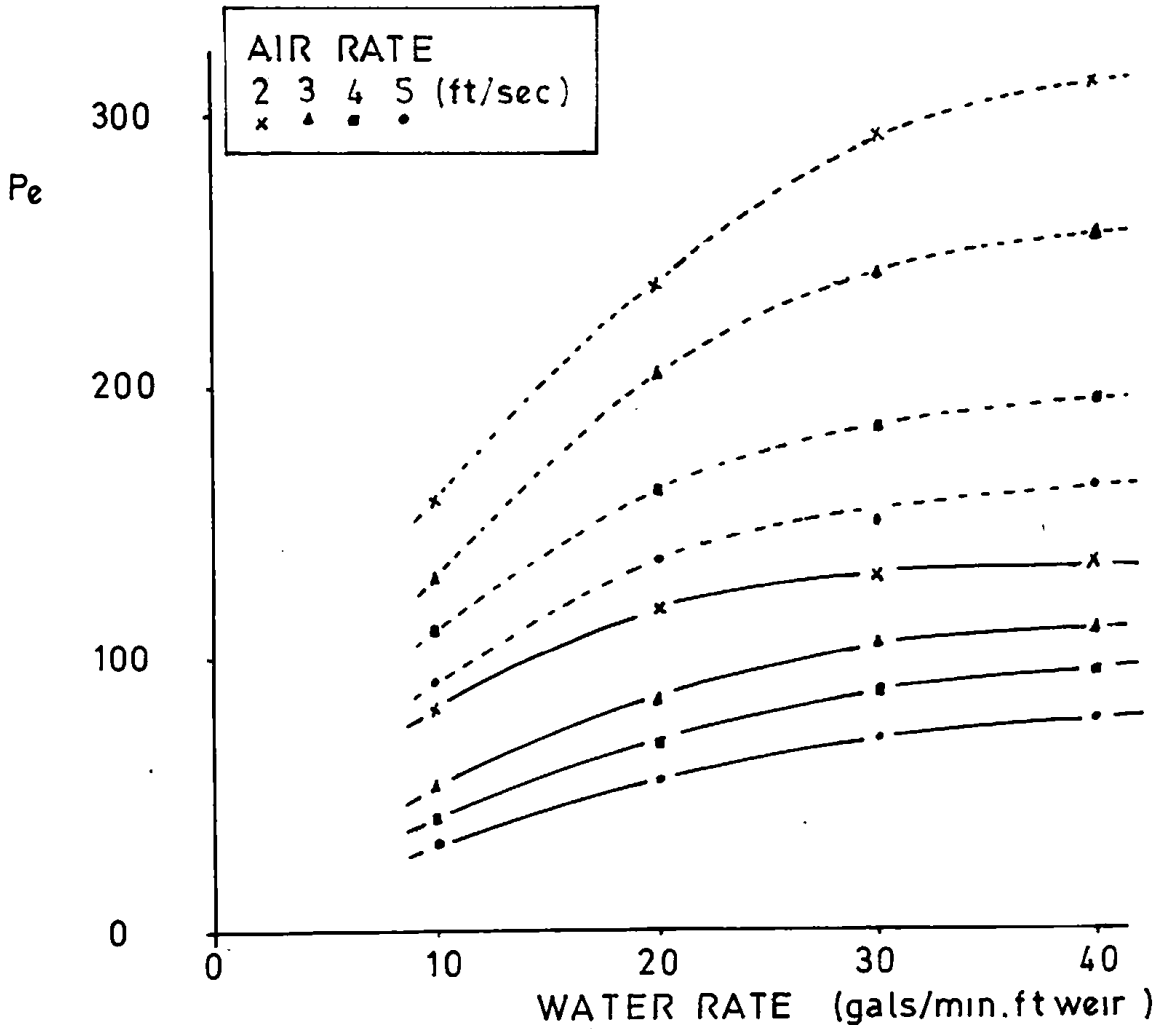
Oscillation of the froth on the tray was not observed under the conditions that could be used for this study. Authors (201,230) disagree on the effect of this phenomenon on mass transfer, but its effect on the mechanical requirements for the column and its foundations is definitely detrimental.

FIGURE 4·10 PRESENT WORK

68"x14" COLUMN AIR/WATER SYSTEM

WOVEN GLASS CLOTH AD.225.

WEIR HEIGHT :- 1"----,2½" ——



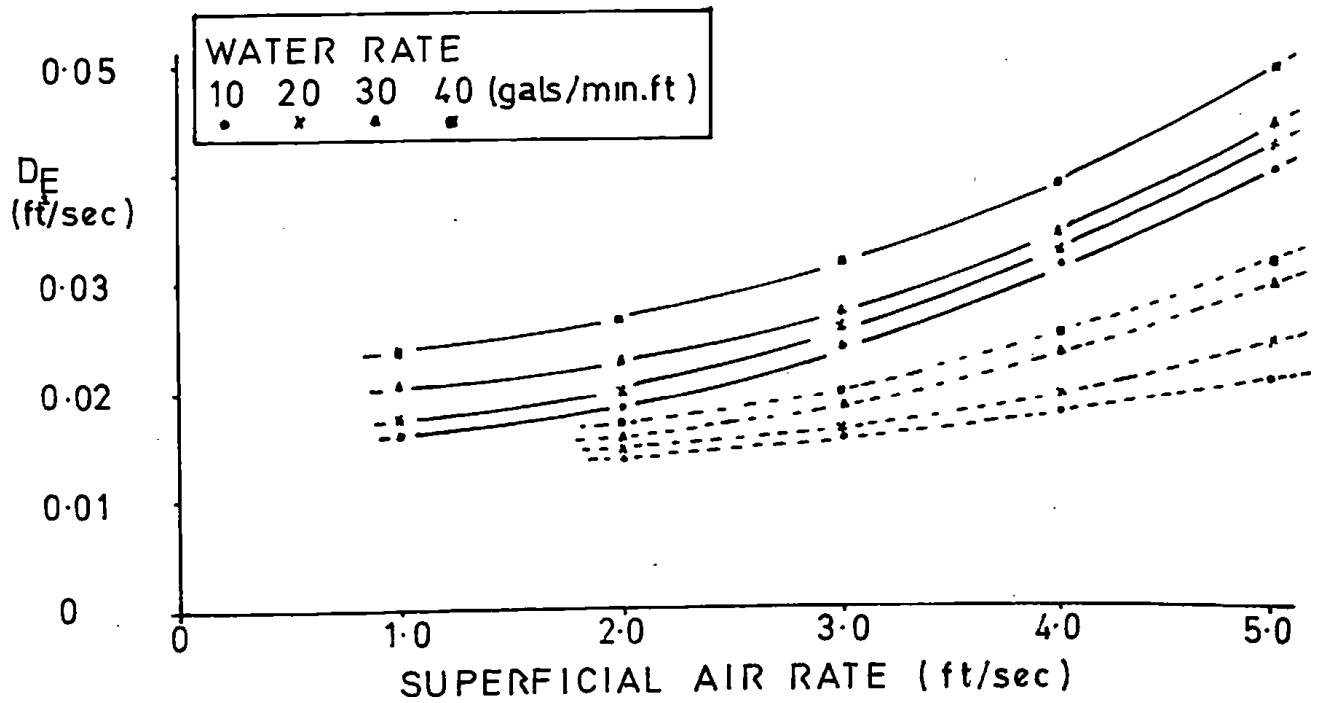
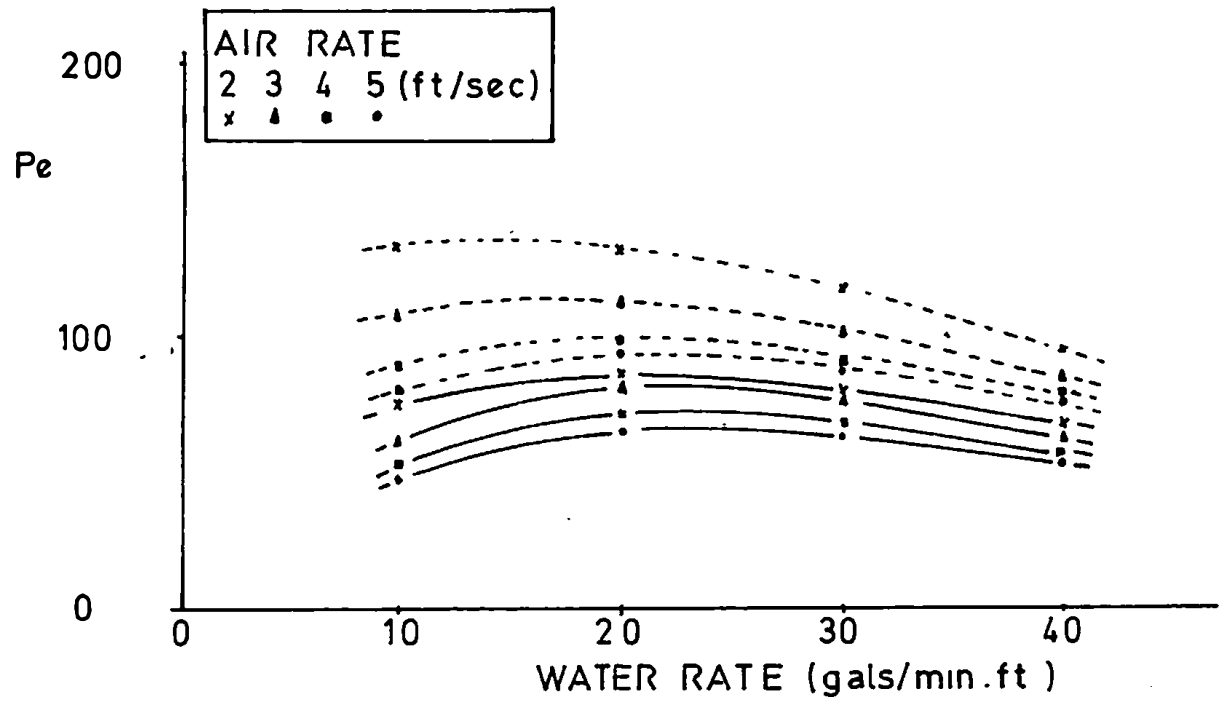


FIGURE 4-11 DELAWARE REPORT[141]

TRAY WITH 3" DIA. BUBBLECAPS

AIR/WATER SYSTEM

WEIR HEIGHT :- 1"----, 2½"—



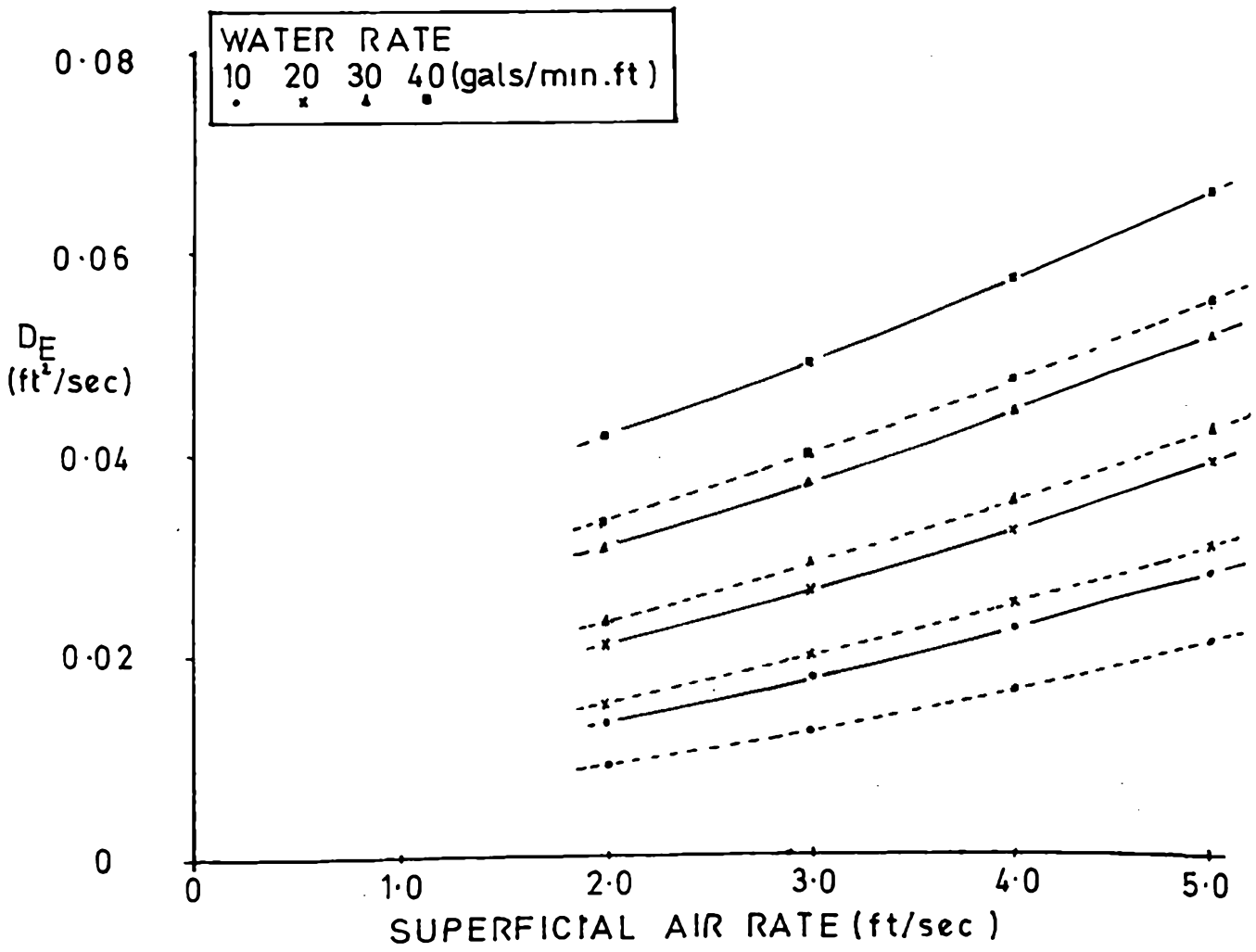
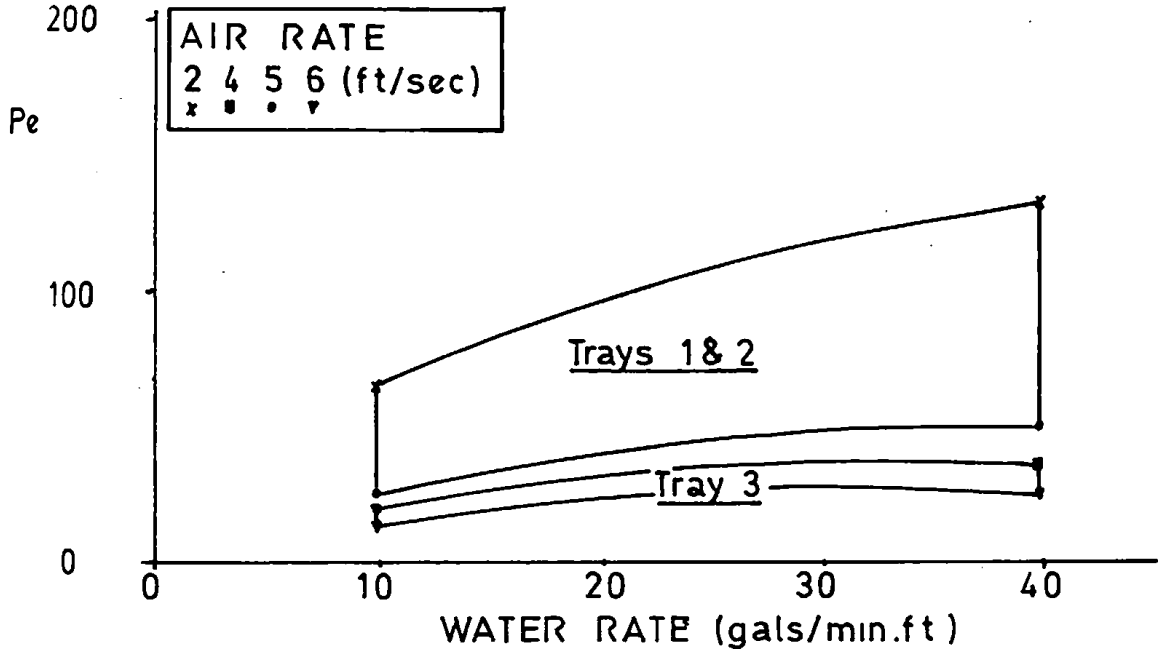


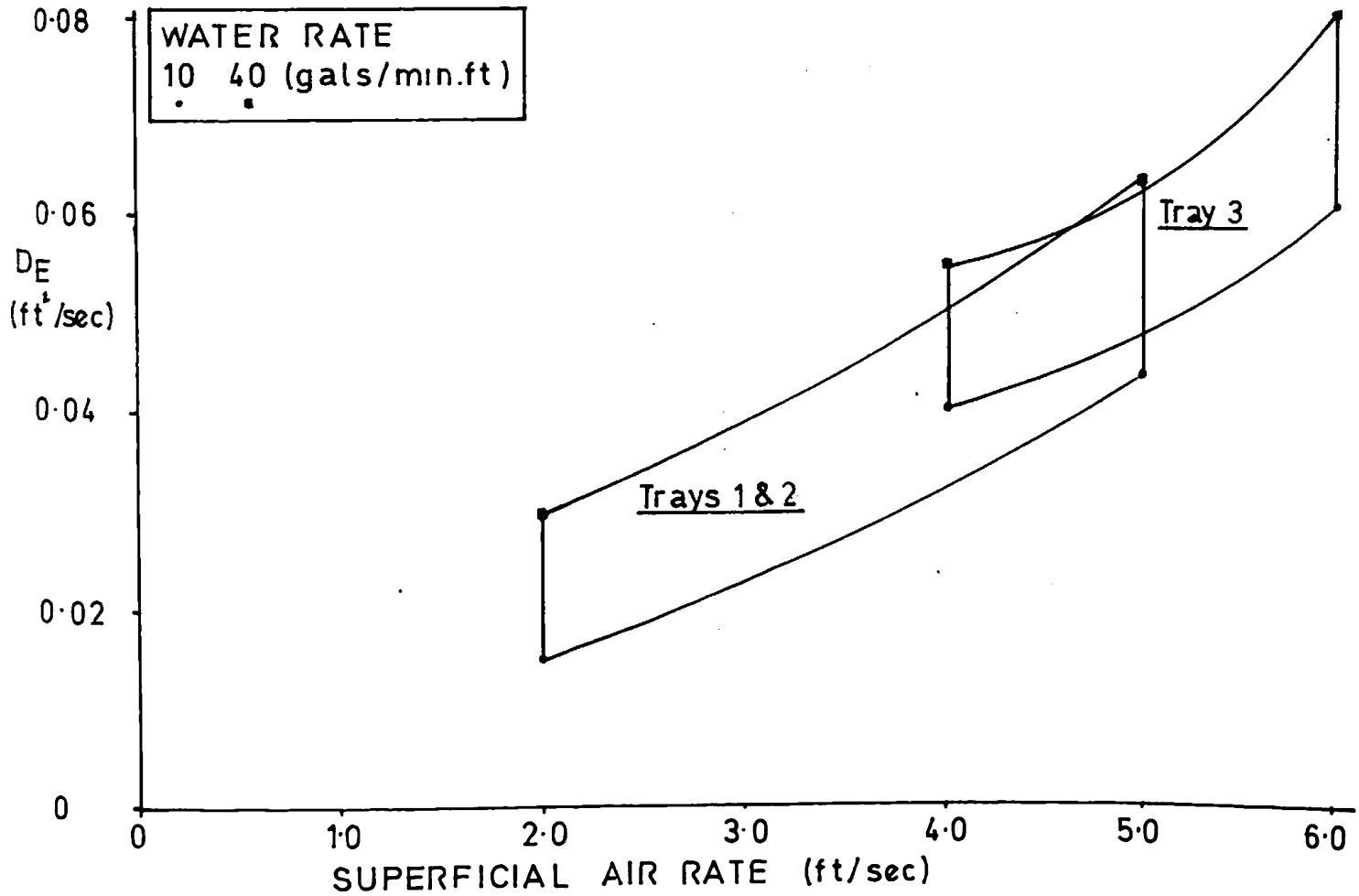
FIGURE 4·12 PREVIOUS WORKERS (203, 277, 278)

6 8"x14" COLUMN. AIR/WATER SYSTEM.

SIEVE TRAYS :- 1 3/16" HOLE DIA. x 5½ % FREE AREA
2 ½" " " x 5½ % " "
3 ½" " " x 15 % " "

2½" WEIR HEIGHT





SECTION 5.

ACTUAL DISTILLATION STUDIES.

SECTION 5. ACTUAL DISTILLATION STUDIES.

Encouraging results had been obtained using the proposed new tray in apparatus simulating the hydraulic conditions on a distillation tray. It was therefore proposed to verify that these results could be repeated under actual distillation conditions by studying the performance of the new tray using an actual distillation system. Moreover by using this system the mass transfer performance of the trays can also be determined.

Many definitions have been used to correlate the mass transfer performance of distillation trays, the most useful being the concept of separation efficiency. This serves to permit the calculation of the behaviour of an actual distillation column by comparing it with a theoretical column. The behaviour of the theoretical column can be calculated using material and enthalpy balances and phase equilibrium data without reference to the mechanisms of heat, mass and momentum transfer occuring on the actual trays. These calculations are relatively simple and thus the use of the separation efficiency makes the calculation of the performance of an actual distillation column equally simple.

Lewis (137) attempted to represent the deviation from theoretical behaviour for a whole column but his definition holds many drawbacks and was therefore soon superceded by definitions involving individual trays in the column.

Once the behaviour of a single tray is considered the actual mechanisms of heat, mass and momentum transfer can be included in the definition of the separation efficiency. That is, the efficiency of an actual tray can be predicted from the rates of heat and mass transfer, the interfacial area, the contact times and the extent of mixing within the phases.

Murphree (136) assumed constant molal or pseudomolal flow rates within the column. He then defined the tray efficiency for each phase, in terms of the composition changes in that phase, when it flowed through an actual and a theoretical tray. That is, for the vapour phase:-

$$E_{mv} = \frac{y_n - y_{n+1}}{y_n^* - y_{n+1}}$$

where Yn is the composition of the vapour leaving tray n and Y_n^* is the composition of the vapour in equilibrium with liquid leaving tray n.

Similarly for the liquid:-

$$E_{mL} = \frac{x_{n-1} - x_n}{x_{n-1} - x_n^*}$$

where x_n^* is the composition of the liquid in equilibrium with the vapour leaving the actual tray n.

There are many drawbacks to these definitions of efficiency but the most serious involves the assumption of equilibration of the phases in the actual column. Moreover, the streams which need to be in equilibrium for the definition to hold, depend on the phase being considered.

Furthermore the efficiencies defined for the different phases only have the same values when the equilibrium and the operating lines are parallel. In the other cases the relationship between the two phase efficiencies is given by:-

$$\left(\frac{1}{E_{mL}} - 1\right) = \left(\frac{1}{E_{mV}} - 1\right)\frac{L}{mV}$$

Other definitions have been proposed using temperatures, driving forces and enthalpies but the same criticisms can be levelled against each one.

Standart (138), following Hausen (240), tried to solve this problem by considering the total change of the properties of a phase occuring across an actual tray and across an eqivalent equilibrium tray. In this case the overall, the liquid and the vapour phase efficiencies are equal for each component and for the overall mass and heat balances. However this still leaves M+2 definitions of efficiency, one from each of the M components and two from the heat and mass balances. Fortunately their definitions are interrelated and so only one is independent. It is generally convenient to choose the overall material efficiency, E, which can be expressed as a weighted mean of the composition efficiencies, Ei:

$$E = \frac{V_n^* \left[\Sigma_i E_i y^*_{n,i} \right] - V_n \left[\Sigma_i E_i y_{n+1,i} \right]}{V_n^* \left[1 + (\Sigma_i E_i y^*_{n,i}) - (\Sigma_i E_i y^*_{n+1,i}) \right] - V_n}$$

Many authors (140) have praised this definition of efficiency for distillation trays as it has less fundamental limitations. However Standart admitted that "it is extremely difficult if not virtually impossible to make the measurements necessary to permit the accurate and direct evaluation of this efficiency" (138).

Moreover, since the original paper containing the new definition, at least two papers have been published by Standart (114, 241) in which he uses Murphree's definition for the evaluation of the efficiency of his trays. As no published work has appeared including actual results employing Standart's definition of efficiency it was proposed to revert to the most widely used alternative, namely Murphree's.

5.1 Distillation Studies using a 12" Diameter Column.

So many methods, systems and apparatus have been used to evaluate the distillation performance of trays that most cannot be compared directly for that reason. Zuiderwig et al (6) noted this when they published a comprehensive comparison of conventional trays using consistent apparatus and systems throughout.

As well as studying the performance of the new cloth trays it was considered that this work should include a valid comparison with conventional trays. It was decided, therefore, that the work of Zuiderweg et al should be chosen for this purpose.

There were, however, certain limitations imposed on performing an exact comparison with their work. For example, the reboiler and condenser available in the Department would not give the required throughput if the same diameter column, namely 18", were used. A smaller, 12" diameter, column was therfore designed and built. In general, however, the experimental study was kept as similar as possible to theirs. The same system, namely toluene - n heptune and the same equilibrium data, obtained by private communication from Dr. Zuiderweg, were used.

Similarly the average Murphree efficiency was determined by taking samples from the reflux line and from the liquid leaving each tray.

5.1.1 Apparatus.

A complete set of engineering drawings covering the distillation column and ancillary equipment can be found in Appendix A5.5. Figures 5.1 and 5.2 give a general view of the apparatus both lagged and unlagged.

The distillation apparatus consisted of upper and lower column sections, a steam-heated reboiler, and a water-cooled total condenser. Three distillation trays were fitted in the upper column section whilst the lower column section remained empty. All the major parts were made principally from copper with brass or steel flanges.

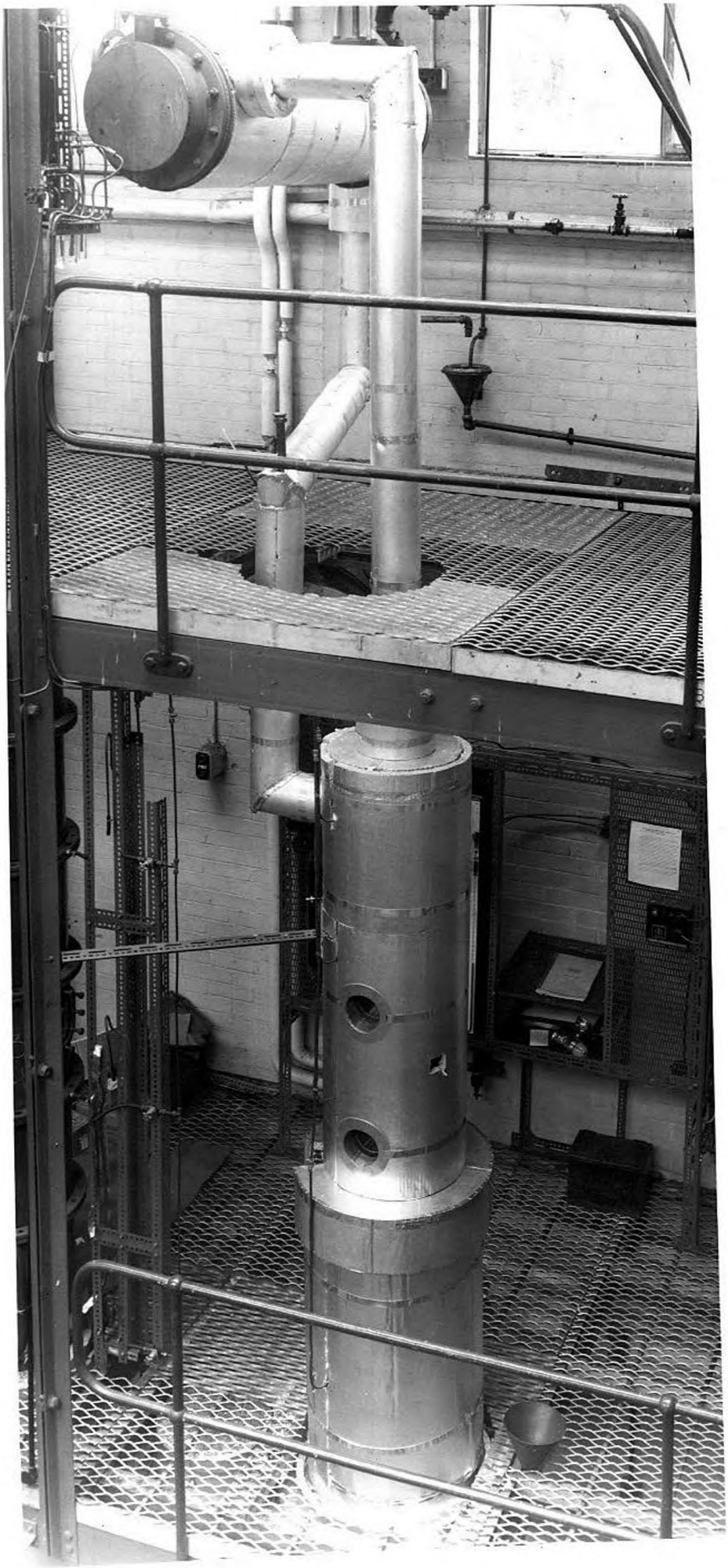
Liquid samples could be taken from the bottom of each downcomer and from the reflux liquid pipe.

5.1.1.1 Distillation Column.

The column shell was in two parts, the upper being 12" in diameter whilst the lower was 18" in diameter. The lower 7 feet of the column, part of a previous apparatus, was used empty and served as a disentrainment section for the vapour rising from the reboiler. This part of the column was made out of 10 gauge copper with beaten-over flanges using mild steel backing flanges.

FIGURE 5.1

12" DIAMETER DISTILLATION COLUMN.



Thick cork-neoprene gaskets had to be used for sealing because the faces of the flanges had not been machine finished.

The upper part of the column was in three sections, each being 18" high and 10 gauge thick. A machined brass flange, 5/8" thick, was brazed on both ends of each section; for details see Appendix A5.5 figures A5.5/1 & /2. Hard compressed asbestos fibre gaskets could be used between the machined faces of the flanges and the trays. Two of the sections had each two 5" diameter sight glasses on opposite sides of the section from each other. (fig. A5.5/3) These allowed visual study of the hydraulic performance of the lower and middle trays.

The distillation trays were fastened between the flanges of each of the upper sections and between the bottom of the upper sections and a 5/8" thick brass spacer plate which held the two column sections together. The vapour outlet pipe flange was fastened to the top of the top section and the liquid reflux pipe was brazed through its wall.

The general arrangement and details of the distillation column can be seen in Appendix A5.5 figures A5.5/1, /2 and /3.

5.1.1.2 Distillation Trays.

In view of the previous work the woven glass cloth AD.225 was chosen as the tray floor material for this study due to its more promising performance. However, little relevant performance data was available on which to base the design of cross flow trays using this material as a tray floor. The "design" of the first set of trays will therefore appear to be rather arbitary. The only information available required provision to be made for possible higher throughputs than conventional trays and for high but flat pressure drop characteristics. Large segmental downcomers were therefore specified to prevent downcomer flooding and to enable the expected high throughput range to be studied. An arbitary value of about 50% larger than those used by Zuiderweg et al (6) was chosen. When the dimensions were rounded for ease of construction, the finished downcomers occupied 13.7% of the total cross sectional area of the column per side.

Eliminating the total dead area in the column, namely that occupied by the downcomers, internal fittings, fastening rings etc., the total active bubbling area was only 39.6% of the total column cross sectional area. This value is rather lower than normal industrial practice but with the very limited performance information available at that time it was decided to accept this tray design.

The set of three trays were fabricated to the drawing in Appendix A5.5 figure A5.5/4. The trays were constructed from copper and consist of a 3/16" thick ring brazed to a 1/16" thick segmental downcomer. The inlet weir height was fixed, 1.3/4" high, but the outlet weir was variable in 1" steps from 1" to 4" high. The gap between the fixed and variable parts of the outlet weir was packed with asbestos rope to prevent undue leakage.

The cloth tray floor was held in position by a support ring, bolted through the cloth to the underside of the tray. As in the previous work an upper support grid of flattened expanded metal No.F.E.3404 was used to prevent the cloth bowing upwards in operation. No grid was used underneath the cloth nor were any gaskets used in securing and sealing the tray floor to the tray ring and downcomer assembly.

To maintain a liquid seal in the downcomers by preventing the liquid flow bypassing the inlet weirs, thin brass strips were fitted between the outer edges of the inlet weirs and the column walls. Similarly a seal pan was fitted to the bottom of the lowest tray's downcomer to maintain a liquid seal and thus prevent vapour up-flow.

5.1.1.3 Liquid Sampling System.

Liquid samples could be taken from behind the inlet weirs at the bottoms of the downcomers for the upper two trays and from the bottom of the reflux return pipe.

Each sampling point consisted of a modified brass union body with 1/4" B.S.P. threads on each end and a nut facing in the centre. The body was screwed into the column wall 1.3/4" above the tray floor and was sealed by hard fibre washers at the outside by the nut facing of the union body and at the inside by a 1/4" B.S.P. nut. A hyperdermic needle, brazed through a 5/16" diameter brass rod, passed through a small hole in the union body. The rod was then secured and sealed into the union body from the outside by a 1/4" B.S.P. olive and nut. When not in use the hyperdermic needle was sealed by a small tap fitted into its socket.

A 5 ccs. sample of liquid was withdrawn from the column through the needle and tap by the suction of a syringe. Before a sample was taken the syringe was filled with liquid from the column and emptied back through the tap and needle to flush out any liquid remaining from the previous sample.

The syringe was then emptied into a 5 ccs sample bottle and sealed with a polythene cap. It was found that using this simple procedure of sample transfer from syringe to bottle a negligible loss of the sample occured by evaporation. No difference was found between the refractive index of samples obtained in this way and that of samples kept in a sealed syringe or put into an ice cooled sample bottle before analysis.

5.1.1.4 Column Pressure Measurement.

The pressure tappings on the column were similar to the liquid sampling points but were located 4" from the top of each of the upper column sections and 24" from the top of the lower column section. The other differences were that each brass union body had a 1/4" diameter hole through it and a pressure line of 5/16" copper pipe fastened to its outside by a nut and olive.

The pressure differences across the individual trays were measured using manometers filled with normal-butyl-phthalate (sp.gr. = 1.0) and across the column by a mercury manometer. The manometers were mounted on a panel by the main condenser so that any condensed vapour could run back into the column and not interfere with the pressure reading.

However this system proved inadequate and so was augmented by a flow of nitrogen, controlled in conjunction with visual bubblers. This nitrogen bled along each pressure line to flush out the vapour continuously. A drawing of this system is given in Appendix A5.5. figure A5.5/5.

5.1.1.5 Reboiler Circuit.

The tube and shell reboiler was of the vertical thermo-syphon type. A tube bundle of 64 x 3/4" bore copper tubes was enclosed by a 3/16" thick mild steel shell, 6 feet long and 11" in diameter. The reboiler was manufactured by Bennett Sons & Shears Ltd. to their drawing No. BV.50/3(234)

The shell-side of the reboiler was heated by steam from the mains at 100 p.s.i.g. or from a Bastian and Allen "type 440" electrode boiler at 150 p.s.i.g. The electrode boiler was used when steam was not available from the mains.

The boil-up rate of the test mixture was controlled by a Bristol proportional controller. The latter operated a 2" pneumatic valve in the reboiler steam supply pipe to maintain a constant steam pressure in the reboiler shell. The condensate passed through a steam trap to waste or to the electrode boiler feed water tank. Provision was made to collect the condensate so that the boil-up rate could be determined.

A diagram of the reboiler circuit and stream control system can be found in Appendix A5.5 figure A5.5/6. The liquid test mixture was passed from the bottom of the column through a 3" diameter copper pipe. From the top of the tube-side of the reboiler the boiling liquid and vapour mixture flowed through a short 5" diameter tube into the lower column section. The liquid was disentrained from the vapour as it rose through four feet of empty column before reaching the lower distillation tray. The liquid from the reboiler and from the lower tray downcomer fell to the bottom of the column from where it was recirculated to the reboiler.

The reboiler circuit held about 35 gallons of hydrocarbon test mixture.

A check upon the design limitations of the reboiler was made using Kern's method (231). The maximum allowable heat load for the reboiler was 882,000 BTU/hr., slightly less than the maximum heat available from the electrode boiler (280 KW or 970,000 BTU/hr). The recirculation ratio was found to be 4:1 and the pressure drop through the tubes 0.08 p.s.i.

5.1.1.6 Condenser System.

The arrangement of the condenser system can be seen in Appendix A5.5 figure A5.5/6. The vapour flowing from the column passed through a 4" diameter copper pipe to the main condenser. The overhead vapour was condensed shell-side and the liquid reflux flowed back onto the top tray of the column through a 2" diameter copper pipe. This pipe was designed large enough to eliminate any possible accumulation of liquid in the condenser shell.

The condenser itself, which was constructed by Bennett Sons & Shears Ltd. to their drawing No. BV.50/2 (234), had a horizontal bundle of 86 copper tubes, of the same diameter and on the same pitch as those in the reboiler. The tube bundle was contained in a 12 gauge thick copper shell, 10" in diameter and 60" long.

The cooling water system, which was double-pass on the tube-side of the main condenser, was supplied from a large head tank through a 2" B.S.P. ring main. The head tank which was about 45 feet above ground level, could replenish itself at a maximum rate of 6,000 gallons per hour but the water rate needed to remove the maximum load produced by the reboiler was only 900 gallons per hour, assuming a water temperature gain of $100^{o}F$.

The water from the condenser passed through a 2" B.S.P. pipe to ground level where it discharged to waste. The flow rate in the pipe was measured using an orifice plate and manometer. A 1" diameter orifice was used for high flow rates and a 3/4" diameter for lower rates. The calibration of both orifice plates is given in Appendix A5.1.

Oil filled thermometer pockets were brazed into the relevant pipes to measure the temperatures of all streams flowing into or out of the main condenser.

The main condenser water rate was adjusted such that the liquid reflux to the column was as near to boiling as possible. Therefore, for safety, a small backing condenser with an independent water supply was fixed vertically above the main condenser and joined to it by a short 4" diameter copper tube. The backing condenser consisted of a vertical copper shell 10" in diameter and 3 ft. high containing a cooling coil of 50 ft. of 1/2" diameter copper pipe.

A 1" diameter atmospheric vent line was taken from the top of the backing condenser and lead outside the building. A Sunvic temperature sensor was located in an oil-filled thermometer pocket in the vent line directly above the backing condenser.

Using this device warning was given if some malfunction of the equipment caused uncondensed vapour to overflow to atmosphere.

5.1.1.7 Lagging.

The apparatus, (reboiler, column, condenser and interconnecting pipes), was insulated with Bestobell "Viceroy" asbestos and aluminium lagging type L.44. The column and reboiler were lagged in two layers - the inner layer being 2" thick and the outer 1" thick. The condenser and all relevant hot pipes were lagged to a thickness of 2".

Using Bestobell's handbook a total heat loss from the column of 2,000 BTU/hr was obtained assuming a column wall temperature of 212°F. and an air temperature of 75°F. in the building. The loss is therefore less than ½% of the heat used in the reboiler at half load.

5.1.2. Procedure.

The outlet weir of each tray was set to the required height, then the column reassembled and relagged. The orifice plate in the condenser cooling water pipe was chosen to correspond to the expected flow rate.

The air supply to the controller and the nitrogen purge for the pressure lines were turned on and adjusted.

The cooling water supply to the main and backing condensers were turned on and adjusted to the desired flow rates.

The set point of the reboiler steam pressure controller was set to about 12 p.s.i.g. and the steam supply was turned on.

When the temperature of the vapour input to the condenser had reached a steady value the controller set-point was adjusted to give the desired boil-up rate. After the steam pressure in the reboiler shell had re-stabalised, the boil-up rate was found by weighing the condensate flow from the steam trap. The main condenser cooling water rate was adjusted such that the liquid reflux to the top tray was almost at its boiling point.

It had been found, by experiment that the column reached steady state less than one hour after all the flow rates had been fixed. Therefore after one hour liquid samples were taken from each tray and at the same time the following readings were taken and measurements were made; the reboiler condensate rate, the reboiler shell steam pressure, the inlet and outlet condenser cooling water temperatures, the inlet vapour and outlet liquid reflux temperatures, the tray and column pressure drops, the column head pressure and atmospheric pressure. The hydraulic conditions on the trays were also noted by observation through the sight glasses in the lower sections of the column.

The above readings were retaken after a further hour.

The liquid samples were analysed at 25°C. using an Abbe Refractometer. The calibration can be seen in Appendix A5.2.3.

To shut down the apparatus the services were turned off in the reverse order from start-up.

The experiment was repeated using different boil-up rates and then different outlet weir heights.

5.1.3 Distillation Systems and Components

The work of many authors in studying the performance of various distillation devices cannot be directly compared one with another as widely differing types of systems, conditions and apparatus have been used. Zuiderweg and Harems (152) showed that the surface tension type of the system and the size of the apparatus had an appreciable effect on the results obtained.

It was therefore decided to choose the system, normal Heptane and toluene so that a direct comparison could be made with the work done by Zuiderweg (6) et al in comparing conventional devices.

The purity of the components used was checked by finding their refractive indexes and comparing them with those found by other workers.

	Present Study	Other Workers
Toluene	1.4937	1.4940 (232) 1.4941 (233)
n-Heptane	1.3848	1.3851 (233)

(Zuiderweg et al (6) carried out their analysis at 20°C but this temperature was not convenient in this Department so their analysis data was not used.)

The relevant physical properties and equilibrium data of the components can be found in Appendix A5.2.

However before the main test system was available for use a mixture of toluene and methyl-cyclo-~~hexane~~ hexane was used for commisioning and preliminary test work. Edgley (234) and Rustin (235) had used this same system in their experiments in the Department.

TABLE 5.1

Comparison of Pressure Drop Results using Actual and Simulated Distillation Conditions for Glass Cloth AD.225.

F B	L	1" Weir Height		$2\frac{1}{2}$" Weir Height	
$lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}secs$)	(galls/min.ft)	12" dia.Col.	68"x14"Col	12"diaCol	68"x14"Col
0.75	1.30	3.46	11.1	5.15	12.5
1.0	1.73	3.8	12.2	5.35	13.5
1.25	2.16	4.07	12.9	5.48	14.3
1.50	2.59	4.4	13.4	5.68	15.1

In the above table the pressure drop across the trays is given in cms of water gauge.

The following methods were used to determine the results.

12" diameter Distillation Column (Toluene - n Heptane System).

The values of the pressure drop were obtained and interpolated from figure 5.7 and divided by the liquid density (0.738 gms/cc.) to compensate for the liquid head. The liquid loadings were calculated as in Appendix A.5.3.

68" x 14" Column (Air-Water System.)

The values of pressure drop were extrapolated from figure 4.7 at corresponding flow conditions as those for the 12" diameter column.

5.1.4. Results & Discussion.

The results obtained from studies using the 12" diameter distillation column were evaluated from the experimental readings as shown in the sample calculation given in Appendix A5.3. The results using the system toluene - normal heptane are given individually by weir height in figures 5.3 to 5.6 and are collected in figure 5.7. ✓ Appendix A 5.4

It can be seen by consultation with the above figures that the results follow quite predictable trends. The pressure drop curves increase steadily with both F factor and weir height. However these pressure drop results are not similar to the results found in the previous two studies using an air-water system. Not only are the magnitudes of the pressure drops different but the trends with respect to the vapour rate also. These observations still hold after compensating for the differences in physical properties of the systems and the inter-dependence of vapour and liquid rates at total reflux. Table 5.1 gives the comparative values but this effect is studied more closely in Section 6 and will not therefore be considered further here.

Now to compare the results found by Zuiderweg et al (6) using the same system, toluene - n. heptane, with an outlet weir height of 2.95", the F factor through the active bubbling area of the tray, FB, was used. This basis for the comparison was chosen so that the tray floors themselves could be studied, undistorted by the difference in the active area ratios of the two sets of trays.

In figure 5.8, it can be seen that in the same region the pressure drop is similar in magnitude but the trend with increase in vapour rate is greater for the conventional trays, particularly the Bubble cap trays.

The pressure drop results using the systems toluene-n-heptane and toluene-methyl cyclo hexane, shown in figures 5.7and 5.9 respectively, are almost identical for the same weir heights and vapour rates. The pressure drop results for conventional trays found by previous workers in the Department (234), using the system toluene methyl-cyclo-hexane, show similar results to the work of Zuiderweg et al (6) and thus are similar in magnitude but have a steeper gradient than the results obtained using the new tray at the same F factor.

Considering the mass transfer performance of the new tray for the system n-heptane-toluene it can be seen that the efficiency results for different weir heights all fall on similar shaped curves. These curves have four regions, two where the efficiency changes little with increased F factor and two transition regions. The two constant efficiency regions correspond well to the two different types of vapour - liquid dispersions on the tray as observed through the sight glasses in the column wall. At lower F factors the dispersion on the tray is of the froth type with vapour bubbles. At higher weir heights this region gives a slowly falling efficiency as the reduction in the residence time of the vapour flowing through the dispersion is not fully compensated by the increase in interfacial area produced by the increase in the foam height. This region should extend backwards to the weep point of the tray but the column and ancillary equipment would not operate stably at low enough boil-up rates to find the weep point. In the case of lower weir heights this equipment limitation eliminates anything but an extrapolation of the results into the frothing region. It would appear that as the boil-up rate was decreased all the curves tend to similar high values of efficiency.

The transition from the bubbling region to the spray region is accompanied by a sharp decrease in the efficiency due to the decrease in the interfacial area. Also the difference between the two regimes will be exaggerated by the small holes in the tray floor producing a very stable foam with high interfacial area. This is particularly so for the lower weir heights. As expected the transition occurs at a lower value of F-factor for lower weir heights due to the bubbly dispersions being more stable at higher liquid hold-ups on the tray.

As the vapour rate is increased the dispersion expands due to the increased momentum of the vapour and liquid hold-up due to the increased liquid rate. However, it would appear that the decrease in contact time due to the higher vapour velocity is compensated by an increase in contact due to the increase in the height of the dispersion caused by the increased vapour and liquid rates. An increase in the weir height increases the liquid hold-up on the tray and thus the efficiency due to the increased interfacial area of the droplets.

Also as the liquid hold-up depends less on the weir height as the latter is increased so the increase in efficiency will be less for higher weirs.

At higher vapour rates still a further stage is reached where the liquid on one tray is entrained by the vapour and carried to the tray above. Also the liquid flowing down the column reaches such a rate that the downcomer area is insufficient and the liquid backs up onto the tray above. Either one of the above, entrainment or flooding, can cause a sharp loss in efficiency. In this case a combination of the two causes would appear to be effective. The extent of the entrainment can be noted qualitatively by the impingement of the liquid droplets against the overhead vapour pipe to the condenser. The onset of flooding can be detected by a sharp increase in the pressure drop across the top tray.

The efficiency results confirm the observations of entrainment and flooding in the column in that the efficiency of the trays with higher weirs is affected more severely at lower vapour rates.

Comparing the corresponding results, namely 3" weir height curves, with the work of Zuiderweg et al. (6) given in figure 5.8 it will be seen that the efficiencies are of the same magnitude for the same boil-up rates, but that the range of operation at high efficiency is wider for the cloth trays.

The efficiency results obtained using the system toluene-methyl cyclo hexane show the same characteristic curves as those using the main test system. The hydraulic conditions on the tray must, therefore, be very similar. However, the values of F. factor at which the hydraulic conditions on the tray change are consistently higher than the corresponding change for the main system. This is due to the higher surface tension of the methyl cyclo hexane-toluene mixture (17 dynes/cms. as opposed to 14 dynes/cms.) holding the liquid in the dispersion together (163,164).

In the foam region the two systems tend to give similar high values of efficiency. This is expected from Zuiderweg & Harems (152) predictions, as both systems are surface tension positive. However, in the spray region the methyl cyclo hexane toluene mixture consistently shows higher values of efficiency than the main system even though the latter is more positive. This situation is explained by Bainbridge and Sawistowski (153) and others (140) by considering the formation of droplets from a liquid surface. Their experiments show that in the spray region the less positive the system the higher will be its efficiency.

The methyl cyclo hexane-toluene system had been used in the Department by previous workers (234,235) and some of their results are given in figure 5.9. It can be seen

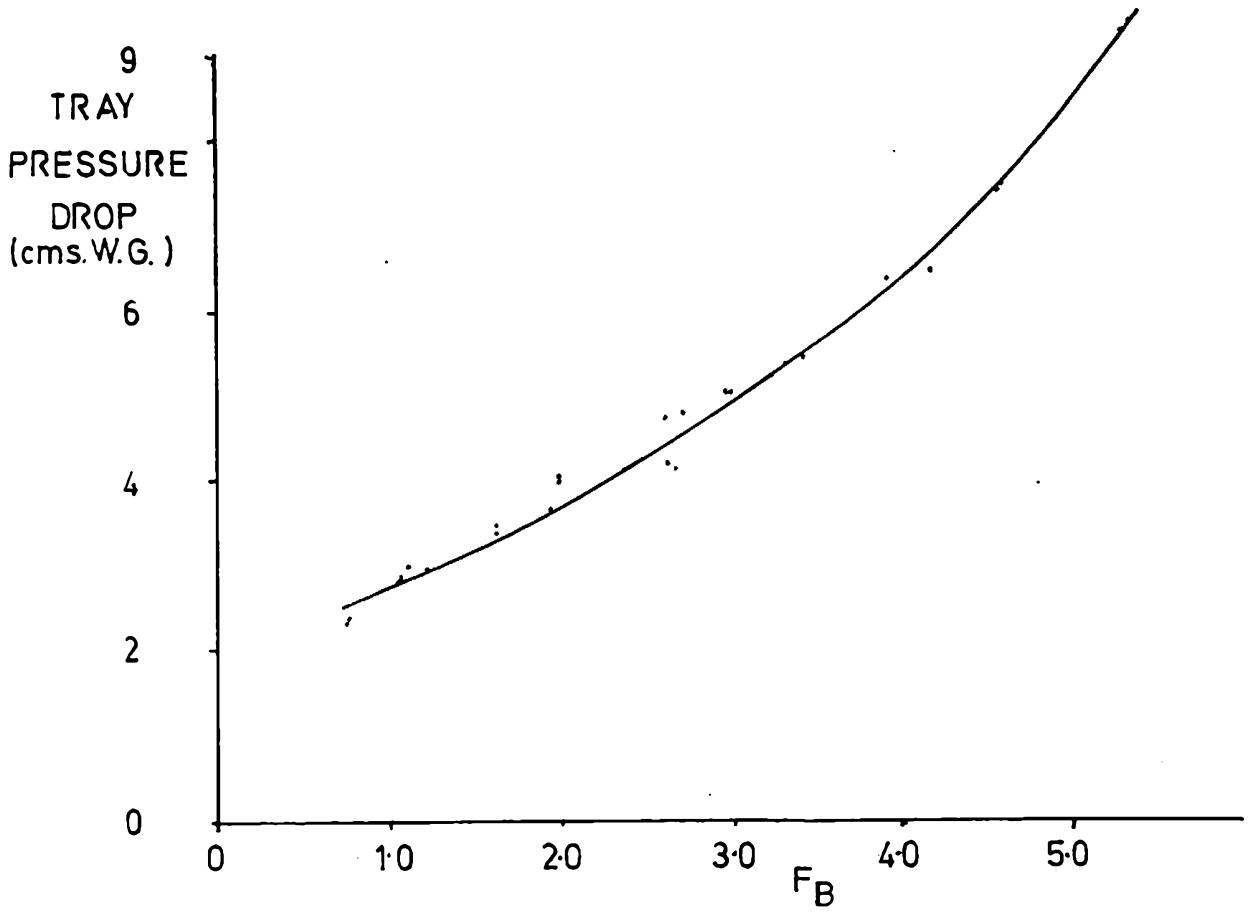
that this work on conventional trays was confined to a much smaller operating range, but for comparable conditions the efficiency is lower and the range of high efficiency operation is narrower.

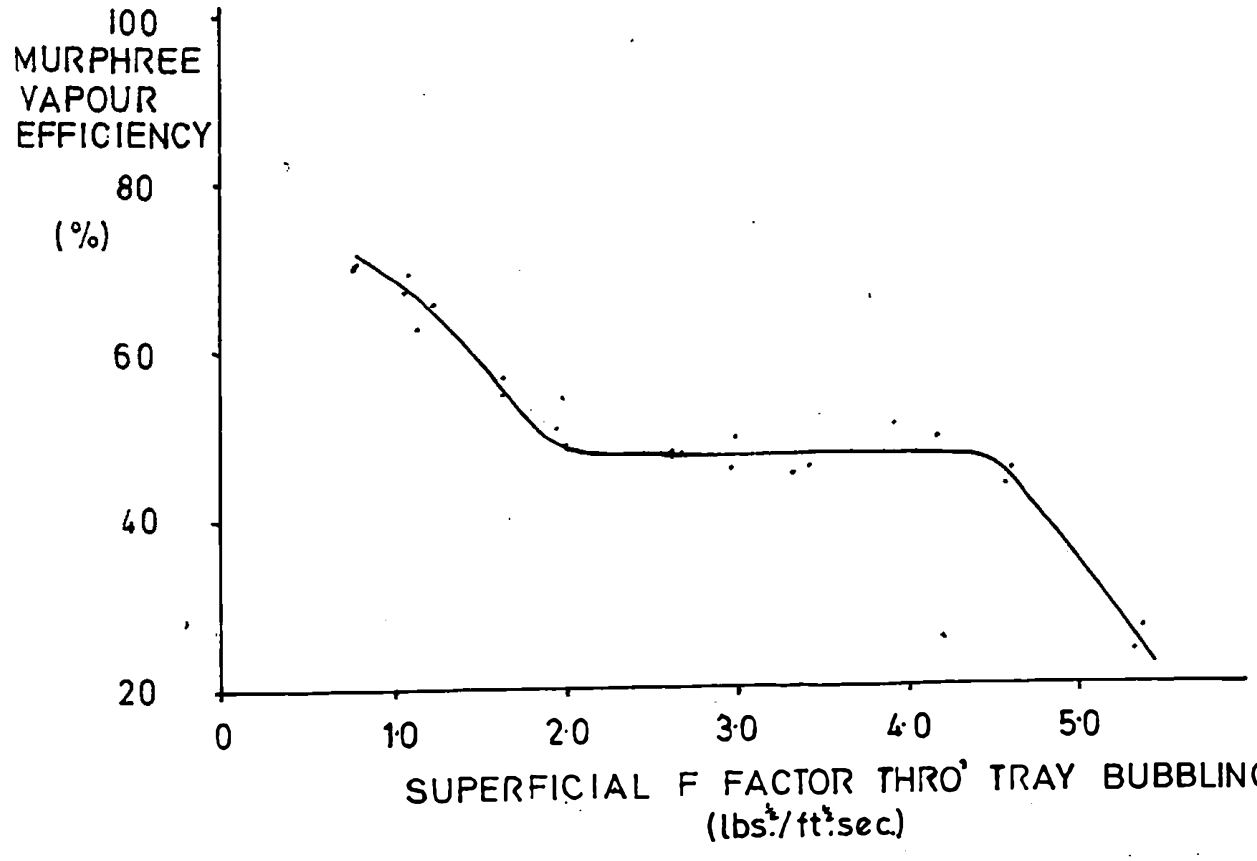
PRESENT WORK FIG 5·3

GLASS CLOTH AD 225

12" DIA COLUMN TOLUENE nHEPTANE SYSTEM

1" WEIR HEIGHT



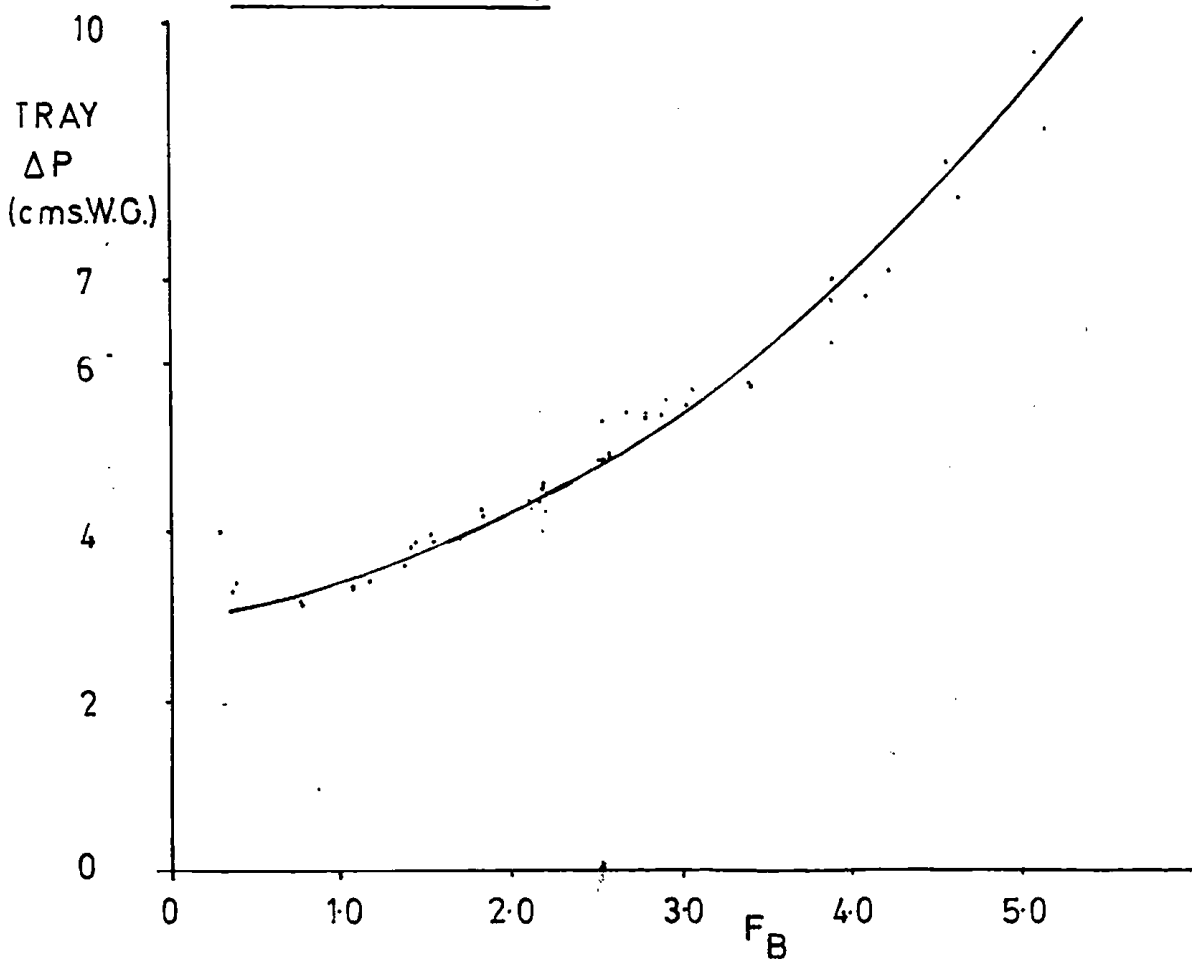


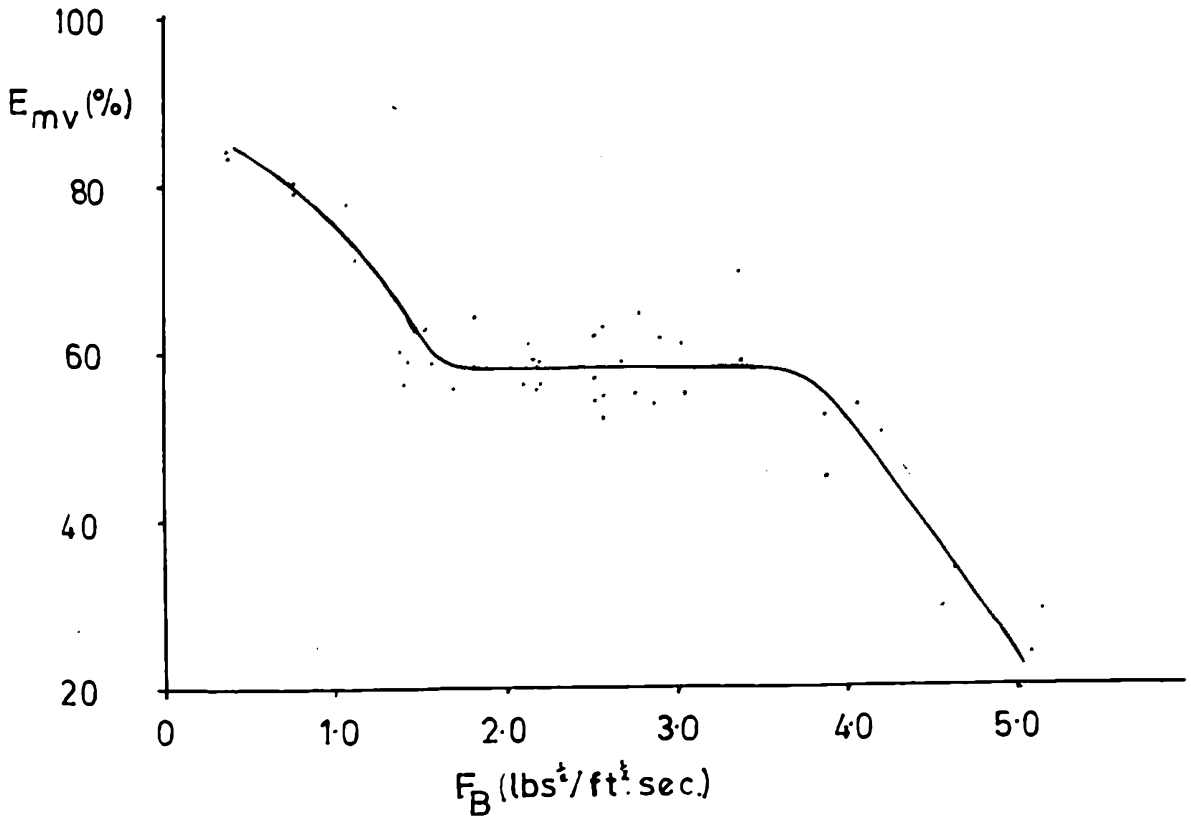
PRESENT WORK FIG 5·4

GLASS CLOTH AD225

12"DIA COLUMN TOLUENE nHEPTANE SYSTEM

2" WEIR HEIGHT



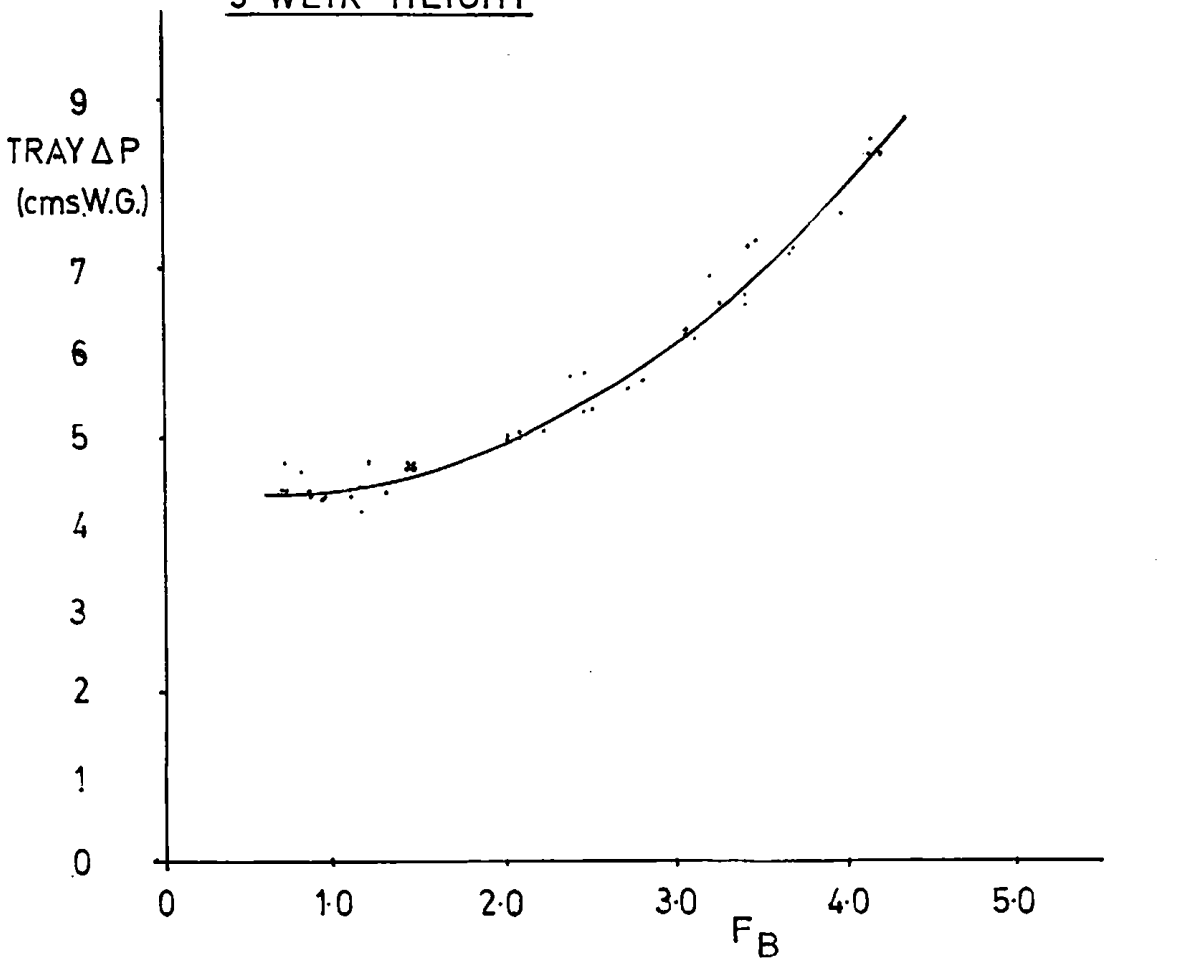


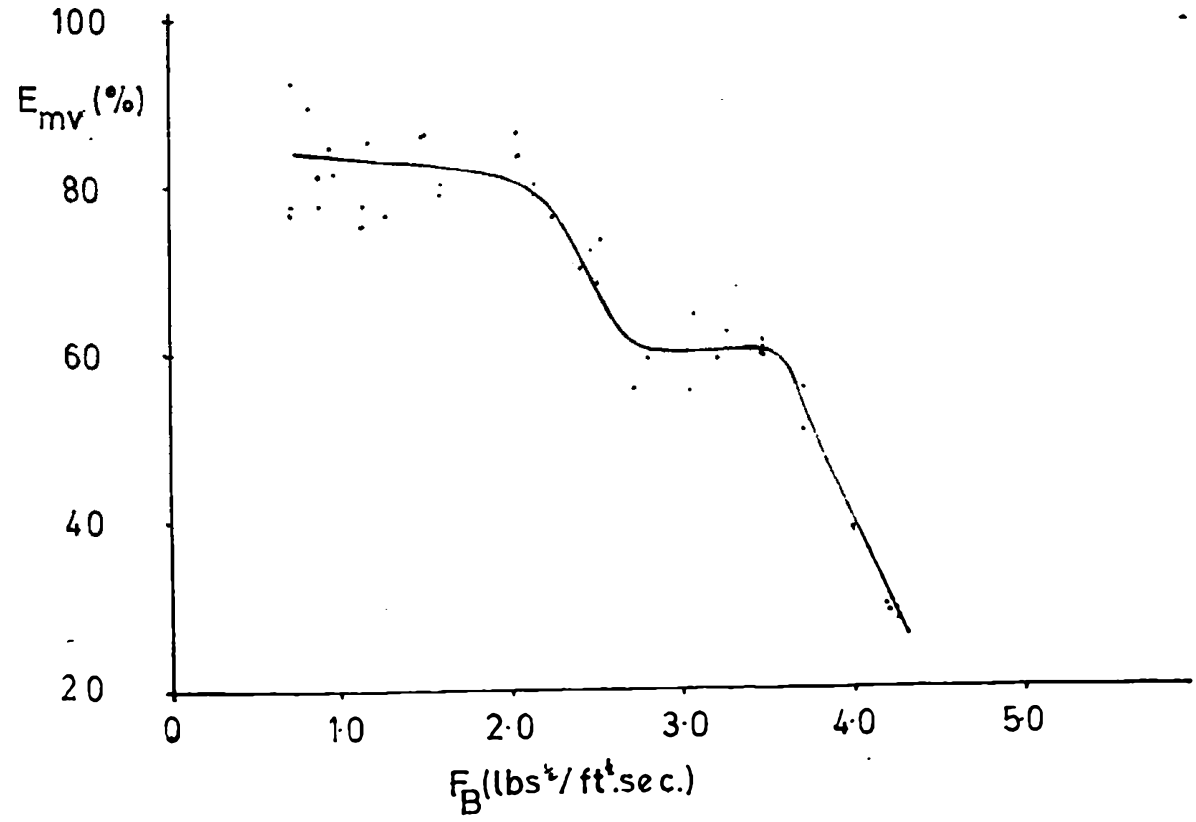
PRESENT WORK FIG 5·5

GLASS CLOTH AD225

12" DIA COLUMN TOLUENE nHEPTANE SYSTEM

3" WEIR HEIGHT



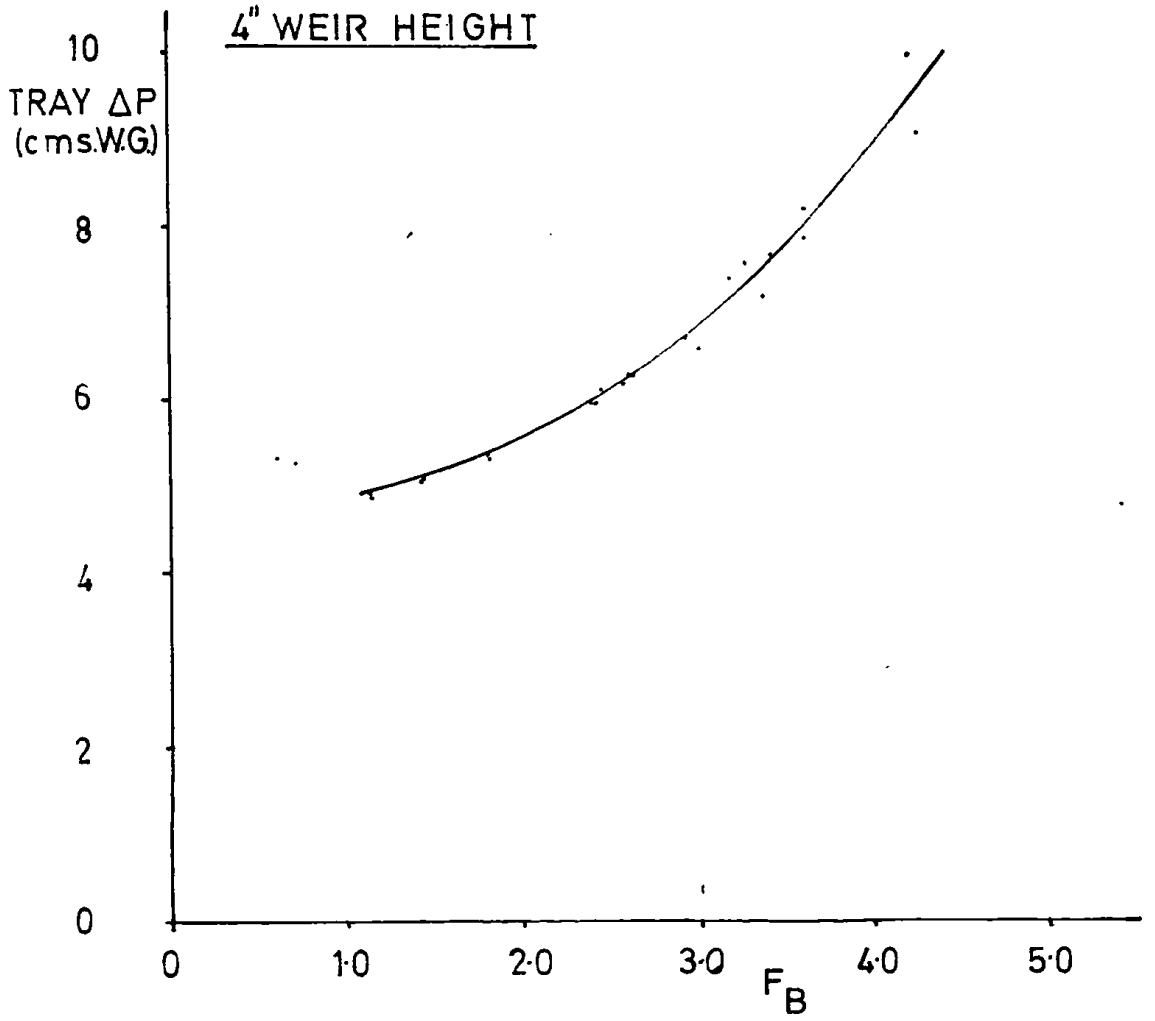


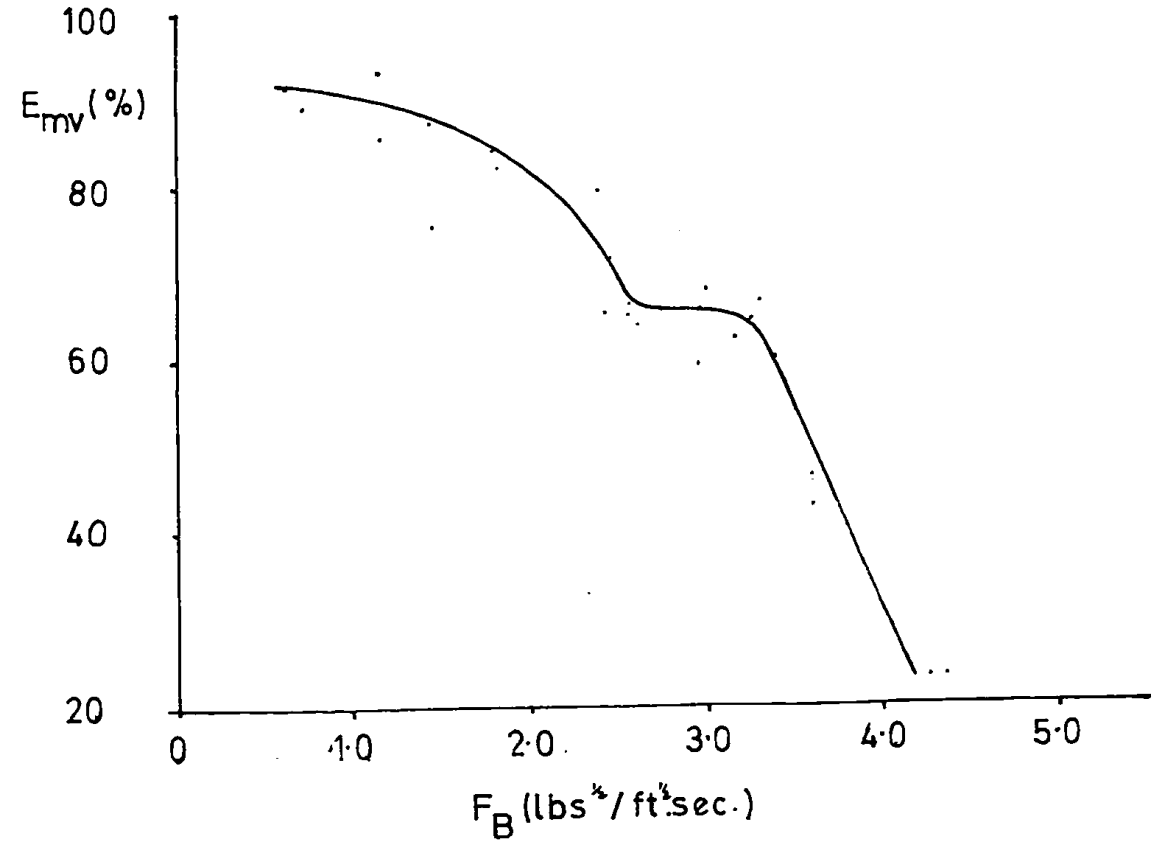
PRESENT WORK FIG 5·6

GLASS CLOTH AD 2·25

12" DIA COLUMN TOLUENE nHEPTANE SYSTEM

4" WEIR HEIGHT



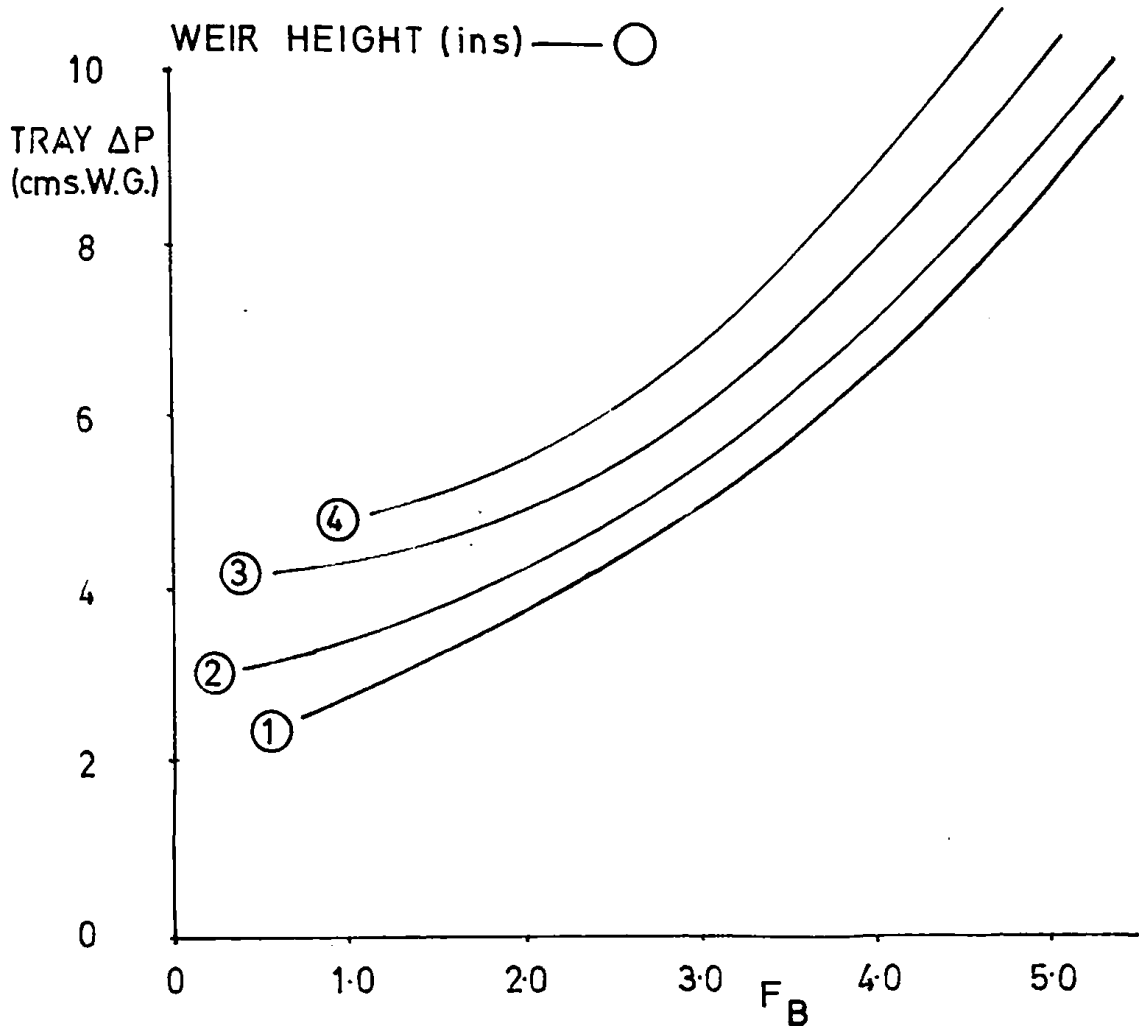


PRESENT WORK FIG 5·7

GLASS CLOTH AD 225

12" DIA. COLUMN TOLUENE nHEPTANE SYSTEM

WEIR HEIGHT (ins) —— ○



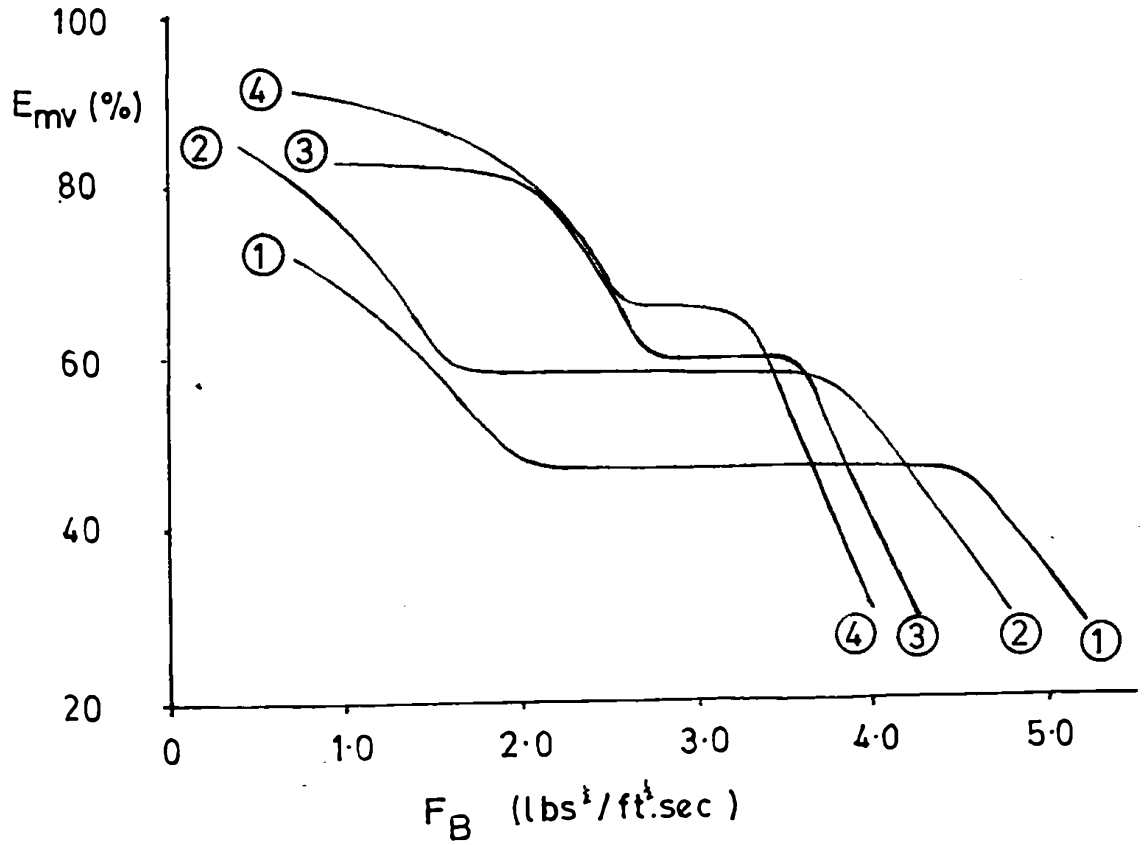
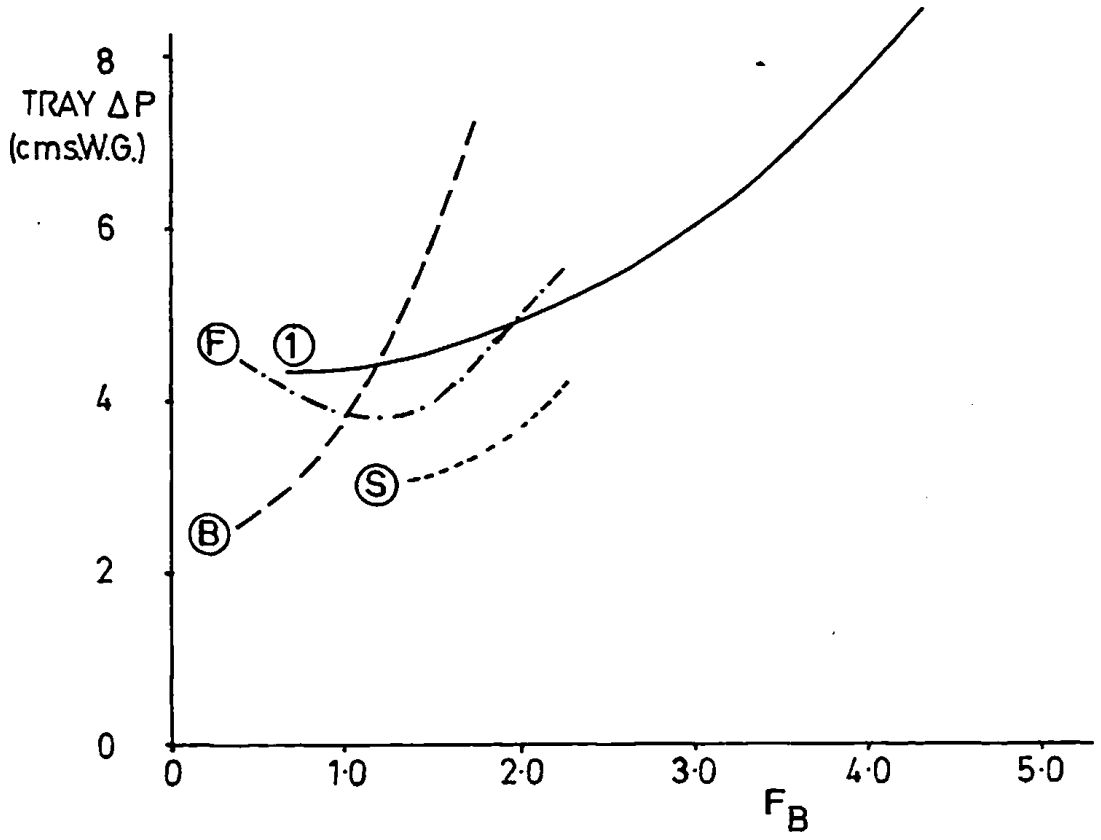


FIGURE 5·8.

TOLUENE-n HEPTANE SYSTEM

PRESENT WORK 12" DIA. COLUMN, 3" WEIR HEIGHT.
GLASS CLOTH AD 225 ① ———
F.J. ZUIDERWEG et.al.[6] 0·45 M. DIA. COLUMN, 75 mm (2·95") WEIR HT.
SIEVE TRAY (10mm holes, 15% F.A.) Ⓢ - - - -
BUBBLE CAP TRAY (10x75mm dia) Ⓑ — —
FLOATING CAP TRAY (24x40 mm dia) Ⓕ —·—



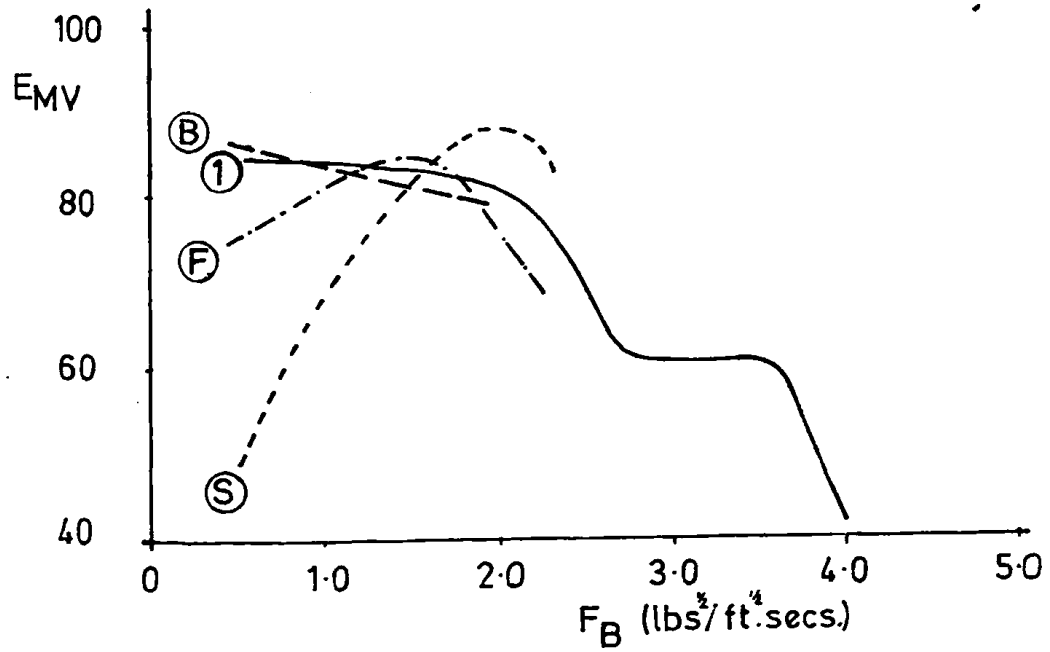


FIGURE 5·9

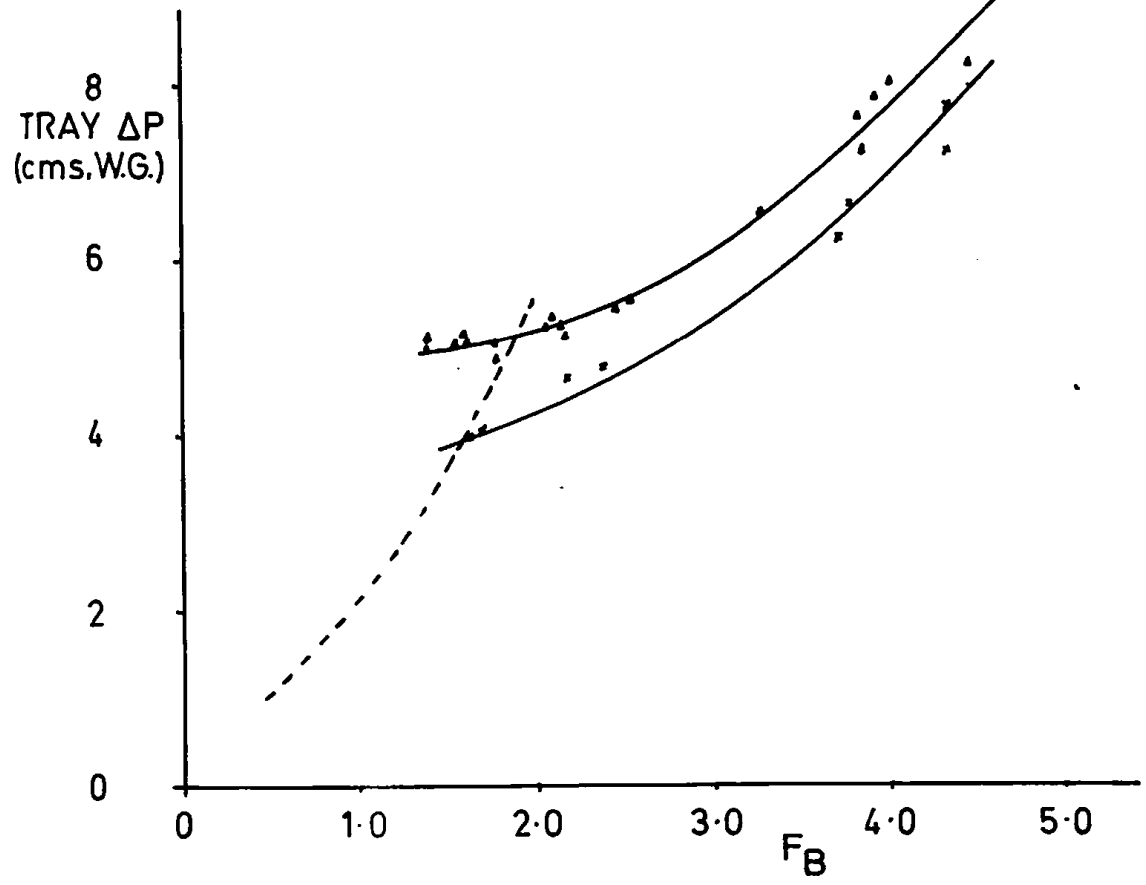
TOLUENE Me-c-HEXANE SYSTEM

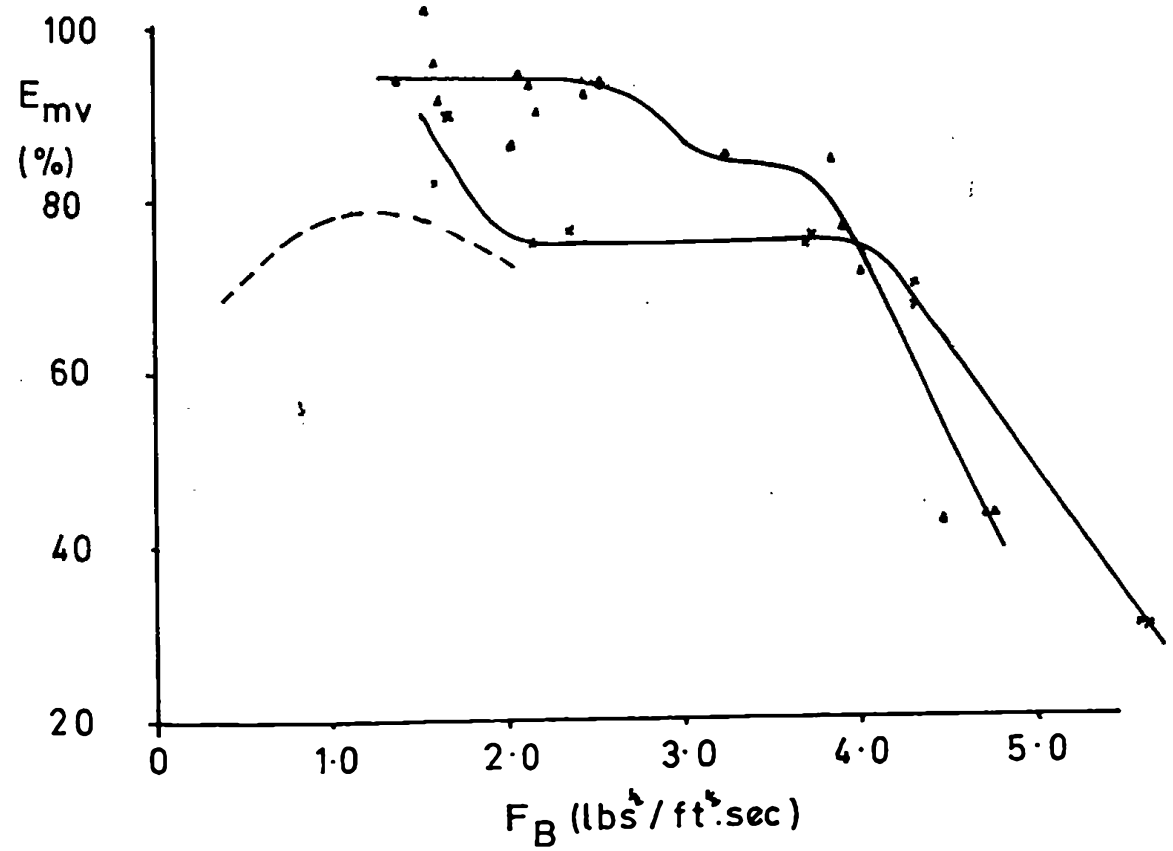
PRESENT WORK 12" DIA COLUMN. WEIR HEIGHT

GLASS CLOTH AD.225 2" -x- 3" -▲-

J.S.EDGLEY[234] 18" DIA COLUMN.

BUBBLE CAP TRAY 1¾" -----





5.2 Further Distillation Studies.

It has been suggested that the best method of comparison of commercial trays is on the basis of the vapour flow rate through the total column cross sectional area (242). If this is done for the results obtained in the previous study, it is apparent from figure 5.10 that the much lower ratio of the active bubbling area of the tray to the total cross sectional area of the column, greatly distorts the comparison for the glass cloth trays from that given in figure 5.8.

To compensate for this and to give a better comparison with conventional trays a new set of trays was needed whose design could be based on the information obtained in the previous study.

From this performance data and other tray design data from Hydronyl Ltd. it was possible to propose a new tray design with the ratio of the active bubbling area to the total column area much nearer to that of the trays used by Zuiderweg et.al. (6).

5.2.1 Apparatus and Procedure.

The experimental apparatus and procedure used in this study were virtually identical to those used in the previous study and which are fully described in sections 5.1.1 and 5.1.2. There were many obvious but small changes and modifications needed so that the new set of trays could be

used in the existing 12" diameter column, but these were all minor.

A drawing of the new high active bubbling area tray, designated tray No. 2, is given in Appendix A.5.5 figure A5.5/7. The new trays were fabricated in a similar manner to the original trays, namely as a tray ring with a segmental downcomer, but the material used was mild steel. The downcomers occupied 8.93% of the total column cross sectional area per side and the active bubbling area of the tray was raised to 70%.

As data for only one weir height was required a fixed outlet weir height of 3" was chosen as giving a fair comparison with the previous study and the work of Zuiderweg et al (6). Also the bottom edge of the downcomer was brought sufficiently close to the tray below the dispense with the need for an inlet weir to maintain a liquid seal in the downcomer.

Initially the cloth used for the tray floor was glass cloth AD225. This cloth was first stitched to a support frame and then the frame and cloth were clamped to the underside of the tray ring using one hook bolt in each corner.

Towards the end of the project a glass cloth, AD1224, which had been developed specifically as a tray floor material, became available. The performance of the newer cloth was, therefore, evaluated to give a fuller comparison with

conventional trays and to test the potential distillation performance available from a glass cloth made specifically for this duty.

5.2.2 Results and Discussion

5.2.2.1 Glass Cloth AD225.

The results determined using glass cloth AD225 and tray No. 2 are given in Appendix A.5.6.1 and are plotted in figures 5.11 and 5.12 based on the F factor through the tray bubbling area and through total column area respectively.

In figure 5.11 the pressure drop results are very similar to the corresponding results found for the original tray design and the same tray floor material. At first sight it would be expected that when only the active area were considered, as in this case, the two results should be identical. However, it is reasonable to suppose that the higher active area fraction of tray No. 2 would provide a better vapour distribution for the tray and thus give a more aerated liquid by reducing the amount of clear liquid over the dead spaces on the trays. The liquid hold-up will tend to be lower for the newer tray design for the same F factor through the active area of the tray. The pressure drop across tray No. 2 will, therefore, be lower than that across the original tray at the same F factor.

For the same reason the efficiency of any dispersion

regime, bubbly, spray or transitional, will be higher for the newer tray design. However, the F factor at which the transitions between the dispersion regimes occur will be lower. That is, the higher active area of tray No. 2 will promote a greater tendency to the spray regime due to the lower liquid hold-up. Moreover, the entrained liquid droplets have less chance of falling back into the dispersion as the vapour velocity in the column above the dispersion is higher than for the original tray at the same bubbling area F-factor. This is due to the ratio of active bubbling area to total column area being much higher for tray No. 2. It follows that the capacity point due to excessive entrainment should be reached at a lower F factor through the bubbling area for the newer tray design. However, it is doubtful that excessive entrainment caused the trays to reach their capacity point as the top trays flooded first. At this point the entrainment from the dispersion on the lower trays seemed not to be excessive when observed through the sight glasses in the column. However, mass transfer data could not successfully be taken at higher rates as the column operates unstably when the downcomers are flooded.

Figure 5.12 gives the comparison of the results for the

original and newer tray designs with those found by Zuiderweg et al (6). for conventional trays. All are given on the basis of the F factor through the total column cross sectional area. A more favourable comparison for both pressure drop and efficiency results is obtained from the newer tray design than when the same cloth was used in the original tray design. This is only to be expected as the active area ratio of all the trays, except the original, is similar.

The pressure drop results for the glass cloth AD225 in tray No. 2 gives a flatter curve which has similar or lower values than all but the high free area Sieve tray. The efficiency in the bubbling regime is higher and more constant than all the other devices. Also even with the rapid fall into the spray regime the efficiency remains comparatively high and the capacity of the tray is only reached due to downcomer flooding at a throughput as high as any other tray.

This comparison is most promising as even with a cloth not specifically developed as a tray floor material the performance characteristics are favourably comparable with correctly designed and high developed conventional trays.

5.2.2.2 Glass Cloth AD1224.

The results determined using tray No. 2 in conjunction with glass cloth AD1224 are given in Appendix A.5.6.2 and are

compared with the results for conventional trays in figure 5.13.

The pressure drop results for the new cloth show a favourable comparison with conventional trays. This result is as expected from a cloth which was developed using hydraulic data. However, the large free area Sieve trays still give a lower pressure drop indicating that further development of the cloth is necessary.

The efficiency results for the new cloth give a curve of very similar shape and magnitude to that obtained using glass cloth AD.225 in the same tray. However, as the pressure drop is lower for the newer cloth the onset of flooding, which appeared to determine the capacity point of the tray, was delayed to a higher vapour rate. Moreover the entrainment, as assessed by observation through the sight-glasses in the column, seemed very low at all boil-up rates. This would indicate that a further advantage could be gained by use of a smaller tray spacing.

The transition between the two vapour-liquid dispersion regimes occurs at about the same vapour rate as the previous cloth tray, and the values of the efficiency obtained are slightly higher. Nevertheless the efficiency for the newer cloth tray is higher than for conventional trays at lower vapour rates, but slightly less at higher rates. However,

within each dispersion regime the efficiency is much more contant and overall the mass transfer flexibility would appear to be better than for all the conventional trays. Also the capacity is as good and even better than some of the other trays.

All in all, therefore, the newer cloth has been shown to give performance characteristics which are as good as, if not better than, the major types of conventional trays.

FIGURE 5·10.

TOLUENE-nHEPTANE SYSTEM

PRESENT WORK 12" DIA. COLUMN, 3" WEIR HEIGHT.

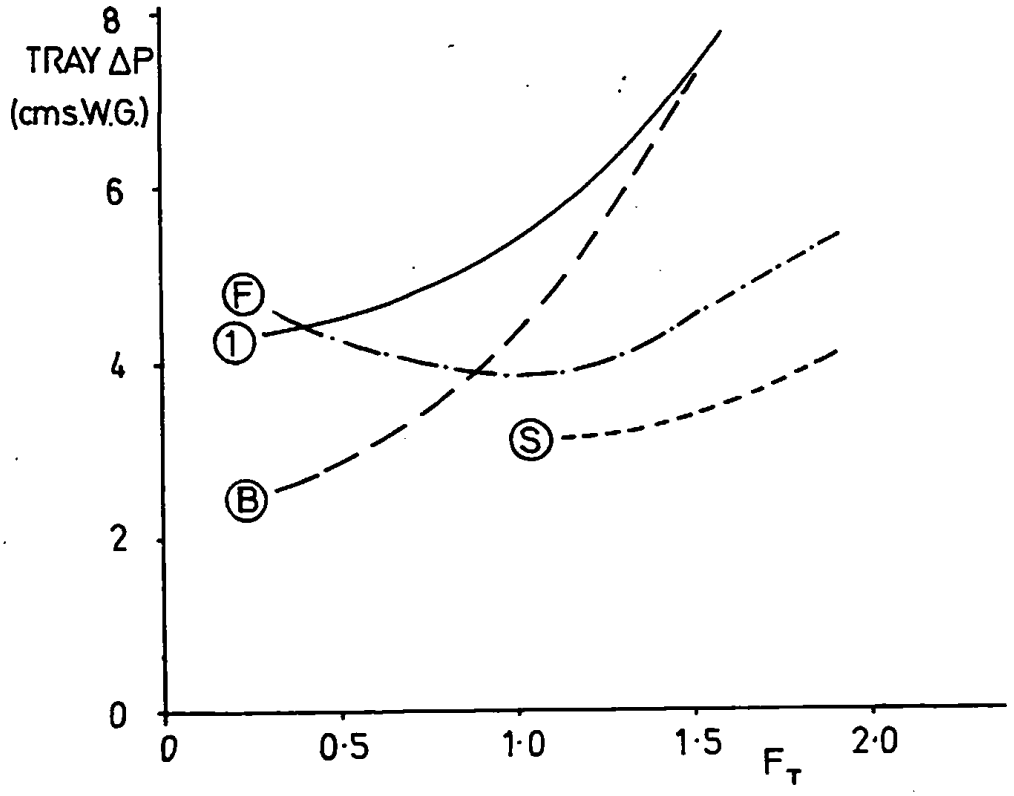
GLASS CLOTH AD225 ①———

F.J.ZUIDERWEG et.al.[6] 0.45M COLUMN, 75mm(2.95") WEIR HT.

SIEVE TRAY Ⓢ - - - - -

BUBBLE CAP TRAY Ⓑ — — —

FLOATING CAP TRAY Ⓕ —·—·—



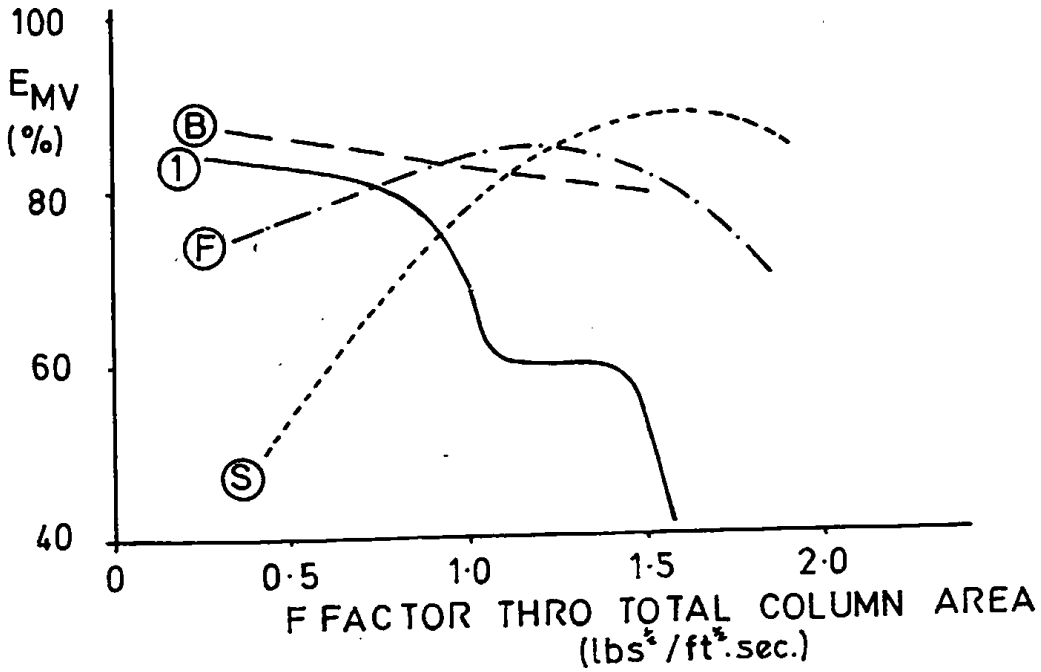
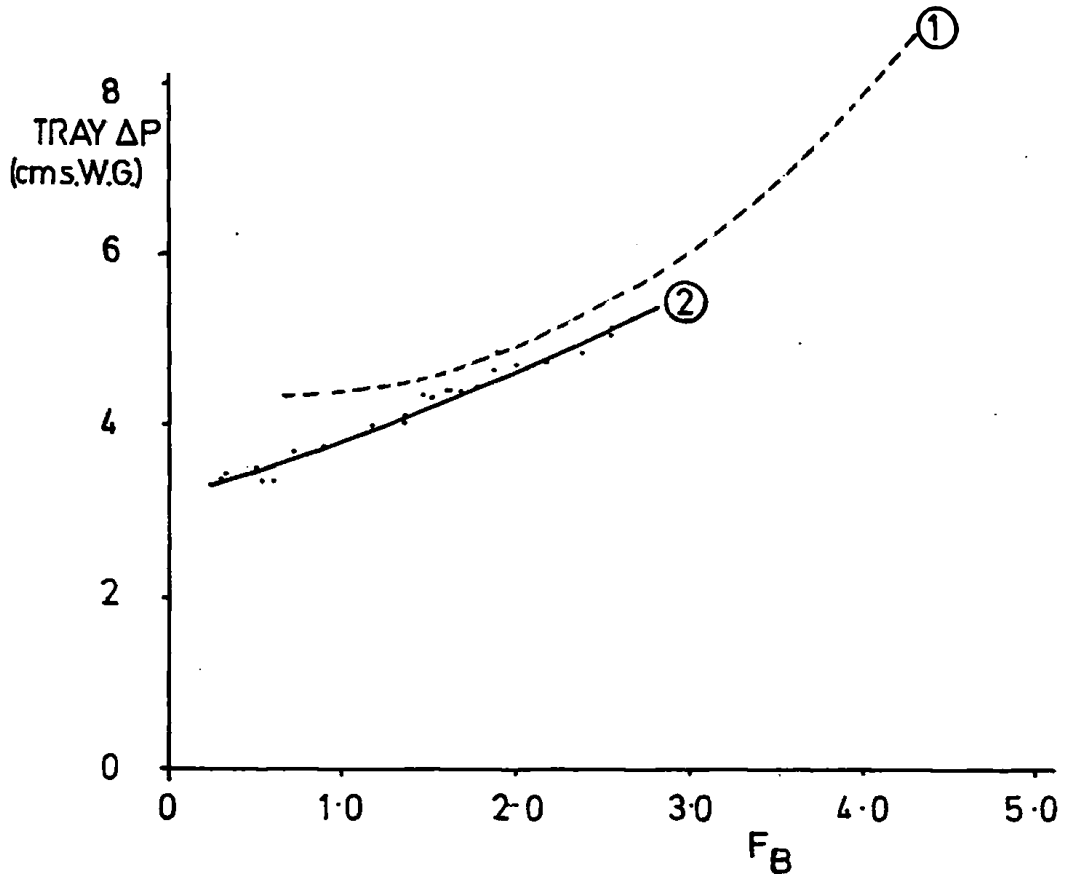


FIGURE 5·11.

PRESENT WORK TOLUENE-nHEPTANE SYSTEM
12" DIA. COLUMN , 3" WEIR HEIGHT
GLASS CLOTH AD225 ORIGINAL TRAY ①----
TRAY N° 2 ②——



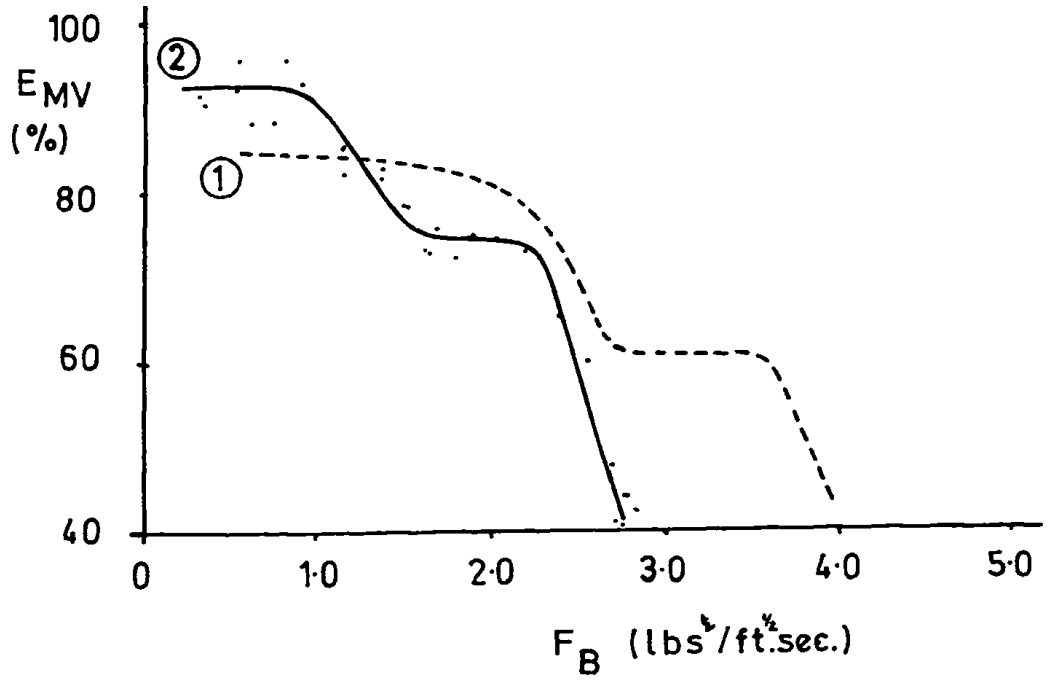
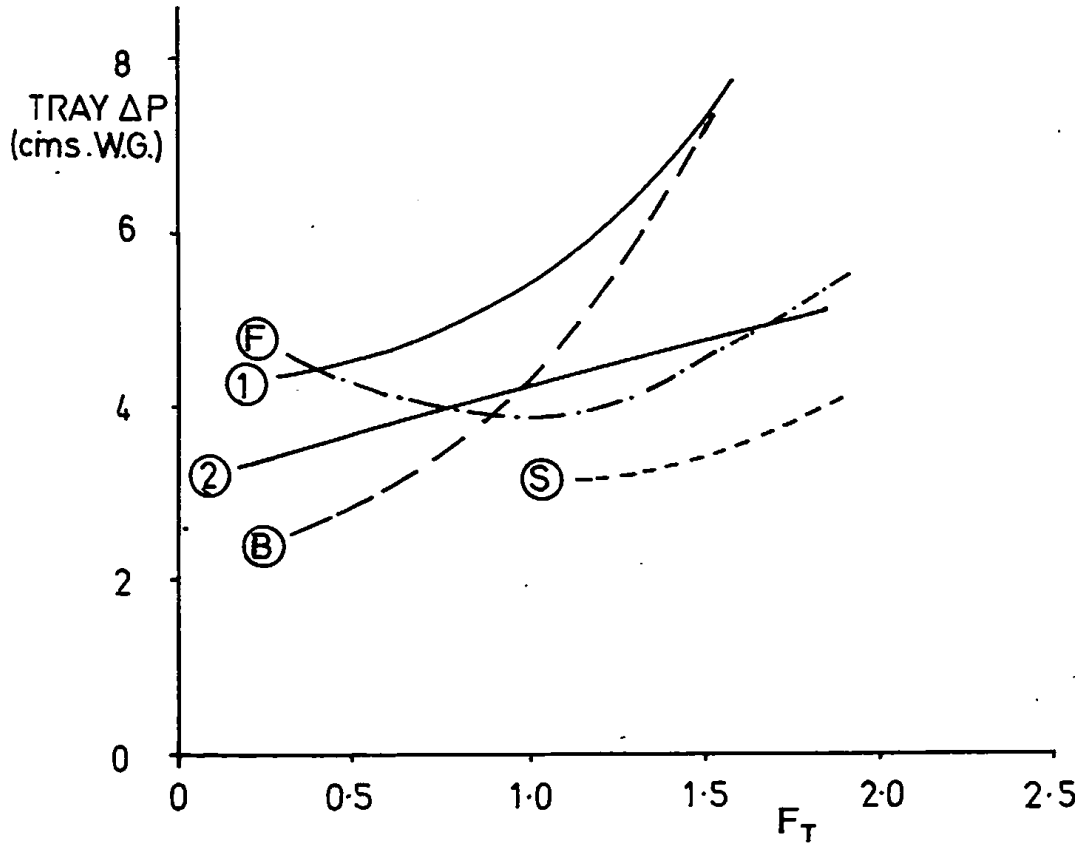


FIGURE 5·12.

TOLUENE-n HEPTANE SYSTEM

PRESENT WORK 12" DIA. COLUMN, 3" WEIR HEIGHT
GLASS CLOTH AD 225 ORIGINAL TRAY ① ———
TRAY N° 2 ② ———

F.J. ZUIDERWEG et al.[6] 0·45M. DIA. COLUMN, 75mm (2·95") WEIR HT.
SIEVE TRAY Ⓢ -------
BUBBLE CAP TRAY Ⓑ — — —
FLOATING CAP TRAY Ⓕ —·—·—·—



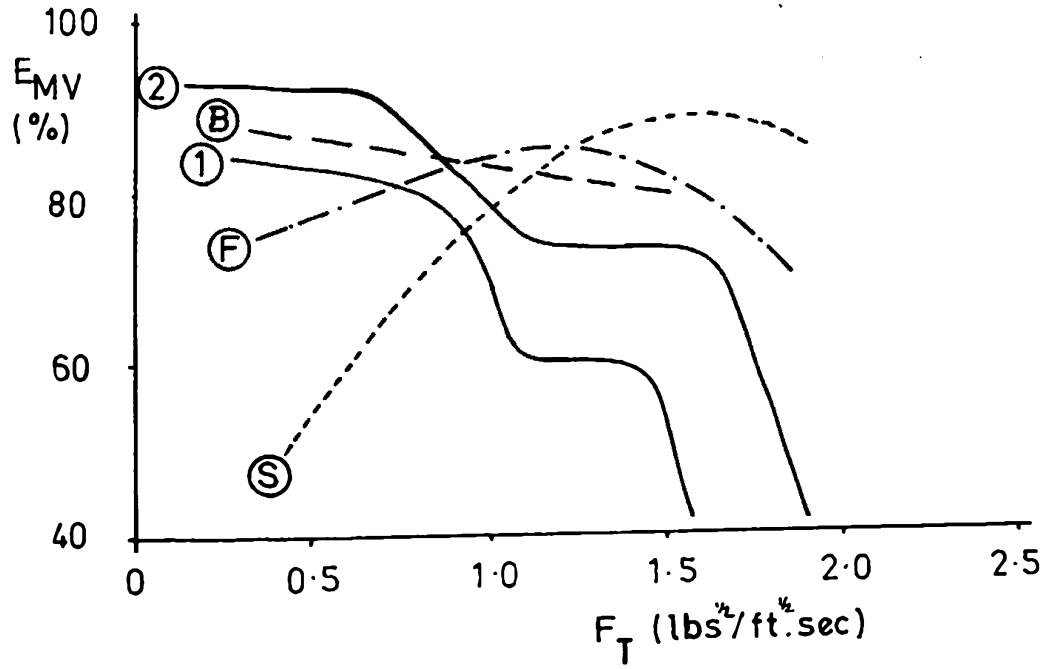


FIGURE 5·13.

TOLUENE-n HEPTANE SYSTEM

PRESENT WORK 12" DIA. COLUMN, 3" WEIR HEIGHT

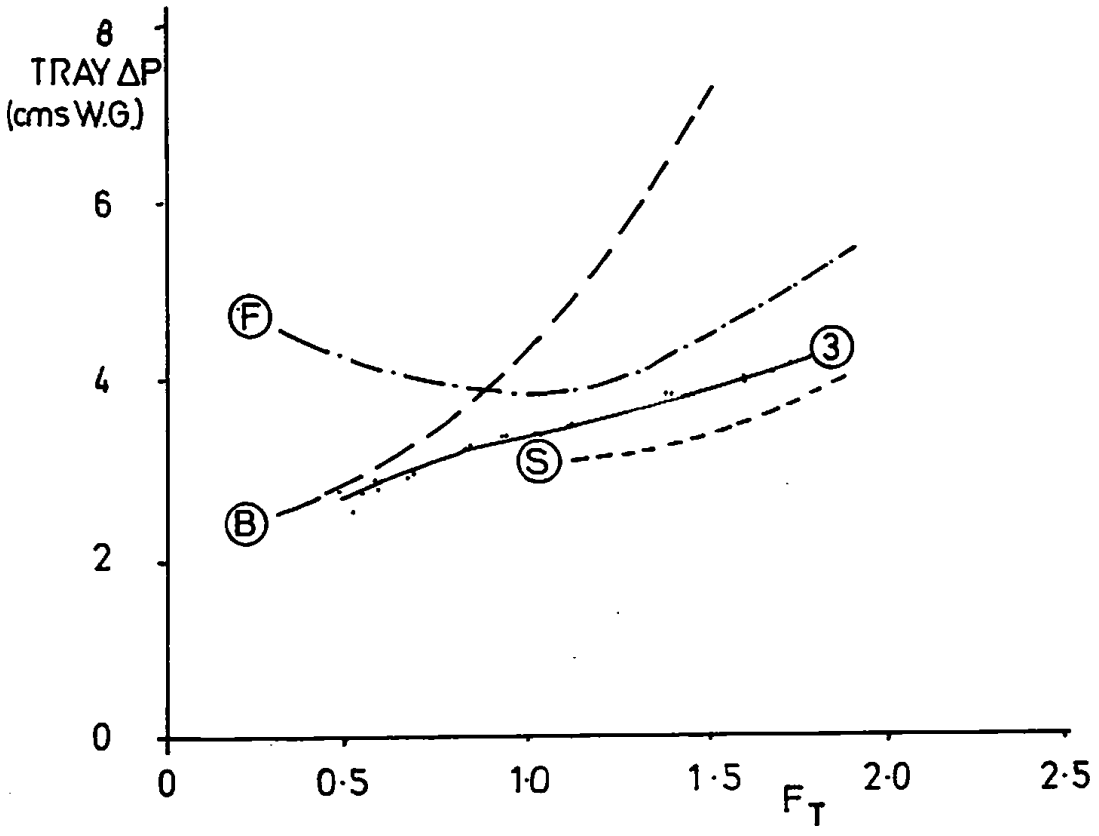
GLASS CLOTH AD1224 TRAY N°2 ③ ———

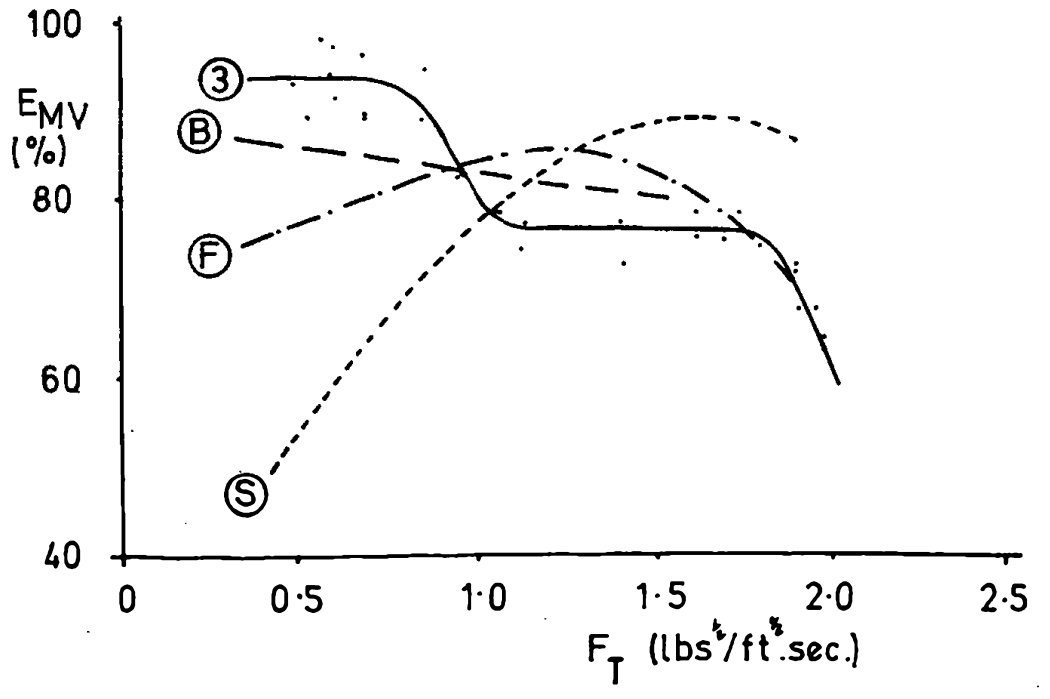
F.J. ZUIDERWEG et al[6] 0·45M. DIA. COLUMN, 75mm (2·95") WEIR HT.

SIEVE TRAY Ⓢ - - - - - -

BUBBLE CAP TRAY Ⓑ — — —

FLOATING CAP TRAY Ⓕ —·—·—·—





5.3 Conclusions.

The initial experiments in this study indicated that the actual distillation performance of the proposed tray floors was most promising. These indications were verified using an improved tray design, but the original material. The mass transfer performance was more than adequate when compared with conventional trays, but the pressure drop results left much to be desired. Moreover, the pressure drop characteristics were not consistent with those found in the previous studies using an air-water system. This anomaly is, however, studied in Section 6.

When a material specifically intended for tray floors was used the pressure drop characteristics were found to be much improved whilst the mass transfer performance, rather than impaired, was slightly enhanced by giving increased capacity.

Overall, this study has demonstrated that the use of this type of tray floor construction can lead to better distillation performance than conventional trays. Also it has indicated that further improvements are possible with development of the cloth and tray designs.

SECTION 6.

ANALYSIS OF TRAY PRESSURE DROP.

Section 6 Analysis of Tray Pressure Drop.

The aim of this study is to find the factors which affect the pressure drop across a cloth tray and study their magnitude and mechanism of operation. In this way information will be made available for the improvement and selection of new cloths for commercial use and for some of the anomalies encountered in the previous sections of this work to be explained.

The pressure drop across a bubble tray in operation can be found by considering the effects due to the vapour flow through the tray itself and due to the liquid-vapour dispersion above the tray. The effect of the latter quantity is more or less the same for all bubble trays and is a function of the dispersion, that is, of the flow rates in the column and the physical properties of the system. The effect is widely reported and can easily be seen by comparing the pressure drop differences for various clear liquid heights found in Section 3 for the same air rate. Another example is the reflection of the clear liquid height values in the pressure drop curves found in section 4.

In the present study, however, more interest is concentrated on the action of the tray itself. For conventional Sieve trays the dry plate pressure drop usually gives the tray's contribution to the total pressure drop across

the tray when in operation. In most cases the value of the dry plate pressure drop depends largely on the free area for vapour flow and to a lesser extent on the hole size. Unfortunately, for glass cloth trays the pressure drop due to the tray itself does not depend only on the dry plate pressure drop, but also on many other factors and conditions. The situation in the case of cloth tray floors is, therefore, much more complex than for those of conventional design. However, in general, the same design variables, namely the free area and the hole size, can be considered even though their value changes with the conditions on the tray.

If a quantitative result leading to an empirical relationship were required, the effect of each factor could be most easily studied by applying a series of statistically designed experiments to the problem. All the known variables should be studied for many cloths so that a general relationship might be obtained. However, the values of the variables relating to the cloth tray floor are not known accurately and cannot be changed easily or reproducably. Furthermore many different cloth variations are not available and the time needed for a comprehensive study of this type is not available to be included in the present work. The present study must, therefore, be confined to a consideration and evaluation of factors which affect the

pressure drop across the tray and study of the mechanisms by which the free area and hole size are changed.

The effects can most conveniently be studied in two parts. The first group of effects which alter the available free area and effective hole size of a given cloth can be studied using a single type of cloth. The investigation of the effect of the weave geometry is left to be studied in section 6.2.

6.1 The Effects on the available free area.

The free area and hole size that are available for vapour flow under given operating conditions will depend on the make up of the cloth and its state under those conditions.

It is possible for the geometric properties of the tray to be altered by the movement or the bending of the free fibres on the yarn due to the forces acting on them. As the air flow rate is increased the force on the fibres will increase and the fibres may move to accommodate this change. In this way the holes may open up mechanically like flap valves as the air rate increases and close as the rate decreases. However, preliminary studies showed that this mechanism could not account for any significant effect as the free fibre on the yarn does not move an appreciable amount with changes in air flow rate.

It is known that the liquid penetrates the cloth and reduces the effective free area and hole size. From preliminary studies it was found that in experiments carried out starting with the cloth dry, the underside of the cloth remained dry, but if the same conditions were applied starting with a wet cloth the underside never became dry. The pressure drop results for the two starting conditions were also found to be different. Moreover, the pressure drop results from a dry start were not consistent in themselves

showing that differing amounts of liquid were trapped in the cloth. However, reproducable results could be obtained if the experiments were carried out from a wet start. Fortunately the wet start conditions correspond closely to practical operation where the underside of the tray will be continuously wet by the entrained liquid from the tray below.

To study the factors affecting the available free area requires a knowledge of the liquid held in the cloth and the variables which can change the amount and position of the liquid. It was found from preliminary studies that the principle variables are:-

a) The vapour velocity. An increase in the velocity will increase the pressure drop across the tray and thus the nett force on the liquid in the cloth. The liquid which is not held firmly enough to overcome the increased force will be removed into the vapour stream. If the vapour rate is decreased the cloth will be able to hold more liquid in a stable manner and liquid will, therefore, migrate down from the dispersion on the tray. At a given vapour rate an equilibrium will thus be achieved and a stable amount of liquid held in the cloth.

b) The surface tension of the liquid. The lower the surface tension the lower will be the force retaining the liquid in the cloth. The amount of liquid held in the cloth will be smaller for a lower surface tension liquid if all the

other variables are held constant.

c) The free fibre on the yarn. The holes between the basic yarn structure of the cloth are spanned by fibres which decrease the distance the liquid must bridge to hold itself in the cloth. In this way both the effective free area and the hole size are drastically reduced as the liquid can be held across the short spans between the fibres but not across the comparatively large distances between the basic yarn structure of the cloth.

It is the aim, therefore, of this part of the study to consider the effect and mechanism of each factor by varying each in turn whilst holding the others constant.

6.1.1 Apparatus and Procedure.

Two apparatuses were used in this part of the study; one to evaluate the pressure drop under various conditions and the other to observe and record the action of the tray floor in operation.

The first apparatus was virtually identical to the 3" diameter column used in section 3.3. The only difference was provision for removing the exhaust gases outside the building when toluene was used as the working liquid.

The second apparatus was constructed using the major components of the previous column, so that the underside of the tray could be observed and photographed whilst the

column was in operation. To achieve this aim the air was sucked up through the tray and then through a rotameter before being discharged to atmosphere by the blower.

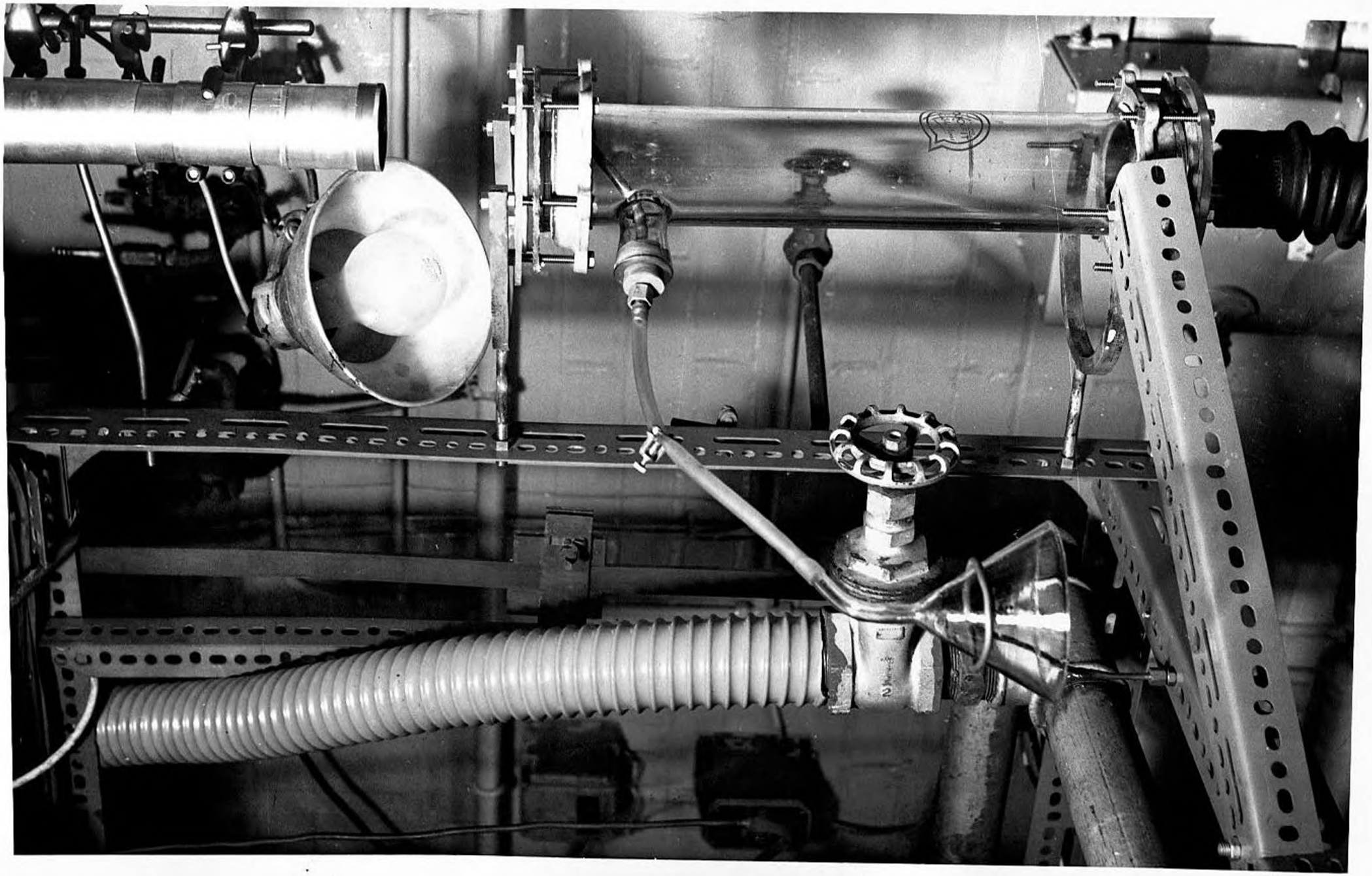
Photographs of the tray in operation were taken using a camera mounted vertically below the tray. The camera's lens was held in an extension tube to give a small magnification and focused on a marked intersection of the yarn in the cloth. Lighting was provided by a 500 watt lamp mounted either above or below the level of the tray. The general arrangement of the apparatus can be seen in figure 6.1.

It had been noted from the preliminary studies mentioned in the introduction to this section that consistent pressure drop results can only be obtained if the experiment were started using a wetted tray floor. Therefore, in the present study the cloth was saturated with liquid for the start of each run in the following manner. 500 ccs of the liquid were poured onto the tray and aerated by increasing the air rate. The liquid was then dumped through the tray by closing the air valve and opening the column drain valve. This operation was repeated three times and it was then considered that the cloth was saturated with the liquid.

The liquid and air rates for the run were set and the readings taken or the photograph taken.

FIGURE 6.1

PHOTOGRAPHIC RIG USING
3" COLUMN.



6.1.2 The Effect of Air Rate.

Pressure drop runs were carried out at various air rates with the cloth moist and with clear liquid heights of 1" (116 ccs) and 2" (232 ccs) of water. Pressure drop readings were taken, $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$ and 2 minutes after the air flow had been started and the water added. The results are given in appendix A.6.1 and plotted in figure 6.2.

There is a marked difference between the two results at zero clear liquid height, namely the dry and moist pressure drops. Also the wet curves have slopes which give a trend in the opposite direction from that of the dry curve. Both these effects can be explained by consulting figure 6.3 which shows the operation of the tray floor at various air rates for a 1" clear liquid height. The free area available for air flow is much less than the dry free area. At one foot per second the free area is reduced to about one quarter of its dry value. This observation easily explains the large increase in pressure drop and initial sharp, rise with increasing air rate. However, it can also be seen that the available free area increases with air rate and is about double the 1 ft./sec. value at 6 ft/sec. The increase in free area will, therefore, cause the pressure drop curves to flatten out whilst the dry plate pressure drop increases slowly.

It is also obvious by inspecting the positions of the free fibre on the yarn at different air rates that they are unchanged. It can, therefore, be concluded that the movement of the fibres cannot play any significant part in changing the free area of the cloth.

Considering the results plotted in figure 6.2 once more it will be seen that the values for the same conditions after different running times correspond by falling amounts due to evaporation and entrainment, (see appendix 6.1 for calculated losses). As expected the higher clear liquid height results show bigger falls mainly due to increased losses. However, the moist plate results show pressure drop losses that are much larger than expected from the above considerations. This is due to the water being displaced from the cloth and not being replaced by liquid from the tray as happens when there is a froth on the tray. This phenomenon could not be recorded photographically, but it was noticed that the underside of the cloth dried out quite rapidly and a spray of the displaced liquid appeared above the tray.

The moist tray is of little commercial interest as such, but it is useful when the total pressure drop and the moist tray pressure drop are compared, For the conditions studied the total pressure drop can be found approximately by adding the clear liquid height to the moist pressure

drop at the corresponding air rate.

6.1.3 The Effect of Liquid Surface Tension.

To find the effect of the liquid surface tension many liquids with as wide a range of surface tension as possible should be studied. However, the range available is very limited if water is not considered. All readily available and convenient liquids fall in the narrow range from about 20-30 dynes/cm. whereas water at ambient conditions has a surface tension of about 72 dynes/cm.

Mixtures of glycols with water or heavy oils have been used, but their high viscosity introduces experimental drawbacks.

The previous studies had been carried out using water and as no convenient intermediate surface tension liquids were available a low surface tension liquid only was used in the study of the present effect. Toluene was chosen as an example of the latter type of liquid as it was readily available.

The procedure used was identical to that used in the previous section except 135 ccs. of toluene were used as a clear liquid height of one inch to compensate for its different specific gravity. The results obtained in this study can be found in appendix A.6.2 and in figures 6.4 and 6.5.

Figure 6.5 gives the pressure drop results one quarter

of a minute after the start-up for both toluene and water systems. The pressure drop results for toluene after longer times tend to be much less meaningful due to the large evaporation loss. (See appendix A.6.2 for calculated losses). However, it can easily be seen that the toluene system gives much lower pressure drop results than the water system both in the magnitude and in the slope of the curve. These effects point to a higher effective free area being available for gas flow for the toluene runs.

Comparing the photographs of the tray in operation using water (figure 6.3) and toluene (figure 6.4) the effect on the free area would appear similar. However, as the surface tension of toluene is much lower than water we would expect it to be held less strongly in the cloth. The toluene shows its tendency to weep by covering the bottom of the cloth with a layer of liquid. Water does not do this and the appearance of the underside of the cloth is, therefore, quite different. Closer inspection of figure 6.4 reveals that as well as the large holes through the cloth many small holes have been opened up. This is not so for the water system and could, therefore, explain the increase in available free area in the case of the toluene system.

Nevertheless the approximate relationship for the total pressure drop still holds, namely the total pressure drop can

be found from the sum of the moist tray pressure drop and the equivalent clear liquid height.

6.1.4 The Effect of Yarn Free Fibre.

It has been noticed in the earlier sections of this study that the free fibre on the yarn enables the liquid to bridge the space between the basic yarn structure of the cloth. This effect causes a large reduction in the free area and thus a large increase in the pressure drop characteristics of the tray. It is reasonable to suppose that if all the free fibre were removed and the liquid could not bridge the whole distance between basic structure of the cloth the effective free area would be greatly increased and the pressure drop greatly reduced. However, if the free area were made too high the liquid would dump or at least weep severely through the tray floor.

Bearing in mind the two opposing considerations a sample of woven glass cloth AD225 was prepared by removing the majority of the free fibre from the yarn. This was accomplished by trapping the free fibres spanning the basic structure between a sharp blade and backing board. The modified cloth, designated AD225 (B), can be compared with a sample of the original cloth by consulting figure 6.6.

Experiments were carried out using glass cloth AD225 (B) in exactly the same way as in the previous two parts of this

study. Unfortunately the modified cloth wept at the edges of the column so photographs of the cloth in operation could not be taken. However, photographs were taken of the cloth before and after it had been thoroughly wetted in preparation for a run. The photographs of the cloths in the static condition are very similar to their appearance in operation, as was noted from visual studies. For comparison the original and modified cloths can be seen both dry and wet in figures 6.6 and 6.7 respectively.

The removal of the free fibre from the yarn can be seen to have a profound effect on the free area available for gas flow. A film of water forms over most of the surface of the original cloth and is held stably in position by the free fibres spanning the gap between the basic weave structure of the cloth. In the case of the modified cloth the majority of the liquid is held round the yarn and only between the yarn in very few places. Using toluene the result appears to be the same.

The modified cloth tended to weep at the edges of the column due to its high free area and the artificially high clear liquid height at its edges due to the wall effect (239). No reasonable pressure drop-time curves could be obtained as these require a detailed evaluation of the weeping characteristics of the tray. Using toluene as the liquid

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both the higher evaporation rate and the higher weep rate give little meaning to the results of runs lasting more than a short time. However, pressure drop experiments using both toluene and water were carried out and the results are given in figure 6.9 and appendix A.6.3.

The pressure drop curves for both liquids bear out the photographic evidence in that their magnitude is much lower and the slopes are less than those for the original cloth shown in figure 6.5 Nevertheless the same approximate relationship can be used for the total pressure drop as before. Moreover the small amount of liquid held in the modified cloth leads to a reduction in the effect of the vapour rate and the liquid surface on the moist pressure drop. This is shown in figure 6.9 where the lower surface tension toluene does not produce such a large reduction in pressure drop over the water system as it did for the original cloth. Also the wet and moist curves tend to follow the dry tray pressure drop more closely.

FIGURE 6·2

3" DIA COLUMN. AIR/WATER SYSTEM.

GLASS CLOTH AD 225.

CLEAR LIQUID HEIGHT:- dry moist 1" 2"

TIME AFTER START:- ¼ min ——; 2 mins ------.

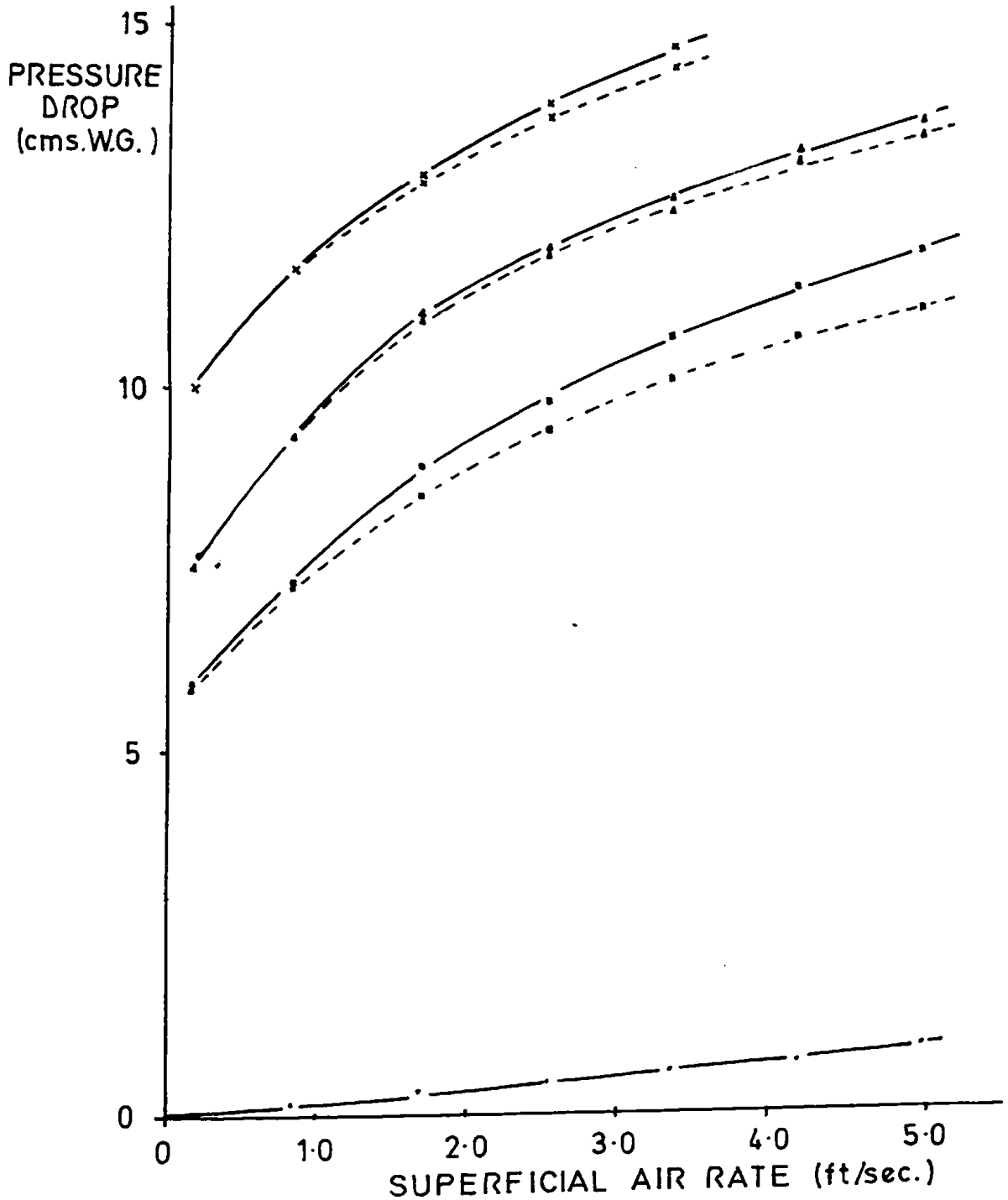


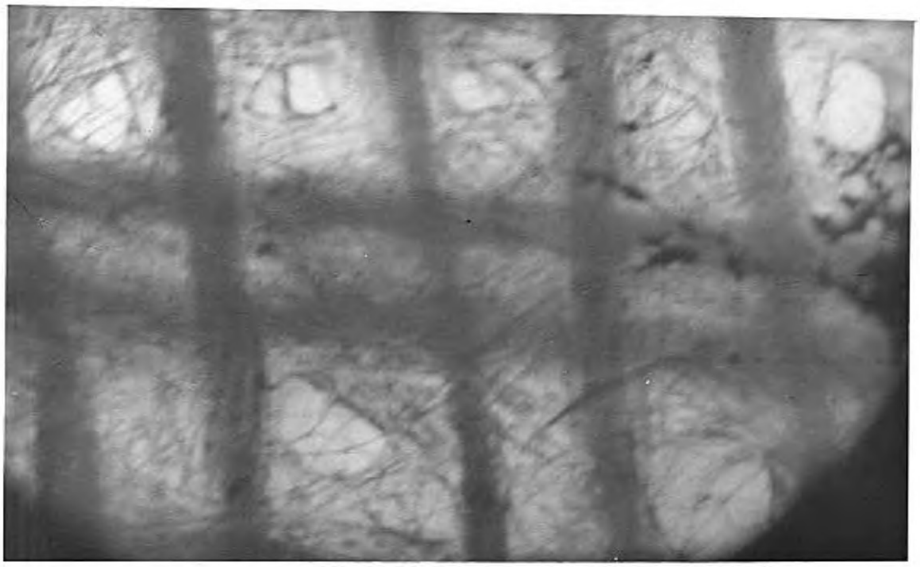
FIGURE 6.3

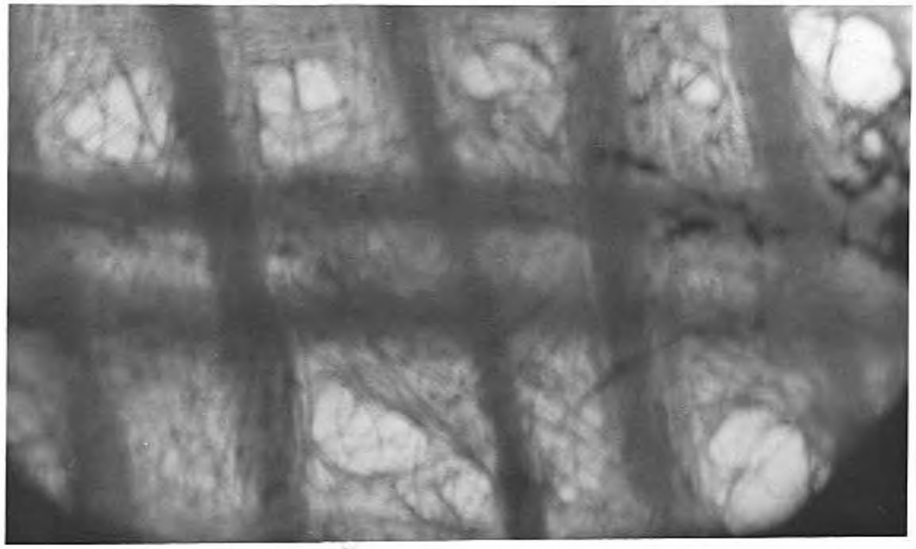
PHOTOGRAPHS OF GLASS CLOTH AD225 IN OPERATION AT VARIOUS AIR RATES USING WATER (MAGNIFICATION x 10)

a) 1 foot/sec.

b) 3 feet/sec.

c) 6 feet/sec.





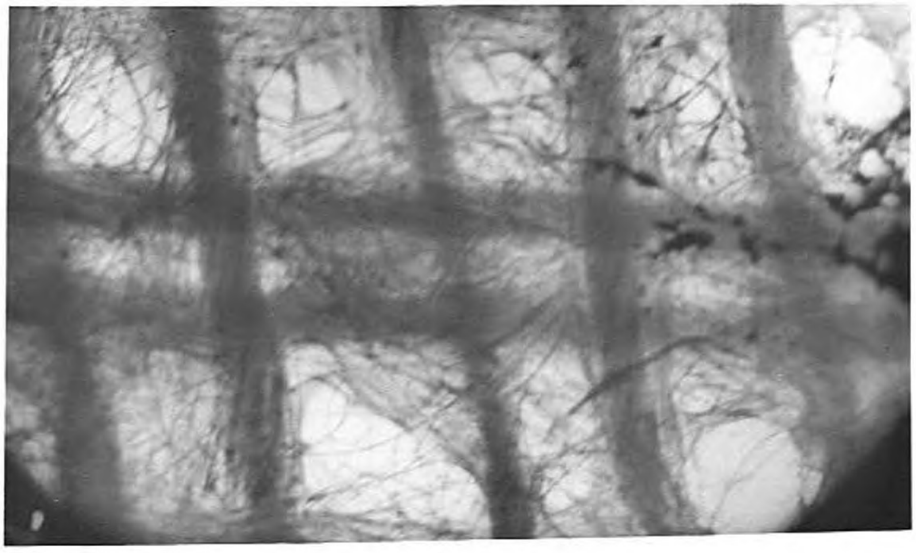


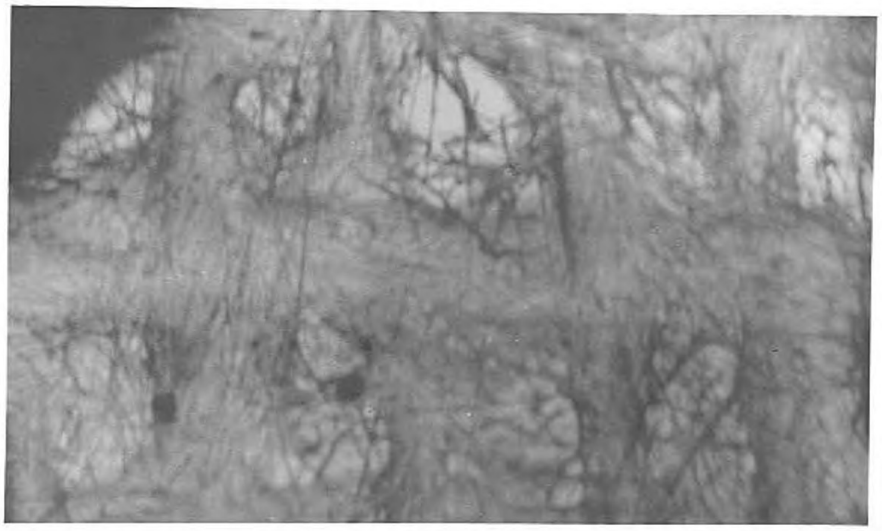
FIGURE 6.4

PHOTOGRAPHS OF GLASS CLOTH AD225 IN OPERATION AT VARIOUS AIR RATES USING TOLUENE (MAGNIFICATION x 10)

a) 1 foot/sec.

b) 3 feet/sec.

c) 6 feet/sec.



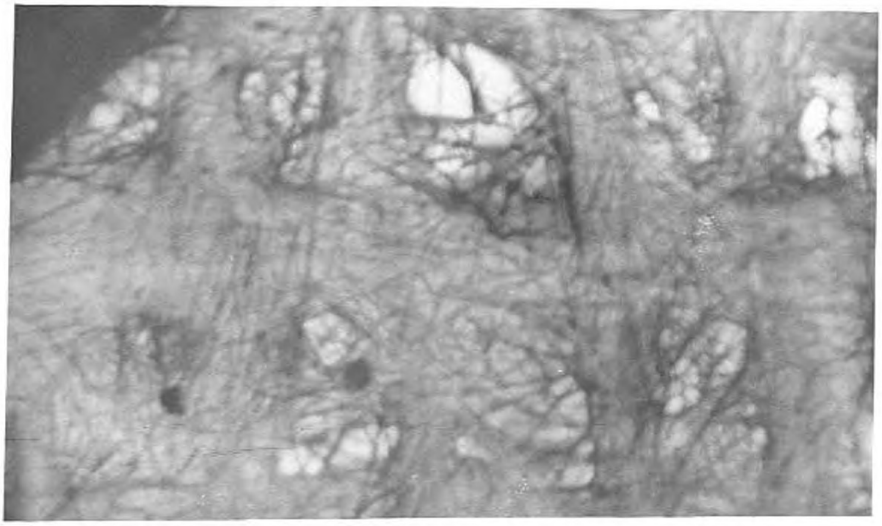


FIGURE 6·5

3" DIA. COLUMN. GLASS CLOTH AD 225.

AIR / WATER ——, AIR/ TOLUENE ------.

CLEAR LIQUID HEIGHT:- dry moist 1" 2"

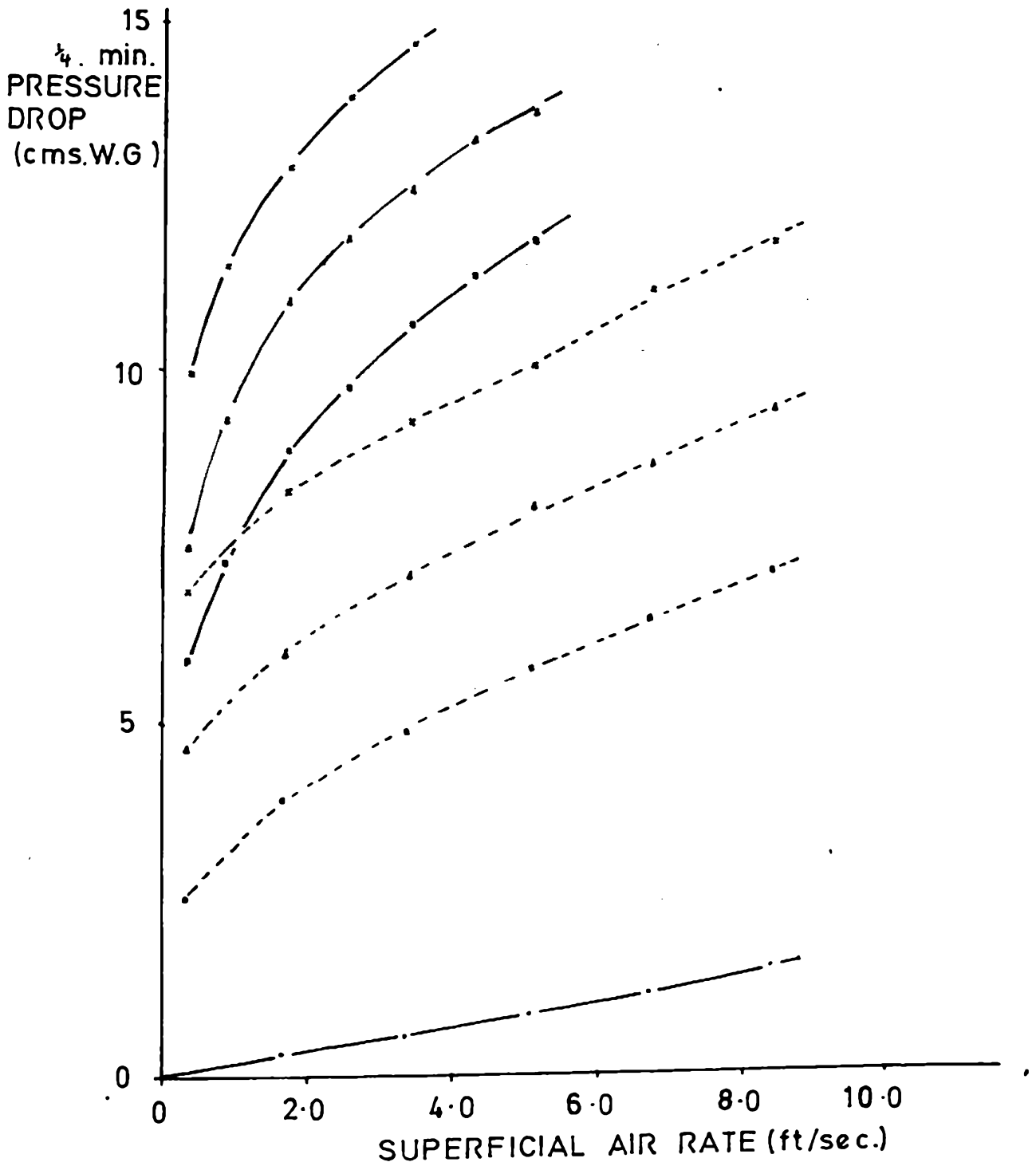


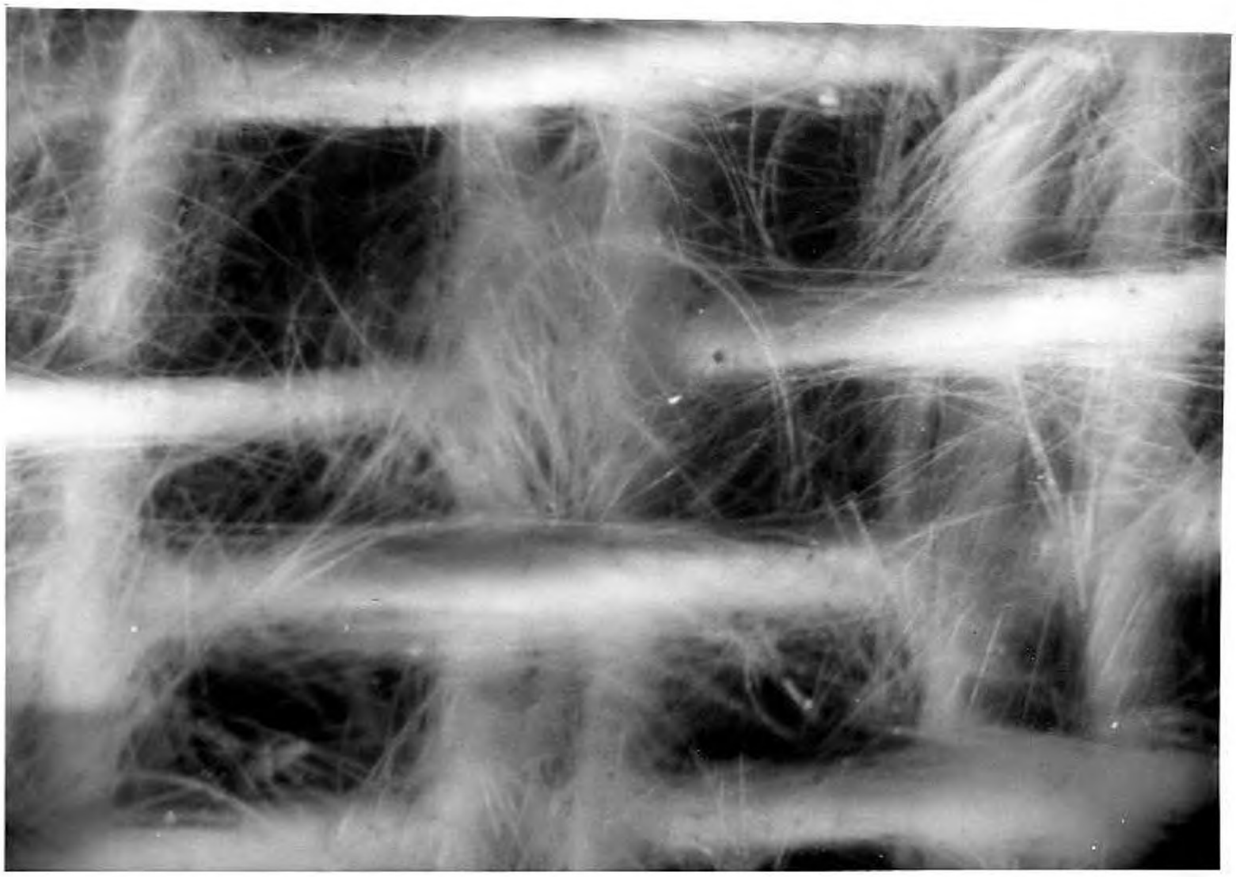
FIGURE 6.6

PHOTOGRAPHS OF DRY GLASS CLOTHS

(MAGNIFICATION x 15)

a) Glass Cloth AD225

b) Glass Cloth AD225 (B)



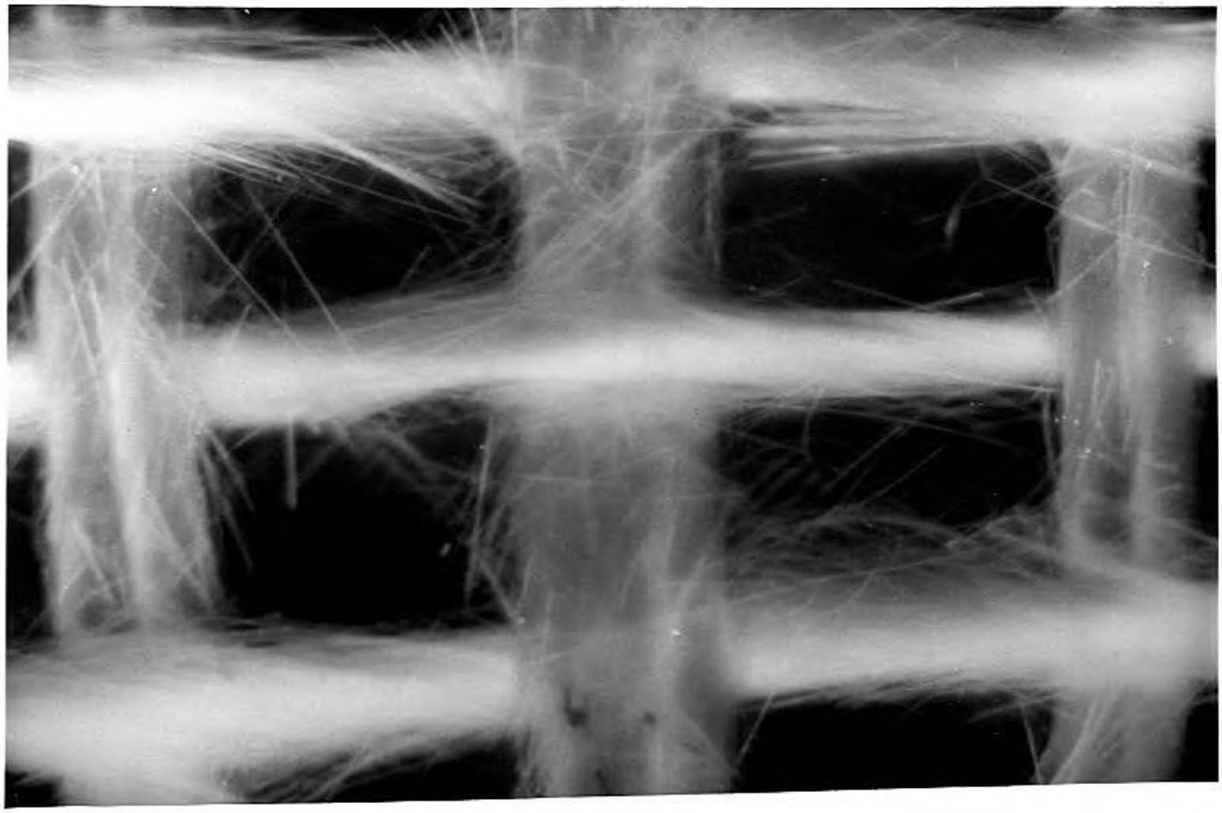


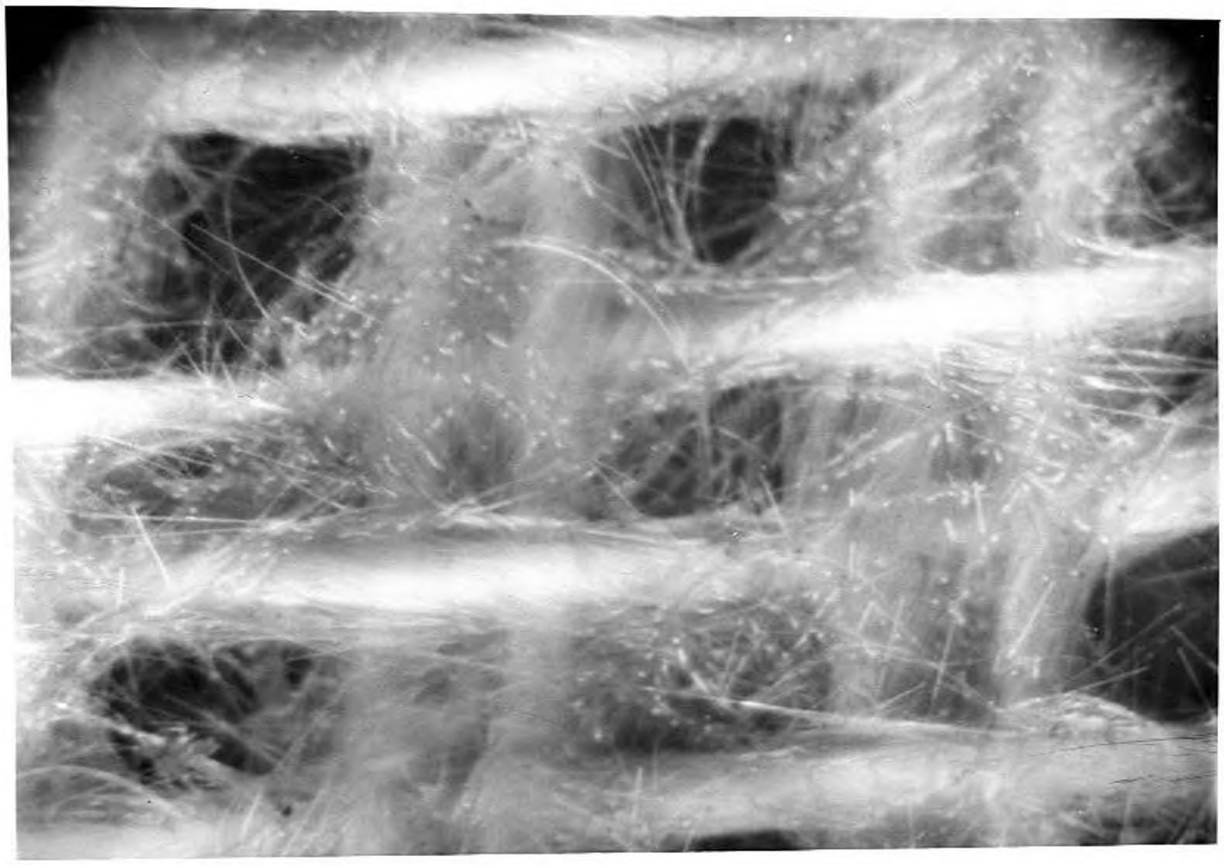
FIGURE 6.7

PHOTOGRAPHS OF GLASS CLOTHS WET WITH WATER

(MAGNIFICATION X 15)

a) Glass Cloth AD225

b) Glass Cloth AD225 (B)



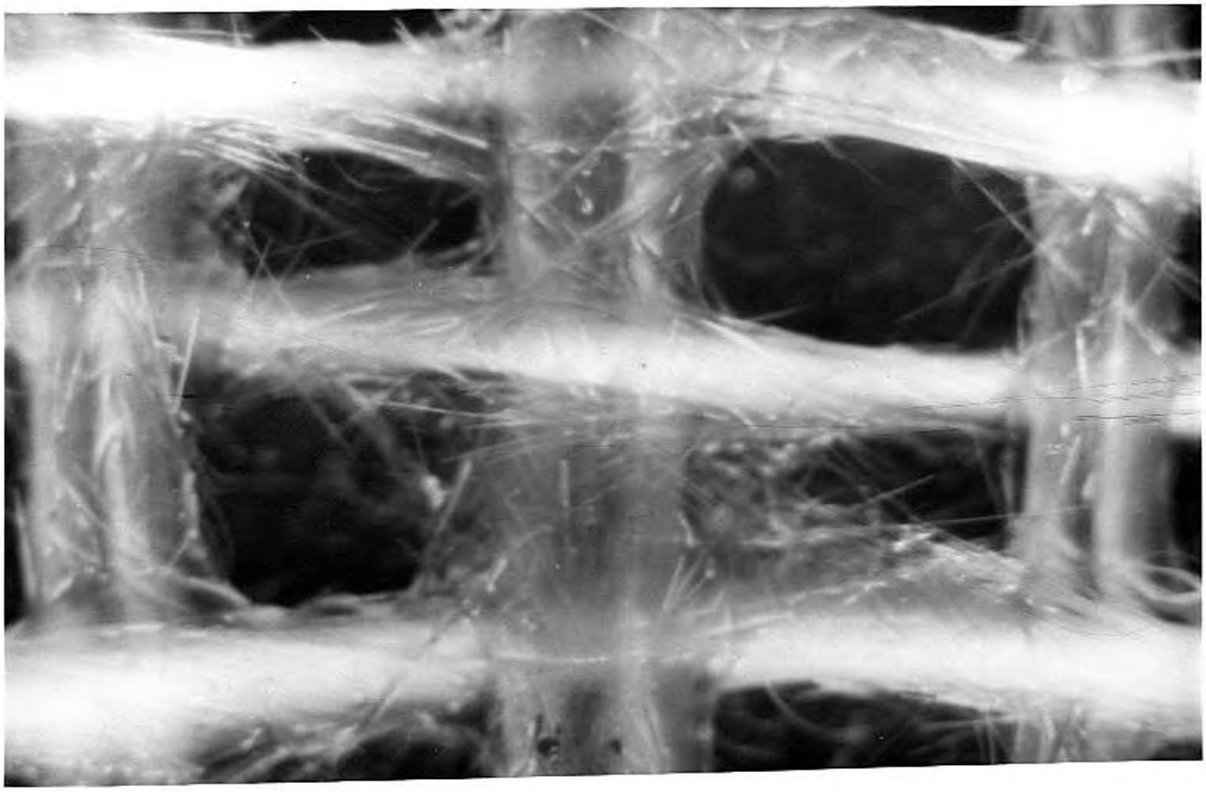
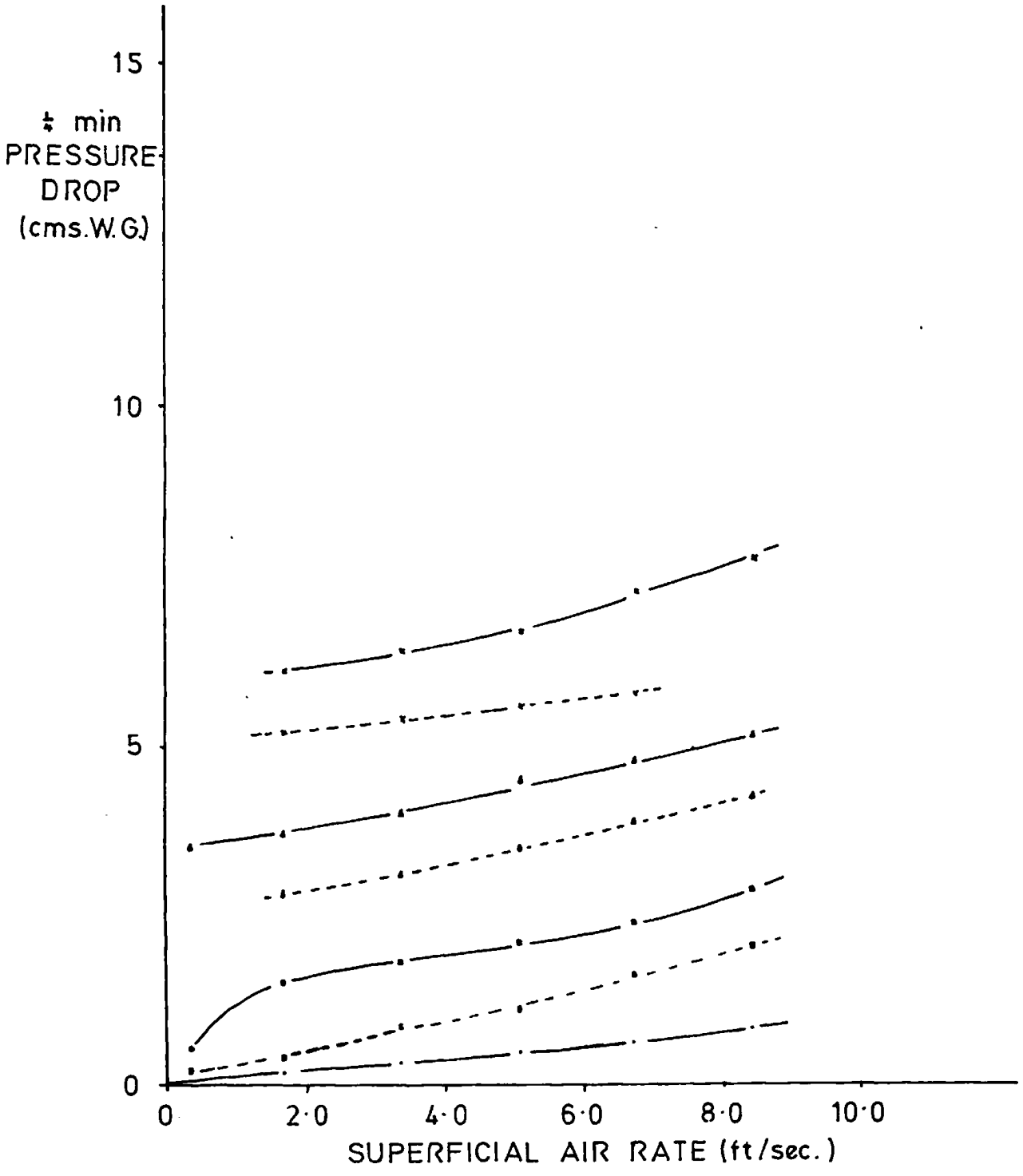


FIGURE 6·8

3" DIA. COLUMN. GLASS CLOTH AD 225(B).

AIR/WATER——— ,AIR/TOLUENE- - - - - - .

CLEAR LIQUID HEIGHT:- dry moist 1" 2"



6.2 The Effect of Cloth Weave Geometry.

The need to know the effects of the cloth weave on the pressure drop is obviously important particularly when the performance of a proposed new cloth is considered. The situation is, however, highly complex as not only the effects studied so far, but the effect of the weave of the cloth on both the wet and dry areas must be considered. Furthermore, a cloth can be woven from the same yarn into different types of weave at the same settings. In previous studies in this work plain weaves have been used exclusively, but twill weaves are used to good effect in gas filtration and give a lower pressure drop per unit weight of cloth (226). This saving in pressure drop may show itself in distillation applications as twill weaves give higher dry free areas per unit weight of cloth than plain weaves. This is due to the holes through the cloth being inclined at angles to the gas flow and not perpendicular to it. However, twill weaves are not as mechanically stable as the comparative plain weave. There are other fancy weaves, but these do not seem to offer any marked advantages.

Unfortunately it was not possible to obtain samples of twill or fancy weaves in time to be included in this work. The study must, therefore, be confined to the more important study of the effect of weave setting on the pressure

drop of cloths woven from the same yarn. As any yarn can be used for this study it is reasonable and useful to choose a yarn and series of cloths that are being developed for tray floor use as all known improvements will have been applied to their fabrication. The cloths used were AD1224 series made from taslaned glass yarn with a stainless steel wire incorporation for strength and rigidity. Details of the cloths used are given in Appendix 6.4.1.

6.2.1 Apparatus and Procedure.

The same 3" diameter column as described in section 3.2 and 6.1 was used to find the pressure drop characteristics of the cloths. As the cloths are quite rigid, a grid was not necessary to hold down the trays when in operation.

The pressure drop readings were all taken $\frac{1}{4}$ minute after a totally wet start and with a clear liquid height of one inch. The results are given in Appendix 6.4.2 and in figure 6.9.

6.2.2 The Effect of Weave Settings.

There are two distinct ways by which the weave setting can affect the pressure drop of the cloth. Firstly and most importantly it affects the dry free area which is the base upon which all the other effects act. When all the other factors are held constant by the yarn and the system, the changes in the dry free area, due to difference in the

weave settings, produce families of curves as shown in figure 6.9. The highest free area samples give low flat curves whilst the lowest free area samples give high steep curves.

Secondly the weave settings affect the wet free area of the cloth. In the case of the highest free area samples the slope of the curves tends to increase more rapidly with air rate. This effect is similar to that encountered when using AD225 (B) in section 6.1.4 where the wet free area was little affected by air rate due to the small amount of liquid held in the cloth. The same explanation seems valid in this case also.

Not only do the weave settings affect the amount of liquid in the cloth, but where and how stably it is held. Compare the pressure drop results given by the two weave settings which give a dry free area of 24%, namely 10 x 15 and 12 x 13. Both cloths have similar equivalent hole sizes, 0.0154 square inches for the 10 x 15 sample and 0.0148 square inches for the 12 x 13 sample, but the holes have quite different shapes. The 10 x 15 sample has oblong holes, 0.0576" x 0.0267", whilst the 12 x 13 sample has almost square holes, 0.04" x 0.037".

At low air rates both holes will hold a reasonable amount of water and their pressure drops should be similar.

However, as the air rate is increased the water will more easily be stripped from the long sides of the 10 x 15 sample and its pressure drop curve will fall below that of the 12 x 13 sample. At higher air rates when most of the water has been stripped from the long sides of the 10 x 15 sample the square sides of the 12 x 13 sample will lose their water more easily than the short sides of the oblong holes. The two curves will then reapproach as the slope of the curve for the 10 x 15 sample will increase whilst that for the 12 x 13 sample will decrease.

FIGURE 6·9

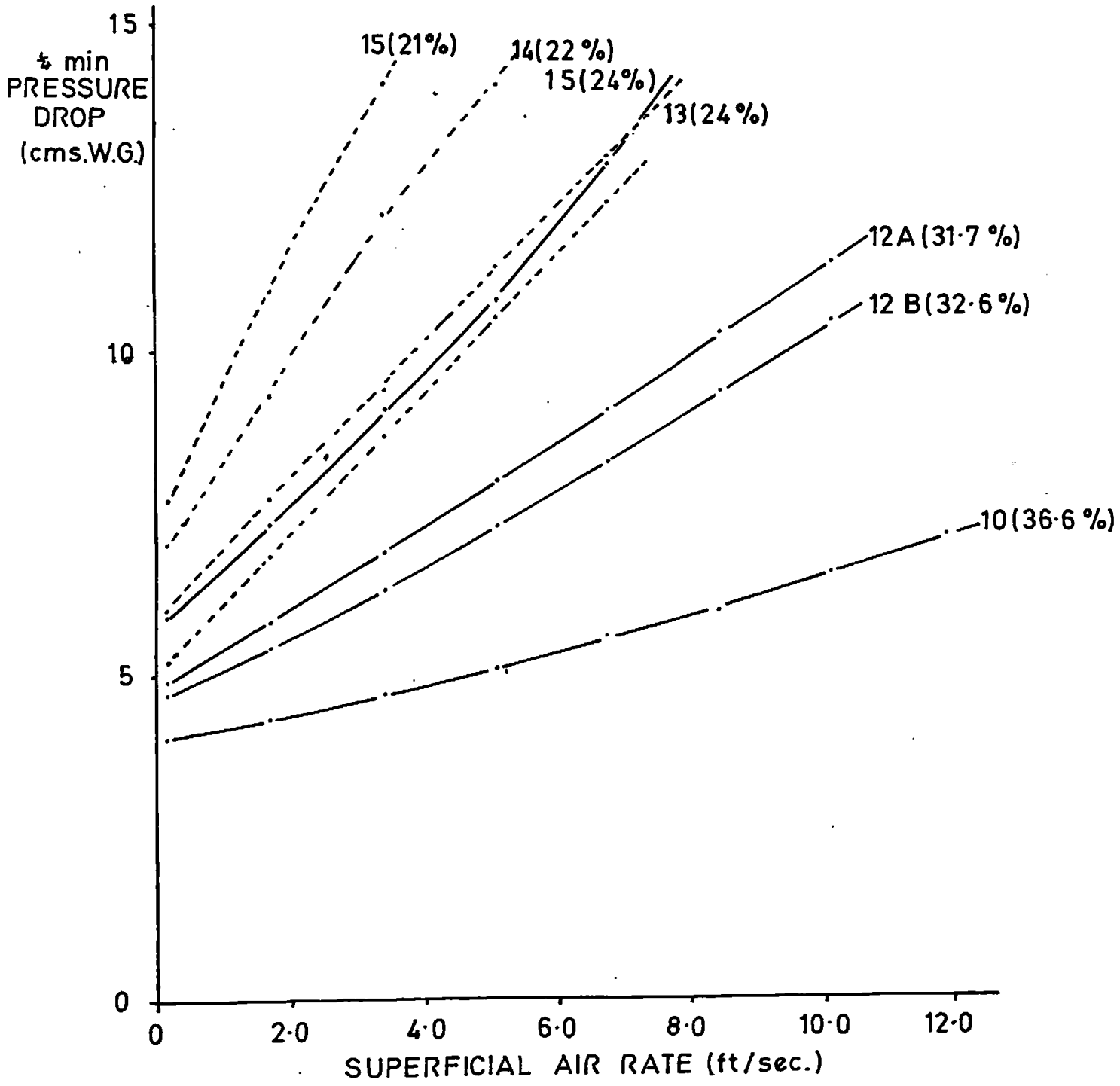
3" DIA. COLUMN. AIR/WATER SYSTEM.

GLASS CLOTH AD1224.

10 ends/inch x picks/inch (dry free area). ——— .

12 " " x " " (" " "). - - - - - .

1" CLEAR LIQUID HEIGHT.



6.3 Conclusions.

The mechanism of operation of a cloth tray floor is much more complex than that of a conventional Sieve tray floor. Many factors affect the free area and thus the pressure drop both directly and indirectly so that the prediction of the pressure drop from fundamental considerations would be exceptionally difficult, if not impossible. However, the principle effects have been studied and a method can be proposed for the empirical prediction of the total tray pressure drop.

It has been found that:-

$$P = P_m + h_c$$

where P and Pm are the total and moist tray pressure drops and hc is the equivalent head of liquid corresponding to the liquid hold-up on the tray. Unfortunately this method involves the determination of the moist tray pressure drop at the required vapour rate for the particular cloth in use. At present, the only way to determine this quantity for a new cloth is by experiment. If an air-water system were used for the tests the value found would probably be higher than that encountered in commercial operation due to surface tension and wetness effects. The prediction of a pessimistic value is advantageous as it will give a safety factor. Alternatively a useful gain can be obtained when a low surface tension liquid is used or the cloth is not saturated with the

liquid as in the experimental technique, However, with cloths which give lower, and more useful, pressure drops, these effects are much less marked and the moist plate pressure drop value obtained using an air-water system will be reasonably reliable.

It has been found that the principle factors governing the free area of the moist cloth and thus its pressure drop, are due to the cloth itself. The weave settings principally affect the dry free area, but they can modify the moist free area by affecting the stability of the positions at which the liquid can be held within the cloth. Coupled with this factor, the free fibre on the yarn can exert a considerable influence by reducing the distance between the basic yarn structure of the cloth. By this means much more liquid can be held in the cloth than would be expected. The moist free area is drastically reduced and the pressure drop greatly increased.

The pressure drop anomilies encountered in the earlier sections of this work can all be easily explained by the effects studied in this section. The high values of the wet pressure drop curves compared with the low values of the dry pressure drop curves as found in sections 3 and 4 can be explained by the presence of liquid in the cloth. The liquid causes a large reduction in the effective free area for gas

flow through the cloth and thus a large increase in the pressure drop. From this explanation it would appear that curves of pressure drop with increasing air rate should be steep. However, the reason that the slopes of the curves are very low, is found to be that the liquid is removed from the cloth at higher air rates. It is this effect rather than the movement of the free fibre which causes the effective free area to increase with air rate.

A reduction in the surface tension of the liquid was found to decrease the amount of liquid held in the cloth and thus the pressure drop characteristics. The large difference in the surface tensions of the air-water and distillation systems, therefore, gives the latter quite different and much lower pressure drop curves.

SECTION 7.

CONCLUDING SECTION.

7.1 General Discussion and Conclusions.

In general the aim of the study has been fulfilled. A new device for vapour-liquid contacting has been proposed by studying the present knowledge of this contacting process. Also by experimental study it has been shown that improved performance could be obtained and that further improvements are possible if the new device were developed for commercial use.

The literature abounds in information and performance data on the various methods by which vapour and liquid can be contacted and on the devices in which this operation can be carried out. After considering this information and paying particular notice of the ways in which improved contacting could be achieved it was concluded that sieve type trays with downcomers offered the best performance and potential. However, when considering methods by which the performance of conventional Sieve trays could be improved it was found that the tray floor design to give the best performance required small holes and a high free area. Unfortunately this design leads to an unacceptably high cost for the tray floor. A new device was, therefore, proposed, the tray floor of which was to be made from a material having holes preformed through its bulk. In this way the tray floor design to give the best performance could

could be chosen unhampered by the economic restraint of the production of the perforations.

Various porous materials were tested to determine their ability to satisfy the performance requirements and glass cloths showed as being the most promising. However, although glass cloths satisfied the majority of the requirements they were found lacking particularly in their rigid strength and high pressure drop characteristics. The former disadvantage was overcome for the majority of this work by using a reinforcing metal grid on the top of the tray floor. A better commercial solution is to reinforce the glass yarn internally with wires. Although the pressure drop of the glass cloth used in the present work had a higher pressure drop than conventional trays the slope of the curve with increased throughput was much less. Moreover from the knowledge obtained by studying the factors and effects on the pressure drop it was found to be possible to prepare glass cloth tray floors with very low pressure drop characteristics. Moreover the two main disadvantages of the glass cloth used in the majority of this work have been overcome and strong reinforced glass cloths have been found to give much better performance.

Nevertheless using glass cloth AD225 with an upper retaining grid as a tray floor the performance obtained in both small scale, but actual distillation and large scale,

TABLE 7.1.

COMPARISON OF THE LIQUID MIXING PERFORMANCE.

As all the trays gave similar curves for their liquid mixing properties the results given below were chosen at flow conditions in the middle of the range studied, namely at an air flow rate of $3\frac{1}{2}$ ft/sec. and a water flow rate of 25 gals/min.ft. The values were found by interpolation from figures 4.10,4.11 & 4.12 for glass cloth AD225, Bubble-cap trays and high and low free area Sieve trays respectively.

	Glass Cloth Tray		Bubble-cap Tray		Sieve Trays	
					High F.A.	Low F.A.
Weir Height (ins")	1"	$2\frac{1}{2}$"	1"	$2\frac{1}{2}$"	$2\frac{1}{2}$"	$2\frac{1}{2}$"
Pe	200	90	104	76	38	78
DE (ft^2/sec)	0.019	0.0295	0.027	0.0345	0.045	0.036

but simulated studies adequately demonstrated that the conclusions leading to the proposition of the tray floor requirements were valid. The degree of liquid mixing on the new trays was found to be lower than conventional trays. This can easily be confirmed by consulting Table 7.1 in which the mid-range results of the liquid mixing study have been presented and compared with those for some conventional trays. In all cases the Peclet number for the glass cloth tray is higher and the eddy diffusion coefficient is lower. The difference is more marked between the glass cloth and the lower weir heights. Results were not available for the Bubble-cap tray for the Sieve trays under these conditions but the trend is similar. From these results, therefore, a greater enhancement of the overall tray efficiency will be achieved by the new trays if used in a column with long liquid flow paths on the trays.

Some useful parameters for comparing the performance of distillation devices were proposed by the European Federation of Chemical Engineers in conjunction with its Ludwigshafen Symposium (242).

The values of these performance parameters for the glass cloth trays are set out in Table 7.2 and are also compared with those for some conventional trays.

The capacity of the glass cloth trays lies in the middle of the range provided by the conventional trays.

TABLE 7.2

COMPARISON OF DISTILLATION PERFORMANCE.

In the table given below the following definitions, which were proposed by the European Federation of Chemical Engineers in conjunction with its symposium "The Comparison of Industrial Fractionating Devices" held at Ludwigshafen on 19th June, 1967 (242), have been used.

The maximum value of the loading parameter, L, was used to define the capacity point of the column.

$$L = F_{TMAX} \quad (d_L - d_V)^{-\frac{1}{2}} \qquad (M/sec.)$$

The flexibility was defined as the ratio, A/B, in which A is the range of vapour flow rates over which the efficiency is greater or equal to that at 85% maximum vapour loading and B is the maximum vapour loading.

The pressure drop per tray (in cms W.G.) at 85% maximum vapour loading has been taken to characterise this property.

The Volumetric efficiency, V.E. was used to characterise the performance of the column and was expressed in terms of the efficiency, E, and the loading parameter at 85% maximum vapour rate and the tray spacing T; $V.E. = E.L./T.$

	Tray No.2		Bubble cap Tray	Sieve Tray	Floating cap Tray
	AD225	AD1224			
Capacity	0.0718	0.0786	0.0674	0.0832	0.0763
Flexibility	0.907	0.823	0.737	0.107	0.291
Pressure Drop	4.6	3.9	5.8	3.6	4.5
Volumetric Efficiency	9.85	11.2	9.93	13.65	11.95

However, an improvement was achieved when a glass cloth which was specifically produced for distillation use, namely AD1224, was employed. The capacity of tray design No. 2 was limited principally by downcomer flooding and not by the tray floor performance, it is reasonable to suggest, therefore, that a further improvement could be made by better downcomer design. Moreover the smaller diameter of the test column used for the glass cloth trays increases the effect of the dead spaces in the column. The effective capacity would, therefore, be lower than that found in the larger column used to test the conventional trays.

The flexibility of both the glass cloth trays is far superior to that of conventional trays. Of these Bubble-cap trays give by far the best performance, but do not approach the performance of the new trays on this score.

The pressure drop performance of the improved glass cloth AD1224 compares very favourably with all, but high free area Sieve trays. A great improvement was achieved in the pressure drop performance of the cloths as a result of the work recorded in Section 6 of this thesis and further small improvements will be possible with further development.

The volumetric efficiency and the capacity of the trays are closely related as the values of the efficiency are

similar. (This can be seen by reference to figures 5.12 & 5.13). However, the glass cloth trays suffer in that the efficiency is measured in a region where their efficiency is lower than that of the conventional trays and no consideration is given to the fact that it is higher at lower vapour loadings.

As with the capacity there is scope for improved performance by better downcomer design and the removal of the disadvantages associated with a smaller test column. Furthermore as the capacity is not limited by entrainment the value of the volumetric efficiency could be improved by reducing the tray spacing. Nevertheless using the improved cloth the volumetric efficiency of the new trays fall in the centre of the range similar to Floating-cap trays and better than Bubble-cap trays.

It can be seen, therefore, that the new trays perform well by all these criterion and give better overall performance than the conventional trays. Moreover greater potential for the development of both cloth and tray design exists. This development should yield greater improvements in performance than for the much more highly developed conventional trays.

It is also relevant to note that the porous materials used for this type of tray floor construction are cheap and

readily available. An added advantage can, therefore, be gained by reducing the cost of a given sized tray floor as well as improving the performance available from it.

It can be concluded, therefore, that the proposed trays can give improved vapour-liquid contacting performance in their present form and should give even better performance when developed further. Moreover this improvement can be achieved at a lower cost than that for conventional trays.

7.2 Recommendations for Future Work.

There is obviously a need for a design method to predict the performance of the new type of tray with some certainty. It would appear that the method used for conventional Sieve trays could be employed, but would be of little use as the conservative predictions obtained would remove any advantage. However, more precise methods will require much more performance data from actual commercial tray floors in actual distillation operation to be available.

In the meantime much useful work can be done using the present 12" diameter column and the newer high active bubbling area trays.

This work should use not only total reflux conditions as in the present work, but employ finite reflux ratios by passing a proportion of the reflux flow directly into the reboiler.

The high efficiency performance of the new tray has been demonstrated in this work, but a comprehensive study using different test systems and different commercial tray floor materials is desirable. In this connection it would be convenient to await the report of the European Federation of Chemical Engineer's Working Party on Distillation Systems. However, in the meantime it would appear that a surface tension positive, (e.g. u Heptane/Toluene), and a negative

or neutral (e.g. benzene/Toluene) system of hydrocarbons and an aqueous system (e.g. methyl alcohol/water) should be considered as possibilities for use.

The various factors and effects on the pressure drop of the new tray floor materials have been studied briefly, but it would be useful to determine the effects of the cloth structure on other tray properties also, such as the efficiency or the degree of mixing.

Further the sharp drop in efficiency between the two dispersion regimes merits closer study. This could be done be considering the factors which change the position of the transition region and thus the mechanisms involved.

Similarly the efficiencies found at the extreme ends of the concentration ranges would provide an interesting study as these effects have only been able to be studied on a small scale before (243).

The limiting factor for the capacity of the present trays has appeared to be downcomer flooding rather than excessive entrainment. In evaluating the performance of various glass cloth trays, as suggested beforehand, it would be reasonable to consider the effects of tray spacing and downcomer size. However, if these effects were to be studied using an actual distillation system a new column or at least a new set of trays,

probably in a cartridge assembly, would be required.

7.3 The Hyflex Tray.

The following is a short account of the beginning of the commercial exploitation of the improved vapour-liquid contacting device invented and studied in this work.

By Spring 1965 the new tray floor concept had been proposed and materials for it had been selected and found suitable in both the small scale, 4" diameter and large scale, 68" x 14", columns. Constructors John Brown Ltd., from whom the author held a research scholarship, were approached with a view to exploiting the tray commercially. With the aid of this company, through the late Mr. J.C.Odams, a provisional patent (244) was filed on 11th August, 1965 in the joint names of Dr. P.E. Barker and the author to safeguard the invention.

Constructors John Brown Ltd. turned down the first option for the invention so other contracting and constructing companies were approached. Meanwhile encouraging results were being obtained from the actual distillation and liquid mixing studies. In Spring 1966, an agreement was signed with Hydronyl Ltd. and the provisional patent assigned to them. Out of this agreement patent applications were filed by 11th August, 1966 in many countries including, Australia, Belgium, Canada, France, Germany, Holland, Italy, Japan, United Kingdom, United States and U.S.S.R. Also the trade

name of "Hyflex Tray" was sought for any device embodying the invention.

Hydronyl Ltd. and British Belting and Asbestos Ltd. proceded with development of the tray and the cloth designs respectively. The resulting commercial tray was first shown publicly at the International Chemical Engineering Exhibition at Olympia, London in June 1966. (245-247).

The first tray was installed for trial in December, 1966 in a 2ft. diameter column used for the distillation of a highly corrosive system for Distillers Co. Ltd. at Hull. In the meantime more trays have been installed both in service and on trial for other companies. It is, however, too early to have definite results from the companies using these trays, but no major difficulties have been reported up to the present date. Even so the design of both the tray and its floor material are continuing to be developed as more information on their performance becomes available.

7.4 Nomenclature.

The following meanings and units have been given to the symbols used in this thesis.

A	= 1/mv	(dimension less)
a	= interfactial area	(ft^{-1})
c	= concentration difference parameter	(dimension less)
D	= equivalent hole diameter	(ins.)
DE	= eddy diffusion coefficient	(ft^2/sec)
d_L, d_V	= density of liquid and vapour respectively	(lbs/ft^3)
Eo, Ep	= overall tray and point efficiencies	(%)
Eml, Emv	= murphree liquid and vapour phase efficiencies	(%)
e	= ends per inch	(ins^{-1})
F	= F factor = U (dv) $\frac{1}{2}$	($lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs)
FB	= F factor through tray bubbling area	($lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs)
FT	= F factor through total column area	($lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs)
f	= free area	
h	= head of liquid in manometer	(cms)
hc,hf	= clear liquid and froth heights respectively	(cms)
K, K_1, K_2	= constants	
K_g	= gas phase mass transfer coefficient	(ft/sec)
K_1, K_2	= roots of auxilary equation to 2nd order differential equation.	
L	= liquid rate	(galls/min.ft weir)
l	= liquid rate	(lbs/hr. ft^2)
m	= ratio of slopes of equilibrium and operating lines	

n	=	number of pools on tray.	
P, P_m	=	total and moist tray pressure drops (cms W.G.)	
Pe	=	peclet number	(dimensionless)
p	=	picks per inch	(ins^{-1})
R	=	hf/hc	(dimensionless)
R.I.	=	refractive index	(dimensionless)
r	=	z/Z	(dimensionless)
S	=	splashing factor	(dimensionless)
T	=	relative time = ratio of actual and average residence time on the tray	(dimensionless)
t	=	time (contact or from start of run)	(mins)
U	=	superficial air rate	(ft/sec)
UB	=	vapour rate through tray bubbling area	(ft/sec)
UT	=	vapour rate through total column area	(ft/sec)

(for sections 3, 4 and 6 U = UB = UT)

V	=	vapour rate through column	(lbs/ft^2hr)
W	=	water rate	(lbs/hr)
w	=	weir height	(ins)
x	=	component concentration in liquid	(%)
y	=	component concentration in vapour	(%)
Z	=	length of tray	(ins)
z	=	distance from inlet weir	(ins)

The units have been chosen for convenience of figures and reference to published data and not for overall consistency. Thus the use of an orifice diameter quoted as

$\frac{3}{4}$" rather than 0.0625 ft or a pressure drop of 1 cm rather than 0.033 ft. can be justified. Whilst it might be considered that an academic study should give a lead in consistency of units the work has to be read in comparison with other work and for this reason also mixed units have been used.

7.5 References.

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The following abbreviations have been used for the titles of journals:-

A.I.Ch.E.J.	-	American Institute of Chemical Engineers Journal.
B.Ch.E.	-	British Chemical Engineering
C.A.	-	Chemical Abstracts
Can.J.Ch.E.	-	Canadian Journal of Chemical Engineering
Chem. Engg. (N.Y.)	-	Chemical Engineering (New York)
Chem. Engr. (London)	-	The Chemical Engineer (London)
C.E.P.	-	Chemical Engineering Progress
C.E.S.	-	Chemical Engineering Science
C.I.T.	-	Chemie-Ingineur-Technik.
C.P.E.	-	Chemical & Process Engineering
Chem. Tech.	-	Chemie-Technik (Berlin)
I/EC	-	Industrial & Engineering Chemistry
Int. Symp.Dist.	-	International Symposium on Distillation (Brighton 1960) Editor P.A. Rottenburg.
Int. Chem. Eng.	-	International Chemical Engineering
J. Inst. Pet.	-	Journal of the Institute of Petroleum
J. Appl. Sci.	-	Journal of Applied Science.
J. Phys. Chem.	-	Journal of Physical Chemistry
Khim. Prom.	-	Khimicheskaya Promyshlennost
Khim Mash	-	Khimicheskoc Mashinostroenie
Pet. Engr.	-	Petroleum Engineer
Pet. Ref.	-	Petroleum Refiner
T.A.I.Ch.E.	-	Transactions of the American Institute of Chemical Engineers

T.I.Ch.E. - Transactions of the Institute of Chemical Engineers.

Other abbreviations have been used, but these are in such general use that they are thought to be self explanatory.

THE APPENDIX

CONTENTS OF THE APPENDIX.

FIGURE 6.6

PHOTOGRAPHS OF DRY GLASS CLOTHS

(MAGNIFICATION x 15)

a) Glass Cloth AD225

b) Glass Cloth AD225 (B)

FIGURE 6.7

PHOTOGRAPHS OF GLASS CLOTHS WET WITH WATER
(MAGNIFICATION X 15)

a) Glass Cloth AD225

b) Glass Cloth AD225 (B)

6.2 The Effect of Cloth Weave Geometry.

The need to know the effects of the cloth weave on the pressure drop is obviously important particularly when the performance of a proposed new cloth is considered. The situation is, however, highly complex as not only the effects studied so far, but the effect of the weave of the cloth on both the wet and dry areas must be considered. Furthermore, a cloth can be woven from the same yarn into different types of weave at the same settings. In previous studies in this work plain weaves have been used exclusively, but twill weaves are used to good effect in gas filtration and give a lower pressure drop per unit weight of cloth (226). This saving in pressure drop may show itself in distillation applications as twill weaves give higher dry free areas per unit weight of cloth than plain weaves. This is due to the holes through the cloth being inclined at angles to the gas flow and not perpendicular to it. However, twill weaves are not as mechanically stable as the comparative plain weave. There are other fancy weaves, but these do not seem to offer any marked advantages.

Unfortunately it was not possible to obtain samples of twill or fancy weaves in time to be included in this work. The study must, therefore, be confined to the more important study of the effect of weave setting on the pressure

drop of cloths woven from the same yarn. As any yarn can be used for this study it is reasonable and useful to choose a yarn and series of cloths that are being developed for tray floor use as all known improvements will have been applied to their fabrication. The cloths used were AD1224 series made from taslaned glass yarn with a stainless steel wire incorporation for strength and rigidity. Details of the cloths used are given in Appendix 6.4.1.

6.2.1 Apparatus and Procedure.

The same 3" diameter column as described in section 3.2 and 6.1 was used to find the pressure drop characteristics of the cloths. As the cloths are quite rigid, a grid was not necessary to hold down the trays when in operation.

The pressure drop readings were all taken $\frac{1}{4}$ minute after a totally wet start and with a clear liquid height of one inch. The results are given in Appendix 6.4.2 and in figure 6.9.

6.2.2 The Effect of Weave Settings.

There are two distinct ways by which the weave setting can affect the pressure drop of the cloth. Firstly and most importantly it affects the dry free area which is the base upon which all the other effects act. When all the other factors are held constant by the yarn and the system, the changes in the dry free area, due to difference in the

weave settings, produce families of curves as shown in figure 6.9. The highest free area samples give low flat curves whilst the lowest free area samples give high steep curves.

Secondly the weave settings affect the wet free area of the cloth. In the case of the highest free area samples the slope of the curves tends to increase more rapidly with air rate. This effect is similar to that encountered when using AD225 (B) in section 6.1.4 where the wet free area was little affected by air rate due to the small amount of liquid held in the cloth. The same explanation seems valid in this case also.

Not only do the weave settings affect the amount of liquid in the cloth, but where and how stably it is held. Compare the pressure drop results given by the two weave settings which give a dry free area of 24%, namely 10 x 15 and 12 x 13. Both cloths have similar equivalent hole sizes, 0.0154 square inches for the 10 x 15 sample and 0.0148 square inches for the 12 x 13 sample, but the holes have quite different shapes. The 10 x 15 sample has oblong holes, 0.0576" x 0.0267", whilst the 12 x 13 sample has almost square holes, 0.04" x 0.037".

At low air rates both holes will hold a reasonable amount of water and their pressure drops should be similar.

However, as the air rate is increased the water will more easily be stripped from the long sides of the 10 x 15 sample and its pressure drop curve will fall below that of the 12 x 13 sample. At higher air rates when most of the water has been stripped from the long sides of the 10 x 15 sample the square sides of the 12 x 13 sample will lose their water more easily than the short sides of the oblong holes. The two curves will then reapproach as the slope of the curve for the 10 x 15 sample will increase whilst that for the 12 x 13 sample will decrease.

6.3 Conclusions.

The mechanism of operation of a cloth tray floor is much more complex than that of a conventional Sieve tray floor. Many factors affect the free area and thus the pressure drop both directly and indirectly so that the prediction of the pressure drop from fundamental considerations would be exceptionally difficult, if not impossible. However, the principle effects have been studied and a method can be proposed for the empirical prediction of the total tray pressure drop.

It has been found that:-

$$P = P_m + h_c$$

where P and Pm are the total and moist tray pressure drops and hc is the equivalent head of liquid corresponding to the liquid hold-up on the tray. Unfortunately this method involves the determination of the moist tray pressure drop at the required vapour rate for the particular cloth in use. At present, the only way to determine this quantity for a new cloth is by experiment. If an air-water system were used for the tests the value found would probably be higher than that encountered in commercial operation due to surface tension and wetness effects. The prediction of a pessimistic value is advantageous as it will give a safety factor. Alternatively a useful gain can be obtained when a low surface tension liquid is used or the cloth is not saturated with the

liquid as in the experimental technique, However, with cloths which give lower, and more useful, pressure drops, these effects are much less marked and the moist plate pressure drop value obtained using an air-water system will be reasonably reliable.

It has been found that the principle factors governing the free area of the moist cloth and thus its pressure drop, are due to the cloth itself. The weave settings principally affect the dry free area, but they can modify the moist free area by affecting the stability of the positions at which the liquid can be held within the cloth. Coupled with this factor, the free fibre on the yarn can exert a considerable influence by reducing the distance between the basic yarn structure of the cloth. By this means much more liquid can be held in the cloth than would be expected. The moist free area is drastically reduced and the pressure drop greatly increased.

The pressure drop anomilies encountered in the earlier sections of this work can all be easily explained by the effects studied in this section. The high values of the wet pressure drop curves compared with the low values of the dry pressure drop curves as found in sections 3 and 4 can be explained by the presence of liquid in the cloth. The liquid causes a large reduction in the effective free area for gas

flow through the cloth and thus a large increase in the pressure drop. From this explanation it would appear that curves of pressure drop with increasing air rate should be steep. However, the reason that the slopes of the curves are very low, is found to be that the liquid is removed from the cloth at higher air rates. It is this effect rather than the movement of the free fibre which causes the effective free area to increase with air rate.

A reduction in the surface tension of the liquid was found to decrease the amount of liquid held in the cloth and thus the pressure drop characteristics. The large difference in the surface tensions of the air-water and distillation systems, therefore, gives the latter quite different and much lower pressure drop curves.

SECTION 7.

CONCLUDING SECTION.

7.1 General Discussion and Conclusions.

In general the aim of the study has been fulfilled. A new device for vapour-liquid contacting has been proposed by studying the present knowledge of this contacting process. Also by experimental study it has been shown that improved performance could be obtained and that further improvements are possible if the new device were developed for commercial use.

The literature abounds in information and performance data on the various methods by which vapour and liquid can be contacted and on the devices in which this operation can be carried out. After considering this information and paying particular notice of the ways in which improved contacting could be achieved it was concluded that sieve type trays with downcomers offered the best performance and potential. However, when considering methods by which the performance of conventional Sieve trays could be improved it was found that the tray floor design to give the best performance required small holes and a high free area. Unfortunately this design leads to an unacceptably high cost for the tray floor. A new device was, therefore, proposed, the tray floor of which was to be made from a material having holes preformed through its bulk. In this way the tray floor design to give the best performance could

could be chosen unhampered by the economic restraint of the production of the perforations.

Various porous materials were tested to determine their ability to satisfy the performance requirements and glass cloths showed as being the most promising. However, although glass cloths satisfied the majority of the requirements they were found lacking particularly in their rigid strength and high pressure drop characteristics. The former disadvantage was overcome for the majority of this work by using a reinforcing metal grid on the top of the tray floor. A better commercial solution is to reinforce the glass yarn internally with wires. Although the pressure drop of the glass cloth used in the present work had a higher pressure drop than conventional trays the slope of the curve with increased throughput was much less. Moreover from the knowledge obtained by studying the factors and effects on the pressure drop it was found to be possible to prepare glass cloth tray floors with very low pressure drop characteristics. Moreover the two main disadvantages of the glass cloth used in the majority of this work have been overcome and strong reinforced glass cloths have been found to give much better performance.

Nevertheless using glass cloth AD225 with an upper retaining grid as a tray floor the performance obtained in both small scale, but actual distillation and large scale,

TABLE 7.1.

COMPARISON OF THE LIQUID MIXING PERFORMANCE.

As all the trays gave similar curves for their liquid mixing properties the results given below were chosen at flow conditions in the middle of the range studied, namely at an air flow rate of $3\frac{1}{2}$ ft/sec. and a water flow rate of 25 gals/min.ft. The values were found by interpolation from figures 4.10,4.11 & 4.12 for glass cloth AD225, Bubble-cap trays and high and low free area Sieve trays respectively.

	Glass Cloth Tray		Bubble-cap Tray		Sieve Trays	
					High F.A.	Low F.A.
Weir Height (ins")	1"	$2\frac{1}{2}$"	1"	$2\frac{1}{2}$"	$2\frac{1}{2}$"	$2\frac{1}{2}$"
Pe	200	90	104	76	38	78
DE (ft^2/sec)	0.019	0.0295	0.027	0.0345	0.045	0.036

but simulated studies adequately demonstrated that the conclusions leading to the proposition of the tray floor requirements were valid. The degree of liquid mixing on the new trays was found to be lower than conventional trays. This can easily be confirmed by consulting Table 7.1 in which the mid-range results of the liquid mixing study have been presented and compared with those for some conventional trays. In all cases the Peclet number for the glass cloth tray is higher and the eddy diffusion coefficient is lower. The difference is more marked between the glass cloth and the lower weir heights. Results were not available for the Bubble-cap tray for the Sieve trays under these conditions but the trend is similar. From these results, therefore, a greater enhancement of the overall tray efficiency will be achieved by the new trays if used in a column with long liquid flow paths on the trays.

Some useful parameters for comparing the performance of distillation devices were proposed by the European Federation of Chemical Engineers in conjunction with its Ludwigshafen Symposium (242).

The values of these performance parameters for the glass cloth trays are set out in Table 7.2 and are also compared with those for some conventional trays.

The capacity of the glass cloth trays lies in the middle of the range provided by the conventional trays.

TABLE 7.2

COMPARISON OF DISTILLATION PERFORMANCE.

In the table given below the following definitions, which were proposed by the European Federation of Chemical Engineers in conjunction with its symposium "The Comparison of Industrial Fractionating Devices" held at Ludwigshafen on 19th June, 1967 (242), have been used.

The maximum value of the loading parameter, L, was used to define the capacity point of the column.

$$L = F_{TMAX} \quad (d_L - d_v)^{-\frac{1}{2}} \qquad (M/sec.)$$

The flexibility was defined as the ratio, A/B, in which A is the range of vapour flow rates over which the efficiency is greater or equal to that at 85% maximum vapour loading and B is the maximum vapour loading.

The pressure drop per tray (in cms W.G.) at 85% maximum vapour loading has been taken to characterise this property.

The Volumetric efficiency, V.E. was used to characterise the performance of the column and was expressed in terms of the efficiency, E, and the loading parameter at 85% maximum vapour rate and the tray spacing T; $V.E. = E.L./T.$

	Tray No.2		Bubble cap Tray	Sieve Tray	Floating cap Tray
	AD225	AD1224			
Capacity	0.0718	0.0786	0.0674	0.0832	0.0763
Flexibility	0.907	0.823	0.737	0.107	0.291
Pressure Drop	4.6	3.9	5.8	3.6	4.5
Volumetric Efficiency	9.85	11.2	9.93	13.65	11.95

However, an improvement was achieved when a glass cloth which was specifically produced for distillation use, namely AD1224, was employed. The capacity of tray design No. 2 was limited principally by downcomer flooding and not by the tray floor performance, it is reasonable to suggest, therefore, that a further improvement could be made by better downcomer design. Moreover the smaller diameter of the test column used for the glass cloth trays increases the effect of the dead spaces in the column. The effective capacity would, therefore, be lower than that found in the larger column used to test the conventional trays.

The flexibility of both the glass cloth trays is far superior to that of conventional trays. Of these Bubble-cap trays give by far the best performance, but do not approach the performance of the new trays on this score.

The pressure drop performance of the improved glass cloth AD1224 compares very favourably with all, but high free area Sieve trays. A great improvement was achieved in the pressure drop performance of the cloths as a result of the work recorded in Section 6 of this thesis and further small improvements will be possible with further development.

The volumetric efficiency and the capacity of the trays are closely related as the values of the efficiency are

similar. (This can be seen by reference to figures 5.12 & 5.13). However, the glass cloth trays suffer in that the efficiency is measured in a region where their efficiency is lower than that of the conventional trays and no consideration is given to the fact that it is higher at lower vapour loadings.

As with the capacity there is scope for improved performance by better downcomer design and the removal of the disadvantages associated with a smaller test column. Furthermore as the capacity is not limited by entrainment the value of the volumetric efficiency could be improved by reducing the tray spacing. Nevertheless using the improved cloth the volumetric efficiency of the new trays fall in the centre of the range similar to Floating-cap trays and better than Bubble-cap trays.

It can be seen, therefore, that the new trays perform well by all these criterion and give better overall performance than the conventional trays. Moreover greater potential for the development of both cloth and tray design exists. This development should yield greater improvements in performance than for the much more highly developed conventional trays.

It is also relevant to note that the porous materials used for this type of tray floor construction are cheap and

readily available. An added advantage can, therefore, be gained by reducing the cost of a given sized tray floor as well as improving the performance available from it.

It can be concluded, therefore, that the proposed trays can give improved vapour-liquid contacting performance in their present form and should give even better performance when developed further. Moreover this improvement can be achieved at a lower cost than that for conventional trays.

7.2 Recommendations for Future Work.

There is obviously a need for a design method to predict the performance of the new type of tray with some certainty. It would appear that the method used for conventional Sieve trays could be employed, but would be of little use as the conservative predictions obtained would remove any advantage. However, more precise methods will require much more performance data from actual commercial tray floors in actual distillation operation to be available.

In the meantime much useful work can be done using the present 12" diameter column and the newer high active bubbling area trays.

This work should use not only total reflux conditions as in the present work, but employ finite reflux ratios by passing a proportion of the reflux flow directly into the reboiler.

The high efficiency performance of the new tray has been demonstrated in this work, but a comprehensive study using different test systems and different commercial tray floor materials is desirable. In this connection it would be convenient to await the report of the European Federation of Chemical Engineer's Working Party on Distillation Systems. However, in the meantime it would appear that a surface tension positive, (e.g. u Heptane/Toluene), and a negative

or neutral (e.g. benzene/Toluene) system of hydrocarbons and an aqueous system (e.g. methyl alcohol/water) should be considered as possibilities for use.

The various factors and effects on the pressure drop of the new tray floor materials have been studied briefly, but it would be useful to determine the effects of the cloth structure on other tray properties also, such as the efficiency or the degree of mixing.

Further the sharp drop in efficiency between the two dispersion regimes merits closer study. This could be done be considering the factors which change the position of the transition region and thus the mechanisms involved.

Similarly the efficiencies found at the extreme ends of the concentration ranges would provide an interesting study as these effects have only been able to be studied on a small scale before (243).

The limiting factor for the capacity of the present trays has appeared to be downcomer flooding rather than excessive entrainment. In evaluating the performance of various glass cloth trays, as suggested beforehand, it would be reasonable to consider the effects of tray spacing and downcomer size. However, if these effects were to be studied using an actual distillation system a new column or at least a new set of trays,

probably in a cartridge assembly, would be required.

7.3 The Hyflex Tray.

The following is a short account of the beginning of the commercial exploitation of the improved vapour-liquid contacting device invented and studied in this work.

By Spring 1965 the new tray floor concept had been proposed and materials for it had been selected and found suitable in both the small scale, 4" diameter and large scale, 68" x 14", columns. Constructors John Brown Ltd., from whom the author held a research scholarship, were approached with a view to exploiting the tray commercially. With the aid of this company, through the late Mr. J.C.Odams, a provisional patent (244) was filed on 11th August, 1965 in the joint names of Dr. P.E. Barker and the author to safeguard the invention.

Constructors John Brown Ltd. turned down the first option for the invention so other contracting and constructing companies were approached. Meanwhile encouraging results were being obtained from the actual distillation and liquid mixing studies. In Spring 1966, an agreement was signed with Hydronyl Ltd. and the provisional patent assigned to them. Out of this agreement patent applications were filed by 11th August, 1966 in many countries including, Australia, Belgium, Canada, France, Germany, Holland, Italy, Japan, United Kingdom, United States and U.S.S.R. Also the trade

name of "Hyflex Tray" was sought for any device embodying the invention.

Hydronyl Ltd. and British Belting and Asbestos Ltd. proceded with development of the tray and the cloth designs respectively. The resulting commercial tray was first shown publicly at the International Chemical Engineering Exhibition at Olympia, London in June 1966. (245-247).

The first tray was installed for trial in December, 1966 in a 2ft. diameter column used for the distillation of a highly corrosive system for Distillers Co. Ltd. at Hull. In the meantime more trays have been installed both in service and on trial for other companies. It is, however, too early to have definite results from the companies using these trays, but no major difficulties have been reported up to the present date. Even so the design of both the tray and its floor material are continuing to be developed as more information on their performance becomes available.

7.4 Nomenclature.

The following meanings and units have been given to the symbols used in this thesis.

A	= 1/mv	(dimension less)
a	= interfactial area	(ft^{-1})
c	= concentration difference parameter	(dimension less)
D	= equivalent hole diameter	(ins.)
DE	= eddy diffusion coefficient	(ft^2/sec)
d_L, d_V	= density of liquid and vapour respectively	(lbs/ft^3)
Eo, Ep	= overall tray and point efficiencies	(%)
Eml, Emv	= murphree liquid and vapour phase efficiencies	(%)
e	= ends per inch	(ins^{-1})
F	= F factor = U $(dv)^{\frac{1}{2}}$	($lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs)
FB	= F factor through tray bubbling area	($lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs)
FT	= F factor through total column area	($lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs)
f	= free area	
h	= head of liquid in manometer	(cms)
hc, hf	= clear liquid and froth heights respectively	(cms)
K, K_1, K_2	= constants	
K_g	= gas phase mass transfer coefficient	(ft/sec)
K_1, K_2	= roots of auxilary equation to 2nd order differential equation.	
L	= liquid rate	(galls/min.ft weir)
l	= liquid rate	(lbs/hr. ft^2)
m	= ratio of slopes of equilibrium and operating lines	

n	=	number of pools on tray.	
P, P_m	=	total and moist tray pressure drops	(cms W.G.)
Pe	=	peclet number	(dimensionless)
p	=	picks per inch	(ins^{-1})
R	=	hf/hc	(dimensionless)
R.I.	=	refractive index	(dimensionless)
r	=	z/Z	(dimensionless)
S	=	splashing factor	(dimensionless)
T	=	relative time = ratio of actual and average residence time on the tray	(dimensionless)
t	=	time (contact or from start of run)	(mins)
U	=	superficial air rate	(ft/sec)
UB	=	vapour rate through tray bubbling area	(ft/sec)
UT	=	vapour rate through total column area	(ft/sec)

(for sections 3, 4 and 6 U = UB = UT)

V	=	vapour rate through column	(lbs/ft^2hr)
W	=	water rate	(lbs/hr)
w	=	weir height	(ins)
x	=	component concentration in liquid	(%)
y	=	component concentration in vapour	(%)
Z	=	length of tray	(ins)
z	=	distance from inlet weir	(ins)

The units have been chosen for convenience of figures and reference to published data and not for overall consistency. Thus the use of an orifice diameter quoted as

$\frac{3}{4}$" rather than 0.0625 ft or a pressure drop of 1 cm rather than 0.033 ft. can be justified. Whilst it might be considered that an academic study should give a lead in consistency of units the work has to be read in comparison with other work and for this reason also mixed units have been used.

Appendix to Section 6.

APPENDIX TO SECTION 3.

APPENDIX A.3.1. SINTERED MATERIALS.

A.3.1.1. Sintered Powder Specification.

The sintered powder discs used in the experiments were obtained from:

B.S.A. Sintered Components Ltd.,
Montgomary Street,
Birmingham.

Material of construction - 18/8 low carbon stainless steel

Mean pore size - 85 microns.

Permeability - 400×10^{10} ins^2

Thickness - 1/8" & 1/16"

A.3.1.2. Sintered Meshes Specification.

The sintered meshes used were of the "Rigidmesh" range manufactured by:

Sintered Products Ltd.,
Hamilton Road,
Sutton in Ashfield, Notts.

Material of construction - 18/8 stainless steel.

MICRON RATING	STANDARD THICKNESS	% FREE AREA FOR GAS FLOW
$2\frac{1}{2}$	0.032"	16
50	0.042"	28
100	0.057"	56

A.3.1.3. Hydraulic Results of Sintered Materials.

Both samples of sintered powder discs and the two lower free area samples of "rigid mesh" gave pressure drops in excess of 30 cms of water gauge at a superficial air rate of 1 foot per second and a clear liquid height of 1 inch.

Results For 56% Free Area "Rigid mesh" Determined Using An Air-Water System In A 4" Diameter Column.

U = superficial air rate, (ft/sec.)

P = Pressure drop, (cms water gauge).

hc = Clear liquid height, (ins).

R = Ratio of froth height to clear liquid height.

U	Dry.	hc = 1"		hc = 2"		hc = 3"	
	P.	P.	R.	P.	R.	P.	R.
0.63	1.0	14.2	5.32	17.6	2.86	21.1	2.79
1.14	1.8	16.0	4.93	19.3	3.06	22.8	2.82
1.65	2.8	17.8	4.14	21.4	3.06	24.3	2.82
2.16	4.0	20.1	3.74	23.4	3.06	26.4	2.96
2.67	5.5	22.3	3.74	25.8	3.75	28.8	3.09
3.22	7.5	25.1	4.14	28.3	3.44	31.4	3.22
3.78	10.0	28.2	4.14	31.3	3.64	34.8	3.35
4.54	12.9	- Limit of Operation of Blower -					
4.92	16.0						
5.49	19.2						
6.10	22.8						
6.65	27.3						

The above pressure drop results are plotted in figure 3.5

APPENDIX A.3.2. PLASTIC FOAMS.

A.3.2.1. Plastic Foams Specification.

The plastic foams used were all polyurethane foams obtained from:

Declon Foam Plastics Ltd.,
Cranbourne Road,
Potters Bar, Middlesex.

The ones used were:

QUALITY	PORES PER LINEAL INCH	THICKNESS	VOIDAGE
Dec 9/10	10	1/2"	97%
Dec 9/30	30	"	"
Dec 9/45	45	"	"
Dec 9/60	60	"	"
Dec 9/100	100	"	"

A.3.2.2. Hydraulic Results of Plastic Foams Determined Using an Air-Water System in a 4" diameter Column.

Only the samples with 100 and 60 pores per inch performed as trays.

A list of nomenclature is given in Appendix A.3.1.3. The pressure drop results given below are plotted in figure 3.6

Sample with 60 pores per inch.

U	DRY.	hc = 1"		hc = 2"		hc = 3"	
	P.	P.	R.	P.	R.	P.	R.
0.17	0	4.6	1.97	6.6	1.38	8.5	1.71
0.85	0.05	5.3	2.67	6.8	1.97	8.7	1.71
1.69	0.15	5.4	3.14	6.9	2.36	8.9	2.1
2.54	0.25	5.5	3.54	6.9	2.76	9.0	2.5
3.38	0.35	5.7	3.94	7.2	2.96	9.3	2.96
4.23	0.45	5.9	4.34	7.4	3.64	9.6	3.15
5.07	0.65	6.1	4.73	7.7	3.57	9.9	3.42
5.92	0.8	6.2	5.52	7.9	3.94	-	-

100 ppi Sample

U	Dry	hc = 1"		hc = 2"		hc = 3"	
	P	P	R	P	R	P	R
0.17	0.2	6.2	1.97	8.1	1.38	10.5	1.31
0.85	0.2	7.6	3.94	9.3	2.36	11.1	1.97
1.69	0.5	8.2	3.54	9.9	2.54	11.9	2.1
2.54	0.8	8.8	3.94	10.6	2.76	12.5	2.46
3.38	1.0	9.2	3.94	11.1	2.96	12.9	2.62
4.23	1.6	9.4	3.94	11.5	3.35	-	-
5.07	1.8	9.8	4.34	11.8	3.35	-	-
5.92	2.2	10.3	5.12	-	-	-	-

APPENDIX A.3.3 GLASS CLOTHS.

A.3.3.1 Glass Cloth Specification.

All Glass Cloths used in this work were experimental glass cloths produced by;

British Belting & Asbestos Ltd.,
Cleckheaton,
Yorkshire.

Cloth Details			Yarn Details	
Ref.No.	Type	Nominal Geometry (per inch)	Type	yds/lbs.
AD225	woven	12 endsx6½ double picks	staple	2500
AD234	woven	12 endsx12½ picks	C.F.*	1250
AD921	woven	8 endsx9 picks	staple	750
150/1/2	knitted	8 needlesx17 stitches	taslaned	7500
150/2/2	"	8 " x17 "	"	3750

* continuous filament.

A.3.3.2 Hydraulic Results of glass cloths determined using on air-water system in a 4" diameter column.

The glass cloth made up from a continuous filament yarn, AD234, did not act as a bubble tray. The liquid was not held above the tray by the air flow.
A list of nomenclature is given in appendix A.3.1.3.

Woven glass cloth AD921.

U	Dry	hc = 1"		hc = 2"		hc = 3"	
	P	P	R	P	R	P	R
0.17	0.05	4.9	1.57	7.7	1.3	10.4	1.18
0.85	0.2	7.8	2.36	10.4	2.6	14.2	2.24
1.69	0.3	9.55	3.15	11.9	3.03	15.0	2.62
2.54	0.6	10.9	3.15	13.8	3.46	-	-
3.38	0.85	11.65	3.64	-	-	-	-
4.23	1.15	11.9	3.94	-	-	-	-
5.07	1.5	-	-	-	-	-	-
5.92	1.7	-	-	-	-	-	-

Woven glass cloth AD225.

0.17	0.05	4.8	1.18	7.1	1.38	9.5	1.29
0.85	0.1	6.5	2.36	8.4	2.17	11.2	2.16
1.69	0.3	7.35	2.76	9.7	2.46	12.05	2.29
2.54	0.45	8.2	3.14	10.5	2.96	13.0	2.58
3.38	0.55	8.7	3.74	11.1	3.46	-	-
4.23	0.7	9.35	3.94	11.6	3.46	-	-
5.07	0.85	9.7	4.33	-	-	-	-

Knitted Glass Cloth 150/1/2.

0.17	0.05	3.0	1.18	5.5	1.18	7.3	1.29
0.85	0.05	3.8	2.36	7.5	2.17	10.0	1.84
1.69	0.05	5.7	2.36	8.75	2.36	11.0	2.29
2.54	0.1	6.1	2.76	9.1	2.76	11.5	2.5
3.38	0.1	6.35	2.65	9.3	2.86	11.8	2.62
4.23	0.15	6.7	2.76	9.55	3.46	-	-
5.07	0.2	6.9	3.54	9.9	3.57	-	-
5.92	0.2	7.2	3.54	-	-	-	-

Knitted Cloth 150/2/2.

0.17	0.05	2.6	1.18	4.9	1.18	7.9	1.18
0.85	0.1	4.1	2.36	7.3	1.79	10.6	1.71
1.69	0.1	5.0	2.76	7.9	2.17	11.9	2.1
2.54	0.15	5.3	3.18	9.0	2.36	13.1	2.5
3.38	0.2	6.25	3.54	10.0	2.76	-	-
4.23	0.4	6.9	3.74	11.0	2.76	-	-
5.07	0.7	7.5	3.94	-	-	-	-
5.92	0.9	8.2	4.34	-	-	-	-

The above pressure drop results are plotted in figures 3.7 and 3.8.

APPENDIX A.3.4 EXTENDED HYDRAULIC RESULTS.

The following results were determined using an air-water system in a 3" diameter column.

A list of the nomenclature used is given in Appendix A.3.1.3. The pressure drop results given below are plotted in figures 3.10 and 3.11.

Woven Glass Cloth AD225.

U	Dry	hc = 1"		hc = 2"		hc = 3"	
	P	P	R	P	R	P	R
1.7	0.3	7.1	4.73	9.7	3.15	12.0	2.89
3.4	0.55	8.6	4.73	11.1	3.5	13.4	2.89
5.1	0.85	9.6	4.73	12.0	3.74	14.2	3.15
6.8	1.15	10.0	5.5	12.8	4.33	-	-
8.5	1.5	10.9	6.3	-	-	-	-
10.2	1.9	11.2	7.1	-	-	-	-
11.9	2.3	-	-	-	-	-	-

Plastic Foam 60 ppi.

1.7	0.1	4.7	2.36	6.9	2.36	9.3	1.97
3.4	0.4	5.5	3.94	7.5	2.76	10.0	2.36
5.1	0.7	5.9	4.73	8.0	3.14	10.6	3.28
6.8	1.1	6.5	4.73	8.7	3.34	11.4	3.94
8.5	1.8	7.1	5.55	9.2	4.33	11.9	3.94
10.2	2.2	7.4	5.91	9.5	4.92	-	-
11.9	2.8	8.3	6.70	-	-	-	-

APPENDIX 3.5 RESILIENCE OF GLASS CLOTHS.

At first sight glass cloths would seem to be rather fragile both with regard to the yarns and fibres from which they are made and from the appearance of the cloth as a whole. It was, therefore, decided to test a sample of glass cloth to destruction to find its life under vapour-liquid contacting conditions.

A.3.5.1 Apparatus.

The four inch diameter column was remodified, as shown in figure A.3.1 so that it could be operated continuously. To make up for entrainment and evaporation losses, water had to be fed to the tray. Also to ensure that the froth height in the column was approximately constant excess water was used and an overflow, through a side arm in the column was provided to run the excess to waste. A disc of 30 pores per inch plastic foam was fastened in the column about one foot above the froth to prevent excessive loss by entrainment.

A.3.5.2 Procedure.

A sample of woven glass cloth AD225 with a flattened expanded metal grid No. FE3404 on the top only, was fastened in the column and the air and water supplies started. The air velocity and water flow rate were checked and adjusted regularly.

One yarn intersection was marked using two lengths of

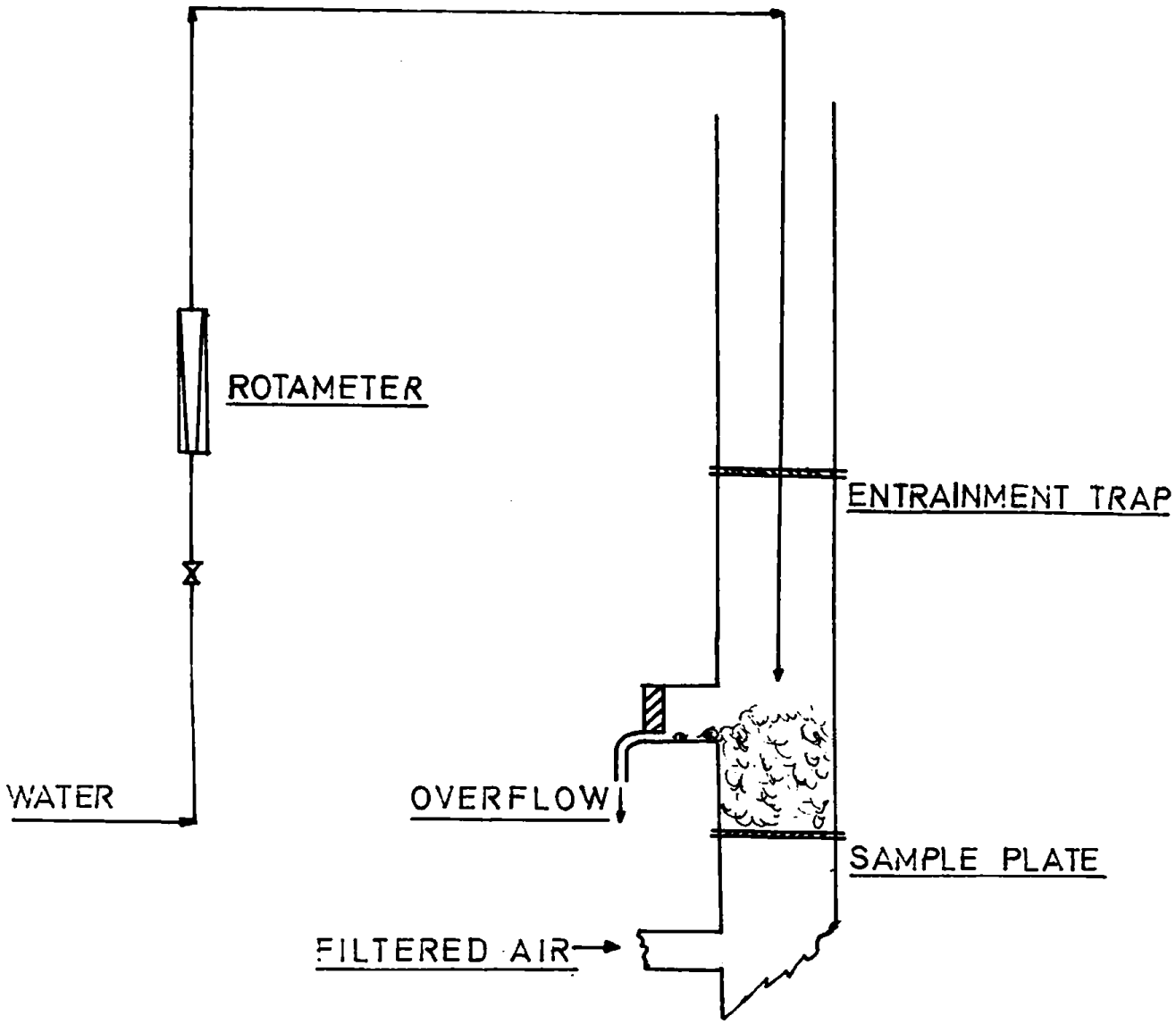


FIG. A3·1

DIAGRAM OF SMALL SCALE RIG ADAPTED FOR USE IN RESILIENCE TEST ON GLASS CLOTHS

black cotton threaded at right angles to each other through the glass cloth. This intersection was photographed initially and every thousand hours afterwards. The photographs were taken at a magnification of approximately twelve times to show the general area of this yarn intersection in the cloth.

A.3.5.3. Results.

At the time of writing the cloth had been in almost continuous operation for more than 8000 hours without any major sign of damage. Photographs of its condition at various times can be seen in figure A.3.2. The only detrimental effect was produced by the corrosion of the retaining grid. The fine rust particles seemed to grow from the grid and to lodge in the cloth.

In conclusion, therefore, it has been shown that glass cloths can be used as tray floors for, at least, an adequate length of time in vapour-liquid contacting conditions without failure.

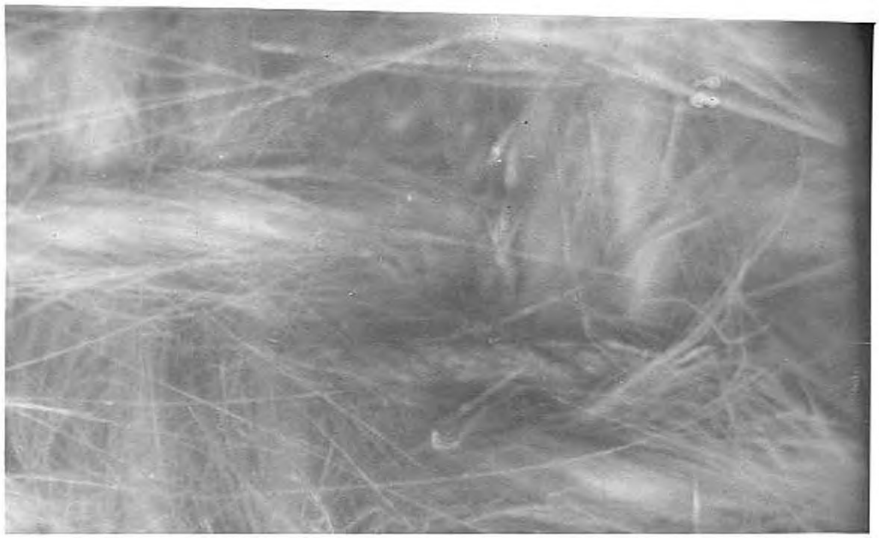
FIGURE A3.2

PHOTOGRAPHS OF GLASS CLOTH AD225 DURING RESILIENCE TEST. (Magnification X12)

a) Initially

b) After 4000 hours

c) After 8000 hours



APPENDIX TO SECTION 4.

APPENDIX A.4.1 CALIBRATION OF VENTURI FOR AIR FLOW.

The venturi was designed to give a maximum pressure differential of 30 cms. of water gauge. Its dimensions are given in figure A.4.1a.

The calibration was carried out according to method 1 of British Standard 1042 (1943) using pitot tubes. Sixteen readings were taken at given points in the duct for each air flow rate. Figure A4.1b gives the location of the test points.

The square root of the average velocity head for each air rate was obtained by averaging the square roots of the individual velocity heads. The average velocity was calculated from the following equation:-

$$U_D = 18.29 \sqrt{\frac{h}{d_v}}$$

where U_D = average velocity in the duct (ft/sec)

h = average velocity head (inches of water gauges)

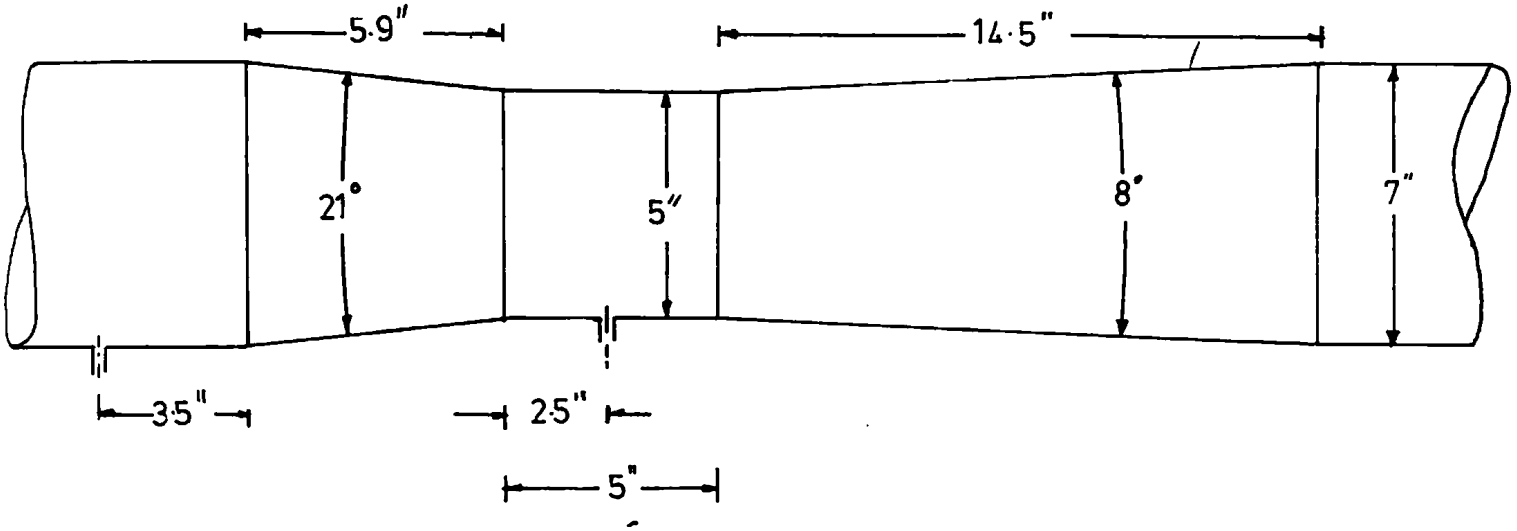
d_v = air density (lbs/cu.ft.)

The air velocity through the tray bubbling area was calculated by compensating for the change in flow area.

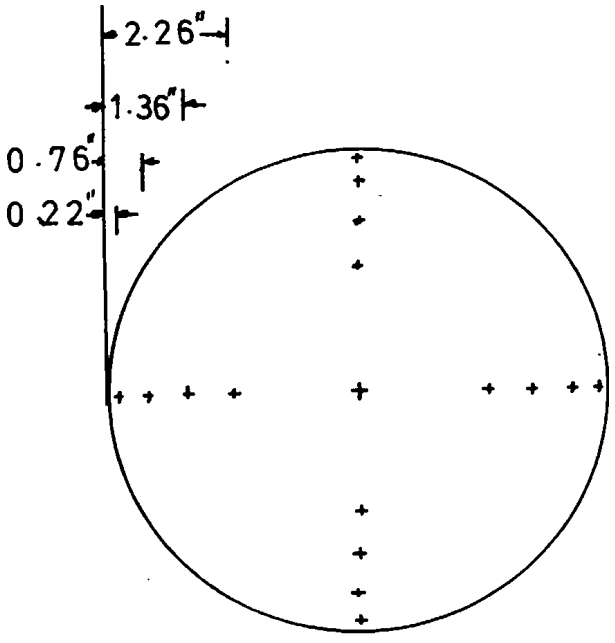
U = superficial air velocity through the tray (ft/sec)

$= 0.199 \times U_D$

h	u	h	u
8.97	4.63	3.91	3.29
7.68	4.34	3.19	3.04
6.34	4.1	1.62	2.06
5.18	3.73		



a) DIMENSION OF VENTURI



b) PITOT TUBE TEST POINTS FOR VENTURI CALIBRATION. FIG. A4·1.

APPENDIX A.4.2. CALIBRATION OF ORIFICE FOR WATER FLOW.

The water flow was measured by means of a 1.678" diameter orifice plate inserted in the straight length of the 2" B.S.P. pipe from the circulating pump to the tray inlet weir. The calibration was carried out by collecting the weighing the water flowing through the orifice at a given pressure drop. The results obtained are given below:-

h = head difference across orifice plate (cms water gauge)

L = water flow rate (gallons/minute/ft. weir width)

h	L	h	L
1.7	9.89	18.5	30.9
2.65	12.46	25.3	36.23
3.3	14.45	32.8	41.12
5.9	17.75	41.2	45.9
12.5	25.48	50.1	50.51

APPENDIX A.4.3 LARGE SCALE TRAY HYDRAULIC RESULTS.

The results were obtained using an upper retaining grid of flattened expanded metal No. FE.3404.

In the results given below the following nomenclature is used:-

U = superficial air rate through tray (ft/sec)
P = tray pressure drop (cms. water gauge)
h_f = average froth weight (cms)
hc = average clear liquid height (cms)

A.4.3.1 60 p.p.i. Plastic Foam.

U	P	h_f	hc	U	P	h_f	hc
Dry Plate							
1.0	0.1	-	-	3.54	0.5	-	-
1.7	0.15	-	-	4.05	0.6	-	-
2.0	0.2	-	-	4.55	0.8	-	-
2.51	0.3	-	-	5.08	0.9	-	-
3.2	0.4	-	-	5.55	1.1	-	-
1" Outlet Weir Height							
10 galls./min/ft.				20 galls./min./ft.			
1.0	5.1	9	3.6	1.0	6.2	12	3.8
2.0	6.0	10	3.5	2.0	6.7	12	3.7
3.0	6.5	12	3.5	3.0	7.0	14	3.7
4.0	6.7	12	3.6	4.0	7.5	15	3.75
5.0	6.9	14	3.7	5.0	7.6	16	3.8
40 gallons/min/ft.							
1.0	6.9	10	4.5	4.0	8.2	16	4.35
2.0	7.6	14	4.4	5.0	8.5	19	4.3
3.0	7.9	14	4.3				

$2\frac{1}{2}$" Outlet Weir Height.

10 galls./min./ft.				20 galls/min./ft.			
1.5	8.0	14	4.8	1.5	8.6	18	5.6
2.0	8.2	15	4.8	2.0	8.9	19	5.4
3.0	8.3	20	4.7	3.0	9.5	25	5.1
4.0	8.5	20	4.7	4.0	9.7	25	5.05
5.0	8.7	20	4.6	5.0	10.2	25	5.1
$2\frac{1}{2}$" Outlet Weir Height.							
40 gallons/minute/ft.							
1.5	9.6	15	6.2	4.0	10.9	22	5.5
2.0	10.0	15	6.1	5.0	11.8	26	5.5
3.0	10.4	20	5.7				

The above results are plotted in figure 4.6 whilst the following results are plotted in figure 4.7.

A.4.3.2. Woven Glass Cloth AD225

U	P	hf	hc	U	P	hf	hc
Dry Plate							
1.0	0.05	-	-	4.0	0.4	-	-
2.0	0.15	-	-	5.0	0.5	-	-
3.0	0.3	-	-			-	-
1" Outlet Weir Height.							
10 galls/min/ft.				20 galls/min/ft.			
1.0	9.5	13	2.06	1.0	10.3	15	2.53
2.0	10.7	11	2.25	2.0	11.3	13	2.83
3.0	12.2	12	2.45	3.0	12.7	13	3.0
4,0	13.2	12	2.57	4.0	13.6	14	3.13
5.0	13.7	14	2.55	5.0	14.5	15	2.97
30 galls/min/ft.				40 galls/min/ft.			
1.0	10.7	17	3.13	1.0	11.2	17	3.53
2.0	12.0	15	3.29	2.0	12.2	15	3.7
3.0	13.1	15	3.37	3.0	13.3	15	3.9
4.0	14.0	16	3.41	4.0	14.6	16	4.0
5.0	14.8	18	3.41	5.0	15.1	18	3.8

$2\frac{1}{2}$" Outlet Weir Height.

10 galls/min/ft				20 galls/min/ft.			
1.0	10.7	15	2.43	1.0	11.0	18	3.73
2.0	12.2	15	3.28	2.0	12.6	18	4.24
3.0	13.3	17	3.77	3.0	13.8	18	4.52
4.0	14.5	18	3.77	4.0	14.7	19	4.45
5.0	15.4	18	3.72	5.0	15.7	21	4.37
30 galls/min/ft				40 galls/min/ft.			
1.0	12.4	19	4.73	1.0	13.0	21	5.16
2.0	13.7	19	5.06	2.0	14.2	21	5.52
3.0	15.0	20	5.12	3.0	15.3	23	5.64
4.0	15.6	22	4.97	4.0	15.8	23	5.40
5.0	16.0	23	4.90	5.0	16.5	25	5.24
4" Outlet Weir Height.							
10 galls/min/ft				20 galls/min/ft.			
1.0	10.7	19	2.4	1.0	12.8	21	3.73
2.0	14.3	19	4.7	2.0	15.7	21	5.20
3.0	15.7	19	4.2	3.0	16.8	22	5.13
4.0	16.9	19	4.1	4.0	17.6	23	4.87
5.0	17.6	20	4.0	5.0	18.3	24	4.7
30 galls/min/ft.				40 galls/min/ft.			
1.0	13.3	23	5.03	1.0	14.6	24	6.37
2.0	16.4	22	6.07	2.0	17.2	24	6.77
3.0	17.4	23	5.87	3.0	18.1	25	6.4
4.0	18.3	24	5.63	4.0	18.8	26	6.3
4.5	18.8	26	5.43	4.5	19.3	27	5.97

APPENDIX A.4.4. DERIVATION OF THE BACKMIXING EQUATIONS.

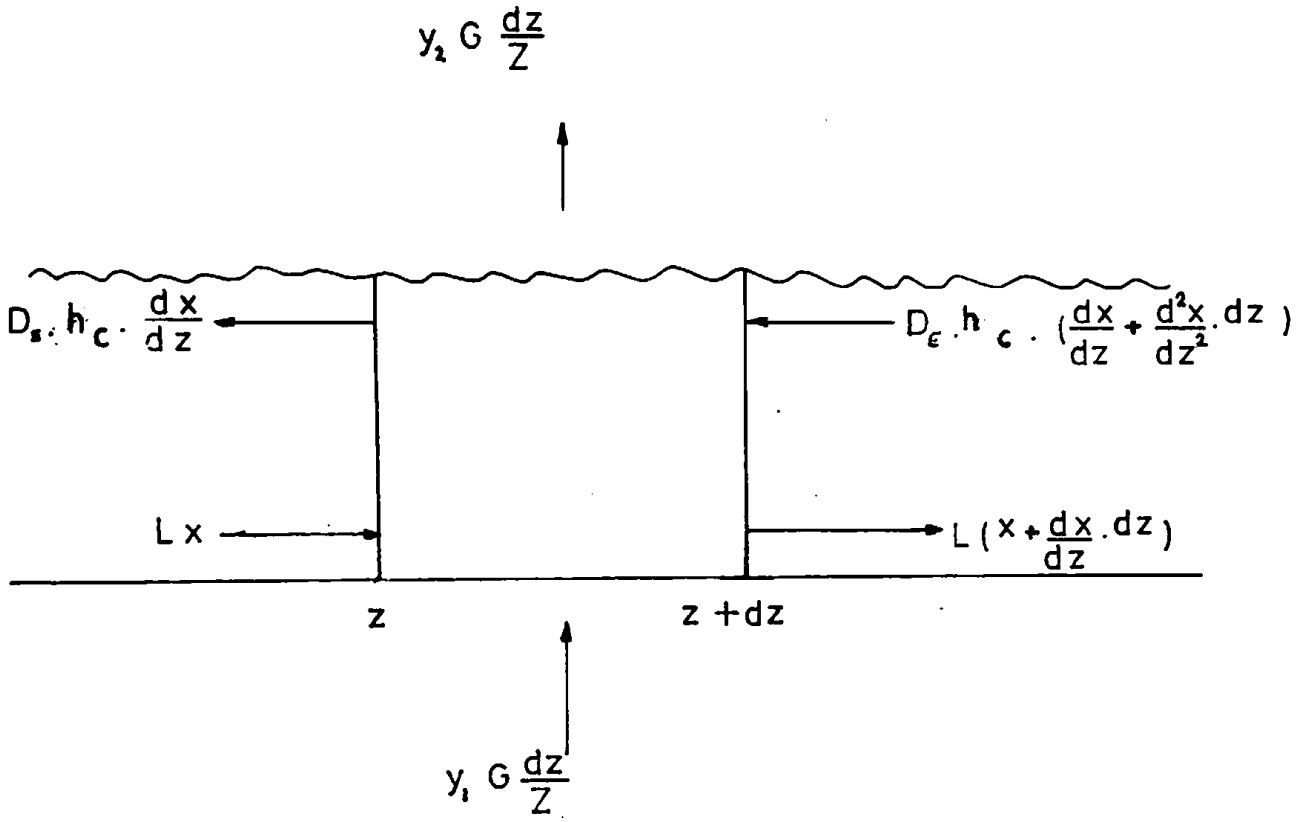
The model chosen depends on the eddy diffusion concept in which the rate of mixing of a component is proportional to the concentration gradient of that component. The basic equation for this model is derived by considering a component mass balance about an incremental vertical slice, dz thick and of unit width, in the aerated liquid. The streams for the mass balance are shown in figure A.4.2 and the nomenclature is as follows:-

z	=	distance from the inlet weir.
Z	=	total distance of aerated liquid path.
hc	=	clear liquid height equivalent of the aerated liquid.
L	=	volumetric liquid flow rate across tray.
x	=	component concentration at point z in the liquid.
G	=	volumetric gas flow rate.
y_1	=	component concentration in the gas stream entering tray 1.
DE	=	eddy diffusion coefficient.

In passing through the slice the amount of component in the gas stream will change due to mass transfer with the liquid phase. The amount of component lost by the gas stream to the slice is given by:-

$$G.(y_1 - y_2)\frac{dz}{Z}$$

In the liquid the component concentration will change both with the bulk liquid flow and against it due to eddy flow.



EDDY DIFFUSION MODEL FIG. A4·2

The component flow into the slice due to:-

$$\text{Eddy flow} = D_E \cdot h_c \cdot \frac{d^2x}{dz^2} \cdot dz$$

$$\text{Bulk flow} = -L \cdot \frac{dx}{dz} \cdot dz$$

Now to steady state the net accumulation in the slice is zero.

$$\therefore D_E \cdot h_c \cdot \frac{d^2x}{dz^2} \cdot dz - L \frac{dx}{dz} \cdot dz + \frac{G}{Z} \cdot (y_1 - y_2) \cdot dz = 0$$

and simplying by dividing by L.dz and letting $z/Z = r$ we get:-

$$\frac{D_E \cdot h_c}{L \cdot Z} \cdot \frac{d^2x}{dr^2} \cdot dz - \frac{dx}{dr} + \frac{G}{Z} (y_1 - y_2) = 0$$

If there is no mass transfer, $y_1 = y_2$. Also the Peclet number, Pe, is the ratio of the tray length, Z, to the mixing length, $D_E \cdot h_c / L$

$$\therefore \frac{1}{Pe} \cdot \frac{d^2x}{dr^2} - \frac{dx}{dr} = 0$$

Therefore, considering the continuous injection of a non-volatile tracer near the outlet weir, then its concentration at any point between the injector and the inlet weir will be given by the solution of the above equation.

The equation solves by substitution;

$$\ln \frac{dx}{dr} = Pe \cdot r + c_1$$

Now if no tracer reaches the inlet weir then the concentration gradient will be zero at that point.

$$\text{ie.} \quad \frac{dx}{dr} = 0 \quad \text{when} \quad r = 0 \qquad \therefore \frac{dx}{dr} = \exp(Pe \cdot r)$$

Solving the above equation with the limits when r=o;x=xo, we get:- $x - xo = \frac{1}{Pe} (\exp. (Pe \cdot r) - 1)$

now, when $Pe \gg 1$, $\exp(Pe \cdot r) \ggg 1$ if r is not in the region of zero.

$$\therefore \quad x - x_0 \simeq \frac{1}{Pe} \cdot \exp(Pe.r)$$

Therefore, plotting the corrected concentration against the fractional distance from the inlet weir, r, on semilogarithmic axes a straight line will be obtained.

Further considering the particular solutions of the equation at points 1 & 2 on the line where $x = x_1, x_2$ & $r = r_1, r_2$.

$$\therefore \quad \ln(Pe(x_1 - x_0)) \simeq Pe.r_1$$

subtracting

$$\ln(Pe(x_2 - x_0)) \simeq Pe.r_2$$

$$\ln\left(\frac{x_1 - x_0}{x_2 - x_0}\right) \simeq Pe(r_1 - r_2)$$

$$\therefore \quad Pe = \frac{1}{(r_1 - r_2)} \cdot \ln\left(\frac{x_1 - x_0}{x_2 - x_0}\right)$$

Now the right hand side of the above equation is the gradient of the line between points 1 & 2 on the above semilogarithmic plot. The Peclet number can, therefore, be determined when the graph has been found experimentally.

APPENDIX A.4.5 CALIBRATION OF THE CONDUCTIVITY BRIDGE.

Sample solutions were prepared by adding a weighed quantity of salt to mains water and then making up to 1000 ccs. As the electrical conductivity of solutions varies appreciably with temperature, the samples were allowed to reach thermal equilibrium immersed in a 25°C constant temperature bath.

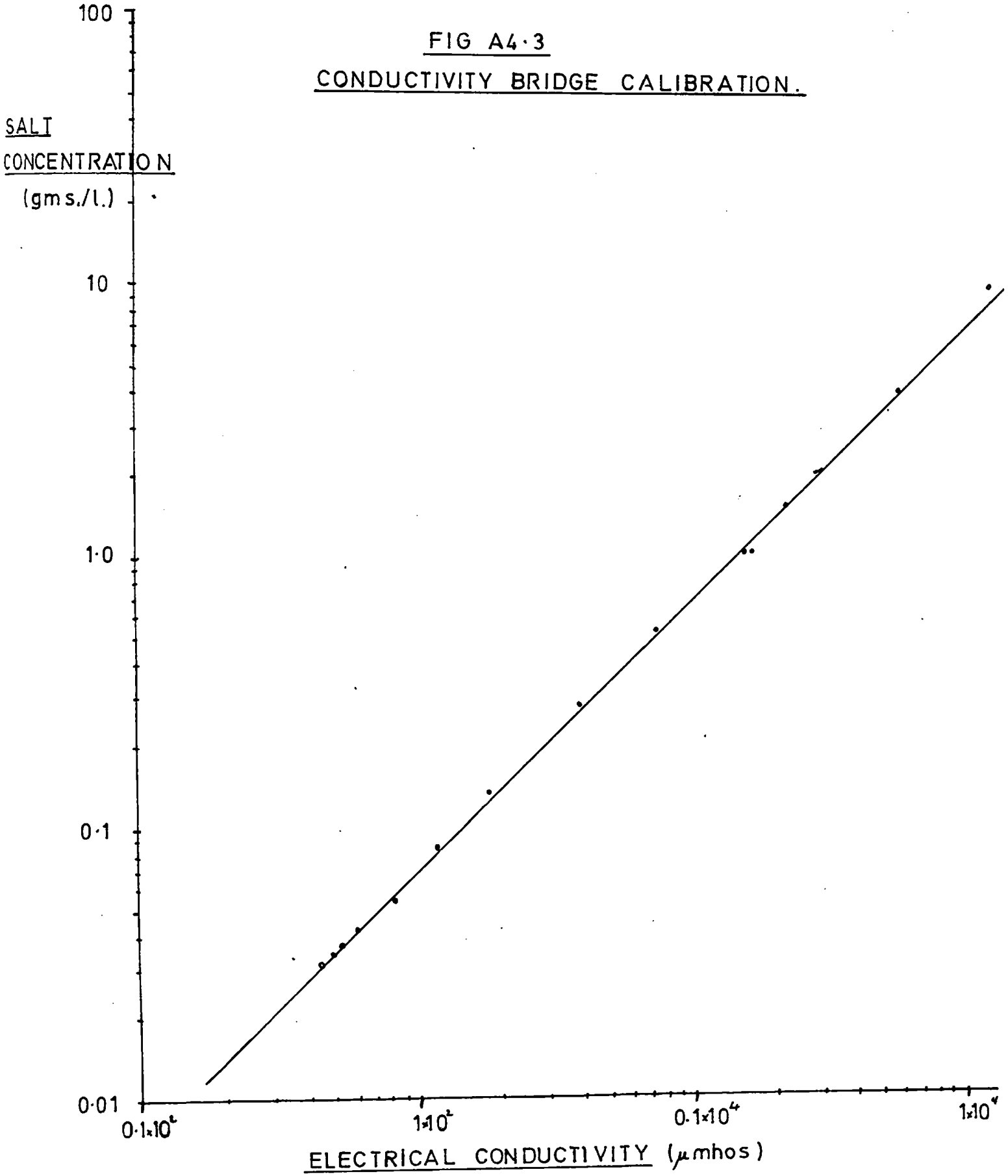
The specific electrical conductivity of each sample was then measured using a Mullard A.C. Bridge with a specific conductivity cell, (type E7591/A).

The results were plotted on linear axes and the zero conductivity found to be 0.0332 gms/litre by extrapolation. The corrected results were replotted on logarithmic axes to give a more compact straight line plot as shown in figure A.4.3.

Added Salt Conc^{n} (gms/litre)	Actual Salt Conc^{n} (gms/litre)	Conductivity (mhos x 10^{-6})
0	0.0332	0.45 x 10^{2}
0.0025	0.0357	0.49 x 10^{2}
0.005	0.0382	0.53 x 10^{2}
0.01	0.0432	0.60 x 10^{2}
0.025	0.0582	0.81 x 10^{2}
0.05	0.0832	1.18 x 10^{2}
0.1	0.133	1.8 x 10^{2}
0.25	0.283	3.9 x 10^{2}
0.5	0.533	7.2 x 10^{2}
1.0	1.03	0.165 x 10^{4}
2.0	2.03	0.218 x 10^{4}
4.0	4.03	0.53 x 10^{4}
10.0	10.03	1.2 x 10^{4}

FIG A4·3

CONDUCTIVITY BRIDGE CALIBRATION.



APPENDIX A.4.6 SAMPLE CALCULATION OF LIQUID MIXING RESULTS.

Consider Run No. AD225/2½"/30/2 which is the run using;

a) woven glass cloth AD225 as the tray floor
b) a 2½" high outlet weir
c) a liquid flow rate of 30 gallons/minute/ft. width of weir.
and d) an air flow rate of 2 feet per second.

A list of nomenclature is given in Appendix A.4.4.
The results obtained were:-

Z (ins)	Conductivity (mhosx10^{-6})	x (gms/litre)	x-xo (gms/litre)
Inlet weir	0.47×10^2	0.033	-
36	0.51×10^2	0.036	0.003
46	0.53×10^2	0.037	0.004
47	0.55×10^2	0.038	0.005
48	0.65×10^2	0.046	0.010
49	2.05×10^2	0.104	0.068
50	8.0×10^2	0.56	0.527
51	0.33×10^4	2.3	2.27
53	0.31×10^4	2.1	2.07
55	0.26×10^4	1.8	1.77

The injector was positioned 51" from the inlet weir. The conductivity readings were converted into salt concentrations using figure A.4.3. and then corrected by subtracting the inlet salt concentration.

Now from Appendix A.4.4 the Peclet number can be found from the gradient of the curve obtained by plotting the corrected concentration, x - xo, against the fractional distance from the inlet weir, r, as given below;

$$Pe = \frac{1}{r_1 - r_2} \cdot \ln \left(\frac{x_1 - x_o}{x_2 - x_o} \right)$$

However, as r = z/Z it is much more convenient to use distances from the inlet weir, z, as these correspond to sample point positions and are thus whole numbers. The

values of r tend to involve fractions which make their repeated calculation and application tedious. Using the absolute distances, therefore, the Peclet number is found from the equation below:-

$$Pe = \frac{Z}{(z_1 - z_2)} \cdot \ln\left(\frac{x_1 - x_0}{x_2 - x_0}\right)$$
$$= Z \text{ (gradient)}$$

Therefore, plotting the above results on semilogarithmic coordinates as shown in figure A.4.4 the gradient of the straight line and thus the peclet number for the above conditions can be obtained. Considering the points A(1.0,50.54) and B(0.01,47.9) the slope of the line is given by:-

$$\text{gradient} = \ln\left(\frac{1.0}{0.01}\right) \times \frac{1}{(50.54 - 47.9)} = 1.805$$

Now as Z = 72"

and Pe = Z (gradient)

$\therefore$ $\underline{Pe = 130}$

Also from Appendix A.4.4.

$$DE = \frac{L.Z.}{Pe.hc}$$

and L = 30 gallons per minute per foot of weir width.

$$= \frac{30}{6.25} \times \frac{1}{60} \quad \text{sq.ft./sec.}$$

$Z = 72" = 6$ ft.

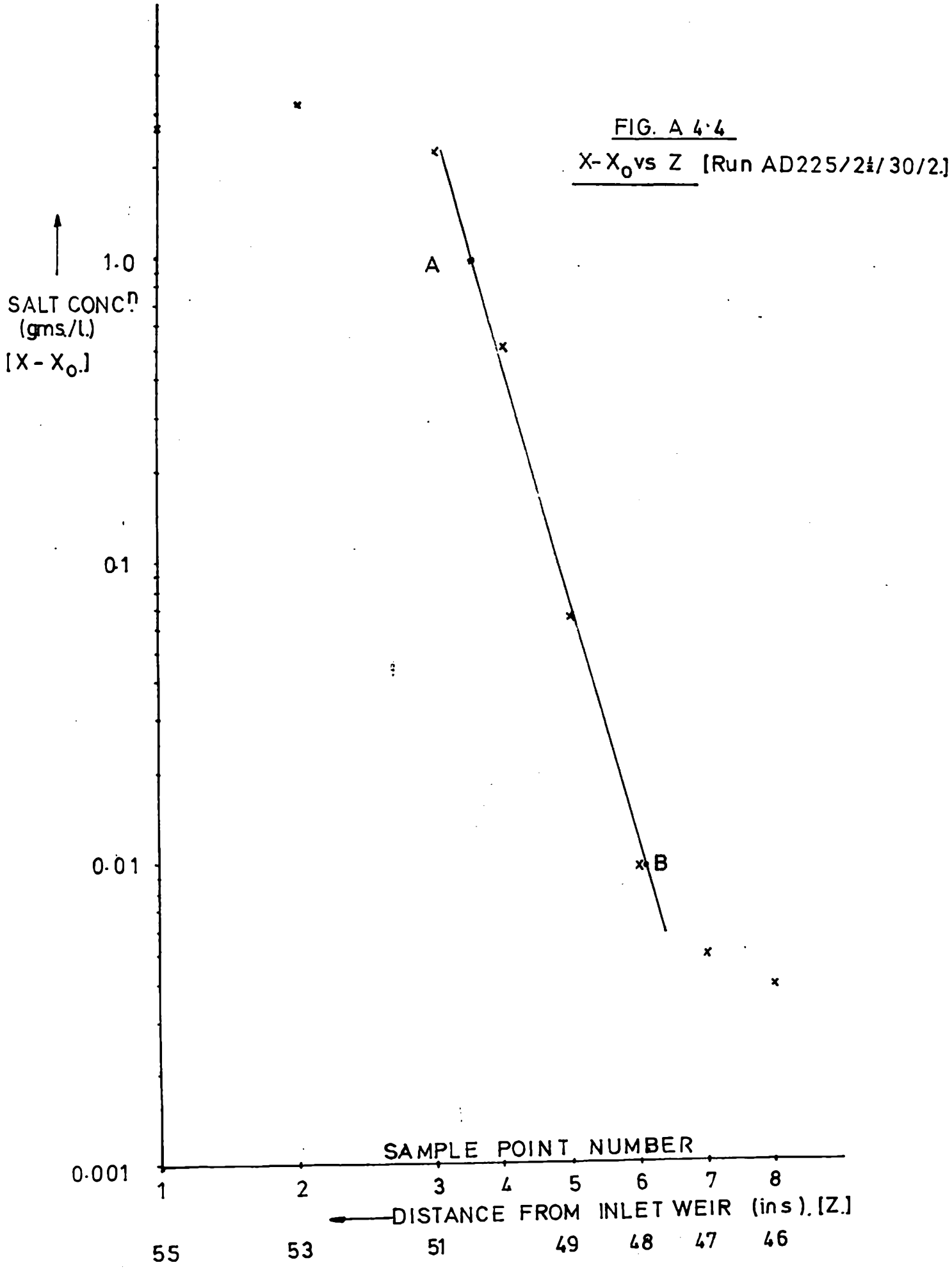
$hc = 5.06$ cms $= \frac{5.06}{2.54} \times \frac{1}{12}$ ft. (from fig. 4.7)

$$DE = \frac{30}{6.25} \times \frac{1}{60} \times \frac{6}{130} \times \frac{2.54}{5.06} \times 12$$

$\underline{DE = 0.0222 \text{ ft}^2/\text{sec}.}$

FIG. A 4·4

$X - X_0$ vs Z [Run AD225/2½/30/2.]



APPENDIX A.4.7. LIQUID MIXING RESULTS.

The results given below were obtained using woven glass cloth AD225 with a flattened expanded metal No. FE.3404 upper retaining grid and were evaluated from the experimental results as shown in Appendix A.4.6.

The nomenclature is given below:-

U = Superficial air rate through tray (ft/sec)
L = Water flow rate (gallons/minute/foot width of weir)
Pe = Peclet number (dimensionless)
D_E = Eddy diffusion coefficient (ft^2/sec.)

U	Pe	DE	Pe	DE	Pe	DE	Pe	De
	L = 10		L = 20		L = 30		L = 40	
1" Outlet Weir Height								
2.0	159	0.0136	236	0.0143	293	0.0152	312	0.0168
3.0	129	0.0156	204	0.0159	241	0.0180	256	0.0197
4.0	110	0.0173	162	0.0193	184	0.0231	196	0.0249
5.0	93	0.0205	137	0.0239	149	0.0289	164	0.0313
2½" Outlet Weir Height								
1.0	125	0.0160	143	0.0172	151	0.0204	162	0.0234
2.0	82.8	0.0180	118	0.0196	130	0.0222	135	0.0261
3.0	53.5	0.0242	83	0.0259	107	0.0267	109	0.0318
4.0	41.4	0.0312	67.6	0.0323	87.1	0.0338	94.7	0.0381
5.0	32.6	0.0399	53.4	0.0419	68.5	0.0435	76.0	0.0490

The above results are plotted in figure 4.10.

APPENDIX TO SECTION 5.

APPENDIX A.5.1. CONDENSER COOLING WATER CALIBRATION.

The two condenser cooling water orifice plates were calibrated by weighing the amount of water flowing in a given time at a given pressure difference. The readings are given below and in figure A5.1.

h = height difference on carbon tetra chloride manometer. (cms. C.T.C.)

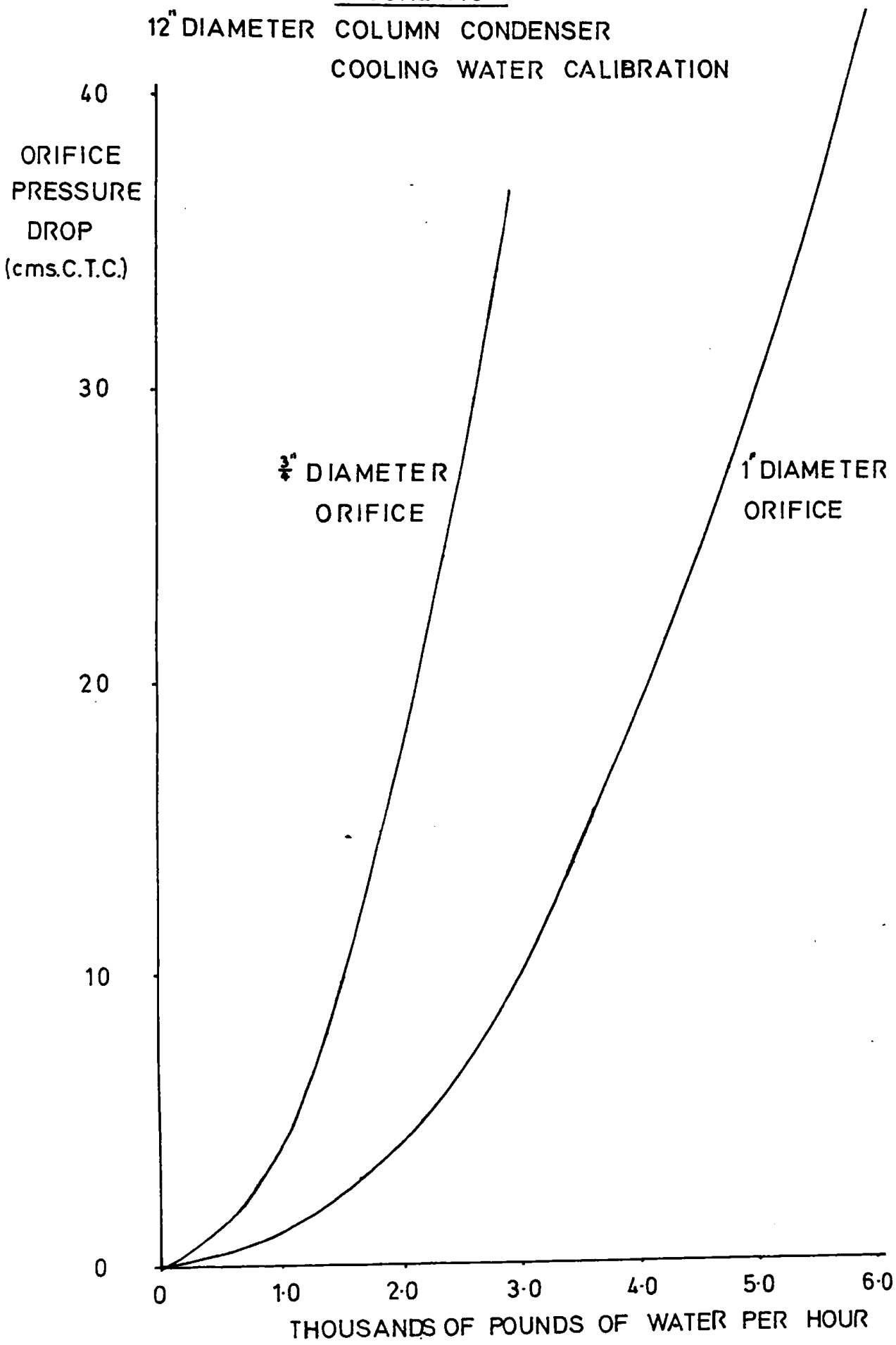
W = water flow rate (lb/hr.)

h.	W.	h.	W.
3/4" Diameter Orifice Plate.			
9.7	1490	43.2	3122
9.7	1490	51.7	3400
18.4	2043	51.7	3414
18.3	2043	24.6	2364
33.0	2776	24.3	2376
36.0	2799	34.1	2811
37.0	2876	33.9	2793
57.9	3648	5.1	1088
58.9	3616	5.2	1087
57.9	3656	15.1	1863
29.7	2591	14.9	1857
29.5	2586	2.0	675
43.0	3078	2.0	673
1" Diameter Orifice Plate.			
21.5	4260	14.0	3380
21.5	4260	13.5	3370
8.5	2560	27.5	4760
8.2	2550	27.5	4760
36.0	5350	3.0	1640
36.0	5350	3.0	1640
41.8	5830	5.0	2160
41.8	5830	5.0	2160
1.0	927	1.0	924

FIGURE A5·1

12" DIAMETER COLUMN CONDENSER

COOLING WATER CALIBRATION



APPENDIX A.5.2 COMPONENT AND SYSTEMS PHYSICAL PROPERTIES AND EQUILIBRIUM DATA.

A.5.2.1. Selected Physical Properties.

PHYSICAL PROPERTY	H	30% H/T	T	45% T/M	M
Molecular Weight	100.2(a)	97.78	92.13(a)	94.82	98.18(a)
Boiling Pt. (°C at 760 mm Hg)	98.4(a)	102.1	110.7(a)	106.3	100.9(a)
Latent Heat of Evap.(BTU/lb)	156.9(b)	163.1	177.4(b)	167.3	154.9(b)
Liquid Density (gm/cc at 25°C)	0.684(a)	0.738	0.863(a)	0.819	0.765(a)
Surface Tension at B.pt. (dynes/cm)	12.0(d)	13.95	18.5(d)	16.93	15.0(d)
Refractive Index at 25°C.	1.3851(e)	-	1.4940(e)	-	1.4206(c)

where H = n Heptane, T = Toluene, M = Methyl cyclo hexane and 30% H/T = 30% n Heptane and 70% Toluene.

a. "Perry's Chemical Engineers Handbook" 3rd Ed. McGraw Hill N.Y. (1963) P.P. 129 - 148.

b. Ibid P. 210 - 218.

c. A.P.I. Project 44 (1953)

d. F.J. Zuiderweg & A. Harems CES 9 89 (1958)

e. R.T.N. Hall & F.H. Garner. J. Inst. Pet. 41 21 (1955)

A.5.2.2. Equilibrium Data.

a. Normal-Heptane/Toluene System.

The equilibrium data for the system n heptane-toluene used in the present study was that used by Zuiderweg et.al. in their work on tray comparison (6).

The actual values of the data used were obtained by private communication.

x = mole fraction of n heptane in liquid.

y = " " " " " vapour.

x.	y.	x.	y.	x.	y.
0.00	0.00	0.20	0.295	0.70	0.749
0.02	0.0369	0.30	0.403	0.80	0.830
0.05	0.0884	0.40	0.498	0.90	0.913
0.10	0.1652	0.50	0.585	0.95	0.956
0.15	0.233	0.60	0.668	1.00	1.00

b. Methyl-cyclo Hexane/Toluene System.

The system methyl-cyclo hexane/toluene had been used by Contractor R (1959) (236), Rustin A (1961) (235) and Edgley J.S. (1967) (234) in the Department. The equilibrium data used by these workers was therefore used in the present study.

x = mole fraction methyl-cyclo hexane in the liquid

y = " " " " " " vapour

x.	y.	x.	y.	x.	y.
0.00	0.00	0.34	0.4175	0.68	0.718
0.02	0.0285	0.36	0.4375	0.70	0.736
0.04	0.0585	0.38	0.4565	0.72	0.752
0.06	0.089	0.40	0.476	0.74	0.769
0.08	0.118	0.42	0.495	0.76	0.786
0.10	0.145	0.44	0.513	0.78	0.803
0.12	0.177	0.46	0.5305	0.80	0.820
0.14	0.197	0.48	0.5475	0.82	0.837
0.16	0.2225	0.50	0.5655	0.84	0.854
0.18	0.247	0.52	0.5825	0.86	0.871
0.20	0.271	0.54	0.599	0.88	0.899
0.22	0.293	0.56	0.6165	0.90	0.907
0.24	0.315	0.58	0.6335	0.92	0.925
0.26	0.336	0.60	0.651	0.94	0.944
0.28	0.3565	0.62	0.668	0.96	0.963
0.30	0.3775	0.64	0.685	0.98	0.9815
0.32	0.399	0.66	0.701	1.00	1.00

A.5.2.3. Refractive Index Calibrations.

a. n Heptane/Toluene.

The following results were obtained by determination of the refractive index of a gravimetrically prepared sample of the mixture.

x = mole fraction of n Heptane in liquid.

R.I. = Refractive index of liquid mixture at 25°C.

x	R.I.	x.	R.I.	x.	R.I.
0.00	1.4937	0.3140	1.4500	0.6960	1.4098
0.05035	1.4858	0.3903	1.4410	0.7567	1.4048
0.09132	1.4797	0.4074	1.4392	0.8042	1.4007
0.1144	1.4763	0.4566	1.4338	0.8686	1.3952
0.1709	1.4683	0.5216	1.4265	0.9390	1.3898
0.2154	1.4627	0.5790	1.4212	1.00	1.3848
0.2414	1.4591	0.6380	1.4150		

b. Methyl-Cyclo Hexane/Toluene.

The following results were those used by Contracter R (236), RustinA(235) and Edgley J.S.

x = mole fraction of methyl-cyclo hexane in the liquid

R.I. = Refractive index of the liquid mixture at 25°C.

x	R.I.	x.	R.I.	x.	R.I.
0.068	1.490	0.383	1.466	0.723	1.442
0.117	1.486	0.437	1.462	0.784	1.438
0.167	1.482	0.494	1.458	0.845	1.434
0.219	1.478	0.550	1.454	0.908	1.430
0.273	1.474	0.608	1.450	0.969	1.426
0.327	1.470	0.666	1.446		

APPENDIX A.5.3. SAMPLE CALCULATION OF RESULTS, FROM THE ACTUAL DISTILLATION STUDIES.

Consider Run No. AD.225/T.H/2"/9/2 which is the run using:

a. woven glass cloth AD.225 as the tray floor

b. the system toluene - n heptane

c. a 2" high outlet weir

d. the reboiler steam pressure controller set at 9 p.s.i.g.

e. the above conditions for the second time.

The results obtained were:

Condenser cooling water temperature (^{o}F); in 60^{o}; out 150^{o}

Condenser cooling water flow rate = 19.4 cms. C.T.C. across a 3/4" orifice plate.

Reboiler steam pressure = 7.8 p.s.i.g.

Reboiler condensate rate = 12.35 lb. in 4 minutes.

Average tray pressure drop = 4.57 cms. W.G.

The average refractive index of the liquid samples were:

1; 1.4448
2; 1.4525
3; 1.4592

at 25^{o}C.

A.5.3.1. Heat Balance on the Apparatus.

i. Heat input Reboiler (shell-side)

Now assuming that all the steam is saturated and looses only its latent heat of evapouration, the heat lost by the steam will be given by:

Condensate collected = 12.35 lb. in 4 minutes.

Steam pressure in reboiler shell = 7.8 p.s.i.g.

From Callendar's steam tables (237) the latest heat of evaporation under the above conditions = 956.2 BTU/lbs.

Total heat input to apparatus

$$= 956.2 \times \frac{12.35}{4} \times 60 = 177{,}000 \text{ BTU/Hr.}$$

ii) Heat Output Condenser (tube side)

The water flow rate from the condenser is found from figure A5.1. For a $\frac{3}{4}$" diameter orifice plate a pressure drop of 19.4 cms C.T.C. ≡ 2100 lbs/hr.

The water inlet and outlet temperature difference

$= 150 - 60 = 90^{\circ}F$

Heat output from condenser = 90 x 2100

= 189,000 BTU/hr.

Heat Balance inaccuracy

$$= \left(\frac{189{,}000 - 177{,}000}{189{,}000 + 177{,}000}\right) \times \frac{1}{2} = 6.7\%$$

A.5.3.2. Vapour Flow Rate.

Due to the difficulties encountered in measuring the heat flow from the condenser it was decided to use only the heat balance over the reboiler for the basis of the calculations for the vapour flow rate. In this case as in all other runs the average composition of the vapour in the column was approximately 30 mole % normal heptane ($\pm$ 3%). For all calculations the values of the physical properties of a 30% mixture were used. The error incurred

by using this simplification is less than $\frac{3}{4}\%$ of the value of the properties. A table of the physical properties of the systems can be found in Appendix A.5.2.1.

Heat input = 177,000 BTU/hr.

Amount of vapour produced = $\frac{177,000}{163.1}$ lbs/hr.

Now the volume of the vapour produced at its boiling point = $\frac{359}{97.78} \times \frac{375.1}{273}$ ft^3/lbs.

volume of vapour produced = $\frac{177,000}{163.1} \times \frac{359}{97.78} \times \frac{375.1}{273}$ ft^3/hr

Now the total cross sectional area of the column = 0.786 ft^2

Therefore, the vapour velocity through the total column area, U_T, is given by:-

$$\frac{177,000}{163.1} \times \frac{359}{97.78} \times \frac{375.1}{273} \times \frac{1}{0.786} \times \frac{1}{3600} \text{ ft/sec.}$$

$$\underline{UT = 1.936 \text{ ft/sec.}}$$

Now as the bubbling area of the tray occupies 39.6% of the total column cross section area, the vapour velocity through the tray bubbling area is; $U_B = \frac{1.936}{0.396} = 4.89$ ft/sec.

Now the F factor = U x $(dv)^{\frac{1}{2}}$

and density of vapour, $d_v = \frac{97.78}{359} \times \frac{273}{375.1} = 0.1982$ lbs/$ft.^3$

$(\text{density of vapour})^{\frac{1}{2}} = 0.4452\ (\text{lbs/ft}^3)^{\frac{1}{2}}$

F factor through total column area, F_T =

$1.936 \times 0.4452 = 0.862$ $lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs.

and F factor through tray bubbling area, $F_B = 4.89 \times 0.4452 =$

2.18 $lbs^{\frac{1}{2}}/ft^{\frac{1}{2}}$ secs.

A.5.3.3. Liquid Flow Rate.

At total reflux, the liquid rate = vapour rate.

$\frac{177,000}{163.1}$ lbs/hr of liquid flows down the column.

From the table of selected data in Appendix A.5.2.1. the density of the mixture is 0.738 gms/ccs.

$$\text{liquid flow} = \frac{177,000}{163.1} \times \frac{1}{0.738} \times \frac{1}{10} \times \frac{1}{60} \text{ galls/min}$$

now the width of the weir = 8" = 0.667 ft.

$$\text{liquid flow over the weirs} = \frac{177,000}{163.1} \times \frac{1}{0.738} \times \frac{1}{10} \times \frac{1}{60} \times \frac{1}{0.667}$$

= 3.68 gallons per minute per foot of weir width.

A.5.3.4. Tray Efficiency.

The murphree tray efficiency for the nth plate using liquid samples is:-

$$EML = \frac{x_{n-1} - x_n}{x_{n-1} - x_n^*}$$

Now consulting figures A5.2 & A5.3 and taking the refractive index of sample 1, 1.4448. Move from A on the refractive index axis via B on the liquid composition curve to C on the composition axis where x_o = 35.65%
At total reflux the liquid entering and the vapour leaving any tray have the same composition, therefore, the liquid in equilibrium with the vapour leaving the top tray, x_1^*, can be found by following CBDE to F where x_1^* = 25.55%.

FIGURE A5·2

DISTILLATION COLUMN STREAM NOMENCLATURE

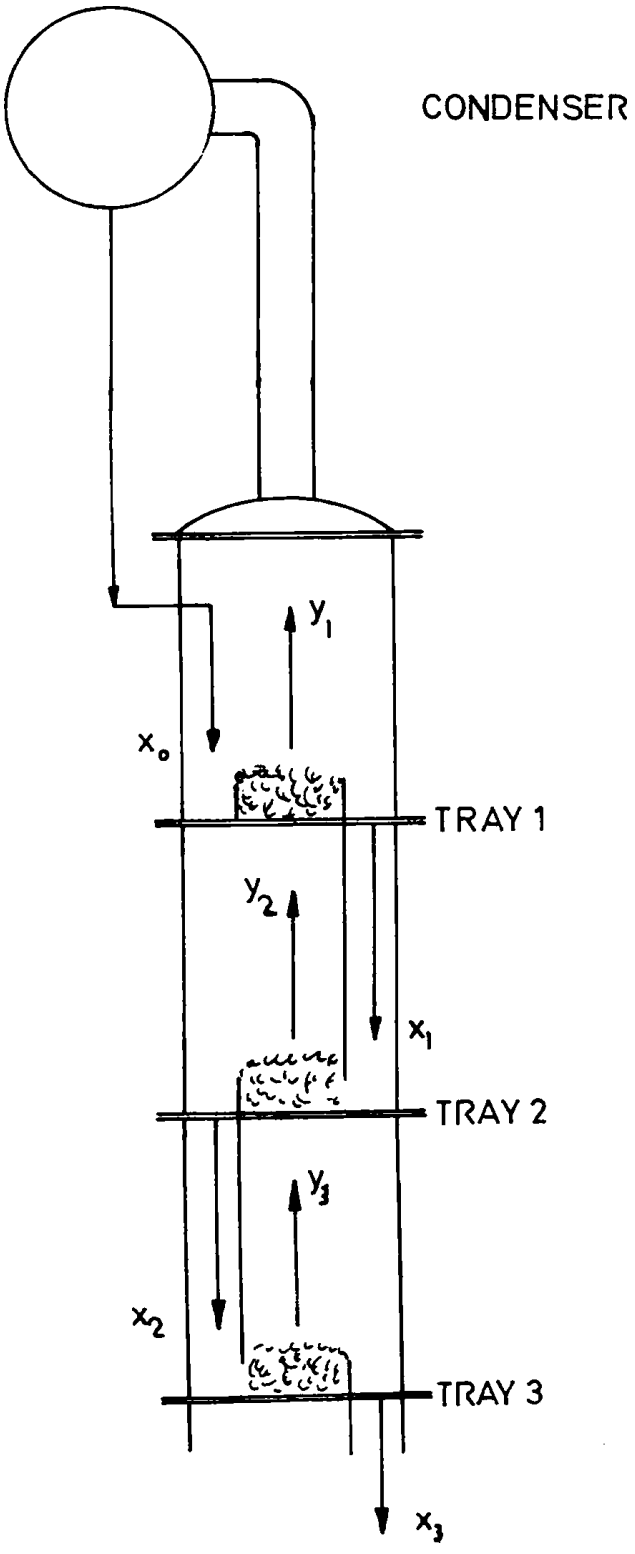
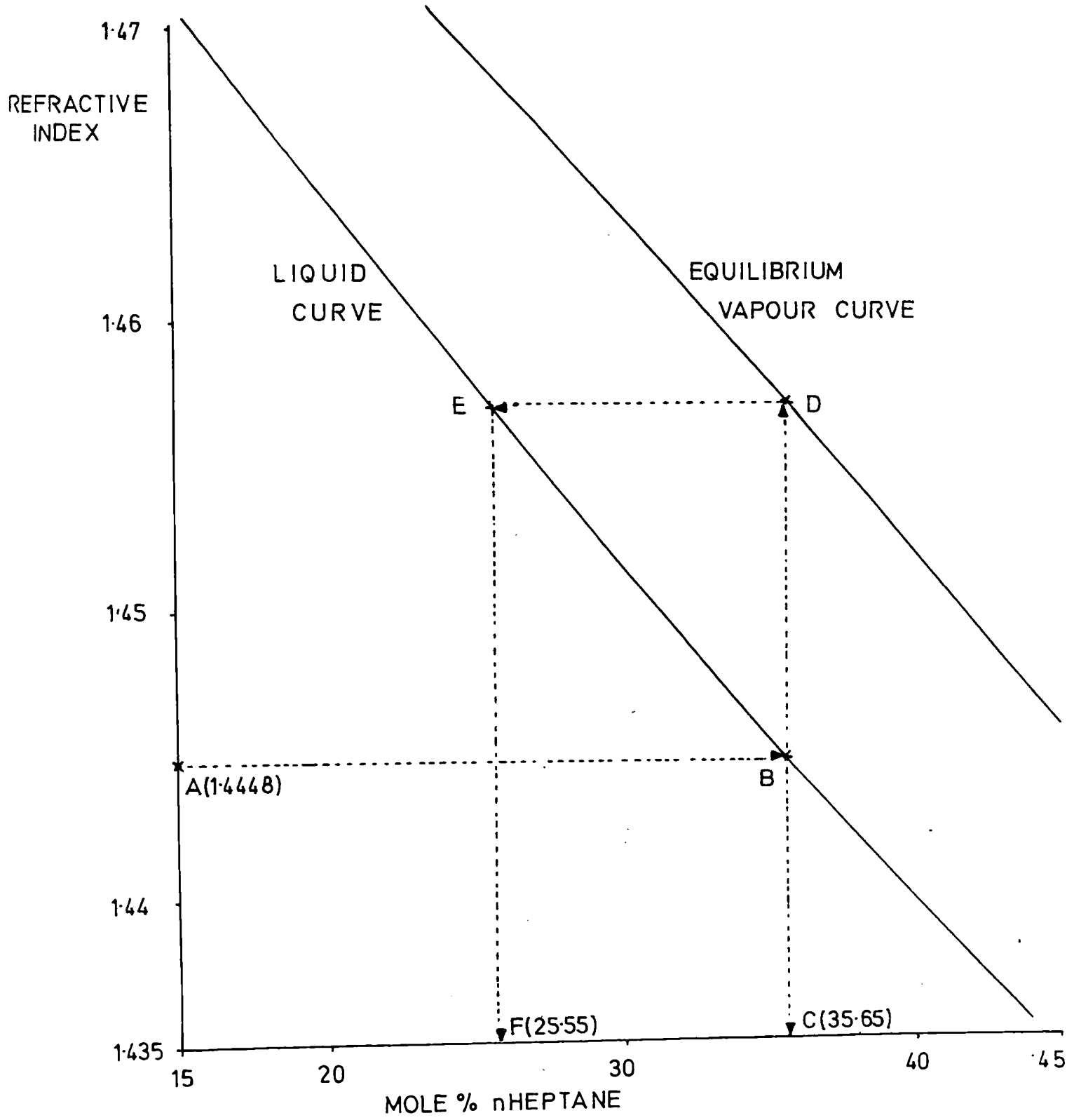


FIGURE A 5·3

TOLUENE/nHEPTANE SYSTEM AT 760 mm. Hg.

REFRACTIVE INDEX & EQUILIBRIUM DIAGRAM



Similarly for samples 2 and 3;-

$x_1 = 29.35\%$; $x_2^* = 19.95\%$

$x_2 = 24.00\%$; $x_3^* = 14.60\%$

Therefore, for tray 1 $EML = \frac{35.65 - 29.35}{35.65 - 25.55} = \frac{6.3}{10.1} = 62.4\%$

and tray 2 $EML = \frac{29.35 - 24.00}{29.35 - 19.95} = \frac{5.35}{9.4} = 56.9\%$

$\therefore \quad \overline{EML} = 59.65$

J.H. Perry (238) gives the relationship between the vapour and liquid phase murphree efficiencies in the region where the equilibrium and operating lines are straight.

$$EMV = \frac{EML}{\left(EML \pm \frac{MG}{L}(1-EML)\right)}$$

Now the slope of the equilibrium line (m) in the operating region is 1.05 and at total reflux L = G, therefore;

$$EMV = \frac{EML}{(1.05 - 0.05\ EML)}$$

and $\underline{EMV = 58.4\%}$

The results for the system methyl cyclo hexane-toluene were evaluated in the same way the physical properties of a 55 mole % mixture of methyl cyclo hexane were used.

APPENDIX A.5.4. RESULTS OF THE ACTUAL DISTILLATION STUDIES.

FT = F factor of vapour through total column area ($lbs^{\frac{1}{2}}/ft^2$ secs.)

FB = F factor of vapour through tray bubbly area

= FT/0.396

P = average tray pressure drop (cms. water gauge)

EMV = average murphree vapour efficiency (%)

A.5.4.1 Normal Heptane - Toluene System.

FB	P	EMV	FB	P	EMV
1" Outlet Weir Height.					
1.12	3.0	62.7	1.64	3.5	57.0
1.23	2.97	65.6	1.64	3.4	54.7
1.95	3.67	50.9	1.08	2.87	69.3
2.0	4.0	48.7	1.07	2.83	67.0
2.0	4.07	54.5	3.33	5.4	45.1
3.0	5.07	49.7	3.43	5.47	46.0
2.97	5.07	46.0	0.757	2.4	70.3
3.92	6.43	51.1	0.764	2.33	70.2
4.17	6.53	49.6	4.58	7.47	43.9
2.72	4.83	47.6	4.6	7.53	45.7
2.61	4.77	47.6	2.67	4.17	47.6
5.33	9.33	23.7	2.63	4.23	47.8
5.37	9.47	26.5			
2" Outlet Weir Height.					
3.87	6.77	52.8	2.54	5.33	62.3
3.86	7.02	45.2	1.82	4.27	58.5
4.62	8.0	34.0	1.84	4.2	64.5
4.55	8.4	29.5	3.39	5.76	59.3
5.14	8.8	29.1	3.38	5.8	70.0
5.07	9.7	23.9	1.07	3.33	77.7
2.52	4.87	57.2	1.14	3.43	71.1
2.58	4.9	52.5	0.767	3.2	80.2
1.53	3.97	63.0	0.767	3.17	79.0
1.79	3.93	55.8	4.08	6.83	54.1
2.18	4.6	55.9	4.21	7.13	50.6
2.18	4.57	58.4	1.56	3.9	59.0
0.362	3.3	84.3	2.14	4.3	61.5
0.376	3.4	83.3	2.11	4.4	56.6
2.79	5.37	55.3	2.21	4.27	59.3

FB	P	EMV	FB	P	EMV
2" Outlet Weir Height (continued)					
2.18	4.4	58.0	2.69	5.47	59.5
2.21	4.5	56.6	1.38	3.6	60.6
3.06	5.73	55.6	1.41	3.83	56.5
2.87	5.4	54.5	1.44	3.87	59.4
2.79	5.43	65.6	2.59	4.93	55.3
3.04	5.53	61.5	2.54	4.9	54.8
2.91	5.6	62.1	2.58	4.87	63.9
3" Outlet Weir Height					
2.1	5.0	81.0	0.72	4.37	77.8
2.1	5.07	79.7	0.72	4.37	76.8
1.46	4.63	-	3.42	6.57	60.5
1.46	4.7	-	3.42	6.7	61.9
0.83	4.6	89.5	0.978	4.3	81.5
0.73	4.7	92.4	0.947	4.27	84.7
2.4	5.73	70.2	1.32	4.33	76.5
2.49	5.77	68.5	1.18	4.43	85.2
3.5	7.33	60.2	0.885	4.37	81.4
3.44	7.27	60.9	0.893	4.3	77.7
2.04	4.97	86.7	1.14	4.4	75.2
2.04	5.0	83.8	1.14	4.37	77.8
1.47	4.63	86.1	3.22	6.9	59.6
1.49	4.67	86.2	3.07	6.23	64.9
1.19	4.13	-	3.28	6.6	62.6
1.24	4.76	-	3.12	6.17	62.3
3.7	7.2	51.4	2.74	5.6	55.8
3.71	7.6	56.5	2.48	5.3	72.2
4.23	8.36	30.8	2.25	5.07	76.6
4.16	8.36	30.6	2.53	5.37	73.4
4.2	8.65	29.2	3.07	6.27	55.3
4.0	7.65	39.2	2.82	5.67	59.4
4" Outlet Weir Height.					
2.58	6.2	66.8	1.83	5.33	82.6
2.62	6.3	64.3	1.81	5.37	84.4
3.41	7.7	60.4	3.61	8.2	43.2
3.17	7.4	63.0	4.36	7.85	46.9
1.44	5.07	87.7	4.26	9.55	23.2
1.457	5.1	75.5	3.28	9.95	23.2
3.01	6.6	68.4	3.38	7.6	65.1
2.94	6.73	66.1	2.58	7.2	67.3

FB	P	EMV	FB	P	EMV
4" Outlet Weir Height (continued).					
0.624	5.35	91.8	2.47	6.3	65.5
0.702	5.3	89.3	2.43	6.13	72.1
2.43	5.97	65.8	1.16	4.9	93.5
2,4	5.97	80.0	1.16	4.9	85.8

The above results have been plotted by weir height in figures 5.3 - 5.6 and have been combined in figure 5.7.

A.5.4.2 Methyl cyclo Hexane - Toluene System.

FB	P	EMV	FB	P	EMV
2" Outlet Weir Height					
1.69	4.1	89.5	3.70	6.3	74.7
1.62	4.0	81.6	4.32	7.3	69.4
2.16	4.7	74.6	4.33	7.8	67.3
2.37	4.8	76.2	5.65	11.0	31.0
3.75	6.7	75.6	5.66	11.0	31.0
3" Outlet Weir Height					
1.83	4.9	-	2.45	5.5	92.0
1.83	5.1	-	2.54	5.6	93.5
2.17	5.2	90.0	3.9	7.9	76.7
2.05	5.3	85.6	3.82	7.7	81.2
3.24	6.6	85.0	4.0	8.1	71.2
3.85	7.3	84.5	4.76	9.2	43.2
4.46	8.3	42.2	1.55	5.07	101.8
4.72	9.4	43.0	1.61	5.1	91.4
2.09	5.4	94.6	1.6	5.2	95.6
2.14	5.3	93.0	1.39	5.17	94.1
			1.38	5.03	93.6

The above results are plotted in figure 5.9.

APPENDIX A.5.5 DETAILS OF DISTILLATION COLUMN. AND ITS ANCILLARY EQUIPMENT.

Figure A5.5/1 General Column Details.

/2 Column Flange Details.

/3 Sight Glasses and Vapour Outlet Details.

/4 Original Tray Details.

/5 Tray Pressure Drop and Nitrogen Purge System.

/6 Reboiler Steam Controller and Condenser Water Systems.

/7 Tray No. 2 Details.

COLUMN DETAILS

3 - $\frac{3}{16}$" THICK TRAYS

18" TRAY SPACING

12" INSIDE DIAMETER

16" FLANGE DIAMETER

MATERIALS OF CONSTRUCTION

10G COPPER SHELL WITH BRASS FLANGES

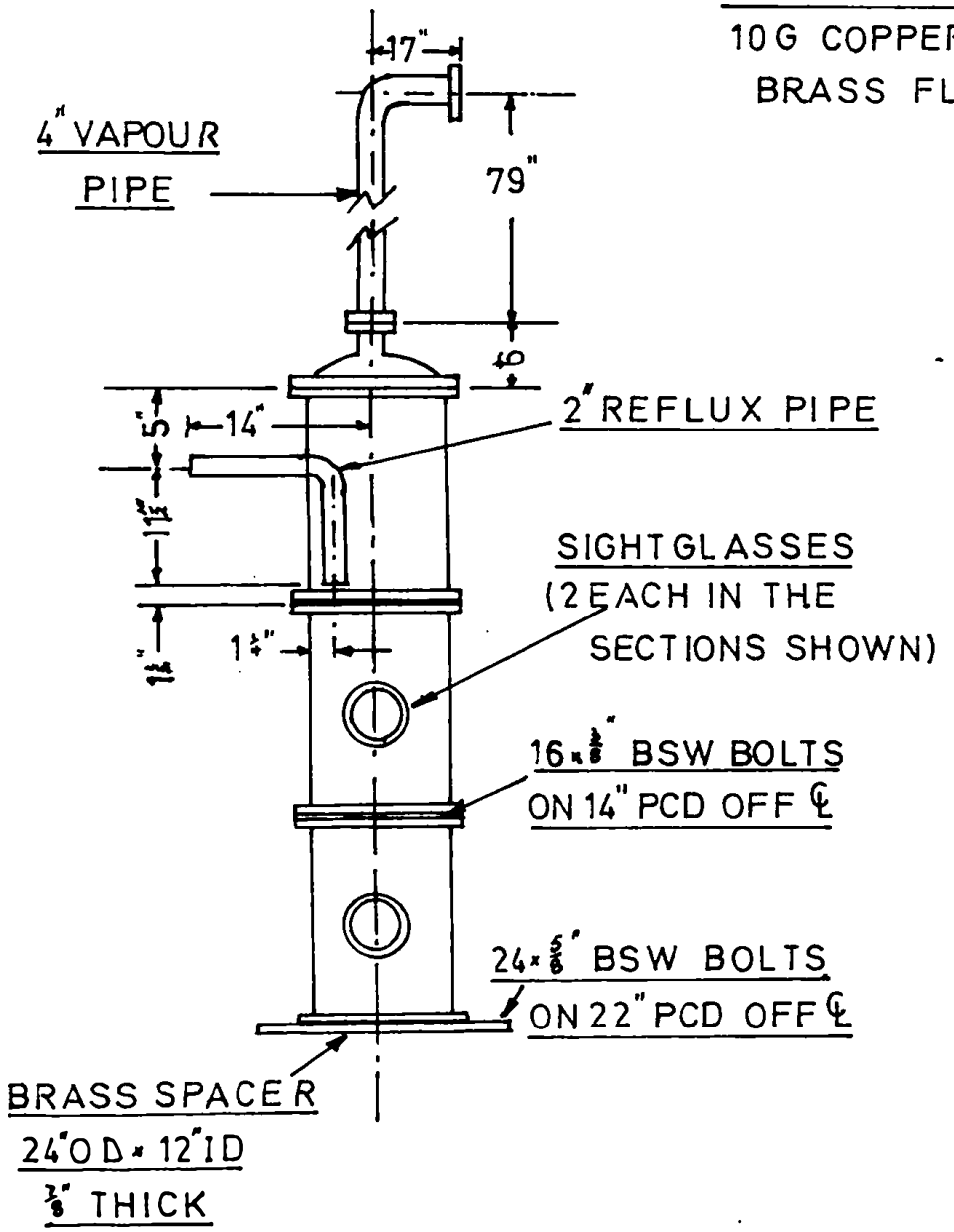
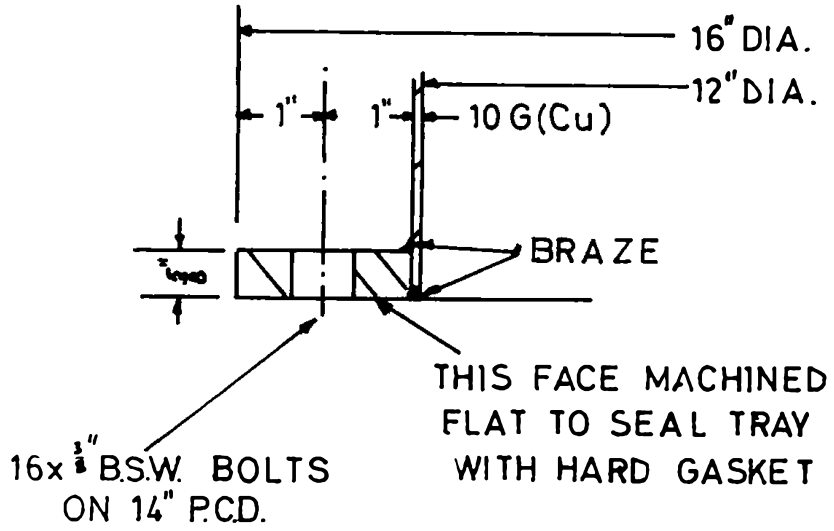


FIGURE A5·5/1.

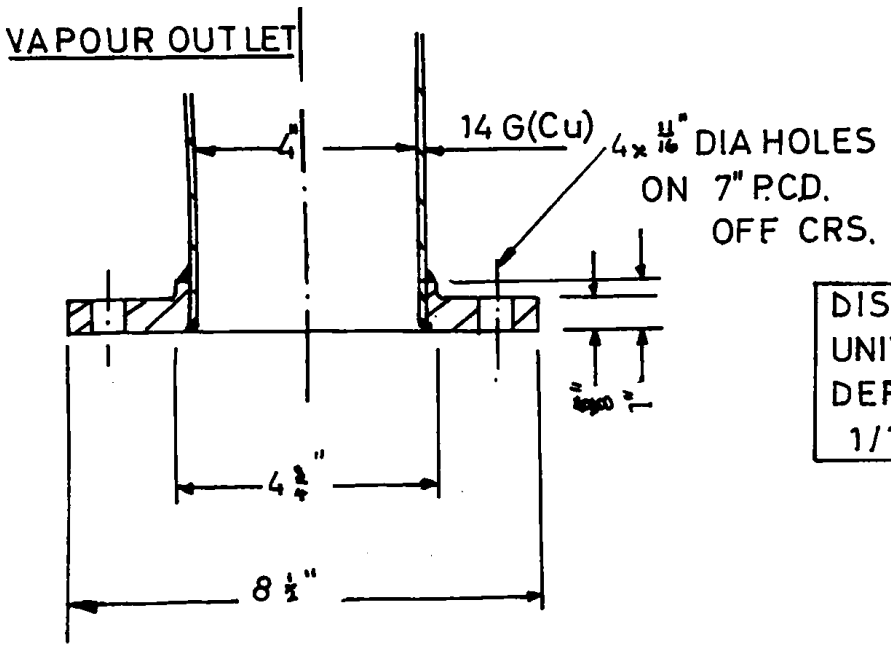
DISTILLATION COLUMN
UNIVERSITY OF BIRMINGHAM
DEPT CHEM ENGG
1/7/65 M.A. BRIGGS

FIGURE A5·5/2.

COLUMN FLANGE DETAIL



ALL FLANGES BRASS



DISTILLATION COLUMN DETAIL
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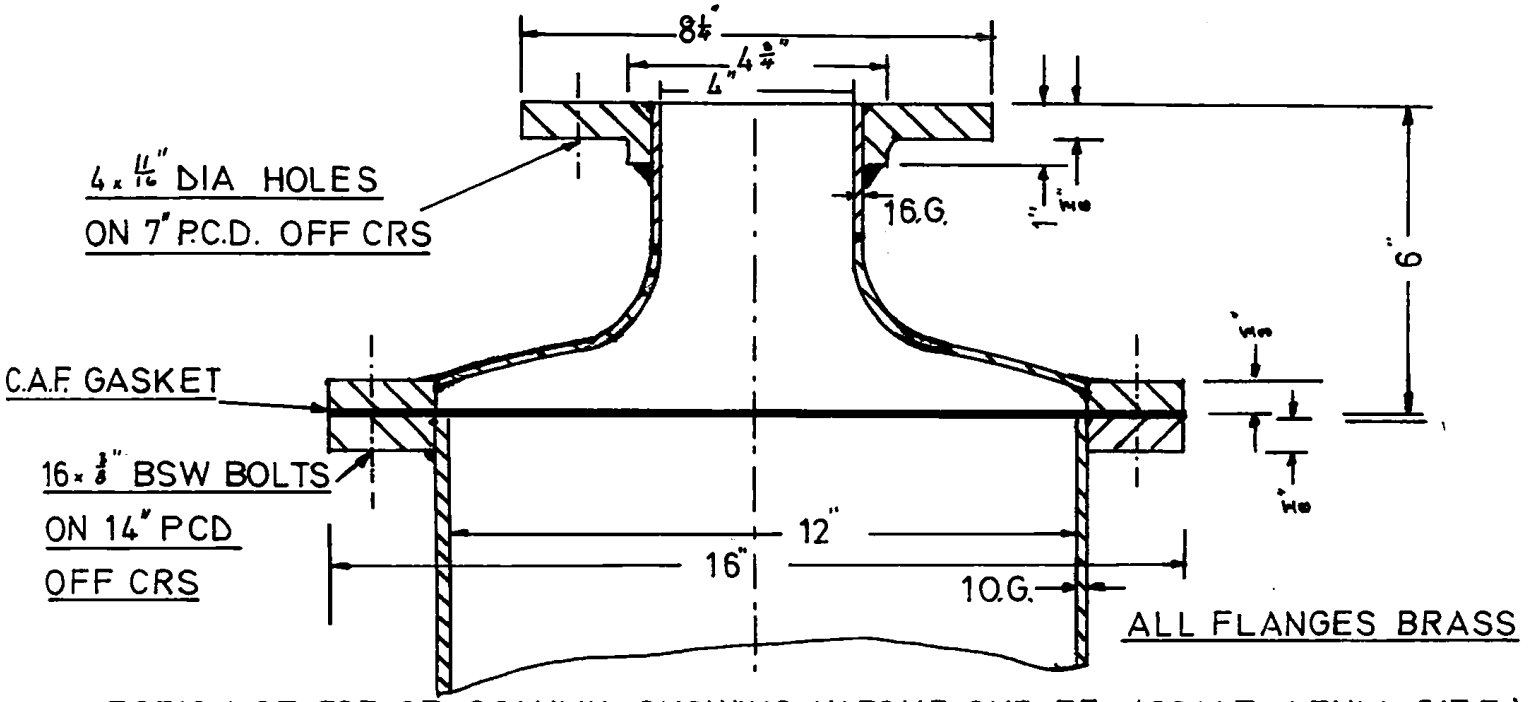
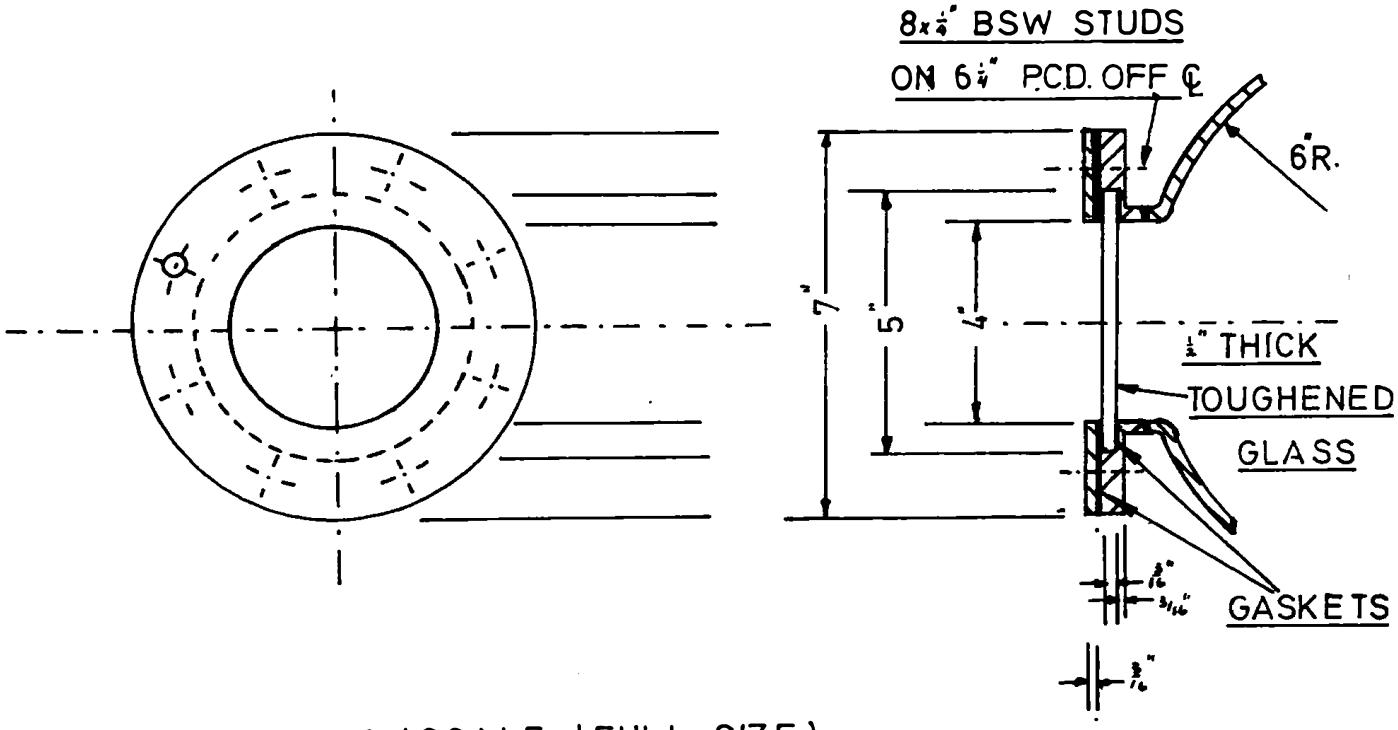
1/7/65 M.A.BRIGGS



SECTION OF TOP OF COLUMN SHOWING VAPOUR OUTLET (SCALE:- ¼ FULL SIZE)



SIGHT GLASSES (SCALE:- ¼ FULL SIZE)
(2 ON OPP. SIDES OF COLUMN
IN 2 SECTIONS ONLY)

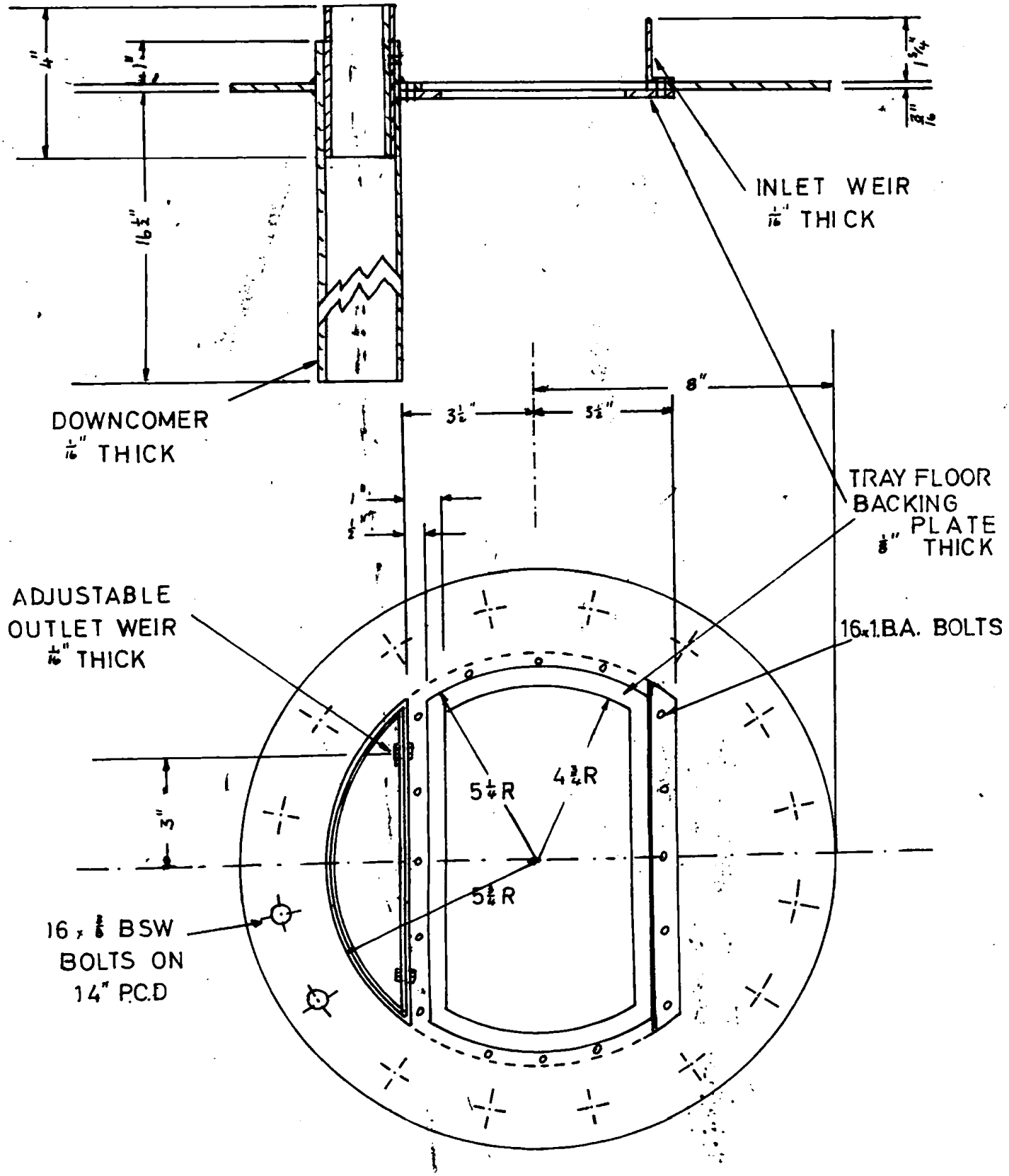
FIGURE A5·5/3.

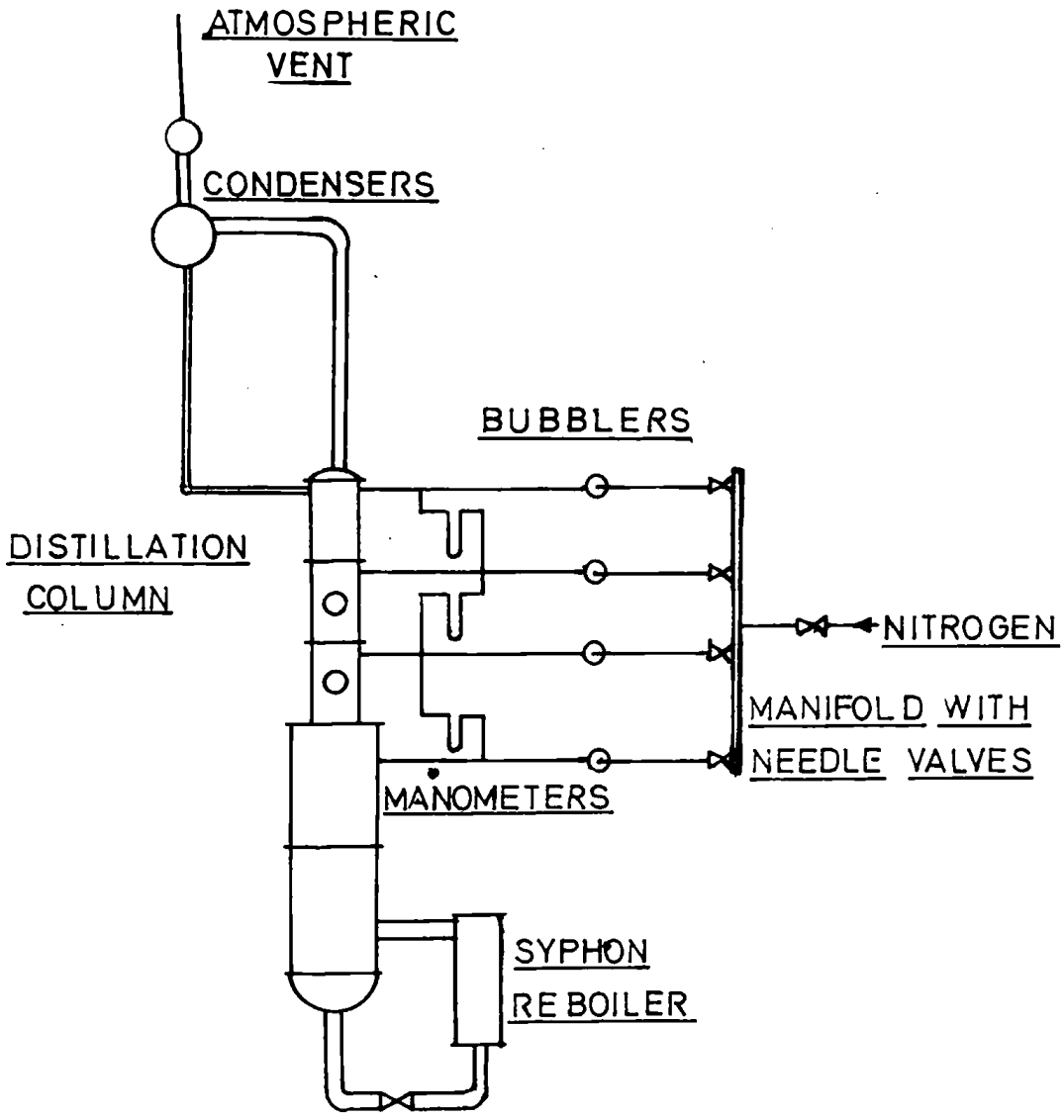
DISTILLATION COLUMN DETAIL
UNIVERSITY OF BIRMINGHAM
DEPT. CHEM. ENGG.
1/7/65 M.A.BRIGGS

TRAY DETAIL FOR 12" DISTILLATION COLUMN

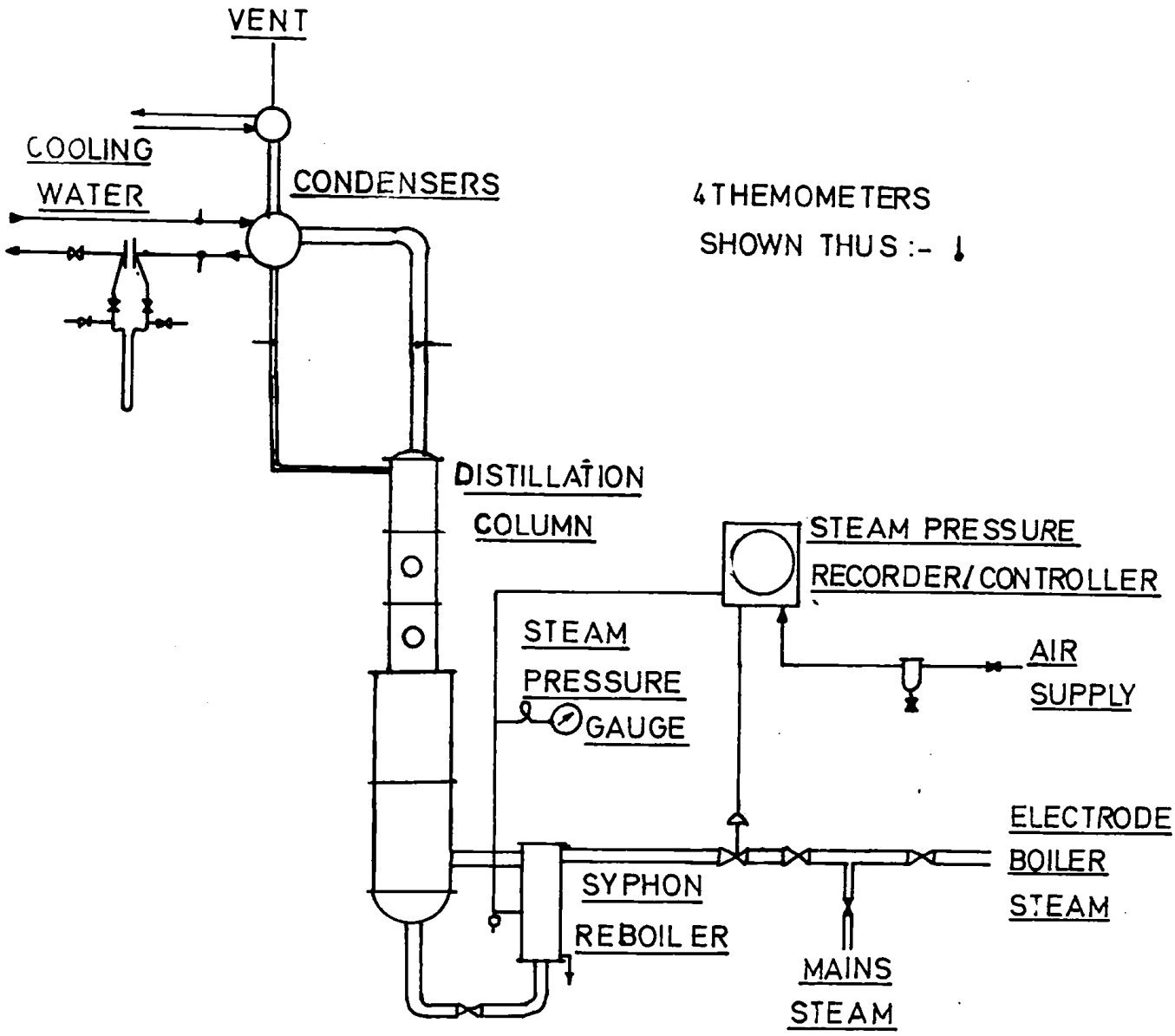
SCALE ½ FULL SIZE MATL. COPPER.

FIGURE A55/4.





TRAY PRESSURE DROP & NITROGEN PURGE SYSTEM FIG.5·5/5.

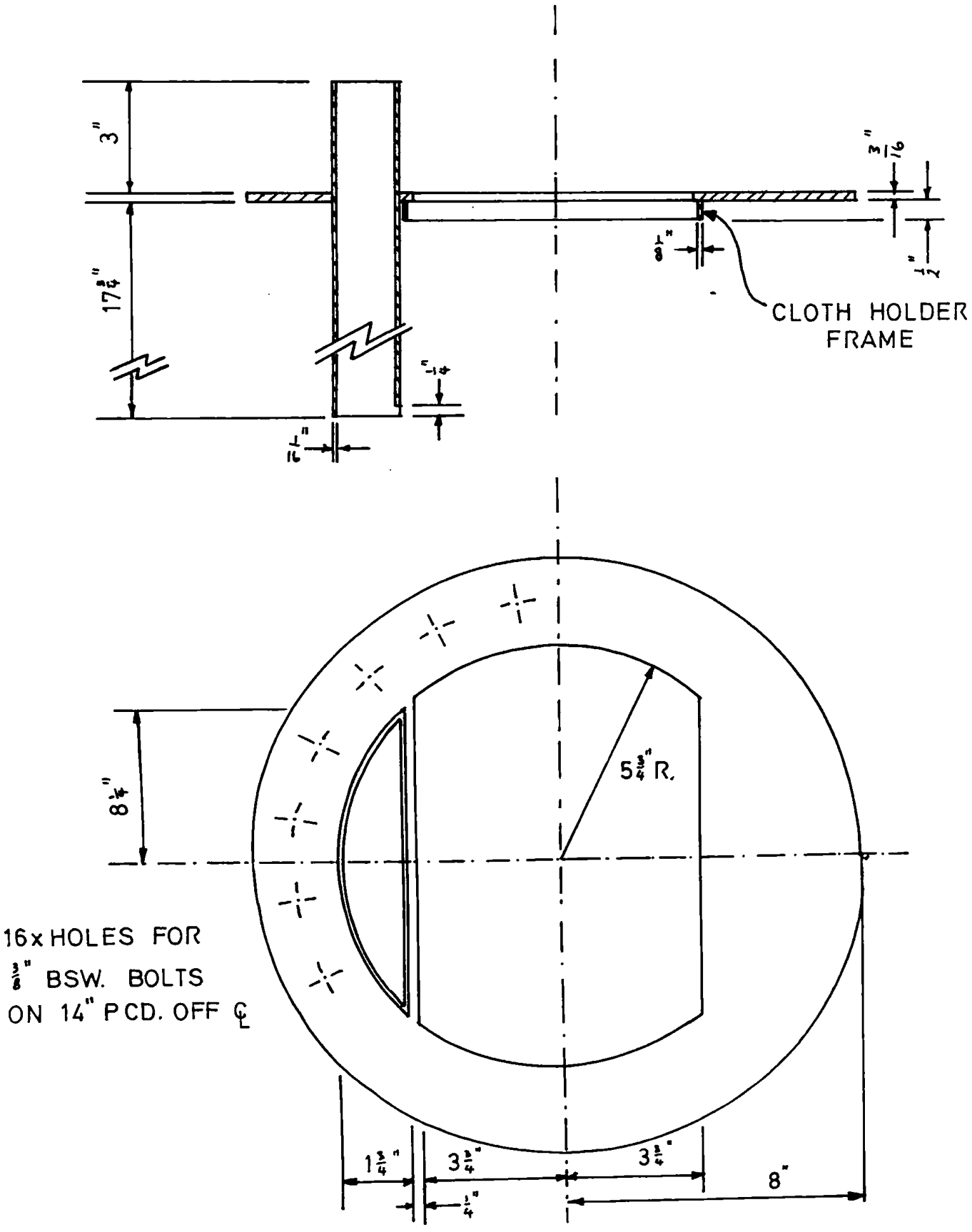


REBOILER STEAM CONTROLLER & CONDENSER WATER SYSTEMS FIG.5·5/6.

TRAY DETAIL FOR 12" DISTILLATION COLUMN (TRAY NO 2)

SCALE:- ¼ FULL SIZE MATL:- MILD STEEL

FIGURE A5·5/7



APPENDIX A.5.6 FURTHER DISTILLATION SUDIES RESULTS.

The following results were determined using Tray No. 2 with a 3" high outlet weir in the 12" diameter distillation column using a toluene-n heptane system at atmosphere pressure.

The results were derived as given in Appendix A.5.3. except that FB = $F_T/0.70$ for tray No. 2. The other nomenclature is as given in Appendix A.5.4.

A.5.6.1. Glass Cloth AD225

FT	FB	EMV	P	FT	FB	EMV	P
1.55	2.2	73.1	4.8	0.96	1.375	83.1	4.06
1.675	2.4	65.7	4.9	0.96	1.375	82.0	4.16
1.79	2.56	60.2	5.1*	1.06	1.52	78.7	4.36
1.79	2.56	60.2	5.2*	1.04	1.49	78.8	4.4
1.325	1.895	75.2	4.7	0.525	0.75	88.4	3.73
1.14	1.63	73.1	4.46	0.438	0.628	88.1	3.4
1.88	2.69	40.1	5.3*	0.378	0.542	95.8	3.4
1.88	2.69	48.0	5.3*	0.373	0.535	92.2	3.53
1.95	2.79	43.6	**	0.245	0.322	91.3	3.4
1.91	2.73	43.6	**	0.251	0.344	90.2	3.46
0.562	0.804	95.8	3.7	1.18	1.69	75.4	4.43
0.63	0.915	93.1	3.8	1.14	1.63	73.3	4.53
0.805	1.15	85.4	3.93	1.255	1.8	72.5	4.5
0.84	1.2	82.3	4.03	1.46	2.09	74.3	4.7
				1.41	2.02	74.8	4.75

* - Top trays flooding
** - Column flooded

The above results are plotted in figures 5.11 & 5.12.

A.5.6.2 Glass Cloth AD1224

FT	FB	EMV	P	FT	FB	EMV	P
0.83	1.19	88.9	3.27	1.395	2.0	72.7	3.87
0.844	1.21	94.4	3.3	1.385	1.98	77.1	3.87
1.03	1.47	78.4	3.43	1.6	2.3	75.6	4.0*
1.04	1.485	78.4	3.43	1.6	2.3	78.2	4.1*
1.125	1.615	77.4	3.53	1.72	2.46	78.8	4.2*
1.115	1.595	74.4	3.5	1.675	2.395	75.4	4.1*
				0.672	0.96	96.4	2.93

0.6	0.857	91.3	2.9	1.94	2.78	67.3	6.3**
0.59	0.845	97.7	2.8	1.895	2.715	67.3	6.1**
0.677	0.968	89.8	2.97	1.965	2.81	64.3	6.7**
0.677	0.968	89.1	3.0	1.965	2.81	64.3	6.8**
0.946	1.36	83.0	3.4	0.483	0.69	93.3	2.77
0.937	1.34	82.8	3.4	0.525	0.752	89.6	2.53
1.85	2.65	71.8	6.0**	0.552	0.79	98.2	2.77
1.85	2.65	72.4	6.2**	0.577	0.826	94.3	2.9

The above results are plotted in figure 5.13.

APPENDIX TO SECTION 6.

APPENDIX A.6.1. THE EFFECT OF THE AIR FLOW RATE.

The pressure drop results given below were found using an air-water system in a 3" diameter column and a tray floor of glass cloth AD225 with an upper grid of flattened expanded metal No. FE.3404.

The following nomenclature was used:-

P = tray pressure drop (cms, W.G.)
U = superficial air rate, (ft./sec.)
hc = clear liquid height (ins)
t - time from start of air flow, (mins.)

t \ u	0.34	0.85	1.7	2.55	3.4	4.25	5.1
		AD225 hc = o (DRY PLATE)					
-	-	0.15	0.3	0.4	0.55	0.65	0.85
		AD225 hc = o (MOIST PLATE)					
¼	5.9	7.3	8.9	9.8	10.7	11.4	11.9
½	5.9	7.3	8.8	9.7	10.5	11.5	11.8
¾	5.9	7.3	8.7	9.6	10.4	10.95	11.65
1	5.8	7.25	8.6	9.6	10.3	10.8	11.5
1½	5.8	7.2	8.5	9.5	10.2	10.8	11.3
2	5.8	7.2	8.5	9.4	10.1	10.7	11.1
5	5.7	7.1	8.3	8.7	8.5	7.3	5.5
		AD225 hc = 1" (116ccs.water)					
¼	7.5	9.3	11.0	11.9	12.6	13.3	13.7
½	7.5	9.3	11.0	11.9	12.6	13.3	13.7
¾	7.5	9.3	10.9	11.9	12.6	13.3	13.6
1	7.5	9.3	10.9	11.9	12.5	13.2	13.6
1½	7.5	9.3	10.9	11.8	12.5	13.2	13.5
2	7.5	9.3	10.9	11.8	12.4	13.1	13.5

t \ u	0.34	0.85	1.7	2.25	3.4	4.25	5.1
AD225 hc = 2" (232 ccs water)							
$\frac{1}{4}$	10.0	11.6	12.9	13.9	14.7	-	-
$\frac{1}{2}$	10.0	11.6	12.9	13.9	14.6	-	-
$\frac{3}{4}$	10.0	11.6	12.9	13.9	14.6	-	-
1	10.0	11.6	12.9	13.8	14.5	-	-
$1\frac{1}{2}$	10.0	11.6	12.8	13.8	14.5	-	-
2	10.0	11.6	12.8	13.7	14.4	-	-

The above results are plotted in figure 6.2. The loss in pressure drop, due to the evaporation of the water assuming that the air was humidified from 50% to 90% relative humidity at 20°C as it passed through the tray is given below:-

Air Rate (ft/sec)	Pressure Drop Loss (cms.W.G./ min.)
0.34	0.0046
0.85	0.012
1.7	0.023
2.25	0.035
3.4	0.046
4.25	0.058
5.1	0.069
6.8	0.092
8.5	0.115

APPENDIX 6.2 THE EFFECT OF SURFACE TENSION OF THE LIQUID.

The pressure drop results given below were found using an air-toluene system in a 3" diameter column. The tray floor, namely glass cloth AD225, used a flattened expanded metal grid No. FE.3404 as an upper support.

To compensate for the difference in liquid densities of water and toluene, 135 ccs of toluene was used as equivalent to 1" clear liquid height of water.

A list of the other nomenclature used for the results given below appears in Appendix A6.1.

The surface tensions of the two liquids at 20°C are given below:- water - 72.8 dynes/cm.
toluene - 28.9 dynes/cm.

t \ u	0.34	1.7	3.4	5.1	6.8	8.5
		AD225 hc = o (DRY PLATE)				
-	-	0.3	0.55	0.85	1.15	1.5
		AD225 hc = o (MOIST PLATE)				
¼	2.5	3.9	4.9	5.8	6.5	7.2
½	2.5	3.8	4.0	3.0	2.6	-
¾	2.4	3.6	2.0	1.1	1.7	-
1	2.3	3.4	0.8	1.1	1.7	-
1½	2.3	1.5	0.6	-	-	-
2	2.2	0.4	0.6	-	-	-
		AD225 hc = 1" (135 ccs Toluene)				
¼	4.6	6.0	7.1	8.1	8.7	9.5
		AD225 hc = 2" (270 ccs Toluene)				
¼	6.9	8.3	9.3	10.1	11.2	11.9

The above results are plotted in figures 6.5.

The loss in pressure drop due to evaporation was calculated assuming the air to be 50% saturated at 20°C with toluene as it left the column.

P.L. = loss in pressure drop, (cms W.G./min.)
U. = superficial air rate, (ft/sec.)

U.	0.34	1.7	3.4	5.1	6.8	8.5
P.L	0.314	1.57	3.14	4.71	6.28	7.85

APPENDIX A.6.3. THE EFFECT OF THE FREE FIBRE ON THE YARN.

The following pressure drop results were found in a 3" diameter column. The tray floor was prepared from a sample of glass cloth AD225 by removing the majority of the free fibres from the yarn. A photograph of the modified cloth sample, designated AD225 (B), is given in figure 6.6. A list of the nomenclature is given in Appendix A.6.1.

AIR-WATER SYSTEM.

t \ u	0.34	1.7	3.4	5.1	6.8	8.5
AD225 (B) hc = o (DRY PLATE)						
-	-	0.25	0.3	0.45	0.6	0.8
AD225 (B) hc = o (MOIST PLATE)						
$\frac{1}{4}$	0.5	1.5	1.8	2.1	2.4	2.9
$\frac{1}{2}$	0.5	1.5	1.8	2.1	2.4	2.9
$\frac{3}{4}$	0.5	1.5	1.8	2.1	2.4	2.9
1	0.5	1.5	1.7	2.0	2.4	2.9
$1\frac{1}{2}$	0.5	1.5	1.7	2.0	2.3	2.8
2	0.5	1.5	1.7	2.0	2.3	2.7
AD225 (B) hc = 1" (116ccs water)						
$\frac{1}{4}$	3.5	3.7	4.0	4.5	4.8	5.2
AD225 (B) hc = 2" (232 ccs water)						
$\frac{1}{4}$	5.6 (dumping)	6.1	6.4	6.7	7.3	7.8

AIR-TOLUENE SYSTEM.

t \ u	0.34	1.7	3.4	5.1	6.8	8.5

AD.225 (B) hc = o (DRY PLATE)

-	-	0.25	0.3	0.45	0.6	0.8
AD225 (B) hc = o (MOIST PLATE)						
$\frac{1}{4}$	0.2	0.4	0.85	1.1	1.6	2.05
$\frac{1}{2}$	0.2	0.4	0.8	1.1	1.5	1.8
$\frac{3}{4}$	0.2	0.35	0.7	1.0	1.3	1.3
1	0.2	0.35	0.6	0.9	0.7	0.9
$1\frac{1}{2}$	0.2	0.3	0.45	0.5	0.6	0.85
2	0.2	0.3	0.35	0.45	0.6	0.85
AD225 (B) hc = 1" (135 ccs Toluene)						
$\frac{1}{4}$	Dumping	2.8	3.1	3.5	3.9	4.3
AD225 (B) hc = 2" (270 ccs Toluene)						
$\frac{1}{4}$	Dumping	5.2	5.4	5.6	5.8	-

The above results are plotted in figure 6.8.

The evaporation losses for both systems are given in Appendices A6.1 & A6.2 respectively.

APPENDIX A.6.4. THE EFFECT OF THE WEAVE SETTINGS OF THE CLOTH.

A.6.4.1 The Weave Specification.

For this study an experimental cloth, AD1224, woven from taslaned glass yarn with a weight of 585 yds/lbs. was used. The yarn had a 38 gauge stainless steel wire incorporated in it so the cloth did not require a support grid.

Various weave settings were used to make up different cloths using the same yarn. Their nominal and actual weave specifications can be found below. The free area for gas flow through the cloths was calculated using a yarn diameter of 1/25".

p = number of picks per inch of cloth.
e = number of ends per inch of cloth.
f = free area for gas flow (%)
D = equivalent hole diameter (inches).

Nominal Geometry		Actual Geometry		Hole Data	
e	p	e	p	f	D
10	10	10.25	9.5	36.6	0.0692
10	12(A)	10.25	11.6	31.7	0.0583
10	12(B)	10.25	11.3	32.6	0.0604
10	15	10.25	15.0	24	0.0433
12	12	12.5	11.7	26.7	0.0483
12	13	12.5	13.0	24	0.0433
12	14	12.5	14.0	22	0.04
12	15	12.5	14.7	21	0.0385

A.6.4.2. Pressure Drop Results for Various Weave Settings.

The following pressure drop results were found using an air-water system in a 3" diameter column. The runs were all started with the cloth saturated with water and the readings were taken $\frac{1}{4}$ minute after the air flow was started.

u = superficial air rate (ft/sec.)

10 Ends per inch x p Picks per inch

u \ p	Pressure Drop (cms.W.G.)			
	10	12A	12B	15
0.34	4.0	4.9	4.7	5.9
1.7	4.3	5.8	5.4	7.3
3.4	4.7	6.9	6.3	9.1
5.1	5.1	8.0	7.3	10.8
6.8	5.6	9.1	8.3	12.9
8.5	6.0	10.3	9.4	-
10.2	6.6	11.4	10.5	-
11.9	7.2	-	-	-

12 Ends per inch x p Picks per inch

u \ p	12	13	14	15
0.34	5.2	6.0	7.0	7.7
1.7	6.8	7.7	9.3	10.9
3.4	8.7	9.4	12.1	14.1
5.1	10.5	11.3	14.1	-
6.8	12.3	13.0	-	-

The above results are given in figures 6.9.