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BOILING FILM COEFFICIENTS IN CLIMBING FILM EVAPORATION

by

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Abstract of Thesis by R.R. Mehta.

The main purpose of the research has been to find the heat transfer coefficients for boiling liquids in climbing film evaporators. Two small evaporators, one in glass and the second in stainless steel, have been designed, constructed, and used for the work.

The first unit is equipped with a single glass tube, ½ inch in diameter and 5 ft. long, jacketed by a 1 inch diameter glass tube. Hot water circulating at constant velocity in the annulus is used as the heating medium. Visual observations of the boiling phenomena under a range of operating conditions are described and discussed. Experimental data for different liquids boiling under vacuum over the whole length of the tube and covering a range of operating conditions are given. Boiling film coefficients are determined by an indirect method using a Wilson plot and have been related to the heat flux temperature difference and feed rate.

The second unit is equipped with a single stainless steel tube, ½ inch in diameter and 5¼ feet long, jacketed by a 1 inch diameter stainless steel tube. The unit is fitted with a travelling thermocouple to measure the liquid temperature at any point along the tube. Hot water circulating at high velocity in the annulus is again used as the heating medium. Experimental data are given for water, sucrose and

Teepol solutions, and isopropyl alcohol, when boiling under vacuum over the whole length of the tube for a wide range of operating conditions. Overall and boiling film coefficients have been determined by the same method as in the first unit and have been related to the temperature difference, heat flux, feed rate, surface tension, viscosity, Prandtl number and boiling temperature. The problem of recirculation and the influence of pressure drop through the tube are discussed. The data are compared with the meagre information given in the literature. The results, when compared with submerged boiling, show that the climbing film unit is particularly efficient when operated at low temperature differences.

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Errata

Page	Line	
10	13	for "sine" read "since"
15	7	Equation (3) should read $U_{NB} = 0.06 \left(\frac{c \cdot \Delta T_{NB} \rho^2}{\mu_{NB}} \right)^{0.7}$
	13-14	insert " ρ = Density, lbs/cu. ft."
20	19	for "curve" read "were"
26	15	for "scaled" read "sealed"
40	9	insert "and" after "eliminated"
67	21	insert comma after "tank"

Chapter 1.

INTRODUCTION.

Since P. Kestner introduced the tube, or climbing film evaporator in 1899, its virtues have resulted in its ever-increasing use in the chemical industry. The short time of contact, the low hold up and relatively simple construction are factors that appeal to most industrial users of process equipment. Its use is not now confined to the concentration of aqueous liquors but it is used as a vertical reboiler for distillation units where the liquors are not too viscous. Despite its undoubted popularity, there are relatively few papers in the literature giving precise details of the performance of these units and at present they are designed largely from experience and not from any agreed relationships between the operating conditions, physical properties of the fluids and the consequent heat flux or transfer coefficient. This thesis contains an account of the construction and operation of two small experimental evaporators. The first unit was of glass and was primarily designed to enable a visual picture to be obtained of the type of boiling taking place. It has, however, been possible to obtain data on the influence of a number of factors on the boiling film transfer

coefficient and to provide some form of empirical correlation between the variables. This data could be applied to the design of small units such as are used in the concentration of pharmaceutical products. The greater part of the work, however, was devoted to the construction and operation of a stainless steel unit in which it was possible to obtain more accurate and complete data on the working. Some attempt has been made to express the results for heat transfer in the form of a general equation, although there is hardly sufficient data to be specific about its final form. It has however been possible to relate in a quantative manner a number of the factors that influence the operation and these results do, it is thought, offer a much wider range of conditions than those hitherto available and should be of help in design. In the early part of the thesis, an account is given of previous published work and the relation of the present data to that is discussed in later chapters. The factors that have been given special examination are:

Feed rate to the unit;
Temperature difference, overall
and across the boiling film;
Temperature level; and
Viscosity and surface tension
of the fluid.

The general question as to the desirability of recirculation in this kind of equipment is also discussed.

CHAPTER 2.

Review of Earlier Work.

A History of Climbing Film Evaporator.

The early years of the 19th century saw two big advances in evaporation technique, which established the basis for design of much of the plant in use today. The first was the introduction of steam heating by means of fixed coils immersed in the liquid; and an extension of this method by William Cleland and Wetzel [1a] whereby partly immersed coils were rotated and a crude form of film evaporation took place. The second was the invention of the vacuum pan by Howard. One of the most important aspects of Howard's work is the stimulus it gave to the development of multiple effect evaporation. Between 1825 and 1840, numerous crude forms of multiple effect were tried out both in the sugar and salt industries, but the first efficient double and triple effect evaporators were due to the pioneer work of Norber Rillieux [1b]. By the middle of the century, the process of multiple effect evaporation had been extensively adopted by the sugar industry in the West Indies, America and Europe.

The general question of the importance of the movement of the liquor and of the use of the films was expressed as

long ago as 1830 by Dubrunfaut who enumerated the desirable features for sugar evaporators. He suggested the advisability of:-

(1) Concentrating the juice as rapidly as possible to avoid decomposition,

(2) Giving the liquor high velocity over the heating surface,

and (3) If possible, accelerating the movement of the liquor so as to evaporate in the form of a thin film.

These ideas were realised when P. Kestner introduced his climbing film unit in 1880. In his evaporator, the tubes were 22 ft. long by 2 in. O.D. The hot feed was introduced at the bottom of the tubes and heat was supplied by steam passing over the outside surface. Under these conditions, part of the feed was at once vaporised and the vapour rising rapidly up the tube not only pushes the liquor as a film up the walls, but also entrained part of it. The mixture of liquor and vapour issuing from the top was separated in a vapour-liquid separator and the concentrated liquor run from the separator, either as product or for further evaporation. This form of construction met all the requirements outlined above and relying on natural circulation did not require power for operation. Another name given to climbing film evaporators is 'long tube' evaporators.

Before passing to a review of the previous experimental work with this type of evaporator, it will be necessary to note the meaning of some common terms used in connection with its operation.

(1) When liquor is fed cold to the evaporator tube, heated from outside, it starts boiling at some point along the tube. The length of the tube between this point and the bottom may be called the heating section, the remainder being the boiling section.

(2) In the process of boiling, vapour bubbles rise upward to a region of lower pressure and carry liquid along with them. The boiling action by which a series of small columns of liquid or 'slugs' is pushed upwards by vapour bubbles may be termed 'slug action'. The boiling action in which the liquid is spread over the tube surface in the form of a film with vapour travelling in the centre of the tube may be termed 'film action'. In 'froth action', the liquid and vapour are uniformly mixed.

(3) The apparent temperature difference denotes the average temperature of the heating medium, minus the temperature of the vapour - liquid mixture at the top of the tube (or vapour head).

(4) The true, effective or average temperature difference is defined as the average temperature of the heating

medium minus the average temperature of boiling liquid.
(5) Boiling film temperature difference is the average temperature difference across the boiling film.

B. Work of Previous Investigators.

The original papers by Kestner describe the working of this type of unit and they do not give any extensive data on the performance, though good figures were claimed. Kerr[2], in a general investigation of evaporators in the sugar industry, did not claim particularly good results for these units, but his data was not really obtained under sufficiently controlled conditions to be convincing.

2.1. The work of Badger and his associates.

The first attempt at a systematic investigation of climbing film evaporators was made by Badger and his associates, and four papers published by them contain extensive quantitative data and empirical correlations.

(1) First paper (Brookes and Badger)[3].

This contains data relating to a single copper tube, 1.75" O.D. and 20' long. Steam condensing in an annulus outside the copper tube was used as the heating medium. Liquid was fed to the tube at a temperature below boiling point, so that a finite length of tube was used for heating to its boiling point. Liquid temperatures along the tube

were measured by means of a travelling thermocouple. The liquid temperature distribution curve determined during each run showed a maximum at some distance up the tube and the length of the boiling section was taken as the distance from this point to the top of the tube.

Distilled water was used as the working fluid and the feed rate, feed temperature, temperature level and apparent temperature difference (temperature of steam minus the temperature of vapour head) were varied. They only discussed the overall heat transfer coefficient and, for the boiling section, related this to the other factors by the following empirical expression:

$$\frac{U_B V^{0.27}}{W_f^{\,m}} = f\,(\Delta T_{Av.}) \qquad \ldots\ \ldots\ \ldots\ \ldots\ (1)$$

where V = vapour produced, lbs./hr.,
W_f = feed rate to the tube, lbs./hr.,
$\Delta T_{Av.}$ = average overall temperature difference in the boiling section (temp. of steam - average temp. of boiling liquid determined graphically), °F.,
m = exponent varying from 3 to 0.1 for $\Delta T_{Av.}$, ranging from 5 to 30,
and f = a function presented graphically.

This treatment was a great advance on previous work, since it did separate the boiling from the heating section of the tube, whereas the earlier workers had only given an average value for the whole tube.

The data presented show that the heat transfer coefficient in the boiling section (U_B) increases with overall temperature difference and suggest that it decreases with increase in the fraction of the feed evaporated. The authors found no effect of boiling length and temperature level on the heat transfer coefficients.

Some of the reported values of U_B are undoubtedly too high. Thus, values of 3,000 to 10,000 B.T.U./hr./sq.ft./°F seem clearly unreliable. This may be due to inaccuracies in the division of the tube into two sections. Some of the temperature distribution curves for the liquid have no regular shape and the points for maximum temperature on which the division of the tube has been based are not always clear.

Using a glass tube, $\frac{3}{8}$" O.D., in a glass steam jacket, they were able to obtain a visual picture of the nature of the boiling process. Three types of action - froth, slug and film - were found, although no definite relation was found between them and the environmental conditions.

(2) Second paper (Stroebe, Baker and Badger)[4].

This paper describes the first systematic work in which the boiling film coefficients were determined. The investigation was carried out in the same apparatus as

used earlier by Brookes and Badger. Steam was again used as the heating agent and, in addition, a measured quantity of steam was injected at the bottom of the tube to bring the feed to the boiling temperature, corresponding to the pressure at the point. Boiling film coefficients were determined by direct measurement of the tube wall temperatures using thermocouples. The variables mainly studied were feed rate, overall temperature difference and temperature level. The majority of the tests were made using water as the working fluid but a few runs were made with sugar solutions and Duponol (a surface active solution).

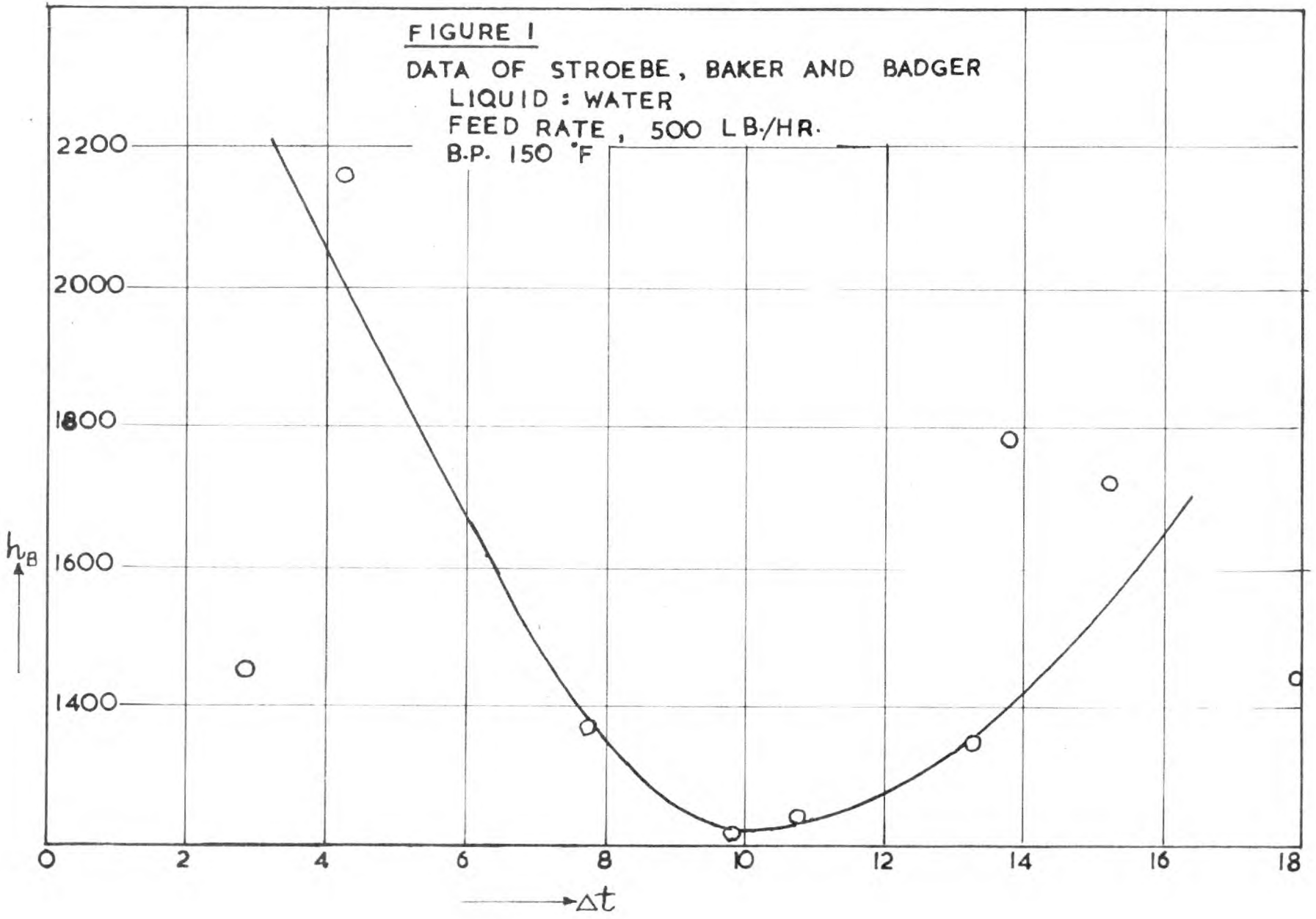
The functions of different variables were found empirically and the final correlation dervied was

$$h_B = \frac{7.8 \times 10^6 \times v^{0.1}}{\left(\frac{Cp\,\mu}{K}\right)^{0.3} \sigma^{2} (\Delta t)^{0.13}} \quad .. \quad .. \quad .. \quad .. \quad (2)$$

where h_B = boiling film coefficient, B.T.U./(hr)(sq.ft)(°F
v = specific volume of vapour, cu.ft./lb.,
Cp = specific heat of liquid at constant pressure,
μ = viscosity of liquid, lbs./(hr)(ft),
K = thermal conductivity of liquid, B.T.U./(hr)(sq.ft.)(°F)(ft),
σ = surface tension, dynes/cm.,
and Δt = boiling film temperature difference, °F.

No variation in the length and diameter of the tube was made. The variables, feed rate and temperature level, were studied but were not included in the correlation, although

Brookes and Badger had introduced these factors into their correlation expression given as equation (1). The results differ considerably from those of Brookes and Badger in the effect of temperature difference. It is important to note that in equation 2 the exponent for temperature difference (Δt) is -ve, whereas in equation 1 it is +ve. The wide difference in the form of the two correlations is difficult to justify when the apparatus and the working liquid were the same. It must be remembered that the negative index for Δt is contradictory to all previous experiments on boiling and seems most unlikely. The explanation put forward by the investigators is that, as the temperature difference is increased, more vapour is formed and, sine the larger portion of the surface of the tube remains covered with vapour, less will be wetted by the liquid. This suggestion does not seem convincing when we remember that, for submerged boiling of water, there is a rapid increase in liquid film heat transfer coefficient with increase in liquid film temperature difference up to a value of 45°F. This has been shown by Jakob et al. to be due to considerable agitation on the surface by vapour bubbles. It is only beyond 45°F that vapour binding takes place and the heat transfer coefficient falls with further increase in temperature difference. Although it is difficult to


FIGURE 1
DATA OF STROEBE, BAKER AND BADGER
LIQUID : WATER
FEED RATE, 500 LB./HR.
B.P. 150 °F
2200
2000
1800
1600
1400
h_B
0
2
4
6
8
10
12
14
16
18
Δt

judge from their data, some representative plots of boiling film coefficient (h_B) versus liquid film temperature difference (Δt) indicate that h_B falls rather rapidly with increase in temperature difference from 2° to about 8°F, and increases steadily beyond 10°F. One such plot is shown in Figure 1. The points in the graph are widely scattered and make it difficult to establish exactly the nature of the curve.

The plots also show that the boiling film coefficient increases with temperature level, and it is therefore rather surprising that this factor has not been included in the correlation.

The effect of surface tension reported was much higher than observed before.

The visual observations on the type of boiling were made by the authors, through sight glasses suitably placed in the vapour head and, although it was presumed that all the three types of boiling (froth, slug and film) occurred, it was believed that film boiling occurred over the major portion of the tube.

(3) Third paper (Badger)[5].

This gives only a qualitative discussion of the more important phenomena that take place in the evaporator tube and the types of boiling that may occur.

First the author points out that static level has no significance. This is only true when the liquid boils over the whole length of the tube. If the feed is below boiling temperature, heating of the liquid to boiling temperature will take up some proportion of the length of the tube and that proportion will depend on a number of factors.

He discusses at length the boiling phenomena that would occur when the feed rate is kept low, feed temperature below boiling point and the temperature difference is increased slowly:

(1) At low temperature differences, heat transfer to the liquid during heating will be very small and the length of the tube occupied for heating will be large. In the limiting condition when the total heat supplied is not enough to bring the liquid to its boiling temperature, the evaporator will work only as a heater.

(2) By increasing the temperature difference, a stage will occur when the liquid begins to show incipient boiling.

(3) On further increasing the temperature difference, there will be sudden ejection of considerable amounts of non-boiling liquid from the tube, followed by a puff of steam, and then the tube will be perfectly quiet until another slug of liquid is ejected.

(4) On still further increasing the temperature difference, the successive periods between the slugs will become shorter and the top part of the tube surface will be covered with large slow moving drops of liquid. The core of the tube will be occupied by a jet of steam. It is stated that many evaporators operate in practice in this way.

(5) With very high temperature differences, the limiting condition will be found when all the liquid on the surface evaporates and there remains only a stream of vapour containing some liquid particles in suspension and travelling at a very high speed.

The author presents curves showing the temperature of the fluid along the tube length for different operating conditions. No regularity in the curves was found and it was suggested that the nature of the curve depended on the rate of feed, the physical properties of the liquid, the difference in temperature between the feed and the boiling liquid, the effective temperature difference, the tube proportions and possibly other factors.

The negative index for the influence of temperature difference was again discussed. The author cited some of the runs from Brooke's data, which are:

Run No.	L_B	U_B	ΔT
L-23	14.0	972	6.5
L-6	14.2	903	7.5
L-13	14.9	740	10.3
L-18	14.6	551	16.6

where L_B = boiling length in ft.

U_B = overall heat transfer coefficient in the boiling section, B.T.U./(hr)(sq.ft.)(°F).

ΔT = average overall temperature difference, °F.

It may be recalled here that Brookes' data showed an increase in the heat transfer coefficient with temperature difference and it is surprising to note that some runs from the same data show the reverse effect. All these contradictory statements emphasise the necessity for furthere work in this direction.

(4) Fourth paper (Cessna, Lientz and Badger)[6].

Using a single copper tube, 1.25" O.D. and 18.5 ft. long, steam as the heating agent, water and sucrose solutions were evaporated under varying conditions. The lengths of heating and boilding sections were determined by means of a travelling thermocouple and were allowed to vary according to operating conditions. The authors dealt with overall heat transfer coefficients in the two sections separately. The feed rate was kept constant and

the variables studied were feed temperature (125-140°F), apparent temperature difference (10-60°F) and boiling point (150-200°F).

The overall heat transfer coefficients in the heating section were correlated by the natural convection type equation:

$$U_{NB} = 0.06 \left(\frac{C.\Delta T_{NB}}{\mu_{NB}}\right)^{0.7} \qquad .. \quad .. \quad .. \quad (3)$$

where U_{NB} = overall heat transfer coefficient in the heating section, B.T.U./(hr)(sq.ft)(°F),

C = specific heat of liquid, B.T.U./(lb)(°F),

ΔT_{NB} = temperature difference in the non-boiling section, °F,

and μ_{NB} = viscosity of liquid, lbs/(ft.)(hr).

The scatter of the points in their graph was attributed to some tests being taken with water in the transitional range of flow, and to variation in the steam film coefficient.

Overall heat transfer coefficients in the boiling section were reported but not correlated. It is surprising to find that many values of the overall boiling coefficients were two to three times those reported by Brookes[3] and by Stroebe[4]. These differences would be still larger if values of the boiling film coefficients were compared. The values of overall heat transfer coefficients in the boiling section for 40 per cent sucrose solutions were

reported from 2,000 to 3,000 B.T.U./(hr)(sq.ft)(°F) for a number of runs. These values are undoubtedly too high. Even for the same operating conditions and the same boiling length, the values vary from 1,000 to 3,000. These wide variations were assumed to be due to some inaccuracy in the division of the tube into two sections. It may also be due to serious errors involved in the determination of heat flux from the steam condensate collected. It was mentioned by the authors that, although difficult to judge from the tables, plotting showed an increase of the overall boiling coefficients with decrease in temperature difference for constant boiling lengths. As mentioned earlier, this is contradictory to all the published work on natural circulation evaporators, and also to the work of Brookes and Badger[3] for this evaporator. The wide variations in the values of heat transfer coefficients and some contradictory statements emphasise again the need for further work.

2.2. The Work of V.A. Rachko[7,8].

Two papers were published by this author on the performance of vertical tube evaporators, in a Russian Journal in 1946. Experimental data on the boiling of water inside a vertical tube were presented. The water entered the tube at a temperature below boiling point. The conclusions reached in the first paper[7] were:

(1) There is no increase in the heat transfer coefficient if the velocity through the tube is increased by steam injection into the bottom of the tube;

(2) The ratio of length to diameter of the tube has no influence on the heat transfer coefficient. This means a standard calendria will give the same heat transfer coefficient as a long tube evaporator; and

(3) The material of construction is unimportant and has no effect on heat transfer.

The second paper[8] covers experiments designed to show the effect of diameter on the boiling coefficient in a vertical tube. The work was carried out in an iron tube, the diameter varying from 1.8 to 25 cms. The conclusions reached were:

(1) The heat transfer coefficient is dependent on the heat flux only and it varies as a 0.455 power of the flux below 70,000 cals/sq.meter/hr., i.e. 25,800 B.T.U./sq.ft/hr. in British units and 0.21 power at values above 70,000 cals/sq.meter/hr.

(2) The coefficient of heat transfer is independent of the Reynold's number or Prandtl's number.

(3) The relation between heat flux and temperature difference is different at the top and the bottom of the tube.

The results of this Russian experiment are very different from those of other workers in this field, but a detailed discussion is not possible as only an abstract of their paper is available.

2.3. The Work of F. Rumford[9]

Rumford used a ½-inch diameter, 12 S.W.G., 9 feet long, single vertical stainless steel tube, with hot water as the heating medium. The liquids used were water, ethyl alcohol, toluene and nitric acid. Except in a few runs with water, liquid was fed cold to the tube and the resulting two sections, heating and boiling, were allowed to vary according to operating conditions. Boiling liquid temperatures were measured by means of a travelling thermocouple.

This consisted of a long thermocouple which could be drawn in and out of a central glass tube (0.1" O.D.) passing down the centre of the evaporator. Boiling film coefficients were determined by an indirect method which consisted in (1) taking a series of runs with varying feed rates of cold water in the inner tube and constant flow rate of hot water in the annulus, (2) plotting the reciprocals of the overall heat transfer coefficients versus the reciprocal of the inner film coefficients calculated from a modified Dittus-Boelter expression and (3) using the

intercept derived from the above graph for the determination of the boiling film coefficients.

The two heating and boiling sections were distinguished by means of the travelling thermocouple, on the assumption that the boiling starts at the maximum temperature. When film coefficients were calculated for the boiling section only, the values increased very rapidly to unreal values such as 12,000 B.T.U./hr/sq.ft/°F, with a sixfold increase in feed rate. The values when calculated for the whole length of the tube, neglecting the division into two sections, remained almost constant. It is rather difficult to explain these extremely wide differences in the two sets of values. The author suggests that, for very high values of film coefficients calculated for boiling section only "the heat required for boiling was provided in the lower part of the tube", i.e. in the heating section. He concluded that the division of the tube into two sections is unwarrantable and the high values reported for film coefficients were wrong. The explanation given for the constancy of the film coefficients when calculated for the whole length of the tube was that the principal factor in determining linear fluid velocity was the volume of vapour formed which varied very little with feed rate. These explanations are not convincing, in view of the considerable differences in the two

sets of values obtained. The following reasons are more likely to be responsible for the abnormal results:

(1) The largest error seems to be in the measurement of boiling liquid temperatures and especially in finding out the maximum temperature for division of the tube into two sections. The travelling thermocouple function was not kept in direct contact with the liquid but was sheathed in an empty small diameter glass tube. The movement of the thermocouple in such a small tube will undoubtedly disturb the temperature gradient set up inside, and tend to equalise the temperatures and thus will make the task of accurate division of the tube extremely difficult.

(2) All experiments were carried out at very low overall temperature differences, from 12 to 16 °F in the boiling section, and the slight errors in the measurements of the boiling liquid temperatures will result in large errors in the values of the overall heat transfer coefficients.

(3) Though not reported in the paper, it seems from the data presented that the values of heat flux curve calculated from the vapour condensate collected. The values given do not seem to be correct, since no account is taken of the flash evaporation of liquid from the tube top to the condenser. The possible vaporisation in the heating section, as indicated by the author, and the heat loss from

evaporator to condenser will also introduce errors.

It is interesting to note the differences in the values of the film coefficients calculated for the whole length of the tube for two sets of experiments with water (1) feeding cold and (2) feeding hot. The values are almost doubled by changing the feed temperature. This shows the desirability of hot feed for this type of evaporator. The magnitude of the boiling film coefficients calculated for the whole length of the tube and with cold feed were as under:

Water	500-800 B.T.U./hr./sq.ft./°F.
Ethyl alcohol	200-300 B.T.U./hr./sq.ft./°F.
Toluene	250-300 B.T.U./hr./sq.ft./°F.
Nitric acid	100-150 B.T.U./hr./sq.ft./°F.

It is difficult to interpret these values, in view of the irregular variations, as much as 50 per cent with increase in feed rate, and also the inclusion of the unknown length of heating section with the boiling length.

2.4. The Work of Shunichi Uchida and his associates[10].

This is described in a recent paper published in a Japanese Journal. The authors carried out experiments in vertical tubes 2.5 metres long and of three different diameters (11.9, 18.6, 25.5 mm. I.D.) using water and methanol mixtures. Steam was used as the heating agent. The vapour

and liquid were separated in a cyclone and measured individually. At the top of the evaporator, the vapour and liquid were found to be in equilibrium. The authors dealt with the overall heat transfer coefficient and gave a relation:

$$\frac{U}{\lambda} = 30.4 \left(\frac{4\Gamma}{\mu}\right)^{0.56} \left(\frac{V}{F}\right)^{0.37} (Pr.)^{2/3} \quad .. \quad .. \quad .. \quad (4)$$

where U = overall heat transfer coefficient,

F = feed rate,

V = vapour produced,

Γ = mass rate of liquid per unit length of the periphery of the evaporator tube,

μ = viscosity of the liquid,

λ = thermal conductivity,

and Pr.= Prandtl's number.

This equation neglects the influence of temperature difference and of surface tension. The work is somewhat unsatisfactory in that:

(1) The liquid was fed cold to the evaporator tube and the values of the overall heat transfer coefficients were calculated for the heating and boiling sections together.

(2) The temperature difference was allowed to vary according to operating conditions.

(3) The values of overall heat transfer coefficients were based on the temperature difference derived by a log mean relation which does not hold ture in the present case of boiling.

C. Method of Approach to the Problem.

The correlations discussed in the previous section are all empirical and, in almost all cases, cover the actual experimental data only with moderate success. When we consider the influence of such vital factors as temperature difference, feed rate and temperature level, the conclusions reached are not in agreement and certainly form no sound basis for design. The majority of workers have presented correlations only for overall heat transfer coefficients, a simplifying technique that does not advance to an appreciable extent our fundamental knowledge of the process. Whilst offering this criticism, it must be remembered that the earlier work was more in the nature of a qualitative assessment of a new form of equipment than an analytical approach based on the mechanism of boiling. There are few examples of an anlytical approach involving the use of individual film coefficients. It is convenient in examining the problem to set out a number of features which have either been neglected or received insufficient attention, and which singly or together are probably responsible for the inconsistencies in the published data:

(1) Steam has been used as a heating medium by almost all workers. Experience has shown that steam film coefficients

vary considerably with only slight alterations in conditions. This complicates the calculation of film coefficients. Moreover, values of heat flux calculated from measurements of steam condensate collected in a given time are liable to show variations of up to 50%. In early experiments with the glass evaporator, it was found that steam heating gave errors of as much as 30% which could not be explained. It is therefore believed that heating should be effected by circulating a hot liquid through the annulus when much more stable conditions are obtained.

(2) Most previous workers have used a copper tube. It is believed that the surface of copper changes considerably with the continuous boiling of many liquids, including water. Since the surface conditions are so important, stainless steel should be a better material, even though its low thermal conductivity is a draw back.

(3) The importance of keeping the feed temperature at the boiling point has not been sufficiently realised. This evaporator is not suitable for heating and, if the feed is cold, there will be a heating section, a boiling section and probably an intermediate section where boiling and re-condensation occur. Attempts to separate these sections have not been entirely satisfactory. Moreover, it is difficult to interpret data presented in the form of

overall transfer coefficients for the whole length of the tube when two entirely different mechanisms are involved. (4) The very low hold up of this type of evaporator means that it is sensitive to small variations in conditions and hence accurate control of feed temperature, rate and pressure is necessary.

Equipment used in present work.

With these considerations in mind, two units have been designed and built, one in glass and the second in stainless steel. The first was largely designed to give a visual picture of the climbing film process, but some practical data have been obtained with it. The second unit has been operated with a variety of liquids and over a wide range of operating conditions and this has enabled a better picture to be obtained of the general performance of these units. The heat flux used in the glass unit was very low, on account of the low thermal conductivity of the glass, whilst in the steel unit the flux is comparable with that found in industrial practice.

PART ONE.

THE LONG TUBE GLASS EVAPORATOR.

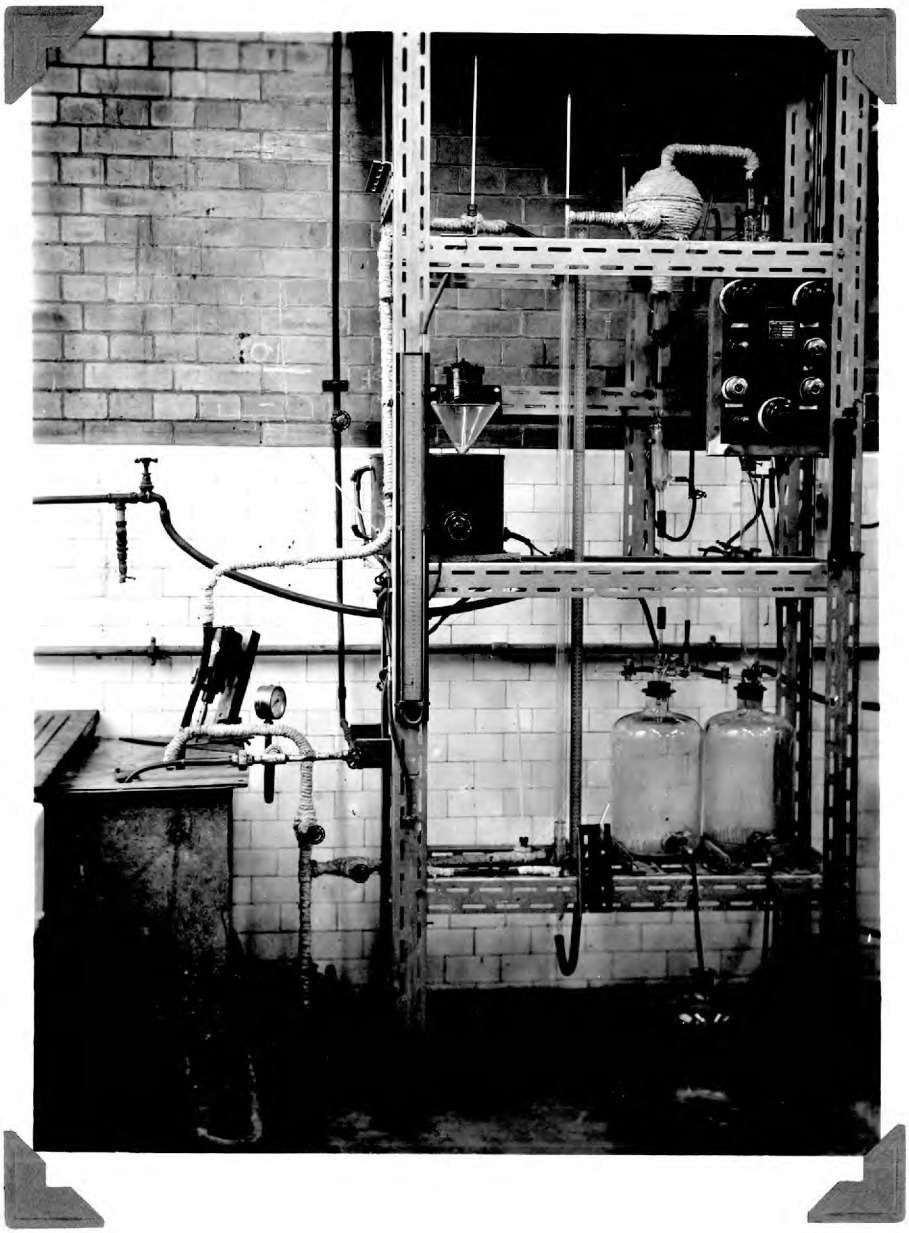
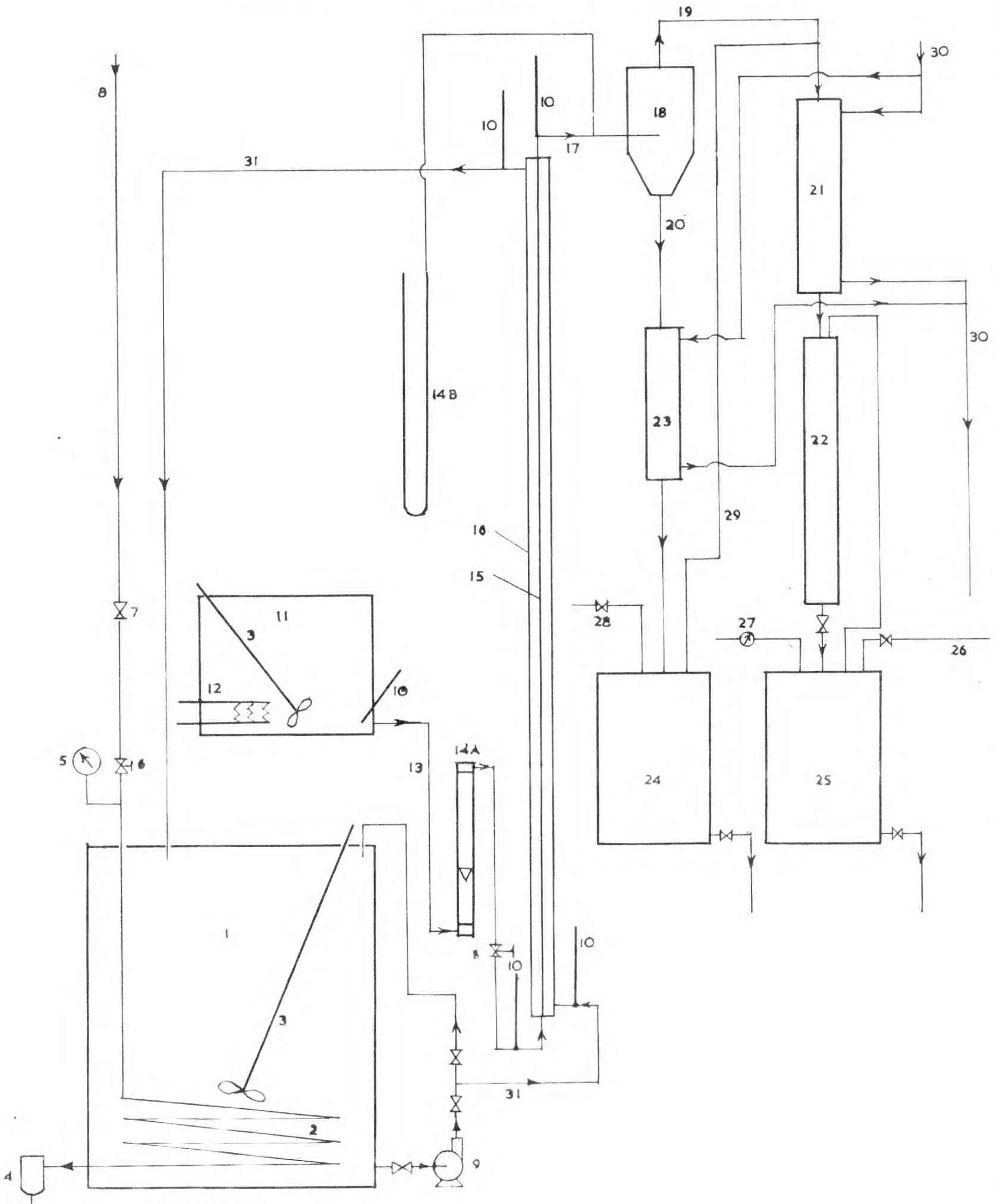


Plate 1. The Long Tube Glass Evaporator.

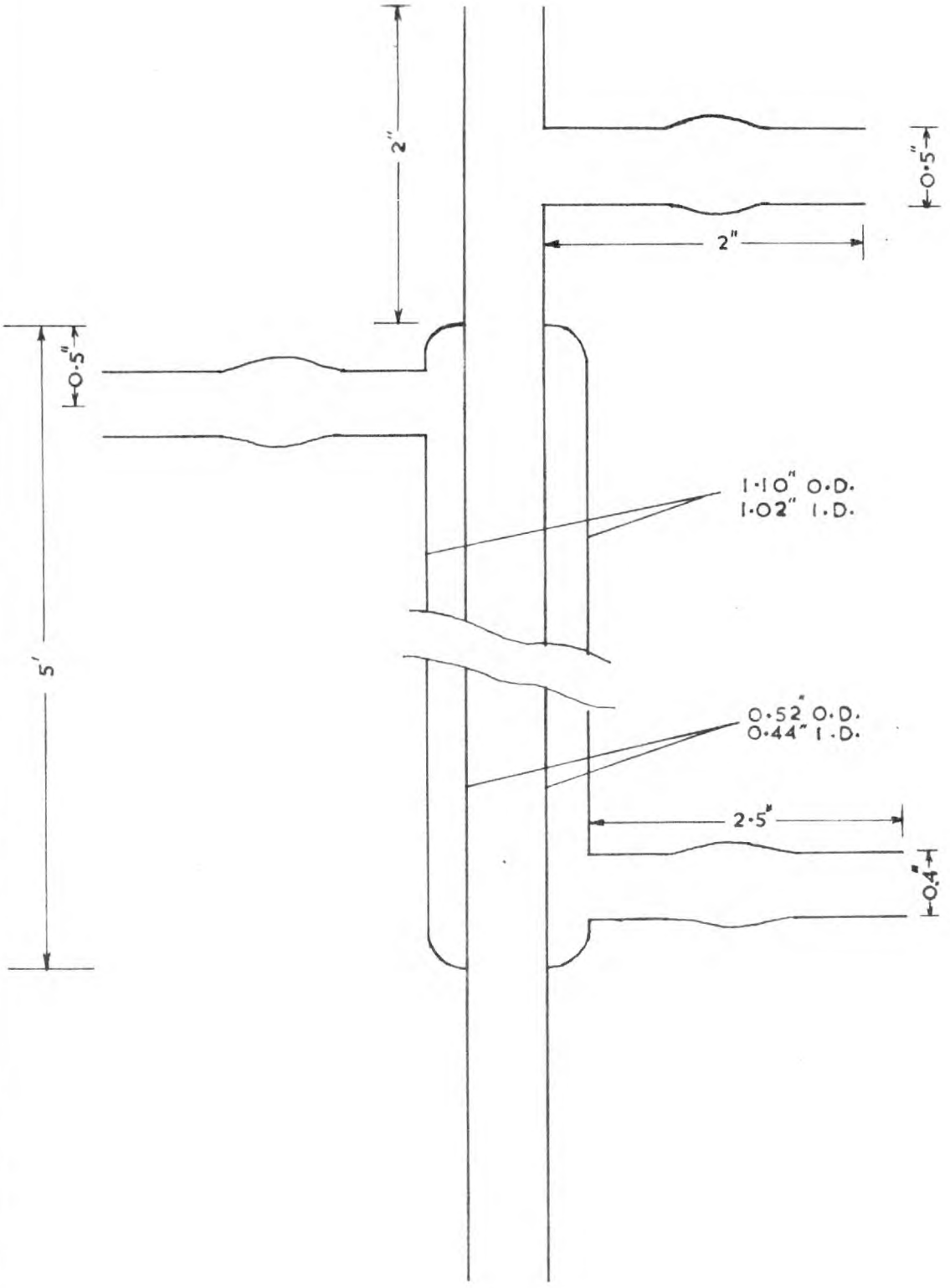
FIGURE 2 THE EQUIPMENT FLOWSHEET



EXPLANATION

1 HOT WATER TANK
2 STEAM COIL
3 STIRRER
4 STEAM TRAP
5 STEAM PRESSURE GAUGE
6 NEEDLE VALVE
7 GLOBE VALVE
8 STEAM LINE
9 HOT WATER CIRCULATING PUMP
10 THERMOMETER
11 FEED TANK
12 ELECTRIC IMMERSION HEATER
13 LIQUID FEED LINE
14A ROTAMETER
14B MERCURY MANOMETER
15 GLASS EVAPORATOR TUBE
16 GLASS JACKET
17 VAPOUR LIQUID MIXTURE LINE
18 VAPOUR SEPARATOR
19 VAPOUR LINE
20 CONCENTRATE LINE
21 CONDENSER
22 GRADUATED GLASS TUBE
23 COOLER
24 CONCENTRATE RECEIVER
25 CONDENSATE RECEIVER
26 VACUUM LINE
27 AIR ADMITTANCE CONTROL VALVE
28 VACUUM RELEASE LINE
29 PRESSURE EQUALISING LINE
30 COOLING WATER LINE
31 HOT WATER CIRCULATING LINE

FIGURE 3 DETAIL OF LONG TUBE GLASS EVAPORATOR



CHAPTER 3.

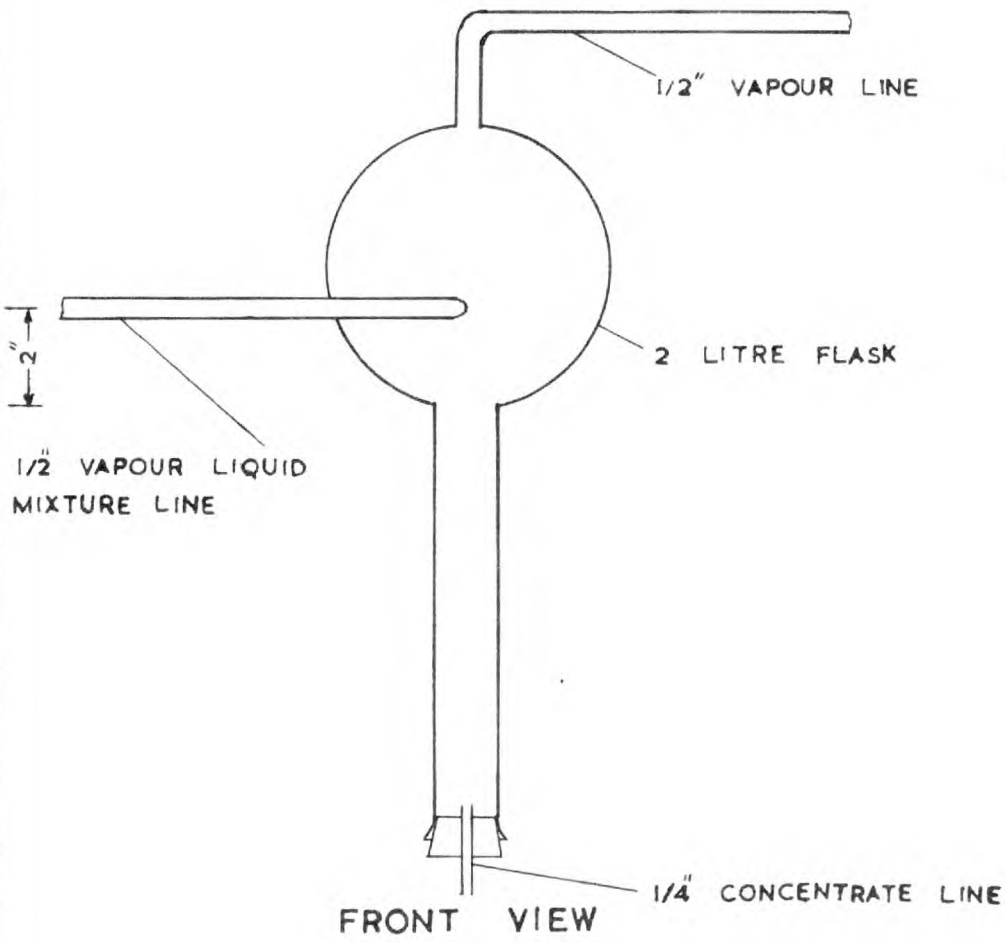
A. Description of Equipment.

With a view to obtaining visual observations of climbing film evaporation, a small unit was constructed of glass. A photograph of the unit is shown in Plate 1 and the equipment flowsheet in Figure 2. It was possible with such a unit to observe when boiling commenced and at the same time to obtain heat transfer data over the range of operating conditions.

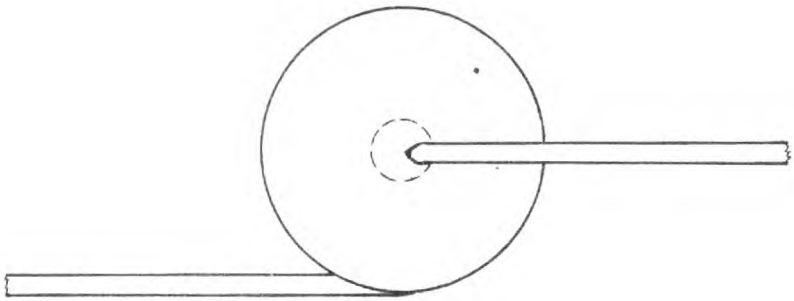
3.1. Evaporator.

This consisted of a pyrex glass tube, internal diameter 0.44 inch and outside diameter 0.52 inch, jacketed by another pyrex glass tube, internal diameter 1.02 inches and outside diameter 1.10 inches. The outer tube was scaled to the inner tube at the ends, as shown in Figure 3. The jacketed length was 5 ft., so that the ratio of length to inside diameter was 137:1, which is considered within the usual range for a long tube evaporator. The effective surface area for heat transfer on the basis of inside diameter was 0.572 sq.ft. The evaporator is shown as items 15 and 16 in Figure 2, and structural details are given in Figure 3. Tee connections at the top and bottom were provided for fixing thermometers. The top

FIGURE 4 DETAIL OF VAPOUR SEPARATOR



FRONT VIEW



TOP VIEW

outlet tube from the evaporator to the vapour separator was kept as short as possible to reduce the pressure drop as well as the heat loss.

3.2. Vapour Separator, Feed Tank & other units.

The vapour separator, shown in Figure 4, was constructed from a 2-litre round bottomed flask fitted with tangential side piece for admission of the vapour-liquid mixture. This form of centrifugal separator gave no measurable entrainment when tested with a weak dye solution. The high vapour velocity of 150 ft./sec. at the outlet, whilst giving good mixing in the tube, enables good separation to be achieved in the separator.

A round brass tank of 4 gallons capacity with a flat bottom was used as the feed tank. It was provided with a 1250 watts immersion heater, a bimetallic thermostat for temperature control, a stirrer and a thermometer pocket.

A cooler and condenser available from the laboratory were fitted up in the concentrate and vapour line, respectively. As the condenser was handling low temperature vapour, a large surface area was required. The surface area in any one condenser was not sufficient, and three condensers were connected together.

Two aspirator bottles, each of 10 litres capacity and fitted with outlet taps, were used as concentrate

and condensate receivers.

A long graduated tube was specially made and fitted in the condensate line in order to measure the amount of condensate collected during a definite time interval. A bypass connection to vacuum was fitted to it.

A large rectangular galvanised iron tank of 47 gallons capacity was used for heating water. This large size of the tank, when fitted with an efficient stirrer, was very useful in smoothing out irregularities in the heat load and gave good control of temperature. Electric immersion heaters with a total capacity of 5 kilowatts were provided for heating. Later on, a closed steam coil immersed in the tank was used and found more convenient.

Hot water was circulated by a centrifugal pump, the maximum available flow rate through the annulus being 1070 lbs./hr. This gave a maximum temperature drop of 4 °F from inlet to outlet. A ½" brass pipe line was used for recycling hot water.

All the connections for the feed tank, rotameter, evaporator, receivers, etc., were made by pressure rubber tubing and rubber stoppers. It is of interest to note that, in spite of the number of such fittings, practically no vacuum leakage occurred.

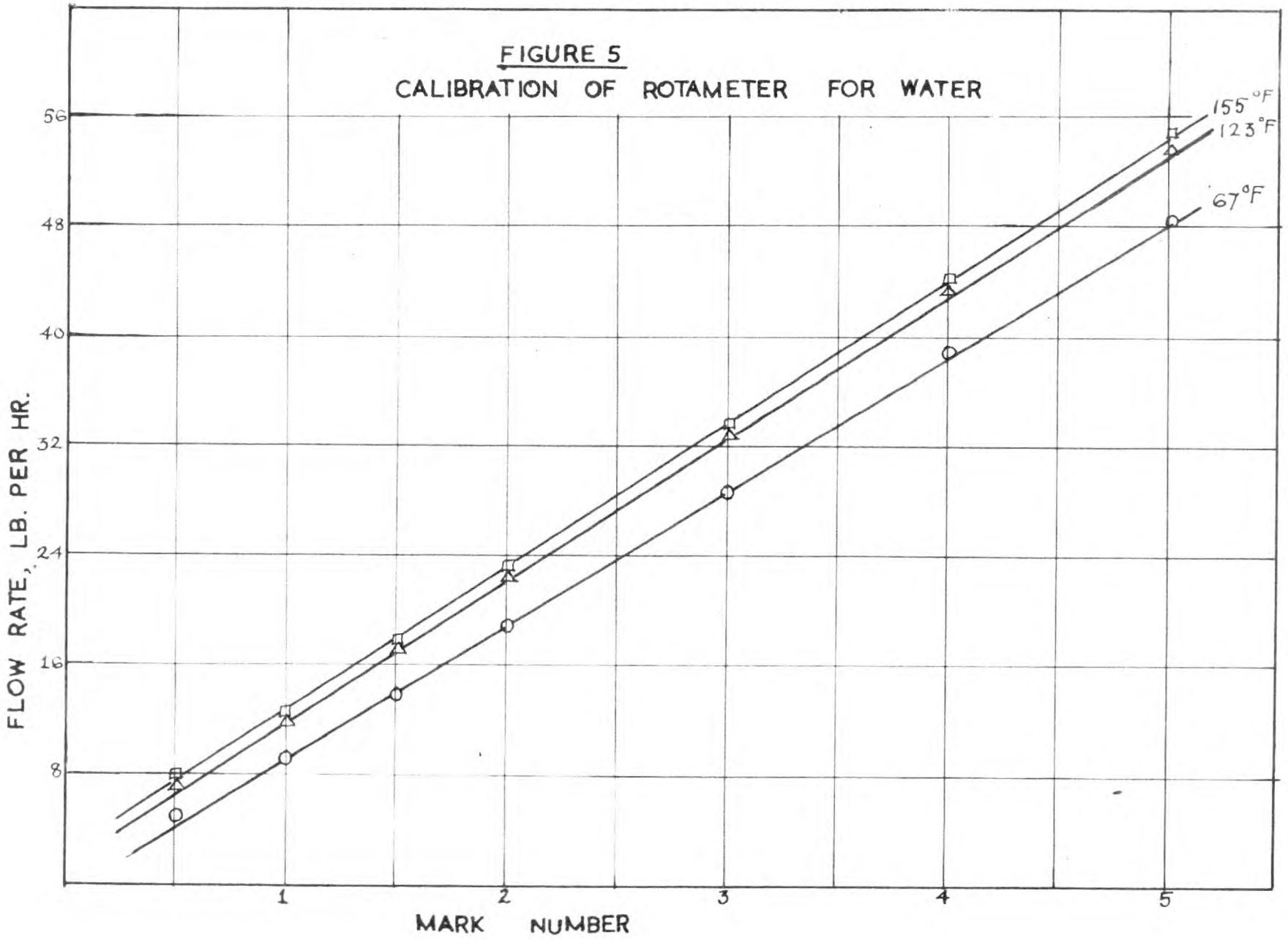

FIGURE 5
CALIBRATION OF ROTAMETER FOR WATER
155 °F
123 °F
67 °F
56
48
40
32
24
16
8
FLOW RATE, LB. PER HR.
1
2
3
4
5
MARK NUMBER

FIGURE 6

CALIBRATION OF ROTAMETER FOR 40 PER CENT SUCROSE SOLUTION

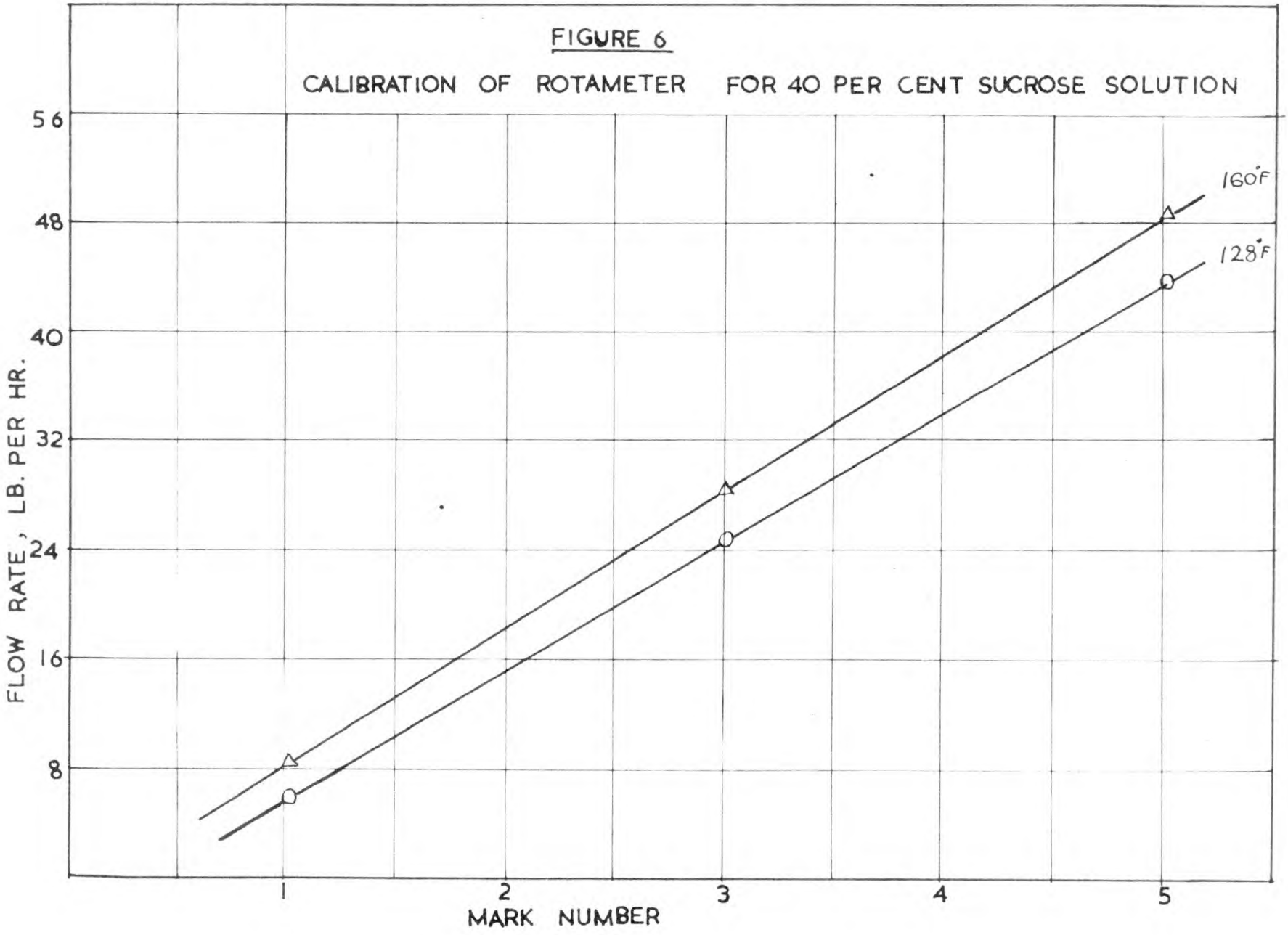
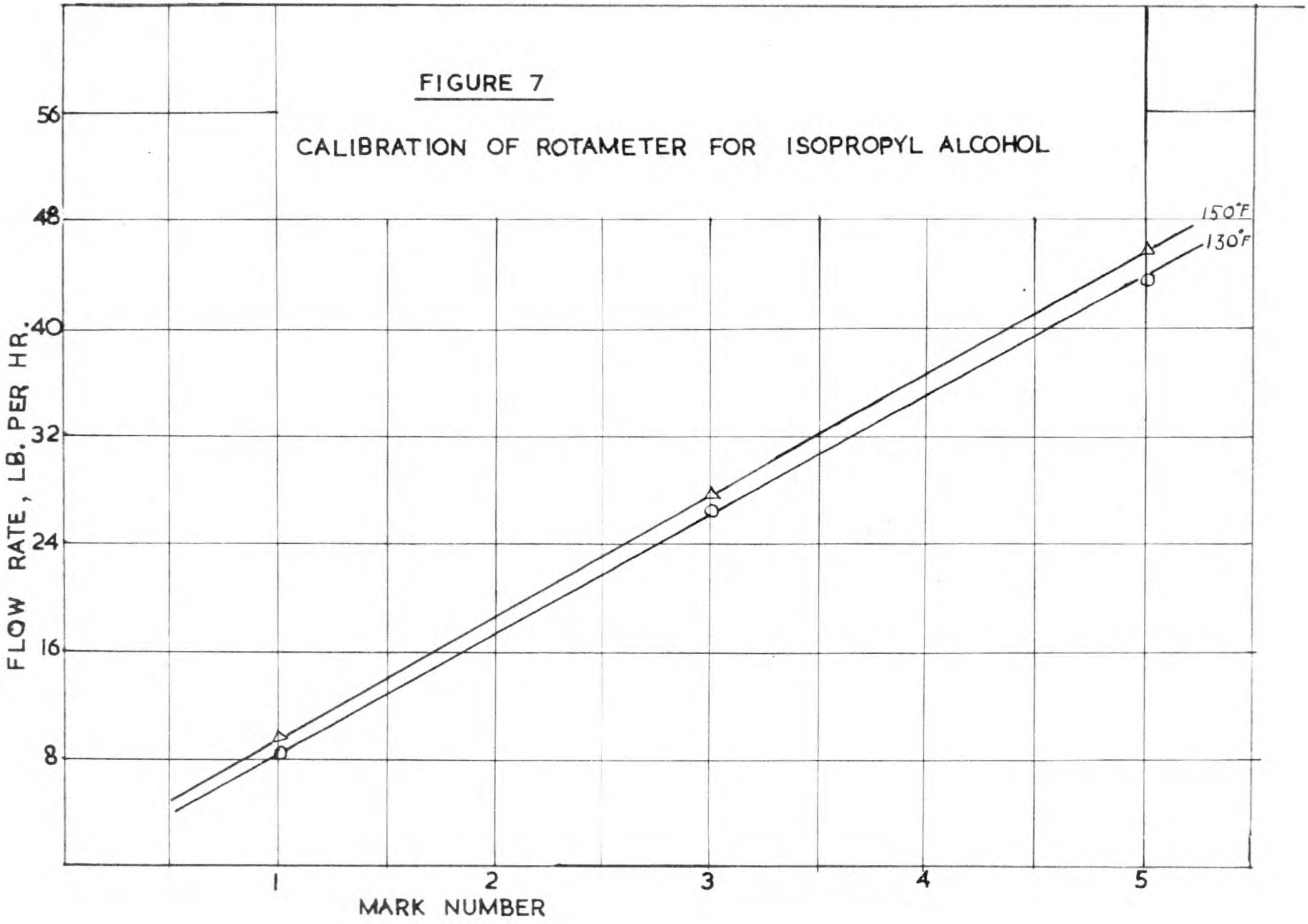


FIGURE 7

CALIBRATION OF ROTAMETER FOR ISOPROPYL ALCOHOL



The feed line to the evaporator and the vapour line from the evaporator to the separator were lagged with asbestos rope. The separator was also lagged in the same way. In order to make visual observations of the boiling phenomena, the evaporator was kept unlagged.

The plant was assembled and supported by 'Dexion' angle structure occupying a space of about 35 cubic ft.

B. Measurement and Control Devices.

The flow rate for the feed was measured by a rotameter and controlled by a stainless steel needle valve. Due to large changes in the viscosities of the liquids with temperature, calibration graphs had to be prepared for different temperatures and for each liquid. Figures 5, 6, 7 show such calibration curves for condensate water, 40 per cent sucrose solution and isopropyl alcohol respectively.

By keeping 40 gallons of hot water in circulation, the level of water in the large tank was maintained at about 4 inches from the top. In this way, the suction head on the circulating pump was held steady and, with the outlet valve wide open and the bypass valve closed, the pump continuously gave its maximum output at a steady rate. There was some difficulty encountered in the initial experiments. The pump was driven by a D.C. motor

and the voltage fluctuations in D.C. supply led to speed variations. On changing to an A.C. motor, no further trouble was experienced with the circulation of hot water.

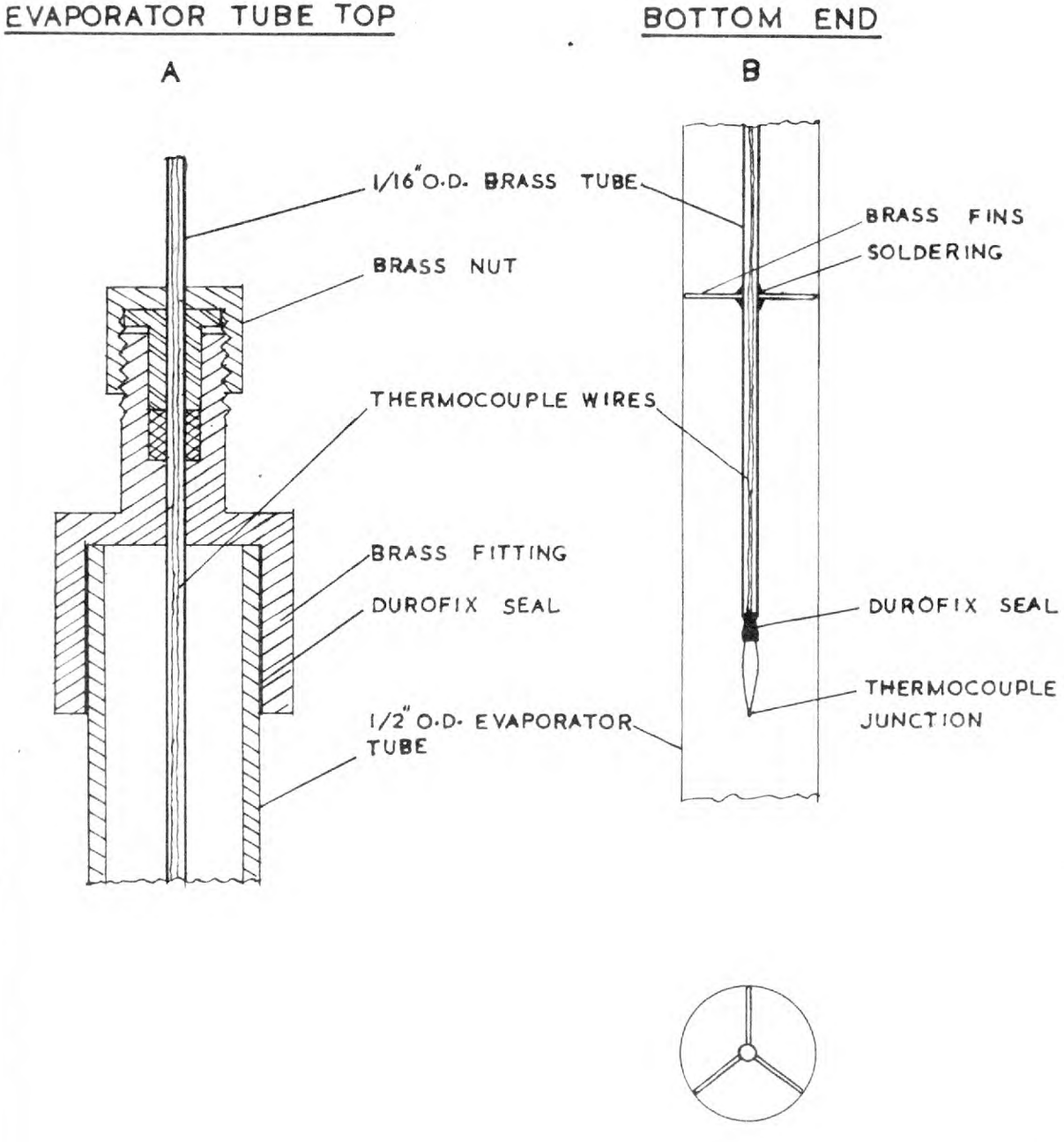
The temperature in the feed tank was shown by a thermometer and controlled automatically by means of bimetallic thermostat in conjunction with a high vacuum switch. This device was suitable for dealing with the large range of operating temperatures.

The hot water tank was fitted with one immersion heater of 2 KW and three heaters of 1 KW. A bimetallic thermostat control similar to that on the feed tank was connected to one of the 1 KW heaters, and the other heaters were fitted with individual switches. With this arrangement, suitable control of the electric heating system was obtained. Later, during the operation of the stainless steel tube evaporator for which steam heating was adopted because of the necessity for higher heat flux, it was found that good control of the temperature could be obtained by means of a needle valve fitted in the steam line. The electric heating system to the glass evaporator unit was then replaced by a steam coil with control by needle valve. This method proved better because, once carefully adjusted, the valve maintained the temperature

constant for a long period, whereas in the case of electric heating there is continuous fluctuation in heat supply, due to 'Of' and 'On' action.

At the outset, thermometers with graduations of 0.2°F were used for the measurement of hot water inlet and outlet temperatures. To obtain higher accuracy in the determination of heat flux, thermometers with graduations of 0.1°F were used. These thermometers, with very short ranges of temperature, longer length and wider spacing of graduations, could be read to 0.02°F. The heat flux could thus be found to $\pm$ 20 B.T.U./hr. from the temperature drop of hot water from inlet to outlet. This accuracy in the heat flux measurements, which is the basis of all heat transfer calculations, is almost unattainable when using direct steam heating. The temperature of boiling liquid which varied over the tube length from 5 to 10°F could not be measured better than 0.2°F. It should be noted that the error of 0.2°F in the temperature measurement of boiling liquid will cause an error in the value of the heat transfer coefficient of less than 3 per cent when working at as low as 10°F overall temperature difference. In order to check against calibration errors, if any, the inlet and outlet thermometers were interchanged under the

FIGURE 8 DETAIL OF CONSTRUCTION OF TRAVELLING THERMOCOUPLE



(SCALE 2:1)

condition of idle running of the evaporator and no difference in the temperature drop of hot water was noted.

In the earlier stages of the investigation, vacuum was maintained by means of a high pressure water ejector. The vacuum obtained was quite sufficient for the plant, but the control was rather difficult, due to variations in water pressure. Later, when a vacuum pump was available, the control became much better and was obtained by admitting air through a fine bore pressure rubber tube controlled by a screwed clip. An alternative control was by a fine air admittance control valve. Both were equally satisfactory. A mercury manometer, constructed from $\frac{1}{8}$" bore glass tube was used for measuring the vacuum in the system.

In order to get some idea of the temperature gradient of boiling liquid along the tube, a travelling thermocouple was constructed. A $\frac{1}{16}$" O.D. brass tube, with fine bore and 6 ft. in length, was used for encasing 32 S.W.G. enamelled and silk covered copper and constantan wires. The thermocouple junction projected about half an inch from the end of the brass tube, to minimise conduction errors. The sealing at the end of the brass tube was carried out with 'Durofix'. The construction is shown in Figure 8b. Three brass fines were soldered to the brass tube some two inches from the end to keep the thermocouple junction in the

centre of the evaporator tube. The construction for fixing at the top of the evaporator tube to maintain a vacuum tight system during the movement of thermocouple tube is shown in Figure 8a. The whole fitting was fastened to the evaporator tube by 'Durofix'. The movement of the travelling themocouple was carried out by pushing the tube up or down manually. The thermocouple was calibrated against a standard themometer before use. The temperature readings were obtained with a normal potentiometer circuit. After taking about 40 runs, a crack in the evaporator tube was noticed at a point where the thermocouple fitting was attached. This was thought to be due to the frequent jerks occurring while moving the couple up and down. The more elaborate arrangement for the travelling thermocouple evolved for the stainless steel tube evaporator will be described later.

C. Range of Experiments.

The main variables studied were:

1. Feed rate - 4 to 48 lbs./hr.
2. Apparent temperature difference - 8 to 55°F.
3. Feed temperature - 65 to 125°F.
4. Temperature level - 105 to 160°F.
5. Range of physical properties, by using:
   (i) condensate water,
   (ii) 0.01% Teepol solution,
   (iii) 40% sucrose solution,
   (iv) isopropyl alcohol.

   (Physical properties of the above liquids are given in Table No. A, on page 38)

Hot water was used as the heating agent. The higher limit for temperature in the hot water tank was fixed at about 185°F. In order to study a reasonable range of temperature difference without placing an excessive demand for condenser surface area, the boiling temperature of the liquid at the top was arbitrarily fixed at 130°F and for the sake of regularity, it was maintained constant throughout, except for runs taken to study the effect of temperature level.

D. Test Procedure.

In the beginning, a number of preliminary runs were taken with condensate water keeping the feed temperature below boiling point. For all the later runs which are reported in detail the feed was kept at the boiling temperature. This enabled the average boiling temperature to be taken from the temperature at the bottom and top of the tube, so that heat transfer coefficients could be calculated on the basis of true temperature difference.

A fun consisted of continuous operation under constant conditions for a period of 10 minutes. This time interval was considered sufficient with this unit of very small holding capacity. During the operation, the temperatures of hot water and the inlet and outlet temperatures of boiling liquid at the bottom and the top were noted every

3 minutes. Vacuum, feed rate, and hot water temperature were maintained constant. The values used for calculations were the averages of the three readings taken in each case. Vapour condensate was collected in the graduated tube during the time interval and the amount noted at the end of the run.

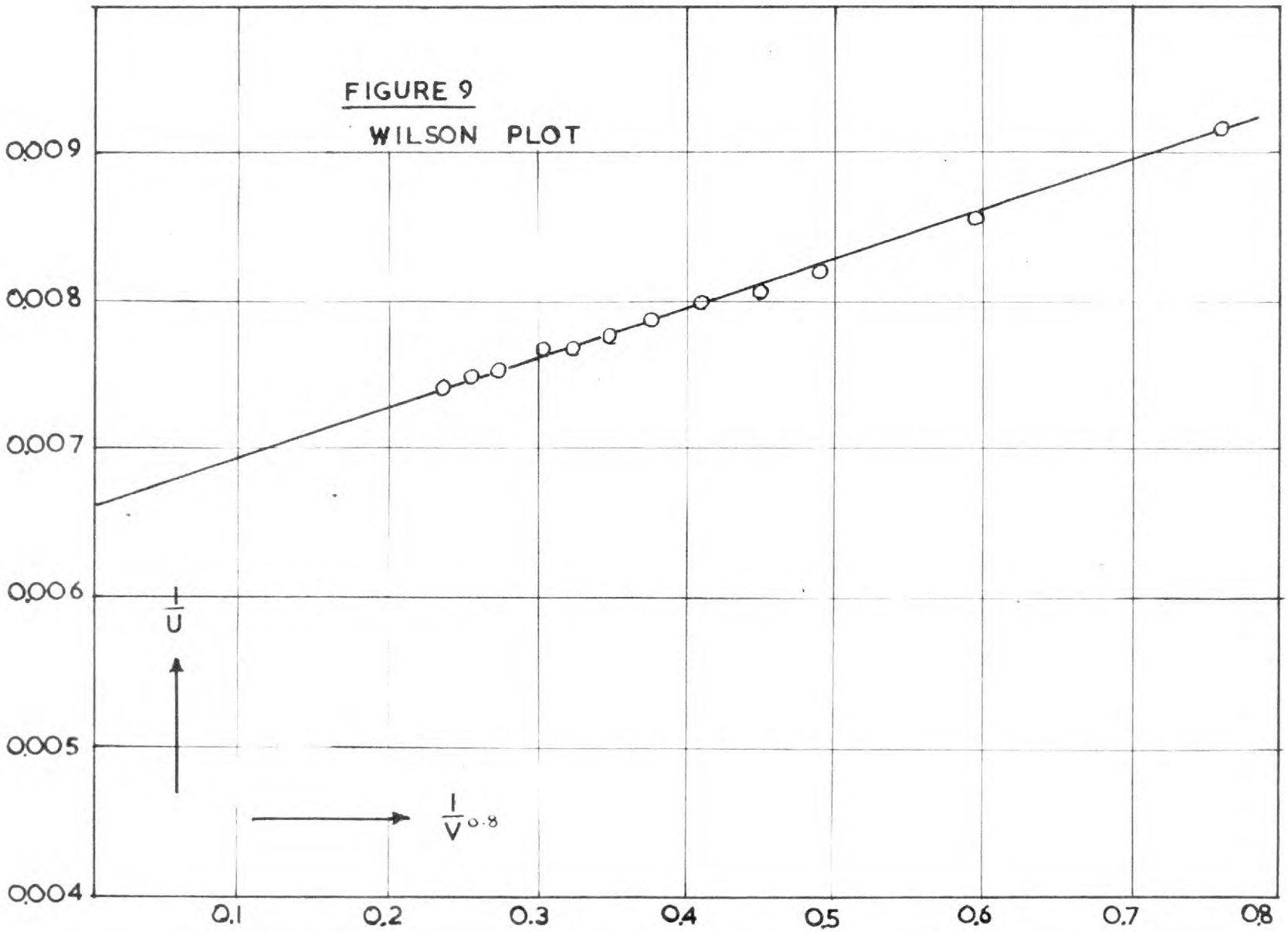
Heat flux was determined from the temperature drop of the hot water from inlet to outlet. The temperature drop of the hot water with no liquid in the inner tube was also determined for every run. This, when deducted from the previous readings, gave the actual temperature drop of hot water due to heat transfer to the boiling liquid.

The feed temperature had to be adjusted for every run, so that the liquid boiled at the bottom of the evaporator.

E. Determination of Boiling Film Coefficients.

It was desirable to determine the boiling film coefficients (h_B) and, in view of the high thermal resistance of the glass wall, this coefficient would be much greater than the overall heat transfer coefficient. Even though this film coefficient cannot be found with great accuracy for this evaporator, it is of interest to compare the values with those found later with the stainless steel unit.

Two methods were available, namely the direct method depending on tube wall temperatures and the indirect method


FIGURE 9
WILSON PLOT
0.009
0.008
0.007
0.006
0.005
0.004
1/U
1/V^0.8
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

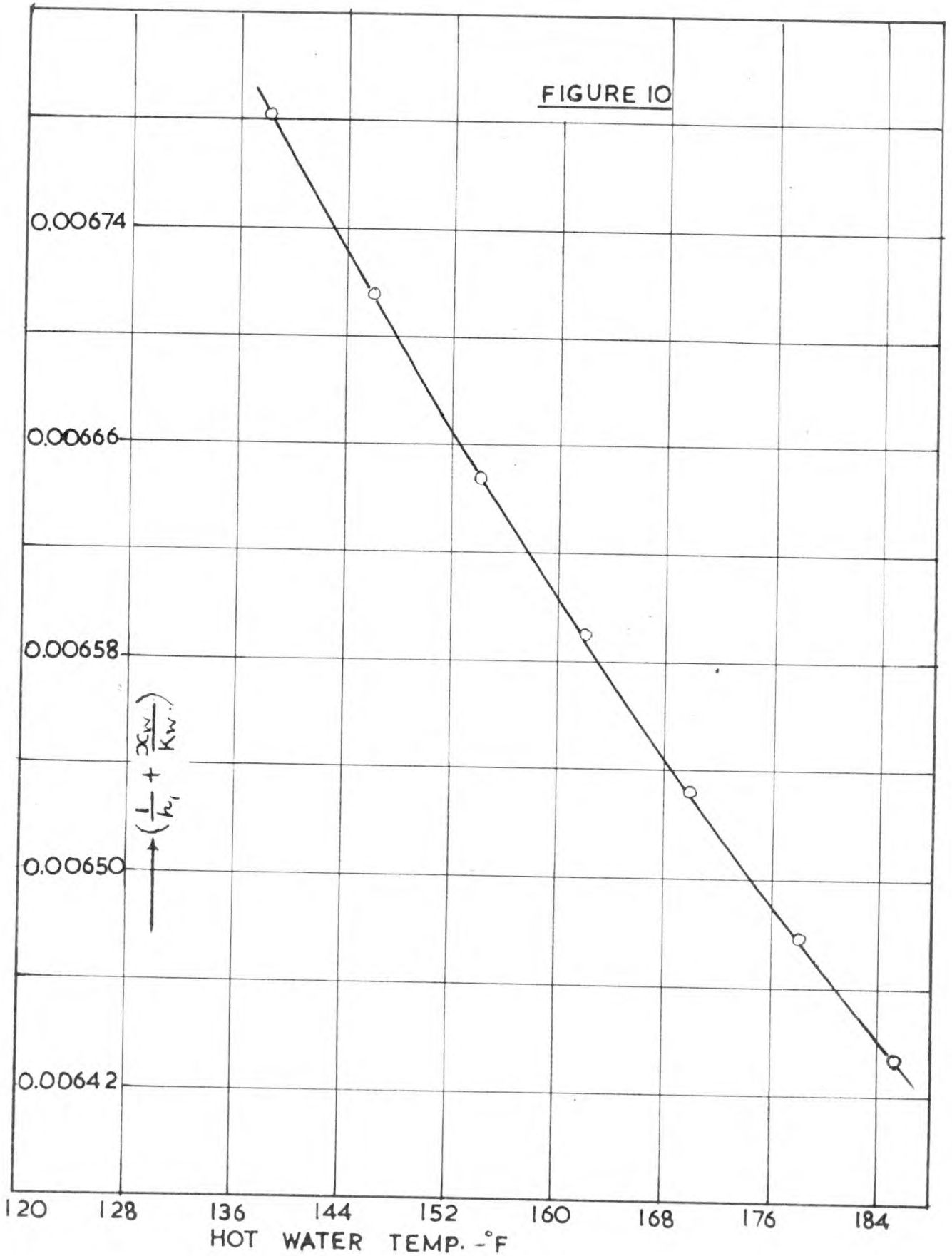
using the Wilson plot. The first method is difficult with glass surfaces and hence the second method was used. This is considered fairly accurate when hot water is used as the heating medium for the annulus film coefficient will remain constant. The method is to pass hot water through the annulus at a constant rate and temperature and cold water through the inner tube at varying rates, so that it does not boil but is only heated. A series of tests were carried out and the values of the heat transfer coefficients from hot to cold water were obtained. The values, with other calculated results, are presented in Table I. A plot of $\frac{1}{U}$ versus $\frac{1}{V^{0.8}}$ is shown in Figure 9. Referring to the curve, the intercept on the Y axis gives the value of $(\frac{1}{h_1} + \frac{xw}{Kw})$, the combined resistance of the outer film (h_1) and the tube wall $(\frac{xw}{Kw})$. Deducting the value of the resistance of the tube wall from the value of the intercept gives the annulus film resistance for one temperature. The values of the annulus film resistance for other temperatures were obtained by the simplified relation

$$h \propto (1 + 0.011\ t)$$ where t = bulk temperature of water, °F.
h = film coefficient.

for water derived from the equation

$$\frac{hD}{K} = 0.023 \left(\frac{DG}{\mu}\right)^{0.8} \left(\frac{C\mu}{K}\right)^{0.4} \quad .. \quad .. \quad .. \quad (5A)$$

and shown by McAdams[16].


FIGURE 10
0.00674
0.00666
0.00658
0.00650
0.00642
$\left(\frac{1}{h_i} + \frac{x_w}{K_w}\right)$
120
128
136
144
152
160
168
176
184
HOT WATER TEMP. - °F

The combined values of the resistance $(\frac{1}{h_1} + \frac{x_W}{K_W})$ versus hot water temperature were plotted as shown in Figure 10.

In the equation for individual resistances, when carrying out evaporation, is

$$\frac{1}{UA} = \frac{1}{h_1 A_1} + \frac{x_W}{K_W A_W} + \frac{1}{h_B A_B} \quad .. \quad .. \quad .. \quad .. \quad (5B)$$

where h_B = boiling film coefficient. The values of $\frac{1}{UA}$ and $(\frac{1}{h_1 A_1} + \frac{1}{K_W A_W})$, when substituted gave the value of the boiling film coefficient.

CHAPTER 4.

Appearance of Boiling Liquid during Evaporation.

Visual observations were made of the boiling phenomena in the glass tube evaporator, with different liquids, over a range of operating conditions. The influence of the following factors was noted:-

1. Temperature difference.
2. Feed temperature.
3. Feed rate.
4. Physical properties, by using
   (i) condensate water,
   (ii) sucrose solution,
   (iii) 0.01 per cent Teepol solution,
   (iv) isopropanol.

The physical properties of the above liquids together with the vapour density at 140°F are given in Table No. A.

Table No. A.

Liquid.	ρ_L	μ_l	K	C	σ	λ	$\frac{C\mu}{K}$	ρ_v
Condensate water.	61.2	0.45	0.381	1.00	66.2	1003	2.86	0.008
0.01% Teepol solution.	61.2	0.45	0.381	1.00	47.0	1003	2.86	0.008
0.10% Teepol solution.	61.2	0.45	0.381	1.00	33.0	1003	2.86	0.008
20% sucrose solution.	66.8	0.82	0.339	0.86	67.2	1003	5.03	0.008
30% sucrose solution.	69.5	1.26	0.317	0.79	67.6	1003	7.60	0.008
40% sucrose solution.	72.6	1.96	0.296	0.74	69.3	1003	11.86	0.008
Isopropanol.	49.0*	0.79	0.080	0.76	21.7*	286	18.00	0.060

* 20°C.

ρ_l = density of liquids, lbs./cu.ft.
ρ_v = density of saturated vapour, lbs./cu.ft.
μ_l = viscosity, centipoises.
K = thermal conductivity, B.T.U./hr./ft./°F.
C = specific heat, B.T.U./lb./°F.
σ = surface tension, dynes/cm.
λ = latent heat of vaporisation, B.T.U./lb.
$\frac{C\mu}{K}$ = Prandtl's number.

A. Effect of Temperature Difference.

Operating the evaporator with the condensate water, with the feed rate of 17.5 lbs./hr., feed temperature at boiling point, top temperature, 130°F, the apparent temperature difference was varied from 8° to 55°F.

At very low temperature difference, such as 8°F, it took some five to six minutes to obtain steady boiling throughout the length of the tube. Slugs of liquid pushed upward by rising vapour bubbles moved with fairly high velocity. With further increase in temperature difference, the frequency of slug formation increased and their lengths decreased. With the temperature difference of about 20°F, the slugs just before reaching the top of the tube, appeared to break into thick irregular film of liquid moving up rather slowly over the tube surface. This action at the top of the tube may be considered as of the film type. With still further increase in temperature difference, the length of the slug action decreased and that of film action increased till, at 55°F, the slug length was reduced

to about 6 inches. At high temperature difference, the liquid film over the tube surface assumed the shape of rings, probably due to the combined action of the rising liquid film under the influence of high vapour velocity, and falling under the influence of gravity. These observations show that the rate of vaporisation plays an important part in the boiling regime and indicate that, if steam is injected from the bottom of the tube, slug formation would be completely eliminated the boiling action over the whole length would be more or less uniform. From these observations it would seem probable that the type of boiling action encountered with a metal tube evaporator would be predominantly of the film type, save under the conditions of very low temperature difference.

B. Effect of Feed Temperature.

Using condensate water at a feed rate of 17.5 lbs./hr., top temperature 130°F and hot water temperature 162°F, the feed temperature was varied from 65°F to the boiling temperature at the bottom (137°F). The following effects were observed:

(1) The length of the heating section decreased and that of the boiling section increased gradually.

(2) The vaporisation rate gradually increased, with the result that the extent of slug action in the boiling section progressively decreased.

C. Effect of Feed Rate.

Two sets of experiments were carried out with condensate water to study the effect of feed rate with (a) cold feed and (b) hot feed (boiling temperature). The operating conditions were hot water - 162°F and top temperature - 130°F.

(a) Cold feed: At very low feed rates, the division between the heating and boiling section was fairly well defined and no bubbles of vapour were observed in the heating section. With increase in feed rate, the division into two sections became less marked, due to the presence of bubbles in the heating section. At high feed rate of the order of 48 lbs./hr., vapour bubbles of varying size formed at certain spots on the heating surface and appeared to travel upwards. There was an intermediate length of about 12 inches before true boiling started, the liquid and vapour being uniformly distributed in that length. These observations clearly show the presence of surface boiling in the heating section. Under these conditions, the heat transfer coefficients in the heating section would be higher in values than those given by Nusselt's equation for heating liquids inside the tubes. The presence of surface boiling in natural circulation evaporators has been mentioned by

Badger and Lindsay[11] in their recent review on evaporation.

(b) Feed at boiling temperature: With the same operating conditions as in (a), the feed was introduced at the boiling temperature so that the heating section was eliminated. With increase in feed rate, the slugs at the bottom of the tube and the film of liquid over the top surface of the tube appeared to move faster. The film of liquid at higher feed rate appeared to be thicker than that at lower feed rate.

D. Effect of Physical Properties.

To observe the effect of varying the physical properties of the liquid, sucrose solution, Teepol solution and isopropyl alcohol were used.

	Liquid.	Properties.
(a)	sucrose solutions.	higher viscosity.
(b)	0.01% Teepol solution.	reduced surface tension.
(c)	Isopropyl alcohol.	lower thermal conductivity, lower latent heat of vaporisation, higher vapour density, etc.

Physical properties are given in Table No. A (page 38).

(a) Sucrose solutions.

20-40% Solutions were used to study the effect of viscosity. A noticeable change in the boiling with increase in the

concentration of sucrose was in the time taken in reaching steady operation. The time taken with 40 per cent solution was 3 to 4 times that required with water. This was evidently due to very low heat transfer and, hence, the greater time required to produce sufficient vapour needed for the operation. During the operation, the liquid film moved slowly over the tube surface because of its greater viscosity. At very low feed rate and high temperature difference, the concentration of the liquid became so high at the top that the liquid layer thickened and moved very sluggishly. Even at very low temperature difference, of the order of 5-7°F, it was possible however to start the boiling operation.

(b) 0.01 per cent Teepol solution.

With this solution, the boiling phenomena was accompanied by the formation of considerable amounts of foam and by a large temperature drop along the length of the tube.

Operating at an apparent temperature difference of 8°F, a feed rate of 17.5 lbs./hr. and with the feed temperature at boiling point, the whole length of the tube was filled with foam moving rather slowly and no slug or liquid film could be seen. The foam appeared to decrease

a little while reaching the top of the tube. With increase in the temperature difference, the foam progressively decreased and at 24°F part of the tube surface at the top, with a thin film of liquid moving slowly over it, was visible. At the temperature difference of 55°F, the foam was confined to the bottom one third length of the tube. This decrease in the foam with increase in vaporisation rate showed that the chances of entrainment due to foam would be very much reduced in a metal tube evaporator operating with high heat flux.

(c) Isopropyl alcohol.

Isopropyl alcohol, although having physical properties very different from the other liquids, had no specific effect on the boiling phenomena, although the film action appeared to start at a rather lower temperature difference. The liquid film was more clearly defined and the annular rings were thinner and closer than those with water. The boiling action was more continuous and accompanied by smaller fluctuations in the boiling temperature at the top and the bottom of the tube. The maximum vapour velocity at the outlet was 60 ft./sec., while that for water, under the same conditions, was 160 ft./sec. This was due to the large difference in the specific volumes of isopropyl alcohol vapour and steam.

CHAPTER 5.

Presentation of Results.

Some 81 tests have been made with four different liquids under a range of operating conditions. Feed temperature was kept at boiling point for all the runs. The results of those tests are presented in Tables 2-5. The letter succeeding each run number indicates the series number. The explanation for the symbols used in the tables, together with the specimen calculation, is given at the end of the chapter.

Series:	Variable under Study:	Operating Conditions:
A	Temperature difference.	Feed rate 7.5 lbs./hr. Hot water temperature: 138-185°F. Top temperature: 130°F.
B	Temperature difference:	Feed rate 17.5 lbs./hr. Hot water temperature: 138-185°F. Top temperature: 130°F.
C	Feed rate.	Variation in feed rate. Hot water temperature: 162°F. Top temperature: 130°F.
D	Feed rate.	Variation in feed rate. Hot water temperature: 186°F. Top temperature: 130°F.
E	Temperature level.	Feed rate: 17.5 lbs./hr. Variation in boiling temperature Average overall temperature difference: 20°F.

A few preliminary tests with cold feed are described in the next Chapter (Section A.) and the details are given of the tests in Series A-E.

Table 1.

(Runs for Wilson plot).

Run No.	W_f	t_1	t_2	t_1'	t_2'	Q	Δt (log mean).	V	U	$\frac{1}{V^{0.8}}$	$\frac{1}{U}$
1	330	51.72	70.60	164.35	158.12	6203	99.79	1.41	109.1	0.760	0.00916
2	451	51.37	66.45	164.47	157.61	6803	101.80	1.93	116.9	0.592	0.00856
3	571	50.90	63.55	164.52	157.30	7224	103.50	2.44	122.0	0.490	0.00820
4	635	50.65	62.30	164.60	157.15	7404	104.20	2.71	124.3	0.450	0.00805
5	715	50.45	60.95	164.55	156.92	7510	104.80	3.05	125.2	0.409	0.00799
6	797	50.25	59.90	164.40	156.92	7695	105.40	3.40	127.4	0.375	0.00785
7	878	50.00	58.90	164.30	156.45	7810	105.90	3.75	129.0	0.347	0.00775
8	972	49.80	57.95	164.20	156.25	7920	106.40	4.15	130.2	0.321	0.00768
9	1041	49.77	57.42	164.10	156.15	7965	106.50	4.43	130.7	0.302	0.00765
10	1197	49.70	57.52	164.60	156.40	8165	107.30	5.11	133.0	0.271	0.00751
11	1314	49.60	55.90	164.60	156.40	8280	107.60	5.61	133.9	0.252	0.00747
12	1423	49.55	55.40	164.80	156.50	8330	107.90	6.07	135.2	0.236	0.00740

W_f = cold water feed rate, lbs./hr.

t_1, t_2 = cold water inlet and outlet temperatures, °F.

t_1', t_2' = hot water inlet and outlet temperatures, °F.

Q = heat transfer, B.Th.U./hr.

Δt = log mean temperature difference, °F.

V = velocity of cold water in the inner tube, ft./sec.

U = overall heat transfer coefficient (based on inside surface area of the tube). (B.Th.U./hr./sq.ft/°F)

Table 2.

Condensate Water.

Run No.	1A	2A	3A	4A	5A	6A	7A
W_f	7.5	7.5	7.5	7.5	7.5	7.5	7.5
t_1	134.2	133.9	134.1	134.3	134.3	134.5	135.0
T_1	138.40	146.63	154.48	163.10	170.18	178.50	185.84
T_2	137.67	145.35	152.63	160.81	167.28	175.00	181.67
t_2	129.9	129.9	129.9	130.0	129.8	130.0	130.3
$t_{Av.}$	132.1	131.9	132.0	132.15	132.05	132.25	132.60
$T_{Av.}$	138.03	145.99	153.05	161.96	168.73	176.75	183.75
$\Delta T_{Av.}$	5.93	14.09	21.05	29.81	36.68	44.50	51.15
cc.	25	73	116	155	190	258	274
m.	10	10	10	10	10	10	10
E	0.33	0.96	1.53	2.05	2.51	3.41	3.62
Ep	4.4	12.8	20.4	27.3	33.4	45.4	48.2
Q	410	1004	1555	2225	2765	3337	3996
Q/A	717	1756	2719	3890	4833	5834	6985
U_B	121.0	124.5	129.0	130.5	131.5	131.0	136.5
h_B	681	764	915	930	944	870	920
$t\Delta$	4.3	4.0	4.2	4.3	4.5	4.5	4.7
Δp	13.0	12.5	13.0	13.5	13.5	14.0	16.0
Δt	1.05	2.30	2.97	4.18	5.12	6.70	7.59
V_1	14	41	64	86	105	143	151

Table 2 (continued).

Condensate Water.

Run No.	8B	9B	10B	11B	12B	13B	14B
W_f	17.5	17.5	17.5	17.5	17.5	17.5	17.5
t_1	135.0	135.2	135.4	135.6	135.6	135.8	135.9
T_1	138.56	146.69	154.88	162.61	170.52	178.32	185.60
T_2	137.78	145.40	152.96	160.40	167.72	174.89	181.51
t_2	130.0	130.1	129.9	129.9	130.0	130.0	130.1
$T_{Av.}$	138.15	146.05	153.94	161.50	169.12	176.6	183.55
$t_{Av.}$	132.50	132.55	132.70	132.70	132.80	132.90	133.00
$\Delta T_{Av.}$	5.65	13.50	21.24	28.80	36.32	43.70	50.55
cc.	37	84	122	165	215	246	298
m.	10	10	10	10	10	10	10
E	0.49	1.11	1.61	2.18	2.84	3.25	3.93
Ep	2.8	6.3	9.2	12.4	16.2	18.6	22.5
Q	389	983	1555	2138	2857	3261	3909
Q/A.	680	1718	2719	3739	4644	5702	6834
U_B	120.3	127.3	128.0	130.0	128.0	130.0	135.0
h_B	654	875	871	898	776	844	1040
$t\Delta$	5.0	5.1	5.5	5.7	5.6	5.8	5.8
Δp	16.0	16.5	17.0	18.0	18.0	19.0	19.5
Δt	1.04	1.96	2.75	4.16	5.98	6.75	6.57
V_1	20	46	67	91	119	136	164

Table 2 (continued).

Condensate Water.

Run No.	15C	16C	17C	18C	19C
W_f	7.5	17.5	24.5	36.5	48
t_1	134.3	135.6	136.2	137.2	138.2
T_1	162.65	162.50	162.57	162.45	162.70
T_2	160.30	160.20	160.27	160.16	160.42
t_2	130.0	130.1	130.1	130.0	129.9
$T_{Av.}$	161.47	161.35	161.42	161.31	161.56
$t_{Av.}$	132.15	132.85	133.15	133.60	134.05
$\Delta T_{Av.}$	29.32	28.50	28.27	27.71	27.51
cc.	157	162	168	185	188
m	10	10	10	10	10
E	2.07	2.14	2.22	2.44	2.48
Ep	27.6	12.2	9.10	6.7	5.2
Q	2106	2052	2052	2041	2031
Q/A	3681	3588	3588	3569	3550
U_B	125.5	126	127	129	129
h_B	725	739	775	850	861
$t\Delta$	4.3	5.5	6.1	7.2	8.3
Δp	13.8	18	20	24	27.5
Δt	5.08	4.86	4.63	4.20	4.12
V_1	87	89	93	102	104

Table 2 (continued).

Condensate Water.

T

Run No.	20D	21D	22D	23D	24D	25D
W_f	4.5	7.5	17.5	24.5	86.5	48
t_1	134.3	134.6	135.7	136.4	137.9	139.0
T_1	186.00	184.84	185.24	185.37	185.40	185.12
T_2	181.69	180.67	181.08	181.21	181.28	181.07
t_2	130.2	130.0	129.8	129.8	130.0	130.0
$T_{Av.}$	183.84	182.75	183.16	183.29	183.34	183.09
$t_{Av.}$	132.25	132.30	132.75	133.10	133.95	134.50
$\Delta T_{Av.}$	51.59	50.45	50.41	50.19	49.39	48.59
m	10	10	10	10	10	10
cc.	270	279	285	297	316	320
E	3.56	3.68	3.76	3.92	4.17	4.22
Ep	79	49	21	16	11	9
Q	3985	3833	3823	3823	3780	3704
Q/A	6966	6702	6683	6683	6609	6476
U_B	135	133	133	133	134	133
h_B	1029	916	902	930	963	936
$t\Delta$	4.1	4.6	5.9	6.6	7.9	9.0
Δt	6.77	7.32	7.41	7.19	6.86	6.92

Table 2 (continued).

Condensate Water.

Run No.	26E	27E	28E	29E	30E	31E
W_f	17.5	17.5	17.5	17.5	17.5	17.5
t_1	116.1	126.6	137.5	148.3	157.2	164.7
T_1	134.11	145.02	157.76	167.67	178.08	184.75
T_2	132.34	143.17	155.65	165.80	176.08	182.67
t_2	108.0	121.1	132.5	144.0	153.8	161.8
$T_{Av.}$	133.23	144.09	156.7	166.73	177.08	183.71
$t_{Av.}$	112.05	123.85	135.0	146.15	155.50	161.80
$\Delta T_{Av.}$	21.18	20.24	21.70	20.58	21.58	21.91
m	10	10	10	10	10	10
cc.	120	111	120	110	119	116
E	1.58	1.46	1.58	1.45	1.57	1.53
Ep	9	8.4	9.0	8.3	9.0	8.7
Q	1479	1501	1642	1479	1555	1557
Q/A	2586	2624	2869	2586	2718	2722
U_B	122.1	129.6	132.2	125.4	126	126
h_B	748	1001	1066	710	686	666
$t\Delta$	8.1	5.5	5.0	4.3	3.4	2.9
Δt	3.46	2.62	2.69	3.64	3.96	4.14

Table 3.

0.01% Teepol Solution.

Run No.	32B	33B	34B	35B	36B	37B	38B
W_f	17.5	17.5	17.5	17.5	17.5	17.5	17.5
t_1	135.3	136.1	136.8	137.1	137.5	137.8	137.8
T_1	138.40	146.18	154.23	162.82	170.16	178.2	185.37
T_2	137.58	144.81	152.27	160.28	167.02	174.48	181.02
t_2	129.9	130.0	129.9	130.0	130.0	130.0	130.0
$T_{Av.}$	137.99	145.50	153.25	161.55	168.59	176.34	183.19
$t_{Av.}$	132.60	133.05	133.35	133.55	133.75	133.9	133.9
$\Delta T_{Av.}$	5.39	12.45	19.90	28.00	34.84	42.44	49.29
m	10	10	10	10	10	10	10
cc.	36	79	135	178	227	276	340
E	0.47	1.04	1.78	2.35	3.00	3.63	4.49
Ep	2.8	6.0	10.2	13.4	17.1	20.8	25.6
Q	410	972	1566	2268	2818	3424	3700
Q/A	717	1700	2738	3965	4926	5985	6469
U_B	133.1	136.5	137.6	141.6	141.5	141	142.1
h_B	1368	1634	1610	2110	2193	1520	1788
$t\Delta$	5.4	6.1	6.9	7.1	7.5	7.8	7.8
Δt	9.52	1.04	1.70	1.88	2.25	3.94	3.62

Table 3 (continued).

0.01% Teepol Solution.

Run No.	39C	40C	41C	42C	43C	44C
W_f	3.8	7.5	17.5	24.5	36.5	48
t_1	133	133.5	137	138.8	141.2	142.4
T_1	163.25	163.15	162.80	162.93	162.70	162.70
T_2	160.65	160.55	160.30	160.49	160.37	160.39
t_2	130.0	130.0	130.0	130.0	130.0	130.0
$T_{Av.}$	161.95	161.85	161.55	161.71	161.54	161.54
$t_{Av.}$	131.50	131.75	133.50	134.40	135.60	136.20
$\Delta T_{Av.}$	30.45	30.10	28.05	27.31	25.94	25.34
m	10	10	10	10	10	10
cc.	165	174	182	188	203	208
E	2.18	2.30	2.40	2.48	2.68	2.75
Ep	57.3	30.6	13.7	10.1	7.3	5.7
Q	2364	2364	2236	2171	2052	2031
Q/A	4134	4134	3908	3795	3588	3550
U_B	135.8	137.4	139.3	139.0	138.3	140.1
h_B	1290	1445	1697	1644	1558	1818
t_A	3.0	3.5	7.0	8.8	11.2	12.4
Δt	3.20	2.86	2.30	2.31	2.30	1.95

Table 4.

40% Sucrose Solution.

Run No.	45B	46B	47B	48B	49B	50B	51B
W_f	17.5	17.5	17.5	17.5	17.5	17.5	17.5
t_1	135.9	136.1	137.1	136.9	136.4	136.5	136.2
T_1	138.07	146.77	154.48	162.99	170.29	178.48	185.27
T_2	137.45	145.64	152.90	160.93	167.72	175.34	181.60
t_2	129.9	129.9	129.8	130.0	129.7	130.3	129.8
$T_{Av.}$	137.76	146.20	153.69	161.96	169.00	176.91	183.43
$t_{Av.}$	132.90	133.00	133.45	133.45	133.05	133.40	133.00
$\Delta T_{Av.}$	4.86	13.20	20.24	28.51	35.95	43.51	50.43
m	10	10	10	10	10	10	10
cc.	22	67	102	140	179	220	255
E	0.29	0.88	1.35	1.85	2.36	2.90	3.37
Ep	1.7	5.0	7.7	10.6	13.5	16.6	19.2
Q	302	832	1253	1825	2279	2808	3315
Q/A	529	1454	2191	3191	3984	4909	5795
U_B	108.7	110.1	108.2	111.9	110.9	112.8	114.9
h_B	415	423	386	426	401	419	441
$t\Delta$	6.0	6.2	6.3	6.9	6.7	6.2	6.4
Δt	1.27	3.44	5.68	7.48	9.93	11.70	13.15

Table 4 (continued).

40% Sucrose Solution.

Run No.	52E	53E	54E	55E	56E	57E
W_f	17.5	17.5	17.5	17.5	17.5	17.5
t_1	113.8	121.4	132.2	140.3	148.5	158.4
T_1	129.15	137.87	148.37	157.11	167.63	177.52
T_2	127.64	136.32	146.78	155.47	165.99	175.78
t_2	101.0	111.8	123.9	134.0	143.7	154.0
$T_{Av.}$	128.39	137.10	147.58	156.29	166.81	176.65
$t_{Av.}$	107.40	116.40	128.05	137.15	146.10	156.20
$\Delta T_{Av.}$	20.99	20.70	19.53	19.14	20.71	20.45
m	10	10	10	10	10	10
cc.	106	98	94	90	97	100
E	1.40	1.29	1.24	1.19	1.28	1.32
Ep	8.0	7.4	7.1	6.8	7.3	7.5
Q	1275	1220	1231	1210	1285	1296
Q/A	2228	2133	2152	2114	2247	2266
U_B	106.0	103.0	110.0	110.5	108.5	110.8
h_B	394	342	424	414	376	394
$t\Delta$	12.8	9.6	8.3	6.3	4.8	4.4
Δt	5.66	6.23	5.08	5.11	5.97	5.74

Table 4. (continued).

40% Sucrose Solution.

Run No.	58C	59C	60C	61C	62C
W_f	9.0	17.5	24.5	36.5	48.0
T_1	162.49	162.39	162.36	162.65	162.86
T_2	160.49	160.42	160.32	160.64	160.87
t_1	135.4	136.8	137.5	139.3	141.0
t_2	130	130	130	130	130
$T_{Av.}$	161.49	161.40	162.34	161.65	161.87
$t_{Av.}$	132.70	133.40	133.75	134.65	135.50
$\Delta T_{Av.}$	28.79	28.00	28.59	27.00	26.37
m	10	10	10	10	10
cc.	142	140	145	166	185
E	1.87	1.85	1.91	2.19	2.44
Ep	20.8	10.6	7.8	6.0	5.1
Q	1760	1728	1782	1750	1728
Q/A	3077	3021	3116	3059	3021
U_B	106.9	107.8	109.0	113.2	114.6
h_B	361	373	386	447	467
$t\Delta$	5.4	6.8	7.5	9.3	11.0
Δt	8.51	8.10	8.06	6.85	6.47

Table 5.

Isopropyl Alcohol.

Run No.	63B	64B	65B	66B	67B	68B	69B
W_f	17.5	17.5	17.5	17.5	17.5	17.5	17.5
t_1	132.3	132.0	131.8	131.6	131.7	131.7	131.8
T_1	138.01	146.62	154.28	162.31	170.45	178.53	185.35
T_2	137.30	145.49	152.70	160.64	168.25	175.84	182.18
t_2	129.8	130	130	130	130	130	130
$T_{Av.}$	137.65	146.06	153.49	161.48	169.35	177.18	183.77
$t_{Av.}$	131.05	131.00	130.90	130.80	130.85	130.85	130.90
$\Delta T_{Av.}$	6.60	15.06	22.59	30.68	38.50	46.33	52.87
m	10	10	10	10	9	7	6
cc.	68	190	295	390	470	441	443
E	0.70	1.97	3.06	4.04	5.41	6.53	7.65
Ep	4.0	11.3	17.5	23.10	30.9	37.3	43.7
Q	302	724	1166	1566	2019	2495	2938
Q/A	529	1265	2039	2738	3530	4361	5136
U_B	80.1	84	90.3	89.3	91.7	94.1	97.1
h_B	175	192	226	217	228	241	259
$t\Delta$	2.5	2.0	1.8	1.6	1.7	1.7	1.8
Δp	14	12	12	10	10	10	10
Δt	3.00	6.57	9.04	12.63	15.45	18.10	19.81
V_1	6.8	15.0	24	32	41	51	60

Table 5 (continued).

Isopropyl Alcohol.

Run No.	70C	71C	72C	73C	74C	75C
W_f	12.4	17.5	24.5	36.5	48	58
t_1	131.4	131.7	132.0	132.7	132.9	133.8
T_1	162.86	162.53	162.75	162.56	162.22	162.50
T_2	161.11	160.77	160.98	160.75	160.41	160.65
t_2	130.0	130.0	130.0	130.0	129.9	130.0
$T_{Av.}$	161.98	161.65	161.87	161.66	161.31	161.58
$t_{Av.}$	130.70	130.85	131.00	131.35	131.40	131.90
$\Delta T_{Av.}$	31.28	30.80	30.87	30.31	29.91	29.68
m	10	10	10	10	10	9
cc.	388	400	436	500	480	464
E	4.02	4.15	4.52	5.18	4.97	5.34
Ep	32.4	23.7	18.4	14.2	10.4	9.2
Q	1588	1600	1609	1652	1652	1695
Q/A	2774	2795	2813	2889	2889	2964
U_B	88.7	90.7	91.1	95.3	96.5	99.9
h_B	214	225	228	256	266	292
$t\Delta$	1.4	1.7	2.0	2.7	3.0	3.8
Δt	13.0	12.4	12.3	11.3	10.9	10.1

Table 5. (continued).

Isopropyl Alcohol.

Run No.	76E	77E	78E	79E	80E	81E
W_f	17.5	17.5	17.5	17.5	17.5	17.5
t_1	107.8	114.9	122.0	128.8	137.3	145.1
T_1	127.49	135.07	141.70	149.15	157.55	165.22
T_2	126.21	133.72	140.31	147.80	156.02	163.98
t_2	104.0	112.1	120.0	127.9	136.0	144.1
$T_{Av.}$	126.85	134.39	141.00	148.48	156.79	164.60
$t_{Av.}$	105.90	113.50	121.00	128.80	136.65	144.60
$\Delta T_{Av.}$	20.95	20.89	20.00	19.68	20.14	20.0
m	10	10	10	10	10	10
cc.	275	258	245	246	228	225
E	2.85	267	2.54	2.55	2.36	2.33
Ep	16.3	15.3	14.5	14.6	13.5	13.3
Q	994	1004	983	972	1026	1004
Q/A	1737	1756	1718	1700	1794	1756
U_B	82.9	84	85.9	86.3	89.1	87.8
h_B	194	197	205	205	217	208
$t\Delta$	3.8	2.8	2.0	1.8	1.3	1.0
Δt	8.96	8.93	8.38	8.29	8.23	846

Explanation for Symbols and Specimen Calculation.

Reference: Run No. 5A (Table 2.)

Symbol.	Value.	Units.	Explanation.
W_f	7.5	lbs./hr.	feed rate of the liquid to the evaporator tube.
t_1	134.3	°F.	temperature of the boiling liquid at the bottom of the tube. (average of three readings).
t_2	129.8	°R.	temperature of the boiling liquid at the top (average of three readings).
T_1	170.18	°F.	temperature of hot water inlet to evaporator jacket. (average of three readingts).
T_2	167.28	°F.	temperature of hot water outlet to evaporator jacket. (average of three readings).
$t_{Av.} = T$	132.05	°F.	average temperature of boiling liquid (arith. mean of 134.3 and 129.8).
$T_{Av.}$	168.73	°F.	average temperature of hot water. (arith. mean of 170.18 and 167.28).
$\Delta T_{Av.} = \Delta T$	36.68	°F.	average overall temperature difference (168.73-132.05).
cc.	190	cubic cm.	vapour condensed from separator.
m	10	mins.	duration of test.
E	2.51	lbs./hr.	rate of evaporation $\frac{190}{1000} \times 0.22 \times \frac{60}{10} \times 10 = 2.51$
E_p	33.4	%	$\frac{\text{Evaporation}}{\text{Feed rate}} \times 100 = \frac{2.51}{7.50} \times 100 = 33.4$
Q	2765	B.T.U./hr.	(actual temp. drop of hot water - temp. drop during idle running) x 1070 = 2765

Symbol.	Value.	Units.	Explanation.
$\frac{Q}{A}$	4833	B.T.U./hr./sq.ft.	$\frac{2765}{\text{(surface area of heating tube based on inside diameter)}}$ $= \frac{2765}{0.572} = 4833$
U_B	131.5	B.T.U./hr./sq.ft/ °F.	$\frac{Q}{A.\Delta T_{Av.}} = \frac{4833}{36.68}$ $= 131.5$
h_B	944	B.T.U./hr./sq.ft/ °F.	$\frac{1}{U_B} - (\frac{1}{h_i} + \frac{x_w}{K_w}) = \frac{1}{h_B}$ $\frac{1}{U_B} = 0.007605$ $(\frac{1}{h_i} \quad \frac{x_w}{Kw}) = 0.006545$ (Value for 168.7°F read from Figure 10) $\therefore h_B = 944$
$t\Delta$	4.5	°F	temperature drop of boiling liquid from tube bottom to top 134.3 - 129.8 = 4.5
Δt	5.12	°F	average temperature differenc across boiling film $= \frac{Q}{A.hB} = \frac{4833}{944} = 5.12$
Δp	13.5	mms. of Hg.	pressure drop along tube length = vapour pressure of water at 134.3 - vapour pressure of water at 129.8 (Figure 57) = 128.5 - 115 = 13.5

Symbol.	Value.	Units.	Explanation.
V_1	105	ft./sec.	vapour velocity at the top of the tube.

Specific volume of vapour at 129.8°F (Fig.46) 156 cu.ft/lb.

Evaporation, lbs./sec = $\frac{2.51}{3600}$

Cross-sectional area of evaporator tube = 0.001043 sq.ft.

$\therefore$ vapour velocity = $\frac{2.51}{3600} \times \frac{156}{0.001043} = 105$

CHAPTER 6.

The Interpretation and Discussion of the Results.

A. Effect of Feed Temperature.

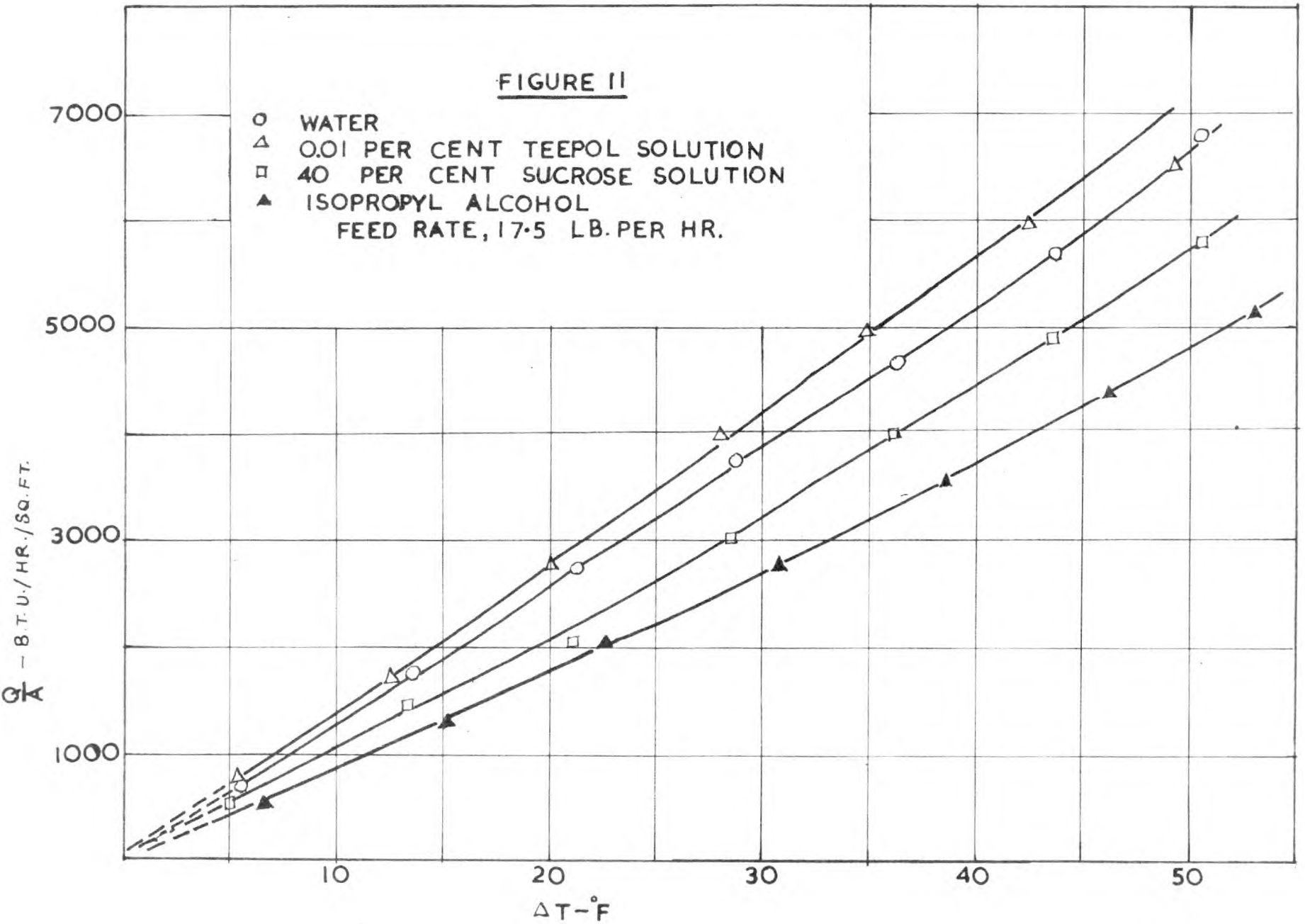
With some early runs in which the feed was cold, true heat transfer coefficients could not be obtained because the temperature of the boiling liquid was only measured at the top. These runs have not been reported. Increase in feed temperature gave a regular increase in evaporation and steady increase in the length of boiling.

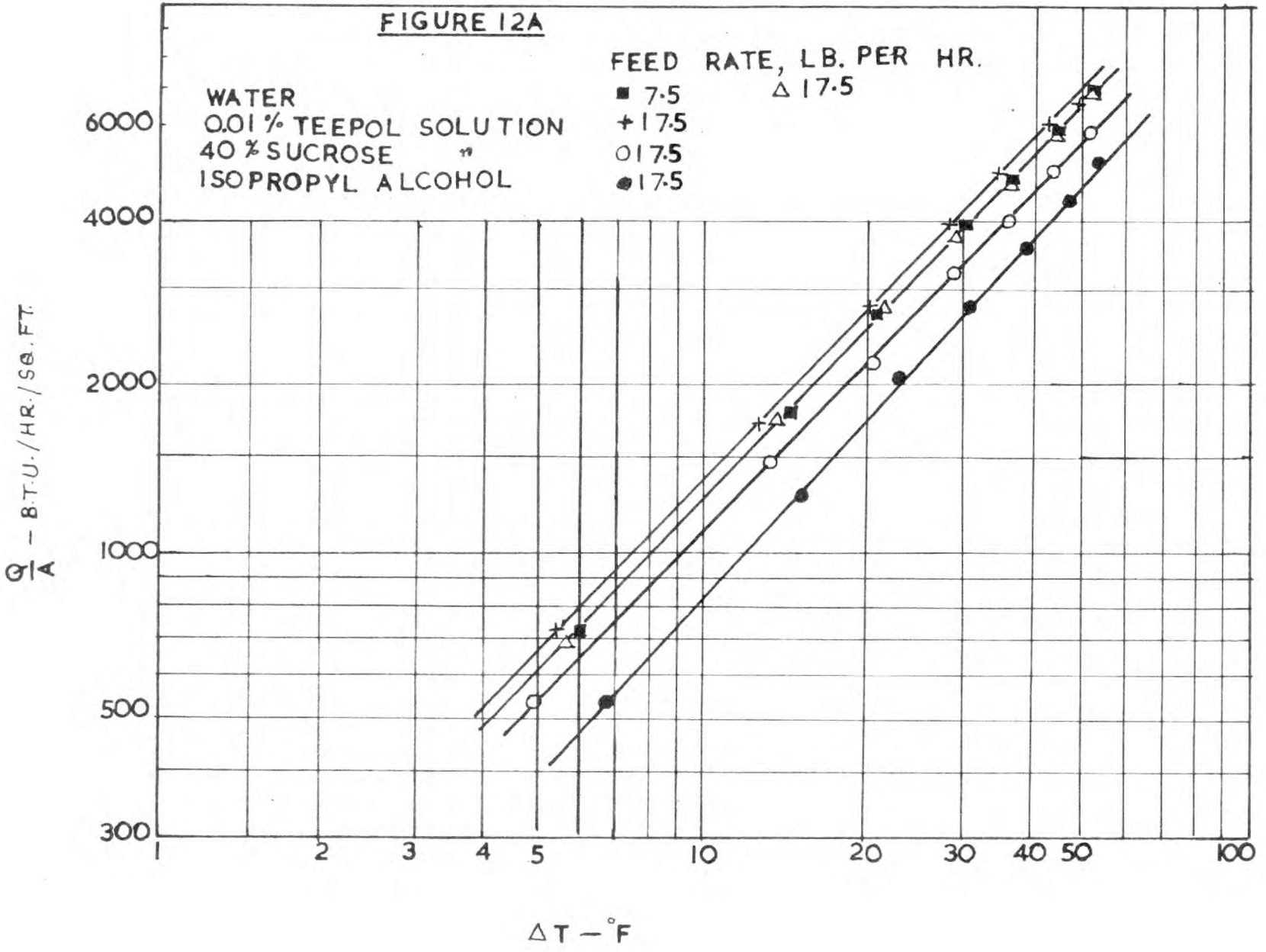
Some tests were made with the aid of a travelling thermocouple arranged in the centre of the tube, so that the temperature of the boiling liquid was obtained over the tube length. The results of a few runs taken with water are given below:

t_1	L_B	E	$\frac{Q}{A}$	U_B
71	130	1.74	3558	124.0
81	133	1.79	3522	123.0
89	134	1.89	3679	129.0
100	136	1.93	3720	131.0
110	137	1.94	3715	129.5
119	139	1.99	3761	131.0

where t_1 = feed temperature, °F,
L_B = length of boiling section, cms.,
E = evaporation, lbs./hr.,
$\frac{Q}{A}$ = heat flux in the boiling section, B.T.U./(hr.)(sq.ft.)

and U_B = overall heat transfer coefficient in the boiling section, B.T.U./(hr.)(sq.ft.)(°F).

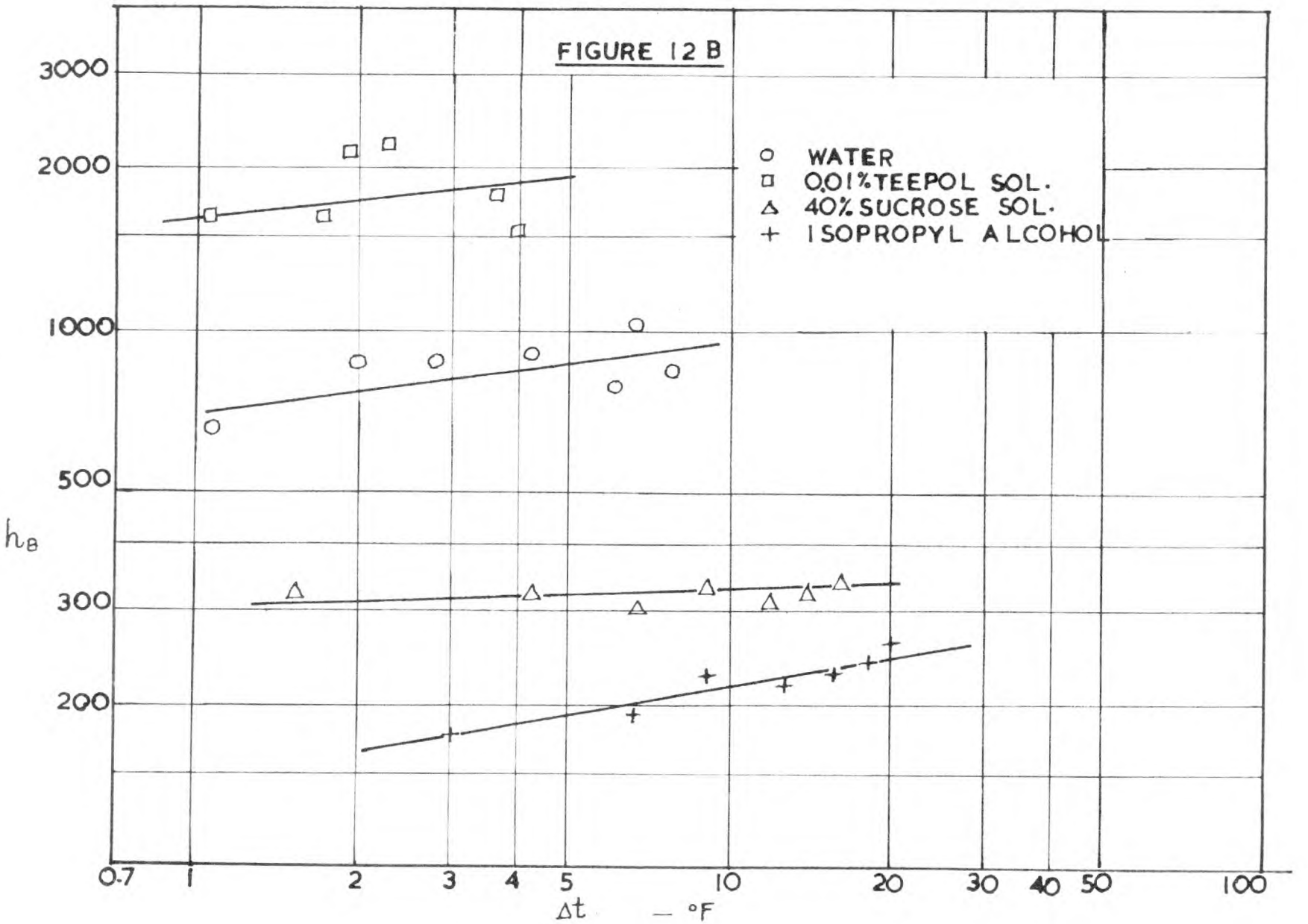

FIGURE 11
WATER
0.01 PER CENT TEEPOL SOLUTION
40 PER CENT SUCROSE SOLUTION
ISOPROPYL ALCOHOL
FEED RATE, 17·5 LB. PER HR.
7000
5000
3000
1000
10
20
30
40
50
ΔT - °F
Q/A - B.T.U./HR./SQ.FT.


FIGURE 12A
FEED RATE, LB. PER HR.
WATER
0.01% TEEPOL SOLUTION
40% SUCROSE "
ISOPROPYL ALCOHOL
■ 7·5
△ 17·5
+ 17·5
○ 17·5
● 17·5
6000
4000
2000
1000
500
300
1
2
3
4
5
10
20
30
40
50
100
Q/A – B.T.U./HR./SQ. FT.
ΔT – °F

It will be seen that increasing the feed temperature increases the length of the boiling section, as determined by means of the travelling thermocouple. This alters the ratio of the length to diameter of the boiling section. The steady increase in overall heat transfer coefficient in the boiling section is obtained. This increase is expected in this evaporator, due to the average increase in the vapour velocity; and is in agreement with some of the data of Brookes and Badger[3].

B. Effect of Temperature Difference.

Figure 11 shows results for plotting the heat flux ($\frac{Q}{A}$) against overall temperature difference for four different liquids. In these tests, the feed rate was 17.5 lbs./hr., the temperature at the top of the tube 130°F, and the temperature difference altered by changing the temperature of the hot water in the annulus. The points for each liquid lie on a smooth curve showing a steady increase in heat flux with temperature difference. The same plots, when drawn on logarithmic coordinates are shown in Figure 12a, which includes data for water with a feed rate of 7.5 lbs./hr. All the points fall on straight lines and lie almost parallel to each other. The plot for condensate water with feed rate 7.5 lbs./hr. almost coincides with that for 17.5 lbs./hr., suggesting that the feed rate has no effect on the heat


FIGURE 12 B
WATER
0.01% TEEPOL SOL.
40% SUCROSE SOL.
ISOPROPYL ALCOHOL
h_B
3000
2000
1000
500
300
200
0.7
1
2
3
4
5
10
20
30
40
50
100
Δt — °F

flux. The average slope of all the lines was 1.06. Thus the relation would be

$$\frac{Q}{A} \propto \Delta T^{1.06} \qquad .. \quad .. \quad .. \quad .. \quad .. \quad (6)$$

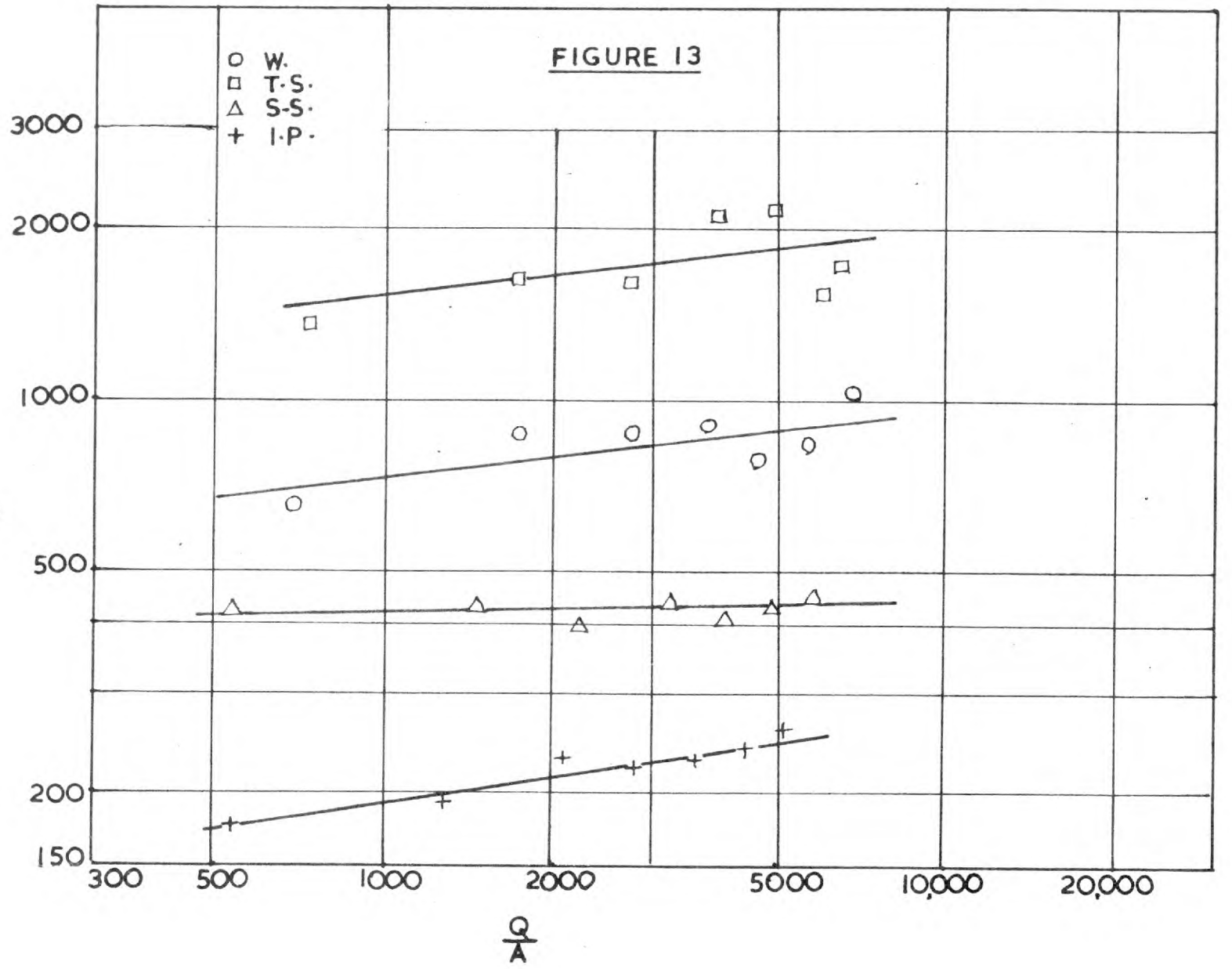
and $$\frac{Q}{A.\Delta T} = U_B \propto \Delta T^{0.06} \qquad .. \quad .. \quad .. \quad .. \quad (7)$$

The values of boiling film coefficients (h_B) were calculated from the overall heat transfer coefficients by an indirect method of Wilson plot described earlier. The temperature difference over the boiling film (Δt) was calculated for every test from the value of h_B and of heat flux ($\frac{Q}{A}$):

$$\frac{Q}{A} = hB\ \Delta t \qquad .. \quad .. \quad .. \quad .. \quad .. \quad (8)$$

$$\therefore\ \Delta t = \frac{Q}{A.h_B}$$

The values of h_B and Δt plotted for four different liquids are shown in Figure 12b. All the points tend to fall approximately on four separate straight lines. The points for Teepol and condensate water are scattered, probably owing to slight experimental errors involved in the determination of the overall heat transfer coefficients and multiplied many times in the calculated values of h_B and Δt. For example, in the case of Teepol solution, the values of h_B, are 13 to 15 times those of U_B, while in the case of isopropyl alcohol they are only two to three times as great. The plot for 40 per cent sucrose solution is very nearly a


FIGURE 13
W.
T·S·
S-S·
I·P·
3000
2000
1000
500
200
150
h_g
300
500
1000
2000
5000
10,000
20,000
$\frac{Q}{A}$

straight line parallel to the x axis. In this case, the normal increase of h_B with Δt is probably offset by the large increase in the viscosity of the liquid over the tube surface. This is supported by the visual observations described earlier.

We may write

$$h_B \propto \Delta t^{0.15} \qquad .. \quad .. \quad .. \quad .. \quad (9)$$

The exponent for temperature difference is much lower than expected for boiling liquids, but may be attributed to the very low heat flux. Comparison with experimental data in the literature is difficult because of the contradictory statements as indicated in the earlier section.

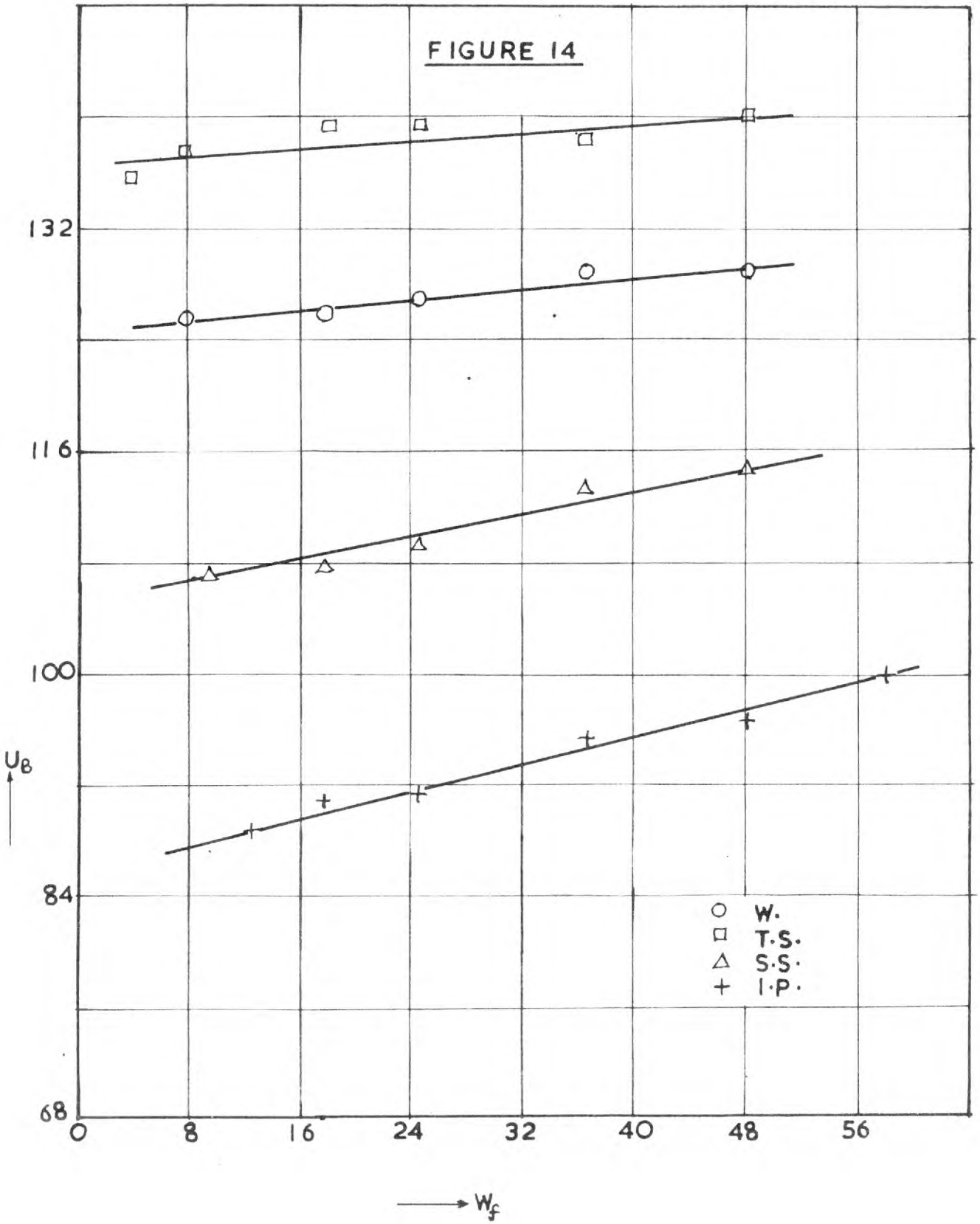
A plot of h_B versus $\frac{Q}{A}$ is shown in Figure 13 from which we have:

$$h_B \propto \left(\frac{Q}{A}\right)^{0.13} \qquad .. \quad .. \quad .. \quad .. \quad (10)$$

The lines for individual liquids are indicated by

W: condensate water,
T.S: 0.01 per cent Teepol solution,
S.S: 40 per cent sucrose solution,
and I.P: isopropyl alcohol.

Both types of plot, h_B vs. Δt, and h_B vs. $\frac{Q}{A}$, have been used in the past, though the first one is more common and has been advocated by McAdams[12]. The argument put forward is that there is always a large fractional change in $\frac{Q}{A}$ for a small fractional change in Δt. This is not always the case,


FIGURE 14
132
116
100
84
68
U_B
0
8
16
24
32
40
48
56
W_f
W.
T.S.
S.S.
I.P.

as shown by deriving the relation between the three variables and comparing them. Thus, if

$$h \propto \left(\frac{Q}{A}\right)^m$$

$$= K \left(\frac{Q}{A}\right)^m$$

$$= K(h.\Delta t)^m$$

$$h^{1-m} = K \Delta t^m$$

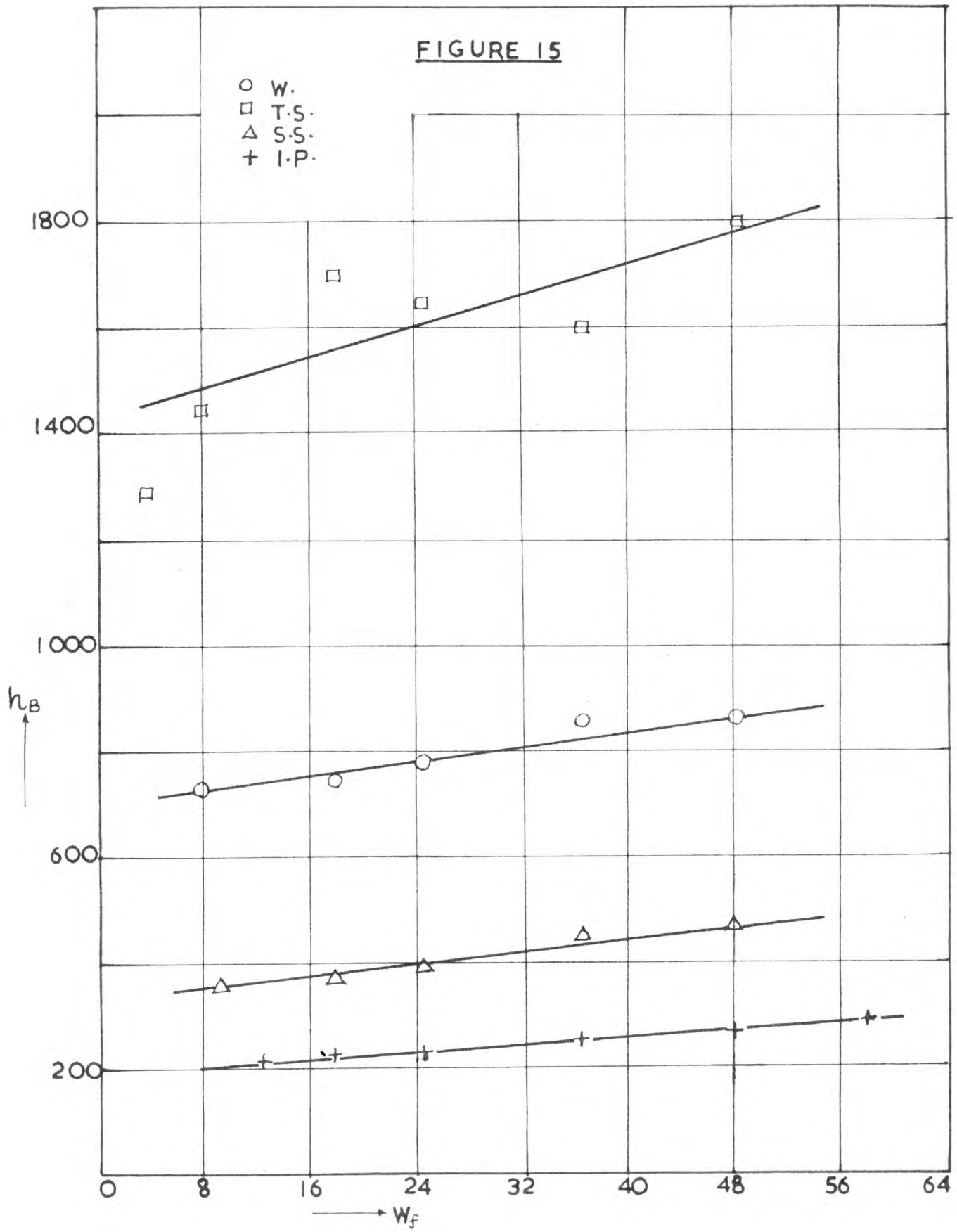
$$\therefore h \propto \Delta t^{\frac{m}{1-m}} \quad .. \quad .. \quad .. \quad .. \quad (11)$$

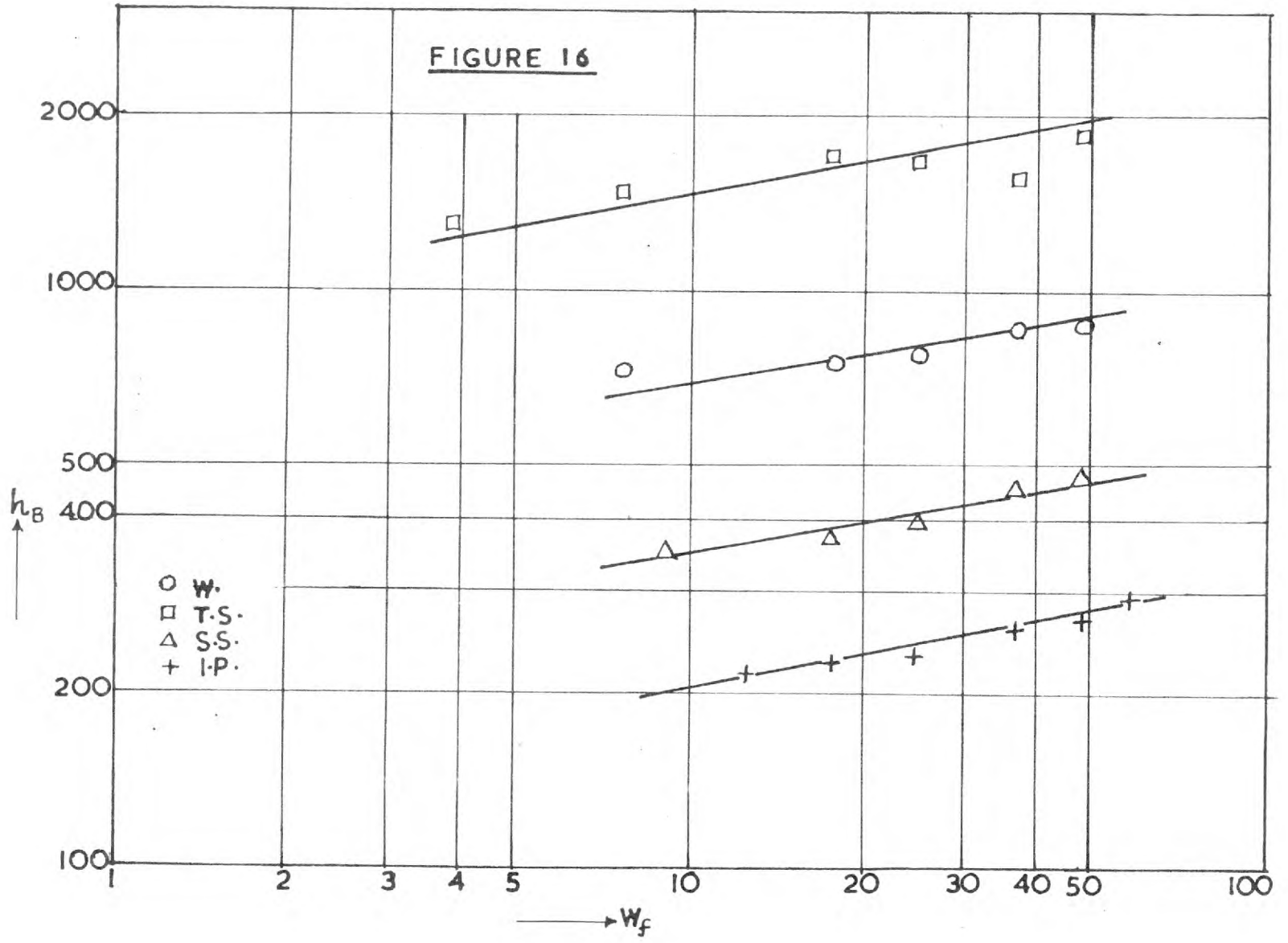
Now, the variation in the fractional change of $\frac{Q}{A}$ compared to Δt depends on the value of m. Taking a specific example from the present data, we find that the relation $h \propto \left(\frac{Q}{A}\right)^{0.13}$ (Equation 10), when converted to $h \propto \Delta t^n$ becomes $h \propto (\Delta t)^{\frac{0.13}{1-0.13}}$, i.e. $h \propto \Delta t^{0.15}$. The value 0.15 agrees with the measured value. We find that there is very little difference in the exponents of Δt and $\frac{Q}{A}$, when the actual value is low. This may be confirmed by referring to the two types of plots shown in Figures 12b and 13, which are almost identical.

C. Effect of Feed Rate.

Figure 14 shows results for plotting the feed rate (W_f) against overall heat transfer coefficient (U_B) for four different liquids with the following factors constant:

1. Hot water temperature - 162°F.
2. Boiling temperature at the top - 130°F.
3. Feed at the boiling temperature.


FIGURE 15
O W.
□ T.S.
△ S.S.
+ I.P.
1800
1400
1000
600
200
h_B
0
8
16
24
32
40
48
56
64
W_f


FIGURE 16
2000
1000
500
400
200
100
h_B
O W.
□ T.S.
△ S.S.
+ I.P.
1
2
3
4
5
10
20
30
40
50
100
W_f

Before discussing the results, it should be made clear that no attempt was made to maintain the average temperature difference (ΔT) exactly the same for all the tests. In view of the very low exponent (0.06) of ΔT in the relation with U_B, the effect of a small variation in ΔT on U_B is negligible.

Looking at the plot (Figure 14), we find that sixfold increase in feed rate causes only a slight increase in U_B with each liquid. In a purely heating operation, one would expect a considerable increase in the heat transfer coefficient. From the plots, it appears that the rate of increase in U_B with feed rate is different for different liquids. This is not the case when the boiling film coefficients (h_B) are plotted, as may be seen from Figure 15. The points for condensate water, 40 per cent sucrose solution and isopropyl alcohol fall on straight lines having nearly the same slope, while for Teepol soln. the slope is greater. Using logarithmic coordinates, the results are shown in Figure 16, from which:

$$h_B \propto W_f^{0.20} \qquad .. \quad .. \quad .. \quad .. \quad (12)$$

From Table 2 and Figure 16, we can see that an increase in feed rate from 7.5 to 48 lbs./hr. reduces the effective temperature difference from 29.3 to 27.5°F and consequently the heat flux from 3680 to 3550 B.T.U./hr./sq.ft. U_B, on the other hand increases from 125.5 to 129 B.T.U./hr./sq.ft./°F. This can be explained by the derived ralations between $\frac{Q}{A}$,

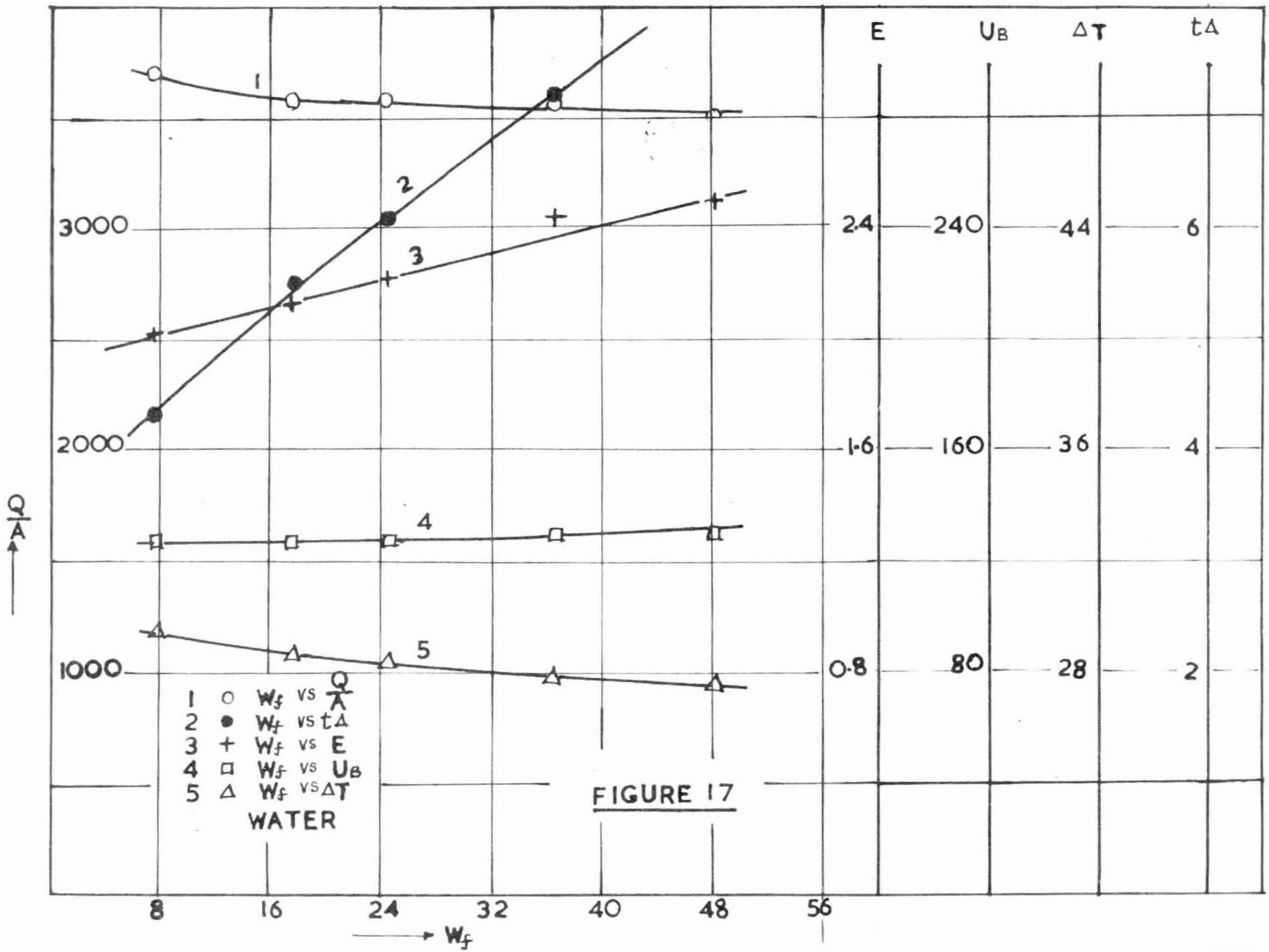

E
U_B
ΔT
$t\Delta$
3000
2000
1000
2.4
240
44
6
1.6
160
36
4
0.8
80
28
2
Q/A
1
2
3
4
5
1 ○ W_f vs $\frac{Q}{A}$
2 ● W_f vs $t\Delta$
3 + W_f vs E
4 □ W_f vs U_B
5 △ W_f vs ΔT
WATER
8
16
24
32
40
48
56
W_f

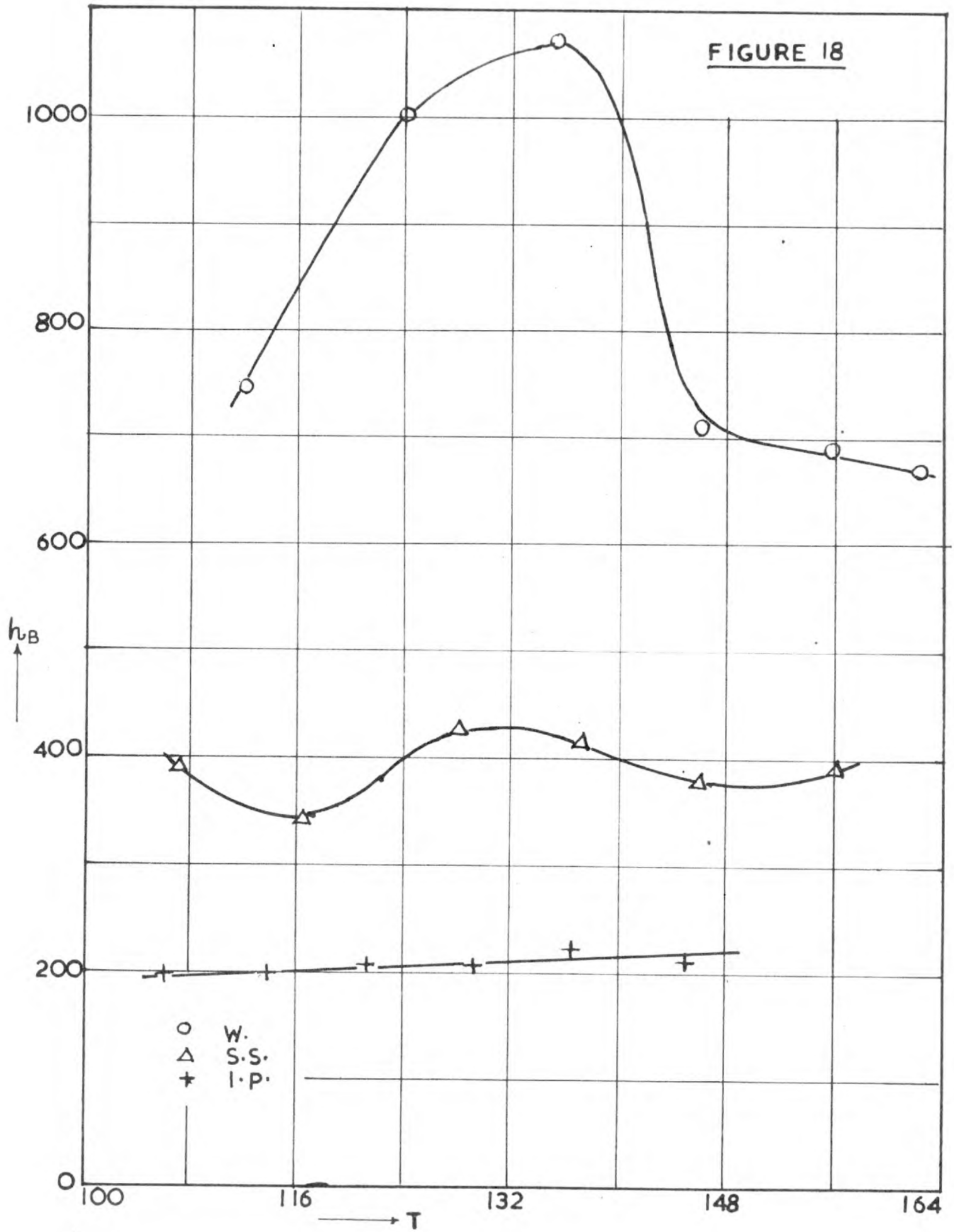
FIGURE 17

U_B and ΔT

$$\frac{Q}{A} \propto \Delta T^{1.06}$$

and $$U_B \propto \Delta T^{0.06}.$$

The reduction of 1.7°F in ΔT caused by increase in the feed rate will not significantly affect U_B or h_B, but will reduce $\frac{Q}{A}$ almost proportionately. The influence of feed rate on heat flux ($\frac{Q}{A}$), temperature drop of boiling liquid from tube bottom to top in °F ($t\Delta$), evaporation rate in lbs./hr. (E), overall heat transfer coefficient (U_B), and effective temperature difference (ΔT), is shown by curves 1, 2, 3, 4 and 5 respectively in Figure 17. It should be noted that different scales have been used for different factors, in order to keep them separate from one another and hence the effect of some factors though small is magnified in the graph. The rate of evaporation is found to increase with feed rate, while heat flux decreases. This is evidently due to increase in flash evaporation with feed rate. With the increase in feed rate, the temperature drop of boiling liquid from tube bottom to top ($t\Delta$) increases steadily, resulting in the decrease of effective temperature difference. The fact that change in the feed rate introduces simultaneous changes in other variables is probably the reason for many of the inconsistencies found in published data.


FIGURE 18
1000
800
600
400
200
0
h_B
100
116
132
148
164
T
O W.
Δ S.S.
+ I.P.

D. Effect of Boiling Temperature.

The effect of boiling temperature on the boiling film coefficient (h_B) was studied with condensate water, 40 per cent sucrose solution and isopropyl alcohol. It was necessary to keep the feed rate and effective temperature difference (ΔT) constant for all the runs. Maintaining the temperature difference (ΔT) constant necessitated trial and error working because of the considerable variation in the temperature drop of boiling liquid along the tube length with boiling temperature. The feed temperature was kept at boiling point and the feed rate at 17.5 lbs./hr. Plots of h_B and the boiling temperature (T) are shown in Figure 18. In the case of isopropyl alcohol, there is a slight increase in h_B with T; for 40 per cent sucrose solution, the regularity is not good, there is likewise slight increase in h_B with T; for condensate water, the curve is very irregular and there is a maximum at 134°F. Attention may be drawn to the fact that the difference in the values of U_B corresponding to the maximum and minimum values of h_B is only 8 per cent. This arises from the high thermal resistance of the glass tube wall. In view of the irregularity of the curves, no relation between h_B with T could be derived.

E. Effect of Surface Tension.

The surface tension was altered by adding 0.01 per cent Teepol to condensate water which reduced the surface tension

by about 30 per cent. The plots for Teepol solution have been already shown earlier along with those of other liquids. The visual observations made have been reported in Chapter 4 (p. 43). For the same operating conditions, the addition of Teepol almost doubled the boiling film coefficient.

After considering the effect on the boiling film coefficients, it is interesting to note its effect on other variables, such as heat flux, temperature difference, etc. It is surprising to find that the values of heat flux obtained with 0.01% Teepol solution are nearly the same as those with condensate water under identical conditions, viz. feed rate 17.5 lbs./hr., hot water temperature, feed at boiling temperature and boiling temperature at the top 130°F. The results are given in the Table B, for the purpose of comparison.

Table B.

Hot water temp. °F.	Water.		Teepol solution.	
	ΔT	$\frac{Q}{A}$	ΔT	$\frac{Q}{A}$
138.5	5.65	680	5.39	717
146.5	13.50	1718	12.45	1700
154.5	21.24	2719	19.90	2738
162.5	28.80	3739	28.00	3965
170.5	36.32	4644	34.84	4926
178.5	43.70	5702	42.44	5985
185.5	50.55	6834	49.29	6469

where ΔT = average overall temperature difference, °F,
and $\frac{Q}{A}$ = heat flux, B.T.U./(hr.)(sq.ft.)(°F).

Mention was made earlier that a considerable drop in the temperature of boiling liquid from tube bottom to top occurred when using Teepol solution due to strong foaming. As it is desirable to increase the heat flux to a maximum under given operating conditions, the increase in the heat transfer coefficient without increasing heat flux has little practical use. It is expected, however, that the temperature drop of boiling liquid will be less when operation is carried out at higher temperatures, such as 175 to 200°F, thus offsetting the effect of foam on heat flux and resulting in the increase of heat flux, as well as of the heat transfer coefficient.

F. Effect of Viscosity.

Results using 40 per cent sucrose solution are shown in the Table C. It will be noted that the boiling film coefficients are reduced to about one-half by increasing the viscosity approximately four times.

Table C.

Hot water temperature. °F.	Water. h_B	40% sucrose solution. h_B
138	654	415
146	875	423
154	871	386
162	898	426
170	776	401
178	844	419
185	1040	441

where h_B = boiling film coefficient. B.T.U./(hr.)(sq.ft.)(°F)

This change can be attributed to very sluggish flow of liquid film over the tube surface and also to thicker films. One interesting point about the boiling of 40 per cent sucrose solution as referred to earlier is that there is relatively little increase of heat transfer coefficient with temperature difference. This is evidently due to the viscosity increasing at a faster rate when boiling at higher concentration.

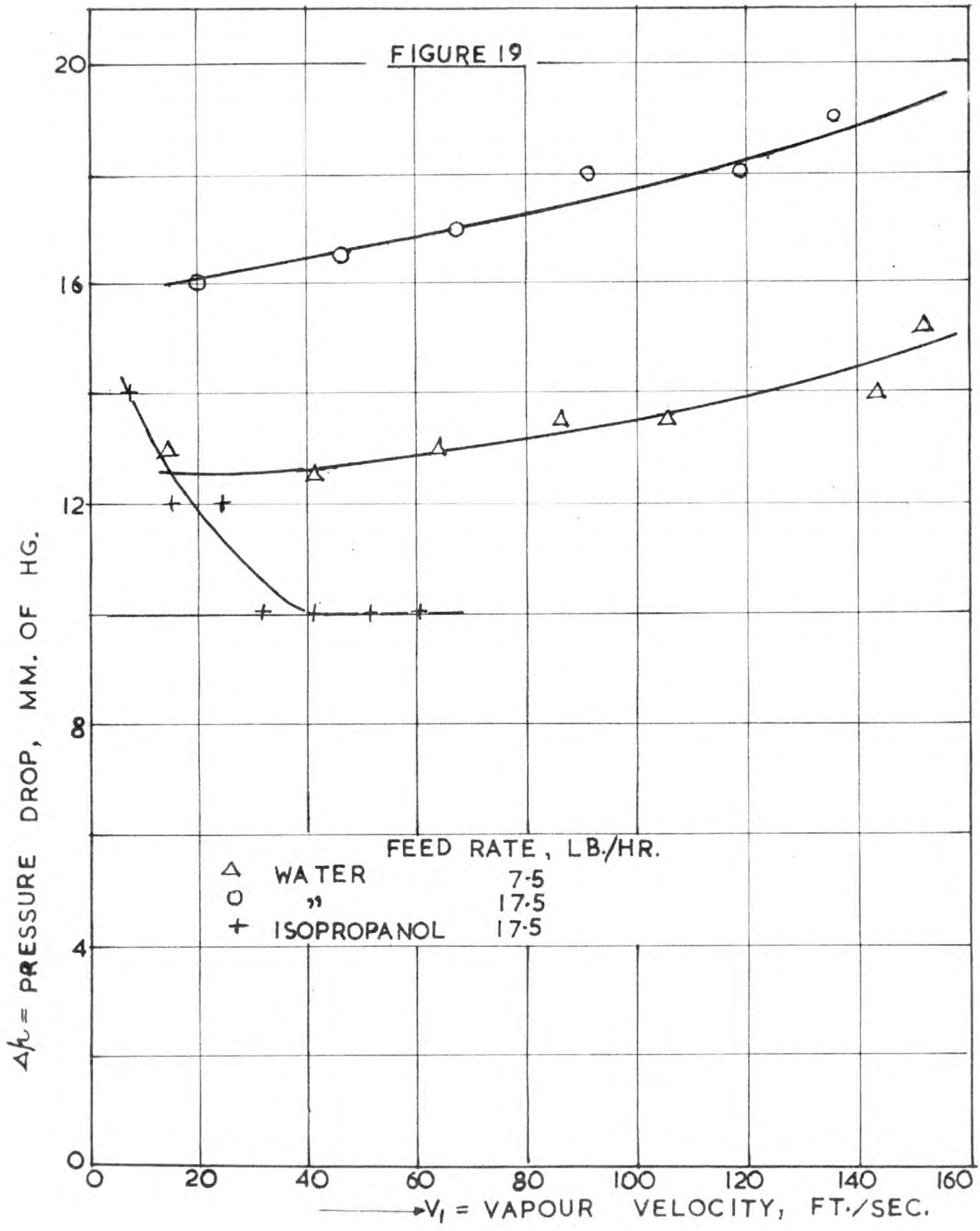
G. Pressure Drop in the Evaporator Tube.

The pressure drop from tube bottom to top may be considered as the sum of several individual pressure drops as follows:

1. The static pressure drop, determined by the weight of the liquid - vapour mixture in the tube.
2. The pressure loss due to the acceleration of the liquid and vapour to the outlet velocity.
3. The other pressure drops, due to friction and outlet losses.

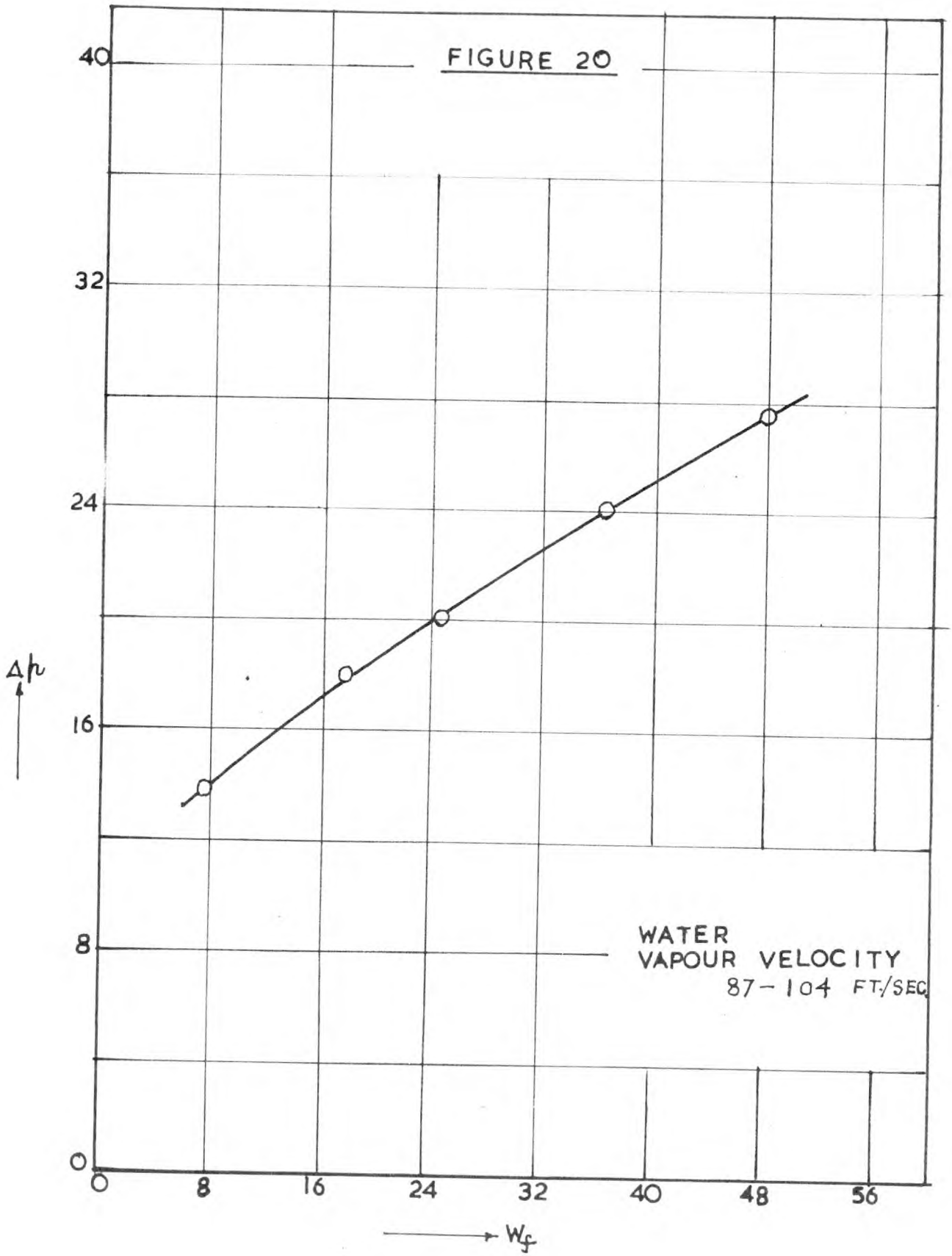
The total pressure drop, and thus the boiling temperatures, will depend on the extent of each of these pressure increments.

Pressure drops (total) were calculated from the temperatures of boiling liquid at the bottom and the top. Vapour velocities at the outlet were calculated from the total


FIGURE 19
20
16
12
8
4
0
0
20
40
60
80
100
120
140
160
Δh = PRESSURE DROP, MM. OF HG.
→V₁ = VAPOUR VELOCITY, FT./SEC.
FEED RATE, LB./HR.
Δ WATER 7·5
O " 17·5
+ ISOPROPANOL 17·5

evaporation, lbs./hr., and specific volume of vapour at the outlet temperature. Calculations were based on the inside cross-sectional area of the tube, in view of the unknown thickness of the liquid layer over the tube surface, so the calculated values of the vapour velocities will be somewhat lower than the actual ones.

The plots of vapour velocity versus pressure drop for condensate water and isopropyl alcohol are shown in Figure 19. With the same feed rate, the pressure drop increases steadily with vapour velocity up to 150 ft./sec., and then tends to increase at a faster rate. The higher pressure drop at the higher feed rate at the same vapour velocity is due to a greater static head of liquid, resulting from thicker films over the tube surface. It will be seen that the plot for isopropyl alcohol is very different from that for condensate water at the same feed rate of 17.5 lbs./hr. This is probably due to the large difference in their physical properties. The vapour velocities in the case of isopropyl alcohol are considerably lower than those of water, due to the low specific volume of the vapour. Below the vapour velocity of 30 ft./sec., the pressure drop increases with decrease in vapour velocity. The slug action which usually takes place at low vapour velocity seems to be partly responsible for this apparently anomalous behaviour.


FIGURE 20
40
32
24
16
8
0
Δh
0
8
16
24
32
40
48
56
W_f
WATER
VAPOUR VELOCITY
87 – 104 FT./SEC.

The other related factor seems to be the minimum critical vapour velocity below which the lifting action of vapour is very much reduced, causing more hold up of liquid in the tube and hence greater pressure drop. It may be noted here that prior to reaching an equilibrium condition of climbing film operation, slug action prevailed for some time and the pressure drop noted from the boiling liquid temperatures as well as from the mercury manometer was always higher.

The plot of feed rate versus pressure drop is shown in Figure 20, and shows that the pressure drop increases with feed rate. The increase due to vapour velocity, which varies from 87 to 104 ft./sec., can only be a small proportion of the total increase.

PART TWO.

The Long Tube Stainless Steel Evaporator.

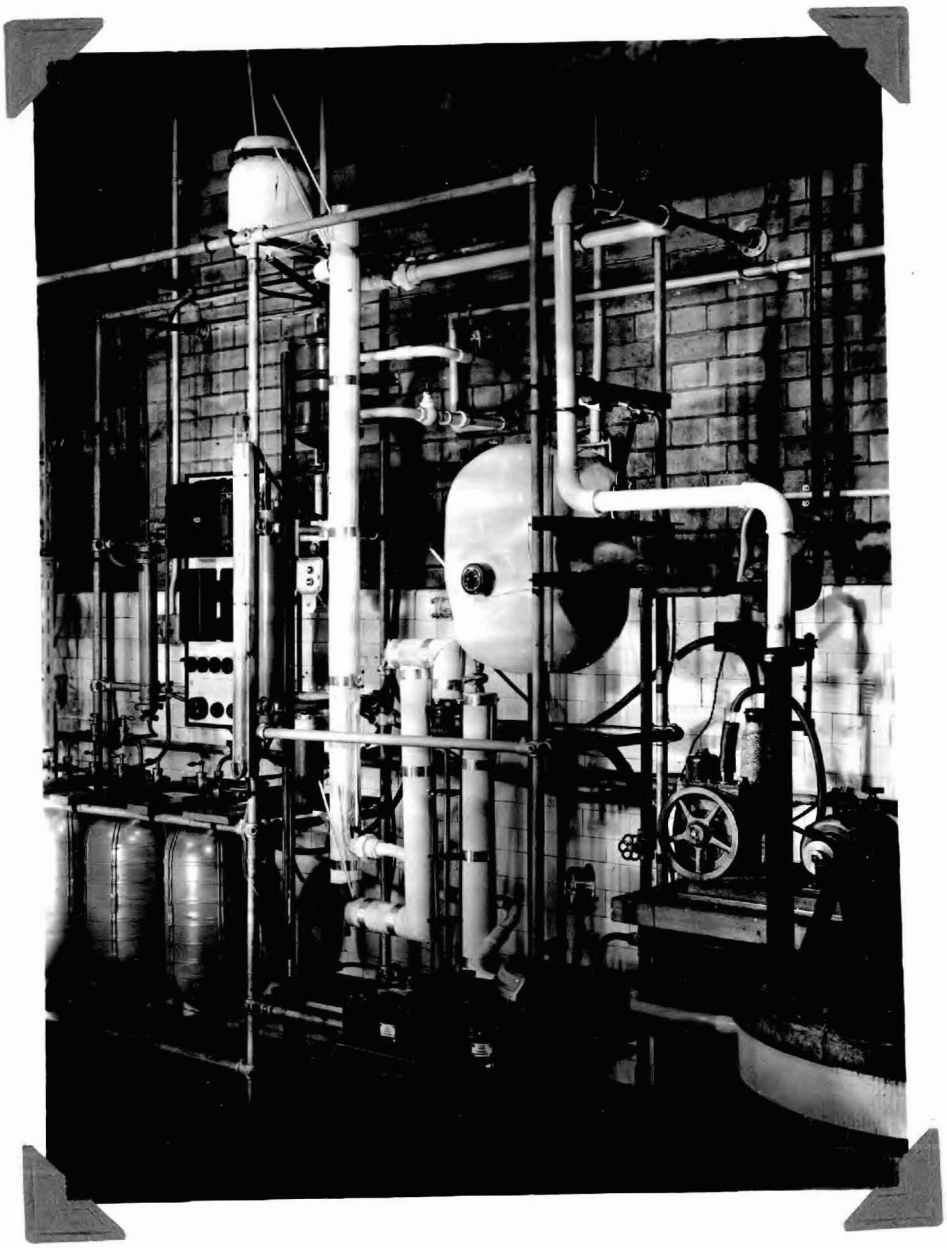
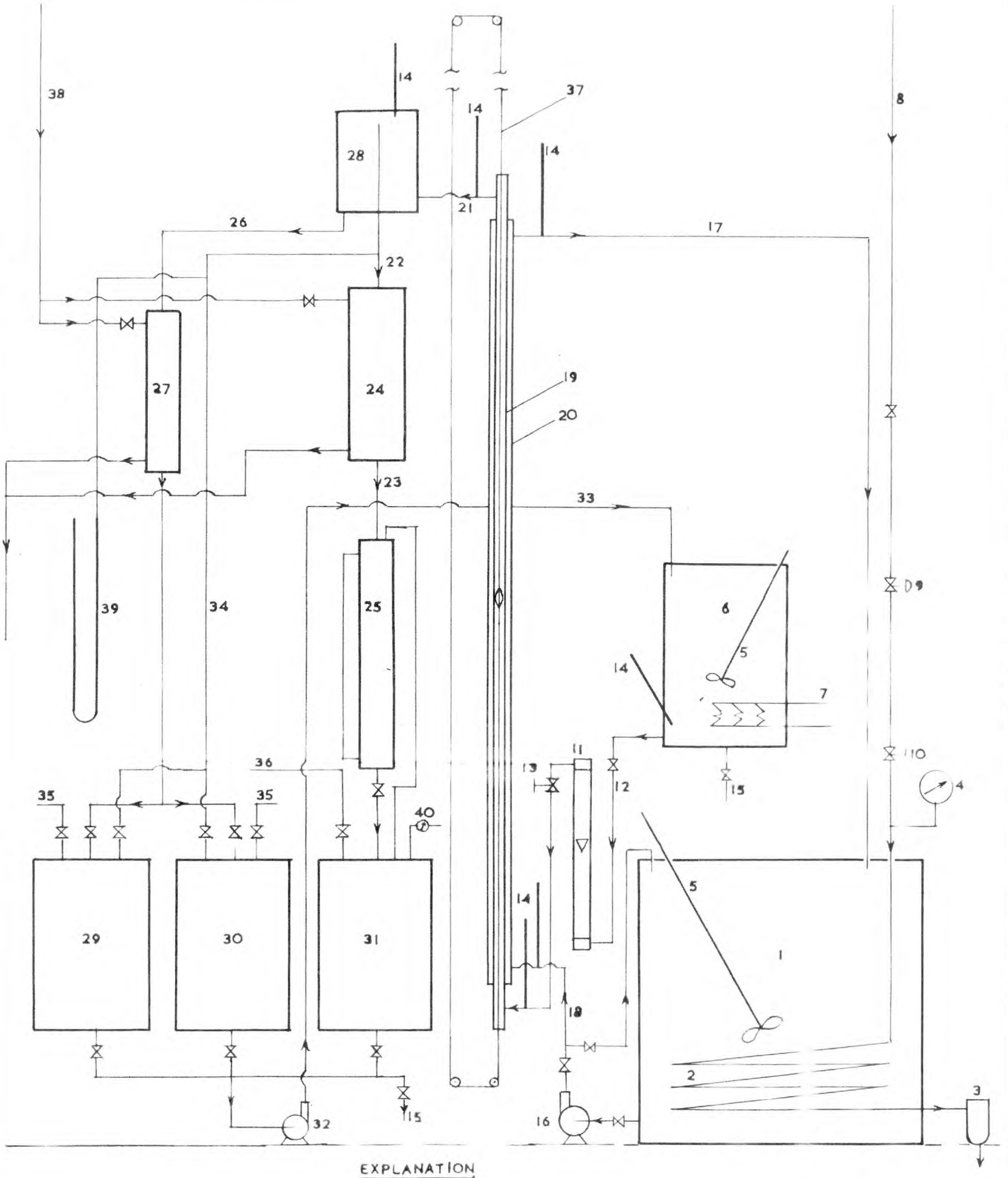


Plate 2. The Long Tube Stainless Steel Evaporator.

FIGURE 21 THE EQUIPMENT FLOWSHEET



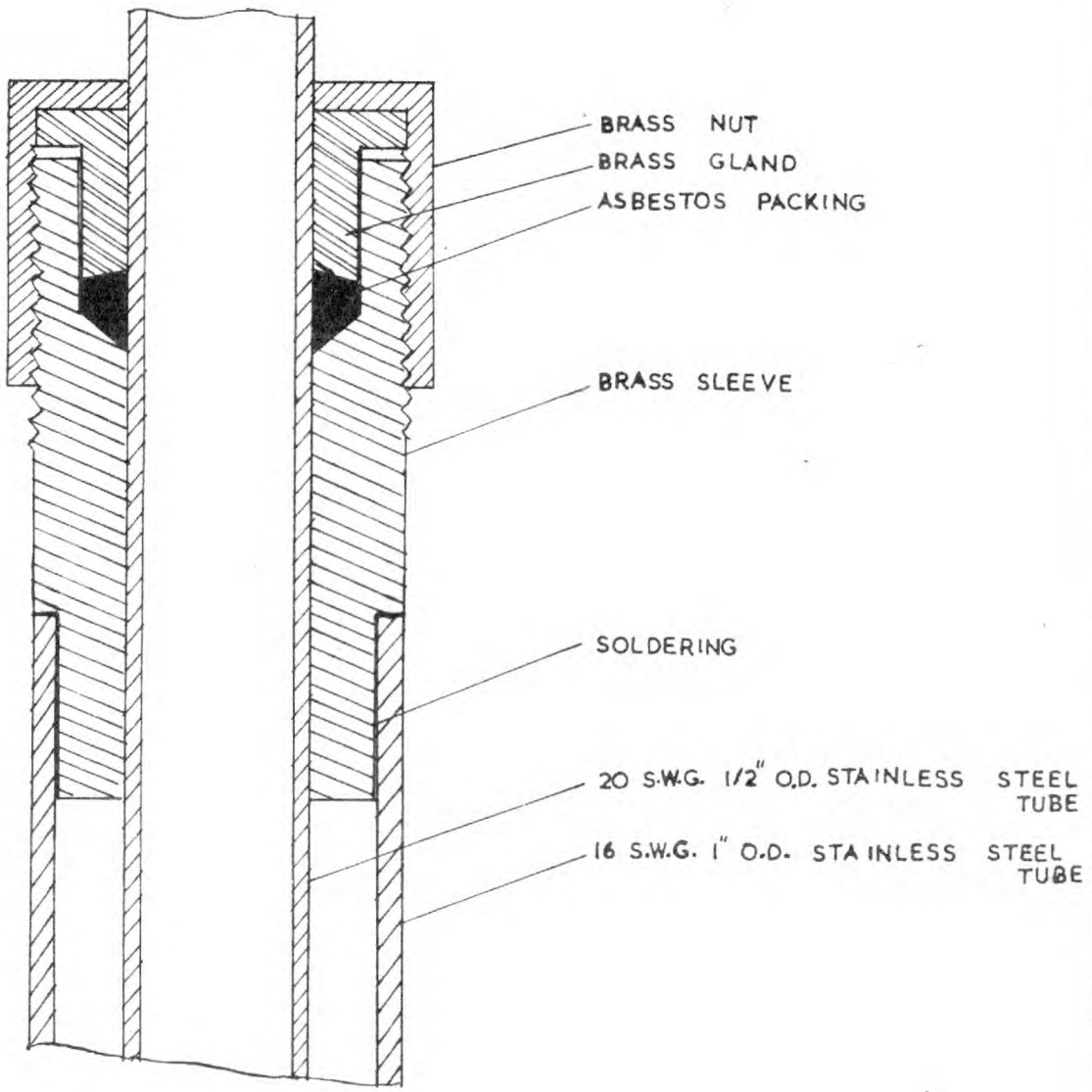
EXPLANATION

1 HOT WATER TANK
2 STEAM COIL
3 STEAM TRAP
4 STEAM PRESSURE GAUGE
5 STIRRER
6 FEED TANK
7 2 KW IMMERSION HEATER
8 MAIN STEAM LINE
9 REDUCING VALVE
10 NEEDLE VALVE FOR STEAM
11 ROTAMETER
12 LIQUID FEED LINE
13 NEEDLE VALVE FOR FEED LINE
15 DRAIN OUT LINE
16 HOT WATER CIRCULATING PUMP
17 HOT WATER OUTLET LINE
18 HOT WATER INLET LINE
19 1/2" O.D. S. STEEL EVAPORATOR TUBE
20 1" O.D. S.STEEL JACKET
21 VAPOUR LIQUID LINE
22 VAPOUR LINE
23 CONDENSATE LINE
24 CONDENSER
25 MEASURING CYLINDER
26 CONCENTRATE LINE
27 COOLER
28 VAPOUR SEPARATOR
29,30 CONCENTRATE RECEIVERS
31 CONDENSATE RECEIVER
32 LIQUID CIRCULATING PUMP
33 LIQUID RETURN LINE
34 PRESSURE EQUALISING LINE
35 VACUUM BREAK LINE
36 VACUUM LINE
37 TRAVELLING THERMOCOUPLE CIRCUIT
38 COOLING WATER LINE
39 MERCURY MANOMETER
40 AIR ADMITTANCE CONTROL VALVE
14 THERMOMETER

FIGURE 22

DETAIL OF EVAPORATOR TUBE AND JACKET JOINT

(SCALE 2:1)



CHAPTER 7.

The Equipment.

To obtain data with a range of heat flux comparable to that obtained in industrial practice, a unit consisting of a single tube stainless steel evaporator was designed and constructed. The photograph of the equipment is shown in Plate No. 2 and the flowsheet diagram in Figure 21. The evaporator and various auxiliary units are now described.

7.1. The Evaporator Assembly.

The tube used was 5½ ft. long, ⅜ inch o.d. and 20 S.W.G., polished outside and descaled on the inside. The jacket was a 16 S.W.G. stainless tube of 1 in. o.d., so that the annulus was only 0.186 in. With a jacket length of 5½ ft., the ratio of tube length to inside diameter was 147. The small annulus was necessary to give a high annulus film coefficient with a reasonable flow of hot water. The thin wall of the main tube, 0.036 in., was necessary to reduce the thermal resistance of the tube, since stainless steel has a relatively low value of thermal conductivity. The effective surface for heat transfer based on the mean diameter of the tube was 0.637 ft.^{2} The detail of construction showing the joint between the inner and outer tube is shown in Figure 22. A brass sleeve was soldered to the

FIGURE 23

COMPRESSION JOINT FOR COPPER TUBE

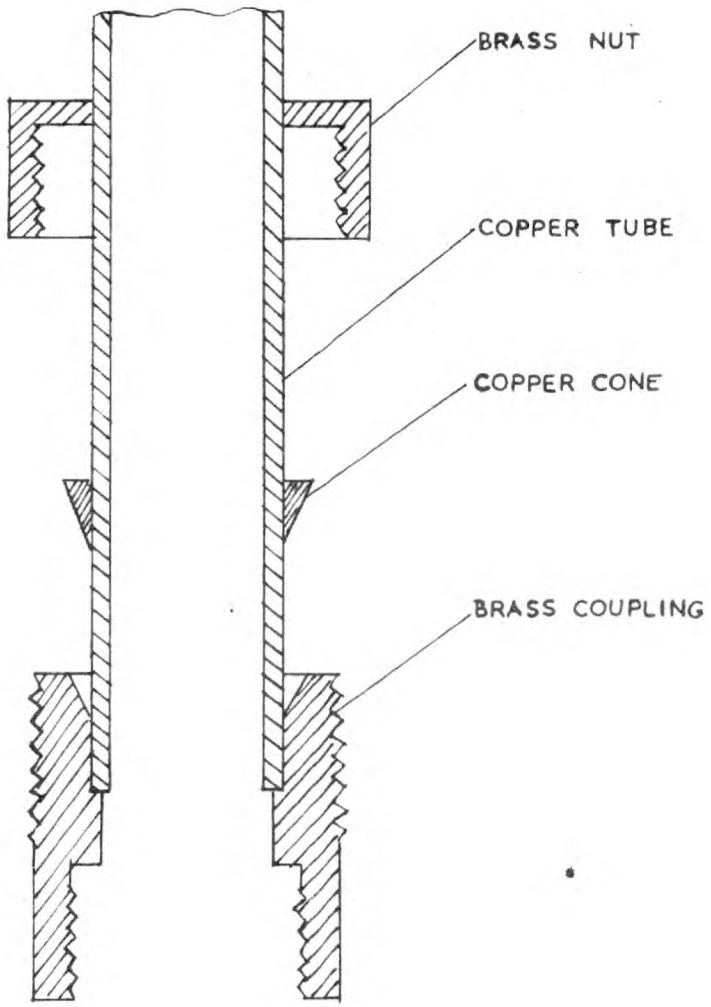
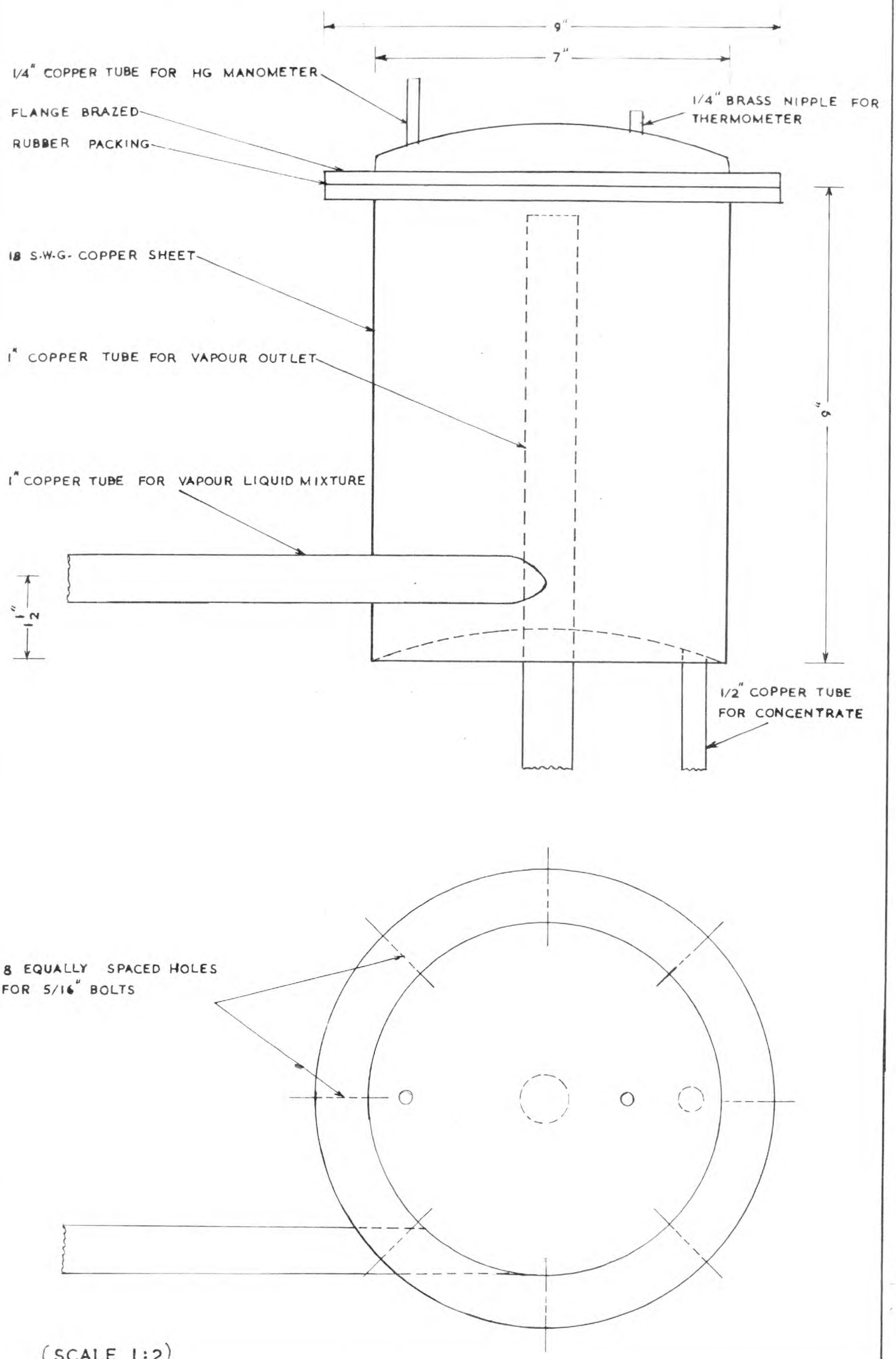


FIGURE 24 DETAIL OF VAPOUR SEPARATOR



inside of the jacket and asbestos used as the packing in the gland as shown. The tee lines for the feed at the bottom and to the separator at the top were welded to the main tube. Fittings for thermometers were fitted to both of these lines.

The equipment was run under a vacuum of some 26 in. of mercury and, for this purpose, special fittings were necessary. The "Prestex" compression joint was found suitable and was extensively used for pipe fittings and gave no trouble. One joint of this type is shown in Figure 23. It shows the sealing action of the copper cone, which, when the nut is screwed to the coupling, makes a leakproof joint.

7.2. Separator.

A centrifugal type vapour separator was used similar to that on the glass equipment. A vessel of some 7 ins. diameter was found suitable and the construction is shown in Figure 24. Some simple experiments were made with a dye to check the performance of this separator. The tangential inlet to the separator, together with the sharp turn from the evaporator tube to the vapour line, gave excellent freedom from entrainment. A thermometer pocket was fitted to the separator and a ¼ in. copper tube for connection of a manometer was fitted at the top.

7.3. Feed Tank, Condenser and Cooler.

An 8 gallon round bottom copper tank was used for the feed tank. Heating was provided by a 2 KW immersion heater, controlled with a bimetallic thermostat. Fittings were provided for the liquor inlet and outlet, a drain connection and for a stirrer. The feed was sucked into the evaporator through a rotameter with a nominal range of 2-20 g.p.h. for water.

The condenser and cooler were taken from items available in the department. The condenser had ½ in. tubes and a surface of 10 sq.ft. The cooler also had ½ in. tubes, with a surface of 1 sq.ft.

7.4. Receivers and Measuring Cylinder.

Three stainless steel pressure vessels available in the department were adapted for use as receivers. These were of some 7 gallons capacity and two were used for the concentrated liquor and the third for the condensed vapour. By using two receivers alternately, the concentrated liquor in one could be pumped back to the feed tank without stopping the plant. These receivers were also used for calibration of the rotameter with the different liquors.

Three lines (one for liquid and two for vapour) were connected by a cross piece to the top of each receiver. The liquid flowed vertically downwards and the gas inlets

were at each side. To prevent any carry over of the liquid into the gas lines, a trap in the form of a 3 in. by ¾ in. copper tube was fitted inside the cross piece. The strong liquor and condensed vapour from the receivers was pumped back to the feed tank with a centrifugal pump of 50 gal/hr. capacity. The liquor outlets from the receivers were connected to a common line feeding the pump, and a drain cock was fitted in this line.

A brass measuring cylinder, 4 in. diameter and 2 ft. long, was connected in the condensate line below the condenser and used to record the rate of evaporation. The cylinder was fitted with a gauge glass with scale, a vacuum tap at the bottom and a vacuum by-pass line from the receivers to its top. A pressure equalising line (No. 34 in Figure 21) was provided for each receiver to permit flow of the concentrated liquor into the receiver under vacuum.

7.5. The Heating System.

A 60 gallon round galvanised tank with closed fitting lid was used to provide a reservoir for the circulating hot water. The water was heated by condensing steam at about 15 lbs./sq.inch, in a coil fitted near the bottom of the tank. A pressure gauge was fitted in the steam line and a needle valve used for final control of pressure.

The water was kept well agitated as a result of the rapid circulation aided by a stirrer.

Circulation of the hot water was effected by a 400 gal./hr. centrifugal pump driven by a ½ H.P. electric motor. A by-pass line was fitted to the pump.

7.6. The Vacuum Equipment.

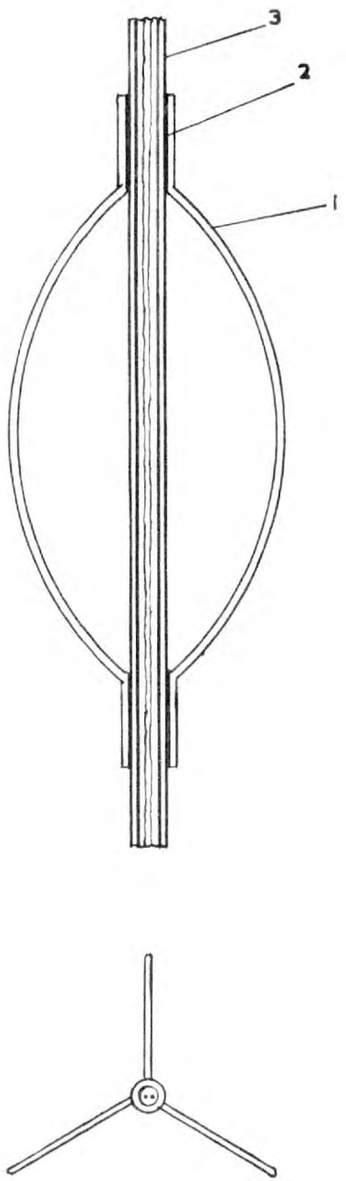
A rotary oil-sealed vacuum pump driven by a ¼ H.P. electric motor was used. This unit had a greater capacity than needed and air was bled into the system as required to control the pressure. A glass tower, filled with silica gel, was fitted in the vacuum line before the pump to prevent any water vapour entering the pump.

The vacuum taps used in the equipment were oil-sealed, hard gunmetal, the viscous sealing compound in the top, preventing entry of air into the system. The silicone lubricant used gave no trouble with these taps.

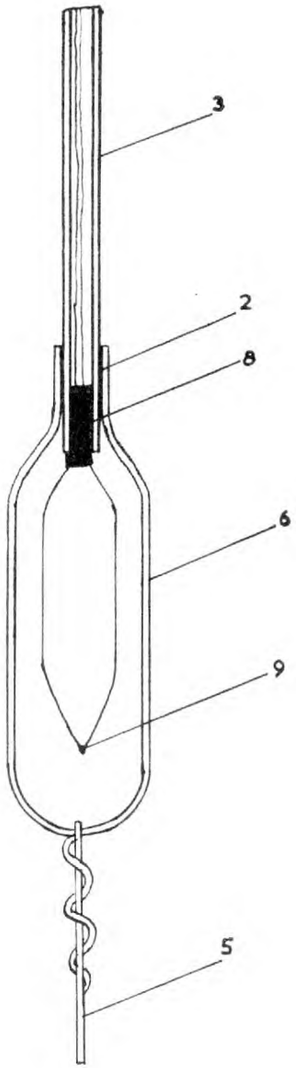
The feed tank, the separator, and the hot water tank were suitably lagged. The various units were supported in a tubular framework, as shown in the photograph, and the equipment arranged so that control could be made from the front. The electrical switches, fuses, signal lights, thermostat controls, were mounted on a panel above the three receivers.

FIGURE 25 DETAIL OF CONSTRUCTION OF TRAVELLING THERMOCOUPLE

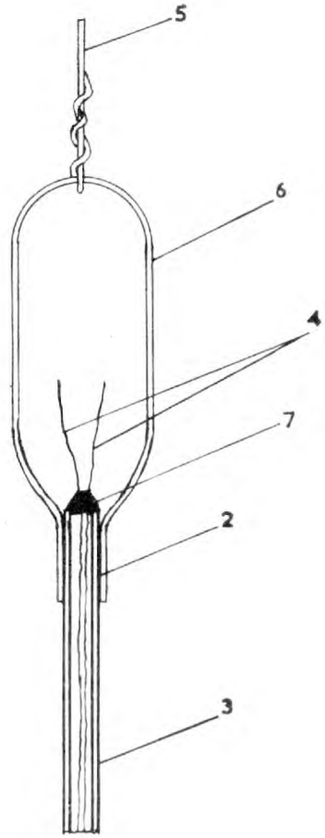
ARRANGEMENT OF SPIDERS



BOTTOM END



TOP END



(SCALE 4:1)

EXPLANATION

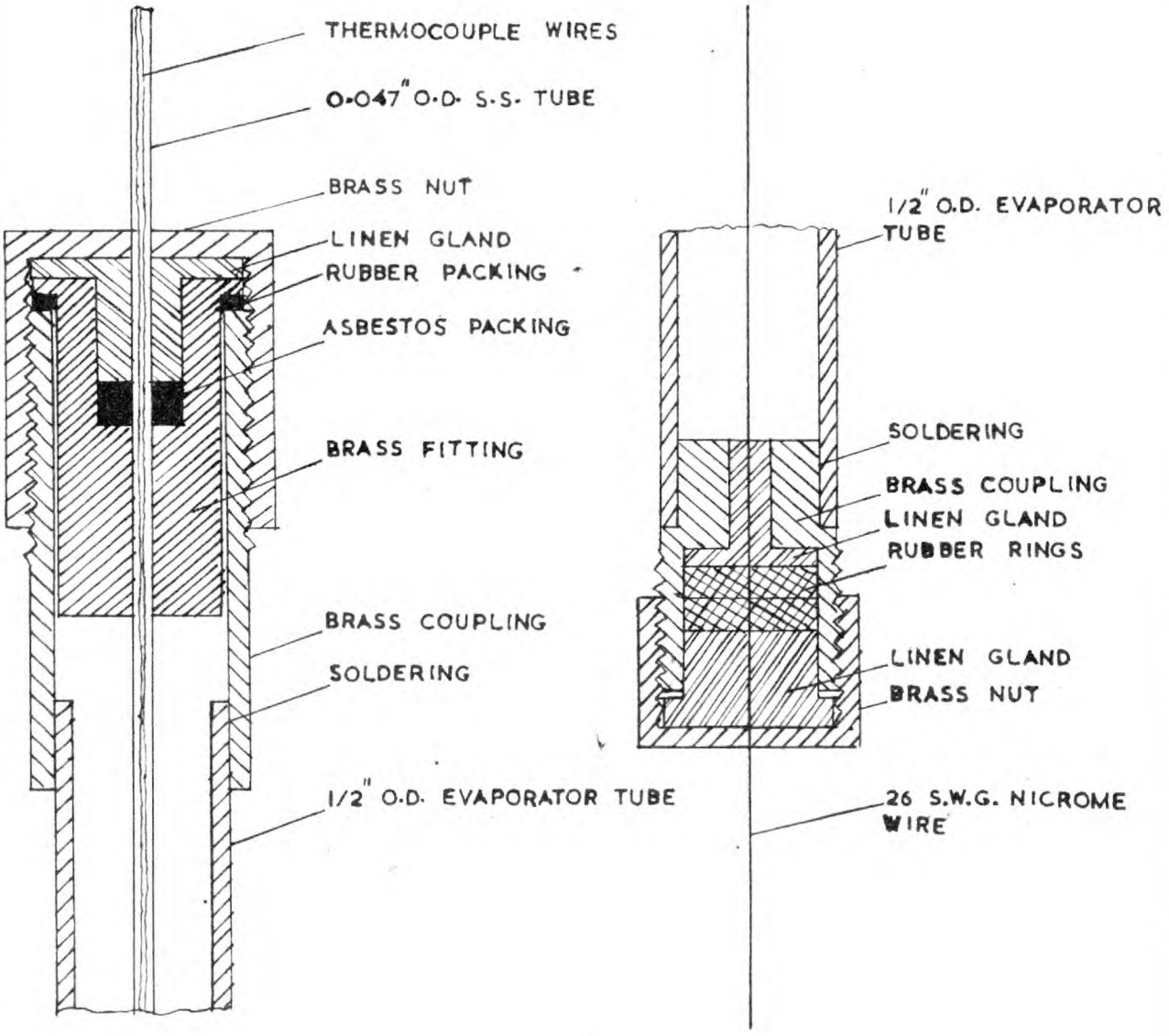
1 24 S.W.G. BRASS WIRE SPIDERS
2 SOLDERING
3 0.047" O.D. STAINLESS STEEL TUBE
4 36 S.W.G. COPPER AND CONSTANTAN WIRES
5 26 S.W.G. NICROME WIRE
6 BRASS WIRE HOOK
7 DUROFIX SEAL
8 N.R.A. BAKELITE CEMENT
9 THERMOCOUPLE JUNCTION

7.7. Travelling Thermocouple.

The development of a suitable travelling thermocouple for measuring the liquid temperature along the axis of the evaporator tube was made in stages. The final method used is described below.

36 S.W.G. enamelled and silk covered copper and constantan wires were passed through a 6 ft. length of 0.028 in. I.D. and 0.047 in. O.D. stainless steel tube. The junction of the two wires projected about ½ in. from the end of the stainless steel tube to eliminate thermal conduction errors. The detail of the construction is shown in Figure 25. Before the thermocouple wires were passed through the small tube, an arrangement of spiders was soldered at about 3 ins. from the bottom, for keeping the thermocouple junction in the centre of the evaporator tube, and brass hooks were fastened at each end for the attachment of pull wires. The spiders were made of 24 S.W.G. brass wire and kept at 120° from each other, as shown in the Figure. The closed circuit of the thermocouple, which was about 30 ft. long, was completed by the pull wire made of 26 S.W.G. nichrome wire which passed over four pulleys, two fitted near the ceiling and two below the evaporator tube. The thermocouple wires at the hot junction end were sealed in place with N.P.A. Bakelite cement drawn

GLAND AND PACKING ARRANGEMENT FOR TRAVELLING THERMOCOUPLE CIRCUIT



A. EVAPORATOR TOP

FIGURE 26

B. EVAPORATOR BOTTOM

FIGURE 27

(SCALE 2:1)

into the tube by suction. The cement was baked for half an hour at a constant temperature of 135°C. The thermocouple circuit was completed by soldering cotton covered copper and constantan wires to the fine wires issuing from the thermocouple tube. The gland and packing arrangement at the top and the bottom of the evaporator tube is shown in Figures 26 and 27. The movement of the couple was smooth and easy and without any air leakage. The position of the junction inside the evaporator tube was shown by an indicator soldered to the pull wire and moving over a scale. It may be of interest to note that this arrangement made practically no difference to the heat transmission to boiling liquid, as compared with the empty evaporator tube.

CHAPTER 8.

Experimental Method of Approach.

8.1. Measurement and Control.

The temperature of the hot water was controlled by operating a needle valve in the reduced pressure steam line. The control by this method was good and, because of the large capacity of the tank, proved better than electrical control. It was possible to adjust the temperature of hot water to within $\pm$ 0.1°F, once steady conditions had been attained.

The temperatures of the hot water inlet and outlet from the evaporator jacket were measured initially by thermometers graduated to 0.2°F and later by specially made long thermometers having a short range of temperature and graduations to 0.1°F. To cover the required range of temperature two sets of thermometers had to be made.

The temperatures of boiling liquid at different heights in the evaporator tube were shown by the travelling thermocouple. The E.M.F. was measured by means of a Junior 5 mv Cambridge Potentiometer, self-contained galvanometer, a 2-volt battery and a standard cell.

The control of the temperature of the cold junction was achieved as follows.

The simple method of keeping the junction in ice is not satisfactory, since the slowly melting ice forms a condensate at the bottom of the vacuum flask and temperature gradients of as much as 1°F are set up within a couple of hours. To stabilise the temperature, it is possible to stir the mixture of ice and condensate and to add fresh ice at intervals. A simpler method was, however, found satisfactory. The vertical space in a 2 in. x 8 in. vacuum flask was divided into two parts by supporting a wire gauze at the centre. The top half was filled with crushed ice and the bottom half was kept for condensate dripping down from the ice. The cold junction was kept at about half an inch above the wire gauze and surrounded by the melting ice. With this method, the ice was kept free from the excess condensate and the temperature of the cold junction could be maintained constant to better than 0.1°F for about three hours. It should be noted that the overall accuracy of the potentiometer and galvanometer was of the order of 0.1°F.

For a rough check of temperatures, thermometers were kept in the feed tank liquid feed inlet to evaporator, vapour liquid mixture outlet and vapour separator. None of these temperatures were involved in the determination of heat transfer coefficients. The temperature of the

feed tank was controlled by means of a bimetallic thermostat in conjunction with a high vacuum switch.

The flow rate for hot water was maintained at a constant maximum value of 4,000 lbs./hr., by keeping the by-pass valve closed. The suction head for the pump was always kept constant by keeping the water level in the tank at four inches from the top. The flow rate was checked at frequent intervals.

The feed rate to the evaporator was measured by means of a rotameter with a nominal range of 2-20 gal/hr., for water and controlled by a fine needle valve.

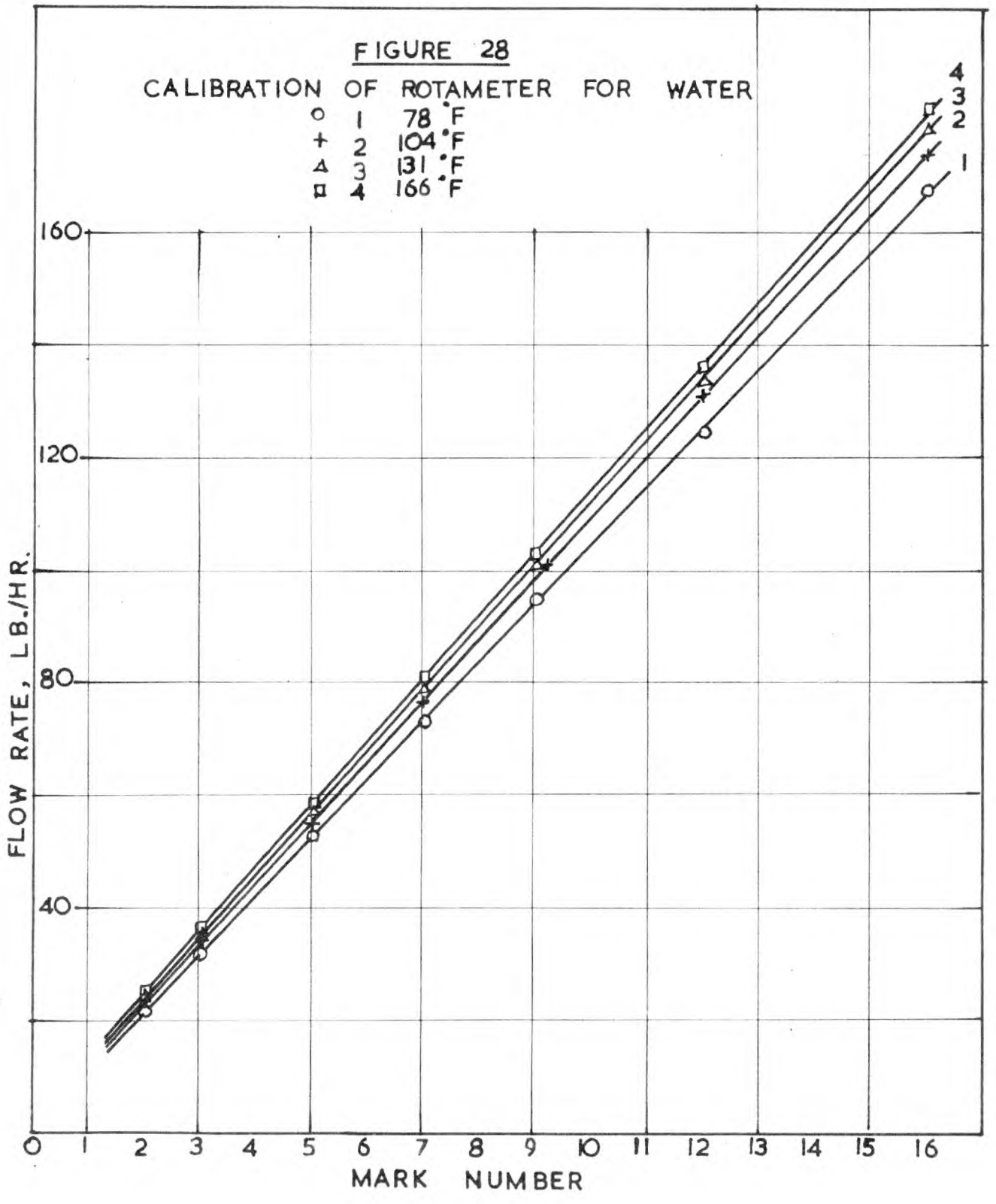
The check on vacuum, and hence the boiling temperature at the outlet, was carried out by means of an 80 cms. long mercury manometer made from small bore glass tubing.

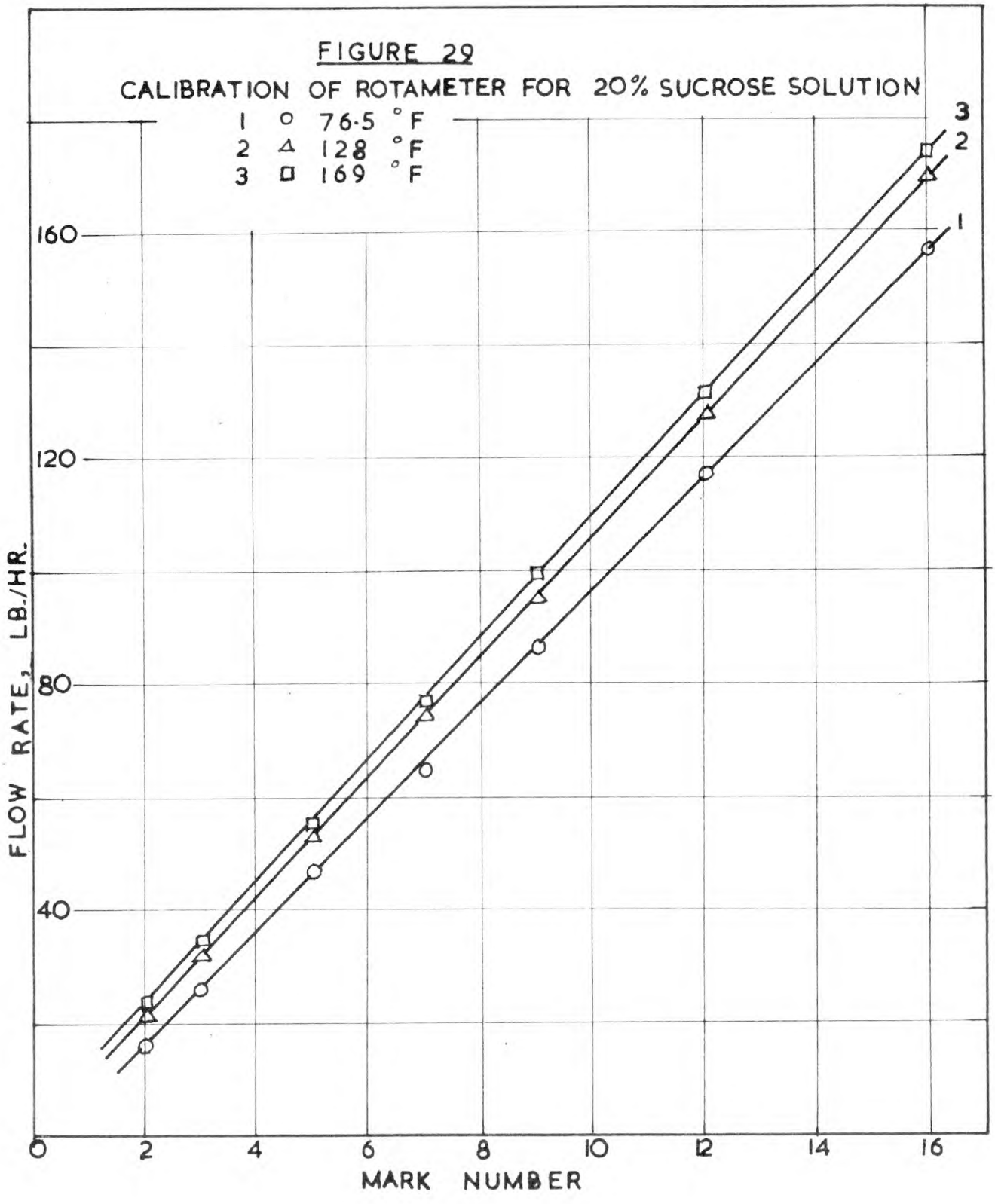
8.2. Experimental Details.

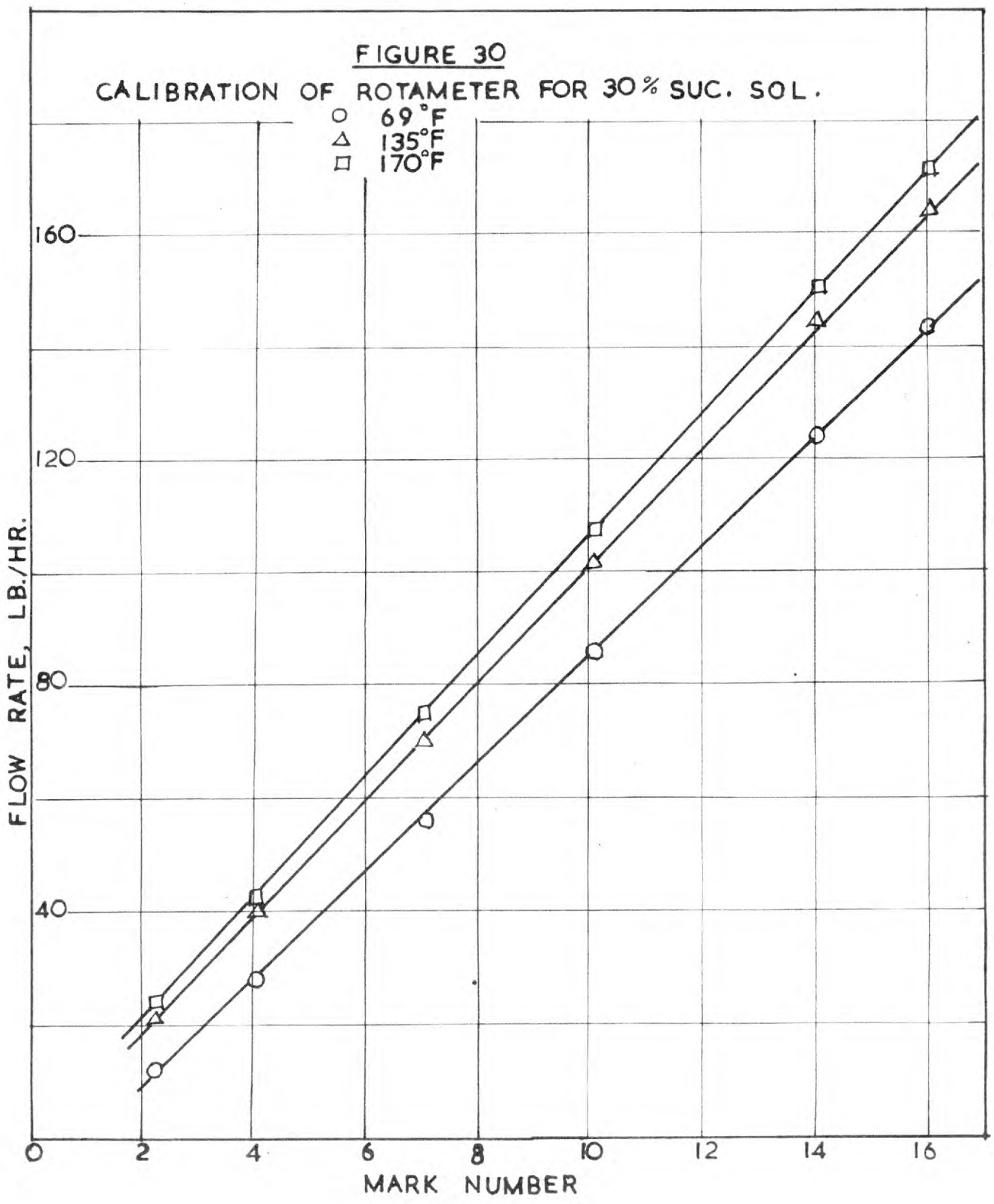
The ranges of variables employed were:-

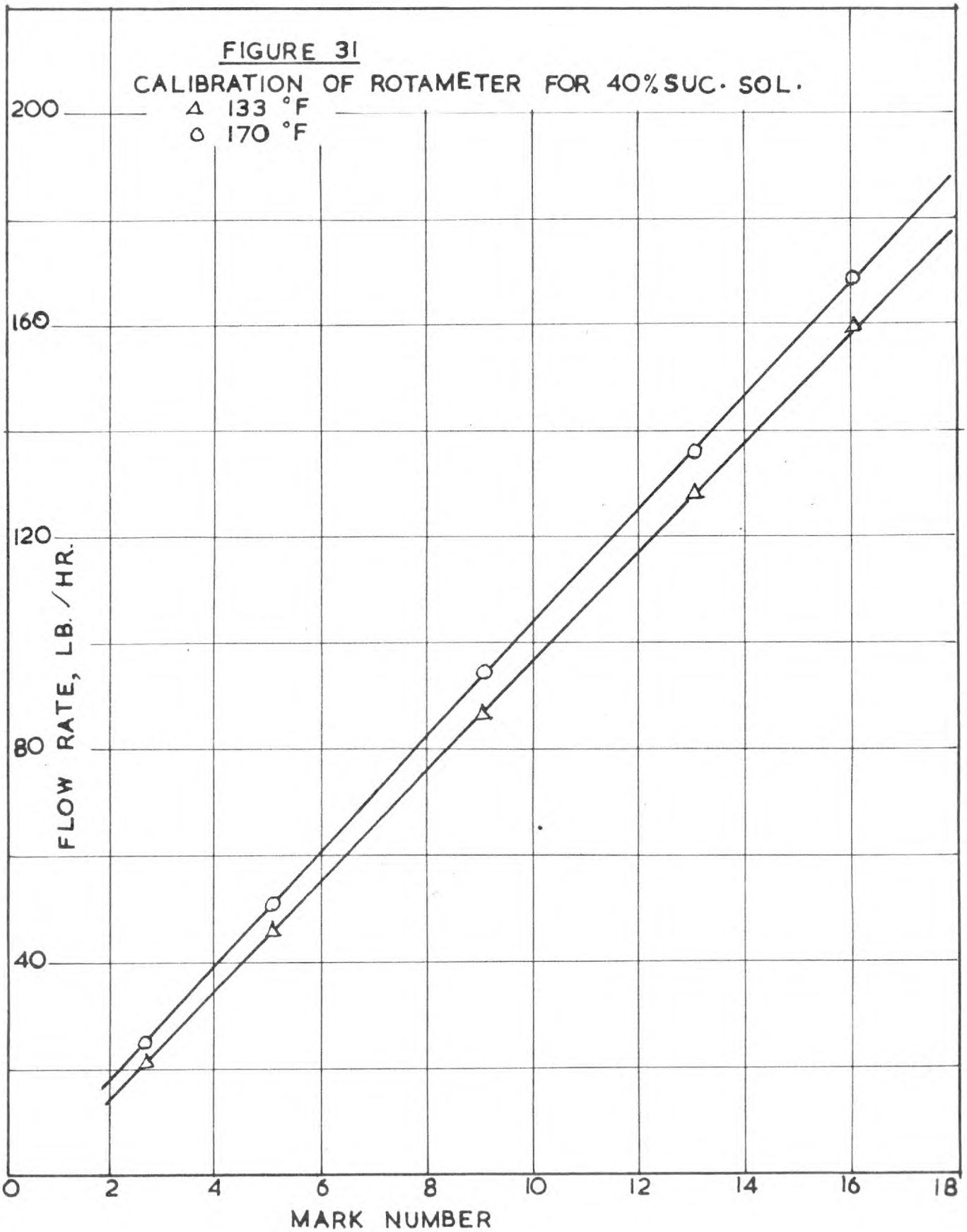
1.	Feed rate.	24.5 - 181.0 lbs./hr.
2.	Apparent temperature difference.	15-62°F.
3.	Boiling temperature:	120-165°F.
4.	Viscosity:	0.45-2.00 centipoises at 140°F.
5.	Surface tension;	21.7-69.3 dynes/cm.
6.	Prandtl's number:	2.86-18 at 140°F.

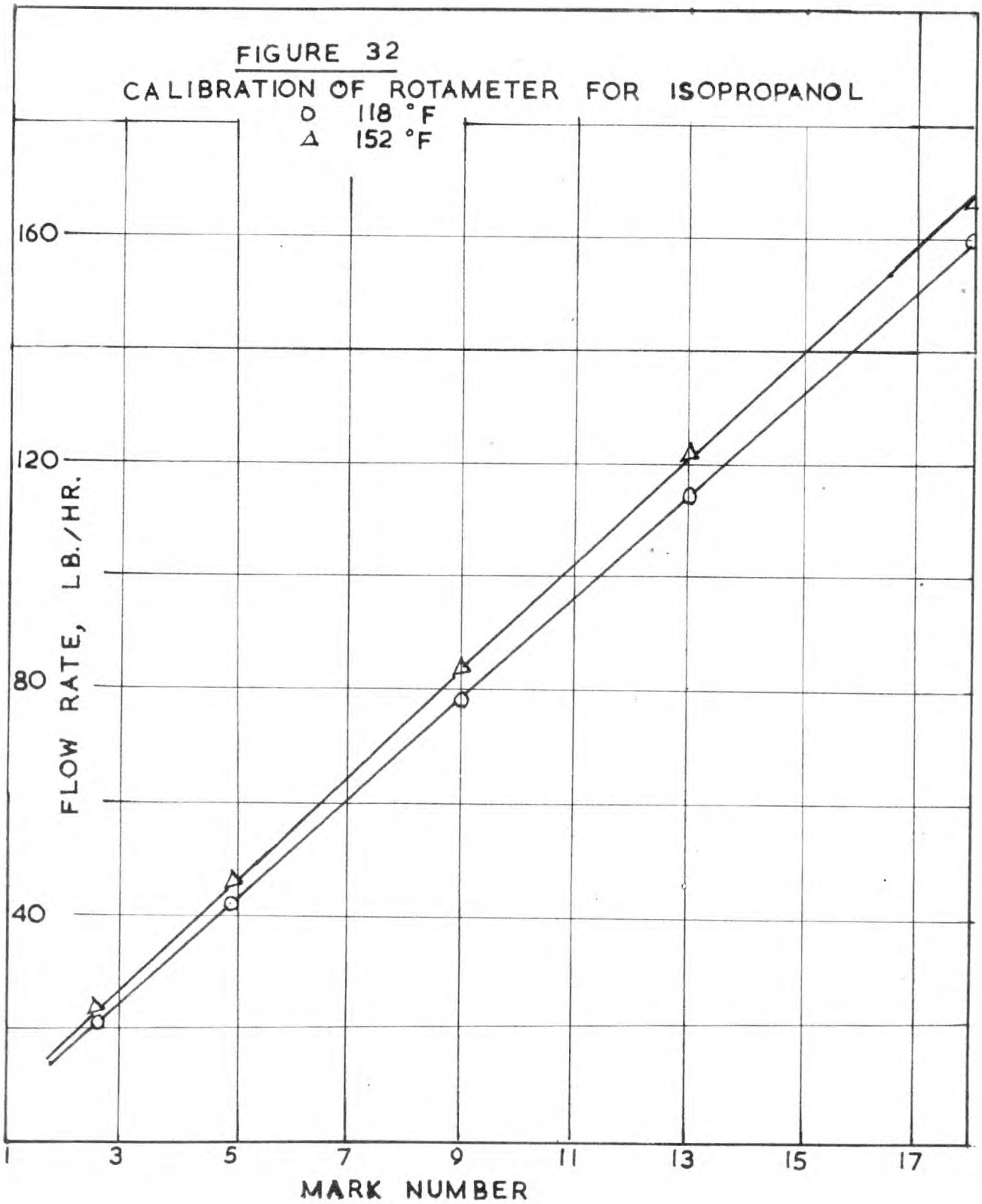
Various sets of experiments were carried out, in which the variables under test was spread over some seven


FIGURE 28
CALIBRATION OF ROTAMETER FOR WATER
○ 1 78 °F
+ 2 104 °F
△ 3 131 °F
□ 4 166 °F
4
3
2
1
160
120
80
40
FLOW RATE, LB./HR.
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
MARK NUMBER


FIGURE 29
CALIBRATION OF ROTAMETER FOR 20% SUCROSE SOLUTION
1 ○ 76·5 °F
2 △ 128 °F
3 □ 169 °F
FLOW RATE, LB./HR.
MARK NUMBER
0
2
4
6
8
10
12
14
16
40
80
120
160
1
2
3


FIGURE 30
CALIBRATION OF ROTAMETER FOR 30% SUC. SOL.
69°F
135°F
170°F
160
120
80
40
0
2
4
6
8
10
12
14
16
FLOW RATE, LB./HR.
MARK NUMBER


FIGURE 31
CALIBRATION OF ROTAMETER FOR 40% SUC. SOL.
△ 133 °F
○ 170 °F
200
160
120
80
40
FLOW RATE, LB./HR.
0
2
4
6
8
10
12
14
16
18
MARK NUMBER


FIGURE 32
CALIBRATION OF ROTAMETER FOR ISOPROPANOL
○ 118 °F
△ 152 °F
160
120
80
40
FLOW RATE, LB./HR.
1
3
5
7
9
11
13
15
17
MARK NUMBER

runs, whilst maintaining the other factors as constant as possible. The limitations in the range of temperature difference was due to the use of hot water as the heating medium. The temperature in the separator was arbitrarily fixed at 123°F, as a lower value would have required the use of very large condensers and also would have increased considerably the pressure drop along the tube. This temperature was only altered when examining the influence of boiling temperature and with isopropyl alcohol.

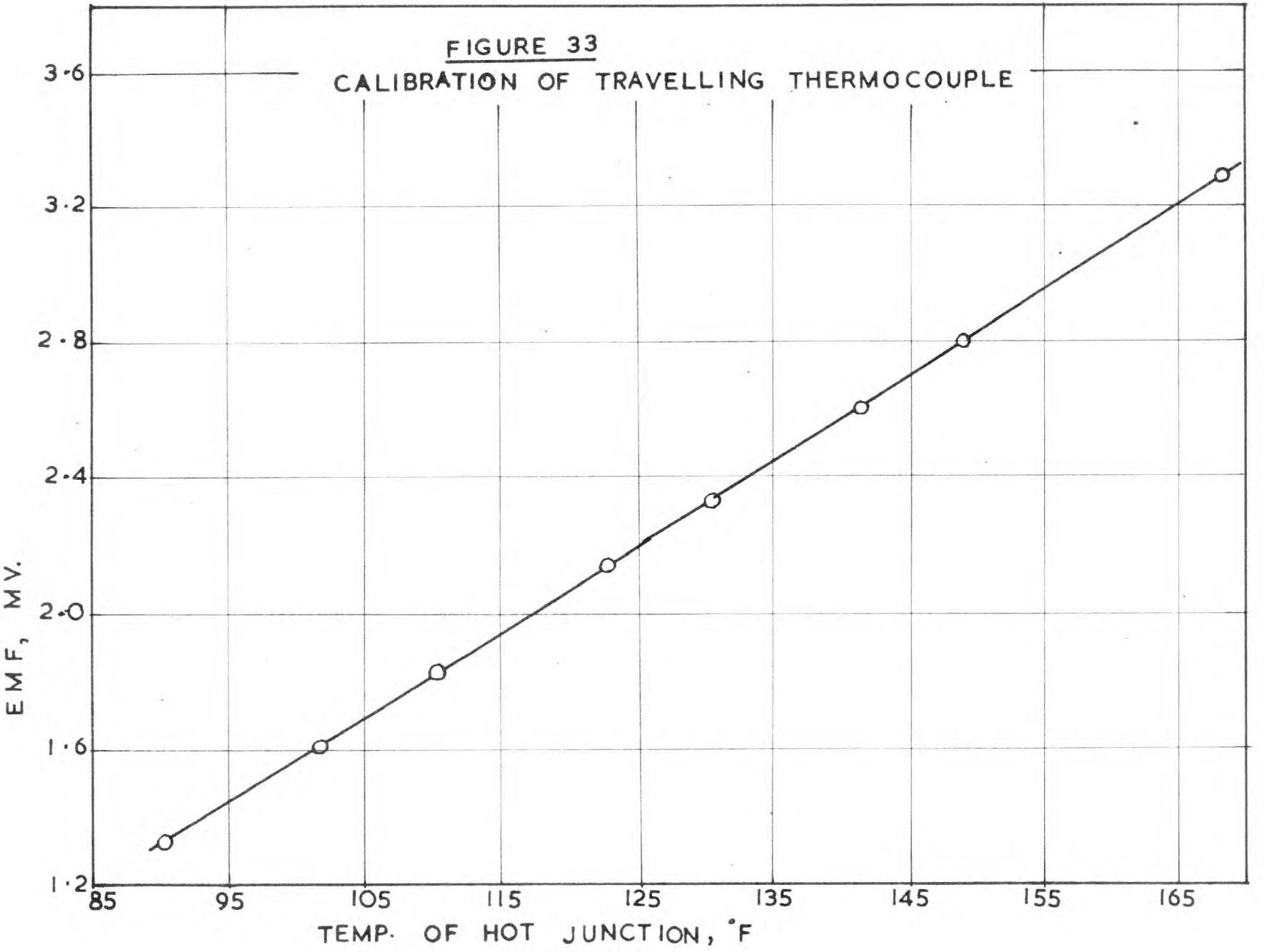
The variation in viscosity was covered by using 20, 30 and 40 per cent sucrose solutions and, in surface tnesion, by adding 0.01 and 0.1 per cent Teepol to the condensate water. The Prandtl number ranged from 2.86 with water to 18 with isopropyl alcohol for a temperature of 140°F. The physical properties of the seven liquids used are given in Table A (page 38).

As already mentioned, the feed rate was measured by rotameter, which was calibrated for each liquid at two or three temperatures. Figures 28, 29, 30, 31 and 32 show such calibration charts for water, sucrose solutions and isopropyl alcohol.

The calibration of the travelling thermocouple was carried out by circulating hot water at about 200 lbs./hr. through the evaporator tube. Using a thermometer graduated

FIGURE 33

CALIBRATION OF TRAVELLING THERMOCOUPLE



to 01°F at the evaporator outlet, readings of the thermocouple E.M.F. were taken at various temperatures. The plot of E.M.F. in millivolts versus temperature of the hot junction is shown in Figure 33. This calibration curve was checked at intervals.

The feed temperature was always adjusted for boiling at the bottom of the tube. Before starting a run, a few readings of the travelling thermocouple were made near the bottom of the tube to determine if boiling actually existed there, as indicated by the maximum liquid temperature being at the bottom.

A run consisted of continuous operation under constant conditions for a period of 20 minutes. The constant conditions to be maintained were feed rate, feed temperature, hot water temperature and liquid temperature at the outlet. Apart from maintaining these conditions constant, a number of temperature measurements had to be carried out quickly and accurately. The boiling liquid temperatures were taken at seven equidistant points along the tube length. Hot water temperatures were taken four times and the boiling liquid temperatures twice, moving the travelling thermocouple upwards and downwards during a run. The values used for the calculations were the averages of the readings taken during each run. The vapour condensate was collected

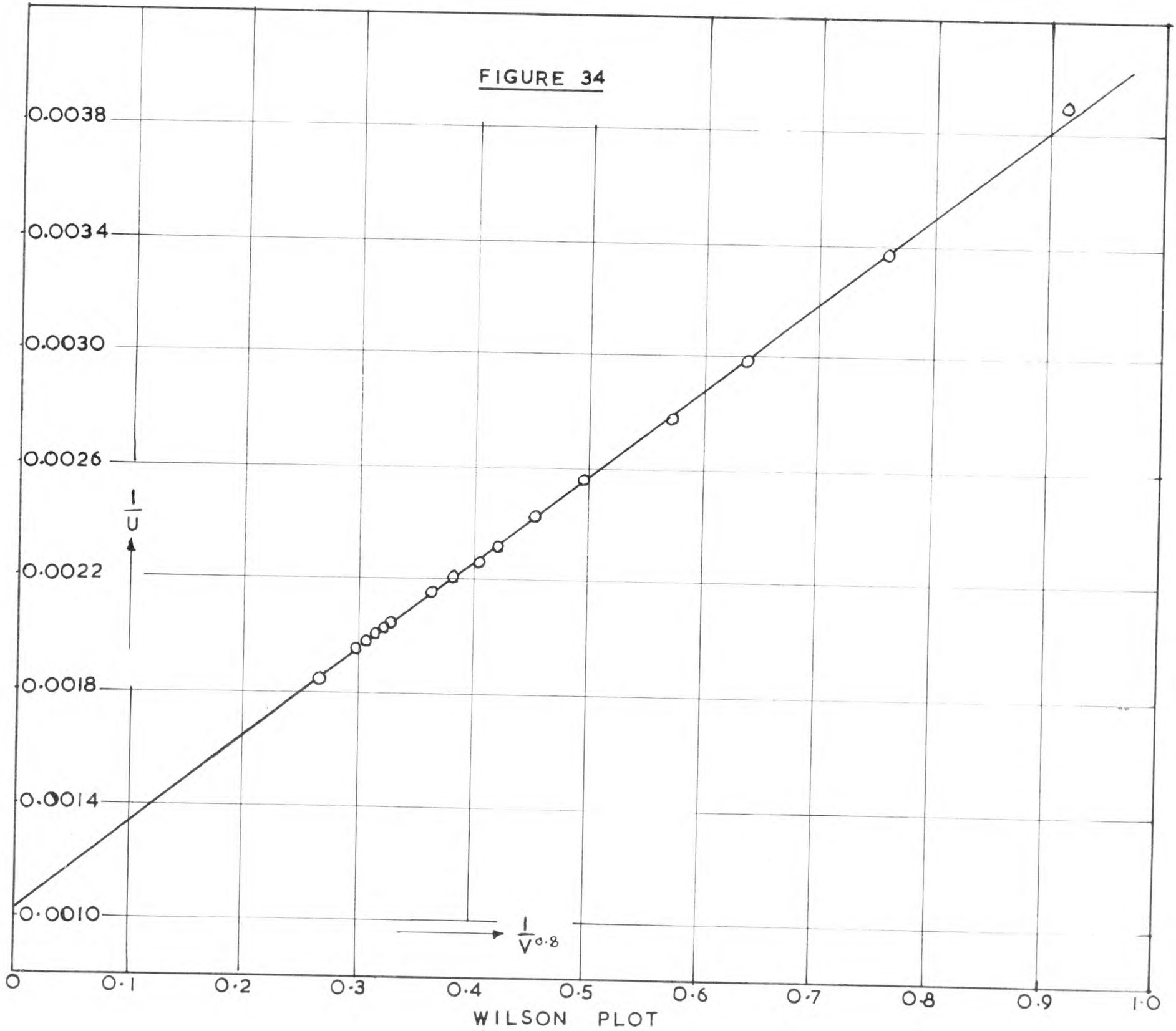
in a measuring cylinder and the amount noted at the end of the run.

Heat flux was determined from the temperature drop of hot water flowing at a constant rate of 4,000 lbs./hr. The temperature drop of hot water with no load was determined for every run. This, when deducted from the previous readings, gave the actual temperature drop of hot water, due to heat transfer to the boiling liquid.

As already mentioned, the apparent temperature difference has little significance in this type of evaporator, especially when working under high vacuum, because of the considerable temperature drop along the tube. In some of the runs taken under certain operating conditions, the values of effective temperature difference were as low as one fourth of the apparent temperature difference. The method of finding out the true temperature difference by the logarithmic mean of the terminal temperature differences is not applicable, because the assumptions on which the log mean relation is derived do not hold in the present case. The method of calculating the true temperature difference was as follows.

The temperature of the boiling liquid was measured at 7 equidistant points along the tube and the average value taken as the boiling temperature of the liquid. The

FIGURE 34



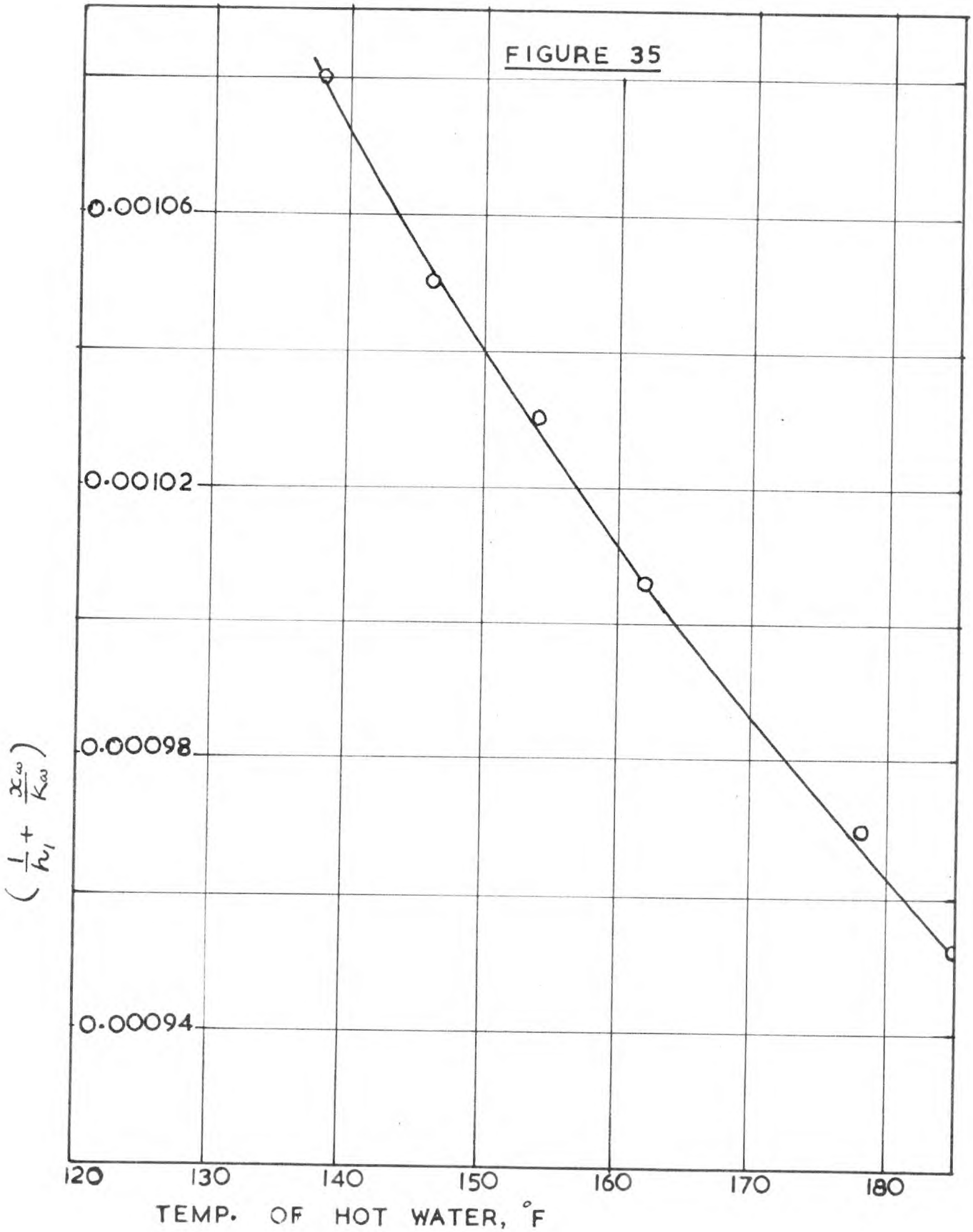
WILSON PLOT

average temperature of the hot water was obtained from the values recorded at the bottom and the top of the jacket. The difference between these two averages was taken as the true temperature difference.

8.3. Determination of Boiling Film Coefficients.

Several methods were used for fixing thermocouples in the thin wall of the stainless steel tube, but they were not entirely satisfactory. An indirect method, using the Wilson plot, was therefore used for determination of the values of the boiling film coefficient. Part of the equipment had to be dismantled for carrying out the tests for Wilson plot. The feed line was connected to the cold water supply and the outlet liquid line from the separator to waste. Keeping the hot water flow rate at 4,000 lbs./hr., with an inlet temperature of 158.5°F, 16 tests were made with varying cold water rate through the evaporator tube, from 250 to 1160 lbs./hr. Experimental data and the calculated values for the Wilson plot are given in Table No. 6 (Chapter 9). The values of the overall resistance ($\frac{1}{U}$) were plotted as shown in Figure 34, against $\frac{1}{V^{0.8}}$, where V is the water velocity in the evaporator tube, in ft./sec. The value of $\frac{1}{U}$ for $\frac{1}{V^{0.8}} = 0$ give the combined resistance of the annulus film and tube wall ($\frac{1}{h_i} + \frac{xw}{Kw}$). To test the reliability of the method, a number of runs were repeated and

FIGURE 35


0.00106
0.00102
0.00098
0.00094
$\left(\frac{1}{h_1} + \frac{x_\omega}{K_\omega}\right)$
120
130
140
150
160
170
180
TEMP. OF HOT WATER, °F

the values of the intercepts $(\frac{1}{h_i} + \frac{Xw}{Kw})$ agreed very closely. The values of annulus film coefficients for different temperatures of hot water were calculated in the same way as described earlier (page 36) and the combined value of annulus film and tube wall resistance have been plotted versus hot water temperature and are shown in Figure 35. This plot helped in the rapid calculation of boiling film coefficients at any temperature of hot water from 138 to 185°F.

CHAPTER 9.

Presentation of Results.

Over 200 runs were carried out under varying conditions, the experimental data being presented in Tables 7-13. Both overall and boiling film coefficients were calculated for each run and are shown in the Tables, together with other values. The letter succeeding each run number indicates the series number. The explanation for the symbols used in the tables, together with a specimen calculation, is given at the end of the chapter. The series of runs taken were:

Series.	Variable under study.	Operating conditions.
A.	Feed rate.	Variation in feed rate. Hot water temperature, 138°F. Outlet temperature, 123°F.
B.	Feed rate.	Variation in feed rate. Hot water temperature, 162°F. Outlet temperature, 123°F.
C.	Feed rate.	Variation in feed rate. Hot water temperature, 185°F. Outlet temperature, 123°F.
D.	Temperature difference.	Feed rate, 24.5 lbs./hr. Variation in hot water temperature. Outlet temperature, 123°F.
E.	Temperature difference.	Feed rate, 58.0 lbs./hr. Variation in hot water temperature. Outlet temperature, 123°F.
F.	Temperature difference.	Feed rate, 135 lbs./hr. Variation in hot water temperature. Outlet temperature, 123°F.

Series.	Variable under study.	Operating conditions.
G	Temperature level.	Feed rate, 58 lbs./hr. Variation in boiling temperature. App. temperature difference, 30°F.
H.	Temperature level.	Feed rate, 58 lbs./hr. Variation in boiling temperature. Average overall temperature difference, 20°F.
J.	Feed rate.	Variation in feed rate. Average overall temperature difference, 20°F. Outlet temperature, 123°F.
K.	Feed rate.	Variation in feed rate. Average overall temperature difference, 20°F. Average boiling temperature, 140°F

In the case of ispropyl alcohol, in view of the smaller temperature drop along the tube, most of the runs were taken with outlet temperature at 133°F and are distinguished by a 'dash'. The various series of runs taken with different liquids were:

	Liquid.	Series.
1.	Condensate water.	A, B, C, D, E, F, G.
2.	0.01% Teepol solution.	B, C, D, E.
3.	0.10% Teepol solution.	B, C, D, E.
4.	20% sucrose solution.	B, D, E, H, J.
5.	30% sucrose solution.	B, D, E, H, K.
6.	40% sucrose solution.	B, D, E, H, K.
7.	Isopropyl alcohol.	B', D', E', H', K', D, E.

Table 6.

Runs for Wilson plot.

Run No.	W_f	t_1	t_2	t_1'	t_2'	Q	Δt (log mean)	V	U	$\frac{1}{V^{0.8}}$	$\frac{1}{U}$
1	252	55.0	103.7	158.7	155.3	12260	74.7	1.12	257	0.913	0.00389
2	316	54.0	100.1	158.7	154.8	14590	77.1	1.41	297	0.760	0.00337
3	395	53.5	96.3	158.7	154.2	16920	79.4	1.76	335	0.637	0.00299
4	452	52.7	93.8	158.8	154.0	18590	81.1	2.01	360	0.571	0.00278
5	540	51.1	89.7	158.6	153.2	20840	83.7	2.40	391	0.496	0.00256
6	605	49.9	87.1	158.9	153.1	22510	85.8	2.69	412	0.453	0.00243
7	663	49.6	85.5	158.6	152.6	23800	86.5	2.95	432	0.421	0.00231
8	695	49.2	84.4	158.8	152.5	24450	87.2	3.09	440	0.405	0.00227
9	747	48.8	82.8	158.4	152.0	25390	87.9	3.32	453	0.382	0.00221
10	794	48.1	81.2	158.5	151.8	26290	89.2	3.54	463	0.364	0.00216
11	898	47.4	79.0	158.8	151.6	28360	90.7	4.00	491	0.330	0.00204
12	923	47.2	78.4	159.1	151.7	28810	91.4	4.11	495	0.323	0.00202
13	945	47.3	77.9	159.0	151.7	28930	91.6	4.21	496	0.317	0.00202
14	987	47.1	77.1	159.1	151.5	29610	92.0	4.39	505	0.306	0.00198
15	1012	46.5	76.2	158.9	151.2	30050	92.6	4.50	509	0.300	0.00196
16	1157	46.1	73.9	158.5	150.3	32160	93.4	5.15	540	0.269	0.00185

W_f = cold water feed rate, lbs./hr.

t_1, t_2 = cold water inlet and outlet temperature, °F.

t_1', t_2' = hot water inlet and outlet temperatures, °F.

Q = heat transfer, B.T.U./hr.

Δt = log mean temperature difference, °F.

V = velocity of cold water, ft./sec.

U = overall heat transfer coeffieient (hased on mean surface area of the tube). B.T.U./hr./sq.ft./°F.

TABLE 7.

Test liquid: condensate water.

Run No.	82A	83A	84A	85A	86A	87B	88B	89B	90B
W_f	24.5	36.5	58.0	80.0	103.0	24.5	36.5	58.0	80.0
T_1	138.30	138.50	138.30	138.30	138.60	162.40	162.60	162.60	162.30
T_2	137.50	137.80	137.70	137.70	138.10	159.90	160.20	160.40	160.20
t_1	130.5	131.1	133.7	135.4	137.2	139.4	140.1	143.6	145.9
t_2	130.1	130.1	132.5	133.5	135.4	139.0	139.2	142.4	144.7
t_3	128.3	128.9	130.5	131.8	133.5	136.9	138.2	141.1	143.4
t_4	127.3	127.3	128.9	130.3	131.6	135.9	137.4	140.1	141.7
t_5	125.9	126.1	127.5	128.5	129.5	134.8	135.9	138.6	139.9
t_6	124.5	124.9	126.3	126.9	127.5	132.9	133.3	135.6	137.4
t_7	124.0	124.0	124.3	124.7	124.9	128.5	129.5	130.3	132.2
$T_{Av.}$	137.90	138.15	138.00	138.00	138.35	161.15	161.40	161.50	161.25
$t_{Av.}$	127.20	127.50	129.10	130.20	131.40	135.30	136.20	138.80	140.70
$\Delta T_{Av.}$	10.70	10.65	8.90	7.80	6.95	25.85	25.20	22.70	20.55
t_{1-7}	6.5	7.1	9.4	10.7	12.3	10.9	10.6	13.3	13.7
m	20	20	20	20	20	20	20	20	20
l	0.484	0.488	0.507	0.500	0.544	1.278	1.259	1.300	1.304
E	3.19	3.22	3.35	3.30	3.59	8.43	8.31	8.58	8.61
E_p	13.0	8.8	5.8	4.1	3.5	34.4	22.8	14.8	10.8
q	3102	2677	2252	2252	1827	9137	8712	7862	7437
Q/A	4870	4202	3535	3535	2867	14340	13680	12340	11680
U_B	455	395	397	453	413	555	543	544	568
h_B	994	941	943	997	958	1352	1287	1292	1424
Δt	5.3	4.8	4.1	3.8	3.2	11.5	11.5	10.3	8.9
t_8	123	123	123	123	123	123	123	123	123

Table 7 (continued).

Test liquid: condensate water.

Run No.	91 B	92 B	93 B	94 C	95 C	96 C	97 C	98 C	99 C
W_f	103.0	135.0	181.5	24.5	36.5	58.0	80.0	103.0	135.0
T_1	162.20	162.40	162.00	185.00	185.10	185.00	185.10	185.10	184.60
T_2	160.30	160.70	160.60	181.00	181.30	181.60	181.90	182.10	181.90
t_1	148.2	150.9	154.9	149.7	151.1	154.3	158.0	160.1	163.8
t_2	146.8	150.0	153.7	149.1	150.2	153.7	157.2	159.3	162.9
t_3	145.7	148.2	152.0	148.0	149.7	153.4	156.0	157.8	161.5
t_4	144.3	146.4	150.4	146.4	147.8	151.5	154.7	156.2	159.7
t_5	143.2	144.3	147.8	144.5	146.6	150.2	153.0	154.9	158.0
t_6	139.0	141.8	144.9	142.0	144.3	147.6	150.2	153.2	154.9
t_7	133.9	135.9	139.2	135.4	137.6	140.7	142.8	145.7	147.8
t_8	123	123	123	123	123	123	123	123	123
$T_{Av.}$	161.25	161.55	161.30	183.00	183.20	183.30	183.50	183.60	183.25
$t_{Av.}$	143.00	145.40	149.00	145.00	146.80	150.20	153.10	155.30	158.40
$\Delta T_{Av.}$	18.25	16.15	12.30	38.00	36.40	33.10	30.40	28.30	24.85
t_{1-7}	14.3	15.0	15.7	14.3	13.5	13.6	15.2	14.4	16.0
m	20	20	20	20	20	20	20	20	20
l	1.356	1.410	1.526	2.097	2.086	2.052	2.154	2.226	2.312
E	8.95	9.31	10.07	13.84	13.77	13.54	14.22	14.69	15.26
E_p	8.7	6.9	5.5	56.5	37.7	23.3	17.8	14.4	11.3
Q	6587	5737	4462	15300	14450	12750	11900	11050	9775
Q/A	10340	9995	7003	24020	22690	20010	18670	17340	15340
U_B	566	557	569	632	623	605	614	613	619
h_B	1414	1363	1430	1715	1655	1542	1596	1592	1630
Δt	7.9	7.9	5.3	15.2	14.9	14.1	12.7	11.8	10.2

Table 7 (continued)

Test liquid: condensate water.

Run No.	100C	101D	102D	103D	104D	105D	106D	107D	108E
W_f	181.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	58.0
T_1	184.40	138.05	146.10	154.10	161.90	167.90	178.10	185.05	138.20
T_2	182.10	137.30	144.70	152.20	159.50	165.10	174.75	181.15	137.55
t_1	167.9	130.3	132.5	134.6	138.2	141.7	146.3	149.2	133.9
t_2	166.7	128.9	130.7	133.3	136.9	140.7	145.5	148.9	132.2
t_3	165.3	127.7	129.1	132.2	136.3	139.4	144.3	147.4	130.7
t_4	163.3	126.5	128.5	131.3	135.0	138.6	143.2	146.3	129.3
t_5	161.6	125.5	127.7	130.5	133.5	136.9	141.5	144.0	127.3
t_6	158.8	124.9	126.7	129.1	132.0	136.1	139.6	142.4	126.1
t_7	151.1	123.8	124.7	126.3	127.9	130.5	134.8	136.5	124.5
t_8	123	123	123	123	123	123	123	123	123
$T_{Av.}$	183.25	137.67	145.40	153.15	160.70	166.50	176.42	183.10	137.87
$t_{Av.}$	162.10	126.80	128.60	131.00	134.30	137.70	142.20	145.00	129.10
$\Delta T_{Av.}$	21.14	10.87	16.80	22.15	26.40	28.80	34.22	38.10	8.77
t_{1-7}	16.8	6.5	7.8	8.3	10.3	11.2	11.5	12.7	9.4
m	20	20	20	20	20	20	20	20	20
l	2.583	0.473	0.762	1.026	1.266	1.458	1.832	2.101	0.496
E	17.1	3.12	5.03	6.77	8.35	9.62	12.09	13.87	3.27
E_p	9.4	12.7	20.5	27.6	34.1	39.3	49.3	56.6	5.6
q	8075	2890	5100	6800	8710	10200	12540	14870	2465
q/A	12680	4536	8005	10680	13680	16010	19680	23340	3869
U_B	600	416	476	482	518	556	575	613	441
h_B	1514	819	1031	1037	1164	1340	1409	1592	912
Δt	9.1	6.0	8.4	11.2	12.7	12.9	15.2	15.9	4.6
V_1		158	251	325	386	415	467	517	164
Δ/ν		18	22.5	25	33	39.5	45	52	29

Table 7 (continued).

Test liquid: condensate water.

Run No.	109 E	110 E	111 E	112 E	113 E	114 E	115 F	116 F	117 F
W_f	58.0	58.0	58.0	58.0	58.0	58.0	135.0	135.0	135.0
T_1	146.00	154.30	162.30	169.75	178.40	185.27	146.07	154.05	162.16
T_2	144.85	152.70	160.15	167.40	175.59	182.06	145.25	152.75	160.45
t_1	136.5	139.9	143.4	147.0	151.0	154.9	143.2	146.1	150.8
t_2	134.8	138.8	142.4	145.9	150.2	154.1	141.8	144.9	149.5
t_3	133.1	137.6	140.7	144.5	149.2	153.3	139.8	143.4	148.0
t_4	131.6	136.1	139.4	143.3	148.2	151.8	137.8	141.5	146.4
t_5	129.9	134.1	138.2	141.6	146.4	150.3	135.4	139.6	144.3
t_6	128.5	132.2	136.1	139.2	143.6	147.1	132.9	136.9	141.5
t_7	125.5	128.3	130.7	133.1	137.7	140.6	127.9	131.6	135.4
t_8	123	123	123	123	123	123	123	123	123
$T_{Av.}$	14542	153.50	161.22	168.57	176.99	183.66	145.66	153.40	161.30
$t_{Av.}$	131.40	135.30	138.70	142.10	146.60	150.30	137.00	140.60	145.10
$\Delta T_{Av.}$	11.02	18.20	22.52	26.17	30.39	33.36	8.66	12.80	16.20
t_{1-7}	11.0	11.6	12.7	13.9	13.3	14.5	15.3	14.5	15.4
m	20	20	20	20	20	20	20	20	20
l	0.764	1.038	1.311	1.518	1.801	2.030	0.849	1.101	1.375
E	5.04	6.85	8.65	10.02	11.89	13.40	5.60	7.23	9.07
E_p	8.7	11.8	14.9	17.3	20.5	23.1	4.1	5.4	6.7
Q	4040	5525	7650	9137	11440	12920	2635	4250	5780
Q/A	6342	8672	12000	14340	17950	20280	4136	6671	9072
U_B	452	476	533	542	591	608	478	521	560
h_B	932	1012	1237	1268	1499	1562	1040	1095	1380
Δt	7.1	9.3	10.5	12.3	13.0	14.1	4.3	6.6	7.1
V_1	240	300	351	386	405	422	152	204	279
Δf	34	39	45.5	54.5	57	65	53	54	64

Table 7 (continued).

Test liquid: condensate water.

Run No.	118 F	119 F	120 F	121 G	122 G	123 G	124 G	125 G	126 G
W_f	135.0	135.0	135.0	58.0	58.0	58.0	58.0	58.0	58.0
T_1	170.01	177.65	185.39	134.12	144.32	154.10	164.15	174.45	184.35
T_2	167.95	175.30	182.60	133.02	142.95	152.42	162.15	172.27	181.92
t_1	154.7	159.3	164.1	125.5	130.9	138.6	146.6	153.5	161.8
t_2	153.7	158.6	163.1	124.0	129.9	137.8	145.9	152.4	160.7
t_3	152.6	157.0	161.4	122.2	128.1	136.3	144.5	151.7	160.1
t_4	150.9	155.6	160.1	120.4	126.7	134.8	143.6	150.8	159.1
t_5	148.9	153.2	158.2	118.8	125.3	133.5	142.4	150.0	158.4
t_6	146.3	150.2	155.6	115.6	123.0	131.3	140.5	148.5	157.0
t_7	139.8	143.4	147.8	111.1	118.6	127.7	137.8	146.3	155.4
t_8	123	123	123	103	113	123	133	143	153
$T_{Av.}$	168.98	176.47	184.00	133.97	143.63	153.26	163.15	173.36	183.13
$t_{Av.}$	149.60	153.90	158.60	119.70	126.10	134.30	143.00	150.50	158.90
$\Delta T_{Av.}$	19.38	22.59	25.40	14.37	17.53	18.96	20.15	22.86	24.23
t_{1-7}	14.9	15.9	16.3	14.4	12.3	10.9	8.8	7.2	6.4
m	20	20	20	20	20	20	20	20	20
l	1.699	2.003	2.301	0.792	0.898	0.933	1.084	1.135	1.215
E	11.21	13.22	15.19	5.23	5.93	6.16	7.15	7.49	8.02
E_p	8.3	9.8	11.3	9.0	10.2	10.6	12.3	12.9	13.8
Q	7055	8287	9945	4250	4972	5865	7012	7565	8627
Q/A	11080	13010	15610	6671	7805	9206	11010	11880	13540
U_B	567	576	615	465	445	485	548	519	559
h_B	1401	1416	1603	1013	905	1051	1314	1144	1293
Δt	8.6	10.0	10.6	7.1	9.3	9.5	9.1	11.2	11.3
V_1	375	485	612						
Δp	68	77	90						

Table 8.

Test liquid: 0.01 per cent Teepol solution.

Run No.	127 B	128 B	129 B	130 B	131 B	132 B	133 C	134 C
W_f	24.5	36.5	58.0	80.0	103.0	135.0	24.5	36.5
T_1	162.27	162.77	162.70	162.71	162.50	162.38	185.44	185.55
T_2	159.82	160.42	160.58	160.76	160.83	161.18	181.79	181.96
t_1	141.7	144.0	148.9	154.8	157.7	161.9	153.0	155.6
t_2	140.4	142.4	146.5	152.1	155.0	159.9	151.8	153.5
t_3	138.4	140.0	143.7	148.5	151.4	156.9	149.5	151.1
t_4	136.5	137.9	140.9	145.1	147.7	152.6	147.2	148.5
t_5	134.3	135.4	138.1	141.7	144.1	147.9	145.4	146.3
t_6	132.2	132.6	134.6	138.5	140.1	142.7	142.6	143.7
t_7	128.4	128.6	129.9	132.7	133.8	135.9	137.5	138.3
t_8	123	123	123	123	123	123	123	123
$T_{Av.}$	160.92	161.49	161.52	161.76	161.67	161.78	183.62	183.76
$t_{Av.}$	135.99	137.27	140.37	144.77	147.11	151.11	146.71	148.14
$\Delta T_{Av.}$	24.93	24.20	21.15	16.99	14.56	10.67	36.91	35.62
t_{1-7}	13.3	15.4	19.0	22.1	23.9	26.0	15.5	17.3
m	20	20	20	20	20	20	20	20
l	1.307	1.326	1.353	1.345	1.372	1.378	1.947	2.022
E	8.62	8.75	8.93	8.88	9.05	9.09	12.85	13.35
E_p	35.2	23.9	15.4	11.1	8.8	6.7	52.4	36.6
Q	9350	8925	7947	7012	6035	4037	14790	14535
Q/A	14680	14010	12470	11010	9473	6337	23210	22810
U_B	589	573	590	648	651	594	629	640
h_B	1555	1491	1562	1996	2022	1584	1693	1768
Δt	10.2	10.2	8.7	6.0	5.1	4.3	14.9	14.0

Table 8 (continued).

Test liquid: 0.01 per cent Teepol solution.

Run No.	135 C	136 C	137 C	138 C	139 D	140 D	141 D	142 D
W_F	58.0	80.0	103.0	135.0	24.5	24.5	24.5	24.5
T_1	185.65	185.63	185.50	185.42	146.35	154.55	162.60	170.70
T_2	182.32	182.67	182.85	183.19	144.92	152.63	160.11	167.79
t_1	160.4	165.1	170.2	174.8	134.6	138.4	141.7	145.5
t_2	158.4	163.6	168.5	173.0	133.5	137.3	140.9	144.7
t_3	155.4	160.5	165.0	169.4	131.0	135.2	139.0	143.0
t_4	152.1	156.5	161.0	165.4	130.1	133.5	137.3	140.7
t_5	149.1	153.0	156.9	160.8	128.8	131.7	135.2	138.8
t_6	145.9	149.3	152.7	155.6	127.1	129.7	133.0	136.5
t_7	140.5	143.0	145.9	148.2	124.7	126.9	129.1	131.1
t_8	123	123	123	123	123	123	123	123
$T_{Av.}$	183.98	184.15	184.18	184.31	145.64	153.59	161.36	169.25
$t_{Av.}$	151.69	155.86	160.03	163.90	130.00	133.24	136.60	140.07
$\Delta T_{Av.}$	32.29	28.29	24.15	20.41	15.64	20.35	24.76	29.18
t_{1-7}	19.9	22.1	24.3	26.6	9.9	11.5	12.6	14.2
m	20	20	20	20	20	20	20	20
l	2.044	2.184	2.207	2.316	0.745	1.060	1.315	1.526
E	13.49	14.42	14.56	15.29	4.92	6.99	8.68	10.07
E_p	23.3	18.0	14.1	11.3	20.1	28.5	35.4	41.1
Q	13430	11860	10540	8755	5227	7395	9520	11520
Q/A	21080	18620	16550	13740	8206	11590	14940	18080
U_B	653	658	685	673	525	570	603	620
h_B	1865	1901	2125	2022	1269	1497	1644	1740
Δt	12.2	10.6	8.4	7.4	7.0	8.4	9.8	11.3

Table 8 (continued)

Test liquid: 0.01 per cent Teepol solution.

Run No.	143D	144D	145E	146E	147E	148E	149E	150E
W_f	24.5	24.5	58.0	58.0	58.0	58.0	58.0	58.0
T_1	178.80	185.60	146.78	154.38	162.15	170.00	178.52	185.10
T_2	175.45	181.88	145.68	152.78	160.05	167.52	175.48	181.85
t_1	149.8	152.8	144.5	147.6	149.8	153.0	157.4	160.7
t_2	148.8	151.9	141.5	144.6	147.2	151.2	155.9	158.9
t_3	146.8	150.0	138.6	141.3	144.3	148.3	152.9	156.1
t_4	144.8	148.1	134.8	137.9	141.5	145.4	149.7	152.6
t_5	142.8	146.2	131.9	135.3	138.7	142.5	146.6	149.4
t_6	140.3	143.2	129.3	132.2	135.2	138.9	143.4	146.2
t_7	134.8	137.7	126.1	128.0	130.5	133.7	137.8	140.7
t_8	123	123	123	123	123	123	123	123
$T_{Av.}$	177.13	183.74	146.23	153.58	161.10	168.76	177.00	183.47
$t_{Av.}$	144.01	147.13	135.24	138.13	141.03	144.71	149.10	152.09
$\Delta T_{Av.}$	33.12	36.61	10.99	15.45	20.07	24.05	27.90	31.38
t_{1-7}	15.0	15.1	18.4	19.6	19.3	19.3	19.6	20
m	20	20	20	20	20	20	20	20
l	1.805	2.022	0.744	1.056	1.319	1.593	1.868	2.060
E	11.91	13.35	5.09	6.97	8.70	10.52	12.33	13.59
Ep	48.6	54.5	8.8	12.0	15.0	18.1	21.2	23.4
Q	13600	15090	3825	6035	7862	9690	12030	13390
Q/A	21340	23680	6005	9443	12340	15210	18880	21020
U_B	644	647	547	613	615	632	677	670
h_B	1862	1822	1393	1803	1732	1831	2138	2000
Δt	12.4	14.1	4.7	5.7	7.7	9.0	9.5	11.4

Table 9.

Test liquid: 0.1 per cent Teepol solution.

Run No.	151B	152B	153B	154C	155C	156C	158C
W_f	24.5	36.5	58.0	24.5	36.5	58.0	80.0
T_1	162.35	162.90	162.30	182.55	182.65	183.72	184.25
T_2	159.37	160.80	160.66	178.88	179.36	181.05	181.37
t_1	149.7	154.5	159.3	160.2	164.3	171.1	174.3
t_2	149.1	153.9	157 .2	158.9	163.1	169.3	172.6
t_3	146.6	151.0	153.9	156.4	159.5	165.7	170.0
t_4	143.3	147.1	149.9	151.9	155.3	161.4	165.4
t_5	138.9	142.4	145.1	147.6	150.4	156.0	159.7
t_6	133.9	135.8	138.6	143.4	144.6	149.1	151.9
t_7	128.9	128.9	129.2	137.2	138.2	140.2	141.2
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	161.16	161.85	161.48	180.71	181.00	182.45	182.55
$t_{Av.}$	141.50	144.80	147.60	150.80	153.63	158.97	162.16
$\Delta T_{Av.}$	19.66	17.05	13.88	29.91	27.37	23.48	20.39
t_{1-7}	20.8	25.6	30.1	23.0	26.1	30.9	33.1
m	20	20	20	20	20	20	20
l	1.311	1.225	1.131	1.984	1.932	1.951	1.928
E	8.65	8.08	7.46	13.09	12.75	12.87	12.73
E_p	35.3	22.1	12.8	53.4	34.9	22.2	15.9
Q	9052	7862	5907	14870	13260	11180	9265
Q/A	14210	12340	9272	23340	20810	17540	14540
U_B	723	724	668	780	760	747	713
h_B	2823	2845	2181	3275	2970	2787	2393
Δt	5.45	4.70	4.61	7.73	7.60	6.82	6.59

Table 9 (continued).

Test liquid: 0.1 per cent Teepol solution.

Run No.	158C	159D	160D	161D	162D	163D	164D
W_f	103	24.5	24.5	24.5	24.5	24.5	24.5
T_1	184.25	146.25	154.20	162.60	170.62	178.00	183.25
T_2	182.30	145.14	152.48	160.23	167.86	174.69	179.56
t_1	179.0	143.3	145.9	150.5	154.3	158.4	160.3
t_2	177.8	140.9	144.2	149.3	153.4	157.0	159.5
t_3	174.7	138.2	141.4	146.3	150.7	154.1	157.0
t_4	170.0	134.9	138.4	143.0	146.4	150.4	152.6
t_5	164.4	132.2	134.8	138.8	142.4	146.1	148.3
t_6	157.0	128.5	129.7	133.9	138.1	141.9	144.1
t_7	144.3	123.6	124.9	129.1	132.5	135.6	137.8
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	183.28	145.69	153.34	161.41	169.24	176.34	181.40
$t_{Av.}$	166.74	134.51	137.04	141.56	145.40	149.07	151.37
$\Delta T_{Av.}$	16.54	11.18	16.30	19.85	23.81	27.27	30.03
t_{1-7}	34.7	19.7	21.0	21.4	21.8	22.8	22.5
m	20	20	20	20	20	20	20
l	1.955	0.673	0.977	1.285	1.567	1.831	2.033
E	12.96	4.44	6.45	8.48	10.34	12.08	13.42
E_p	12.5	18.1	26.3	34.6	42.2	49.3	54.8
Q	7565	3867	6545	9010	10880	13430	14960
Q/A	11880	6070	10280	14150	17080	21080	23480
U_B	718	543	630	712	716	773	782
h_B	2446	1371	1945	2683	2670	3356	3409
Δt	5.26	4.80	5.72	5.71	6.93	6.81	7.43

Table 9 (continued)

Test liquid: 0.1 per cent Teepol solution.

Run No.	165E	166E	167E	168E	169E	170E
W_f	58.0	58.0	58.0	58.0	58.0	58.0
T_1	146.90	154.80	162.50	170.78	178.25	183.95
T_2	146.20	153.67	160.86	168.87	175.82	181.03
t_1	147.2	153.2	158.4	165.0	168.0	171.0
t_2	146.3	152.5	157.7	164.7	167.2	169.8
t_3	145.5	151.9	155.8	161.7	164.7	166.0
t_4	144.7	149.7	151.9	157.2	158.9	162.0
t_5	142.6	144.7	146.8	152.4	154.8	155.8
t_6	135.8	138.0	140.1	145.6	148.2	149.3
t_7	125.1	126.9	129.6	136.0	139.4	140.5
t_8	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	146.55	154.24	161.68	169.82	177.03	182.49
$t_{Av.}$	141.00	145.30	148.60	154.70	157.30	159.20
$\Delta T_{Av.}$	5.55	8.94	13.08	15.12	19.73	23.29
t_{1-7}	22.1	26.3	28.8	29.0	28.6	30.5
m	20	20	20	20	20	20
l	0.548	0.766	1.150	1.345	1.672	2.000
E	3.62	5.05	7.59	8.88	11.03	13.20
E_p	6.2	8.7	13.1	15.3	19.0	22.8
Q	2125	4037	5907	7225	9690	11690
Q/A	3335	6337	9272	11340	15210	18350
U_B	601	709	709	750	771	788
h_B	1765	2852	2643	3151	3315	3398
Δt	2.05	2.41	3.80	3.90	4.97	5.85

Table 10.

Test liquid: 20 per cent sucrose solution.

Run No.	171D	172D	173D	174D	175D	176D	177D	178E	179E
W_f	24.5	24.5	24.5	24.5	24.5	24.5	24.5	58	58
T_1	138.80	146.25	154.15	162.35	170.70	178.35	185.63	138.55	146.50
T_2	138.20	145.10	152.56	160.20	168.26	175.50	182.41	138.10	145.46
t_1	129.7	130.8	133.8	136.6	140.5	144.3	147.5	134.0	136.1
t_2	128.9	130.4	133.2	136.1	140.2	144.1	147.1	132.5	134.6
t_3	128.1	129.6	132.2	135.1	139.4	143.2	146.1	130.7	133.1
t_4	126.6	128.5	131.1	134.0	138.2	141.8	144.8	129.0	131.4
t_5	125.4	127.0	129.8	132.8	136.4	140.0	143.3	127.4	129.6
t_6	124.3	125.9	128.2	131.1	134.3	137.7	140.5	126.0	127.5
t_7	123.4	123.9	125.7	127.5	130.1	132.4	134.5	123.9	124.6
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
T_{Av}	138.50	145.67	153.36	161.27	169.48	176.92	184.02	138.32	145.98
t_{Av}	126.63	128.00	130.57	133.31	137.01	140.50	143.40	129.07	130.99
ΔT_{Av}	11.87	17.67	22.79	27.96	32.47	36.42	40.62	9.25	14.99
t_{1-7}	6.3	6.9	8.1	9.1	10.4	11.9	13.0	10.1	11.5
m	20	20	20	20	20	20	20	20	20
l	0.413	0.680	0.902	1.102	1.307	1.511	1.759	0.428	0.687
E	2.92	4.49	5.95	7.27	8.63	9.97	11.61	2.82	4.53
E_p	11.1	18.3	24.3	29.7	35.2	40.7	47.4	4.72	7.81
Q	2370	4147	5727	7544	9124	10780	12280	1777	3713
Q/A	3719	6509	8989	11840	14320	16920	19280	2789	5828
U_B	313	368	394	424	441	465	474	302	389
h_B	513	651	720	797	849	917	937	485	712
Δt	7.86	10.83	13.53	16.12	18.29	20.01	22.30	6.24	8.87
V_1	142	230	291	338	377	411	454	141	221
Δp	17.0	19.5	24.5	28.5	36.0	45.0	52.0	29.5	34.5

Table 10 (continued).

Test liquid: 20 per cent sucrose solution.

Run No.	180E	181E	182E	183E	184E	185B	186B	187B	188B
W_f	58.0	58.0	58.0	58.0	58.0	24.5	36.5	58.0	80
T_1	154.67	162.90	170.95	178.90	185.60	162.83	162.74	162.64	162.52
T_2	153.20	160.98	168.66	176.25	182.64	160.69	160.66	160.76	160.77
t_1	139.5	143.0	146.9	151.2	155.0	137.3	140.3	144.2	148.1
t_2	138.3	141.8	145.8	150.0	154.2	136.9	139.1	143.2	146.7
t_3	136.6	140.4	144.2	148.4	152.4	136.1	138.2	141.6	145.0
t_4	134.9	138.8	142.7	147.1	150.6	134.7	136.6	139.5	143.1
t_5	133.3	137.0	140.7	144.9	148.4	133.3	135.0	137.7	140.7
t_6	131.1	134.0	137.9	141.1	145.1	131.3	133.0	135.0	137.9
t_7	127.2	129.3	132.7	135.3	138.3	127.8	128.6	130.1	131.9
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	153.93	161.94	169.89	177.57	184.12	161.76	161.70	161.70	161.65
$t_{Av.}$	134.41	137.76	141.56	145.43	149.14	133.91	135.83	138.76	141.91
ΔT_{Av}	19.52	24.18	28.24	32.14	34.98	27.85	25.87	22.94	19.74
t_{1-7}	12.3	13.7	14.2	15.9	16.7	9.5	11.7	14.1	16.2
m	20	20	20	20	20	20	20	20	20
l	0.916	1.146	1.353	1.575	1.771	1.124	1.150	1.191	1.244
E	6.04	7.56	8.93	10.39	11.69	7.42	7.59	7.86	8.21
E_p	10.4	13.0	15.4	17.9	20.1	30.3	20.8	13.5	10.3
Q	5253	6636	8532	9993	11260	7506	7268	6477	5965
Q/A	8245	10420	13390	15690	17670	11790	11410	10160	9363
U_B	422	431	474	488	505	423	441	443	474
h_B	811	821	969	1006	1054	795	855	863	978
Δt	11.03	13.76	14.98	16.91	18.18	16.1	14.5	12.8	10.4
V_1	274	324	344	376	388				
Δp	40	48	55.5	66.0	75				

Table 10 (continued).

Test liquid: 20 per cent sucrose solution.

Run No.	189B	190B	191B	192H	193H	194H	195H	196H	197H
W_f	103.0	135.0	181.5	58.0	58.0	58.0	58.0	58.0	58.0
T_1	162.80	162.77	162.64	138.80	146.85	154.63	162.35	170.77	178.17
T_2	161.17	161.33	161.50	137.59	145.45	153.10	160.68	169.11	176.60
t_1	150.7	153.4	156.7	126.3	132.5	139.1	145.5	152.8	160.7
t_2	149.1	151.6	155.2	125.1	131.1	137.8	144.5	152.2	160.0
t_3	147.2	149.8	152.8	123.5	129.5	136.4	143.3	151.1	159.2
t_4	144.9	147.3	150.8	121.5	127.9	134.8	141.8	149.9	158.4
t_5	142.5	144.7	147.9	118.3	126.7	133.1	140.1	148.8	157.6
t_6	139.1	141.2	144.2	115.1	123.3	131.1	138.3	147.1	156.4
t_7	133.1	134.4	137.5	110.1	118.5	127.4	135.5	145.4	154.8
t_8	123.0	123.0	123.0	99	112	123	133	143.5	153
T_{Av}	161.99	162.05	162.07	138.20	146.15	153.87	161.51	169.94	177.38
t_{Av}	143.80	146.06	149.30	120.00	127.07	134.24	141.29	149.61	158.16
ΔT_{Av}	18.19	15.99	12.77	18.20	19.08	19.63	19.22	20.33	19.22
t_{1-7}	17.6	19.0	19.2	16.2	14.0	11.7	10.0	7.4	5.9
m	20	20	20	20	20	20	20	20	20
l	1.304	1.360	1.474	0.837	0.862	0.905	0.916	0.916	0.872
E	8.61	8.98	9.73	5.52	5.69	5.97	6.04	6.04	5.75
E_p	8.4	6.7	5.4	9.5	9.8	10.3	10.4	10.4	9.9
Q	5491	4751	3555	4779	5135	5491	5648	6044	5727
Q/A	8618	7440	5580	7502	8060	8618	8865	9177	8865
U_B	474	465	437	412	422	439	461	466	467
h_B	978	943	841	805	822	869	928	938	926
Δt	9.60	8.50	7.20	10.09	10.62	10.75	10.35	10.60	10.39

Table 10 (continued).

Test liquid: 20 per cent sucrose solution.

Run No.	198H	199J	200J	201J	202J	203J	204J	205J
W_f	58.0	24.5	36.5	58.0	80.0	103.0	135.0	181.5
T_1	185.79	152.52	154.67	158.35	164.48	166.20	172.38	182.38
T_2	184.15	150.89	152.98	156.56	162.51	164.40	170.51	180.38
t_1	167.2	132.3	1 36.5	141.4	148.0	152.6	160.0	168.3
t_2	166.7	132.2	135.7	140.3	146.4	151.0	157.8	167.8
t_3	165.7	131.5	134.4	138.5	144.7	149.4	156.3	166.0
t_4	165.0	130.6	133.1	136.8	142.7	146.8	154.1	164.0
t_5	164.2	129.4	131.7	135.0	140.5	144.3	151.3	160.2
t_6	163.2	127.9	129.8	132.8	137.6	141.1	147.8	157.1
t_7	161.9	125.4	126.7	128.5	131.8	134.4	140.4	149.3
t_8	161.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	184.97	151.70	153.82	157.45	163.49	165.30	172.44	181.38
$t_{Av.}$	164.84	129.90	132.56	136.20	141.67	145.66	152.53	161.80
$\Delta T_{Av.}$	20.13	21.80	21.26	21.25	21.82	19.84	19.91	19.58
t_{1-7}	5.3	6.9	9.8	12.9	16.2	18.2	19.6	19.0
m	20	20	20	20	20	20	20	20
l	0.932	0.785	0.909	1.034	1.266	1.410	1.736	2.301
E	6.15	5.18	6.00	6.82	8.36	9.30	11.46	15.18
E_p	10.6	21.1	16.4	11.8	10.4	9.0	8.5	8.4
Q	6043	5926	6122	6359	6794	6320	6952	7423
Q/A	9486	9301	9610	9982	10670	9919	10910	11650
U_B	471	427	452	470	489	505	549	595
h_B	926	833	916	979	1037	1106	1303	1483
Δt	11.11	12.11	11.37	11.05	11.14	9.72	9.08	8.52

Table 11.

Test liquid: 30 per cent sucrose solution.

Run No.	206D	207D	208D	209D	210D	211D	212E	213E
W_f	24.5	24.5	24.5	24.5	24.5	24.5	58.0	58.0
T_1	146.69	154.40	162.20	170.55	178.32	185.90	146.96	154.52
T_2	145.60	152.88	160.18	168.21	175.65	182.84	146.00	153.11
t_1	131.1	133.0	135.9	139.1	143.0	146.6	135.9	138.7
t_2	130.9	132.7	135.2	138.9	142.5	146.3	134.8	137.9
t_3	129.9	132.3	135.0	138.2	142.1	145.6	133.2	136.4
t_4	129.0	131.1	133.7	136.9	140.7	143.8	131.7	134.6
t_5	127.6	129.8	132.4	135.4	138.7	142.5	129.7	132.9
t_6	126.2	128.1	130.6	133.3	136.5	139.6	127.2	130.7
t_7	124.1	125.5	127.1	129.0	131.2	133.4	124.9	126.3
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
T_{Av}	146.15	153.64	161.19	169.38	176.98	184.37	146.48	153.82
t_{Av}	128.40	130.36	132.84	135.83	139.24	142.54	131.06	133.93
ΔT_{Av}	17.75	23.28	28.35	33.55	37.74	41.83	15.42	19.89
t_{1-7}	7.0	7.5	8.8	10.1	11.8	13.2	11.0	12.4
m	20	20	20	20	20	20	20	20
l	0.633	0.876	1.053	1.199	1.412	1.627	0.615	0.887
E	4.18	5.78	6.94	7.91	9.32	10.74	4.06	5.85
E_p	17.1	23.6	28.4	32.3	38.0	43.8	7.0	10.1
q	3910	5451	7031	8730	10070	11650	3397	5017
q/A	6138	8561	11040	13710	15810	18290	5332	7874
U_B	346	368	389	408	419	437	346	396
h_B	588	641	691	744	765	812	588	726
Δt	11.3	14.5	17.3	19.9	22.4	24.4	9.82	11.76

Table 11 (continued).

Test liquid: 30 per cent sucrose solution.

Run No.	214E	215E	216E	217E	218B	219B	220B	221B
W_f	58.0	58.0	58.0	58.0	24.5	36.5	58.0	80.0
T_1	162.75	170.70	178.84	185.58	162.92	162.65	162.67	162.91
T_2	160.87	168.51	176.31	182.68	160.91	160.70	160.76	161.12
t_1	142.4	146.7	150.4	154.4	136.1	138.4	141.7	145.9
t_2	141.5	145.9	149.8	153.9	135.9	137.9	141.4	145.5
t_3	140.0	144.3	148.2	152.2	135.7	136.6	140.2	143.8
t_4	138.2	142.3	146.4	150.2	134.6	135.0	138.2	141.8
t_5	135.8	140.2	144.3	148.5	133.2	133.6	136.3	139.0
t_6	133.5	137.8	141.3	144.9	131.3	131.5	133.9	136.2
t_7	128.9	131.9	134.9	137.6	127.4	127.4	128.9	130.7
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
T_{Av}	161.81	169.61	177.58	184.13	161.91	161.67	161.71	162.01
t_{Av}	137.19	141.30	145.04	148.81	133.46	134.34	137.23	140.41
ΔT_{Av}	24.62	28.31	32.54	35.32	28.45	27.33	24.48	21.60
t_{1-7}	13.5	14.8	15.5	16.8	8.7	11.0	12.8	15.2
m	20	20	20	20	20	20	20	20
l	1.086	1.311	1.500	1.785	1.030	1.046	1.105	1.128
E	7.17	8.65	9.90	11.78	6.79	6.90	7.28	7.44
E_p	12.4	14.9	17.1	20.3	27.7	18.9	12.6	9.3
Q	6477	8137	9519	11030	6992	6751	6597	6122
Q/A	10160	12770	14940	17300	10970	10600	10350	9610
U_B	413	451	459	490	351	366	423	445
h_B	762	883	897	992	587	625	631	869
Δt	14.45	15.67	18.05	18.89	20.25	18.37	17.78	12.00

Table 11 (continued).

Test liquid: 30 per cent sucrose solution.

Run No.	222B	223B	224B	225K	226K	227K	228K	229K
W_f	103.0	135.0	181.5	24.5	36.5	58.0	80.0	103.0
T_1	162.71	162.72	162.97	161.50	161.23	161.45	161.45	161.45
T_2	161.06	161.27	161.82	160.07	159.75	159.85	159.75	159.74
t_1	149.8	154.0	159.3	142.9	143.2	145.1	146.1	148.0
t_2	148.5	152.3	157.2	142.4	142.6	144.0	144.2	146.4
t_3	146.2	150.1	155.0	141.4	141.4	142.5	142.8	144.2
t_4	143.8	147.4	152.3	140.2	140.3	140.7	140.5	141.5
t_5	141.3	144.5	149.6	139.3	139.0	138.7	138.7	138.5
t_6	138.3	140.9	145.4	138.7	137.7	136.6	135.4	134.7
t_7	131.5	133.9	138.2	136.7	135.5	133.2	130.4	126.6
t_8	123.0	123.0	123.0	137.0	134.5	130.5	124.0	103.5
$T_{Av.}$	161.88	161.99	162.39	160.79	160.49	160.65	160.60	160.59
$t_{Av.}$	142.77	146.16	151.00	140.23	139.96	140.11	139.73	139.99
$\Delta T_{Av.}$	19.11	15.83	11.39	20.56	20.53	20.54	20.87	20.60
t_{1-7}	18.3	20.1	21.1	6.2	7.7	11.9	15.7	21.4
m	20	20	20	20	20	20	20	20
l	1.190	1.295	1.425	0.737	0.774	0.909	1.083	1.533
E	7.85	8.55	9.40	4.86	5.11	6.00	7.15	10.12
Ep	7.6	6.3	5.2	19.9	14.0	10.3	8.9	9.8
Q	5569	4779	3594	4779	4977	5451	3846	5886
Q/A	8742	7502	5641	7502	7812	8557	9177	9239
U_B	457	474	495	365	381	417	440	448
h_B	914	977	1065	623	666	774	850	881
Δt	10.37	8.33	5.74	13.10	12.70	12.00	11.70	11.40

Table 11 (continued).

Test liquid: 30 per cent sucrose solution.

Run No.	230H	231H	232H	233H	234H	235H	236H
W_f	58.0	58.0	58.0	58.0	58.0	58.0	58.0
T_1	140.52	147.98	154.70	162.45	170.00	178.48	185.65
T_2	139.44	146.64	153.28	160.87	168.53	177.00	184.13
t_1	127.7	134.7	139.2	146.0	153.1	160.3	167.1
t_2	127.0	133.6	137.9	144.7	152.3	159.7	166.6
t_3	125.1	130.8	136.8	143.3	151.1	158.8	165.7
t_4	123.1	128.7	134.6	141.5	150.0	157.8	164.8
t_5	120.6	126.3	132.9	139.7	148.2	156.7	163.6
t_6	117.0	123.6	130.8	137.9	146.7	155.3	162.6
t_7	110.7	118.4	126.7	135.0	144.5	154.0	161.0
t_8	99.5	112.0	123.0	132.5	143.5	153.0	161.0
$T_{Av.}$	139.98	147.31	153.99	161.66	169.27	177.74	184.89
$t_{Av.}$	121.60	128.01	134.13	141.16	149.41	157.51	164.49
$\Delta T_{Av.}$	18.38	19.30	19.06	20.50	19.86	20.23	20.40
t_{1-7}	17.0	16.3	12.5	11.0	8.6	6.3	6.1
m	20	20	20	20	20	20	20
l	0.851	0.853	0.857	0.860	0.853	0.865	0.865
E	5.61	5.63	5.65	5.67	5.63	5.71	5.71
Ep	9.7	9.7	9.8	9.8	9.7	9.8	9.8
Q	4187	4898	5056	5293	5293	5371	5569
Q/A	6572	7688	7036	8309	8309	8431	8742
U_B	357	398	400	405	418	417	428
h_B	631	742	735	738	774	758	783
Δt	11.30	11.20	11.70	12.20	11.60	12.10	12.10

Table 12.

Test liquid: 40 per cent sucrose solution.

Run No.	237D	238D	239D	240D	241D	242E	243E	244E
W_f	24.5	24.5	24.5	24.5	24.5	58.0	58.0	58.0
T_1	146.82	154.81	162.70	170.73	178.58	146.66	154.58	162.51
T_2	145.84	153.42	160.92	168.72	176.29	145.78	153.33	160.85
t_1	131.0	133.1	136.1	138.4	141.9	136.8	139.2	141.6
t_2	130.7	133.0	136.0	138.3	141.4	135.3	137.9	140.5
t_3	130.0	132.4	135.0	137.6	140.2	133.1	135.9	138.7
t_4	128.7	131.1	133.5	135.9	139.0	131.1	134.0	136.6
t_5	127.5	129.5	132.1	134.5	137.0	129.1	131.8	134.7
t_6	126.1	127.9	130.3	132.4	135.1	126.8	129.7	132.4
t_7	124.0	125.3	126.6	127.7	129.3	124.5	125.7	127.6
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	146.31	154.11	161.81	169.72	177.44	146.22	153.95	16168
$t_{Av.}$	128.30	130.33	132.80	134.97	137.70	130.96	133.46	136.01
$\Delta T_{Av.}$	18.01	23.78	29.01	34.75	39.74	15.26	20.49	25.67
t_{1-7}	7.0	7.8	9.5	10.7	12.6	12.3	13.5	14.0
m	20	20	20	20	20	20	20	20
l	0.571	0.789	0.957	1.082	1.270	0.567	0.800	0.974
E	3.77	5.21	6.32	7.14	8.38	3.74	5.28	6.43
Ep	15.4	21.2	25.8	29.1	34.2	6.4	9.0	11.1
Q	3476	4938	6082	7427	8572	3081	4384	5610
Q/A	5456	7750	9548	11660	13460	4837	6882	8804
U_B	303	326	329	335	339	317	336	343
h_B	481	532	532	544	547	515	557	566
Δt	12.9	15.8	19.4	23.2	26.7	10.2	13.4	16.9
V_1	193	258	302	332	373	186	251	286
Δp	20.0	22.5	29.0	35.0	44.5	37.5	44.0	47.5

Table 12 (continued).

Test liquid: 40 per cent sucrose solution.

Run No.	245E	246E	247E	248B	249B	250B	251B	252B
W_f	58.0	58.0	58.0	24.5	36.5	58.0	80.0	103.0
T_1	170.34	178.80	185.57	162.71	162.48	162.20	162.82	162.44
T_2	168.38	176.49	182.92	160.96	160.77	160.57	161.19	160.94
t_1	145.0	148.8	151.6	135.6	139.1	142.3	146.0	148.1
t_2	144.3	147.3	150.6	135.4	138.4	141.1	144.7	146.9
t_3	142.6	145.8	149.4	134.7	137.2	139.7	143.0	144.9
t_4	140.6	144.0	147.2	133.5	135.6	137.6	140.5	142.4
t_5	138.5	141.6	144.7	132.0	133.5	135.4	138.4	139.9
t_6	135.4	139.0	141.5	130.1	131.1	132.8	135.0	136.1
t_7	130.1	132.5	134.6	126.3	126.9	128.0	129.2	130.0
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	169.36	177.64	184.24	161.85	161.61	161.39	162.01	161.69
$t_{Av.}$	139.50	142.70	145.66	132.51	134.54	136.70	139.54	141.19
$\Delta T_{Av.}$	29.86	34.94	38.58	29.34	27.07	25.69	22.47	20.50
t_{1-7}	14.9	16.3	17.0	9.3	12.2	14.3	16.8	18.1
m	20	20	20	20	20	20	20	20
l	1.206	1.390	1.564	1.007	1.037	1.020	1.084	1.120
E	7.96	9.17	10.32	6.43	6.84	6.73	7.15	7.39
Ep	13.7	15.8	17.8	27.1	18.7	11.6	9.8	9.3
Q	7230	8652	10030	5965	5806	5491	5491	4977
Q/A	11340	13580	15750	9363	9114	8618	8618	7812
U_B	380	389	408	319	337	336	383	381
h_B	661	676	723	508	550	547	674	667
Δt	18.6	21.8	23.6	20.0	18.0	17.1	13.8	12.7
V_1	334	360	378					
Δp	55.0	64.0	70					

Table 12 (continued).

Test liquid: 40 per cent sucrose solution.

Run No.	253B	254B	255K	256K	257K	258K	259K
W_f	135.0	181.5	24.5	36.5	58.0	80.0	103.0
T_1	162.81	162.76	161.35	161.37	161.62	161.29	161.50
T_2	161.52	161.74	160.18	160.08	160.24	159.81	160.00
t_1	152.5	157.9	143.3	143.4	145.0	146.0	147.2
t_2	151.2	155.7	142.9	142.4	144.0	144.4	145.2
t_3	149.0	153.3	142.1	141.4	142.6	142.5	143.1
t_4	146.3	150.6	141.0	140.3	140.5	140.3	140.3
t_5	143.2	146.9	139.9	138.8	138.7	137.9	137.5
t_6	139.3	142.8	138.7	137.6	136.5	134.9	134.6
t_7	132.6	135.7	137.8	135.7	133.6	129.7	127.7
t_8	123.0	123.0	137.0	134.5	132.0	125.5	119.5
$T_{Av.}$	162.16	162.25	160.76	160.73	160.93	160.55	160.75
$t_{Av.}$	144.87	148.99	140.81	139.94	140.13	139.40	139.40
$\Delta T_{Av.}$	17.29	13.26	19.95	20.79	20.80	21.15	21.35
t_{1-7}	19.9	22.2	5.5	7.7	11.4	16.3	19.5
m	20	20	20	20	20	20	20
l	1.210	1.334	0.627	0.693	0.797	1.012	1.173
E	7.99	8.80	4.14	4.57	5.26	6.68	7.74
Ep	8.9	8.4	16.9	12.5	9.7	8.3	7.5
Q	4148	3081	3753	4227	4582	4977	5056
Q/A	6510	4837	5889	6634	7193	7812	7936
U_B	377	365	295	319	346	369	372
h_B	654	622	454	508	573	635	641
Δt	10.8	8.4	14.1	14.2	13.6	13.4	13.4

Table 12 (continued).

Test liquid: 40 per cent sucrose solution.

Run No.	260H	261H	262H	263H	264H	265H	266H
W_f	58.0	58.0	58.0	58.0	58.0	58.0	58.0
T_1	141.43	148.12	153.65	161.65	169.60	178.23	185.39
T_2	140.39	146.95	152.45	160.32	168.33	176.95	184.05
t_1	127.9	132.9	138.2	145.9	152.9	160.3	166.8
t_2	126.8	131.6	137.2	144.7	152.3	159.9	166.4
t_3	124.6	129.9	135.6	143.2	151.0	159.0	165.7
t_4	121.7	127.5	133.7	141.6	149.6	157.8	164.8
t_5	119.0	125.1	131.7	139.9	148.4	156.6	163.8
t_6	114.6	122.2	129.3	137.6	146.5	155.4	162.8
t_7	108.1	117.4	125.7	134.8	144.5	153.9	161.5
t_8	94.5	112.0	124.0	133.0	144.0	153.0	161.0
$T_{Av.}$	140.91	147.53	153.05	160.99	168.96	177.59	184.72
$t_{Av.}$	120.40	126.66	133.06	141.10	149.31	157.56	164.54
$\Delta T_{Av.}$	20.51	20.87	19.99	19.89	19.65	20.03	20.18
t_{1-7}	19.8	15.5	12.5	11.1	8.4	6.4	5.3
m	20	20	20	20	20	20	20
l	0.916	0.806	0.783	0.786	0.762	0.791	0.778
E	6.04	5.32	5.17	5.19	5.03	5.22	5.13
Ep	10.4	9.2	8.9	8.9	8.7	9.0	8.8
Q	3989	4187	4227	4384	4464	4582	4859
Q/A	6262	6572	6634	6882	7006	7193	7626
U_B	305	315	332	346	357	359	378
h_B	492	510	546	573	597	598	639
Δt	13.8	14.0	13.2	13.0	12.7	13.0	12.9

Table 13.

Test liquid: Isopropyl alcohol.

Run No.	267D	268D	269D	270D	271D	272E	273E	274E	275E
W_f	24.5	24.5	24.5	24.5	24.5	58.0	58.0	58.0	58.0
T_1	138.87	146.84	154.43	163.02	170.25	138.93	146.41	154.52	162.58
T_2	138.34	146.12	153.36	161.27	168.43	138.38	145.66	153.41	161.11
t_1	125.0	125.6	126.8	128.6	130.6	126.0	127.8	130.6	133.6
t_2	124.8	125.4	126.6	128.4	130.0	125.8	127.6	130.2	133.2
t_3	124.6	125.2	126.4	128.2	129.8	125.6	127.4	130.0	132.4
t_4	124.6	125.0	125.8	127.8	128.6	125.6	126.8	129.2	131.6
t_5	124.4	124.6	125.8	127.2	127.6	125.2	126.2	128.2	130.8
t_6	124.0	124.4	125.4	126.2	126.8	124.6	125.2	127.2	129.2
t_7	123.6	123.8	124.4	125.0	125.6	123.8	123.8	125.2	126.6
t_8	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0	123.0
$T_{Av.}$	138.61	146.51	153.90	162.04	169.34	138.66	146.03	153.97	161.84
$t_{Av.}$	124.43	124.86	125.89	127.36	128.43	125.23	126.40	128.66	131.06
$\Delta T_{Av.}$	14.18	21.65	28.01	34.78	40.91	13.43	19.63	25.31	30.78
t_{1-7}	1.4	1.8	2.4	3.6	5.0	2.2	4.0	5.4	7.0
m	20	20	20	20	20	20	20	20	20
l	0.916	1.517	2.410	2.874	3.257	0.980	1.540	2.255	2.960
E	4.74	7.86	12.48	14.89	16.88	5.08	7.98	11.69	15.33
Ep	19.4	32.1	50.9	60.8	69.0	8.7	13.7	20.1	26.4
Q	1382	2370	3437	16043	6794	1462	2488	3594	4938
Q/A	2170	3720	5394	9486	10670	2294	3905	5641	7750
U_B	153	172	193	273	261	171	199	223	252
h_B	199	227	260	406	381	227	273	314	365
Δt	11.8	17.7	22.5	25.3	30.3	10.9	15.5	19.5	23.0

Table 13 (continued).

Test liquid: Isopropyl alcohol.

Run No.	276D'	277D'	278D'	279D'	280D'	281D'	282E'	283E'
W_f	24.5	24.5	24.5	24.5	24.5	24.5	58.0	58.0
T_1	138.40	146.30	154.73	162.55	170.16	178.15	138.94	146.85
T_2	138.14	145.84	153.81	161.28	168.57	176.02	138.67	146.36
t_1	136.3	135.7	135.5	136.3	137.4	139.5	135.7	136.1
t_2	135.9	135.3	135.1	135.9	137.2	139.3	135.3	135.3
t_3	135.5	134.7	134.7	135.5	137.0	138.7	134.7	134.7
t_4	134.9	134.5	134.3	135.1	136.4	138.3	134.3	134.3
t_5	134.3	134.1	134.1	134.7	135.5	136.8	133.7	133.9
t_6	133.9	133.6	133.5	134.2	134.9	136.0	133.6	133.6
t_7	133.5	133.2	133.2	133.6	134.3	134.9	133.0	132.8
t_8	133.3	133.0	133.0	133.3	133.0	133.5	132.5	132.3
$T_{Av.}$	138.53	146.53	155.19	163.18	169.37	179.21	138.81	146.61
$t_{Av.}$	134.90	134.44	134.34	135.04	136.10	137.64	134.13	134.40
$\Delta T_{Av.}$	3.63	12.09	20.85	28.14	33.27	41.57	4.48	12.21
t_{1-7}	2.8	2.5	2.3	2.7	3.1	4.6	2.7	3.3
m	-	20	20	20	20	20	20	20
l	-	0.650	1.1214	2.053	2.720	3.550	-	0.892
E	-	2.56	6.29	10.64	14.09	18.40	-	4.62
Ep	-	10.4	25.7	43.4	57.5	75.1	-	7.9
Q	316	1343	2844	4148	5886	7861	355	1462
Q/A	496	2108	4464	6510	9239	12340	588	2294
U_B	137	174	214	231	278	297	125	188
h_B	174	231	298	326	416	452	157	254
Δt	3.1	9.9	16.3	21.6	24.1	29.6	3.86	9.79
V_1							9.2	32
Δp							17.0	22.0

Table 13 (continued).

Test liquid: Isopropyl alcohol.

Run No.	284E'	285E'	286E'	287E'	288B'	289B'	290B'	291B'
W_f	58.0	58.0	58.0	58.0	24.5	36.5	58.0	80.0
T_1	154.90	162.64	170.25	178.46	162.65	162.80	162.86	162.90
T_2	154.04	161.40	168.82	176.55	161.57	161.66	161.71	161.82
t_1	136.2	136.8	139.5	142.2	135.9	136.8	138.1	140.3
t_2	135.8	136.6	139.1	141.8	135.5	136.6	137.7	140.1
t_3	134.8	136.0	138.7	141.4	135.1	136.2	137.4	139.3
t_4	133.8	135.4	138.1	140.5	134.7	135.4	137.0	138.7
t_5	133.4	134.6	137.2	139.5	133.9	134.8	136.4	137.9
t_6	133.1	133.8	136.4	138.3	133.5	133.9	135.3	136.6
t_7	132.1	132.7	134.7	136.1	133.1	133.1	133.5	134.3
t_8	131.8	132.0	133.2	133.8	133.0	133.0	133.2	133.0
$T_{Av.}$	154.47	162.02	169.58	177.50	162.11	162.23	162.29	162.36
$t_{Av.}$	134.17	135.13	137.67	139.97	134.53	135.26	136.50	138.17
$\Delta T_{Av.}$	20.30	26.89	31.91	37.53	27.58	26.97	25.79	24.19
t_{1-7}	4.1	4.1	4.8	6.1	2.8	3.7	4.6	6.0
m	20	20	20	20	20	20	20	20
l	1.600	2.330	2.464	3.366	2.042	1.996	2.090	2.000
E	8.29	12.07	12.76	17.44	10.58	10.34	10.82	10.36
Ep	14.3	20.8	22.0	30.1	43.2	28.3	18.7	12.9
Q	2607	4029	5254	6992	4029	4266	4305	4029
Q/A	4092	6324	8247	10970	6324	6696	6757	6324
U_B	202	235	258	292	229	248	262	261
h_B	276	333	375	441	322	358	385	384
Δt	16.09	20.57	23.81	26.95	21.2	20.3	19.0	17.8
V_1	56	83	102	131	80	85	86	82
Δp	27	27	35	47	19	25	32	44

Table 13 (continued).

Test liquid: Isopropyl alcohol.

Run No.	292B'	293B'	294B'	295K'	296K'	297K'	298K'	299 K'
W_f	103.0	135.0	181.5	24.5	36.5	58.0	80.0	103.0
T_1	163.10	162.82	163.00	161.33	161.27	161.43	161.80	161.42
T_2	162.01	161.79	162.00	160.55	160.45	160.62	160.91	160.47
t_1	141.1	143.7	146.5	141.1	141.5	141.9	141.7	142.4
t_2	140.9	143.4	145.7	140.7	141.3	141.7	141.3	142.0
t_3	140.3	142.6	144.9	140.3	140.9	141.3	140.9	141.2
t_4	139.3	141.3	143.5	140.1	140.7	140.7	140.1	140.3
t_5	138.1	139.9	142.2	139.7	140.1	140.1	139.3	139.3
t_6	136.8	138.3	140.3	139.1	139.5	139.5	138.7	138.3
t_7	134.9	135.9	137.0	138.9	139.1	138.7	137.7	136.3
t_8	133.0	133.0	133.0	138.5	138.5	138.0	137.5	135.0
$T_{Av.}$	162.55	162.30	162.50	160.94	160.86	161.03	161.36	160.94
$t_{Av.}$	138.77	140.74	142.87	140.00	140.44	140.56	139.90	139.97
$\Delta T_{Av.}$	23.78	21.56	19.63	20.94	20.42	20.47	21.46	20.97
t_{1-7}	6.2	7.8	9.5	2.2	2.4	3.2	4.0	6.1
m	20	20	20	20	20	20	20	20
l	2.106	2.330	2.734	1.347	1.215	1.222	1.640	1.804
E	10.91	12.07	14.17	6.99	6.29	6.33	8.50	9.35
Ep	10.6	8.9	7.8	28.5	17.2	10.9	10.6	9.1
Q	4068	3832	3713	2844	3002	2963	3278	3516
Q/A	6386	6015	5828	4464	4712	4650	5145	5518
U_B	268	279	297	213	231	227	240	263
h_B	398	419	457	293	325	319	342	387
Δt	17.4	15.5	13.8	16.5	15.7	15.8	16.3	15.5
V_1	84	84	87					
Δp	43	58	72					

Table 13 (continued).

Test liquid: Isopropyl alcohol.

Run No.	300K'	301K'	302H'	303H'	304H'	305H'	306H'	307H'
W_f	135.0	181.5	58.0	58.0	58.0	58.0	58.0	58.0
T_1	161.64	161.66	138.68	146.89	154.65	162.72	170.82	178.38
T_2	160.66	160.63	137.75	145.97	153.68	161.88	169.94	177.40
t_1	143.2	144.3	120.1	128.4	136.1	143.7	152.10	159.3
t_2	142.8	143.9	119.5	128.0	135.7	143.5	151.3	158.9
t_3	142.0	143.0	118.7	127.4	135.3	143.1	150.9	158.5
t_4	140.8	141.7	117.9	126.8	134.7	142.5	150.5	157.9
t_5	139.5	139.9	117.2	125.8	134.1	142.0	150.1	157.5
t_6	138.3	137.9	116.0	125.2	133.2	141.5	149.7	156.9
t_7	135.5	134.3	113.7	124.0	132.0	140.6	149.1	156.1
t_8	133.5	129.5	113.0	122.5	132.0	139.8	148.8	156.0
$T_{Av.}$	161.15	161.14	138.22	146.43	154.16	162.30	170.38	177.89
$t_{Av.}$	140.30	140.71	117.59	126.51	134.44	142.41	150.53	157.87
$\Delta T_{Av.}$	20.85	20.43	20.63	19.92	19.72	19.89	19.85	20.02
t_{1-7}	7.7	10.0	6.4	4.4	4.1	3.1	3.0	3.2
m	20	20	20	20	20	20	20	20
l	2.134	2.902	1.428	1.406	1.262	1.246	0.976	0.722
E	11.06	15.03	7.40	7.28	6.54	6.45	5.06	3.74
E_p	8.2	8.3	12.8	12.6	11.3	11.1	8.7	6.4
Q	3634	3832	2686	2805	2765	3081	3081	3318
Q/A	5705	6015	4216	4402	4340	4837	4837	5208
U_B	273	294	204	221	220	244	244	260
h_B	408	452	284	312	309	349	348	377
Δt	15.1	14.4	16.1	15.3	15.2	15.0	15.1	15.0

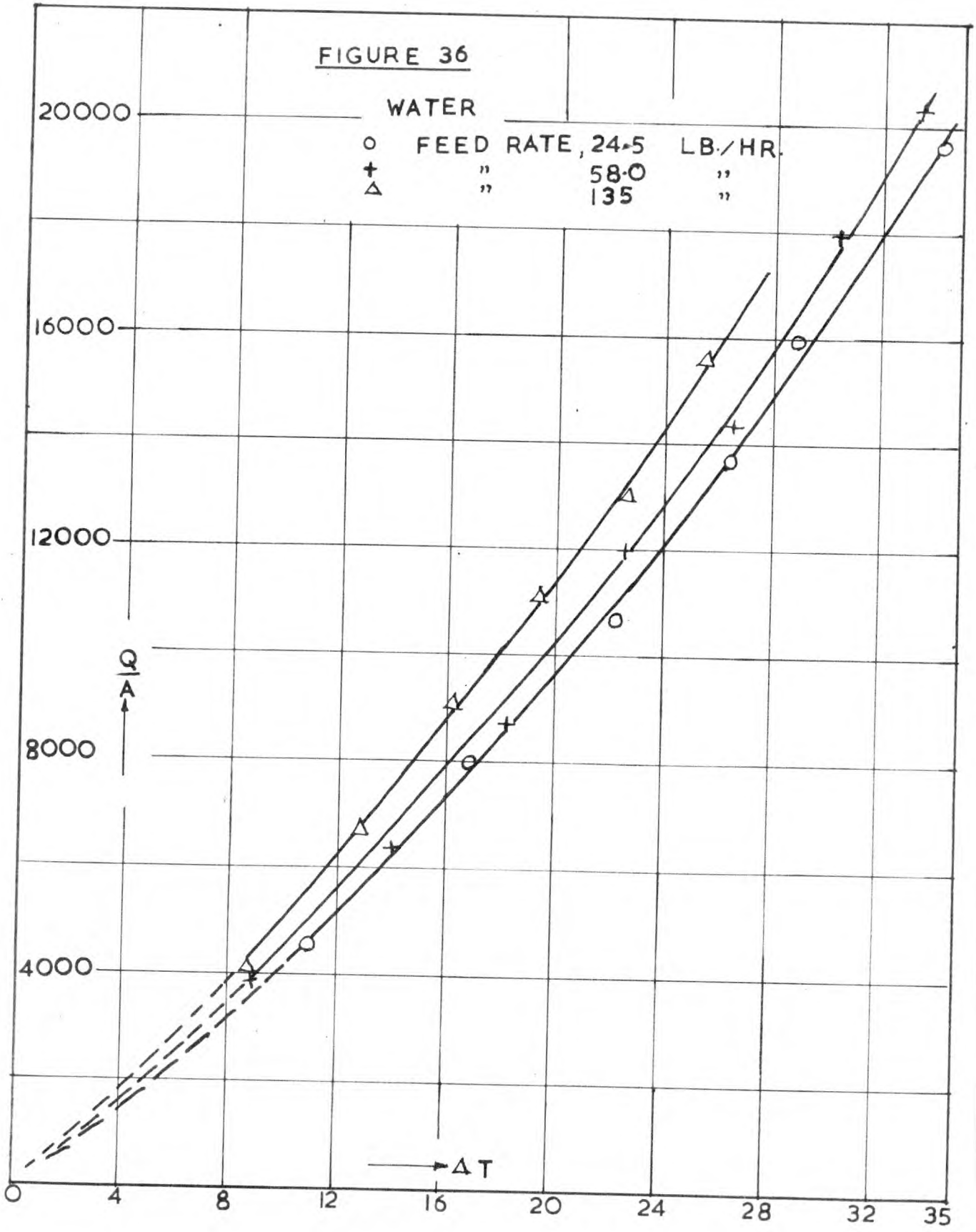
Explanation for Symbols and Specimen Calculation.

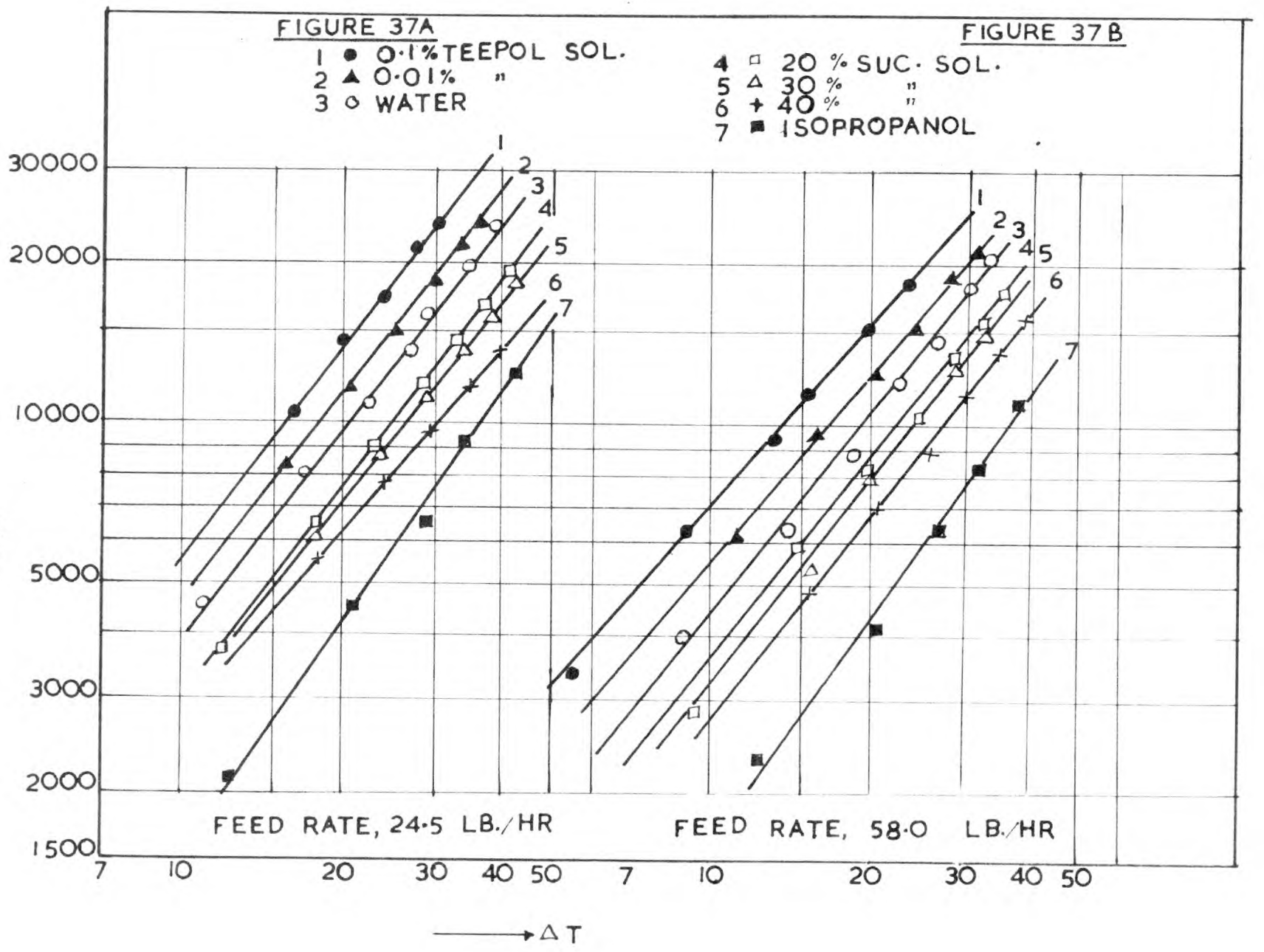
Reference: Run No. 105D (Table 7).

Symbol.	Value.	Units.	Explanation.
W_f	24.5	lb./hr.	feed rate of the liquid to the evaporator tube.
T_1	167.9	°F	temperature of hot water inlet to evaporator jacket (average of four readings).
T_2	165.1	°F	temperature of hot water outlet to evaporator jacket (average of four readings).
t_1 141.7 t_2 140.7 t_3 139.4 t_4 138.6 t_5 136.9 t_6 136.1 t_7 130.5		°F	temperatures of boiling liquid as measured by means of travelling thermocouple from tube bottom to top, at the equal distance of 10½ inches, °F (average of two readings).
t_8	123	°F	temperature of vapour - liquid mixture at the outlet.
$T_{Av.}$	166.5	°F	average temperature of hot water $= \frac{167.90}{165.10} = 166.5$
$t_{Av.}$ $= T$	137.7	°F	average temperature of boiling liquid. arith. mean of 141.7, 140.7, 139.4, 138.6, 136.9, 136.1, 130.5 = 137.7
$\Delta T_{Av.}$ $= \Delta T$	28.8	°F	average overall temperature difference. (average temp. of hot water - average temp. of boiling liquid). = 166.5 - 137.7 = 28.8
t_{1-7}	11.2	°F	temperature drop of boiling liquid along tube length. t_{1-7} = 141.7-130.5 = 11.2
m	20	mins.	duration of test = 20

Symbol.	Value.	Units.	Explanation.
l	1.458	litres.	vapour condensed from separator.
E	9.62	lbs./hr.	evaporation, lbs./hr., $l \times 0.22 \times \frac{60}{m} \times 10$ $= 1.458 \times 0.22 \times \frac{60}{20} \times 10$ $= 9.62$
E_h	39.3	%	$\frac{E}{W_f} \times 100 = \frac{9.62}{24.5} \times 100 = 39.3$
Q	10200	B.T.U./hr.	(temperature drop of hot water during the operation - temperature drop during idle running) x flow rate of hot water $= (2.8 - 0.25) \times 4000$ $= 10200$
$\frac{Q}{A}$	16010	B.T.U./hr/ sq.ft.	heat flux per unit surface area of the evaporator tube (based on mean diameter of the tube) $= \frac{Q}{A} = \frac{10200}{0.637} = 16010$
U_B	556	B.T.U./hr/ sq.ft/°F.	overall boiling coefficient $= \frac{Q}{A.\Delta T_{Av.}} = 556$
h_B	1340	B.T.U./hr/ sq.ft/°F.	$\frac{1}{U_B} - (\frac{1}{h_1} + \frac{xw}{Kw})$ $\frac{1}{U_B} = \frac{1}{556} = 0.0018$ h_1 = annulus film coefficient based on mean surface area of the tube. $\frac{xw}{kw}$ = tube wall resistance. $(\frac{1}{h_1} + \frac{xw}{kw})$ at 166.5°F = 0.00099 (Fig.35) Am = mean surface are of the tube in sq.ft. = 0.637 sq.ft. Ai = inside surface area of the tube = 0.588 sq.ft.

Symbol.	Value.	Units.	Explanation.
			$\therefore h_B = \frac{1}{(0.0018-0.00099)} \times \frac{Am}{Ai}$
			$= \frac{1}{0.00081} \times \frac{0.637}{0.588}$
			$= 1340$
Δt	12.9	°F.	average temperature difference across boiling film
			$= \frac{Q}{Ai \times h_B} \quad \frac{10200}{0.588 \times 1340}$
			$= 12.9$
V_1	415	ft./sec.	vapour velocity at the top of the tube.
			Specific volume of vapour at the temperature 130.5°F = 154 cu.ft/lb. (Fig. 46)
			Flash evaporation from the top of the tube to the outlet temperature of 123°F =
			$\frac{(W_f-E)(\text{temp.drop from top to outlet})}{1000}$
			$= \frac{(24.5-9.07)(130.5-123)}{1000}$
			$= 0.12$ lb.
			$\therefore$ mass rate of vapour at the top of the tube = E - 0.12
			= 9.5 lbs./hr.
			Cross-sectional area of the evaporator tube = 0.00098 sq.ft.
			$\therefore$ vapour velocity at the top
			$= \frac{9.5 \times 154}{3600 \times 0.00098} = 415$
Δp	39.5	mms. of Hg.	pressure drop along tube length.
			Vapour pressure for water vapour at 141.7°F (Fig. 57) = 155.5 mm.Hg.
			Vapour pressure at 130.5°F = 116 mm. Hg.
			$\therefore$ pressure drop = 155.5 - 116.0
			= 39.5


FIGURE 36
WATER
o FEED RATE, 24.5 LB./HR.
+ " 58.0 "
△ " 135 "
20000
16000
12000
8000
4000
Q/A
ΔT
0
4
8
12
16
20
24
28
32
35


FIGURE 37A
1 ● 0·1% TEEPOL SOL.
2 ▲ 0·01% "
3 ○ WATER
FIGURE 37B
4 □ 20 % SUC. SOL.
5 △ 30 % "
6 + 40 % "
7 ■ ISOPROPANOL
30000
20000
10000
5000
3000
2000
1500
Q/A
7
10
20
30
40
50
FEED RATE, 24·5 LB./HR
FEED RATE, 58·0 LB./HR
ΔT

CHAPTER 10.

Correlation of Results.

The results given in the previous chapter enable a relation to be obtained between each of the variable and the overall or film heat transfer coefficient.

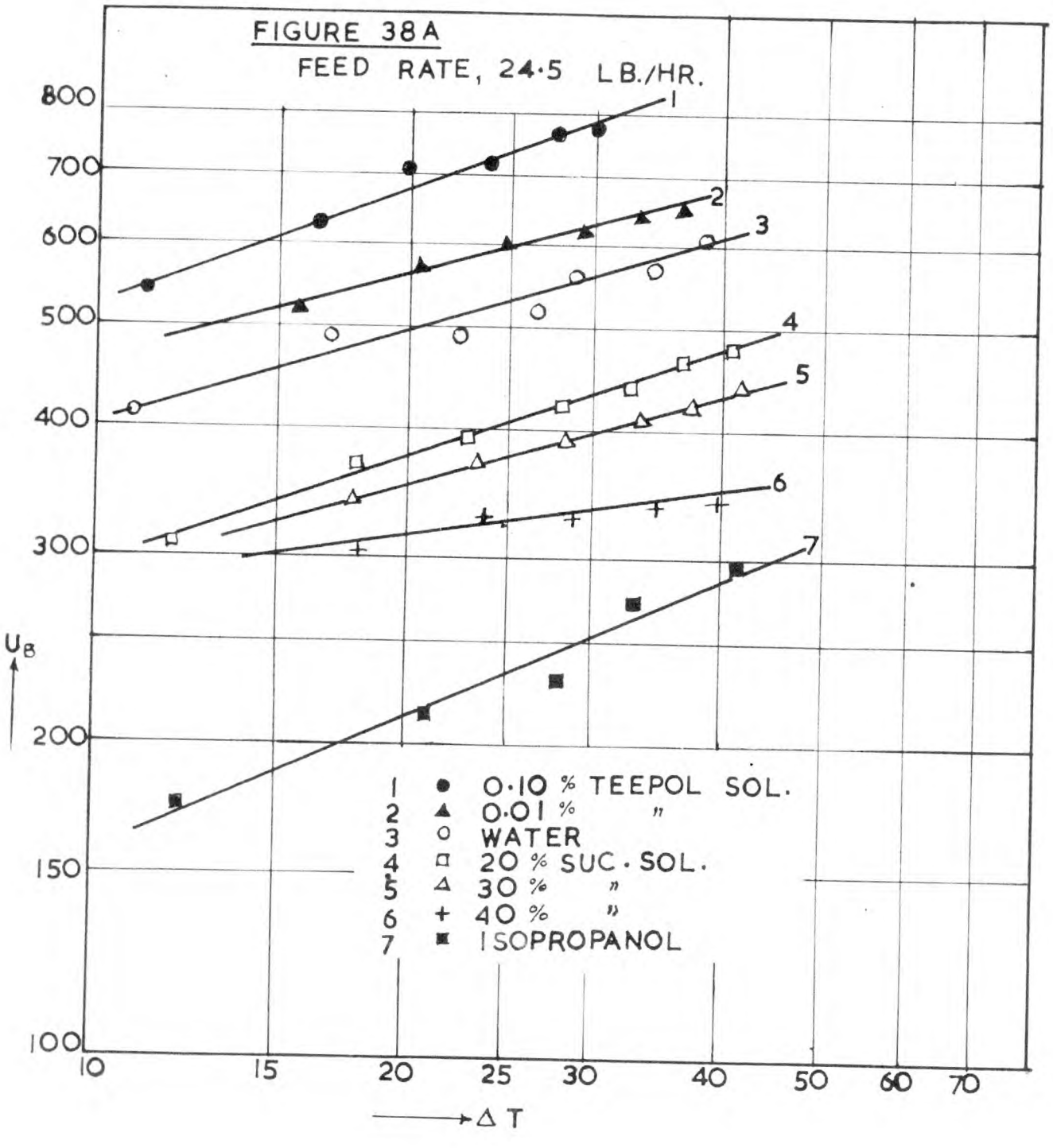
A. Effect of Temperature Difference.

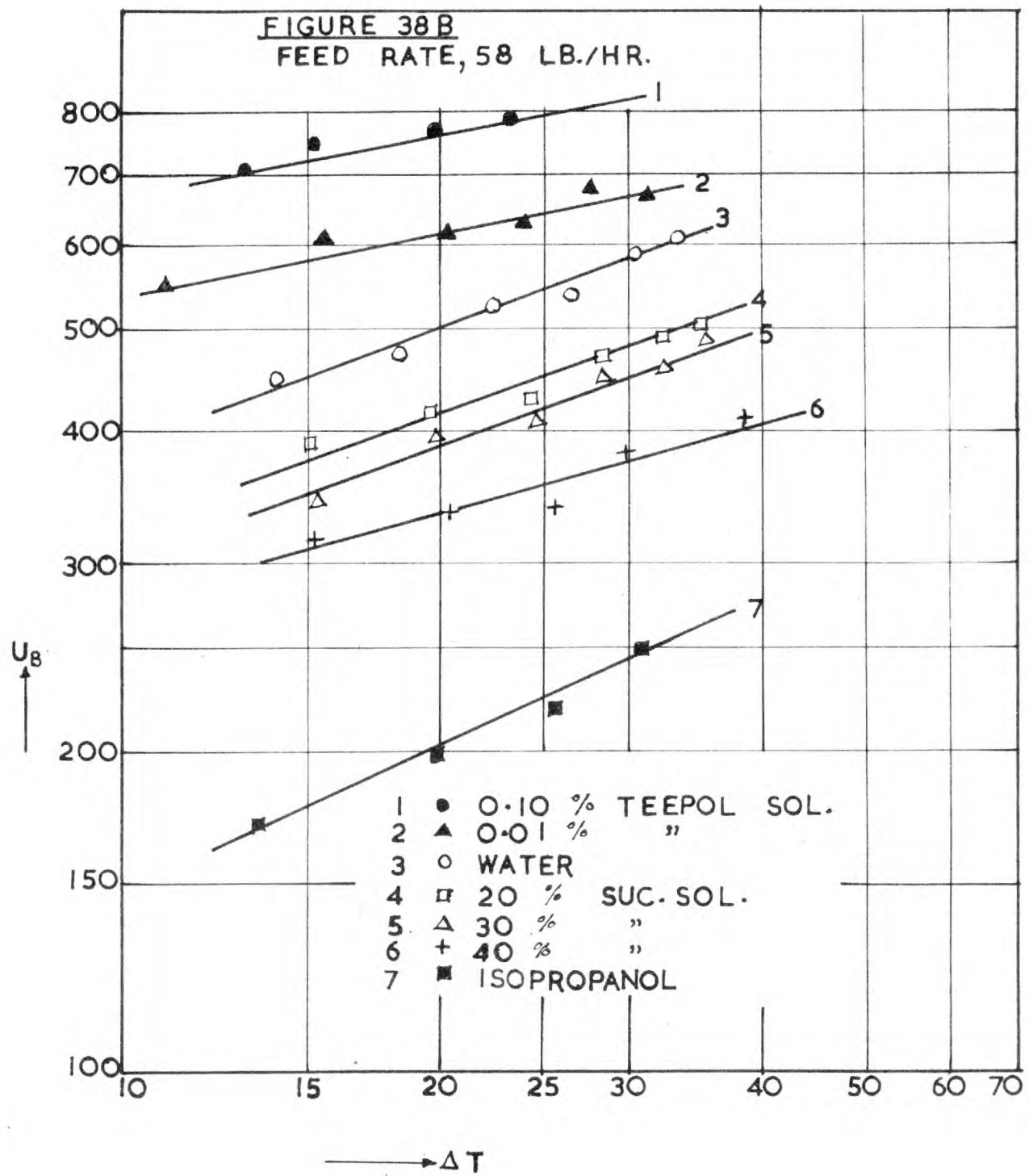
With the feed rate and temperature at the outlet from the evaporator tube constant, the temperature difference was altered by varying the hot water temperature. In series D, the feed was 24.5 lbs./hr., and in E 58 lbs./hr.

Values of the heat flux and the average overall temperature difference (ΔT) with water as the feed liquid are shown in Figure 36, from which it is seen that the heat flux increases regularly with the temperature difference. It is also seen that, with the same value for ΔT, the heat flux increases with feed rate. Corresponding plots with the other liquids are given in Figures 37A and 37B. For all the liquids, the points fall on straight lines with approximately the same slope. Taking an average slope at both feed rates, a relation is obtained

$$\frac{Q}{A} \propto \Delta T^{1.30} \qquad .. \quad .. \quad .. \quad (13)$$

With the 40 per cent sucrose solution and low feed rate of 24.5 lbs./hr., the slope is somewhat less. This


FIGURE 38A
FEED RATE, 24·5 LB./HR.
800
700
600
500
400
300
200
150
100
U_B
10
15
20
25
30
40
50
60
70
→ΔT
1 ● 0·10 % TEEPOL SOL.
2 ▲ 0·01 % "
3 ○ WATER
4 □ 20 % SUC. SOL.
5 △ 30 % "
6 + 40 % "
7 ■ ISOPROPANOL

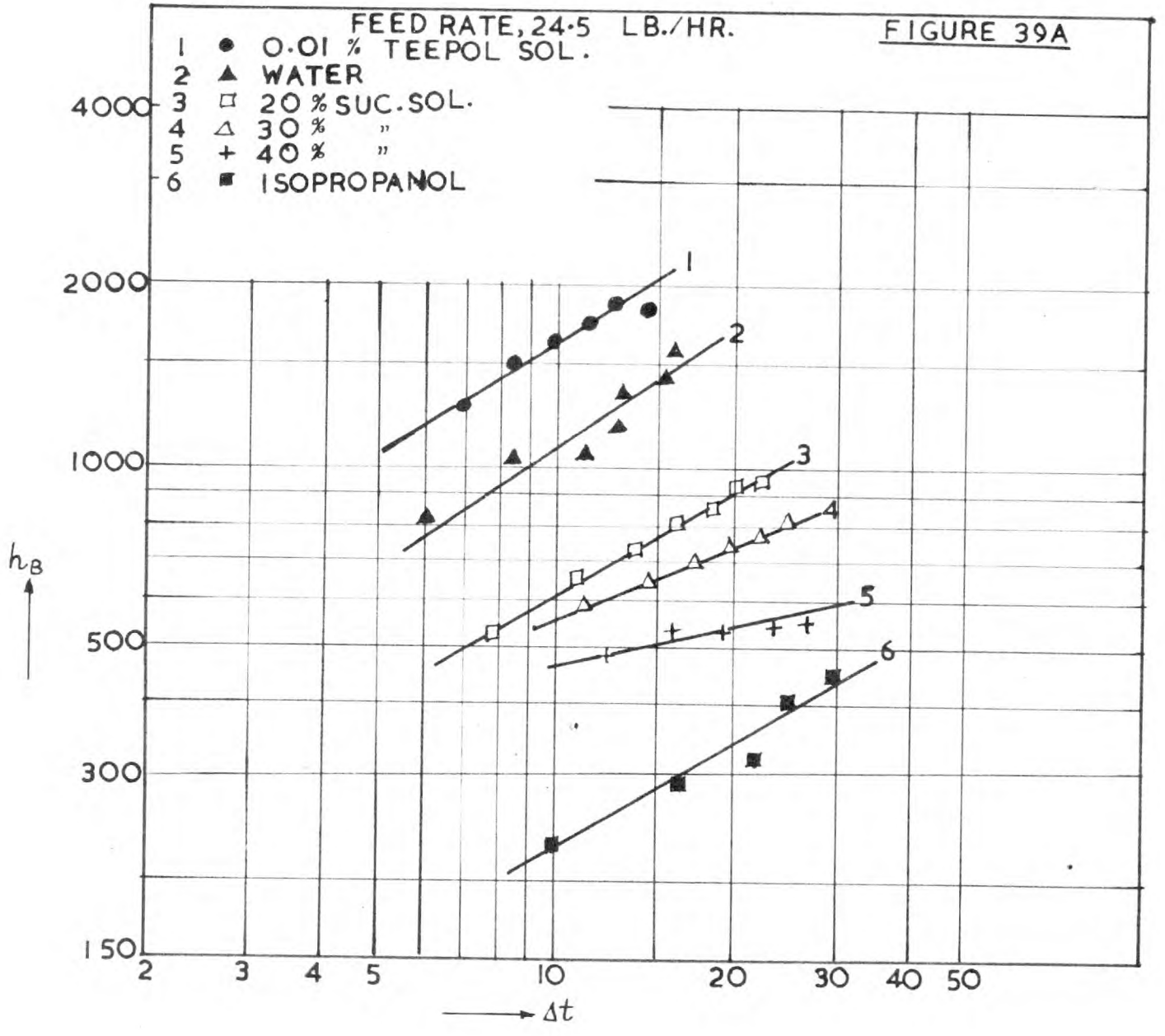

FIGURE 38B
FEED RATE, 58 LB./HR.
800
700
600
500
400
300
200
150
100
U_8
10
15
20
25
30
40
50
60
70
ΔT
1
2
3
4
5
6
7
1 ● 0·10 % TEEPOL SOL.
2 ▲ 0·01 % "
3 ○ WATER
4 □ 20 % SUC. SOL.
5 △ 30 % "
6 + 40 % "
7 ■ ISOPROPANOL

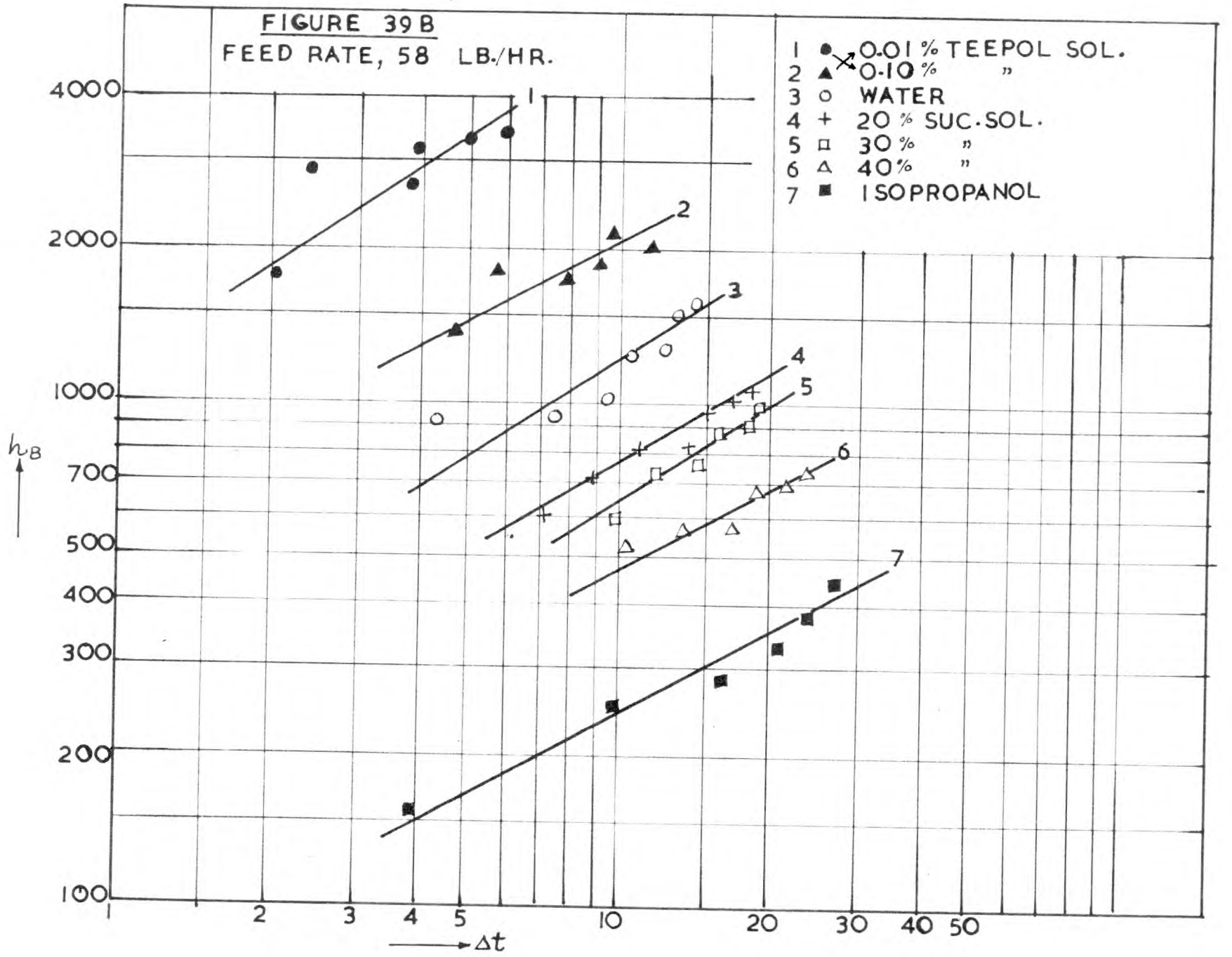
probably arises from the high viscosity of the concentrated liquor at the top and the corresponding sluggish movement of the liquid film over the heating surface. With the higher feed rate of 58 lbs./hr., the lines are all parallel, including that for 40 per cent sucrose solution. It has been mentioned earlier that visual observations on the boiling of 40 per cent sucrose solution indicated a sluggish movement of the liquid film over the heating surface and, at very low feed rate, the movement almost ceased. The above data indicate a similar behaviour with the stainless steel tube evaporator.

Plots of the overall heat transfer coefficient (U_B) and the temperature difference (ΔT) for the two feed rates are shown in Figures 38A and 38B. These points show a wider scatter than in the corresponding plots for heat flux and ΔT. The line for 40 per cent sucrose solution is flatter than those for the other liquids for the reasons already given; with isopropyl alcohol, the slope is a little greater. Taking an average slope for all the liquids at both feed rates, a relation is obtained:

$$U_B \propto \Delta T^{0.30} \qquad .. \quad .. \quad .. \quad (14)$$

For the purpose of comparison, the data in the literature are meagre; that due to Brookes and Badger, however, show an increase of U_B with ΔT.


FEED RATE, 24·5 LB./HR.
FIGURE 39A
1 ● 0·01 % TEEPOL SOL.
2 ▲ WATER
3 □ 20 % SUC. SOL.
4 △ 30 % "
5 + 40 % "
6 ■ ISOPROPANOL
4000
2000
1000
500
300
150
h_B
2
3
4
5
10
20
30
40
50
Δt
1
2
3
4
5
6


FIGURE 39B
FEED RATE, 58 LB./HR.
1 0.01 % TEEPOL SOL.
2 0.10 % "
3 WATER
4 20 % SUC. SOL.
5 30 % "
6 40 % "
7 ISOPROPANOL
4000
2000
1000
700
500
400
300
200
100
h_B
1
2
3
4
5
10
20
30
40
50
Δt

The true nature of the influence of the temperature difference is much more clearly shown by calculating the boiling film coefficient by the method already described and the temperature difference across the boiling film (Δt) from the relation $\Delta t = \frac{Q}{A.hB}$.

Plots of hB and Δt for both feed rates and for various liquids are shown in Figures 39A and 39B. For a feed rate of 58 lbs./hr., the plots are nearly parallel straight lines of slope 0.61. The scattering of the points on the lines is greater than in the plots of overall values, since any experimental errors are more pronounced when the data is used to give film values. The lines for the 40 per cent sucrose solution is further from the others than with previous plots and that for 30 per cent sucrose solution shows a noticeable deviation. Whilst the lines for 58 lbs./hr. are more or less parallel, there are deviations with the strong solution. The points on the lines for Teepol solutions are rather badly scattered. It may be noted here that the results of Teepol solutions were rather inconsistent, especially in the beginning, probably due to some change taking place in their foaming characteristics. The runs reported are taken after attaining nearly steady values. From all the plots drawn in Figure 39A and 39B, the average value of the slope gave:

$$hB \propto \Delta t^{0.60} \qquad .. \quad .. \quad .. \quad (15)$$

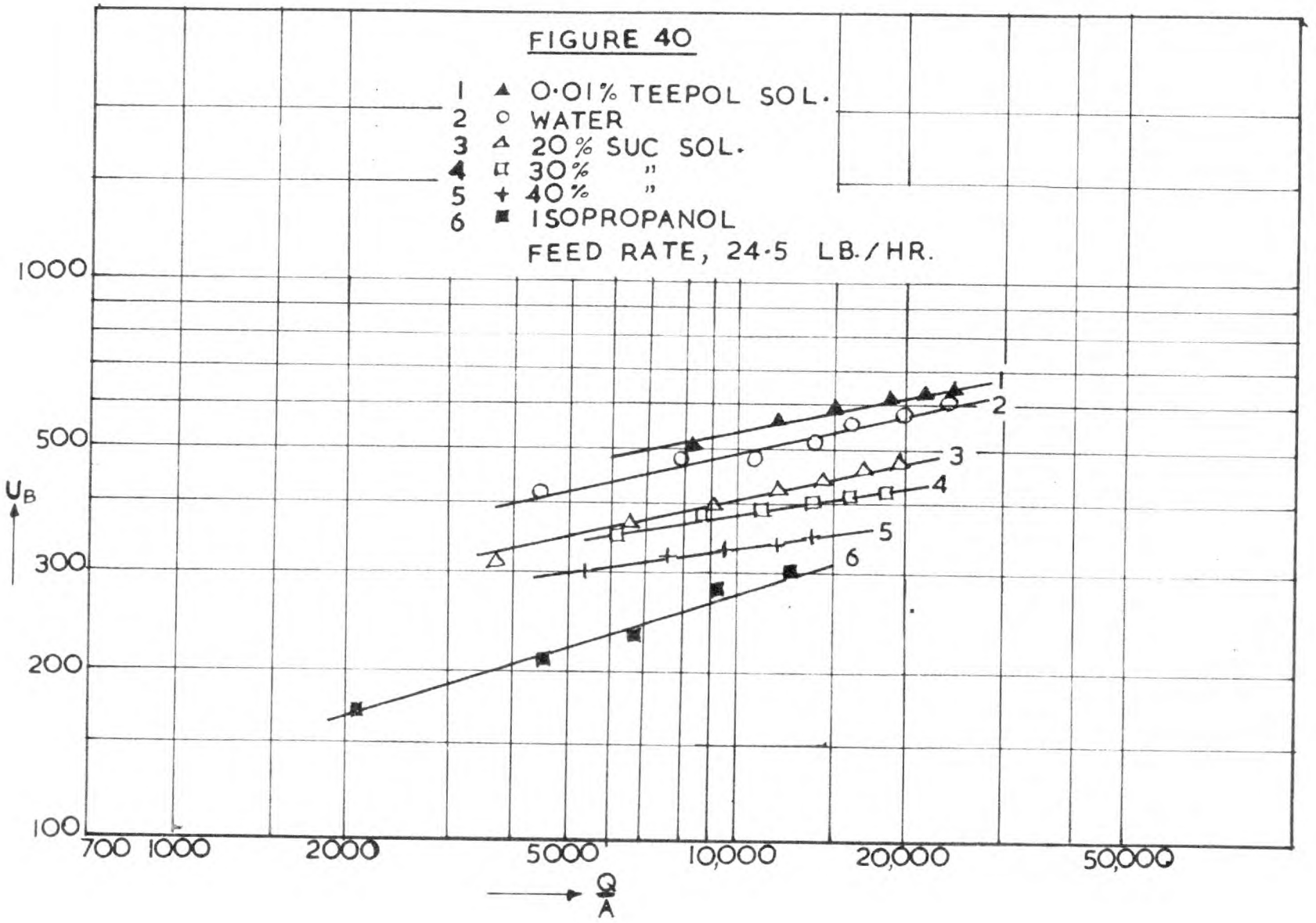
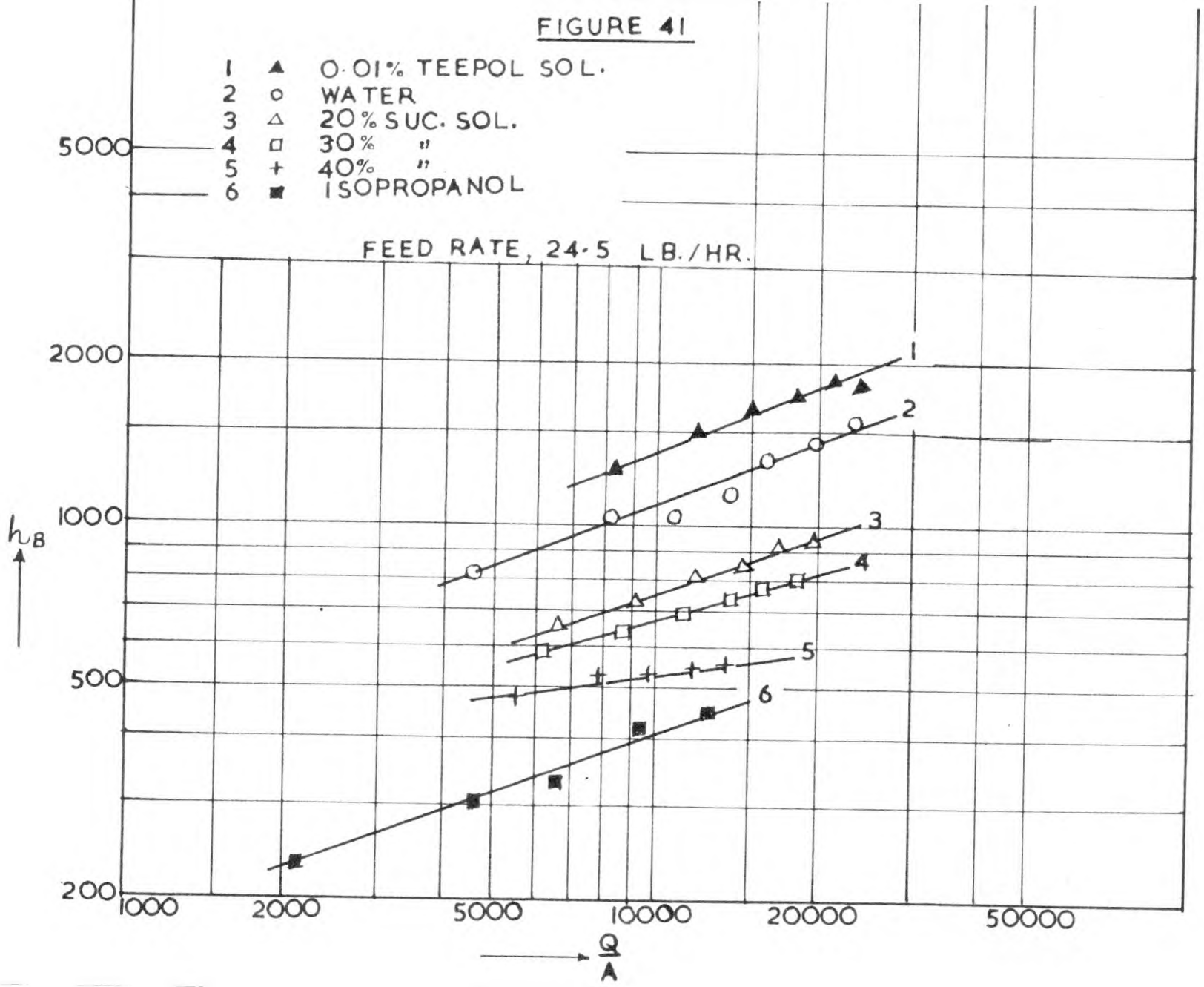

FIGURE 40
1 ▲ 0·01% TEEPOL SOL.
2 ○ WATER
3 △ 20% SUC SOL.
4 □ 30% "
5 + 40% "
6 ■ ISOPROPANOL
FEED RATE, 24·5 LB./HR.
1000
500
300
200
100
U_B
700
1000
2000
5000
10,000
20,000
50,000
$\frac{Q}{A}$
1
2
3
4
5
6

FIGURE 41


1 ▲ 0·01% TEEPOL SOL.
2 ○ WATER
3 △ 20% SUC. SOL.
4 □ 30% "
5 + 40% "
6 ■ ISOPROPANOL
FEED RATE, 24·5 LB./HR.
5000
2000
1000
500
200
h_B
1000
2000
5000
10000
20000
50000
$\frac{Q}{A}$
1
2
3
4
5
6

An alternative method of expressing the importance of temperature difference is to plot overall and film coefficients against heat flux. This has been done in Figures 40 and 41, from which it is seen that the scatter of the points is much less than for the plots with temperature difference. An average relation can be given in the form

$$U_B \propto \left(\frac{Q}{A}\right)^{0.22} \quad .. \; .. \; .. \quad (16)$$

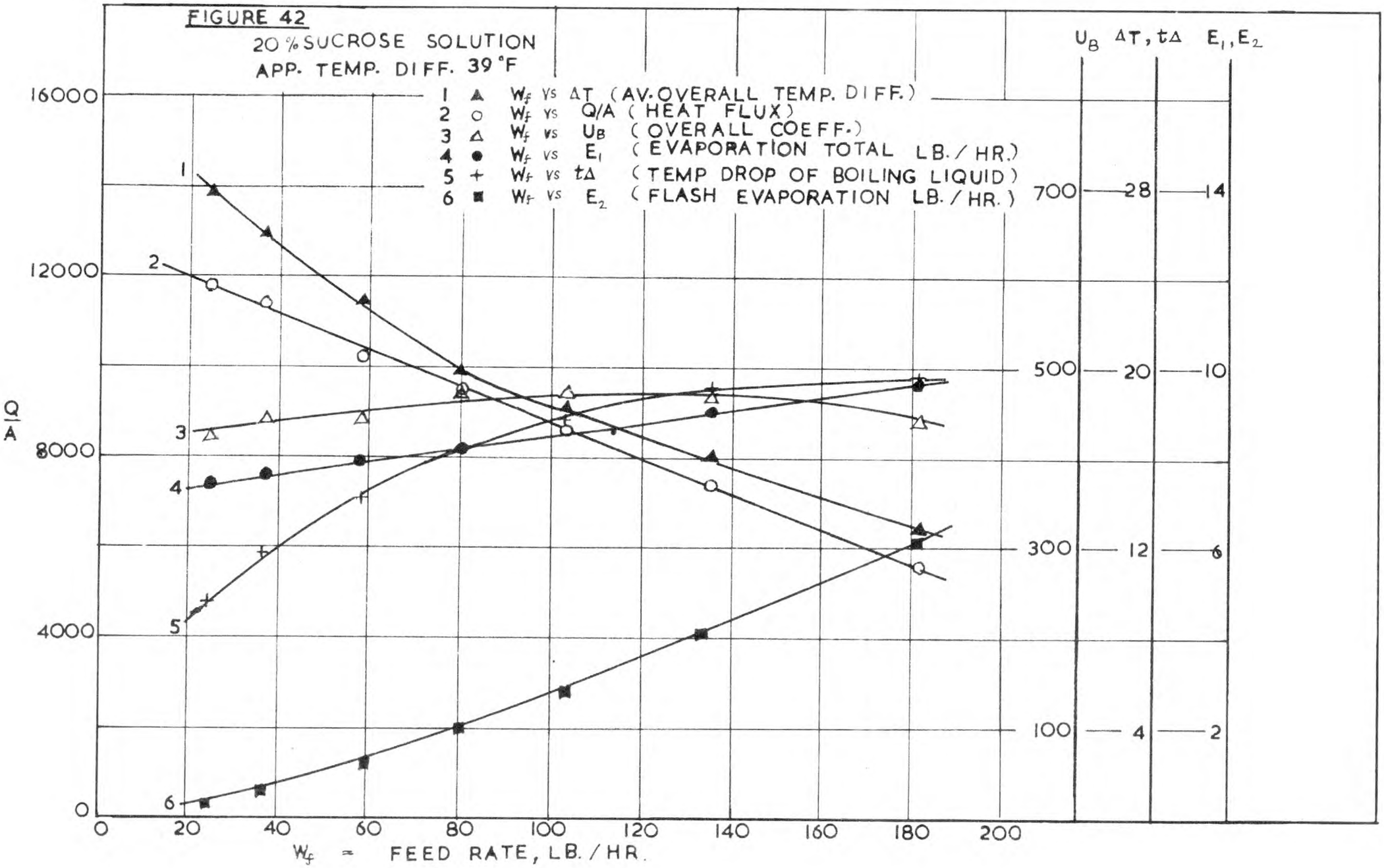
$$h_B \propto \left(\frac{Q}{A}\right)^{0.38} \quad .. \; .. \; .. \quad (17)$$

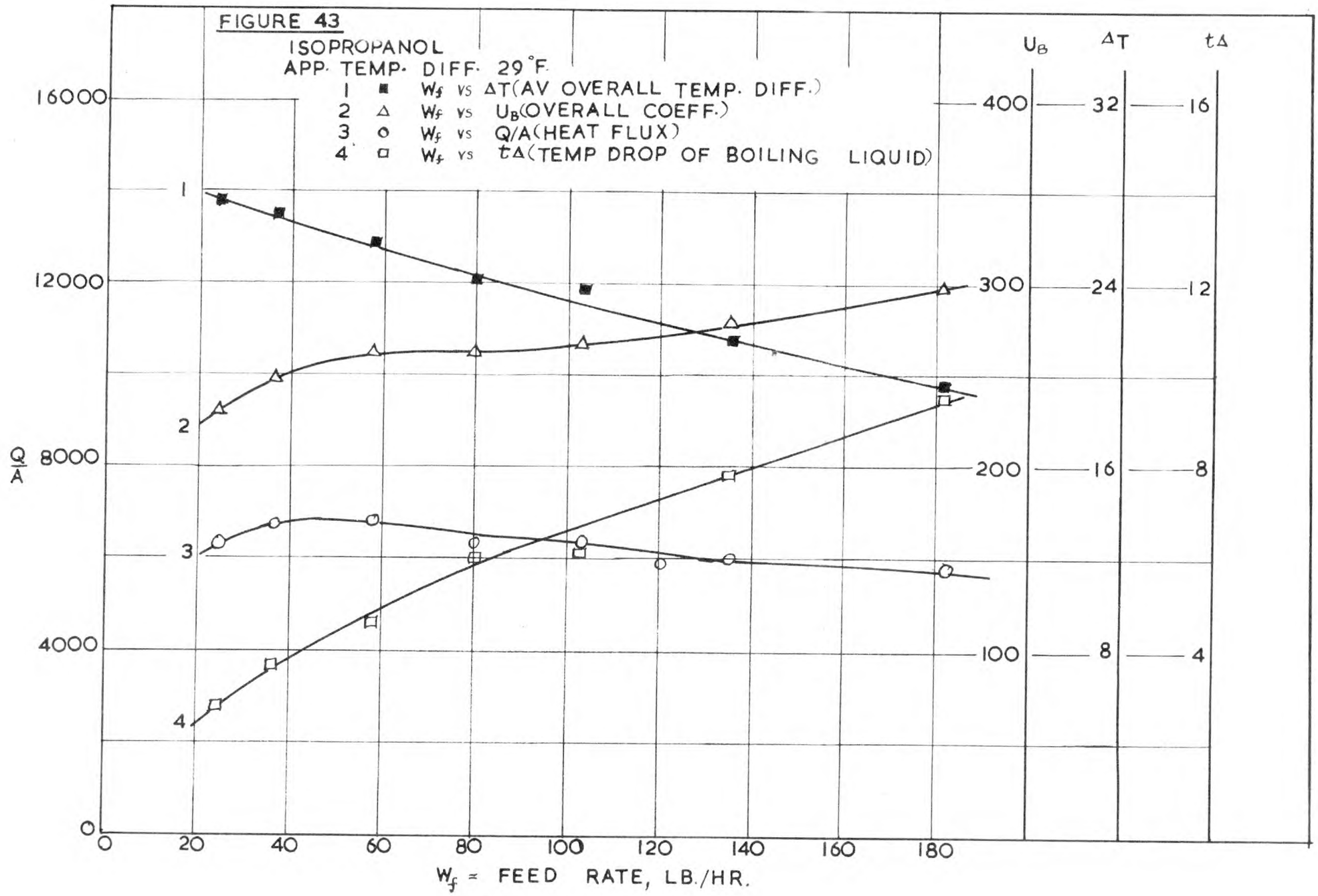
The importance of examining the film coefficient rather than the overall coefficient is again clearly shown.

B. Influence of Feed Rate.

In considering the effect of feed rate on the heat transfer coefficient, it must be realised that, unless special precautions are taken, any alteration in the feed rate will bring about some alteration in other factors, such as the temperature difference, temperature level, and it becomes difficult to assess the controlling factor.

The temperature drops of boiling liquid along the tube were found to increase with feed rate, as in the case of the glass apparatus. Thus, with increase in feed rate and constant temperature at the outlet, it was necessary to increase the feed temperature, in order to maintain boiling conditions at the bottom of the tube. For a


FIGURE 42
20 % SUCROSE SOLUTION
APP. TEMP. DIFF. 39 °F
1 ▲ Wf vs ΔT (AV. OVERALL TEMP. DIFF.)
2 ○ Wf vs Q/A (HEAT FLUX)
3 △ Wf vs UB (OVERALL COEFF.)
4 ● Wf vs E1 (EVAPORATION TOTAL LB./HR.)
5 + Wf vs tΔ (TEMP DROP OF BOILING LIQUID)
6 ■ Wf vs E2 (FLASH EVAPORATION LB./HR.)
UB ΔT, tΔ E1, E2
Q/A
16000
12000
8000
4000
0
700
500
300
100
28
20
12
4
14
10
6
2
0
20
40
60
80
100
120
140
160
180
200
Wf = FEED RATE, LB./HR.


FIGURE 43
ISOPROPANOL
APP. TEMP. DIFF. 29°F.
1 ■ Wf vs ΔT(AV OVERALL TEMP. DIFF.)
2 △ Wf vs UB(OVERALL COEFF.)
3 ○ Wf vs Q/A(HEAT FLUX)
4 □ Wf vs tΔ(TEMP DROP OF BOILING LIQUID)
UB
ΔT
tΔ
16000
12000
8000
4000
0
Q/A
400
300
200
100
32
24
16
8
16
12
8
4
0
20
40
60
80
100
120
140
160
180
Wf = FEED RATE, LB./HR.

constant hot water temperature, this will result in a reduction in the average temperature difference.

In each of the series A, B, and C, the feed rate (W_f) was increased from 24.5 to 181 lbs./hr., whilst the outlet temperature was kept constant at 123°F and the feed temperature adjusted so that the boiling occurred at the bottom. In Series A, the hot water temperature was 138°F, in B 162°F, and in C 185°F.

Plots were first made of W_f versus U_B and h_B, for the several liquids, which gave a clear indication that neither U_B nor h_B was significantly altered by the variation in feed rate. It was found that the plots for water and sucrose solutions differed from that for isopropyl alcohol. Figures 42 and 43 show the results for 20 per cent sucrose solution and for the alcohol respectively, in which the feed rate is plotted in relation to the overall temperature difference (ΔT), heat flux ($\frac{Q}{A}$), overall coefficient (U_B), temperature drop of boiling liquid along the tube ($t\Delta$) and, in the case of 20 per cent sucrose solution, the importance of flash evaporation.

With the sucrose solution, U_B increases slowly and then falls slightly with increase in W_f, but the variation is small (about 10 per cent). The heat flux, however, steadily decreases to about half the original value for

the sevenfold increase in W_f. This apparently anomalous behaviour is a result of the increase in temperature of the feed giving an increased temperature drop up the tube and a corresponding decrease in the effective temperature difference (ΔT) from 28 to 13°F. This effect was much less with the glass tube evaporator, due to lower ranges of feed rate and the lower vaporisation rates. The temperature drop of boiling liquid along the tube in this equipment was as much as 20°F under some conditions and thus masked the true effect of feed rate. The increase in evaporation (line 4) is seen to be largely a result of the increase in self-evaporation (line 6), which is, in fact, greater than the increase in total evaporation.

With isopropyl alcohol (Figure 43), U_B steadily increases with W_f, but only to the extent of about 25 per cent. The heat flux rises slightly at first, but then falls slowly. The important difference between Figures 42 and 43 is that, with the alcohol, the drop in temperature up the tube is much less. This is believed to be due to the decreased specific volume of the vapour and the corresponding smaller drop in pressure up the tube compared with the sucrose solution.

In Series K, the overall temperature difference (ΔT) was kept constant at about 20°F and the average boiling

FIGURE 44

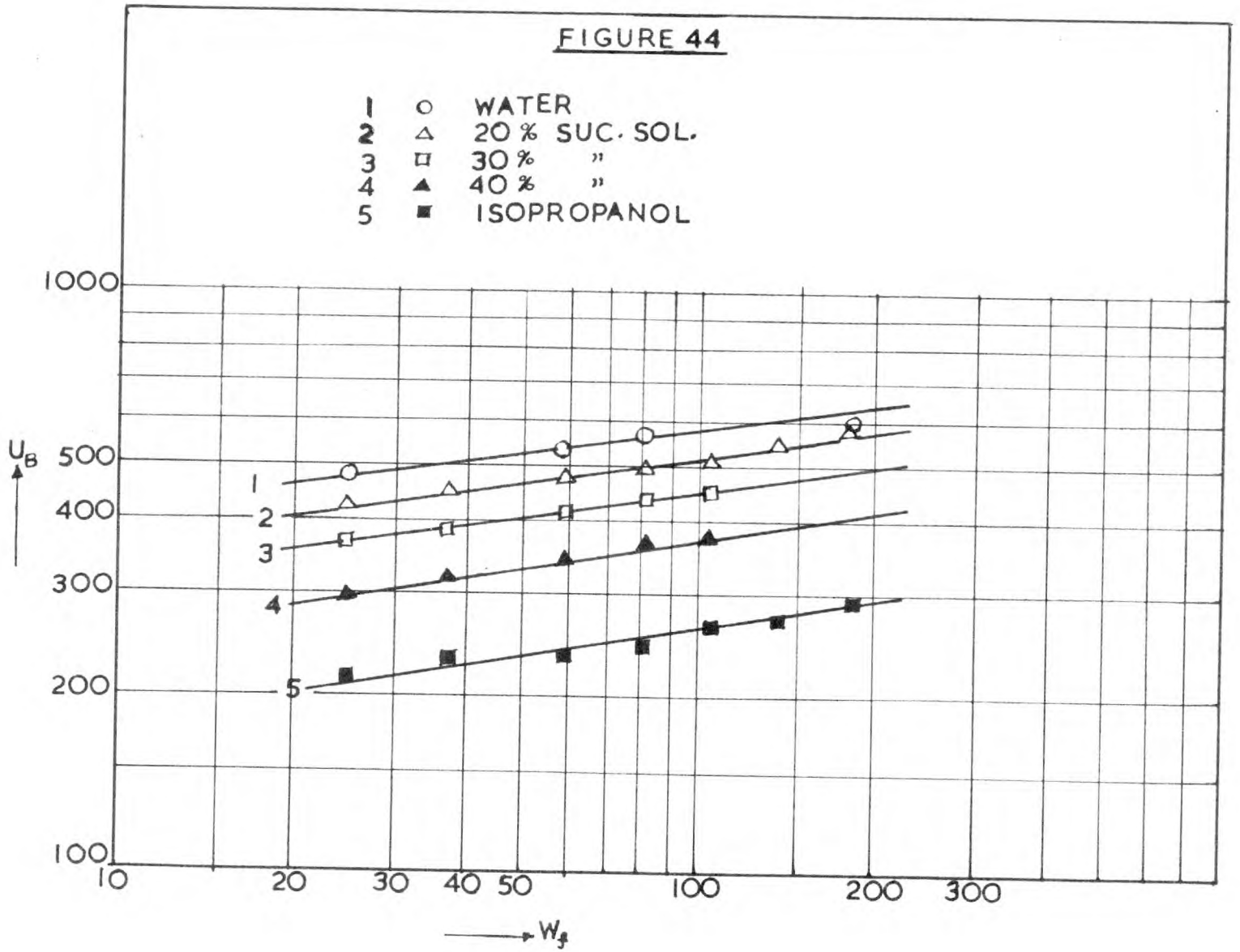
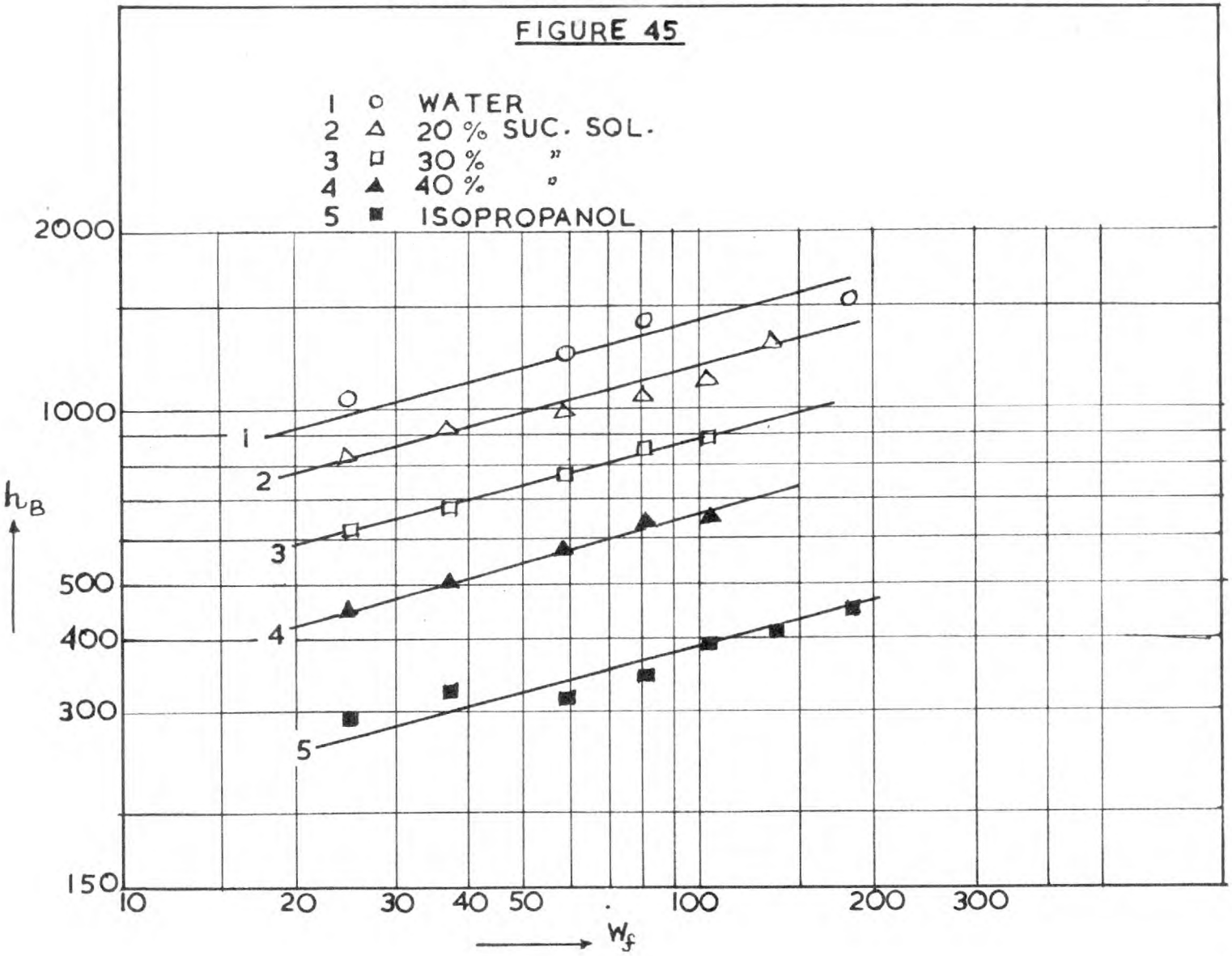

1 ○ WATER
2 △ 20 % SUC. SOL.
3 □ 30 % "
4 ▲ 40 % "
5 ■ ISOPROPANOL
1000
500
400
300
200
100
U_B
10
20
30
40
50
100
200
300
W_s
1
2
3
4
5

FIGURE 45


1 ○ WATER
2 △ 20 % SUC. SOL.
3 □ 30 % "
4 ▲ 40 % "
5 ■ ISOPROPANOL
2000
1000
500
400
300
150
h_B
10
20
30
40
50
100
200
300
W_f

temperature at aboult 140°F, whilst the feed rate was varied. The outlet temperature was allowed to vary. These experiments were difficult to carry out, since the pressure drop up the tube was not known accurately with varying feed rate at varying inlet temperatures. After taking a large number of tests, it was possible to assess this drop in pressure and, in this way, the desired test conditions were obtained. Plots of U_B and h_B against W_f for five liquids are shown in Figures 44and 45 respectively. The points for each liquid lie on straight lines from which the average relations are

$$U_B \propto W_f^{0.17} \quad .. \; .. \; .. \; .. \quad (18)$$

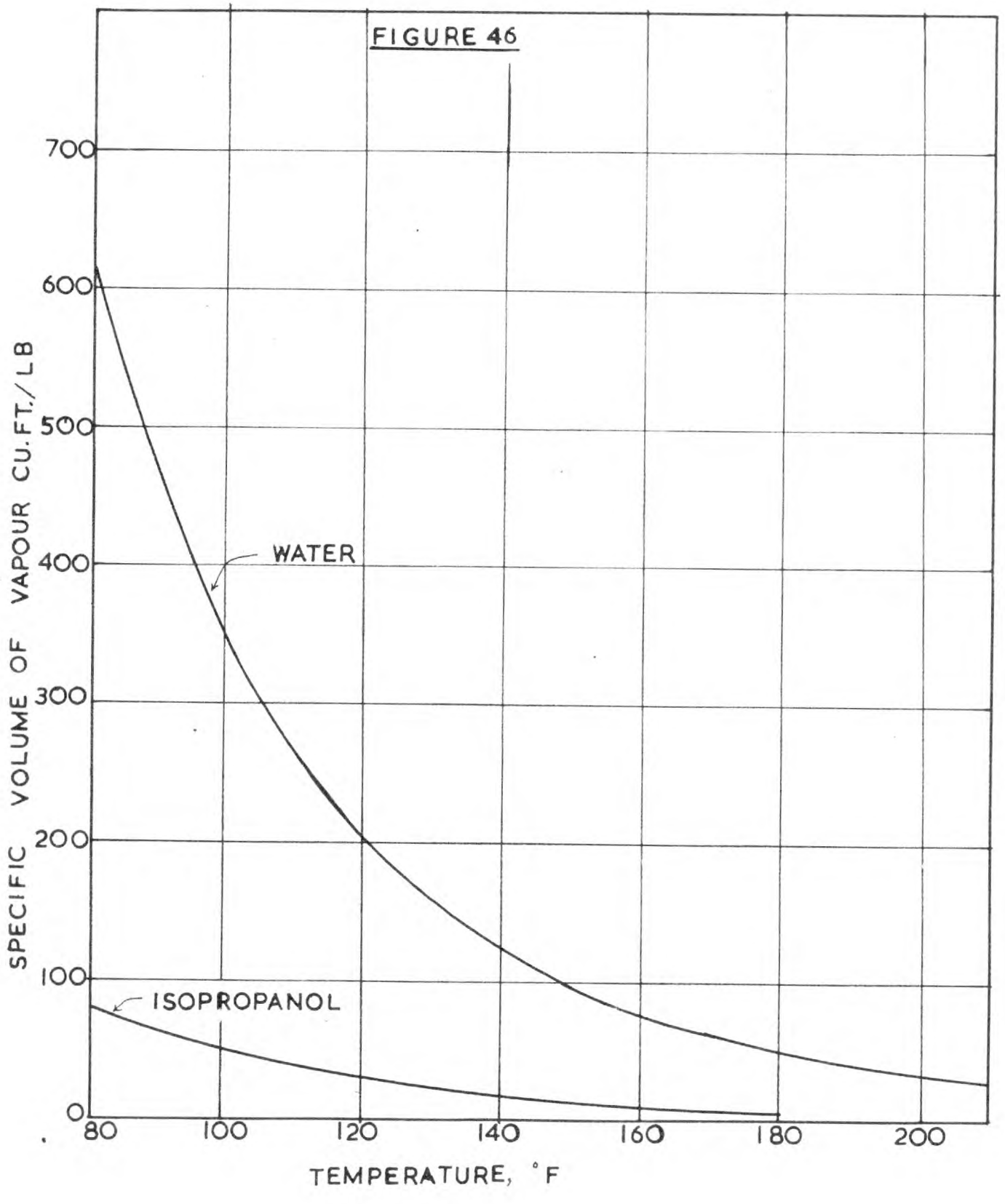
$$h_B \propto W_f^{0.25} \quad .. \; .. \; .. \; .. \quad (19)$$

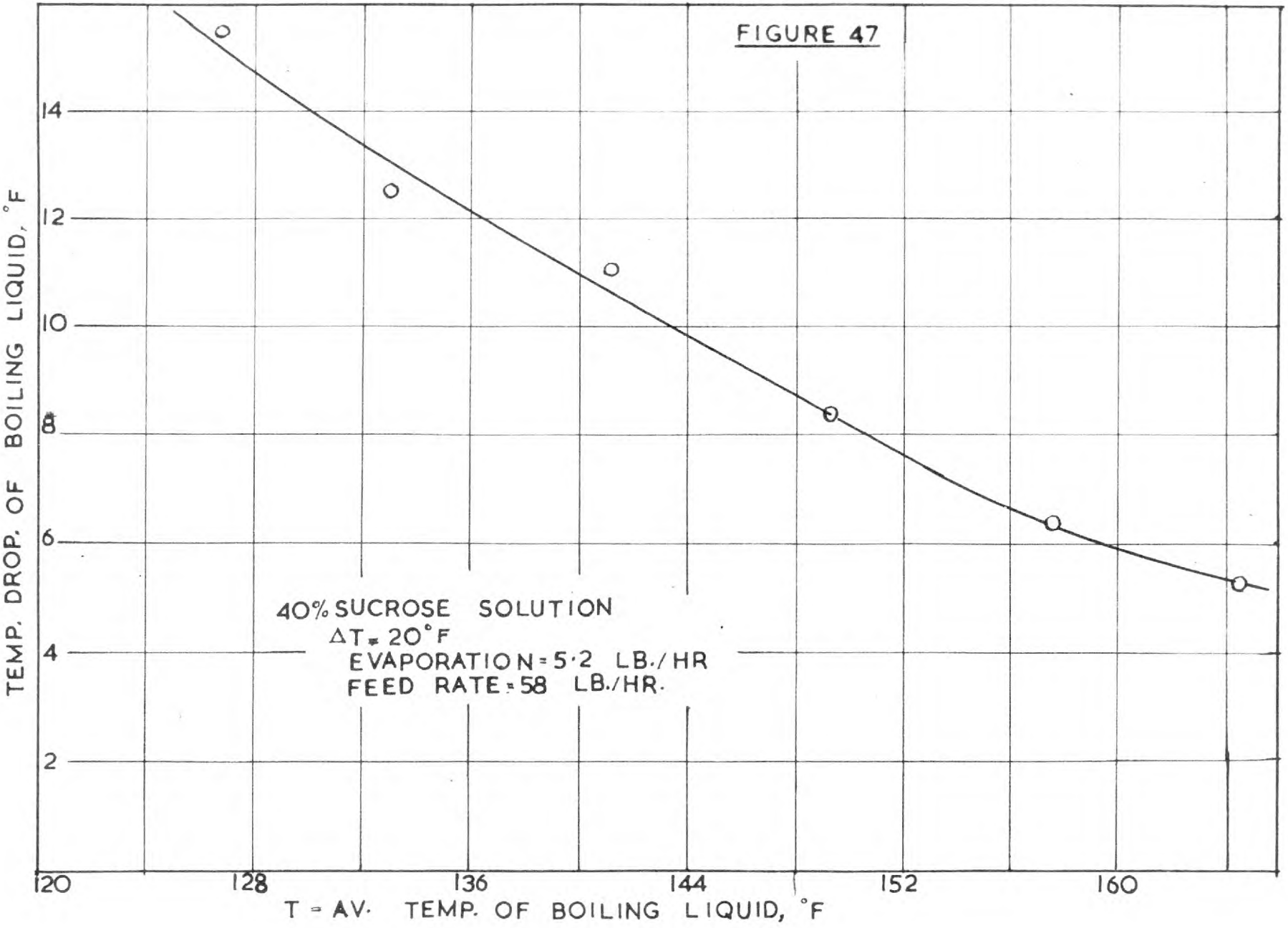
These equations give a much truer picture of the influence of feed rate, but they are not perhaps of immediate practical use since they involve maintaining constant so many factors.

C. <u>The Problem of Recirculation of Liquid</u>.

No separate experiments were carried out to study the effect of recirculation of liquid, but useful deductions can be drawn from the results showing the effects of feed rate. The idea of recirculation would seem to be justified when there is an increase in heat transfer with increase in

FIGURE 46

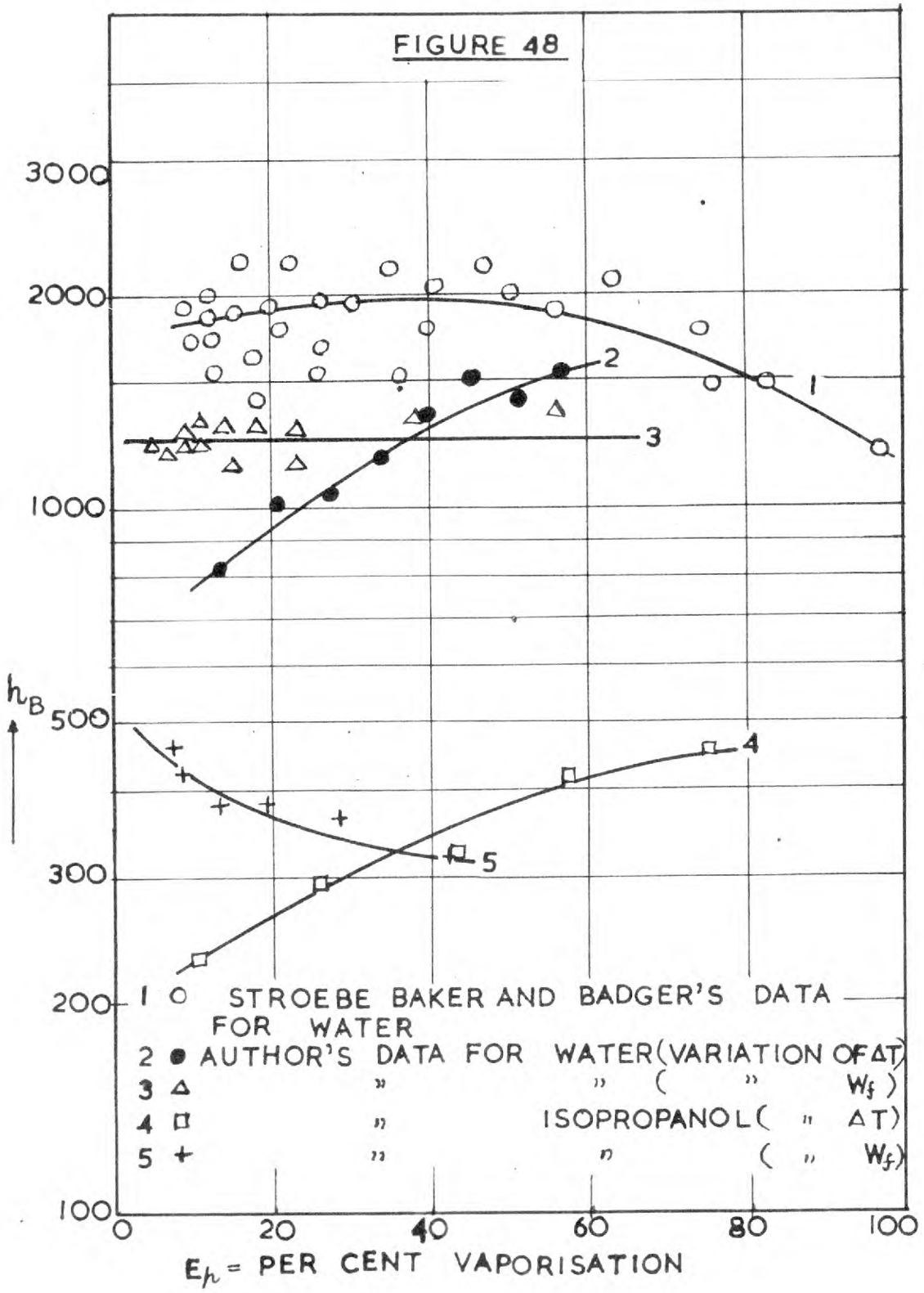

700
600
500
400
300
200
100
0
SPECIFIC VOLUME OF VAPOUR CU.FT./LB
WATER
ISOPROPANOL
80
100
120
140
160
180
200
TEMPERATURE, °F


FIGURE 47
TEMP. DROP. OF BOILING LIQUID, °F
14
12
10
8
6
4
2
40% SUCROSE SOLUTION
ΔT = 20°F
EVAPORATION = 5·2 LB./HR
FEED RATE = 58 LB./HR.
120
128
136
144
152
160
T = AV. TEMP. OF BOILING LIQUID, °F

feed rate. Figures 42 and 43 showed that, with constant temperature of the heating medium and constant temperature at the outlet, the increase in feed rate slightly alters the heat transfer coefficient, but decreases the heat flux considerably in the case of 20 per cent sucrose solutions (Figure 42) and appreciably in the case of isopropyl alcohol (Figure 43). This has been shown to be due to increase in the pressure drop along the tube with feed rate.

Working at a higher temperature level, such as 175 to 200°F, would considerably reduce the pressure drop as a result of the much lower specific volume of vapour. Looking at the plot of specific volume of saturated vapour versus temperature shown in Figure 46, we find that the specific volume of water vapour which is 156 cu.ft./lb. at 130°F is reduced to 50 cu.ft./lb. at 180°F. The plot of temperature drop of boiling 40 per cent sucrose solution along the tube versus the boiling temperature (range 126 to 164°F) given in Figure 47 shows that for constant feed rate and constant vaporisation rate, the temperature drop of boiling liquid along the tube decreases from 16 to 6°F, with increase in average boiling temperature from 125 to 160°F. Hence, it is reasonable to conclude that by working at a higher temperature level, the reduction in the effective temperature difference with increase in the feed rate would be much

FIGURE 48

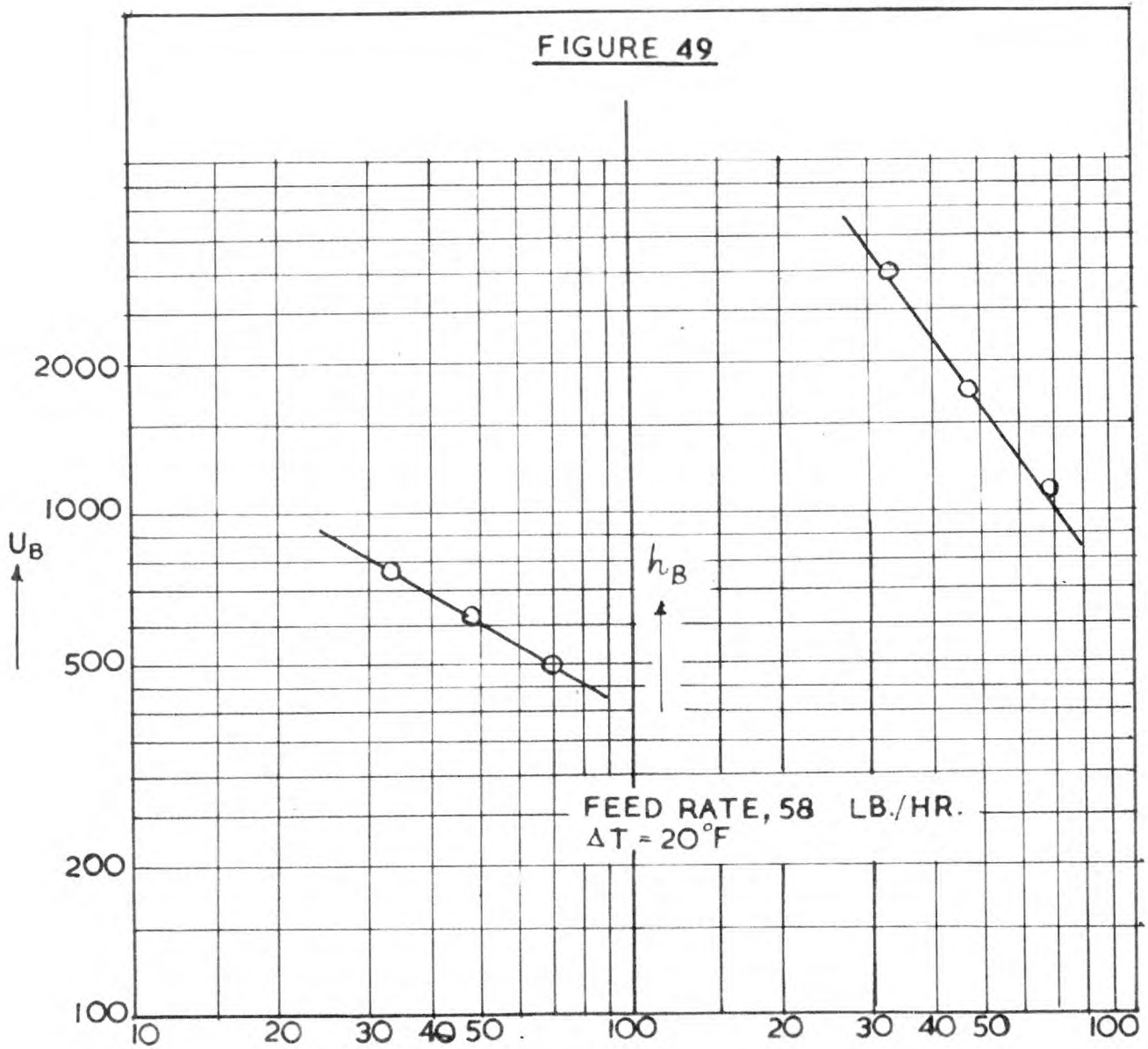

3000
2000
1000
500
300
200
100
h_B
0
20
40
60
80
100
E_h = PER CENT VAPORISATION
1 ○ STROEBE BAKER AND BADGER'S DATA FOR WATER
2 ● AUTHOR'S DATA FOR WATER (VARIATION OF ΔT)
3 △ " " (" W_f)
4 □ " ISOPROPANOL (" ΔT)
5 + " " (" W_f)
1
2
3
4
5

less and the increase in heat flux, as well as heat transfer coefficient, would be possible. Under the present working temperature of 130 to 140°F, the recirculation of liquid does not seem to have any advantage.

D. The Effect of Degree of Vaporisation.

Some suggestions have been made in the past for relating the per cent vaporisation with the heat transfer coefficient. Plots of h_B versus the per cent vaporisation (E_v) have been drawn, but no regularity is apparent. E_v can be varied either by varying the feed rate or the temperature difference. Four plots, two for water and two for isopropyl alcohol are shown in Figure 48 on semilog paper. Of these, lines 2 and 4 are for a constant feed rate of 24.5 lbs./hr., and variation of temperature difference, and lines 3 and 5 for a constant apparent temperature difference and variation of feed rate. Lines 2 and 4 are similar. Whilst the line 3 for water shows almost no influence on h_B, but line 5 for isopropyl alcohol shows a regular decrease in h_B with increase in vaporisation. These results may be compared with those of Stroebe, Baker and Badger[4], whose data are plotted as line 1. The points are very scattered and the curve is that suggested by McAdams[13] from this data. Their values are higher than those of the present work but, if these are corrected for boiling at 175°F, as were Badger's, then the

FIGURE 49


2000
1000
500
200
100
U_B
h_B
FEED RATE, 58 LB./HR.
$\Delta T = 20°F$
10
20
30
40
50
100
20
30
40
50
100
σ = SURFACE TENSION, DYNES/CM.

agreement is better. It is important to notice that Badger's h_B falls off sharply for vaporisation greater than 70 per cent. The present data, even with the maximum temperature difference and minimum flow rate did not give values greater than 75 per cent and no falling off in h_B is apparent (lines 2 and 4). The rapid fall of h_B in Badger's data is probably due to the presence of insufficient liquid to wet the tube surface with much higher vaporisation rates. This factor (E_ρ) is not really a fundamental one, but is dependent on the feed rate and the temperature difference.

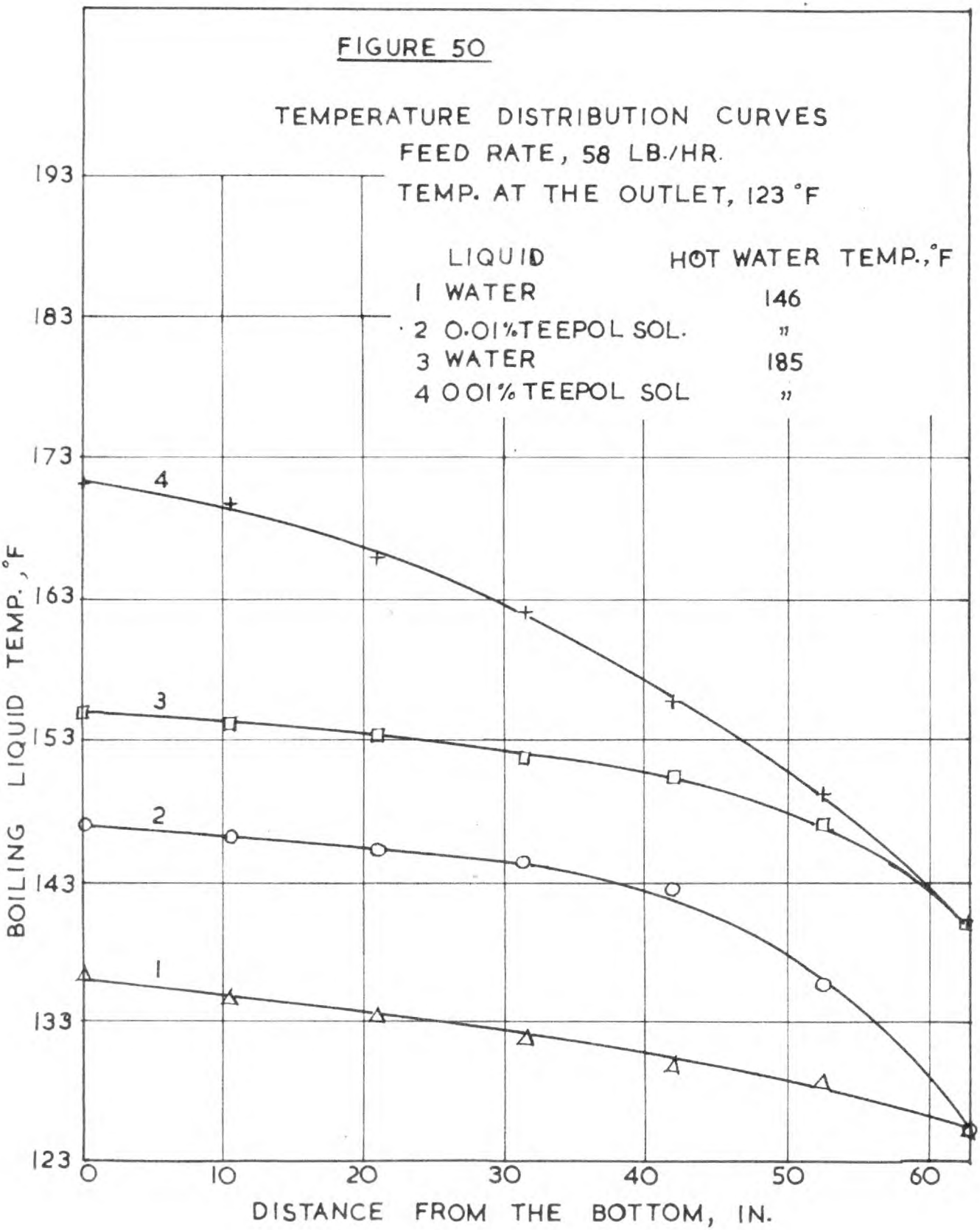
E. Influence of Surface Tension.

The surface tension was varied somewhat artificially by adding 0.01 and 0.10 per cent Teepol to water. This reduced the surface tension from 66.2 dynes/cm. to 47 and 33 dynes/cm. respectively, at 140°F. The results are shown in Figure 49 for a feed rate of 58 lbs./hr., and with an average temperature difference of 20°F. The considerable effect of surface tension is seen by the fact that a reduction by half gives an increase in the film coefficient of from two to three times. These Teepol solutions boiled erratically at first and the figures are given after prolonged boiling. From Figure 49, we can derive the relations:

FIGURE 50

TEMPERATURE DISTRIBUTION CURVES
FEED RATE, 58 LB./HR.
TEMP. AT THE OUTLET, 123 °F

LIQUID	HOT WATER TEMP., °F
1 WATER	146
2 0.01% TEEPOL SOL.	"
3 WATER	185
4 0.01% TEEPOL SOL	"



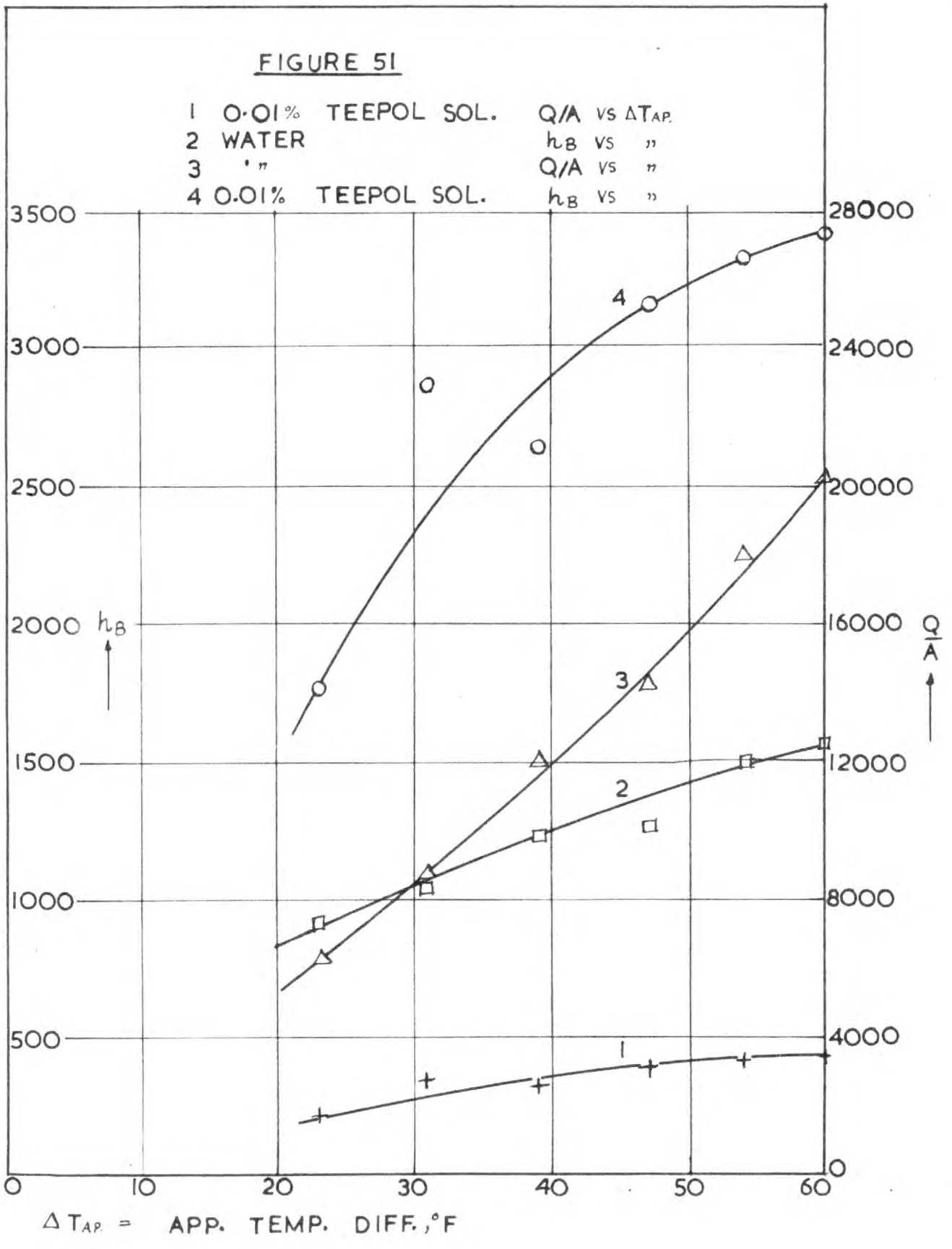
$$U_B \propto \sigma^{-0.6} \quad .. \; .. \; .. \quad (20)$$

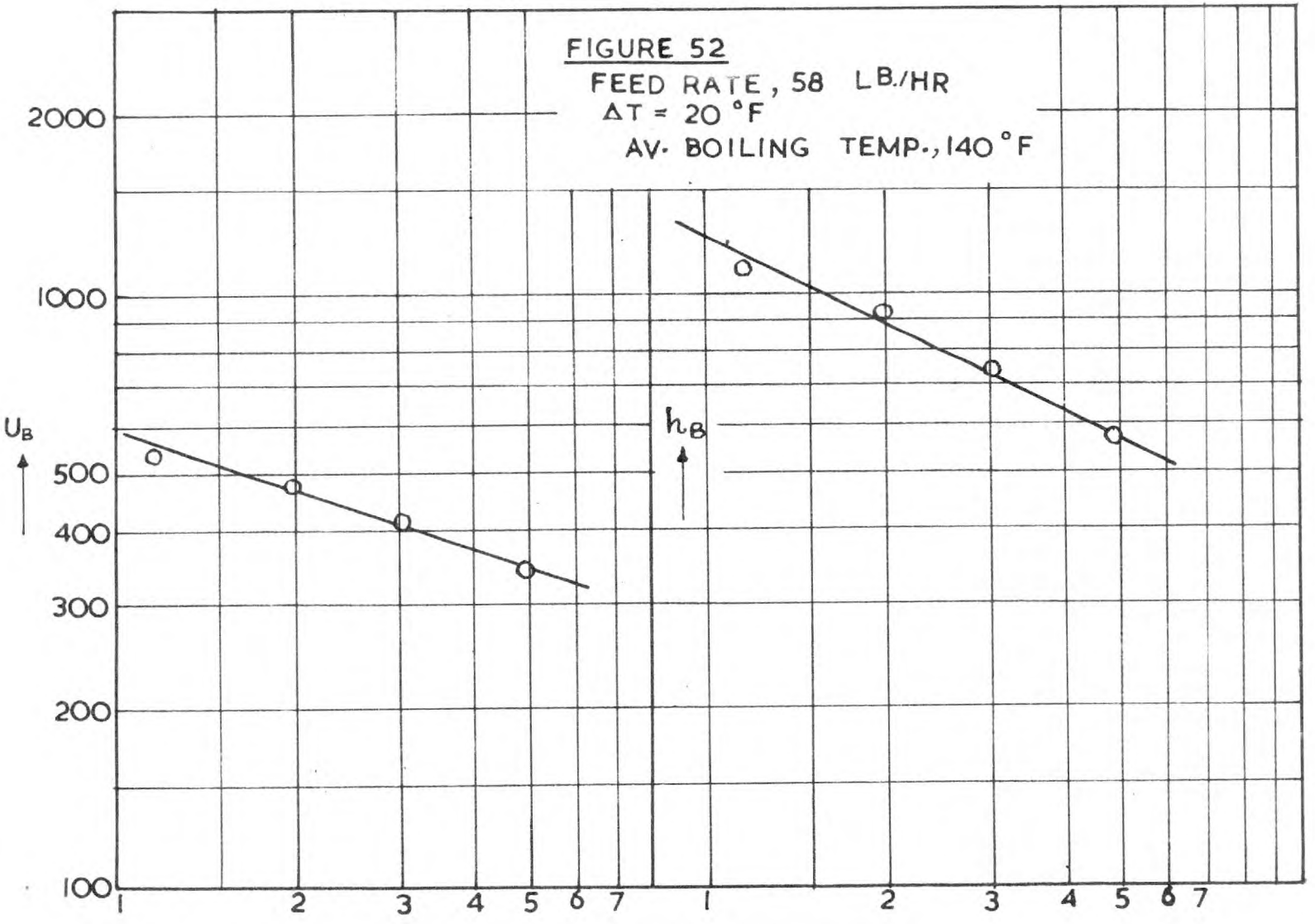
$$h_B \propto \sigma^{-1.4} \quad .. \; .. \; .. \quad (21)$$

where σ is the surface tension in dynes/cm.

Badger and his associates[4] found that h_B was inversely proportional to the square of the surface tension (Equation 2, page 9). As discussed later, the present results are in good agreement with those of Kirschbaum[14], who has suggested that the increase in film coefficient arises from the foaming character of the liquid. He has gone further in suggesting that the foam increases the boiling coefficient in much the same way that the presence of drops increases the condensing coefficient.

In addition to influencing heat transfer coefficients as outlined above, the addition of Teepol alters the operation of the evaporator in a number of ways. Thus, in order to bring the solution to the boiling point at the bottom of the tube, much higher feed temperatures were required than with water, although the temperature at the outlet was the same. A typical plot showing the temperature distribution up the tube, for water and 0.1 per cent Teepol solution, is shown in Figure 50. Curves 1 and 2 are for an apparent temperature difference of 23°F and curves 3 and 4 for 62°F difference. These curves show the big differences in temperature between water and

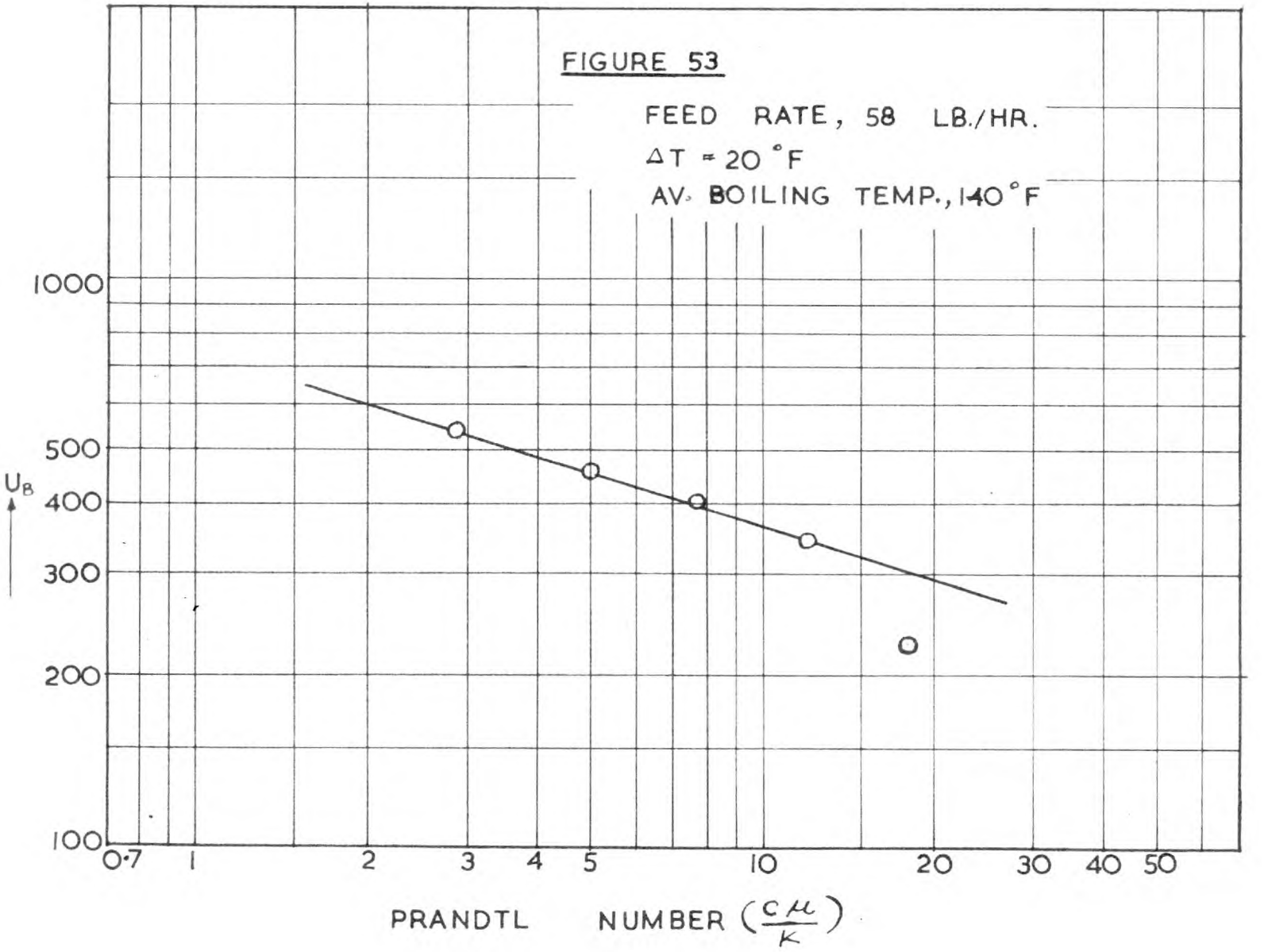

FIGURE 51
1 0·01% TEEPOL SOL. Q/A VS ΔTAP.
2 WATER hB VS "
3 " Q/A VS "
4 0·01% TEEPOL SOL. hB VS "
3500
3000
2500
2000
1500
1000
500
0
hB
28000
24000
20000
16000
12000
8000
4000
0
Q/A
0
10
20
30
40
50
60
ΔTAP. = APP. TEMP. DIFF., °F

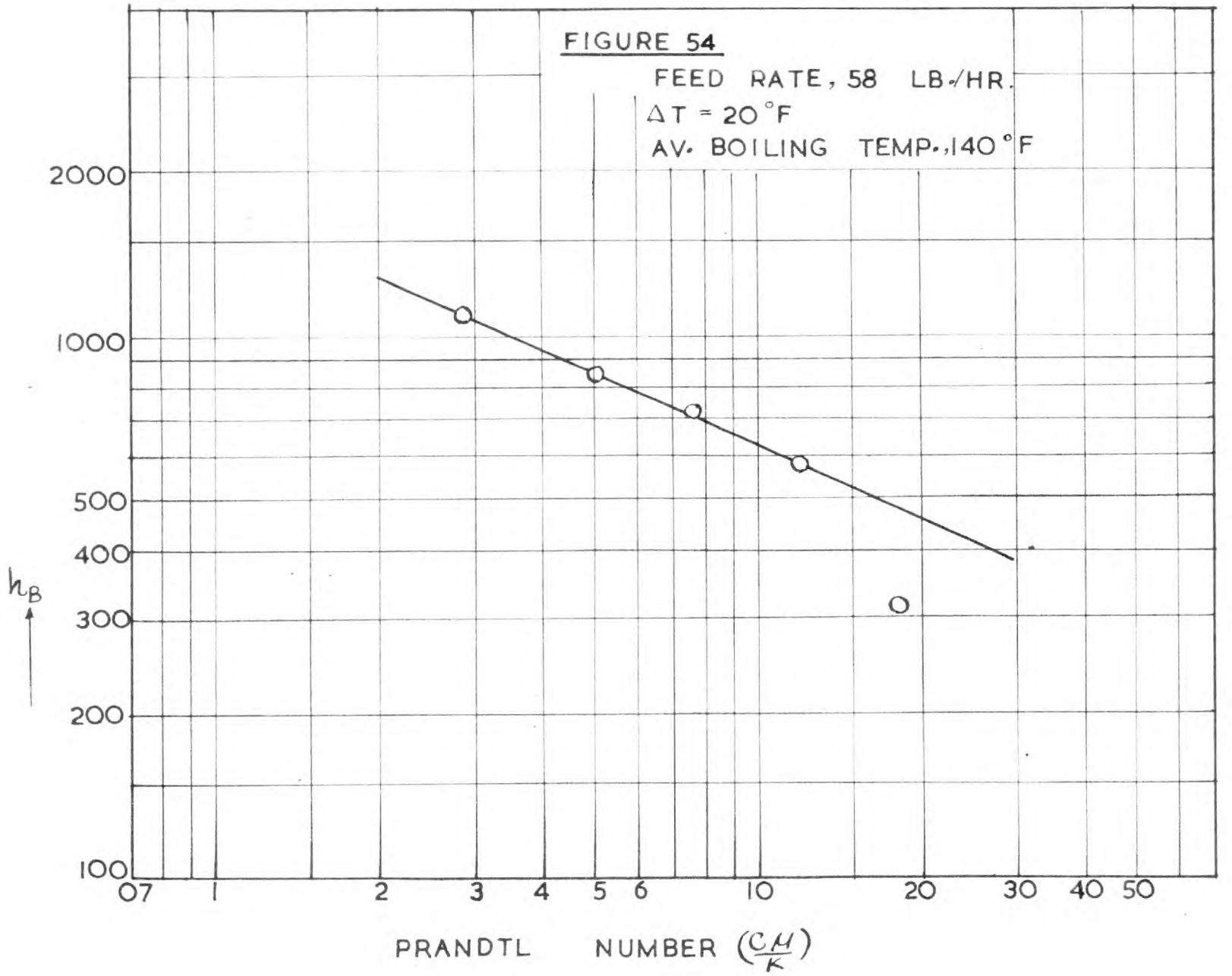

FIGURE 52
FEED RATE, 58 LB./HR
ΔT = 20 °F
AV. BOILING TEMP., 140 °F
2000
1000
500
400
300
200
100
U_B
h_B
1
2
3
4
5
6
7
1
2
3
4
5
6
7
μ = VISCOSITY, LB./HR/FT.

Teepol along the length of the evaporator tube and equalisation in temperature before reaching the outlet of the tube. In the case of curves 1 and 2 for lower temperature difference, the equalisation is rather rapid, while, in the case of curves 3 and 4 for higher temperature difference, the equalisation is gradual. This may be due to difference in vaporisation rates. That the higher temperature drop up the tube has a marked effect on the heat flux is shown in Figure 51. For the same apparent temperature difference, the Teepol solution has a higher heat transfer coefficient (curves 2 and 4), but a much reduced heat flux (curves 3 and 1). This anomaly arises from the relatively high pressure drop with this form of evaporator, when operated under a vacuum, and it is probable that both the heat flux and heat transfer coefficient would rise with decrease in surface tension if the pressure were atmospheric.

F. Influence of Viscosity.

As in the case of surface tension, no special tests were made to check the influence of viscosity, but selected tests from different series have been used. Values of the overall and film coefficient for a range of viscosities are shown in Figure 52 for water and various sucrose solutions using a constant feed rate of 58 lbs./hr. and


FIGURE 53
FEED RATE, 58 LB./HR.
ΔT = 20 °F
AV. BOILING TEMP., 140 °F
1000
500
400
300
200
100
U_B
0·7
1
2
3
4
5
10
20
30
40
50
PRANDTL NUMBER $(\frac{c\mu}{k})$


FIGURE 54
FEED RATE, 58 LB./HR.
ΔT = 20 °F
AV. BOILING TEMP., 140 °F
2000
1000
500
400
300
200
100
h_B
07
1
2
3
4
5
6
10
20
30
40
50
PRANDTL NUMBER $(\frac{C\mu}{K})$

average temperature difference (ΔT) of 20°F, with an average boiling temperature of 140°F.

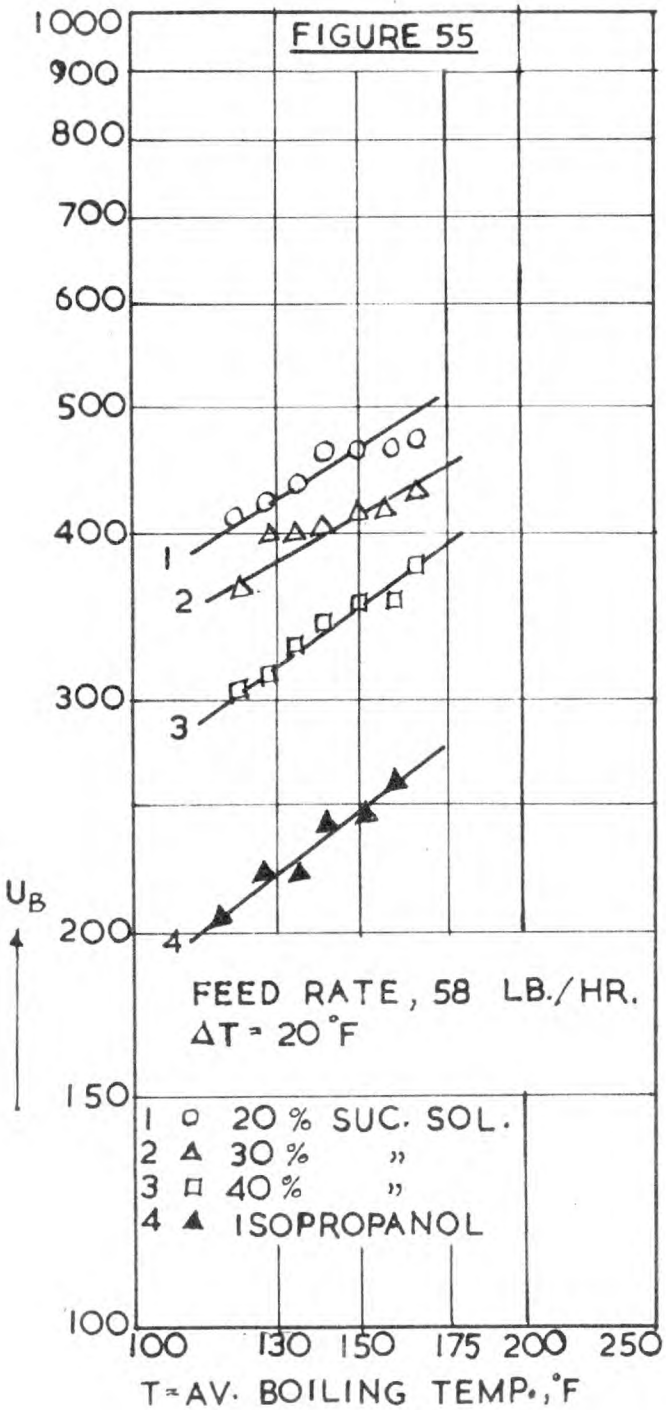
The lines in Figure 52 may be represented by the relations:

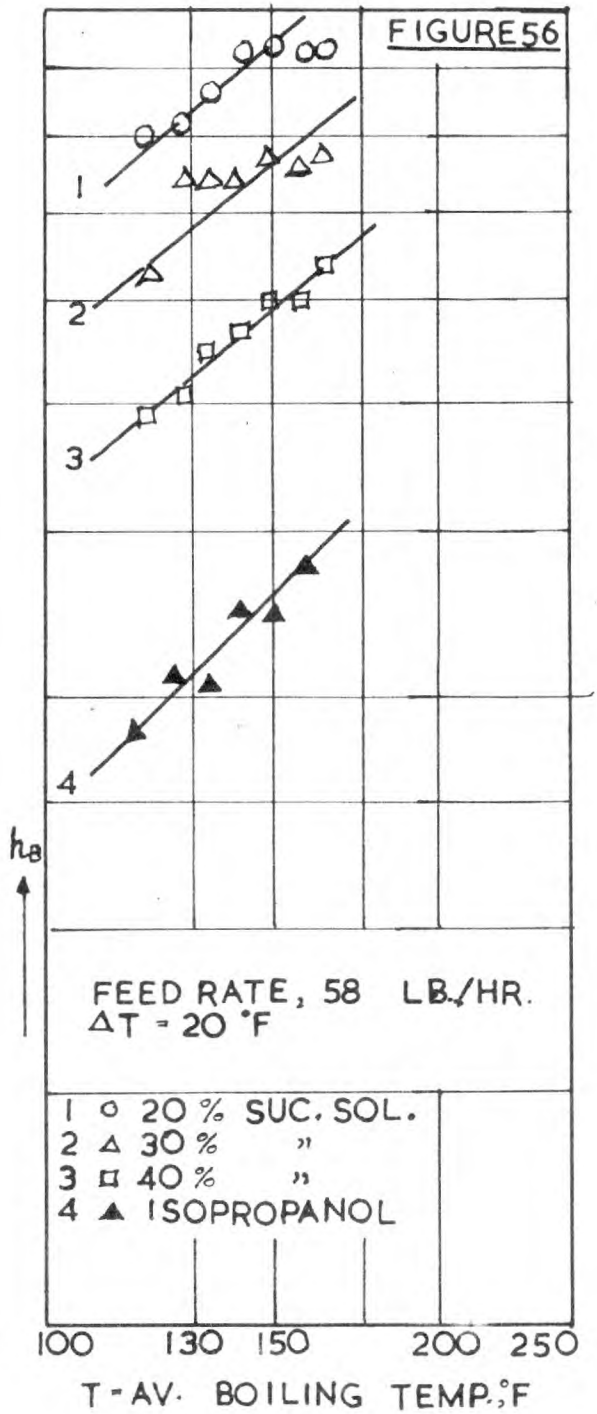
$$U_B \propto \mu^{-0.33} \quad .. \; .. \; .. \; .. \quad (22)$$

$$h_B \propto \mu^{-0.49} \quad .. \; .. \; .. \; .. \quad (23)$$

where μ = viscosity in lbs./ft./hr.

The Prandtl Group: Whilst there is a considerable variation in viscosity of the liquids used to give Figure 52, the specific heat and thermal conductivity are also varying. It was thought useful to see the effect of plotting this data in the form of the Prandtl group ($\frac{C\mu}{K}$) against the heat transfer coefficients. This has been done in Figures 53 and 54, which show the results of various liquids used, including that of isopropyl alcohol. Whilst the points for water and sucrose solutions lie on the same line, the data for isopropyl alcohol lie far below. This is thought to be due to the fact that other properties of the alcohol not accounted for in the Prandtl group are very much different from those of aqueous solutions. The latent heat of vaporisation of alcohol, for example, is less than one third, the specific volume one seventh that of aqueous solutions at the same temperature: again, the surface tension of the alcohol is low (21.7 dynes/cm. at 20°C). The use of


FIGURE 55
1000
900
800
700
600
500
400
300
200
150
100
U_B
1
2
3
4
FEED RATE, 58 LB./HR.
ΔT = 20 °F
1 ○ 20 % SUC. SOL.
2 △ 30 % "
3 □ 40 % "
4 ▲ ISOPROPANOL
100 130 150 175 200 250
T = AV. BOILING TEMP., °F


FIGURE 56
h_B
1
2
3
4
FEED RATE, 58 LB./HR.
ΔT = 20 °F
1 ○ 20 % SUC. SOL.
2 △ 30 % "
3 □ 40 % "
4 ▲ ISOPROPANOL
100 130 150 200 250
T = AV. BOILING TEMP., °F

the Prandtl group has thus provided no improvement over the simpler viscosity relation. The lines of Figures 53 and 54 for water and sucrose solutions may be represented by:

$$U_B \propto \left(\frac{C\mu}{K}\right)^{-0.30} \quad .. \; .. \; .. \quad (24)$$

$$h_B \propto \left(\frac{C\mu}{K}\right)^{-0.44} \quad .. \; .. \; .. \quad (25)$$

which, as mentioned, have similar slopes to those of equations 22 and 23 for viscosity.

G. Effect of Boiling Temperature.

The maximum available temperature of the hot water was 185°F, which limited the range in temperature of the boiling liquid from 120° to 165°F. Tests for series H were made with a feed rate of 58 lbs./hr., and with the average temperature difference of 20°F. The variation in the drop in temperature of the boiling liquid up the tube, with change in boiling temperature, necessitated a good deal of trail and error to maintain the constant value of temperature difference, but, as with the variations in feed rate, this was considered very desirable.

Values of the overall heat transfer coefficient and of the film coefficient for four liquids are shown plotted in Figures 55 and 56 against the average boiling temperature (T). The points for 20 and 30 per cent sucrose solutions are rather irregular, but show a steady rise in the

coefficient with the temperature. The points for the 40 per cent sucrose solution and isopropyl alcohol lie reasonably well on straight lines, which give an average relation of:

$$U_B \propto T^{0.64} \qquad .. \; .. \; .. \; .. \quad (26)$$

$$h_B \propto T^{0.85} \qquad .. \; .. \; .. \; .. \quad (27)$$

The increase in heat transfer coefficient with boiling temperature is expected because of the rapid decrease in the viscosity and slight decrease in the surface tension with temperature. Since the influence of viscosity has been established (equation 23, page 88), we can see if this is responsible for the effects shown above or whether the temperature level has other effects. Values of $h_B \cdot \mu^{0.49}$ for various tests are given below:

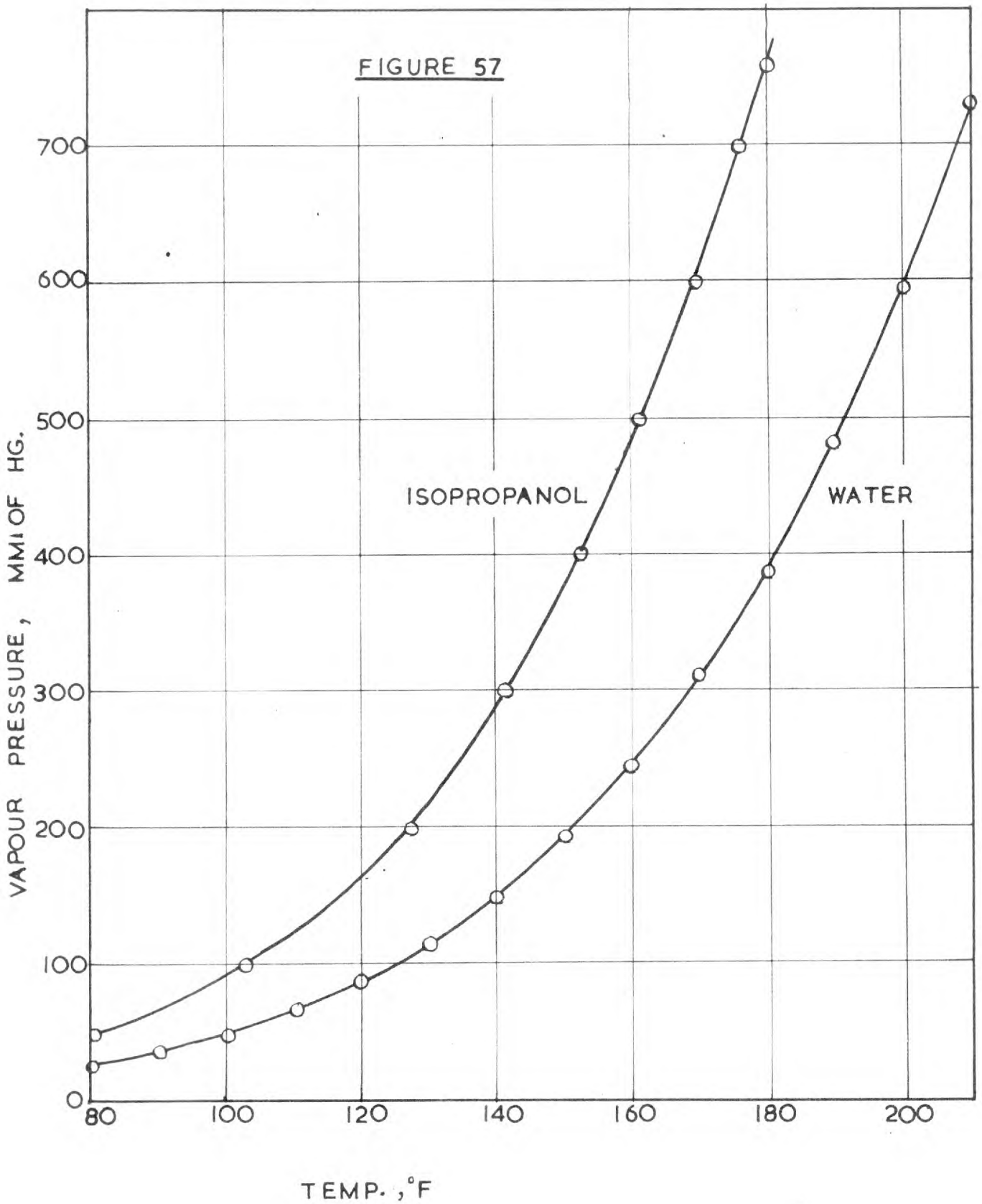
Table D.

$h_B \cdot \mu^{0.49}$

	Temperature, °F.		
	120	140	165
20 per cent sucrose solution	1241	1282	1155
30 per cent sucrose solution	1244	1256	1177
40 per cent sucrose solution	1212	1226	1201

where μ = viscosity, lbs./ft./hr.

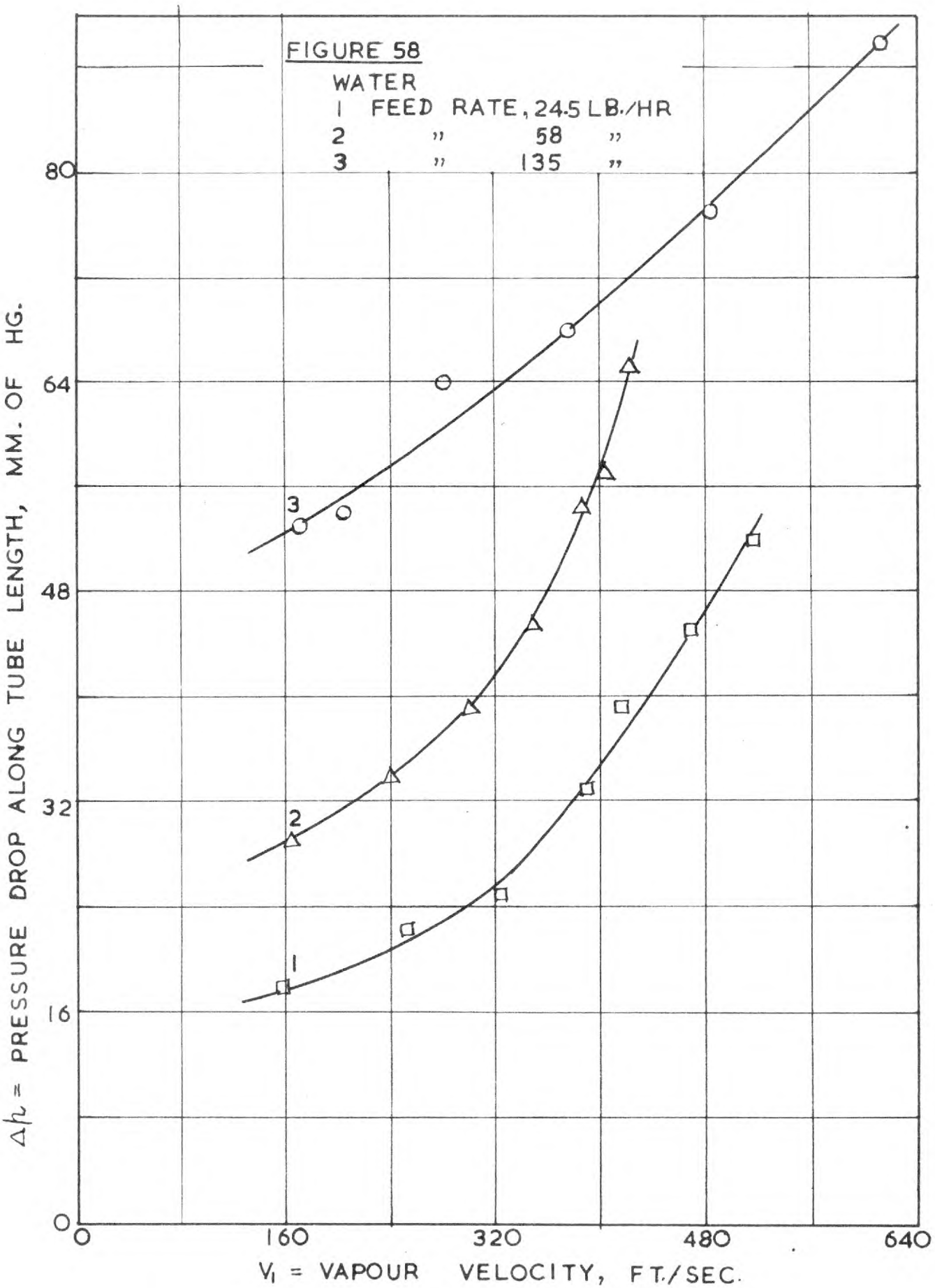
The range of viscosity is from 1.57 to 6.30 lbs./ft./hr. and the boiling film coefficient from 490 to 940 B.T.U./hr./sq.ft./°F. However, the values of $h_B \cdot \mu^{0.49}$ are seen to be independent of the temperature level for each liquid.

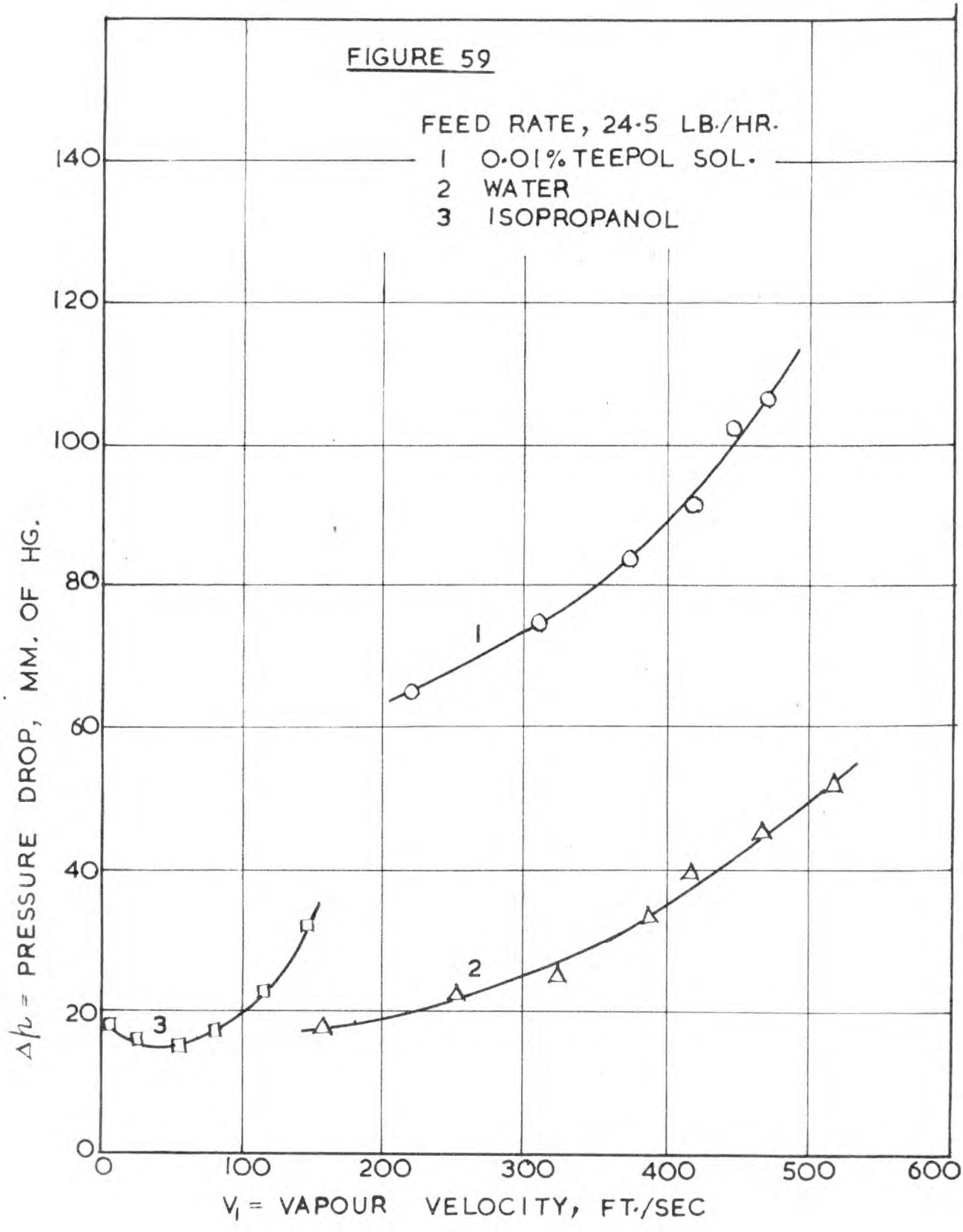

FIGURE 57
700
600
500
400
300
200
100
0
VAPOUR PRESSURE, MM I OF HG.
ISOPROPANOL
WATER
80
100
120
140
160
180
200
TEMP. ,°F

We may conclude then that the effects represented by equations 26 and 27 are really due to changes in the viscosities and not to some other effects of the boiling temperature. It is also worthy of note that the specific volume of the vapour is not considered in the relation, yet this varies more than threefold over the range of temperature (120-165°F). The above results are in good agreement with the empirical correlation (equation 2, page 9) of Badger, which shows the index 0.1 for specific volume of vapour.

H. Pressure Drop in the Evaporator Tube.

It was found, during the investigation, that the pressure drops along the tube were rather high and were affecting the results through the reduction in the effective temperature difference. It was mentioned in the section on the glass tube evaporator (page 56) that the observed pressure drops were the sum of several individual pressure drops. The vapour velocities at the outlet were calculated from the specific volume of the vapour at the outlet temperature and the evaporation in lbs./hr. The specific volume charts for water and isopropyl alcohol vapour are shown in Figure 57. Pressure drops along the tube were calculated from the vapour pressure charts shown in Figure 46. Figure 57 shows that the specific volume of

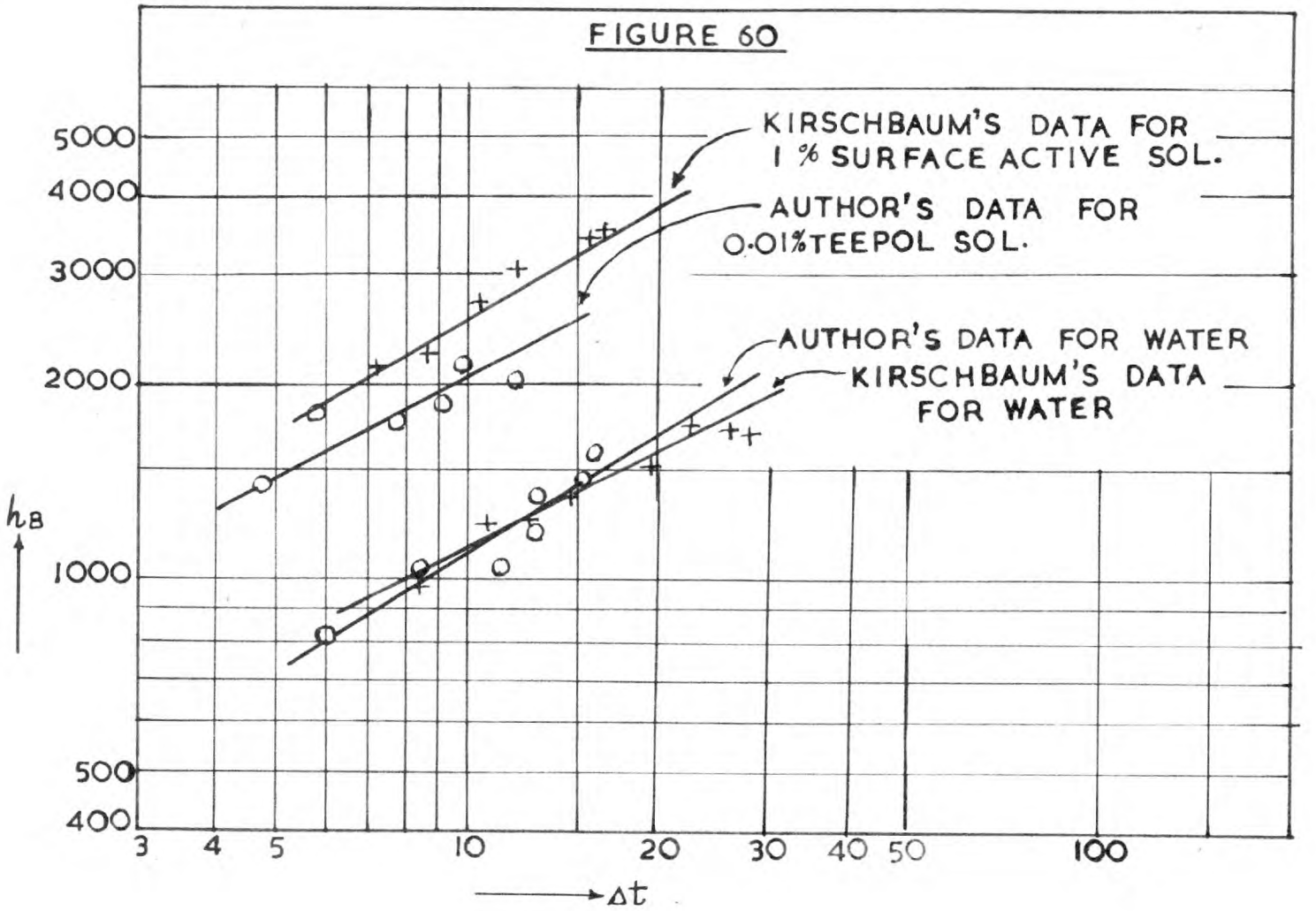

FIGURE 58
WATER
1 FEED RATE, 24.5 LB./HR
2 " 58 "
3 " 135 "
80
64
48
32
16
0
0
160
320
480
640
3
2
1
Δh = PRESSURE DROP ALONG TUBE LENGTH, MM. OF HG.
V1 = VAPOUR VELOCITY, FT./SEC.


FIGURE 59
FEED RATE, 24·5 LB./HR.
1 0·01% TEEPOL SOL.
2 WATER
3 ISOPROPANOL
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
1
2
3
Δh = PRESSURE DROP, MM. OF HG.
V1 = VAPOUR VELOCITY, FT./SEC

vapour increases rapidly as the operating pressure or temperature decreases. The maximum vapour velocity, in the case of water, was about 600 ft./sec., and, in the case of isopropyl alcohol, 150 ft./sec. The plots were drawn of vapour velocities versus pressure drops, under different feed and vaporisation rates, and are shown in Figures 58 and 59. Figure 58 shows that the pressure drop increases rather rapidly with vapour velocity and, for constant vapour velocity, increases with feed rate. Comparing with the similar plots (Figure 19) for the glass tube evaporator, we find that the effect of both vapour velocity and feed rate is much more pronounced in the present apparatus. As mentioned earlier, this is due to the higher feed rates and higher vapour velocities. The higher pressure drop for higher feed rate may here again be due to a greater static head of liquid, resulting from thicker films over the tube surface. Figure 59 shows the change in pressure drop with vapour velocity, for water, 0.1 per cent Teepol solution and isopropyl alcohol, at constant feed rate of 24.5 lbs./hr. The pressure drop for Teepol solution is more than three times that for water, at the same vapour velocity, probably due to the considerable foam produced. The pressure drop in the case of isopropyl alcohol is much less for the reason shown earlier, and the effect of increase in pressure drop with decrease in vapour velocity, at very

low vaporisation rates, is similar to that shown for glass tube evaporator, but less pronounced. This is believed to be due to change in the boiling action at very low vaporisation rates, resulting in more hold up of the liquid in the tube, and hence greater pressure drop.

FIGURE 60

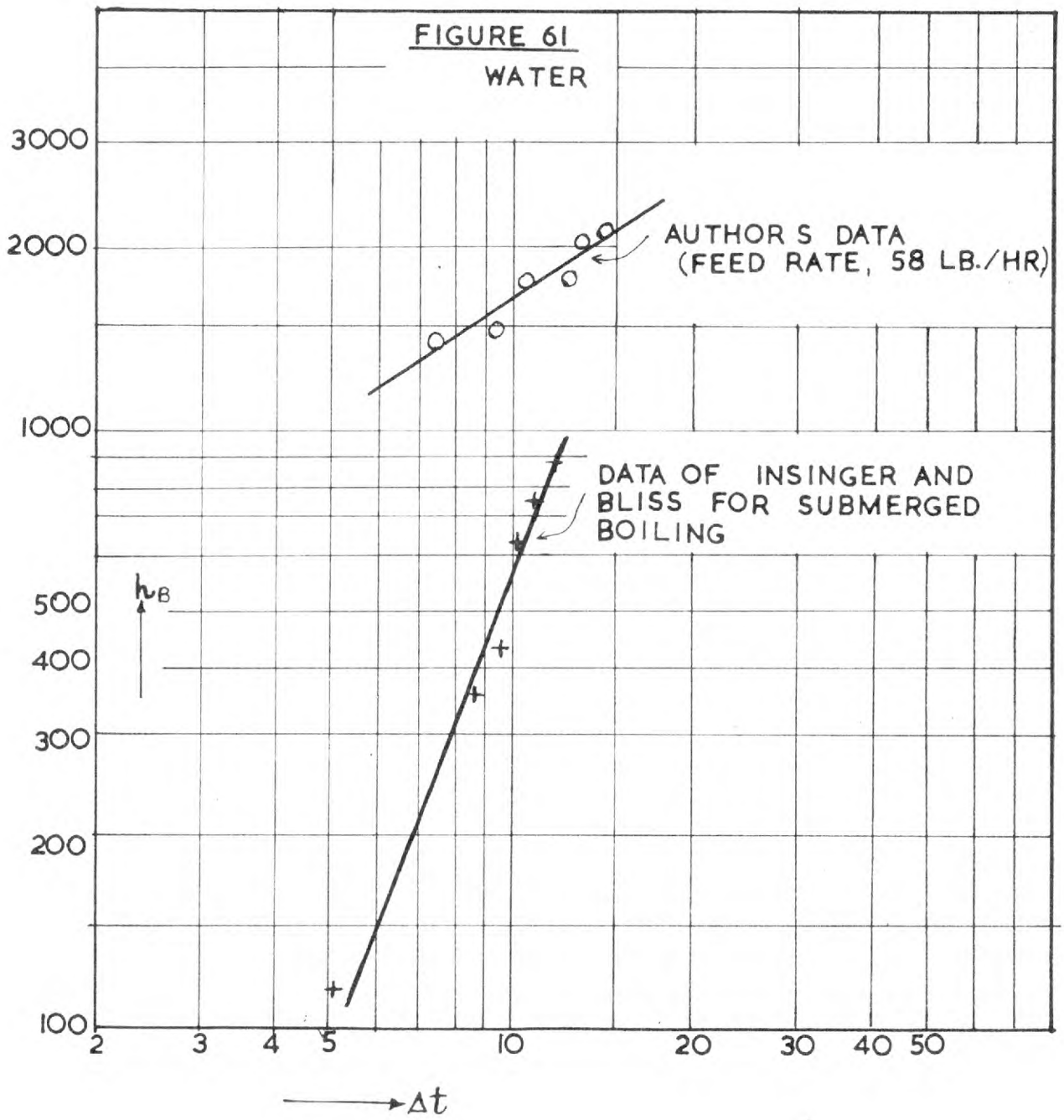

KIRSCHBAUM'S DATA FOR
1 % SURFACE ACTIVE SOL.
AUTHOR'S DATA FOR
0·01% TEEPOL SOL.
AUTHOR'S DATA FOR WATER
KIRSCHBAUM'S DATA
FOR WATER
5000
4000
3000
2000
1000
500
400
h_B
3
4
5
10
20
30
40
50
100
Δt

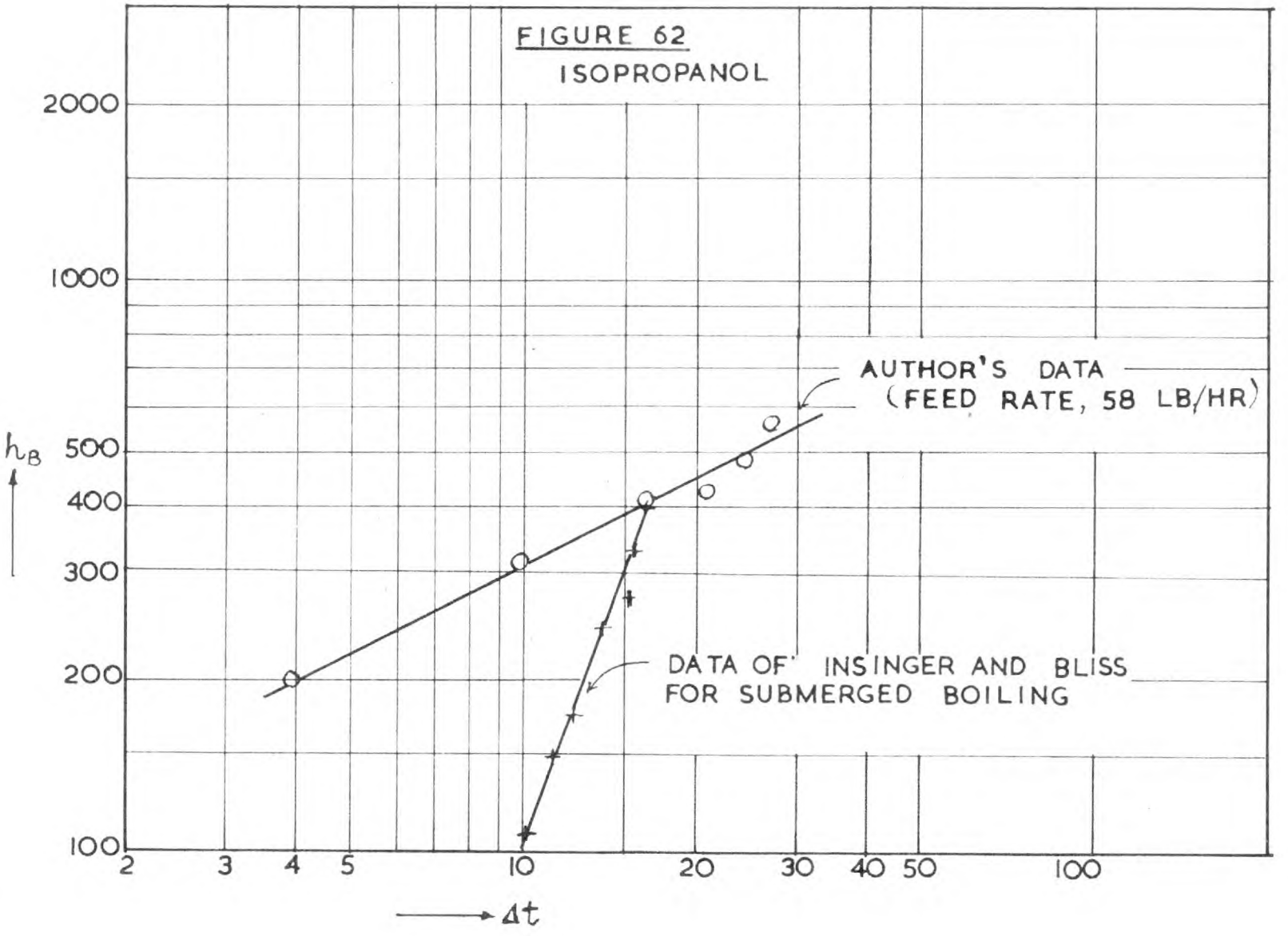
CHAPTER 11.

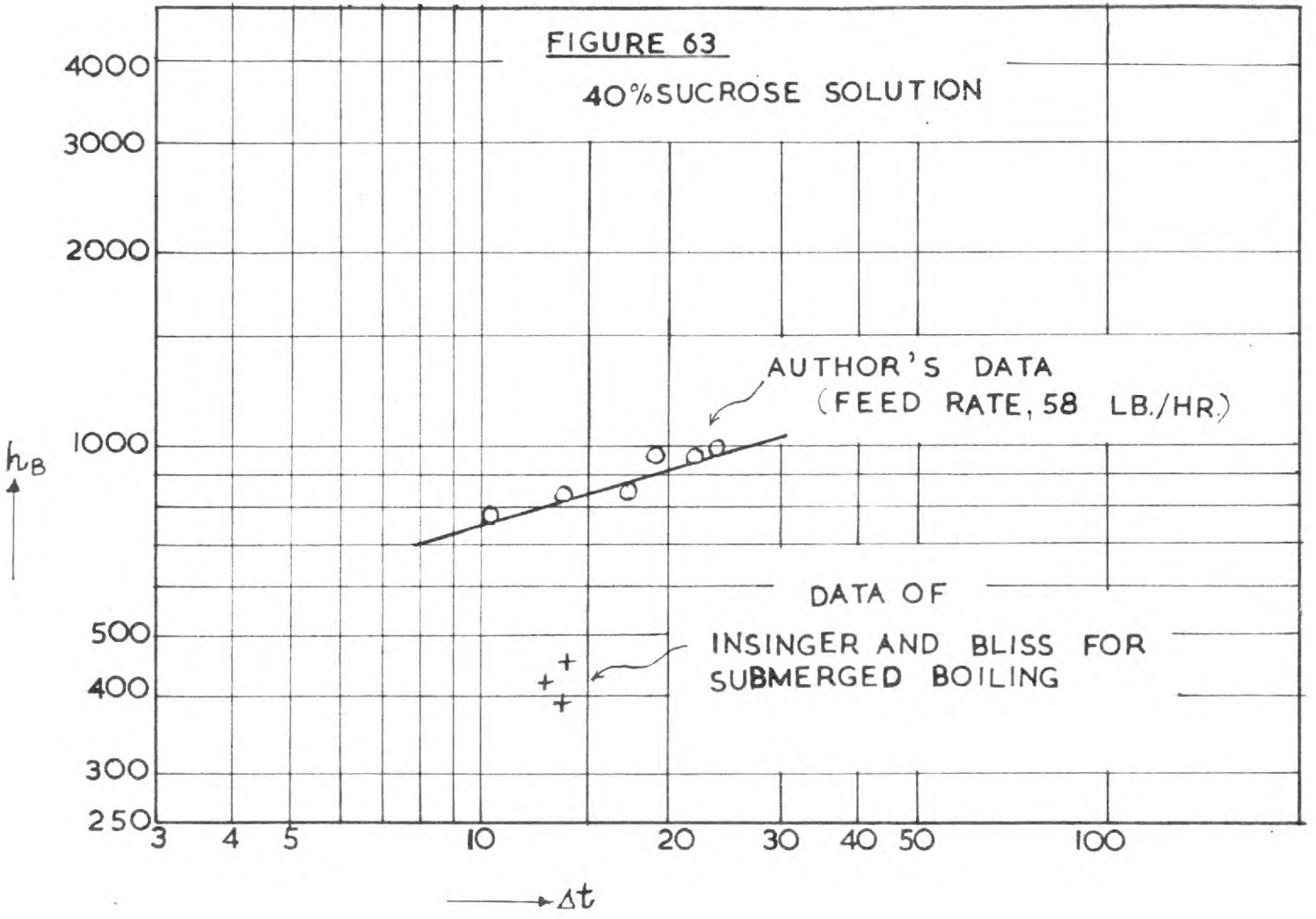
Comparison with Published Work and General Discussion.

We shall now discuss the results presented in the previous section, with those given in the literature, and at the same time try to emphasise the particular merits of this form of evaporator and its place in the chemical industry, in relation to other forms of evaporators.

In equation 15, we have shown that the boiling film coefficient (h_B) increases with the temperature difference across the film (Δt), whereas equation 2 , due to Badger (page 9) gives a negative index. In a very recent paper, Kirschbaum[14] gives results of his measurements of h_B in a long tube evaporator by the direct measurement of the tube wall temperature. His results, for water and for a surface active solution, have been plotted in Figure 60. For water, the data of Kirschbaum and the author agree very well and a single line might be drawn through all the points. This is encouraging, for the values of h_B have been calculated by different methods and the two equipments differ. With the surface active solution, Kirschbaum's data is a little higher, but the slope of the line is much the same as that given by the author in equation 15. The actual surface active agents were different and Kirschbaum's data is for a stronger solution of the active agent. Thus.


FIGURE 61
WATER
AUTHOR S DATA
(FEED RATE, 58 LB./HR)
DATA OF INSINGER AND
BLISS FOR SUBMERGED
BOILING
h_B
3000
2000
1000
500
400
300
200
100
2
3
4
5
10
20
30
40
50
Δt


FIGURE 62
ISOPROPANOL
2000
1000
500
400
300
200
100
h_B
2
3
4
5
10
20
30
40
50
100
Δt
AUTHOR'S DATA
(FEED RATE, 58 LB/HR)
DATA OF INSINGER AND BLISS
FOR SUBMERGED BOILING


FIGURE 63
40% SUCROSE SOLUTION
AUTHOR'S DATA
(FEED RATE, 58 LB./HR.)
DATA OF
INSINGER AND BLISS FOR
SUBMERGED BOILING
h_B
Δt
4000
3000
2000
1000
500
400
300
250
3
4
5
10
20
30
40
50
100

his data supports very well the relation of temperature difference derived from the present work.

Comparison with submerged boiling.

For submerged boiling, it has been shown by a number of workers that the film coefficient increases rapidly with the temperature difference according to the relation $h_B \propto \Delta t^{2.4}$. This would imply that the climbing film unit is somewhat inefficient compared with submerged boiling. Insinger and Bliss[15] have given results for submerged boiling for some of the liquids used in the present work and, in Figures 61, 62 and 63, their results are compared with the author's, for water, isopropyl alcohol and 40 per cent sucrose solutions. Their data were obtained at atmospheric pressure and the present results have been converted to this pressure by the use of equation 27. The points available for 40 per cent sucrose solution were few and for a very short range of temperature difference.

Table E.

Values of Boiling Film Coefficient (h_B).

Film temperature difference. (Δt) °F.	Climbing film evaporation.			Submerged boiling.		
	Water.	Isopropanol.	40 per cent sucrose solution.	Water.	Isopropanol.	40 per cent sucrose solution.
5	1050	220	-	150	Very low	-
8	1420	280	700	320	Very low	-
12	1850	350	800	950	170	400
16	2250	400	-	2000	400	-

The most striking feature of the comparison, as shown in Table E, is that at low values of temperature difference the climbing film unit gives much higher values of the heat transfer coefficient. For water, with a temperature difference of 5°F, the climbing film unit gives heat transfer coefficient seven times that for submerged boiling. For 12°F, the values of water, isopropyl alcohol and sucrose solution are nearly twice. However, with Δt higher than 16°F, they tend to be equal. Very high values of the heat transfer coefficient at very low temperature difference enables a high steam economy to be achieved with this type of evaporator, since, with a given temperature difference, more effects can be installed. It might be thought at this stage that the pressure drop, which is rather high in this type of evaporator, would offset the advantage gained. The pressure drop will be considerably less when working at low temperature difference, due to low vaporisation rates and further reduction in the pressure drop can be achieved by working at a higher temperature level.

It has been shown in the equation 19 that the boiling film coefficient varies as the feed rate to the power 0.25. In the literature, different views (Chapter 2) are expressed on the influence of feed rate. Brookes and Badger give U_B proportional to the feed rate, which is in agreement with

the present work.

If we look at the various relations given in Chapter 10, we see that it is only for the effect of temperature difference, feed rate and viscosity, that any reliable relation has been obtained. The influence of surface tension is not obvious from the available data, though the relation derived is in fair agreement with that of Badger[4]. It is thought that the considerable foam produced during boiling rather than decreased surface tension might be responsible for the increase in the boiling film coefficient. This belief is supported by the results of isopropanol, which having very low surface tnesion and not showing any foaming during boiling gave very low values of boiling film coefficients. It is also believed that very low surface tension, in the case of organic liquids, might have an unfavourable effect on heat transfer coefficients.

The temperature level does not appear to influence the results. From the derived relations, we may write the equation as

$$h_B = K\ (\Delta t^{0.60} . W_f^{0.25} . \mu^{-0.49}) \quad .. \quad .. \quad .. \quad (28)$$

where K will have different values for different liquids.

Finally, it will be useful to compare the results of this stainless steel unit with those of the glass unit. The exponents for the relations derived for the glass

unit are lower than for this unit. This arises from the high thermal resistance of the glass tube wall. The values of the boiling film coefficients for the former are about 35 per cent lower than those for the latter. This may be partly due to the smooth surface of the glass heating tube and partly due to the very low heat flux attained.

CHAPTER 12.

Summary.

Part I. The Long Tube Glass Evaporator.

Visual observations of the boiling action, with different liquids under a range of operating conditions, have been described and discussed. Experimental data for different liquids with boiling occurring over the whole length of the tube under a range of operating conditions have been obtained. It has been shown that:

(1) The boiling film coefficient increases slightly with the film temperature difference and with the feed rate, when the average temperature difference is maintained constant. For constant temperature of the heating water and fixed temperature at the top of the tube, h_B varies very little , while heat flux decreases with increasing feed;

(2) Reduction of the surface tension of water by the addition of 0.01 per cent Teepol, results in about a twofold increase in the boiling film coefficient. The values of heat flux increase very little, due to decrease in the effective temperature difference;

(3) A fourfold increase in the viscosity of the solution decreases the boiling film coefficient by about one half;

(4) The vapour velocity attained at the top of the tube is high with a maximum of 160 ft./sec., and so also is

the pressure drop along the tube. The pressure drops have been found to increase with the vapour velocity and also with the feed rate.

Part 2. The Long Tube Stainless Steel Evaporator.

The various factors studied have been correlated and it has been shown that:

(1) The boiling film coefficients increase with temperature difference and with the feed rate, when an average temperature difference is maintained constant. With constant temperature of the heating water and the outlet of the tube, the heat transfer coefficient remains nearly unaltered with increase in feed rate, but the heat flux decreases considerably with aqueous solutions and appreciably with isopropyl alcohol;

(2) There is no advantage in recirculation of the liquid when working at lower temperature levels;

(3) The degree of vaporisation has been shown to depend on the feed rate and temperature difference and no fall of heat transfer coefficient has been found with vaporisation as high as 75 per cent;

(4) The reduction in the surface tension of water by about 50 per cent by the addition of Teepol results in about a threefold increase in the boiling film coefficient. The heat flux decreases considerably, due to reduction in

the effective temperature difference;

(5) Increase in the viscosity of the solution decreases the boiling film coefficient regularly. Boiling of highly viscous solutions results in comparatively lower exponents for the temperature difference;

(6) Increase in the temperature level increases the boiling film coefficient. The increase is found to be due to decrease in the viscosity with temperature;

(7) The pressure drop along the tube is high, due to very high vapour velocity at the top of the tube, with a maximum of about 600 ft./sec. Increase in the pressure drop with vapour velocity and feed rate have been found higher than in the glass unit. The pressure drops with Teepol solutions are found to be two to three times those for water under identical conditions;

(8) The data have been compared with published work. The values of the heat transfer coefficients agree very well with the recent data of Kirschbaum. The data when compared with that from submerged boiling experiments shows that this evaporator gives very high values of boiling film coefficient at low temperature differences.

Appendix A. Nomenclature.

A = surface area of heating tube, sq.ft.

C = specific heat of liquid, B.T.U./lb./°F.

E = evaporation, lbs./hr.

$E\rho$ = per cent vaporisation.

h_1 = annulus film coefficient, B.T.U./hr./sq.ft./°F.

h_B = boiling film coefficient, B.T.U./hr./sq.ft./°F.

K = thermal conductivity of liquid, B.T.U./hr./sq.ft./°F/ft.

Kw = thermal conductivity of tube wall, B.T.U./hr./sq.ft./°F./ft.

$\Delta\rho$ = pressure drop, mms. of Hg.

$\frac{Q}{A}$ = heat flux, B.T.U./hr./sq.ft.

T = average temperature of boiling liquid, °F.

ΔT = average overall temperature difference, °F.

Δt = boiling film temperature difference, °F.

$t\Delta$ = temperature drop of boiling liquid along tube length, °F.

U = overall heat transfer coefficient from hot water in the annulus to cold water in the evaporator tube, B.T.U./hr./sq.ft./°F.

U_B = overall boiling coefficient, B.T.U./hr./sq.ft./°F.

V = velocity of cold water in the evaporator tube, ft./sec.

V_1 = vapour velocity at the top of the tube, ft./sec.

W_f = feed rate to the evaporator tube, lbs./hr.

x_w = thickness of the tube wall, ft.

μ = viscosity of the liquid, lbs./ft./hr.

σ = surface tension of the liquid, dynes/cm.

$\frac{hD}{K}$ = Nusselt number (dimensionless).

$\frac{DG}{\mu}$ = Reynolds number (dimensionless).

$\frac{C\mu}{K}$ = Prandtl number (dimensionless).

D = equivalent diameter of annulus, ft.
G = mass velocity of water in the annulus, lbs./hr./sq.ft.
h = annulus film coefficient, B.T.U./hr./sq.ft./°F.

} For equation 5A.

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