GAS PHASE EFFICIENCIES

ON

DISTILLATION TRAYS

BY

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PREFACE

The work presented in this thesis was undertaken in an effort to add to the understanding of the variables which affect the mass transfer process occuring on a distillation tray. Three vapor-liquid systems were studied. The majority of the experimentation was conducted on the air-water system. A technique for locating the froth height effective for mass transfer was developed.

I wish to thank Professor Robert N. Maddox whose guidance and understanding were an inspiration. I appreciate the helpful suggestions given by Professors J. B. West, C. L. Nickolls, and F. E. Jewett. I would also like to thank Professor F. A. Graybill for his advice concerning the statistical analysis of the data. Special thanks are due Mr. E. E. McCroskey for his aid in the construction of the experimental apparatus.

I appreciate the financial assistance given by the Texas Eastman Company through their fellowship grant. Their generosity helped make this work possible.

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CHAPTER I

THE PROBLEM

Statement of the Problem

The distillation process occupies a prominent position in the chemical and petroleum industries today. The dependence of these industries on distillation for the separation and purification of their products elevates research in this field to a position of real importance.

Research in the field of distillation can be divided into several rather specific areas of study. A few such areas are vapor-liquid equilibria, tray efficiencies, and basic design techniques. Increasing application of vacuum distillation and the use of more expensive materials of construction have emphasized the need for a better understanding of the factors which affect the efficiency of a distillation tray. If it is total pressure drop which is critical, as is the case in vacuum distillation, the maximum number of trays allowable is known. The design engineer must have reliable data concerning tray efficiencies in order to determine if the allowable number of trays will perform the desired separation.

The actual number of trays must be accurately determined before the capital investment for such equipment can be calculated. Since the actual number of trays is a function of tray efficiencies, expensive materials of construction magnify the importance of accurate data concerning tray efficiencies.

During the past five years, studies have been in progress at the University of Delaware, the University of Michigan and North Carolina State College concerning tray efficiencies(2). One problem which was recognized early in these studies involved an accurate means of determining the gas-liquid contact time.

In order to calculate the contact time it is necessary to have reliable data concerning the froth height. Visual determination of the froth height proved inadequate in these studies, but a satisfactory method was not available.

The knowledge that a means of accurately determining froth heights would be a significant contribution to the study of the transfer process occuring on distillation trays provided the impetus for this study. The problem was to develop and evaluate a technique capable of accurately determining the froth height effective for mass transfer.

Hot-wire anemometry was chosen as the technique to be used for this study. Prior work(1) had shown that froth heights could be determined with the hot wire anemometer. It was believed that the froth heights thus determined were the effective froth heights. Data concerning mass transfer and froth heights were needed to test this hypothesis.

Limitations of the Study

The major portion of the experimental data concerns the study of the air-water system. The concentration of effort on this system was influenced by two factors. First, the gas and liquid were readily available, non-toxic, and caused no fire hazard. Secondly, the compositions of the vapor entering and leaving the column were easily determined without the aid of elaborate instrumentation.

Runs were made for the air-carbon tetrachloride and air-chlorobenzene systems. Data for these systems were needed to verify the fact that the froth height, as determined by the hot-wire anemometer, was the effective froth height for mass transfer.

The probe was centered in the column. It covered an area approximately equal to one-half the cross-section of the column. This section was assumed to be representative of the froth bed at any particular elevation above the tray.

Clarification of Terms

The word froth is used to denote the mixture of gas and liquid which is present above the distillation tray. It includes only the region where neither phase is readily distinguishable. Hence, the density of the froth will always be greater than the gas density and less than the liquid density.

Froth height denotes the distance that the interface between the froth and the gas phase is above the tray. The froth height data were recorded in centimeters, but have been converted to inches for ease in evaluation.

F factor or F value is a measure of the gas velocity with a density factor included. It has been accepted as a useful way to describe gas rates in a distillation tower. The F value, for any given velocity, is the product of the linear gas velocity multiplied by the square root of the density of the gas. The F factor, thus calculated, represents the square root of the pressure head equal to the superficial gas velocity. All quantities have units of feet, pounds or seconds.

Clear liquid holdup is used to describe the amount of liquid on the

tray. For use in the equations it refers to the height of the liquid above the tray. The volume of liquid may be calculated by multiplying the height by the cross-sectional area of the column.

CHAPTER II

REVIEW OF LITERATURE

Historical Background

In an effort to increase the available information concerning the design of distillation columns, the American Institute of Chemical Engineers initiated a research program on plate efficiencies. This program, started in 1952, is being conducted at the University of Delaware, the University of Michigan and North Carolina State College. The investigation of plate efficiencies has amplified the problem of determining the vapor residence time. This residence time is in turn dependent on the froth height.

Visual determination of froth heights has been tried by a number of investigators, but the results have been far from satisfactory. Gerster, et al.,(2) discuss the problems encountered when utilizing this technique. It is logical that a better method could be devised for determining the froth height.

The hot-wire anemometer has properties which make it suitable for locating froth heights. Hot-wire anemometry was utilized as early as 1921 by Griffiths(7) for determining the liquid level in a fuel tank. From that time to the present, the hot-wire anemometer, often called a resistance thermometer, has found many applications. A few such uses have been the measurement of temperature, flow rate, and turbulence of gas streams.

Tray Efficiencies

For the design of distillation columns the engineer must have information concerning the overall column efficiency. This efficiency factor allows him to predict the required number of trays after the number of theoretical trays or equilibrium stages has been determined.

Several investigators have developed correlations which would enable one to predict the overall column efficiency from the physical properties of the feed stream. Although the correlations presented have looked promising, they have not found wide acceptance among design engineers.

Drickamer and Bradford(8) published a correlation in which the column efficiency was plotted as a function of the molal average viscosity of the feed. The viscosity was evaluated at the average tower temperature. Unfortunately, it was found that the correlation was only applicable to towers whose dimensions were approximately the same as those on which the data were taken. The correlation was also limited to fractionations involving feed streams of similar composition to those studied.

In an attempt to remedy the inadequacies of Drickamer and Bradford's correlation, O'Connell(10) suggested that relative volatility of a key component be multiplied by the molal average viscosity of the feed.

The product thus obtained was then used to correlate the overall column efficiency. This provided some improvement, but still was inadequate to predict the efficiency of many towers with a reasonable degree of accuracy.

From a theoretical point of view it seems preferable to study the factors which affect the efficiency of an individual distillation tray. Once one gains an understanding of the operation of a single tray it is then possible to expand this knowledge to include the complete tower.

By utilizing the relationships between plate efficiencies and the number of transfer units Gerster(2) has been able to derive some very simple and useful equations. If one writes a differential material balance around an incremental volume of froth one obtains the following relationship.

$$d(Gy) = K_{og}(adB)(Py^*-Py) \tag{1}$$

assuming G_M and y* are constant this equation reduces to:

$$K_{og}\ aPB/G = -\ln(1-E_{og}) = N_{og} \tag{2}$$

For the case where an inert carrier gas is present the relationship becomes:

$$K_{og}\ aPB/G = \left[1/(y^*-1)\right] \ln(1-y_1)(1-E_{og})/(1-y_2) = N_{og} \tag{3}$$

Noting that G can be expressed as $u\rho_M$ and replacing ρ_M with its equivalent from the ideal gas law, equation 2 reduces to:

$$N_{og} = K_{og}\ aRT\ t_g \tag{4}$$

or at constant temperature:

$$N_{og} = K'_{og}\ a\ t_g \tag{5}$$

The same derivations can be made for the individual phases in which case equations 5 then becomes:

$$N_g = k'_g\ a\ t_g \tag{6}$$

The subscripts g and og refer to "point" properties where the required assumptions are reasonably valid. When the resistance to mass transfer rests largely in the gas phase N_g is essentially equal to N_{og}.

To this point only gas phase resistances have been considered. Gerster(3) has shown that the total resistance to mass transfer can be broken down into its gas and liquid phase components as follows:

$$\frac{1}{K_{og}a} = \frac{m}{k_l a} + \frac{1}{k_g a} \qquad (7)$$

and:

$$\frac{1}{N_{og}} = \frac{mG}{LN_l} + \frac{1}{N_g} \qquad (8)$$

The ability to determine the total resistance to mass transfer from knowledge concerning the individual phase resistances is very valuable. Knowledge of the relationship given by equation 7 makes it feasible for the investigator to examine the resistances separately and thus eliminate many complexities which have hampered mass transfer studies.

Referring to equation 6, it is easily seen that if N_g is plotted as a function of t_g the resulting curve has a slope of $k'_g a$. Gerster, et al., (3) published such a correlation for the absorption of ammonia from air by water. Their data indicate that $k'_g a$ is a constant for vapor rates above three feet-per-second and independent of contact time, t_g. The value of $k'_g a$ was found to be 17.5 seconds^{-1}.

Williams, et al.,(2) conducting similar studies at the University of Michigan on ammonia absorption verified the constancy of the $k'_g a$ term but the value of $k'_g a$ was reported as 22 sec^{-1}.

The efficiency of a distillation tray has been determined as being a function of the Schmidt Number, $\mu/\rho D$, (2). Therefore, it is reasonable to expect that the value of $k'_g a$ determined for the absorption of ammonia from air and the humidification of air to be the same under identical conditions since the values of the Schmidt Numbers for water vapor and ammonia diffusing through air are equal. West, et al.,(16) have published data concerning the humidification of air. The type of distillation tray used was a perforated plate. Analysis of their data yields an average value for $k'_g a$ of 26.5 sec^{-1}.

In each of these investigations the froth heights were determined visually. Considering the violent instability of the froth-gas interface, it seems likely that the discrepancies among the values of $k'_g a$ could be attributed to the inaccuracy of the froth height measurements.

Williams, et al.,(2) have conducted studies to determine the manner in which the physical properties of the system affect the mass transfer rate. Mass transfer coefficients for gaseous diffusion have been well correlated as a function of the Schmidt Number raised to some power. Therefore, they assumed that the properties affecting $k'_g a$ were the gas-phase molecular diffusivity, the gas viscosity and the gas density. It was subsequently determined that the following relation exists between the mass transfer coefficient and the physical properties of the system.

$$k'_g a(\text{system 2}) = k'_g a(\text{system 1}) \frac{(\mu \rho^{0.13} D^{0.5})_{\text{system 2}}}{(\mu \rho^{0.13} D^{0.5})_{\text{system 1}}} \quad (9)$$

From the data collected it was not possible to evaluate the effect of viscosity.

Froth Height

In the study of tray efficiencies it is important that data concerning froth heights be accurate and reproducible. From equation 6 it is seen that the gas residence time, t_g, must be known in order to evaluate $k'_g a$. In the absence of data concerning the point densities or stratification of the froth a constant froth density is generally assumed. Based on this assumption t_g is given by:

$$t_g = (H_f - L_c)/12u \qquad (10)$$

It is possible through pressure measurements to estimate L_c. The determination of the froth height, H_f, is much more complex. To date, no one has developed and evaluated an instrument capable of determining the froth height satisfactorily. Albright(1) investigated the use of the hot-wire anemometer for the location of froth heights. Although his data were taken at extremely low vapor velocities the technique appeared quite promising. Data were not taken concerning mass transfer so its application to this problem is only speculation.

Crozier(5) developed a scheme based on light absorption by the froth. The instrumentation was quite elaborate, however the data presented show little improvement over the visual method. The light absorption technique does appear very useful for determining the density of the froth at any point.

The importance of accurate data concerning froth heights suggests that a generalized correlation be developed to relate the froth height and the independent variables which affect it. Such a correlation would make it possible to determine the residence time by a simple direct calculation.

Patton(11) has developed a correlation for froth height as a function of F factor and clear liquid holdup. This equation had the form:

$$H_f = \alpha + \beta L_c + \gamma F + \delta L_c F \qquad (11)$$

Although the constants obtained were only applicable with in the range of the data, the model appeared to be satisfactory.

Assuming that this model is correct it then follows that a suitable correlation can be developed for residence time. If equation 10 is substituted into equation 9 and replacing u by its equivalent $F/\sqrt{\rho}$ one obtained:

$$t_g = \left[\alpha/F + (\beta - 1)L_c/F + \gamma + \delta L_c\right] \sqrt{\rho} \qquad (12)$$

It is apparent that a correlation of this type would be most useful in the design of distillation trays, for maximum efficiency or optimum operation.

CHAPTER III

METHOD AND PROCEDURE

Apparatus

Column

The column was constructed from pyrex glass pipe having an inside diameter of six inches. The column was mounted on a platform made of three-sixteenth inch steel plate. The base of the column was supported by legs made of two inch angle iron and was positioned approximately two feet above the floor to allow the required piping to be installed. The base plate was equipped with connections for a drain line, a pressure tap and an air inlet. The air inlet was made of one inch pipe.

A section of glass pipe two feet long was attached to the base plate by means of a mounting flange. This section was used to obtain uniform flow distribution of the gas before it reached the tray being studied. A baffle plate containing twenty holes, one-half inch in diameter, was mounted twelve inches above the base plate to aid in obtaining uniform flow distribution over the cross-section of the column.

A section of glass pipe three feet long was mounted on top of the bottom section. The tray being used was installed between the two sections of pipe. The top portion of the column allowed the froth to be studied visually and provided a space where the liquid could be

disentrained from the vapor. Only at the higher velocities were droplets of liquid carried to the top of the column.

The top of the column was open to the atmosphere since all data concerning vapor rates and compositions were taken below this point. For experiments involving a liquid other than water a ventilating hood was placed immediately above the column to exhaust the noxious vapors from the laboratory.

The anemometer probe, wet and dry bulb thermocouples, and a vapor sampling tube were mounted in the top section of the column.

Trays

Two trays were used in this study. The first tray was made of one-eighth inch stainless steel plate. The holes drilled were one-eighth inch in diameter. This plate contained one hundred fourteen holes on 1.15 centimeter triangular pitch. The area of the holes represents approximately five percent of the cross-sectional area of the column.

The second tray was a modification of the tray previously described. Every other row of holes in the first tray were sealed off to obtain the second tray design. The resulting tray contained fifty-eight holes whose total area was about two and one-half percent of the cross-sectional area of the column.

Probe

The anemometer probe was constructed from a piece of fine platinum wire 0.005 inches in diameter and 35 inches in length. The wire was supported by three lucite struts which were connected to the end of a 36 inch glass tube. The electrical leads to the probe were threaded inside the glass tube. The top of the glass tube was attached to a metal arm which allowed probe to be secured at any desired position in the column. The location of the end of the metal arm outside the column

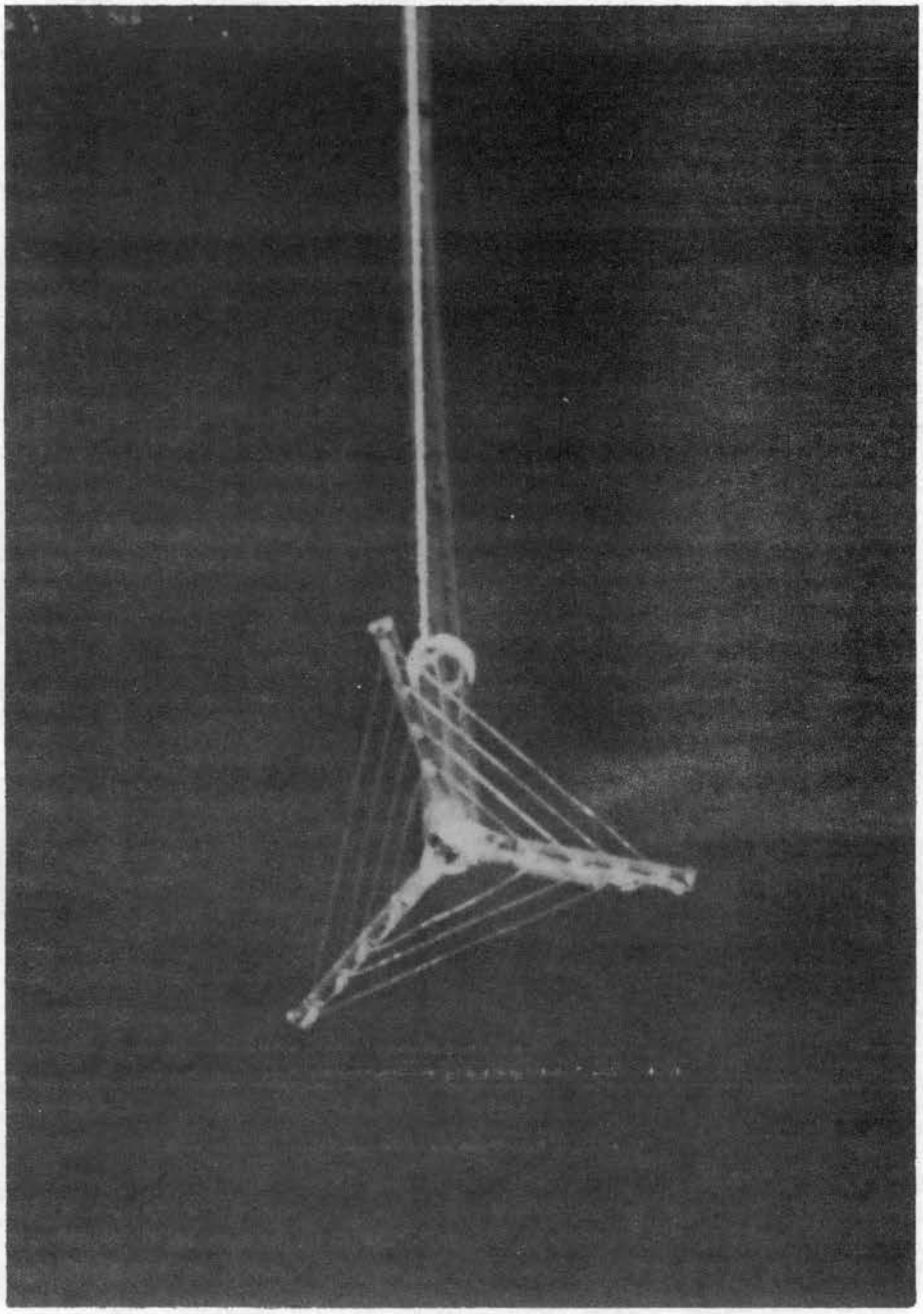

FIGURE 1.
Hot Wire Anemometer Probe.

had a constant relation to the position of the probe inside the column. This allowed the position of the metal arm to be used as an accurate indication of the location of the probe. A photograph of the probe appears in Figure 1.

Auxiliaries

1. A Spencer Turbo-Compressor, No. 26674, was used to supply the air required for this investigation. The blower was driven by a three horsepower General Electric 220/440 induction motor, model number 5K224B235.

2. The air flowing to the column was measured by using a venturi meter. The venturi had a three inch diameter inlet and a throat diameter of one and one-half inches.

3. An inclined manometer was constructed to measure the differential pressure across the venturi. The manometer tube had a slope of 0.50 and was filled with distilled water.

   A U-tube manometer filled with mercury was installed to indicate the pressure upstream from the venturi meter.

   A U-tube manometer was used to measure the pressure drop across the perforated tray. This manometer was filled with distilled water. One leg of the manometer was connected to the pressure tap below the tray. The other leg was connected to a point two inches below the top of the column to allow the pressure measurements to be free from any errors introduced by the suction of the ventilating hood.

4. A rotameter was used in preliminary work to meter a gas sample that was drawn off between the venturi and the column for the purpose of measuring the wet and dry bulb temperature

of the air. The quantity of air thus sampled was measured by a Fischer-Porter model B4N-25-A rotameter. The float used was a glass ball.

5. Three chromel-constantan thermocouples were built to effect the determination of the temperature of the gas stream at various positions in the column. One couple measured the temperature of the air immediately below the tray. The other two were used to measure the wet and dry bulb temperatures of the vapor above the tray.

The wet bulb thermocouple was wrapped with thread taken from a standard wet bulb thermometer mantle. This covering was thoroughly saturated with distilled water before the temperature of the couple was noted. Preliminary studies indicated that the wet bulb temperature of the air did not change as it passed through the column.

A chromel-constantan thermocouple was used as the cold junction. This couple was immersed in a mixture of distilled water and melting ice contained in a vacuum bottle.

6. A Leeds and Northrup Company Student Potentiometer No. 244726, was used to effect the necessary electrical measurements and adjustments. The fixed resistances, used as legs in the Wheatstone Bridge, were each 45 ohms. The slide wire contained 1000 divisions, each representing 0.01 ohm resistance or a total of 10 ohms. A drawing of the electrical circuit appears in Figure 2.

7. The third leg of the Wheatstone Bridge consisted of a 12 ohm rheostat manufactured by the Central Scientific Company.

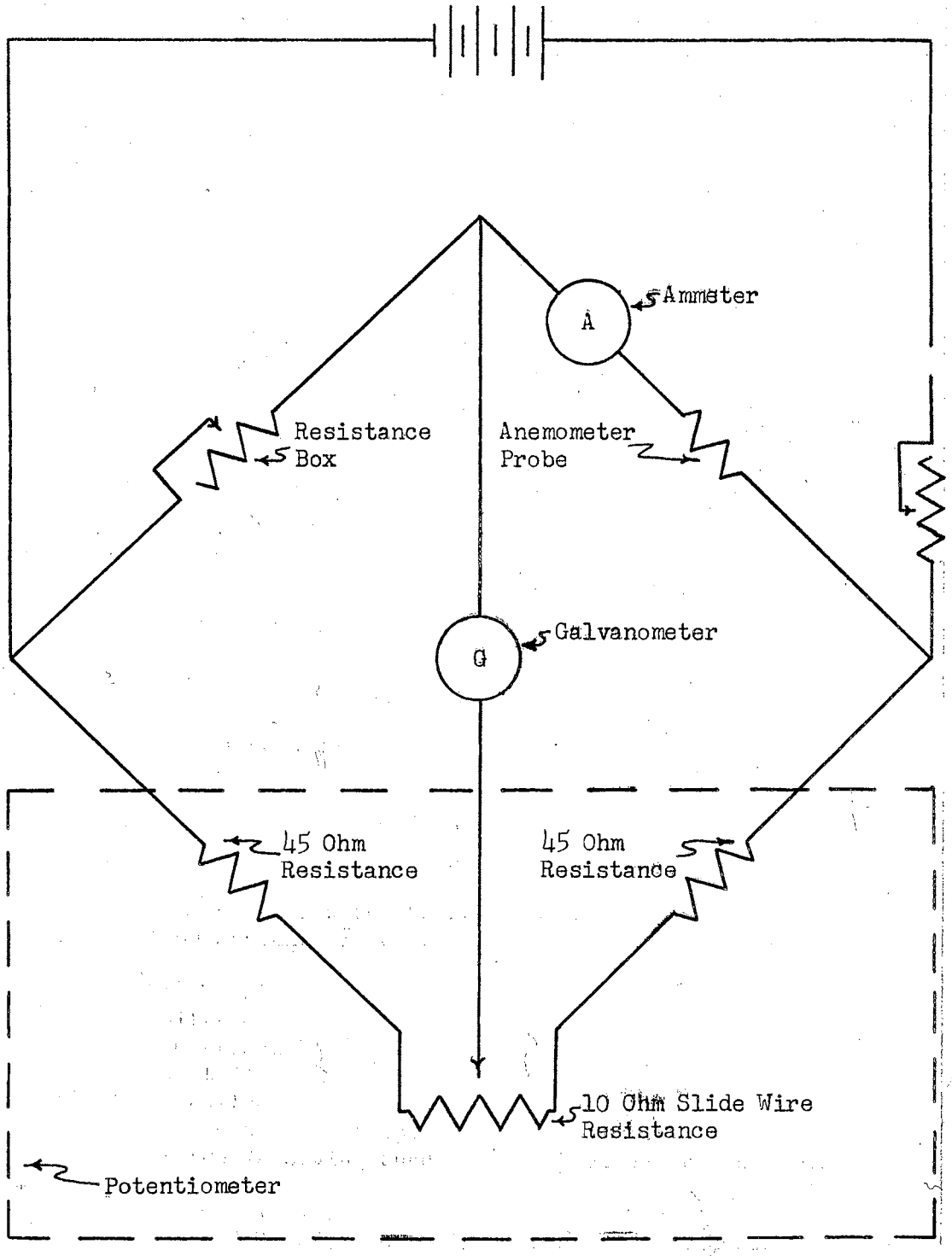

FIGURE 2

Electrical Circuit Diagram

8. A Leeds and Northrup Company model 2420-0 reflected beam galvanometer was used in conjunction with the potentiometer to indicate when the circuits were in balance.

9. A battery eliminator, model BE-5, made by the Heath Company supplied the desired D.C. power for the operation of the anemometer probe.

10. Two 1½ volt batteries were used to provide the required potential for the thermocouple measurements. These were No. 6 Eveready batteries manufactured by the National Carbon Company.

11. The current flowing through the probe was measured by a Weston model 301 D.C. ammeter.

12. A 3" 1MM Fisher mercury thermometer having a range of 0 to 230 F° was used to measure the air temperature upstream from the venturi.

13. A portion of the vapor above the tray was drawn off through the sampling line by means of a vacuum pump. A Cenco Hyvac Pump, No. B-835, manufactured by Central Scientific Company was used for this purpose.

Experimental Procedure

An experimental run consisted of the collection of all pertinent data for a given clear liquid level and one air velocity. To start a run, the blower was turned on and allowed to operate until the air was being delivered at a constant temperature. The desired potential was placed across the Wheatstone Bridge so that the electrical system would also reach equilibrium. Approximately thirty minutes were required to attain equilibrium.

After this time elapsed a predetermined quantity of liquid was measured in a 1000 ml. graduate. The air rate to the column was adjusted to the desired value and the dry plate pressure drop was recorded. The liquid, previously measured, was poured onto the tray and the air rate was again adjusted to the desired value. The wet tray pressure drop was recorded and served as a datum for the adjustment of the liquid make up flow rate.

While the froth was reaching an equilibrium temperature the make up liquid rate was adjusted to maintain the wet plate pressure drop at the recorded value.

A traverse of the froth with the anemometer probe was then made in the following manner:

> The probe was positioned just above the tray and its resistance determined by means of the Wheatstone Bridge. The probe was raised in one centimeter increments and its resistance noted at each position. The current supplied to the probe was maintained at a preselected value for the entire traverse.

The composition of the vapor entering and leaving the column was then determined. The dry bulb temperature of the air below and above the tray was measured by means of thermocouples. When the liquid on the tray was water the wet bulb of the exit air stream was measured with a wet bulb thermocouple. This provided the required data concerning the composition of the vapor.

Additional data recorded during an experimental run were the atmospheric pressure, and the temperature and static pressure upstream from the venturi meter.

A photograph of the experimental apparatus is presented in Figure 3.

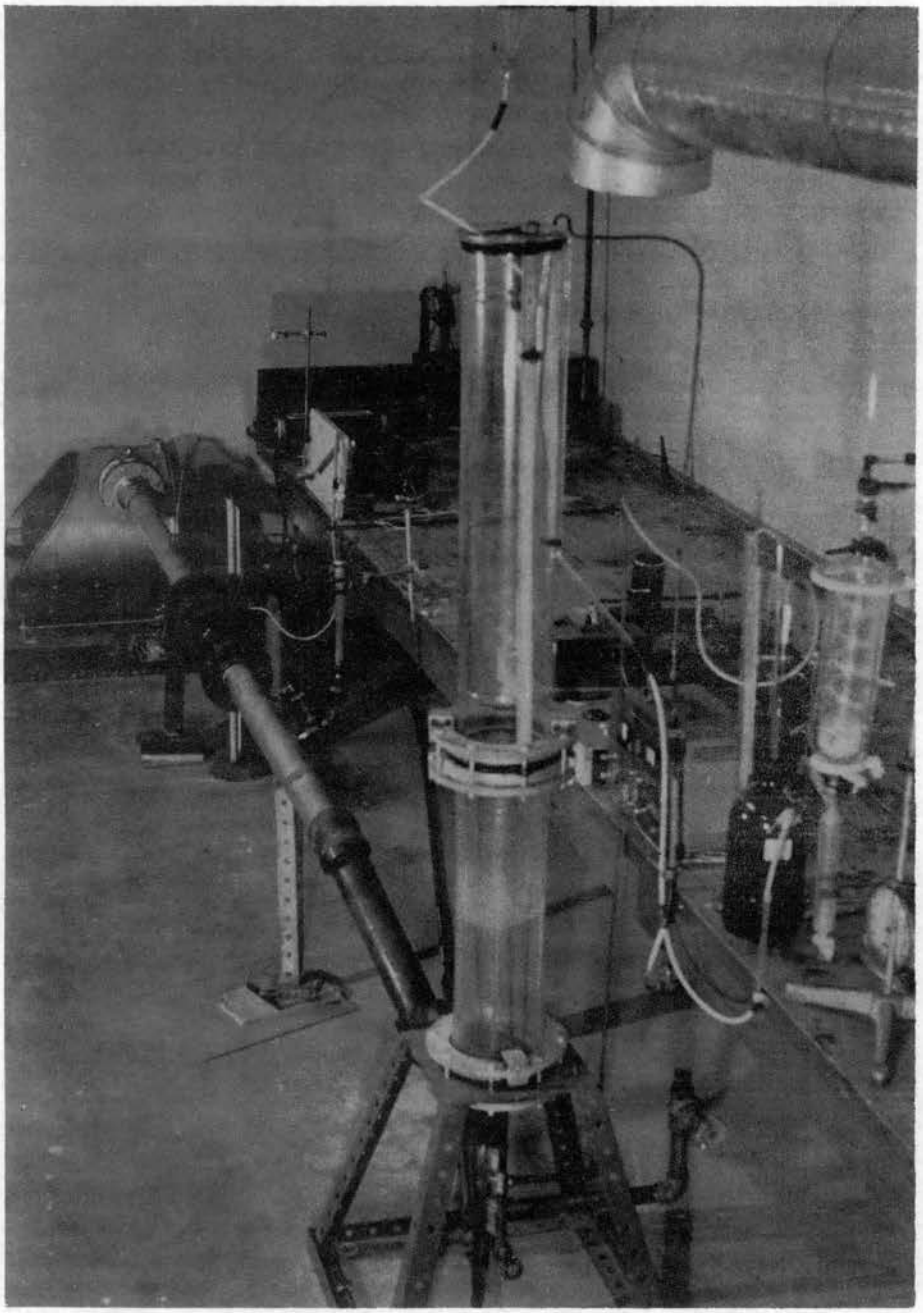

FIGURE 3.
Experimental Apparatus.

CHAPTER IV

RESULTS

Hot-Wire Anemometry

The use of glass pipe in the test column allowed the froth to be studied visually and with photographic techniques. Preliminary studies indicated that above an F factor of 0.80 the interface between the froth and the vapor was poorly defined and a reliable estimate of the froth height could not be obtained visually. Photographs, representative of the froth for high and low vapor rates are presented in Figures 4 and 6. The froth-gas interface in Figure 4 is well defined. This is characteristic of vapor rates below an F factor of 0.54. In contrast, a well defined interface is not discernable in Figure 6. This condition is characteristic of vapor rates above an F factor of 0.80. It is apparent that visual observations of the froth height when the F factor exceeds 0.80 are not reliable.

The use of a hot-wire anemometer provides a marked improvement over the visual technique for locating the froth-gas interface. The anemometer traverses for the froths shown in Figures 4 and 6 are presented in Figures 5 and 7. In both instances a sharp break in the curve is apparent. This rapid change in the slope of the curve indicates the froth height, i.e., the point at which the probe emerges from the froth. The resistance of the probe was constant as long as the probe was submerged in the froth which accounts for the vertical portion of the curve that extends from

the interface to the floor of the tray.

The precision of the probe is excellent. As many as four traverses were made during a single run. In all cases, the froth-gas interface determined for each replication was identical. It should be noted that the resistance of the probe was determined at one centimeter intervals. This interval establishes the accuracy of the data as being plus or minus 0.5 centimeters. This accuracy should be considered in conjunction with the precision when defining the reliability of the probe.

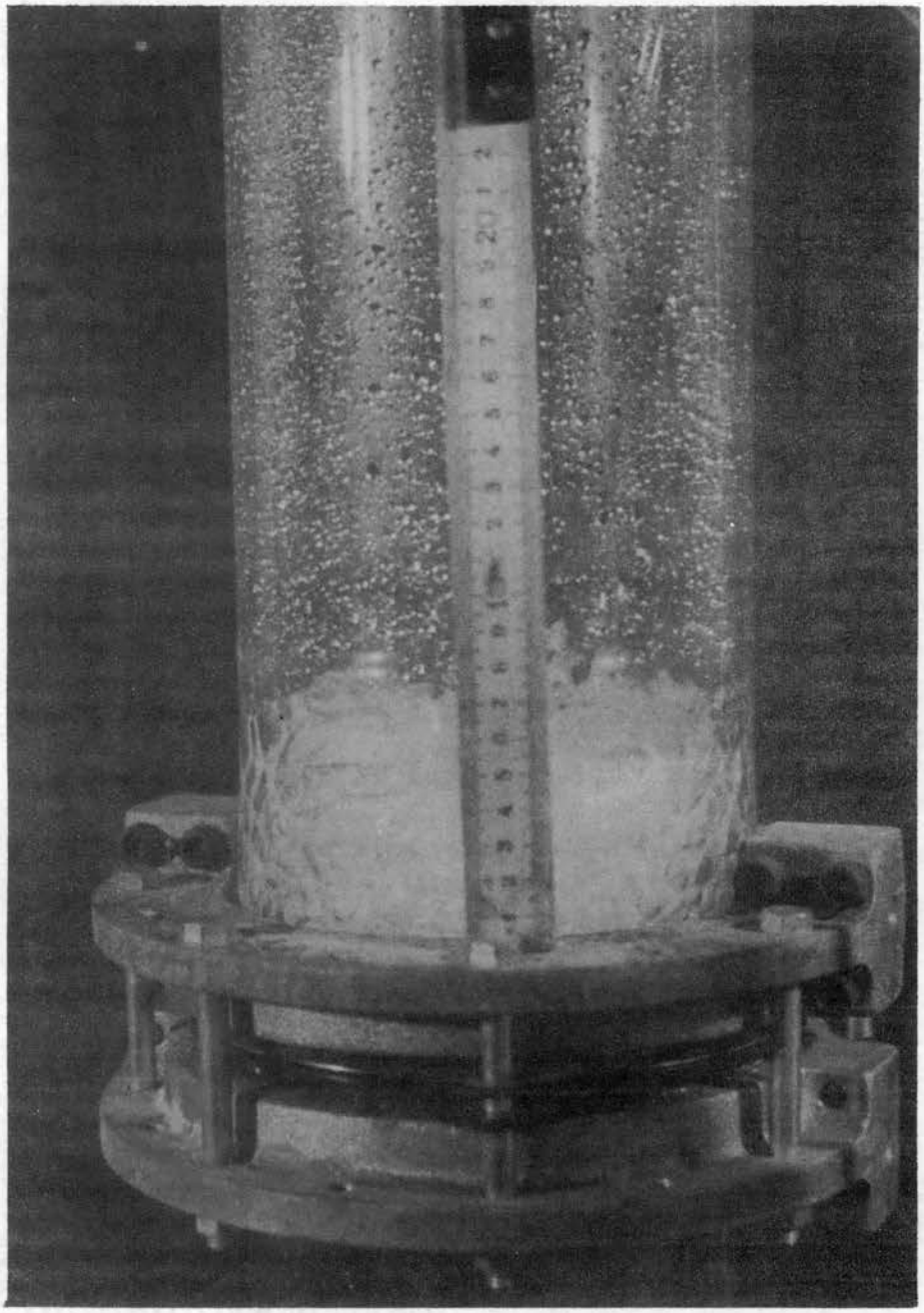

FIGURE 4.
Froth Formation at Low Vapor Rate
Run No. 125 F = 0.535 L_c = 1.0 in.

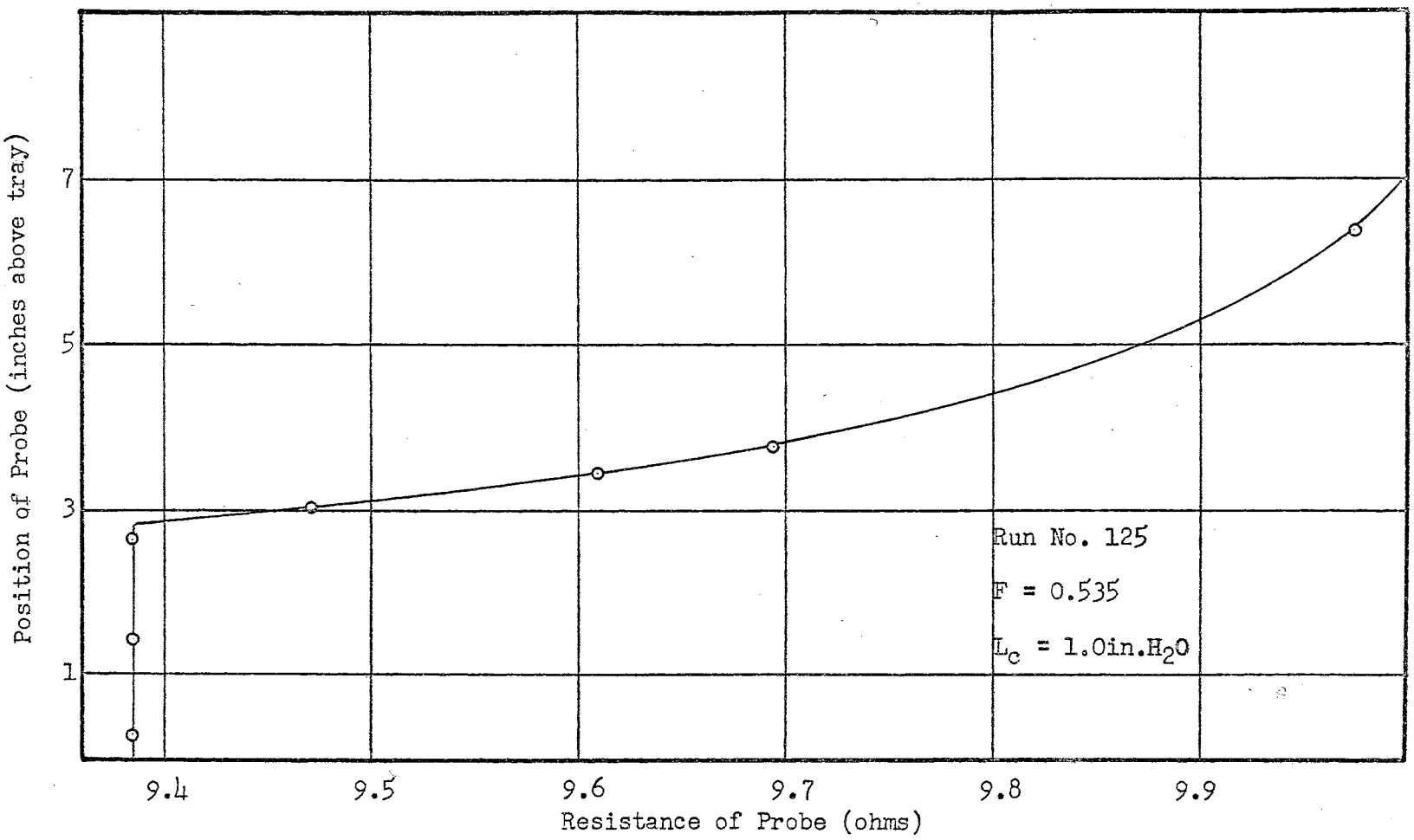

FIGURE 5

Anemometer Traverse for Low Vapor Rate

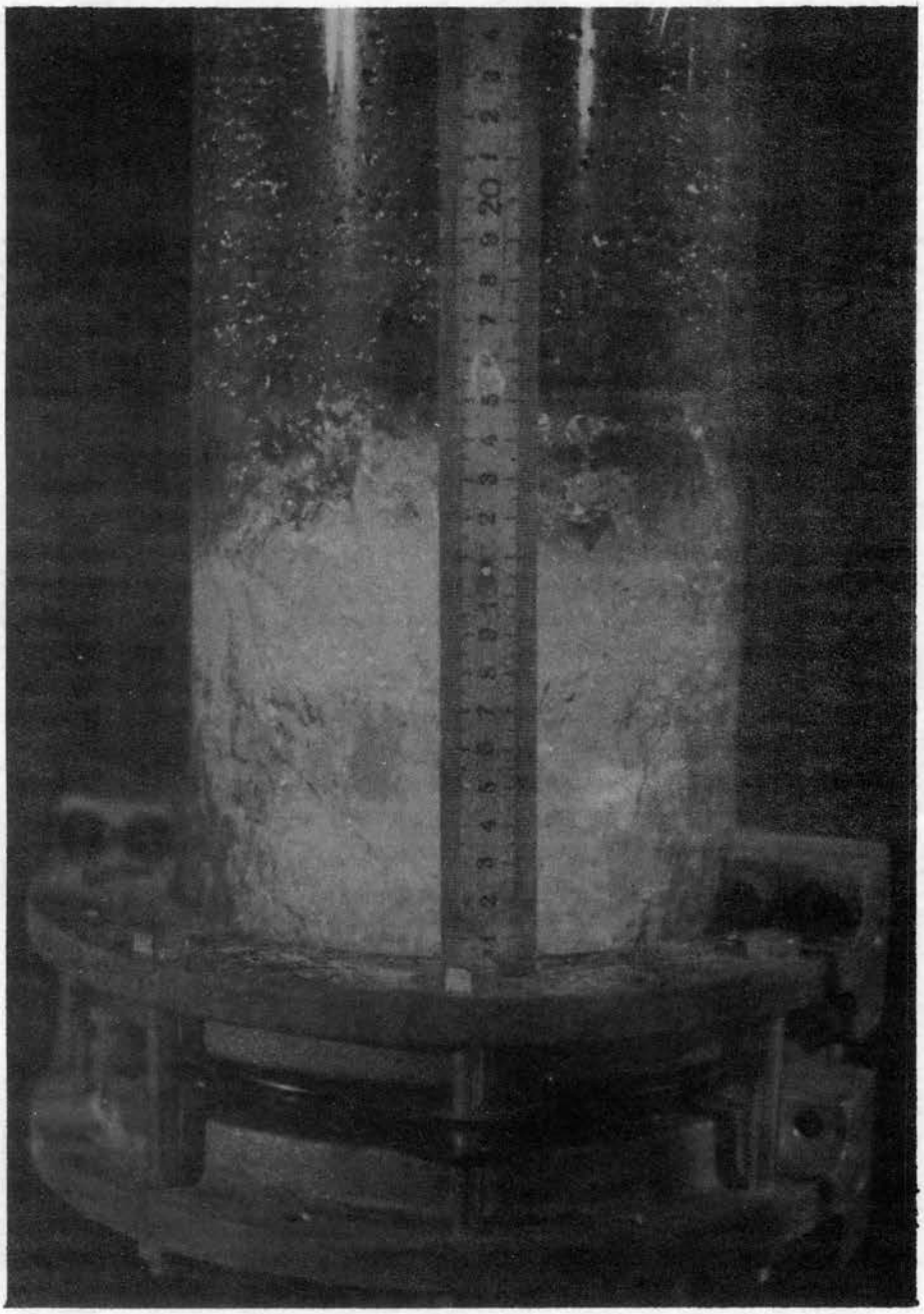

FIGURE 6.
Froth Formation at High Vapor Rate
Run No. 103 $F = 1.31$ $L_c = 1.8$ in.

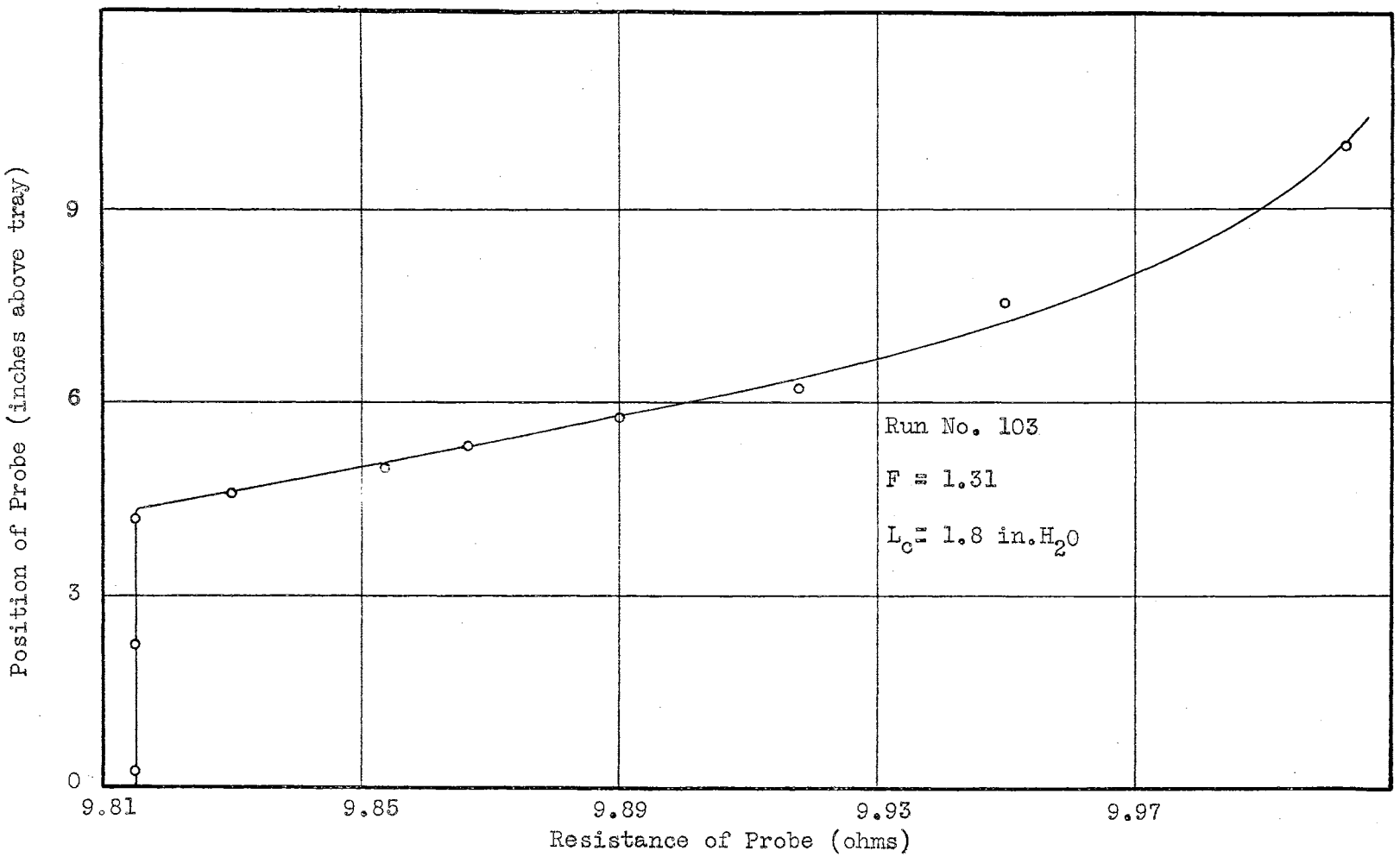

FIGURE 7

Anemometer Traverse for High Vapor Rate

The Air-Water System

It has been previously shown that accurate data concerning mass transfer for one vapor-liquid system must be available before one can proceed to make a reliable prediction of other systems. The data for the air-water system are intended to serve as the basis for such calculations. This study included data covering the commercially feasible range of the variables of gas velocity and clear liquid holdup within the operating limits imposed by the experimental apparatus.

Eighteen different combinations of F factor and clear liquid holdup were investigated. Replications were made for ten of these combinations. The values of tg and Ng were computed from the experimental data and are plotted in Figure 8. The data are well correlated by two straight lines. The first representing data taken at a vapor velocity of two feet-per-second and the second line correlating data taken at or above three feet-per-second.

The tray efficiencies, necessary for the determination of Ng, were calculated from data taken with wet and dry bulb thermocouples. The accuracy of this method was checked by a simple heat balance around the tray and was found to be quite satisfactory. The gas contact time, tg, was obtained after making the assumption that the density of the froth was constant between the tray and the froth gas interface. An assumption as to the density of the froth was necessary as the probe readings did not reflect point to point density changes in the froth.

Figure 9 shows the relationship between froth height and F factor for Runs 100 through 138. These curves, with the clear liquid level as the parameter, are not to be interpreted as generalized correlations. They are applicable to the tray design employed for these runs and are

limited by the range of variables studied. The assumption was made that the curves would have an intercept of L_c at F equal to zero. At this point u is equal to zero.

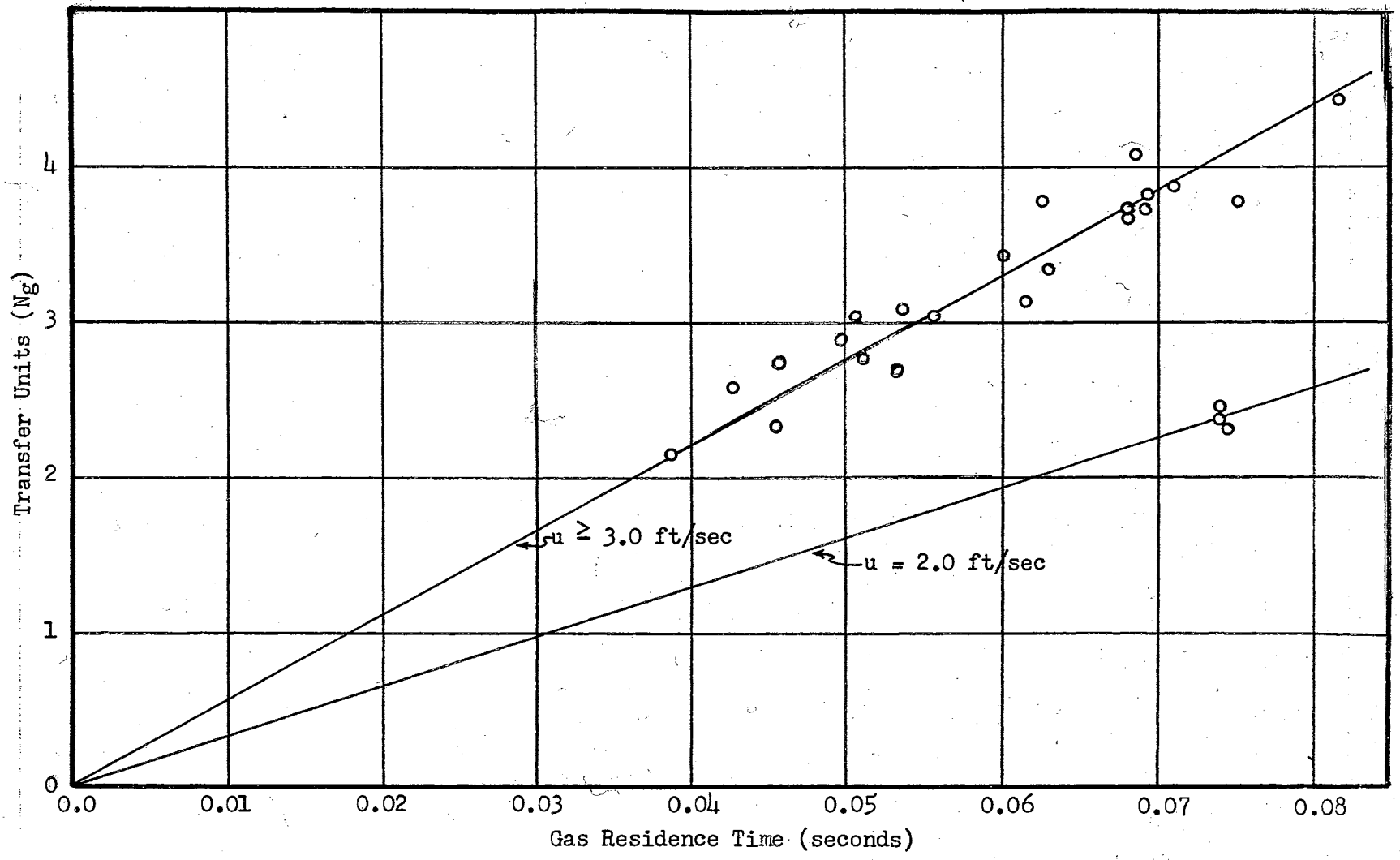

FIGURE 8

Transfer Units as a Function of Gas Residence Time for Low Slot Velocities

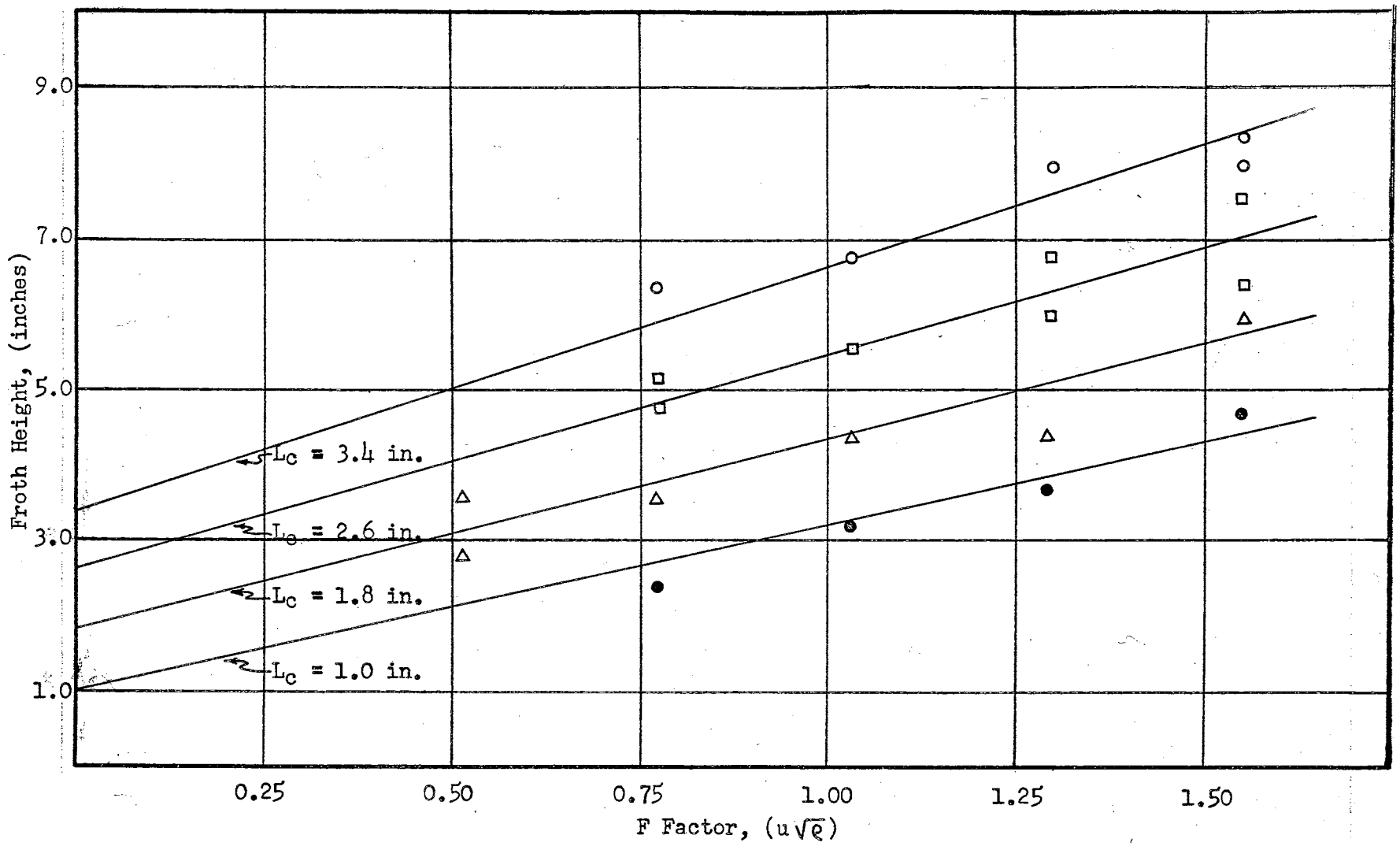

FIGURE 9

Froth Height as a Function of F Factor

Effect of Slot Velocity

In an effort to identify the effect that tray design has on the mass transfer process, the tray used for Runs 100 through 138 was modified. Fifty-six of the original one hundred fourteen holes were sealed. The remaining holes were no longer on a triangular pitch nor were they equally spaced. Six runs were made at conditions studied in the previous runs. The only difference being that in these studies the slot velocities were approximately twice the values they were for the same superficial velocities in the Runs 100 through 138. The high slot velocity runs are identified by the run numbers 200 through 238.

The values of Ng and tg were computed from the experimental data in the same manner as for the previous runs. The resulting values are plotted in Figure 10.

TABLE I

COMPARISON OF FROTH HEIGHTS AT HIGH AND LOW SLOT VELOCITIES

L_c in. H_2O	F	Froth Heights (inches) Series 100	Series 200
1.0	.787	2.40	2.79
1.8	.787	3.58	3.62
1.8	1.05	4.37	4.37
2.6	1.05	5.56	5.55
2.6	.787	4.92	5.20
3.4	.787	6.34	6.38

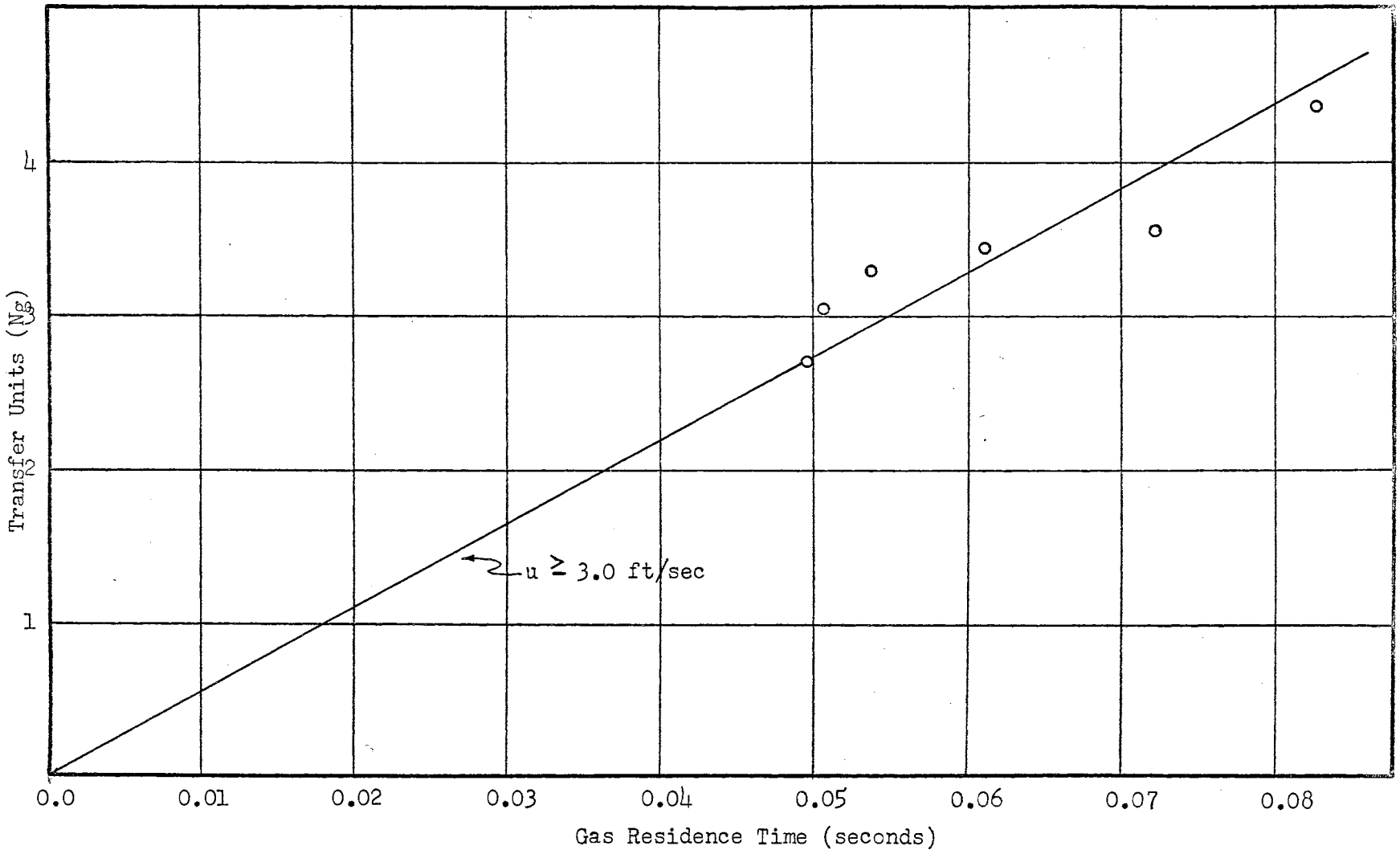

FIGURE 10

Transfer Units as a Function of Gas Residence Time for High Slot Velocities

Froth heights for high and low slot velocities are summarized in Table I. In the table, series 100 refers to the lower slot velocity studies while series 200 indicates the studies at the higher slot velocities. The data indicate that F and L_c have considerable influence on the froth height. The effect of slot velocity is almost negligible. Excessive entrainment and unstable operation limited the high slot velocity studies to F factors equal to or less than 1.05.

Other Liquid Systems

Runs were made using liquids other than water to evaluate the effect the liquid properties have on gas phase efficiencies. Two liquids, carbon tetrachloride and chlorobenzene, were studied. The values of $k'_g a$ for these systems were found to be 29.3 $sec.^{-1}$ and 27.6 $sec.^{-1}$ respectively.

The carbon tetrachloride was difficult to work with due to its comparatively high vapor pressure. Unlike the water and chlorobenzene systems, the froth-gas interface for the carbon tetrachloride system was well defined. This fact allowed the froth height to be determined visually as the duration of the run was not sufficient for a anemometer traverse to be made. The composition of the vapor leaving the tray was determined by material balance.

The chlorobenzene presented no unusual operational difficulties. The composition of the vapor leaving the tray was determined by a heat balance. The use of a heat balance to determine composition was tested with data from the air-water studies and was found to be satisfactory.

CHAPTER V

INTERPRETATION OF RESULTS

Summary and Conclusions

The anemometer traverses which are presented graphically in Figures 5 and 7 illustrate the applicability of the hot-wire anemometer for the determination of froth heights. The performance of the anemometer was evaluated over the range of F factors normally used in commercial design work. The performance was found to be satisfactory at each F factor studied.

The accuracy of the froth height data is a function of the precision of the instrumentation and the size of the increments which constitute a traverse. The increment used in this study was one centimeter. With this size increment, the reproductibility of the froth height measurement for a given run was found to be 100 percent. Utilizing this information it is possible to place limits on the accuracy of the data. Since the froth height can be established as being within a one centimeter increment, a reasonable assumption is that the froth height is located at the center of the increment. This assumption was made in the analysis of the data. The accuracy of the froth height data can then be represented as being plus or minus 0.50 centimeters. At the lower froth heights the maximum error would be approximately eight percent. As the froth height increases this error will be substantially reduced. It is believed that the actual error attributable to the accuracy of

the anemometer technique is about forty percent of the maximum value. A discussion of the actual error is presented in Appendix D.

In the study of gas phase efficiencies, the validity of the theoretical relationship,

$$N_g = k'_g a t_g \,, \tag{6}$$

must be assumed or substantiated by experimental data. It is generally accepted that the number of transfer units is some function of the contact time. To facilitate the use of equation 6 it is necessary to establish the relationship between $k'_g a$ and t_g. A statistical approach is useful in proving that $k'_g a$ is constant for all values of t_g.

The data for Runs 100 through 138 were correlated by the least squares technique using as a model the equation:

$$N_g = k'_g a t_g + \alpha \tag{13}$$

With this model the intercept at $t_g = 0$ is α. The value of thus obtained was 0.243. To determine if α was significantly different from zero, the hypothesis, $\alpha = 0$, was tested. The hypothesis could not be rejected, therefore α may be assumed to be equal to zero.

By making this assumption equation 13 now reduces to equation 6. Using equation 6 as the model the data were again correlated by the least squares technique. Placing limits on $k'_g a$ at the ninety-five percent confidence level, one can state that the true value of $k'_g a$ lies between 53.4 and 56.2.

This same type of analysis was applied to the data for the runs made at the higher slot velocities. The results were very similar to those obtained from the data at the lower slot velocities. The hypothesis that α was equal to zero could not be rejected, therefore the data were correlated by a least squares fit using equation 6 as

the model. Again placing limits on $k'_g a$ at the ninety-five percent confidence level it was found that the value of $k'_g a$ was between 49.4 and 59.0. A summary of the statistical computations appears in Appendix D.

Thus far, the statistical estimates of $k'_g a$ for both the high and low slot velocities have been calculated. The next step is to determine if there is a significant difference between the two values. For this purpose the hypothesis was that $k'_g a$ for the high slot velocities is equal to $k'_g a$ for the low slot velocities. This hypothesis could not be rejected at the ninety-five percent confidence level. It is therefore concluded that the geometry of the plate design has no significant effect of the value of $k'_g a$.

Analysis of the data has shown that $k'_g a$ for a given vapor-liquid system is independent of the clear liquid holdup, the plate design, and the F factor when the value of F exceeds 0.80. The value of these conclusions becomes more significant if they can be used to predict the mass transfer characteristics of other vapor-liquid systems. Assuming that such predictions are exact, $k'_g a$ for any system can be estimated with the same degree of accuracy that is associated with the value of $k'_g a$ determined in this study for the air-water system.

Prior studies in mass transfer have established a relationship between the values of the $k'_g a$ term for different systems. This relationship is given by equation 9. The predicted values of $k'_g a$ for the air-carbon tetrachloride and the air-chlorobenzene systems were calculated by means of this equation. These values, together with the experimental values, are presented in Table II.

TABLE II

MASS TRANSFER COEFFICIENTS FOR NON-AQUEOUS SYSTEMS

System	$k'_g a$(cal.)	$k'_g a$(exp.)
Air-carbon tetrachloride	27.3	29.3
Air-chlorobenzene	28.7	27.6

The term $k'_g a$ is a function of the effective froth height. It was calculated from the froth height which was determined experimentally. The close agreement between the calculated and the experimental values is indicative that the froth height measured by the hot-wire anemometer is the effective mass transfer froth height.

Implication of the Study

The results obtained in this study show that a major problem in the study of tray efficiencies has been resolved. By using the technique developed here, the gas phase resistance to mass transfer can be studied conveniently and with much improved accuracy.

The data collected for other systems illustrate the usefulness of the results obtained in the air-water studies. In most instances the mass transfer characteristics of vapor-liquid systems can be successfully predicted with the desired accuracy. Thus, it is possible to avoid a large amount of expensive and time consuming experimentation.

It is feasible to assume that in the near future our knowledge concerning mass transfer on distillation trays will be as complete as the present knowledge of mass transfer in wetted-wall towers. This new technique of using the hot-wire anemometer to locate froth heights should stimulate additional research in this field. As more data become available, it is reasonable to predict that a major advance in the understanding

of tray efficiencies is in order.

Suggestions for Future Study

In this work, the hot-wire anemometer was used only for the determination of the effective froth height. Consideration of the basic principles which influence the operation of this instrument leads to the belief that the hot-wire anemometer could be utilized for the study of point froth densities. It is also likely that the anemometer could be used to investigate the degree of liquid mixing which occurs on a distillation tray. Both the density and the mixing studies would be a real contribution in the field of distillation.

In this study an attempt has been made to improve the understanding of gas phase efficiencies. The results indicate the potential of the experimental technique, but, admittedly, are only a step in the right direction. Additional work on other vapor-liquid systems is needed before this new information concerning mass transfer will be widely accepted.

Experimental data at conditions of temperature and pressure that are significantly different from those previously studied are important. These data are needed to verify the relationship or $k'_g a$ to both temperature and gas density. The data presented here are not sufficient for this purpose.

The correlation of froth height with F factor indicates that a linear relationship exists between these two variables. This linearity was verified only for the air-water system. It is reasonable to suspect that other vapor-liquid systems would exhibit such linearity. Additional studies to determine the froth height as a function of the

physical properties of the system would be extremely useful. Such a correlation would supply the additional information necessary for the prediction of gas phase efficiencies.

When gas phase efficiencies can be predicted from the physical properites of the system and the operational variables, a valuable contribution toward the understanding of mass transfer will have been made. It is felt that this study represents significant progress in achieving this goal.

NOMENCLATURE

a = interfacial area on distillation tray, sq. ft./cu.ft. of gas holdup.

$\bar{a}$ = interfacial area on distillation tray, sq. ft./cu. ft. of liquid holdup on the tray.

B = gas holdup in froth, cu. ft./sq. ft. of bubbling area.

D = diffusivity, sq. ft./hr.

E = efficiency, fraction.

F = F Factor, $u\sqrt{\rho}$, (ft./sec.)(lb./cu. ft.)$^{.5}$.

G = gas rate, lb. moles/(sq. ft. of bubbling area)(sec.).

H_f = froth height, inches above the tray.

k_g = mass transfer coefficient for gas phase, lb. moles/(sec.)(sq. ft.)(atm.).

k_l = mass transfer coefficient for liquid phase, lb. moles/(sec.)(sq. ft.)(unit concentration).

K_{og} = over-all gas-phase mass transfer coefficient, lb. moles/(sq. ft.)(sec.)(atm.).

L = liquid rate, lb. moles/(sec.)(sq. ft. of tray bubbling area).

L_c = clear liquid holdup, inches above the tray.

m = slope of vapor-liquid equilibrium curve.

N = number of transfer units.

P = total pressure, atm.

R = ideal gas law constant, (atm.)(cu. ft.)/(lb. moles)(^{o}R).

t = contact time, seconds.

T = absolute temperature, ^{o}R.

u = superficial gas velocity based on tray bubbling area, ft./sec.

Greek Letters

α = coefficient for empirical equations.

β = coefficient for empirical equations.

γ = coefficient for empirical equations.

σ = coefficient for empirical equations.

μ = viscosity, lb./(ft.)(sec.).

ρ = density, lb./cu. ft.

ρ_m = molal gas density, lb. moles/cu. ft.

Subscripts

c = clear liquid.

g = gas phase.

l = liquid phase.

og = over-all point based on gas concentration.

ol = over-all point based on liquid concentration.

wb = wet bulb.

Superscripts

* = equilibrium value.

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APPENDIX A

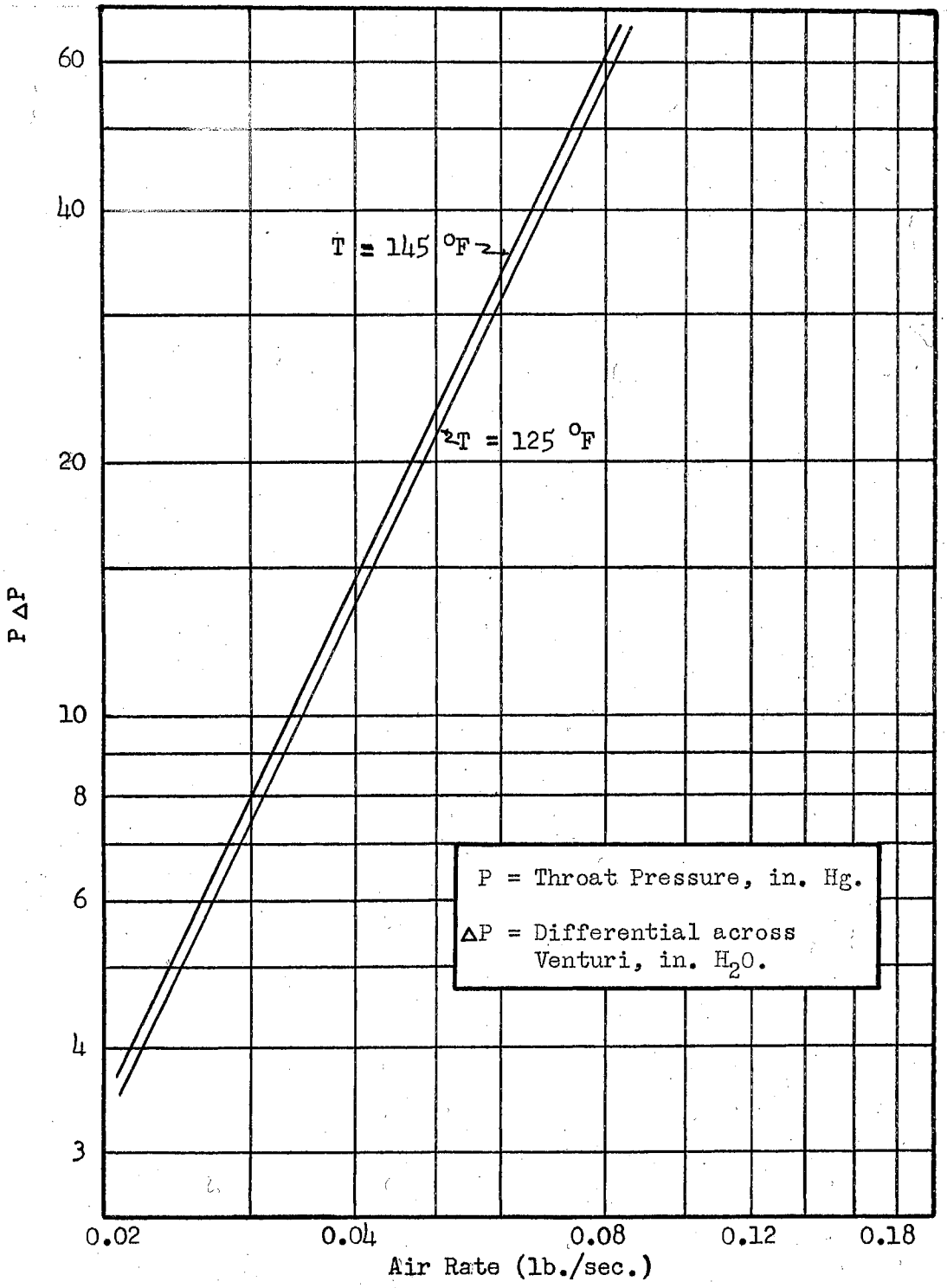

FIGURE 11

Venturi Meter Calibration Curve

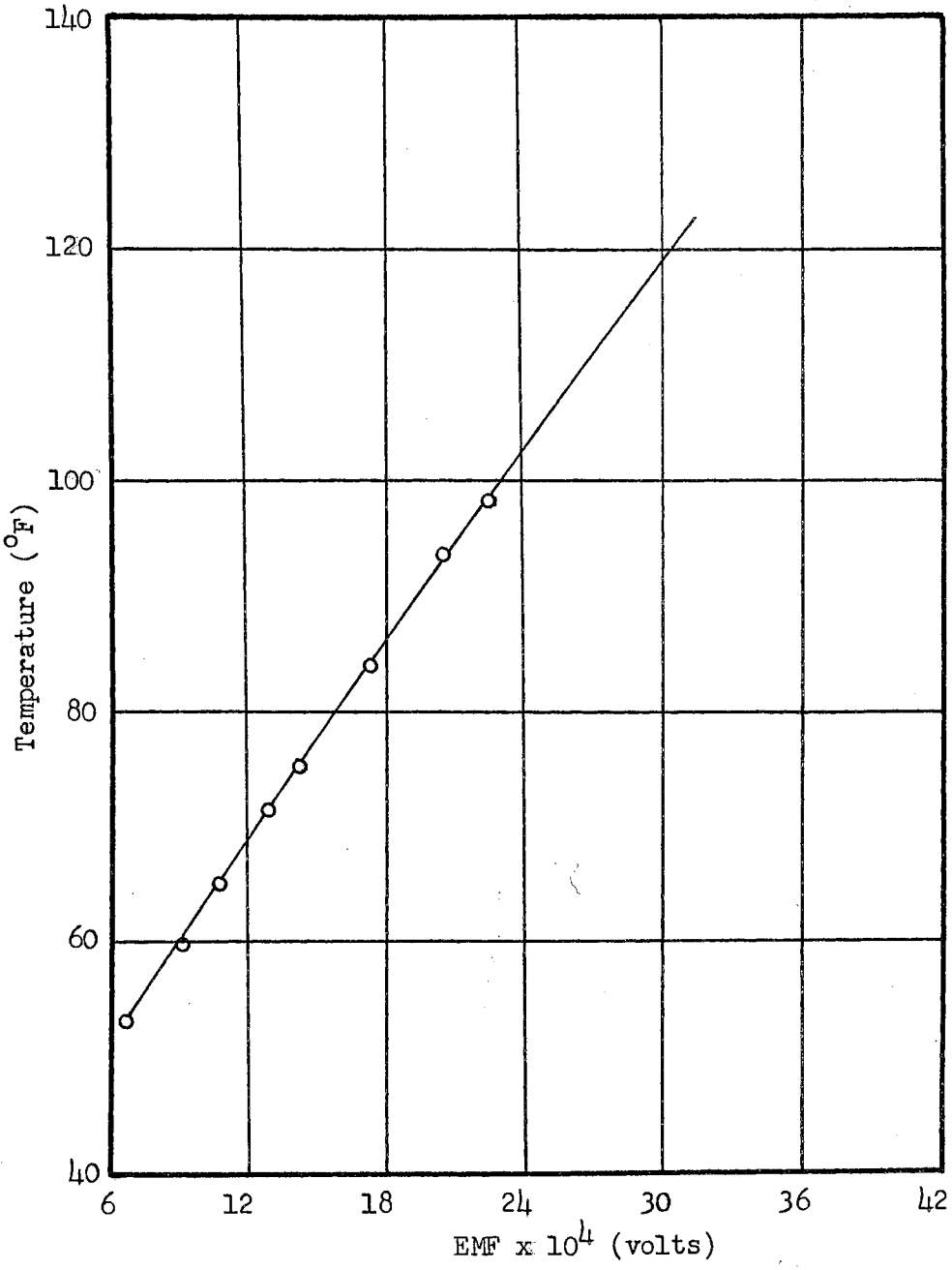

FIGURE 12

Thermocouple, T_1, Calibration Curve

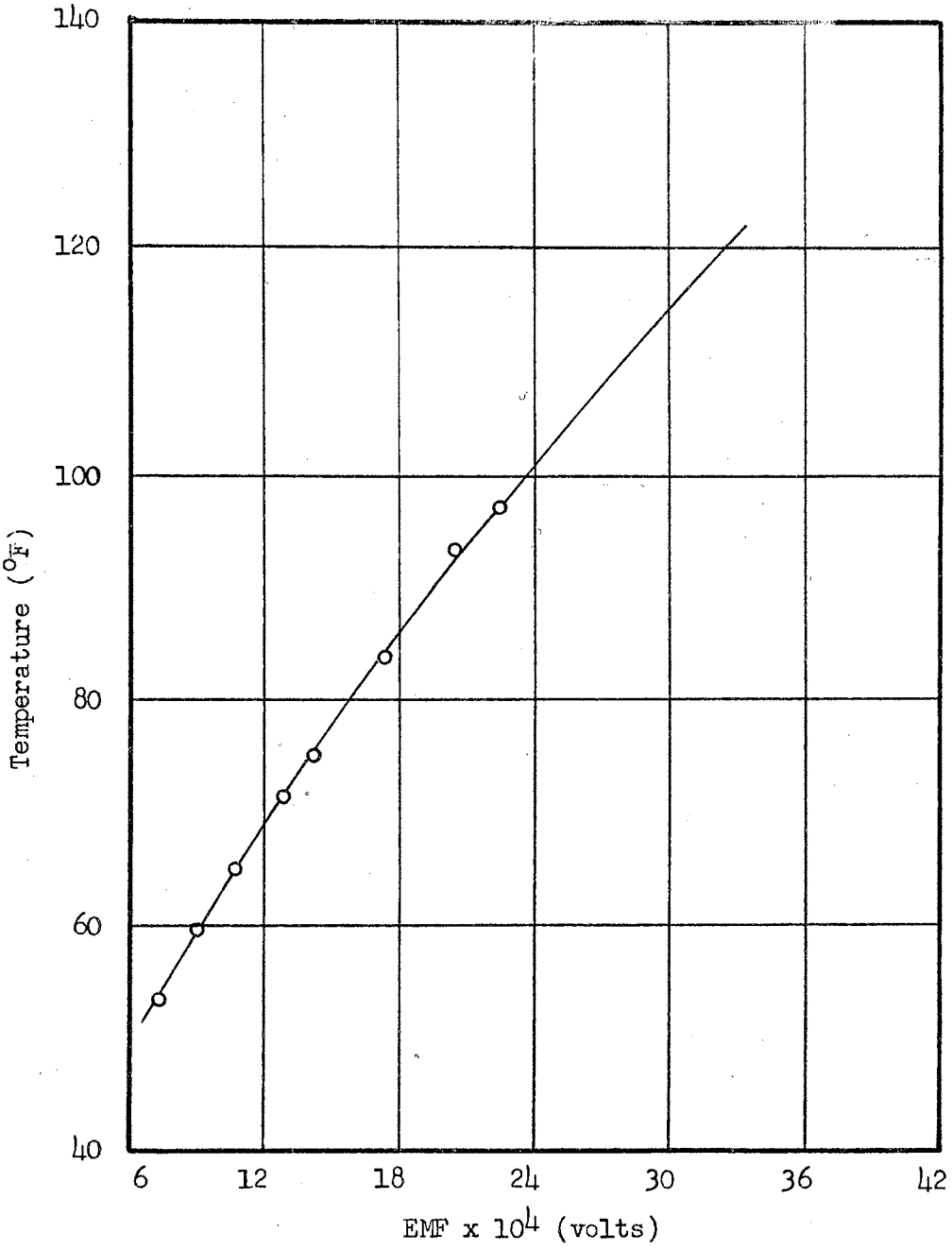

FIGURE 13

Thermocouple, T_2, Calibration Curve

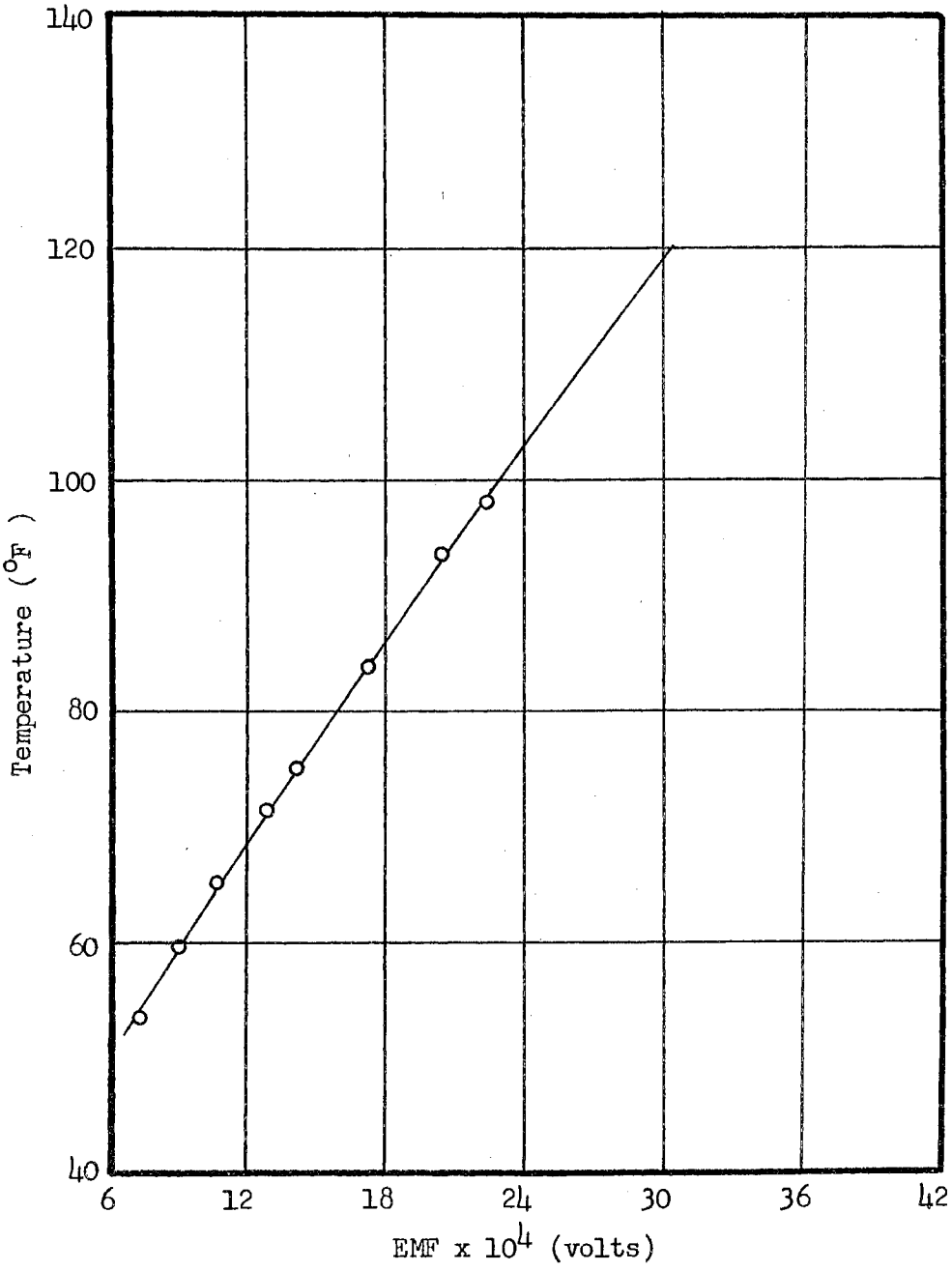

FIGURE 14

Thermocouple, T_3, Calibration Curve

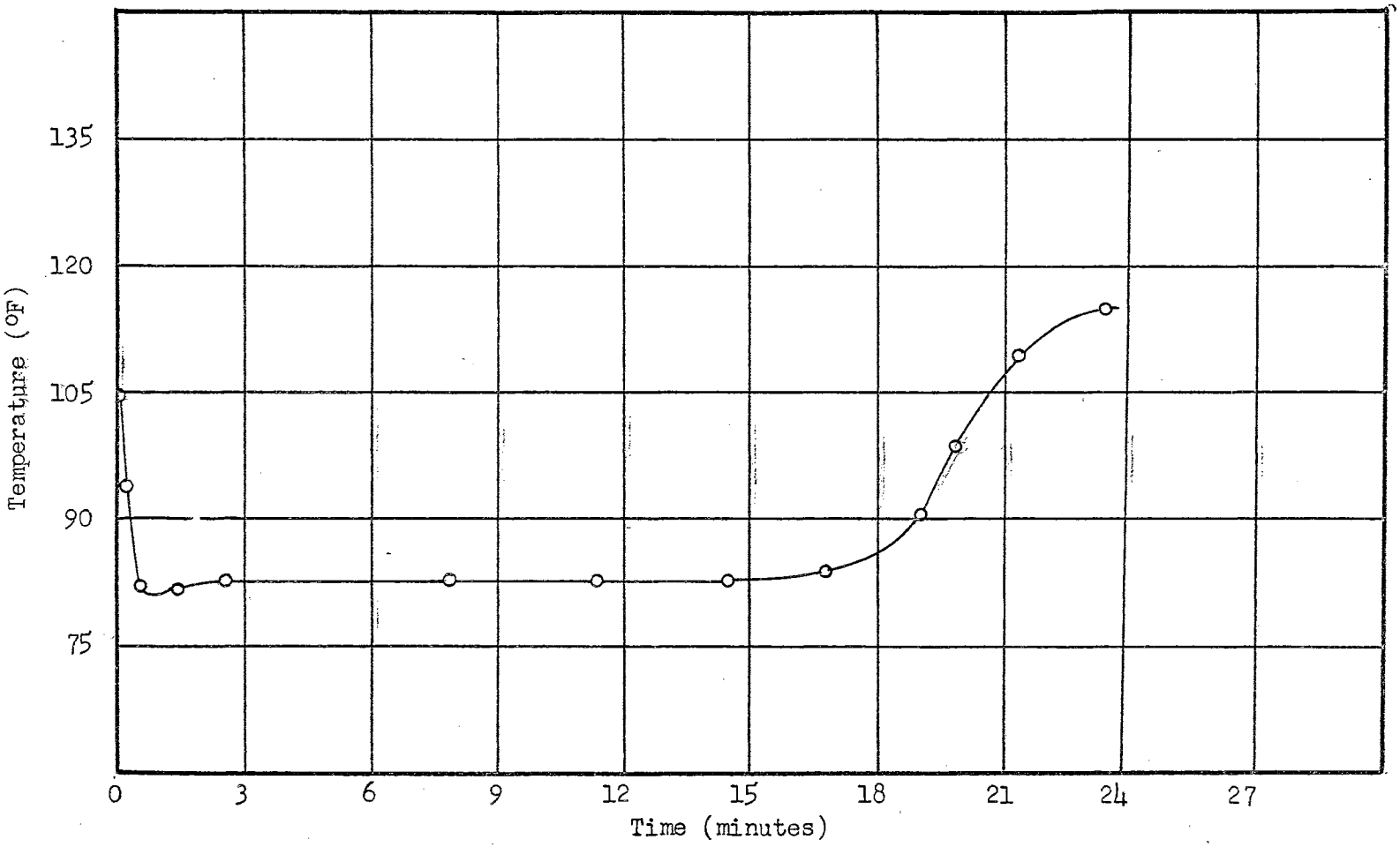

FIGURE 15

Wet Bulb Thermocouple Cooling Curve

APPENDIX B

TABLE III

EXPERIMENTAL DATA FOR RUN NO. 102

System Studied; air-water.
Atm. Pres. = 28.97 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 0.81 in. H_2O.
Visual Froth Height = 8.32 in.
Thermocouple Readings, °F.
T_1 = 86.8; T_2 = 119.8; T_3 = 84.9.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 136° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 2.17 in. H_2O.
Wet Plate Δp = 5.0 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	197	35.5	205
25.5	196	36.5	211
29.5	197	37.5	216
30.5	197	38.5	218
31.5	198	39.5	224
32.5	198	40.5	231
33.5	199	41.5	234
34.5	202	50.5	251

Calculated Values

H_f = 5.56 in.
u = 4.0 ft/sec.
t_g = 0.0617 sec.

Tray Efficiency = 95.6%
Ng = 3.12
F = 1.04

TABLE IV

EXPERIMENTAL DATA FOR RUN NO. 103

System Studied; air-water.
Atm. Pres. = 29.12 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 1.26 in. H_2O.
Visual Froth Height = 7.92 in.
Thermocouple Readings, °F.
T_1 = 88.2; T_2 = 121.6; T_3 = 85.3.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 137° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 3.58 in. H_2O.
Wet Plate Δp = 5.44 in. H_2O.
Current to Probe = 0.75 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	214	33.5	227
22.5	214	34.5	233
24.5	214	35.5	240
26.5	214	36.5	250
29.5	214	37.5	262
30.5	214	38.5	277
31.5	218	39.5	283
32.5	224	49.5	297

Calculated Values

H_f = 4.37 in.
u = 5.0 ft/sec.
t_g = 0.0428 sec.

Tray Efficiency = 92.1%
Ng = 2.55
F = 1.3

TABLE V

EXPERIMENTAL DATA FOR RUN NO. 104

System Studied; air-water.
Atm. Pres. = 29.97 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.23 in. H_2O.
Visual Froth Height = 4.97 in.
Thermocouple Readings, °F.
T_1 = 86.9; T_2 = 105.6; T_3 = 85.0.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 144° F.
Upstream Pres. = 3.7 in. Hg.
Dry Plate Δp = 0.592 in. H_2O.
Wet Plate Δp = 2.64 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Prove Position	Slide Wire	Probe Position	Slide Wire
20.5	188	28.5	189
21.5	188	29.5	196
22.5	188	30.5	204
23.5	188	31.5	215
24.5	188	32.5	230
25.5	188	33.5	235
26.5	188	42.5	272
27.5	188		

Calculated Values

H_f = 3.58 in.
u = 2.0 ft/sec.
t_g = 0.0742 sec.

Tray Efficiency = 90.6%
Ng = 2.37
F = 0.52

TABLE VI

EXPERIMENTAL DATA FOR RUN NO. 105

System Studied; air-water.
Atm. Pres. = 28.99 in. Hg.
Liquid Level = 1.0 in.
Δp across Venturi = 1.81 in. H_2O.
Visual Froth Height = 6.74 in.
Thermocouple Readings, °F.
T_1 = 89.0; T_2 = 122.6; T_3 = 86.2.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 138° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 4.81 in. H_2O.
Wet Plate Δp = 6.11 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Swirling action of froth invalidates traverse data.

Calculated Values

H_f = - - in.
u = 6.0 ft/sec.
t_g = - - sec.

Tray Efficiency = 92.4%
Ng = 2.77
F = 1.56

TABLE VII

EXPERIMENTAL DATA FOR RUN NO. 107

System Studied; air-water.
Atm. Pres. = 29.05 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 1.8 in. H_2O.
Visual Froth Height = 7.52 in.
Thermocouple Readings, °F.
T_1 = 84.8; T_2 = 120.2; T_3 = 82.6.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 131° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 4.68 in. H_2O.
Wet Plate Δp = 6.82 in. H_2O.
Current to Probe = 0.5 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	179	35.5	191
24.5	179	36.5	193
25.5	180	37.5	197
30.5	180	38.5	200
31.5	182	39.5	202
32.5	184	40.5	204
33.5	185	41.5	204
34.5	188	50.5	205

Calculated Values

H_f = 5.54 in.
u = 6.0 ft/sec.
t_g = 0.052 sec.

Tray Efficiency = 94.2%
Ng = 2.75
F = 1.56

TABLE VIII

EXPERIMENTAL DATA FOR RUN NO. 110

System Studied; air-water.
Atm. Pres. = 28.99 in. Hg.
Liquid Level = 1.0 in.
Δp across Venturi = 1.26 in. H_2O.
Visual Froth Height = 5.16 in.
Thermocouple Readings, °F.
T_1 = 90.2; T_2 = 125.4; T_3 = 86.6.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 144° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 3.31 in. H_2O.
Wet Plate Δp = 4.65 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Swirling action of froth invalidates traverse data.

Calculated Values

H_f	= - -	in.	Tray Efficiency = 90.8%
u	= 5.0	ft/sec.	Ng = 2.385
t_g	= - -	sec.	F = 1.3

TABLE IX

EXPERIMENTAL DATA FOR RUN NO. 111

System Studied; air-water.
Atm. Pres. = 29.05 in. Hg.
Liquid Level = 1.0 in.
Δp across Venturi = 1.26 in. H_2O.
Visual Froth Height = 5.16 in.
Thermocouple Readings, ^oF.
T_1 = 85.0; T_2 = 118.8; T_3 = 81.8.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 140° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 3.5 in. H_2O.
Wet Plate Δp = 4.68 in. H_2O.
Current to Probe = 0.5 amps.
R_3 = 11.0 ohms.

Density Traverse

Swirling action of froth invalidates traverse data.

Calculated Values

H_f	= - -	in.	Tray Efficiency = 91.4%
u	= 5.0	ft/sec.	Ng = 2.455
t_g	= - -	sec.	F = 1.3

TABLE X

EXPERIMENTAL DATA FOR RUN NO. 113

System Studied; air-water.
Atm. Pres. = 29.16 in. Hg.
Liquid Level = 1.0 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 3.9 in.
Thermocouple Readings, °F.
T_1 = 90.0; T_2 = 119.8; T_3 = 86.0.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 143° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 1.26 in. H_2O.
Wet Plate Δp = 2.32 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	191	27.5	197
21.5	191	28.5	210
22.5	191	29.5	220
23.5	191	30.5	230
24.5	191	31.5	234
25.5	191	40.5	252
26.5	193		

Calculated Values

H_f = 2.4 in.
u = 3.0 ft/sec.
t_g = 0.0389 sec.

Tray Efficiency = 88.2%
Ng = 2.14
F = 0.78

TABLE XI

EXPERIMENTAL DATA FOR RUN NO. 114

System Studied; air-water.
Atm. Pres. = 29.25 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.9 in. H_2O.
Visual Froth Height = 5.17 in.
Thermocouple Readings, °F.
T_1 = 86.3; T_2 = 105.5; T_3 = 84.5.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 138° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 0.59 in. H_2O.
Wet Plate Δp = 2.56 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	190	30.5	198
21.5	190	31.5	204
26.5	190	32.5	217
27.5	190	33.5	230
27.5	190	34.5	243
28.5	190	43.5	295
29.5	192		

Calculated Values

H_f = 3.58 in.
u = 2.0 ft/sec.
t_g = 0.0742 sec.

Tray Efficiency = 91.4%
Ng = 2.45
F = 0.52

TABLE XII

EXPERIMENTAL DATA FOR RUN NO. 117

System Studied; air-water.
Atm. Pres. = 29.25 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 5.55 in.
Thermocouple Readings, °F.
T_1 = 88.9; T_2 = 120.5; T_3 = 87.0.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 137° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 1.22 in. H_2O.
Wet Plate Δp = 3.19 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	167	30.5	176
22.5	167	31.5	189
24.5	167	32.5	202
26.5	167	33.5	207
27.5	167	34.5	225
28.5	167	35.5	227
29.5	170	44.5	248

Calculated Values

H_f = 3.59 in.
u = 3.0 ft/sec.
t_g = 0.0496 sec.

Tray Efficiency = 94.4%
Ng = 2.88
F = 0.78

TABLE XIII

EXPERIMENTAL DATA FOR RUN NO. 118

System Studied; air-water.
Atm. Pres. = 29.25 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.8 in. H_2O.
Visual Froth Height = 6.35 in.
Thermocouple Readings, °F.
T_1 = 89.6; T_2 = 121.2; T_3 = 87.2.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 145° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 1.22 in. H_2O.
Wet Plate Δp = 4.02 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	171	32.5	191
21.5	171	33.5	197
27.5	171	34.5	202
28.5	171	35.5	211
29.5	172	36.5	216
30.5	175	37.5	218
31.5	183	46.5	231

Calculated Values

H_f = 4.37 in.
u = 4.0 ft/sec.
t_g = 0.0535 sec.

Tray Efficiency = 93.2%
Ng = 2.69
F = 1.04

TABLE XIV

EXPERIMENTAL DATA FOR RUN NO. 119

System Studied; air-water.
Atm. Pres. = 29.27 in. Hg.
Liquid Level = 3.4 in.
Δp across Venturi = 0.8 in. H_2O.
Visual Froth Height = 10.3 in.
Thermocouple Readings, °F.
T_1 = 85.1; T_2 = 113.6; T_3 = 84.4.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 140° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 2.16 in. H_2O.
Wet Plate Δp = 5.65 in. H_2O.
Current to Probe = 0.71 amps.
R_3 = 9.2 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	215	40.5	227
21.5	215	41.5	232
28.5	215	42.5	242
34.5	215	43.5	247
35.5	215	44.5	256
36.5	215	45.5	268
37.5	217	46.5	270
38.5	220	47.5	275
39.5	224	56.5	310

Calculated Values

H_f = 6.73 in.
u = 4.0 ft/sec.
t_g = 0.0695 sec.

Tray Efficiency = 97.6%
Ng = 3.73
F = 1.04

TABLE XV

EXPERIMENTAL DATA FOR RUN NO. 120

System Studied; air-water.
Atm. Pres. = 29.10 in. Hg.
Liquid Level = 3.4 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 8.7 in.
Thermocouple Readings, °F.
T_1 = 85.9; T_2 = 107.3; T_3 = 85.5.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 143° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 1.22 in. H_2O.
Wet Plate Δp = 4.96 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	54	37.5	62
21.5	54	38.5	68
26.5	54	39.5	74
32.5	54	40.5	83
33.5	54	41.5	98
34.5	55	42.5	102
35.5	56	43.5	106
36.5	58	52.5	163

Calculated Values

H_f = 6.34 in.
u = 3.0 ft/sec.
t_g = 0.0817 sec.

Tray Efficiency = 98.8%
Ng = 4.43
F = 0.78

TABLE XVI

EXPERIMENTAL DATA FOR RUN NO. 121

System Studied; air-water.
Atm. Pres. = 29.24 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 1.26 in. H_2O.
Visual Froth Height = 9.5 in.
Thermocouple Readings, °F.
T_1 = 86.1; T_2 = 123.4; T_3 = 85.4.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 140° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 3.07 in. H_2O.
Wet Plate Δp = 6.23 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	115	39.5	124
21.5	115	40.5	130
31.5	115	41.5	135
33.5	115	42.5	138
35.5	115	43.5	140
36.5	115	44.5	151
37.5	118	53.5	156
38.5	120		

Calculated Values

H_f = 6.73 in.
u^f = 5.0 ft/sec.
t_g = 0.0688 sec.

Tray Efficiency = 98.3%
Ng = 4.07
F = 1.3

TABLE XVII

EXPERIMENTAL DATA FOR RUN NO. 122

System Studied; air-water.
Atm. Pres. = 29.24 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 1.79 in. H_2O.
Visual Froth Height = 9.9 in.
Thermocouple Readings, °F.
T_1 = 86.8; T_2 = 124.6; T_3 = 85.7.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 142° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 4.77 in. H_2O.
Wet Plate Δp = 7.65 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	111	40.5	119
21.5	111	41.5	123
28.5	111	42.5	125
33.5	111	43.5	128
36.5	111	44.5	134
37.5	111	45.5	137
38.5	111	46.5	140
39.5	115	55.5	148

Calculated Values

H_f = 7.52 in.
u^f = 6.0 ft/sec.
t_g = 0.0683 sec.

Tray Efficiency = 97.3%
Ng = 3.72
F = 1.56

TABLE XVIII

EXPERIMENTAL DATA FOR RUN NO. 123

System Studied; air-water.
Atm. Pres. = 29.17 in. Hg.
Liquid Level = 1.0 in.
$\triangle$p across Venturi = 0.8 in. H_2O.
Visual Froth Height = 4.57 in.
Thermocouple Readings, °F.
T_1 = 86.8; T_2 = 118.4; T_3 = 83.3.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 138° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate$\triangle$p = 2.13 in. H_2O.
Wet Plate$\triangle$p = 3.35 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	57	29.5	68
21.5	57	30.5	81
23.5	57	31.5	94
25.5	57	32.5	107
26.5	57	33.5	111
27.5	58	42.5	119
28.5	64		

Calculated Values

H_f = 3.19 in.
u = 4.0 ft/sec.
t_g = 0.0456 sec.

Tray Efficiency = 90.1%
Ng = 2.31
F = 1.04

TABLE XIX

EXPERIMENTAL DATA FOR RUN NO. 124

System Studied; air-water.
Atm. Pres. = 29.14 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 1.26 in. H_2O.
Visual Froth Height = 8.5 in.
Thermocouple Readings, °F.
T_1 = 85.9; T_2 = 125.1; T_3 = 83.8.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 143° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 3.42 in. H_2O.
Wet Plate Δp = 6.22 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	86	36.5	93
21.5	86	37.5	98
22.5	86	38.5	105
30.5	86	39.5	114
32.5	86	40.5	122
33.5	86	41.5	125
34.5	86	42.5	128
35.5	88	51.5	140

Calculated Values

H_f = 5.94 in.
u = 5.0 ft/sec.
t_g = 0.0557 sec.

Tray Efficiency = 95.1%
Ng = 3.02
F = 1.3

TABLE XX

EXPERIMENTAL DATA FOR RUN NO. 125

System Studied; air-water.
Atm. Pres. = 29.14 in. Hg.
Liquid Level = 1.0 in.
Δp across Venturi = 0.23 in. H_2O.
Visual Froth Height = 3.39 in.
Thermocouple Readings, °F.
T_1 = 85.8; T_2 = 118.4; T_3 = 82.1.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 150° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 0.55 in. H_2O.
Wet Plate Δp = 1.69 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	106	26.5	106
21.5	106	27.5	128
22.5	106	28.5	162
23.5	106	29.5	176
24.5	106	38.5	255
25.5	106		

Calculated Values

H_f = 2.79 in.
u = 2.0 ft/sec .
t_g = 0.0747 sec.

Tray Efficiency = 89.9%
Ng = 2.29
F = 0.52

TABLE XXI

EXPERIMENTAL DATA FOR RUN NO. 126

System Studied; air-water.
Atm. Pres. = 29.06 in. Hg.
Liquid Level = 3.4 in.
Δp across Venturi = 1.79 in. H_2O.
Visual Froth Height = 12.25 in.
Thermocouple Readings, ^oF.
T_1 = 85.0; T_2 = 123.2; T_3 = 84.0.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 138° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 4.77 in. H_2O.
Wet Plate Δp = 8.35 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	71	42.5	79
21.5	71	43.5	82
28.5	71	44.5	86
37.5	71	45.5	88
38.5	71	47.5	94
39.5	73	49.5	100
40.5	74	51.5	103
41.5	76	60.5	116

Calculated Values

H_f = 8.31 in.
u = 6.0 ft/sec.
t_g = 0.0682 sec.

Tray Efficiency = 97.4%
Ng = 3.65
F = 1.56

TABLE XXII

EXPERIMENTAL DATA FOR RUN NO. 129

System Studied; air-water.
Atm. Pres. = 29.06 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 7.52 in.
Thermocouple Readings, °F.
T_1 = 85.3; T_2 = 112.5; T_3 = 84.4.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1.
Upstream Temp. = 142° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 1.18 in. H_2O.
Wet Plate Δp = 4.1 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	66	34.5	78
21.5	66	35.5	89
28.5	66	36.5	102
29.5	66	37.5	113
30.5	66	38.5	127
31.5	67	39.5	130
32.5	70	48.5	152
33.5	72		

Calculated Values

H_f = 4.77 in.
u^f = 3.0 ft/sec.
t_g = 0.0603 sec.

Tray Efficiency = 96.8%
Ng = 3.445
F = 0.78

TABLE XXIII

EXPERIMENTAL DATA FOR RUN NO. 130

System Studied; air-water.
Atm. Pres. = 29.12 in. Hg.
Liquid Level = 1.0 in.
Δp across Venturi = 0.8 in. H_2O.
Visual Froth Height = 4.57 in.
Thermocouple Readings, °F.
T_1 = 86.9; T_2 = 120.0; T_3 = 84.5.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 139° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 2.13 in. H_2O.
Wet Plate Δp = 3.39 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	63	28.5	70
21.5	63	29.5	80
23.5	63	30.5	93
25.5	63	31.5	104
26.5	63	32.5	108
27.5	64	41.5	113

Calculated Values

H_f = 3.19 in.
u^f = 4.0 ft/sec.
t_g = 0.0456 sec.

Tray Efficiency = 93.4%
Ng = 2.72
F = 1.04

TABLE XXIV

EXPERIMENTAL DATA FOR RUN NO. 132

System Studied; air-water.
Atm. Pres. = 29.14 in. Hg.
Liquid Level = 3.4 in.
Δp across Venturi = 1.26 in. H_2O.
Visual Froth Height = 11.65 in.
Thermocouple Readings, °F.
T_1 = 84.5; T_2 = 120.4; T_3 = 83.6.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 139° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 3.39 in. H_2O.
Wet Plate Δp = 7.05 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	61	43.5	77
21.5	61	44.5	82
30.5	61	45.5	84
36.5	61	46.5	87
37.5	63	47.5	93
38.5	64	48.5	97
39.5	65	49.5	104
40.5	67	50.5	108
41.5	70	59.5	119
42.5	73		

Calculated Values

H_f = 7.92 in.
u = 5.0 ft/sec.
t_g = 0.0753 sec.

Tray Efficiency = 97.7%
Ng = 3.78
F = 1.3

TABLE XXV

EXPERIMENTAL DATA FOR RUN NO. 133

System Studied; air-water.
Atm. Pres. = 29.16 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.90 in. H_2O.
Visual Froth Height = 8.71 in.
Thermocouple Readings, °F.
T_1 = 86.1; T_2 = 120.7; T_3 = 84.8
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 133° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 4.81 in. H_2O.
Wet Plate Δp = 6.93 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	88	35.5	93
21.5	88	36.5	97
28.5	88	37.5	101
29.5	89	38.5	106
30.5	89	39.5	111
31.5	89	40.5	122
32.5	89	41.5	127
33.5	91	42.5	128
34.5	93	51.5	145

Calculated Values

H_f = 6.34 in.
u = 6.0 ft/sec.
t_g = 0.0632 sec.

Tray Efficiency = 96.4%
Ng = 3.325
F = 1.56

TABLE XXVI

EXPERIMENTAL DATA FOR RUN NO. 134

System Studied; air-water.
Atm. Pres. = 29.16 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.81 in. H_2O.
Visual Froth Height = 6.34 in.
Thermocouple Readings, °F.
T_1 = 85.7; T_2 = 116.5; T_3 = 84.2.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 136° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 2.13 in. H_2O.
Wet Plate Δp = 4.25 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	82	32.5	98
21.5	82	33.5	104
27.5	82	34.5	111
28.5	82	35.5	116
29.5	82	36.5	132
30.5	84	37.5	137
31.5	90	46.5	155

Calculated Values

H_f = 4.37 in.
u = 4.0 ft/sec.
t_g = 0.0536 sec.

Tray Efficiency = 95.3%
Ng = 3.06
F = 1.04

TABLE XXVII

EXPERIMENTAL DATA FOR RUN NO. 135

System Studied; air-water.
Atm. Pres. = 29.19 in. Hg.
Liquid Level = 3.4 in.
Δp across Venturi = 1.8 in. H_2O.
Visual Froth Height = 12.25 in.
Thermocouple Readings, °F.
T_1 = 84.8; T_2 = 121.2; T_3 = 84.0.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 135° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 4.81 in. H_2O.
Wet Plate Δp = 8.47 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	93	43.5	102
21.5	93	44.5	104
32.5	93	45.5	106
35.5	93	46.5	110
38.5	93	47.5	112
39.5	93	48.5	115
40.5	95	49.5	120
41.5	97	51.5	126
42.5	100	60.5	145

Calculated Values

H_f = 7.92 in.
u = 6.0 ft/sec.
t_g = 0.0627 sec.

Tray Efficiency = 97.7%
Ng = 3.775
F = 1.56

TABLE XXVIII

EXPERIMENTAL DATA FOR RUN NO. 136

System Studied; air-water.
Atm. Pres. = 29.14 in. Hg.
Liquid Level = 2.6 in.
Δ p across Venturi = 0.47 in. H_2O.
Visual Froth Height = 7.13 in.
Thermocouple Readings, °F.
T_1 = 84.6; T_2 = 108.1; T_3 = 84.1.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 140° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 1.26 in. H_2O.
Wet Plate Δp = 4.17 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	17	34.5	27
21.5	17	35.5	34
29.5	17	36.5	44
30.5	17	37.5	50
31.5	17	38.5	62
32.5	17	39.5	75
33.5	20	48.5	95

Calculated Values

H_f = 5.16 in.
u = 3.0 ft/sec.
t_g = 0.0712 sec.

Tray Efficiency = 97.9%
Ng = 3.865
F = 0.78

TABLE XXIX

EXPERIMENTAL DATA FOR RUN NO. 137

System Studied; air-water.
Atm. Pres. = 29.27 in. Hg.
Liquid Level = 3.4 in.
Δp across Venturi = 0.80 in. H_2O.
Visual Froth Height = 10.29 in.
Thermocouple Readings, °F.
T_1 = 85.3; T_2 = 114.6; T_3 = 84.6.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 138° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 2.13 in. H_2O.
Wet Plate Δp = 5.78 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 9.6 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	263	38.5	266
21.5	263	39.5	267
28.5	263	40.5	269
30.5	263	41.5	274
32.5	263	42.5	280
34.5	263	43.5	286
35.5	263	44.5	294
36.5	263	45.5	305
37.5	265	46.5	308

Calculated Values

H_f = 6.73 in.
u^f = 4.0 ft/sec.
t_g = 0.0695 sec.

Tray Efficiency = 97.8%
Ng = 3.82
F = 1.04

TABLE XXX

EXPERIMENTAL DATA FOR RUN NO. 138

System Studied; air-water.
Atm. Pres. = 29.20 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 1.79 in. H_2O.
Visual Froth Height = 9.9 in.
Thermocouple Readings, °F.
T_1 = 84.1; T_2 = 121.8; T_3 = 82.2.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 139° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 4.65 in. H_2O.
Wet Plate Δp = 7.53 in. H_2O.
Current to Probe = 0.65 amps.
R_3 = 11.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20.5	68	39.5	81
21.5	68	40.5	87
29.5	69	41.5	92
32.5	69	42.5	94
33.5	70	43.5	102
35.5	71	44.5	106
36.5	75	45.5	108
37.5	77	46.5	112
38.5	79	55.5	126

Calculated Values

H_f = 6.34 in.
u = 6.0 ft/sec.
t_g = 0.0518 sec.

Tray Efficiency = 95.2%
Ng = 3.02
F = 1.56

TABLE XXXI

EXPERIMENTAL DATA FOR RUN NO. 202

System Studied; air-water.
Atm. Pres. = 29.18 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 0.81 in. H_2O.
Visual Froth Height = 7.92 in.
Thermocouple Readings, °F.
T_1 = 82.0; T_2 = 111.1; T_3 = 80.9.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 2
Upstream Temp. = 144° F.
Upstream Pres. = 3.7 in. Hg.
Dry Plate Δp = 10.85 in. H_2O.
Wet Plate Δp = 13.05 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 8.8 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
21.5	547	37.5	565
25.5	547	38.5	573
30.5	547	39.5	580
32.5	547	40.5	584
34.5	549	41.5	586
35.5	555	50.5	600
36.5	560		

Calculated Values

H_f = 5.55 in.
u = 4.0 ft/sec.
t_g = 0.0614 Sec.

Tray Efficiency = 96.4%
Ng = 3.42
F = 1.04

TABLE XXXII

EXPERIMENTAL DATA FOR RUN NO. 213

System Studied; air-water.
Atm. Pres. = 29.18 in. Hg.
Liquid Level = 1.0 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 3.98 in.
Thermocouple Readings, ^{o}F.
T_1 = 81.8; T_2 = 102.3; T_3 = 80.3.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 2
Upstream Temp. = 139° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 6.57 in. H_2O.
Wet Plate Δp = 7.48 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 8.8 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
21.5	542	27.5	545
23.5	542	28.5	557
24.5	542	29.5	565
25.5	542	30.5	572
26.5	542	39.5	579

Calculated Values

H_f = 2.79 in.
u = 3.0 ft/sec.
t_g = 0.0497 sec.

Tray Efficiency = 93.2%
Ng = 2.69
F = 0.78

TABLE XXXIII

EXPERIMENTAL DATA FOR RUN NO. 217

System Studied; air-water.
Atm. Pres. = 29.18 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 5.6 in.
Thermocouple Readings, °F.
T_1 = 85.9; T_2 = 110.6; T_3 = 84.6.
Position of Tray = Probe Reading of 20.8 cm.

Plate Design No. 2
Upstream Temp. = 145° F.
Upstream Pres. = 3.7 in. Hg.
Dry Plate Δp = 6.45 in. H_2O.
Wet Plate Δp = 8.27 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 8.8 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
21.5	546	28.5	546
24.5	546	29.5	546
26.5	546	30.5	548
27.5	546	31.5	556

Calculated Values

H_f = 3.62 in.
u = 3.0 ft/sec.
t_g = 0.0506 sec.

Tray Efficiency = 95.1%
Ng = 3.02
F = 0.78

TABLE XXXIV

EXPERIMENTAL DATA FOR RUN NO. 218

System Studied; air-water.
Atm. Pres. = 29.18 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.80 in. H_2O.
Visual Froth Height = 6.73 in.
Thermocouple Readings, °F.
T_1 = 81.5; T_2 = 106.1; T_3 = 80.5.
Position of Tray = Probe Reading of 19.9 cm.

Plate Design No. 2
Upstream Temp. = 136° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 10.85 in. H_2O.
Wet Plate Δp = 12.3 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 8.8 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
21.5	531	33.5	539
24.5	531	34.5	547
28.5	531	35.5	548
29.5	531	36.5	556
30.5	532	37.5	570
31.5	534	38.5	573
32.5	536	47.5	582

Calculated Values

H_f = 4.37 in.
u = 4.0 ft/sec.
t_g = 0.0536 sec.

Tray Efficiency = 96.2%
Ng = 3.27
F = 1.04

TABLE XXXV

EXPERIMENTAL DATA FOR RUN NO. 220

System Studied; air-water.
Atm. Pres. = 29.18 in. Hg.
Liquid Level = 3.4 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 9.14 in.
Thermocouple Readings, °F.
T_1 = 82.1; T_2 = 105.8; T_3 = 81.8.
Position of Tray = Probe Reading of 20.8 cm.

Plate Design No. 2
Upstream Temp. = 143° F.
Upstream Pres. = 3.7 in. Hg.
Dry Plate Δp = 6.5 in. H_2O.
Wet Plate Δp = 10.15 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 8.8 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
21.5	116	39.5	128
28.5	116	40.5	130
33.5	116	41.5	133
35.5	116	42.5	138
36.5	116	43.5	144
37.5	120	44.5	156
38.5	122	53.5	177

Calculated Values

H_f = 6.38 in.
u = 3.0 ft/sec.
t_g = 0.0827 sec.

Tray Efficiency = 98.7%
Ng = 4.35
F = 0.78

TABLE XXXVI

EXPERIMENTAL DATA FOR RUN NO. 229

System Studied; air-water.
Atm. Pres. = 29.18 in. Hg.
Liquid Level = 2.6 in.
Δp across Venturi = 0.47 in. H_2O.
Visual Froth Height = 7.17 in.
Thermocouple Readings, °F.
T_1 = 81.6; T_2 = 107.1; T_3 = 80.8.
Position of Tray = Probe Reading of 20.8 cm.

Plate Design No. 2
Upstream Temp. = 145° F.
Upstream Pres. = 3.7 in. Hg.
Dry Plate Δp = 6.5 in. H_2O.
Wet Plate Δp = 9.22 in. H_2O.
Current to Probe = 0.6 amps.
R_3 = 8.8 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
21.5	550	35.5	555
24.5	550	36.5	560
30.5	550	37.5	571
32.5	550	38.5	575
34.5	552	47.5	598

Calculated Values

H_f = 5.20 in.
u = 3.0 ft/sec.
t_g = 0.0722 sec.

Tray Efficiency = 97.0%
Ng = 3.51
F = 0.78

TABLE XXXVII

EXPERIMENTAL DATA FOR RUN NO. 317

System Studied; air-carbon tetrachloride.
Atm. Pres. = 29.25 in. Hg.
Liquid Level = 1.6 in.
Δp across Venturi = 0.52 in. H_2O
Visual Froth Height = 3.78 in.
Mass Transfer Rate = 0.0134 lb./min.

Plate Design No. 1
Upstream Temp. = 135° F.
Upstream Pres. = 3.8 in. Hg.
Dry Plate Δp = 1.32 in. H_2O
Wet Plate Δp = 4.85 in. H_2O
Temp. of Froth = 43° F.

Calculated Values

H_f = 3.78 in.
u^f = 3.15 ft./sec.
t_g = 0.0589 sec.

Tray Efficiency = 81.2%
N_g = 1.725
F^g = 0.82

TABLE XXXVIII

EXPERIMENTAL DATA FOR RUN NO. 417

System Studied; air- chlorobenzene.
Atm. Pres. = 29.15 in. Hg.
Liquid Level = 1.8 in.
Δp across Venturi = 0.47 in. H_2O
Visual Froth Height = 5.3 in.
Thermocouple Readings, °F.
T_1 = 79.0; T_2 = 112.6; T_3 = 76.1
Position of Tray 2 = Probe Reading of 19.9 cm.

Plate Design No. 1
Upstream Temp. = 136° F.
Upstream Pres. = 3.7 in. Hg.
Dry Plate Δp = 1.25 in. H_2O
Wet Plate Δp = 3.49 in. H_2O
Current to Probe = 0.63 amps.
R_3 = 8.0 ohms.

Density Traverse

Probe Position	Slide Wire	Probe Position	Slide Wire
20	725	30	725
22	725	31	727
24	725	32	735
27	725	33	742

Calculated Values

H_f = 4.17 in.
u = 3.0 ft./sec.
t_g = 0.0657 sec.

Tray Efficiency = 83.7%
N_g = 1.816
F = 0.78

APPENDIX C

Sample Calculations

The following calculations are based on the data collected during Run No. 103.

Analysis of the data from the anemometer traverse shows that the froth-gas interface is located at a probe position of 31.0 centimeters.

$$H_f = 31.0 - 19.9 = 11.1 \text{ cm.} = 4.37 \text{ in.}$$

From Figure 11; u = 5 ft./sec.

By Equation 10:

$$t_g = (H_f - L_c)/12u = (4.37 - 1.8)/12x5 = 0.0428 \text{ sec.}$$

$$\text{Tray efficiency} = (y_2 - y_1)/(y^* - y_1)$$
$$= (T_1 - T_2)/(T_1 - T_{wb})$$

The use of temperature data for calculating tray efficiency can be justified by considering the geometry of the phychrometric chart. The wet-bulb temperature lines were assumed linear over the small temperature range considered. Therefore, T may be substituted for y and:

$$\text{Tray efficiency} = (121.6 - 88.2)/(121.6 - 85.3) = 0.921$$

By equation 2:

$$N_g = -\ln(1 - E_{og}) = -\ln(1 - 0.921) = 2.54$$

APPENDIX D

Statistical Analysis

From theoretical considerations it was determined that the number of transfer units is related to the contact time by the following equation.

$$N_g = k_g' a t_g \tag{6}$$

The terms N_g and t_g are the dependent and independent variables respectively. The nature of $k_g'a$ must be determined by experimentation. An experiment was designed in which the value of N_g could be determined at various levels of t_g. The data were analyzed statistically in order to define $k_g'a$ at the desired confidence level.

It was known that N_g must be zero at t_g equal to zero. Data collected by previous investigators indicated that $k_g'a$ was constant within the range of the variables studied. These facts, while useful, are not sufficient to describe $k_g'a$ completely. It is very important that the term be defined between t_g equal to zero and the minimum value of t_g where no experimental data were taken.

To define $k_g'a$ in this interval the data were correlated by the least squares technique using the model:

$$N_g = \alpha + \beta t_g \tag{14}$$

Next, the hypothesis, $\hat{\alpha} = 0$, was tested using Student's t at the 5% level, where t is given by:

$$t = \hat{\alpha} \sqrt{n(n-2)\Sigma(X_i - \bar{x})^2 / K\Sigma X_i^2} \tag{15}$$

and

$$K = \Sigma Y_i^2 - (\Sigma Y_i)^2/n - [\Sigma(X_i - \bar{x})(Y_i - \bar{y})]^2/\Sigma(X_i - \bar{x})^2 \tag{16}$$

The test showed that the hypothesis could not be rejected. From this the conclusion was that N_g as a function of t_g is described by the following equation.

$$N_g = \beta_1 t_g \tag{17}$$

Comparing equation 17 with equation 6 it is obvious that β_1 is equal to $k_g'a$.

The data were then correlated with the least squares technique using equation 17 as the model. The 95% confidence interval was placed on β_1 using the formula:

$$\beta_1 = \hat{\beta}_1 \pm t\sqrt{s^2/\Sigma X_i^2} \tag{18}$$

where

$$s^2 = \left[\Sigma Y_i - (\Sigma X_i Y_i)^2/\Sigma X_i^2\right] /(n - 1) \tag{19}$$

To evaluate the effect of tray design on the product $k_g'a$ a new series of experiments were conducted with a different tray. $\hat{\beta}_2$ was calculated in the same manner as described for $\hat{\beta}_1$. The hypothesis, $\beta_1 = \beta_2$ was tested using Student's t at the 5% level, where t is given by:

$$t = (\hat{\beta}_1 - \hat{\beta}_2)\sqrt{n_1 + n_2 - 2}\,/\sqrt{d_1 - d_2}\,\sqrt{1/\Sigma X_1^2 + 1/\Sigma X_2^2} \tag{20}$$

and

$$d = \Sigma Y_i - \hat{\beta}\,\Sigma X_i Y_i \tag{21}$$

The hypothesis could not be rejected. The conclusion was that tray design has no significant effect on the value of $k_g'a$.

Measurement Errors

In evaluating experimental results, it is necessary to have some knowledge of the errors associated with the data. In linear regression analysis it is generally assumed that the measurement of the independent variable is exact. Random errors are to be expected, and the magnitude of such errors can be estimated by standard statistical procedures.

In this problem the exact value of the independent variable, t_g, could not be obtained. The error associated with the independent variable has contributed to the scatter of the data, but the errors are relatively small and do not invalidate the assumption of exactness.

Although the error in t_g did not seriously distort the results, it is worth while to note the magnitude and the source of the errors involved. The dependence of t_g on the measurement of froth height is the reason that the value of t_g is not exact.

The froth height was determined as being within a one centimeter interval. This interval establishes the maximum error as being plus or minus 0.5 centimeters. Experience showed that if the froth height was very close to the position of the probe, it was impossible to accurately measure the resistance of the probe. As a conservative estimate, one millimeter is considered to be very close. The erratic behavior of the probe when within one millimeter of the froth height serves to reduce the measurement interval to 0.8 centimeters.

The froth height can be located at any point within this interval. The probability that the froth height is located at any one point is the same for all possible points. With this information it is possible to calculate the average error for the froth height measurements. The average error was found to be plus or minus 0.2 centimeters.

VITA

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