# CORRELATION OF SIEVE PLATE EFFICIENCY AS A FUNCTION OF OPERATING VARIABLES

by

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## SUMMARY

The effects of three operating variables; liquid rate, outlet weir height, and gas rate, on overall plate efficiency on a sieve plate have been studied, using the system ammonia-air-water. Ammonia was absorbed from air into water, using a single 24-in. diameter tray which had a perforated area of 0.2150 square feet. The perforations consisted of 2,534 1/8-in. diameter holes on 3/8-in. equilateral triangular centers and provided a free area equal to 7.69% of the superficial tower free area. The superficial tower free area (2.795 ft.$^2$) is defined as the tower internal area less the area of the segmental inlet water down-comer. Liquid rates ranged from 1,740 to 10,700 lbs. per (hr.)(ft.$^2$); gas rates ranged from 860 to 1810 lbs. per (hr.)(ft.$^2$); and weir heights ranged from zero to 4.70 inches. The gas and liquid rates reported in this thesis are calculated on the same basis as the plate free area calculation, i.e., using the superficial tower free area as defined above in the calculation of column free area.

Murphree plate efficiencies from 60.0% to 94.0% were observed. From these data and analysis of the statistical program, a general correlation has been computed to define the relationship of Murphree plate efficiency to the three operating variables.

The data and statistically-derived expression show that plate efficiency can be increased by increasing the liquid rate and/or by increasing the outlet weir height. Increasing weir height proved to have the greatest effect on efficiency up to about 3.7 inches; at the highest weir height, 4.7 inches, it was noted that efficiency did not increase as one would predict from the derived efficiency equation. This run points to the limit of use of the equation to regions of stable plate operation.

## INTRODUCTION AND BACKGROUND

The designer of a sieve plate distillation column is confronted with three basic problems:

(1) Calculation of the optimum gas and liquid rates in the column.

(2) Determination of the number of theoretical stages required for the separation.

(3) Determination of a suitable plate efficiency to determine the number of actual stages required for the separation.

Following the general procedure outlined above, the designer is eventually confronted with the problem of correlating available literature data on plate efficiency to the system with which he is concerned and then computing a suitable plate efficiency for his particular system based on these data.

The concept of plate efficiency as defined by Murphree (11) in terms of the vapor compositions is:

$$E_{MV} = \frac{Y_{in} - Y_{out}}{Y_{in} - mX_{out}} \qquad (1)$$

where $mX_{out}$ gives the composition of the vapor in equilibrium with the liquid leaving the tray. $E_{MV}$ then represents the percent approach to equilibrium of the outlet gas and the liquid leaving the plate.

Point efficiency, which is probably a more fundamental definition of the true equilibrium characteristics of the plate, is concerned with an infinitely small portion of the plate. In this case point efficiency represents the percentage approach of the gas in this small section to equilibrium with the liquid in the same small section of the plate. Determination of point efficiency for a sieve plate is very difficult as it is almost impossible to take a liquid sample from the plate without simultaneously purging gas with the liquid sample.

To make use of the more fundamental concept of plate efficiency, the transfer efficiency is employed. Transfer efficiency ($E_{OG}$) is defined as:

$$E_{OG} = \frac{Y_1 - Y_2}{Y_1 - mX_{AV}} \qquad (2)$$

where $mX_{AV}$ is the composition of the vapor in equilibrium with the average liquid on the tray. $E_{OG}$ then represents the percent approach to equilibrium of the outlet gas with the average liquid composition of the plate.

Transfer efficiency then represents the mean value of all the point efficiencies of the plate. The transfer efficiency and the point efficiency are equal if the point efficiency is constant everywhere on the plate. This case is usually assumed to be true for sieve plates.

The relationship of Murphree plate efficiency and transfer efficiency can easily be seen by referring to equations (1) and (2). If the liquid on the plate is thoroughly mixed as it flows across the plate, then the transfer efficiency on a vapor basis would be identical with the Murphree plate efficiency. It can also be seen that the transfer efficiency can never be greater than 100%, while, owing to cross-flow and incomplete mixing of the liquid on the plate, the Murphree plate efficiency can be greater than 100%. The relationships between Murphree plate efficiency and transfer efficiency for certain cases of liquid flows across a plate with no mixing have been computed by W. K. Lewis, Jr. (10) with the assumption that the equilibrium line is straight.

Considerable research effort has been directed toward understanding and predicting tray efficiency. Some of the independent variables considered to effect tray efficiency include: liquid depth on the plate; froth depth on the plate; liquid rate; vapor rate; hole size; hole spacing; tray spacing; outlet weir height; and the physical properties of the vapor and liquid. Much of the work which has appeared in the literature prior to 1950 is reviewed by Robinson and Gilliland (13) and by Sherwood and Pigford (16). Much of the experimental work reported in the literature has been carried out in small diameter laboratory columns, in which entrance, exit and wall effects

predominate. The results of these experiments are therefore difficult to evaluate and extrapolate to the design of commercial equipment.

From the standpoint of the present work, several of these earlier investigations merit review. Walter and Sherwood (17) studied the absorption of ammonia and carbon dioxide in water using an 18-in. diameter column. They showed that the rates of absorption of ammonia in water were determined almost entirely by the rate of diffusion of ammonia through the gas film. Drickamer and Bradford (3) correlated plate efficiency with the molar average viscosity of the feed at average tower temperatures for a number of commercial columns. The correlation is limited as only one of the many actual variables enters into the correlation.

In an attempt to find a more theoretical basis for the calculation of transfer efficiency, Geddes (6) presented an analysis of efficiency as a function of individual film diffusional rates and based on unsteady-state molecular diffusion. From the predicted equations he calculated the transfer efficiency for a number of systems for which experimental results were available. The comparison of the calculated and experimental efficiencies were good. Geddes points out that this successful comparison was most fortunate due to the assumptions required to arrive at the working formulas. Gester (8) compared

experimental plate efficiencies for hexane dehydration with those calculated by the method of Geddes. In this case there was quite a large discrepancy in the calculated and experimental efficiencies. In view of these results and taking into consideration the assumptions used by Geddes to arrive at his derivation, it must be concluded that this method at best can only be used to obtain approximations of actual transfer efficiencies.

West, Gilbert and Shimizu (18) attempted to modify Geddes' approach to evaluate mass transfer coefficients and relate them to interfacial area and froth density. To utilize their approach, one must estimate the fractional voids in the froth and relate this and average bubble radius of the froth to efficiency of the tray. Their study is based on the use of 19 and 83 1/8-in. diameter hole sieve trays. Extension of their data to other literature data points to the hazard in extending this type of correlation to plates of different design and utilizing systems other than the one studied in the experimental work.

This general approach to efficiency is still, however, the most promising available. The primary difficulty in utilizing this approach is in defining terms such as bubble radius. One can calculate bubble radius from a single orifice on the plate, but this really doesn't define the bubble radius in the

froth, as coalescing of bubbles occurs at or near the plate surface and varies throughout the froth. It also neglects the effects of the mass transfer area obtained in the form of liquid drops present in the gas stream above the froth.

One of the most promising methods for the correlation and the determination of plate efficiency was presented by Gerster (7). These data are concerned with the desorption of oxygen from water and the adiabatic humidification of air in a 13-in. bubble-cap column. Both of these processes measure directly the transfer efficiency for the liquid film and the gas film, respectively. From these data the overall efficiency for systems where both gas and liquid films are of importance can be obtained. This experimental approach is similar to the one used by Walter and Sherwood (17) and to date is the best method available for predicting plate efficiency. Since the experimental data of these authors deal with air-water systems, a method for conversion of the individual film results of the test system to any system under consideration must be made. Gerster suggests that the pure-systems individual film results be corrected individually by using a suitable ratio of the Schmidt numbers of the two systems. These corrections are:

$$N_G = N_{G_O} \frac{(N_{Sc,\ G_O})^{2/3}}{N_{Sc,\ G}} \qquad (3)$$

$$N_L = N_{L_o} \frac{(N_{Sc,\ L_o})^{1/2}}{N_{Sc,\ L}} \qquad (4)$$

The theoretical basis for the Gerster correlation is the Lewis-Whitman two-film theory. In the calculation of the number of gas-film transfer units, ($N_G$) is calculated on the basis of the change in gas concentration passing vertically through the liquid on the plate. The point efficiency is then:

$$E_{OG} = 1 - \exp\left[-\frac{K_G a P Z v}{G_M}\right] \qquad (5)$$

The number of over-all gas-phase transfer units is defined as:

$$N_{OG} = -\ln(1-E_{OG}) = \frac{K_G a P Z v}{G_M} \qquad (6)$$

Further, since

$$\frac{1}{N_{OG}} = \frac{1}{N_G} + \frac{mG/L}{N_L} \qquad (7)$$

then

$$\frac{1}{-2.3\log_{10}}\ (1-E_{OG}) = \frac{1}{N_G} + \frac{mG/L}{N_L} \qquad (8)$$

The relationship between the over-all mass transfer coefficient ($K_G a$) and the individual gas ($k_G a$) and liquid ($k_L a$) coefficient is:

$$\frac{1}{K_{OG}a} = \frac{1}{k_G a} + \frac{m}{k_L a} \qquad (9)$$

Since the two resistances (in equation 9) refer to two different mass transfer mechanisms, it is expected that the two will be affected differently by the variable influencing efficiency. Since determination of these factors is nearly impossible for most systems, Gerster correlates the individual film resistances in systems where one phase accounts for all or almost all of the resistance to mass transfer.

Objectives of the present work. Much of the work reported in the literature for determining sieve plate efficiencies present either plate efficiency or the number of transfer units as a function of gas rate, liquid rate and weir height. Rush and Stirba (14) measured sieve plate efficiency for systems whose resistance to mass transfer are in the gas phase. They find that they can correlate their data by the use of the Gerster method. Foss and Gerster (5) correlated plate efficiency for a liquid-film controlled system on sieve trays and found that the most important factors affecting liquid-film efficiency were the interfacial area available within the froth and the time of contact of the liquid with the gas. Jones and Pyle (9) present efficiency data for bubble-cap trays and sieve plates and point out the cost and operating advantages of sieve plates over the bubble-cap tray.

All of these authors present data for determination of efficiency, but none of them attempt to present a general

correlation of efficiency as a function of gas rate, liquid rate and weir height. The experimental program for this study was therefore established to develop a general correlation of plate efficiency as a function of the three operating variables.

Choice of System. The air-ammonia-water system was chosen for this study as this system is easy to handle experimentally and offers a system where the gas-film controls the mass transfer process.

Also, the equilibrium relationship of the system is well known, and because of the low values of m, point and Murphree efficiencies are nearly identical.

Choice of Equipment. In order to stay within convenient ammonia concentration ranges, a single sieve tray was installed in the existing 24-in. diameter column, available in the University laboratories. It was decided to use a superficial perforated area of 7.69%, which was accomplished by the use of 2,534 1/8-in. diameter holes on 3/8-in. equilateral triangular centers (a hole area of 0.219 $ft.^2$). It was felt that the design of this plate would be similar to the general purpose plate used in industry, thus permitting the use of a wide range of the operating variables.

Range of Variables Studied. Liquid rates were varied from 1,740 to 10,700 $lbs./(hr.)(ft.^2)$, gas rates ranged

from 860 to 1,810 lbs./(hr.)(ft.$^2$) and weir heights ranged from zero to 4.70 inches. The gas and liquid rates are based on the superficial tower free area (2.795 ft.$^2$).

It was felt that these ranges of the operating variables would encompass a set of conditions which would yield the maximum efficiency for the plate under consideration. It was also felt that these conditions would yield a general correlation of efficiency which could be used as a basis for the prediction of efficiency at conditions of either high or low gas and liquid rates.

Experimental Plan. To obtain a general correlation of plate efficiency as a function of gas rate, liquid rate and weir height, a statistical program was initiated to develop a second degree polynomial equation which would define the desired quadratic response surface. The general form of this second degree polynomial, for a three variable system is:

$$Y_u = \beta_o + \beta_1 X_{1u} + \beta_2 X_{2u} + \beta_3 X_{3u} + \beta_{11} X_{1u}^2 + \beta_{22} X_{2u}^2 + \beta_{33} X_{3u}^2 + \beta_{12} X_{1u} X_{2u} + \beta_{13} X_{1u} X_{3u} + \beta_{23} X_{2u} X_{3u} \qquad (10)$$

In this equation defining response surface, $Y_u$ (plate efficiency), contains linear terms, squared terms and cross product terms of the variables $X_1$, $X_2$, and $X_3$. These variables represent liquid rate, weir height and gas rate, respectively.

The coefficients in this equation are developed from a series of carefully planned experiments; in this case, a rotatable second order design. Cochran and Cox (1) present a detailed discussion of this statistical approach to an experimental program.

It was felt that the equation would relate the primary variables in such a way that the basic factors affecting the mass transfer operation occuring on the plate will be defined by the second order polynomial expression. Thus, any important interaction terms such as gas rate and liquid rate, gas rate and weir height, and liquid rate and weir height, should be established by the selected statistical program.

The rotatable design is carried out in three parts. In the first part of the program, a $2^3$ factorial experimental design is followed to develop the basic relationship of efficiency to the linear terms of equation (10). This design permits establishment of an equation of the following form:

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 \qquad (11)$$

Interaction terms of $X_1X_2$, $X_1X_3$, $X_2X_3$ and $X_1X_2X_3$ can also be determined from this basic $2^3$ factorial design. Davies (2) presents the method for analyzing the $2^3$ factorial experimental program. These basic experiments indicate the magnitude of the

linear coefficients and the possible significance of interaction terms.

In the second part of the program, a series of experiments are run at selected conditions to obtain the detailed interaction and squared term effects.

The third portion of the program is a series of replicated experiments run at the center of the design to obtain an estimate of the experimental error involved in the program.

The completed program will then permit calculation of the coefficients ($b_o$, $b_1$, etc.) in equation (10). The statistical analysis of these data will then complete the program and define the meaning of the derived coefficients.

A block plan of the experimental program is shown in Figure 1.

Experimental Measurements. At a given gas rate, liquid rate and outlet weir height, measurements were made of inlet and outlet vapor compositions, outlet liquid compositions, vapor and liquid temperatures, froth height and the pressure drop across the plate. Over-all plate efficiency was computed directly from the compositions of the inlet and outlet gas and liquid.

FIGURE 1

EXPERIMENTAL PLAN

| Run No. | Variable $X_1$ | $X_2$ | $X_3$ |
|---|---|---|---|
| 9 | -1 | -1 | -1 |
| 16 | 1 | -1 | -1 |
| 13 | -1 | +1 | -1 |
| 11 | 1 | 1 | -1 |
| 14 | -1 | -1 | 1 |
| 10 | 1 | -1 | 1 |
| 12 | -1 | 1 | 1 |
| 15 | 1 | 1 | 1 |
| 25 | -1.682 | 0 | 0 |
| 26 | +1.682 | 0 | 0 |
| 27 | 0 | -1.682 | 0 |
| 28 | 0 | +1.682 | 0 |
| 23 | 0 | 0 | -1.682 |
| 24 | 0 | 0 | +1.682 |
| 17 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 |
| 19 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 |
| 21 | 0 | 0 | 0 |
| 22 | 0 | 0 | 0 |

In this table, the following coding system has been used:

$X_1 = (L'-35)/15$
$X_2 = (W-1.682 \text{ in.})$
$X_3 = (us-65)/15$

## APPARATUS

A 24-in. inside diameter, single-plate column was employed for this study. The sieve plate was bolted between two flanged sections of the column. A segmental downcomer was welded into each of these sections to handle the plates' feed and effluent water streams. The lower section, 38-in. high, was fitted with two small Lucite windows to permit observation of plate leakage. Two 12-in. by 19-in. Lucite windows, scribed at 1-in. intervals above the plane of the tray, were installed in the upper section of the column to permit measurement of froth height.

The 24-in., 1/8-in. thick plate was perforated with 2,534 1/8-in. diameter holes on 3/8-in. equilateral triangular centers. An inlet weir, 2-1/2 in. high and 20 in. long, was located directly in front of the inlet downcomer. The outlet weirs, 18 in. long, were bolted in the plane of the outlet downcomer. The distance between the inlet weir and the first row of perforations was 1/2 in.; between the last row of perforations and the outlet weir, 1-1/4 in. The length of liquid travel across the active perforated area was 13-1/8 in.

A flow diagram of the equipment is shown in Figure 2, and a detailed plate layout in Figure 3.

FIGURE 2 FLOW DIAGRAM

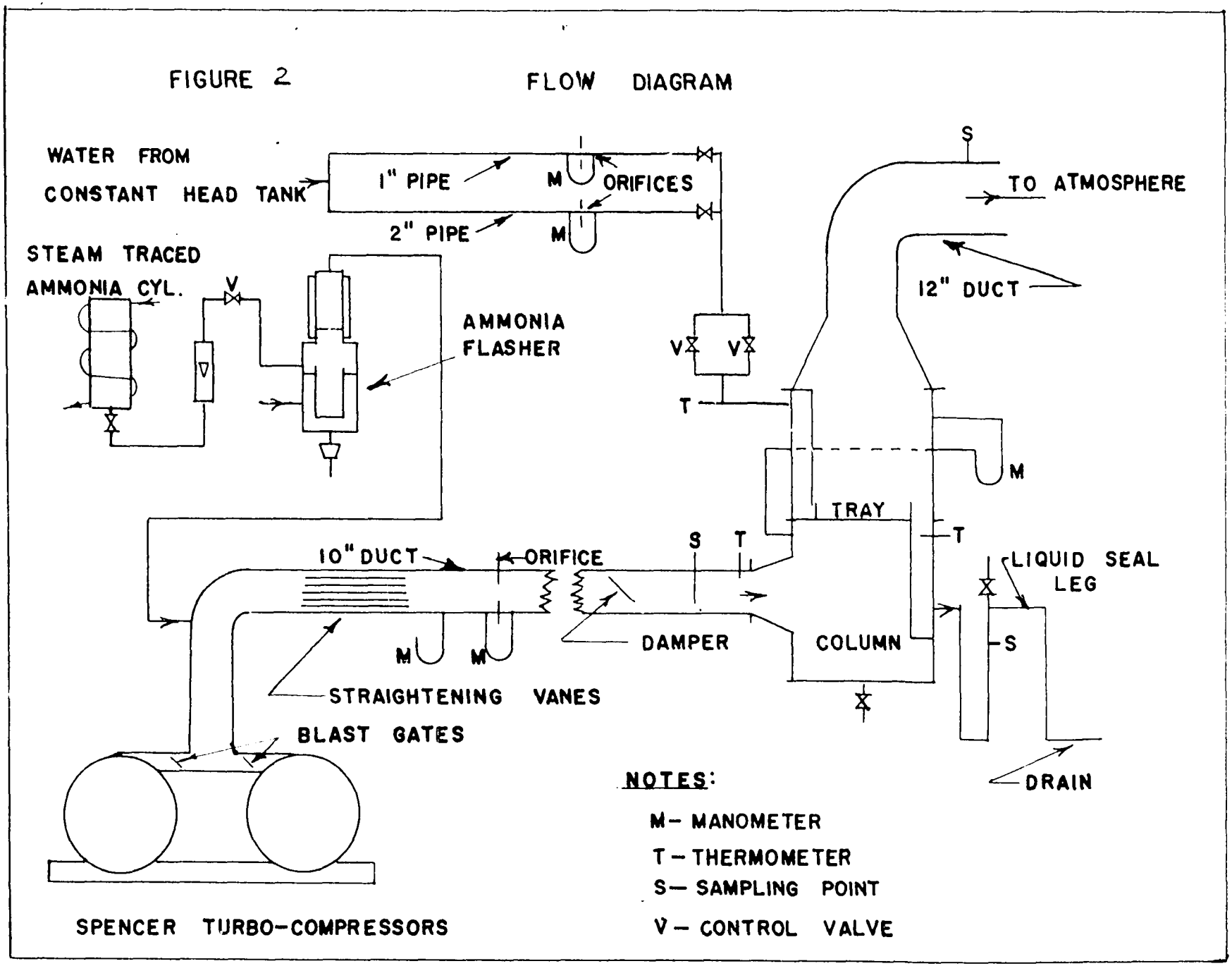
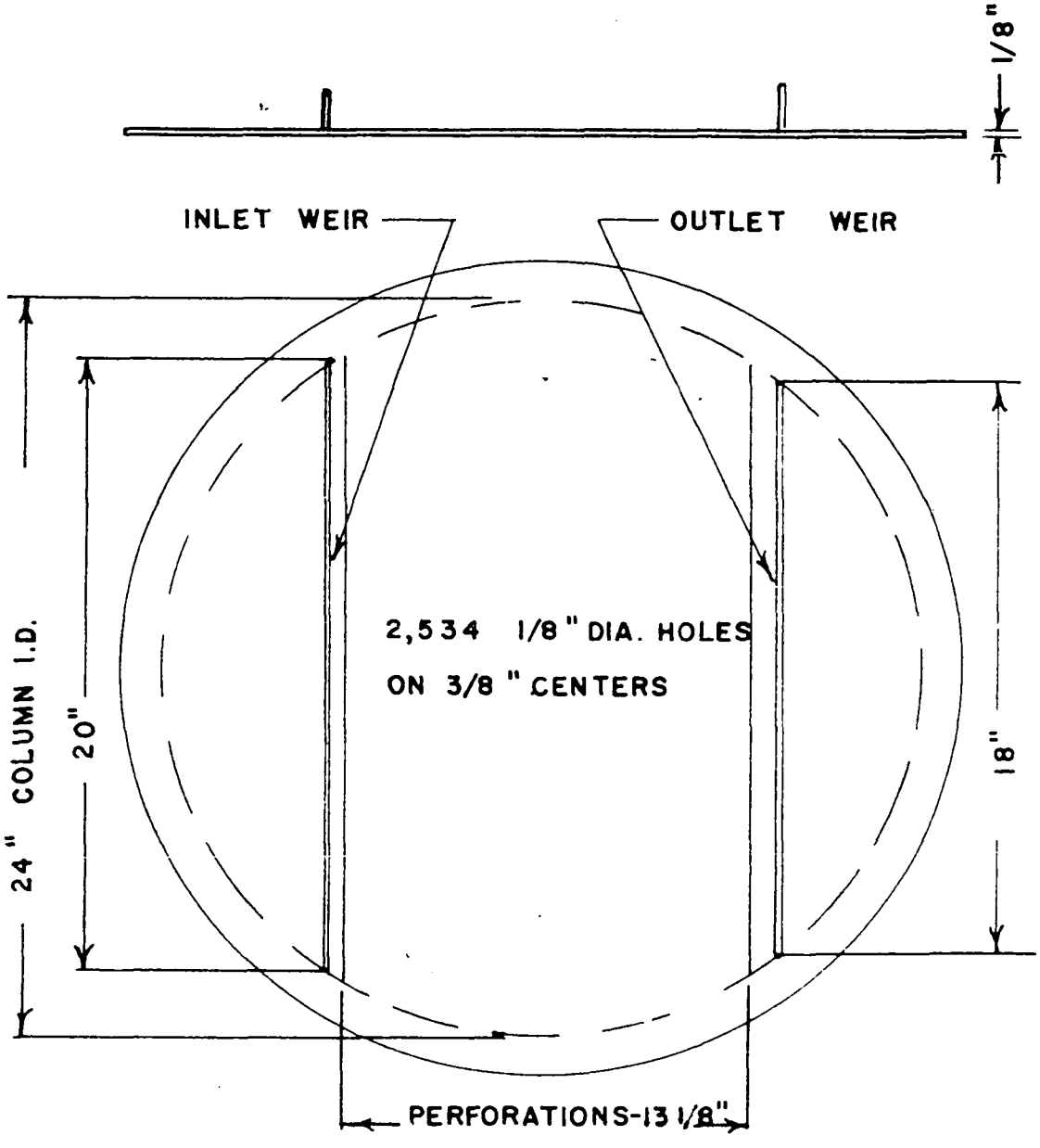


FIGURE 3

PLATE LAYOUT



City water was fed to the column from the building constant-head system. Two brass orifices (1.60 in. and 0.696 in. diameter) for metering water flow were mounted in 18-ft. runs of 2-in. and 1-in. diameter pipe, respectively. The calibration of these orifices is reported by Scriven (15). Flow rates were controlled by means of a 2-in. gate valve and a 1-in. Hancock flow control valve arranged in parallel.

Air was supplied by two Spencer turbo-compressors, each rated at 550 cu. ft./min. at 20 oz., mounted in parallel and connected to the column through a 10-in. diameter galvanized-iron duct. Air flow was controlled by operation of either one or both of the compressors, and by use of a damper installed downstream of the gas metering orifice plate and just upstream of column gas entry port. A 4.900-in. diameter orifice plate was installed in the feed air duct. The orifice was installed 4 ft. from the downstream end of a 17-ft. run of the duct; a 3-ft. length filled with 1-in. straightening vanes was located 5.5 ft. upstream of the orifice. Vena contracta taps were located 10 in. upstream and 6.8 in. downstream of the orifice. A static pressure tap was located 7 in. upstream of the orifice.

Liquid ammonia was drawn from a steam chased commercial cylinder and metered as liquid through a rotameter. The flow rate was controlled by means of a needle valve downstream of the rotameter. The liquid ammonia was then vaporized

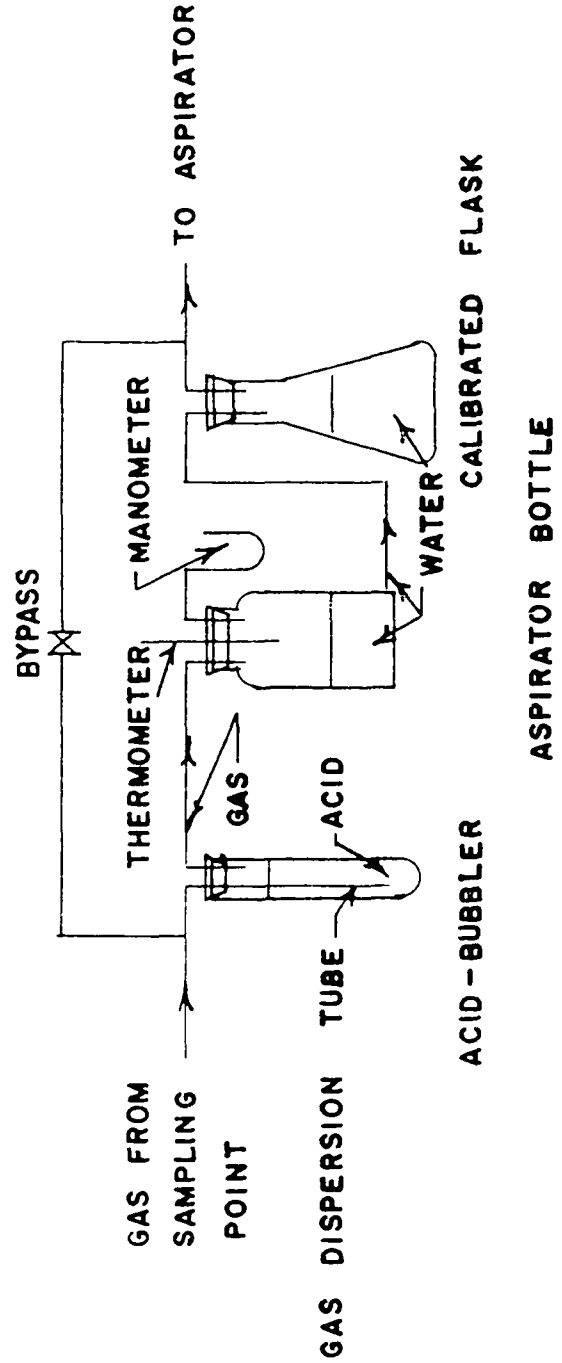
in a steam-heated falling-film flasher, operating at the air supply duct pressure. The vapor passed through an electrically-heated, packed surge chamber where any entrained liquid collected on the packing and was vaporized. The ammonia was injected into the air supply duct at an elbow 2 ft. upstream of the straightening vanes.

Inlet and outlet gas samples are drawn through individual acid-bubblers where the ammonia was absorbed and the residual air was collected over water. The inlet gas-sampling arrangement consisted of: (1) an aluminum probe with several small holes along its length, and sealed at one end; (2) a 15-in. long acid-bubbler containing a fritted gas dispersion tube; (3) a 4-liter aspirator bottle equipped with a thermometer and manometer; (4) a calibrated 2-liter flask; and (5) an aspirator. The probe was inserted in the air supply duct just upstream of its entry into the column. The various components were connected in the order listed with Tygon tubing, with a bypass between the aspirator and a point just upstream of the acid-bubbler. The bypass was installed to permit purging of the sampling system. The outlet gas-sampling train was identical to that used for the inlet gas, with the following exceptions: (1) the outlet gas sample was drawn from a tap mounted flush with the top of the duct wall; and (2) a 2-1/2-liter aspirator bottle was used instead of the 4-liter bottle used in the inlet sampling line.

Figure 4 is a flow diagram of the gas-sampling system.

FIGURE 4

GAS-SAMPLING SYSTEM



The outlet water-sampling tap was located on the drain pipe leading from the column at a sufficient distance from the column to permit complete mixing of the effluent. Six plate probes were installed at various positions on the plate. It was originally anticipated that these probes would serve as a means of obtaining liquid point samples. As the work progressed, it was found to be an impossibility to obtain a liquid sample from these point probes. It was felt that blanking off a portion of the plate around these probes was not a feasible solution to this sampling problem since there was no area in the active bubbling length of the plate which contained anything resembling a clear liquid seal. Another set of three sampling points was located in the outlet downcomer just below the upper edge and in the plane of the sieve tray.

Thermometers were provided for obtaining the temperatures of the gas entering, of the liquid entering and of the liquid leaving the column. The pressure drop of the air passing through the tray was measured by means of a manometer across the plate. Two other manometers were installed above and below the plate to measure the static pressure in the upper and lower sections of the column.

## RUN PROCEDURE, ANALYSIS AND EXPERIMENTAL MEASUREMENTS

In order to carry out a run, the predetermined air and water flow rates were established. After having established these rates, the ammonia rate was set to give a 1% to 2% by volume ammonia concentration in the inlet gas stream. The system was then allowed to come to equilibrium, a period which was at least 5 to 7 minutes (15). In most cases, sampling was started 10 to 12 minutes after starting the ammonia feed. The gas-sampling lines were purged continuously and were ready for sampling after the ten-minute equilibration period.

The inlet and outlet gas streams were sampled by passing a 2000 cc. portion of each stream through about 85 cc. of acid-scrubbing solution. The acid was contained in the 15-in. long acid-scrubbing tube; sufficient acid was added to the solution to provide at least a 200% excess of the acid actually required to neutralize all the ammonia in the sample. The ammonia-free air was then collected over water in the aspirator bottle, which had originally been completely filled with water. The volume of air was measured by the amount of water drawn from the bottle into the calibrated two-liter flask. After shutting off the feed to the sampling train, the temperature and pressure of the air in the aspirator were recorded. An excess of dilute caustic was then added to the acid from the

acid-scrubbing tube. This sample was titrated with dilute acid to the bromphenol blue indicator end point. Previous work by Scriven (15) shows that ammonia absorption was complete when using the aforementioned procedure. In all of the experimental runs the outlet gas samples were free of entrained liquid, for it was observed that no moisture appeared in the gas-sampling line at any time.

The compositions of the liquid samples leaving the plate were found to be constant (maximum deviation noted was ± 1%) after steady state operations were achieved on the plate. Three instantaneous outlet liquid samples were taken from the drain pipe during the gas-sampling operations. Sufficient sample was taken to fill a 250 cc. ground-glass stoppered flask. These samples were analyzed immediately by titration with dilute acid to a bromphenol blue indicator end point.

During the gas-sampling period, the various manometer and thermometer readings were recorded. Spray and froth height, observed as the average height above the tray, were also recorded at this time.

# R E S U L T S

Table III in the Appendix presents a summary of the experimental data and the computed Murphree plate efficiencies for all acceptable runs.

Material Balances. A meterial balance for ammonia has been calculated for each run as pounds of ammonia absorbed in the water leaving the tray per unit time divided by pounds of ammonia stripped from the gas passing through the tray per unit time, expressed as percent. The average material balance is about 90%.

All but one of the material balances ranged from 88% to 94%. These balances were considered acceptable as some water is always in the space below the tray. The incoming gas containing ammonia contacts this liquid before passing through the tray and thereby loses a small portion of the ammonia. The liquid in the bottom of the tower is continuously replenished by plate leakage. In all cases this leakage was small compared to the bulk of liquid flowing across the plate. This loss of ammonia is reflected in the material balances obtained. It accounts at least for a part of the deviation of the balance from the 100% expected value. The remaining portion of the difference is undoubtedly due to analytical errors.

Murphree Plate Efficiencies. Plate efficiency on a vapor basis has been calculated by the formula:

$$E_{MV} = \frac{Y_{in} - Y_{out}}{Y_{in} - mX_{out}} \qquad (12)$$

where $Y_{in}$ denotes the experimentally measured inlet gas composition. It was considered to correct the inlet gas composition to a pseudo value where the pseudo value represents a value calculated from the outlet gas and liquid compositions. This method of calculation was tested, but the moderate variation in the inlet composition had little effect on the efficiency, owing to the nature of equation (12) and to the high solubility of ammonia in water.

The slope of the equilibrium curve, m, was evaluated at the average temperature of the liquid on the tray, using the ammonia-air-water equilibrium data taken from Scriven (15). These data are plotted in Figure 16 and are presented in the sample calculation section in the Appendix.

Point and Transfer Efficiencies. The experimental program was concerned with the measurement of Murphree plate efficiency; however, it is of interest to relate these measured efficiencies to the more fundamental point efficiency (or transfer efficiency, in the case of sieve trays). W. K. Lewis, Jr. (10) has shown that the point efficiency is identical to the plate efficiency when the vapor beneath the tray is of uniform

composition and when the liquid on the tray is well mixed. The other extreme condition of plate behavior is "plug flow", i.e., there is no back mixing of liquid in the direction of liquid travel. In this case the largest difference between point and plate efficiency is observed. In the case of plug flow (10) the two efficiencies are related by:

$$E_{OG} = \frac{1}{mG_M/L_M} \ln(1+E_{MV}mG_M/L_M) \qquad (13)$$

Hence, for the limiting case,

$$E_{OG} = E_{MV} \qquad (14)$$

as $mG_M/L_M \rightarrow 0$

It can be seen that for sufficiently small values of $mG_M/L_M$, the two efficiencies will be very nearly equal regardless of the mixing situation. At all experimental conditions of liquid and gas flows, it was apparent that mixing was taking place in the bulk of the liquid on the tray. Since the value of $mG_M/L_M$ is small for all the runs, and since mixing of froth was observed in the experiments, it is concluded that the measured plate efficiency and point or transfer efficiency are identical.

Selection of the Range of Operating Variables. Before planning the statistical program, a series of runs were made to select maximum and minimum gas and liquid rates which would result in stable tray behavior. The so-called stable tray conditions were determined by arbitrarily observing plate leakage and liquid entrainment in the outlet gas at several weir heights

while varying the gas and liquid rates. For the tray used in this study, the lower limit of gas rate was at a slot velocity of about 40 ft./sec. At this condition, plate leakage was fairly large but was not considered to be severe enough to require the use of a larger value for minimum gas rate. The upper gas rate, approximately a slot velocity of 100 ft./sec., was limited by the capacity of the Spencer Turbo-compressors. At this rate, a fair amount of fine spray was entrained in the outlet gas stream. These drops were observed to be coalescing in the canvas portion of the outlet duct. The upper limit of gas rate was therefore set at a value of 90 ft./sec., where little or no coalescing of spray was noted in the outlet duct.

Liquid rates in the column were determined by the effects of weir height, gas rate and outlet down-comer froth handling capacity. Thus, at a zero weir height, sufficient liquid had to be passed across the tray to prevent the tray from "blowing dry". This condition occurs at low liquid rates when the gas rate was maintained at conditions near the center of design gas rate (a slot velocity of 65 ft./sec.). It was found that liquid rates of about 25 to 35 gpm would prevent the tray from blowing dry at the zero weir height condition. A water flow rate of 35 gpm was then established for the center of design condition. The upper limit of liquid rate, 60 gpm, was determined by the head of water available in the constant head water system.

With the gas range limits set at slot velocities ranging from 40 to 90 ft./sec., and liquid rates of 35 gpm at the center of design and 60 gpm at the upper flow limit, weir heights were varied to determine the range of stable operation. During this evaluation specific sets of conditions were found where froth built up in the outlet liquid down-comer and resulted in an exaggerated froth depth on the plate. It was further found that, in some cases, the froth on the plate and in the down-comer could be reduced to permit normal operation when ammonia was fed to the inlet gas stream. Since it was of interest to include zero weir height in our experimental design (representing a condition of minimum froth height and liquid hold-up on the plate), weir heights for the statistical program were varied from zero to 3.36 inches.

Measurement of Froth Height. The characteristic of the froth was observed at all operating conditions. It was difficult to define the froth height to better than $\pm$ 1 inch in most of the runs. The reason for placing this limit on froth height is due to the physical appearance of the aerated mass of liquid above the tray. In all cases the froth on the tray can be broken down into three zones:

(1) Zone 1 represents an area of froth directly above the tray.

(2) Zone 2 represents an area of large entrained drops of liquid ripped out of Zone 1 by the

gas stream. These drops tend to drop back on the plate, but usually at a point down the tray and along the path of liquid travel.

(3) Zone 3 represents an area of fine spray droplets that are carried at least 21 inches above the level of the tray and which, on coalescing with themselves or the column's interior surfaces, return to the liquid on the tray.

The froth heights reported in Table III of the Appendix are an attempt to differentiate between Zones 1 and 2. This attempt was made because Zone 2 spray height was found to vary greatly at different gas rates. This zone consisted of liquid drops riding in a continuous air stream while Zone 1 was considered to be an area of aerated liquid where a continuous liquid film contained gas bubbles of varying sizes. Since we could not estimate the amount of liquid, the size or number of the drops in Zone 2, this area for mass transfer doesn't offer a means of correlation to the operating variables. The froth height (Zone 1) can be related to the operating variables; however, it should be realized that it was very difficult to find a sharp interface between Zones 1 and 2 and therefore, froth height varies over a fair range to include what appeared to be the zone interface condition.

Statistical Design. In planning the statistical program, the rotatable design was selected for the experimental work. This plan (shown in Figure 1 of the previous Introduction And Background Section) permits ready calculation of experimental error and permits easy determination of the coefficients of the linear and second order terms in the proposed polynomial equation. Table I presents a summary of the meaning of the coding symbols used in the statistical program.

TABLE I

SUMMARY OF STATISTICAL CODING

| Coding Symbol $X_1$, $X_2$ or $X_3$ | Variable | | |
|---|---|---|---|
| | Liquid Rate, gpm | Weir Height, inches | Gas Rate, $u_g$, fps. |
| 0 | 35 | 1.682 | 65 |
| + 1 | 50 | 2.682 | 80 |
| - 1 | 20 | 0.682 | 50 |
| + 1.682 | 60 | 3.364 | 90.23 |
| - 1.682 | 9.8 | 0 | 39.77 |

NOTE:

The resulting code is therefore:

Liquid Rate: $X_1 = (L'-35 \text{ gpm})/15$

Weir Height: $X_2 = (W-1.682 \text{ in.})$

Gas Rate: $X_3 = (u_g-65 \text{ ft./sec.})/15$

The experimental data were correlated very well by the proposed second degree polynomial equation. The final form of the equation was:

$$E_{MV} = 79.43 + 2.37X_1 + 6.76X_2 - 0.14X_3 + 1.75X_1X_2 - 1.33X_1X_3 + 1.52X_2X_3 - 0.28X_1^2 - 1.53X_2^2 + 0.42X_3^2 \quad (15)$$

The coding symbols for gas rate, liquid rate and weir height are used in the derived expression to keep working values of the variables as small numbers.

Several terms in equation (15) have little significance when compared to the mean square of the experimental error. These terms are the $X_3$, $X_1^2$ and $X_3^2$. They have, however, been used in all calculations utilizing the derived correlation. The statistical program calculations are presented in the Appendix.

Equation (15) was utilized to prepare a series of efficiency contours at gas slot velocities of 50 ft./sec. ($X_3 = -1$), 65 ft./sec. ($X_3 = 0$) and 80 ft./sec. ($X_3 = +1$). These efficiency contours are presented in Figures 5, 6 and 7.

FIGURE 5

MURPHREE PLATE EFFICIENCY CONTOURS AT THE GAS RATE LEVEL, $X_3 = -1$

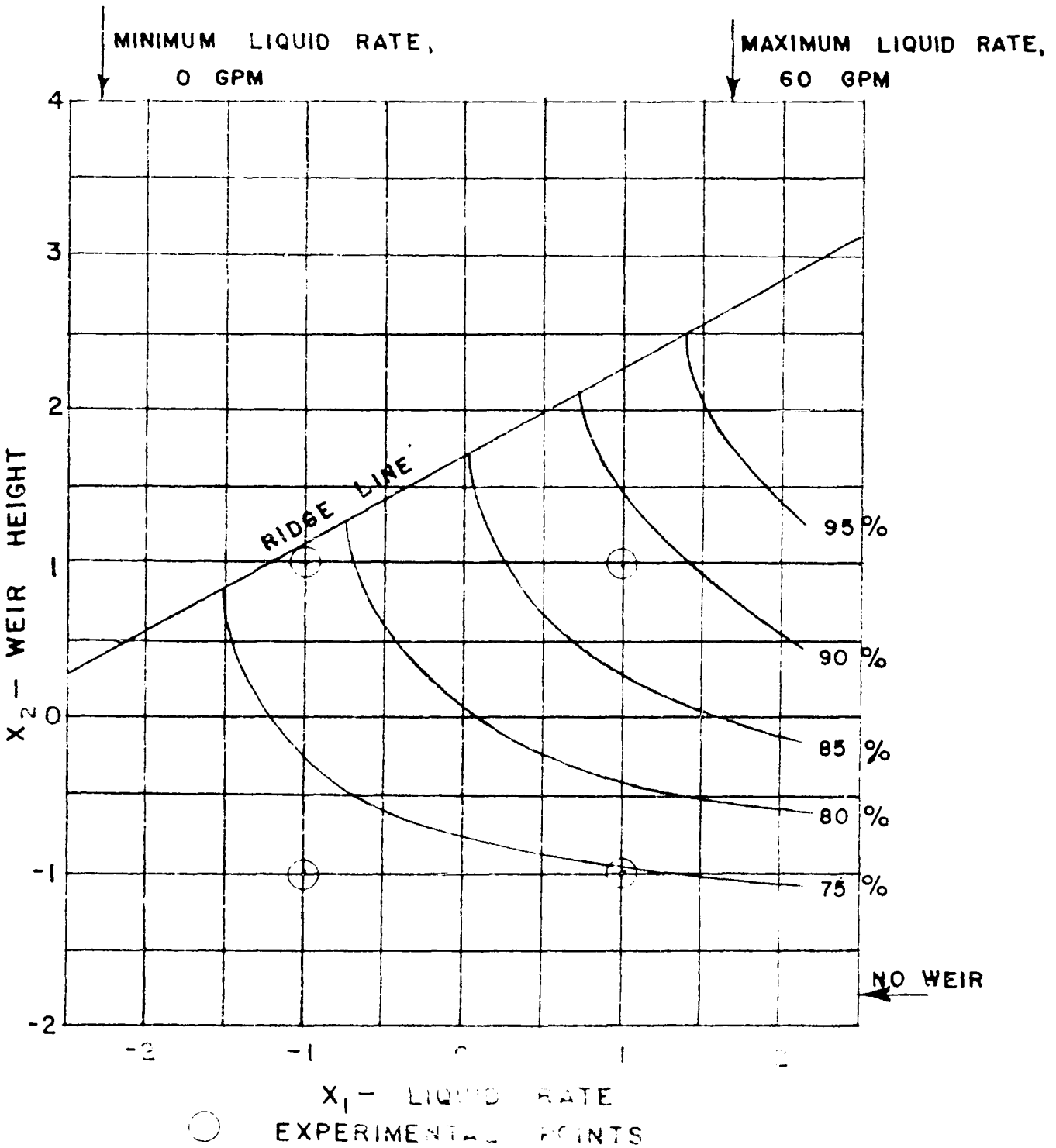


FIGURE 6

MURPHREE PLATE EFFICIENCY CONTOURS

AT THE GAS RATE LEVEL, $X_3 = 0$

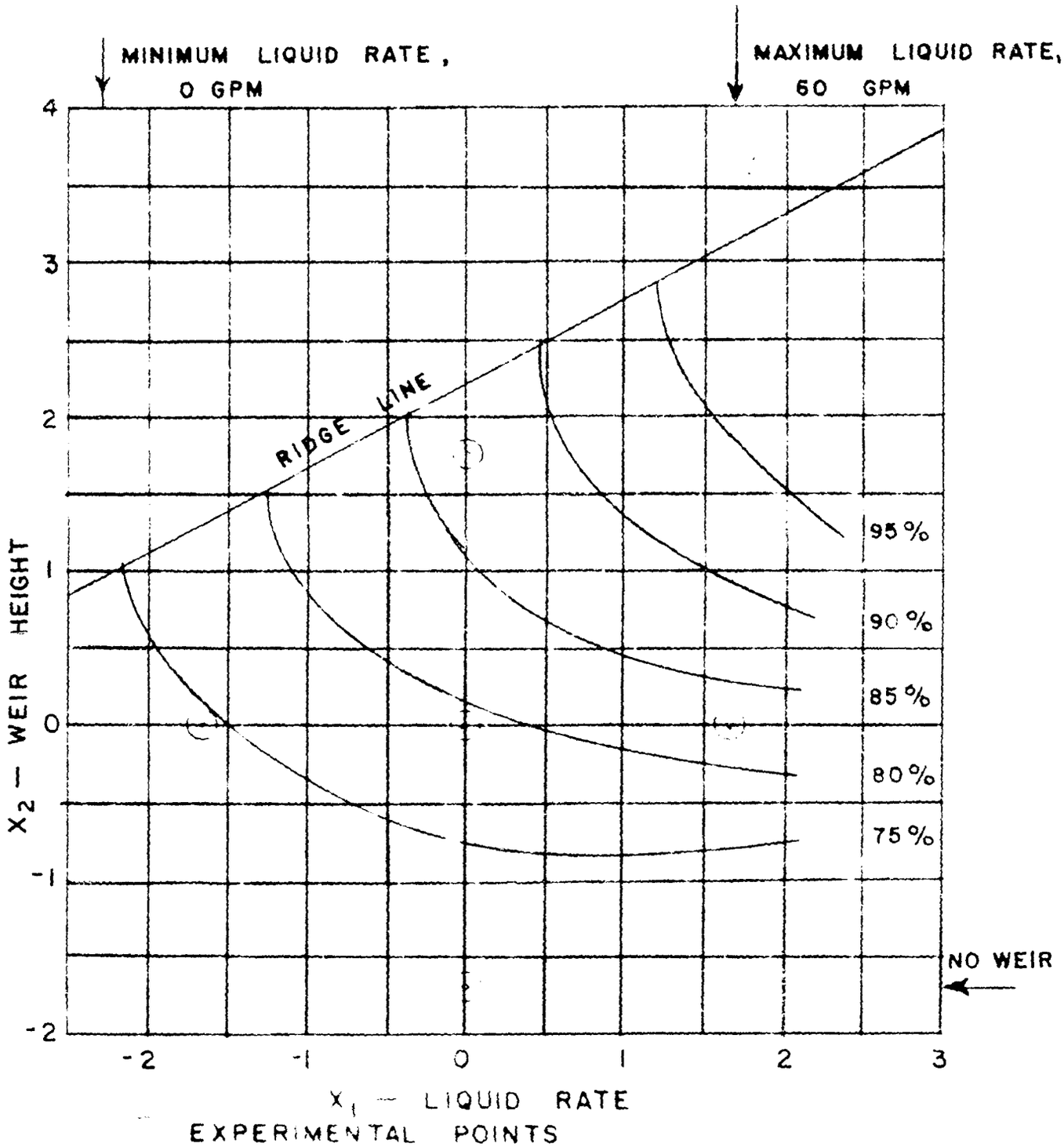
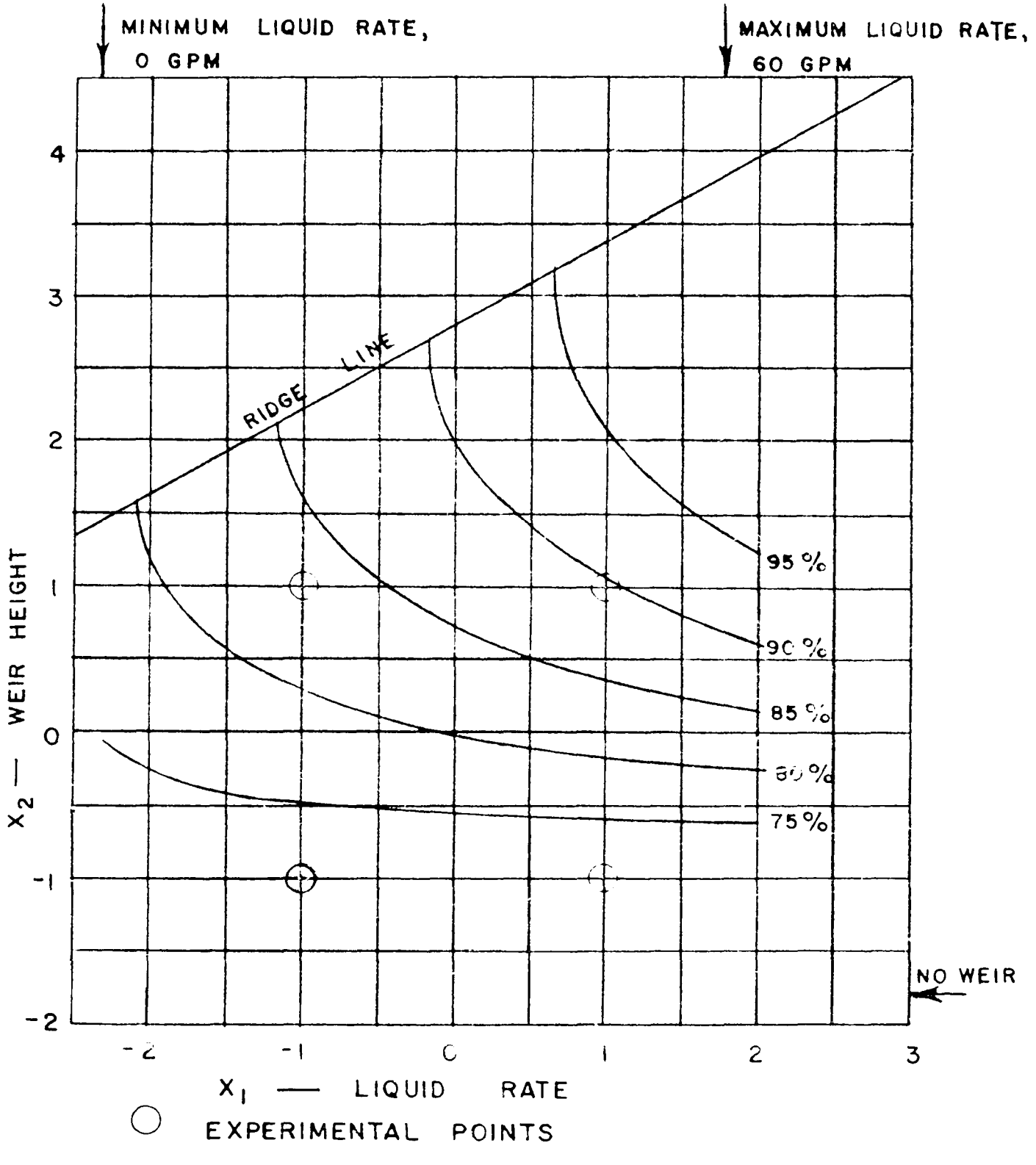


FIGURE 7

MURPHREE PLATE EFFICIENCY CONTOURS AT THE GAS RATE LEVEL, $X_3 = 1$



The foregoing figures present lines of constant Murphree plate efficiency as a function of the fixed gas rate and various combinations of weir height and liquid rate. The ridge line presented on the plot represents the turning point of a parabolic equation, and solutions of equation (15) above this line are discarded as being unreal values. Various points of the experimental plan are included on the figures in order to present the range of the experimental data used to derive the contour maps. The various experimental point efficiencies represented on these figures fall on efficiency contour lines which lie between the lines that have been plotted. The close agreement of the experimental data and equation (15) calculated efficiency is presented in Table VII of the Appendix. The maximum deviation noted is less than $\pm$ 2.55% efficiency units, which is the maximum deviation expected by experimental error.

The individual efficiency contour presents a line which can be interpreted to represent the affect of liquid hold-up and froth height on efficiency, and, of course, relate these factors to the particular condition of weir height and liquid rate required to attain these conditions. The most effective way of increasing the liquid hold-up is, of course, by increasing the weir height on the tray. Changing weir height also increases the frothing action on the tray at any given set of liquid and gas rates. Because of this general relationship we find small changes in weir height at constant liquid rates result in a rapid increase in efficiency.

Increasing liquid rate at constant weir height and gas rate primarily increases the froth height on the tray and thus results in an increased contact time of the gas and liquid on the plate. We, therefore, find that liquid rate has a smaller effect on efficiency than does the weir height.

The effect of gas rate cannot be seen by inspection of any single efficiency contour map. However, if the three contour maps are examined as a series, it can be seen that the ridge line displaces upwards and the efficiency contours to the left as gas rate is increased by moving from Figure 5 to Figure 6 to Figure 7. The terms in equation (15) which are responsible for this effect are the interaction terms of gas rate and liquid rate ($X_1X_3$) and gas rate and weir height ($X_2X_3$) as the linear and squared gas rate terms are small.

At constant weir height and liquid rates the interaction term $X_2X_3$ has more significance than the term $X_1X_3$, i.e., the $X_2X_3$ coefficient is + 1.52 and the coefficient of the $X_1X_3$ term, - 1.33. These two terms represent the effect of the interaction terms on gas-liquid contact time and available interfacial area for mass transfer.

Equation (15) has also been utilized to prepare a series of curves which present efficiency as a function of weir height at various liquid and gas rates. These figures, Figures 8, 9 and 10, are cross-plots of efficiency contours presented in Figures 5, 6 and 7.

FIGURE

MURPHREE PLATE EFFICIENCY AS A FUNCTION OF WEIR HEIGHT AT

GAS SLOT VELOCITY, $u_s$ = 80 fps
AND INDICATED LIQUID RATES

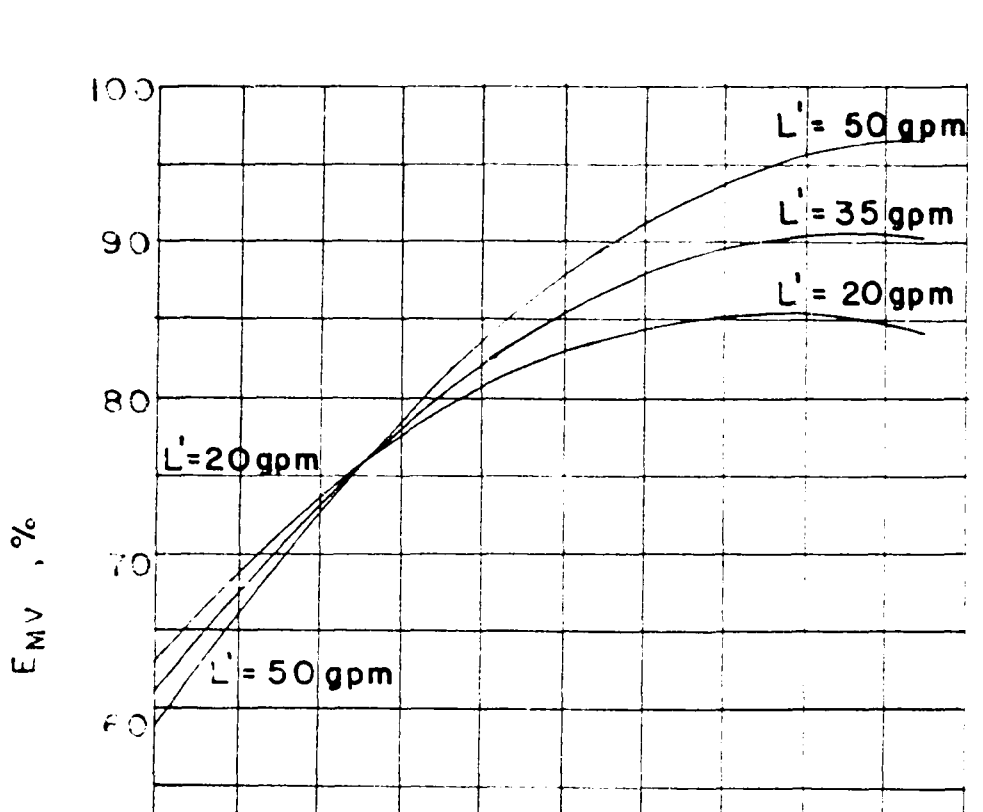
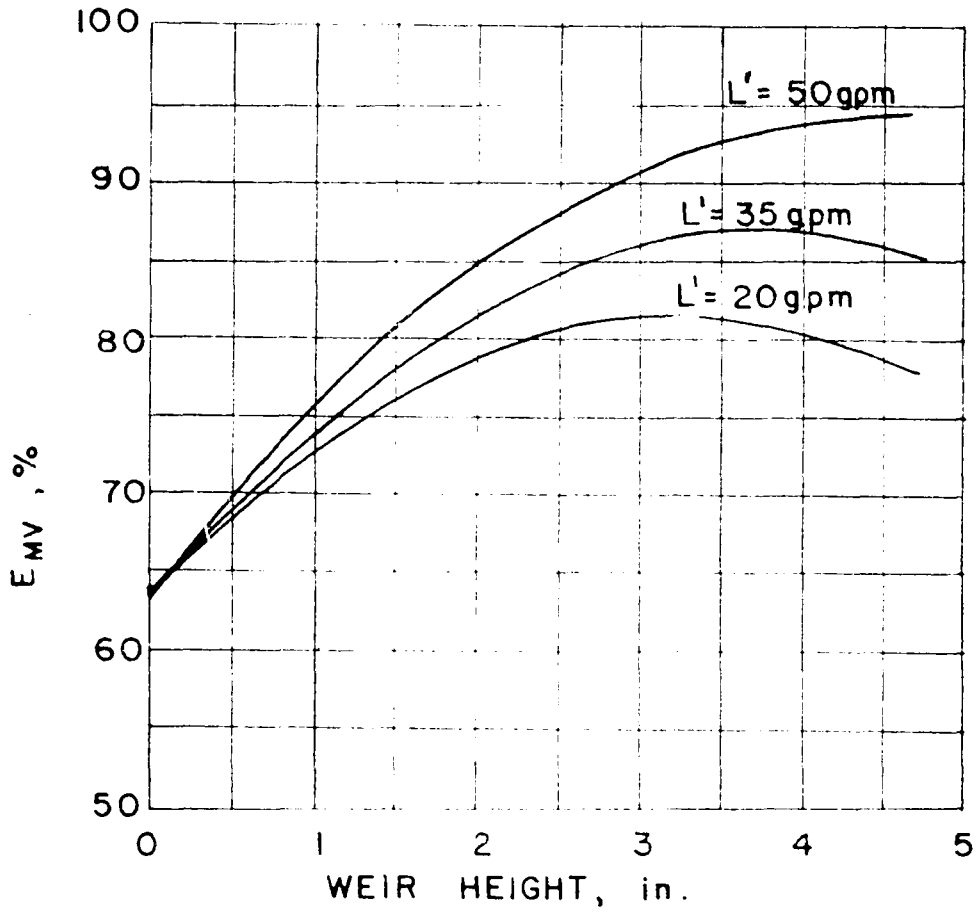


FIGURE 9

MURPHREE PLATE EFFICIENCY AS A FUNCTION OF WEIR HEIGHT AT GAS SLOT VELOCITY, $u_s$ = 65 fps AND INDICATED LIQUID RATES

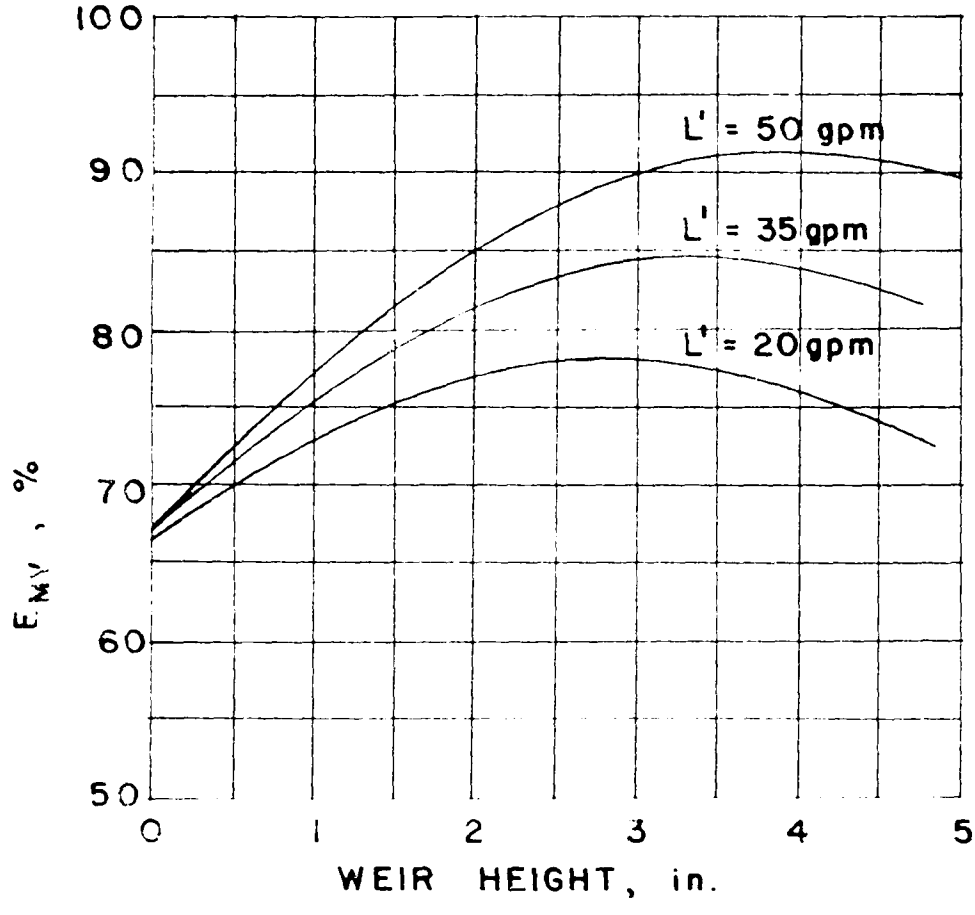


FIGURE

MURPHREE PLATE EFFICIENCY AS A FUNCTION OF WEIR HEIGHT AT

GAS SLOT VELOCITY, $u_s$ = 50 fps

AND INDICATED LIQUID RATES



The general features of Figures 8, 9 and 10 require some interpretation. The interesting aspects of these plots are the prediction of an optimum efficiency at the larger values of weir height, and the convergence (actual cross-over) of the efficiency curves at the lower weir heights.

The cross-over of efficiency lines shown on Figure 8, occurs at a weir height of about 1-1/4 in. and indicates a decreased efficiency at lower weir heights as the liquid rate is increased. This appears to be an anomalous effect as one would expect to observe increased froth height and, therefore, increased gas-liquid contact time and increased efficiency as the liquid rate is increased. To explain the actual results, one must examine the experimental data for two runs at a gas slot velocity of 80 ft./sec. and a weir height of 0.682 in. The liquid rates for these runs were 20 and 50 gpm, respectively. In the 50 gpm case, a stable 6 to 8 in. liquid froth height was observed, while at the 20 gpm rate a violently agitated 5 to 8 in. froth height was noted. Efficiencies were 70.80% for the 50 gpm run and 71.46% for the 20 gpm run. One other experimental observation that is significant is the character of the liquid spray above the tray. At the 20 gpm rate, large diameter liquid drops were carried by the gas as much as 21 inches above the tray, while at the 50 gpm rate, these large diameter drops were confined to a normal height of about 12 inches above the tray. It can be concluded that the greater amount of large diameter liquid drops

observed at the 20 gpm liquid rate afford an increased mass transfer area and gas-liquid contact time which results in a net increase in plate efficiency above the value one would expect if a stable liquid froth had been developed on the tray.

At the 80 ft./sec. gas slot velocity and weir heights of 2.682 in., a stable froth was observed at both the 20 and 50 gpm liquid rates. In this case, an excess amount of large diameter liquid drops were not observed at the lower liquid rate, and one observed a significantly higher plate efficiency at the higher liquid rate.

The cross-over or convergence of efficiency lines is, therefore, attributed to a condition of unstable plate operation; in this case, the failure to establish sufficient liquid head on the plate to cause attainment of a stable liquid froth.

The maximum values obtained in the curve at the greater value of weir height is felt to be real and not due to a fault of the statistical program. One might expect that increasing the depth of liquid on a plate would always result in increased gas-liquid contact time and, therefore, increased efficiency. This would be true if the plate were always in stable operation at the higher weir depth, but we noted that as weir height increased (in the 3 to 5 in. weir height region), the froth on the tray surged violently across the plate. This surging action created some liquid depths greater than the

average froth height, and others much lower. Streams of gas could be seen jetting through the plate at these operating conditions and undoubtedly reduced gas-liquid contact time by gas short circuiting. The exact upper applicability limit of these curves should be considered to be about 3 to 4 inches. At this weir height it is felt that the plate is still in stable operation.

Extension of Experimental Data. Three runs were conducted at gas slot velocities of about 80 ft./sec. and three combinations of weir heights and liquid rates to see if the statistical equation would successfully predict efficiencies outside the range of the original experimental design. Table II presents a summary of run conditions, predicted and observed efficiencies.

TABLE II

TEST OF STATISTICAL EQUATION

| Variable | | | Murphree Efficiency Predicted By Equation (15), % | Observed Efficiency, % | Run |
|---|---|---|---|---|---|
| $X_1$ | $X_2$ | $X_3$ | | | |
| 1 | 3.00 | 1 | 96.79 | 91.28 | 31 |
| 1 | 2.05 | 1 | 94.61 | 93.58 | 29 |
| 0 | 2.05 | 1 | 90.26 | 91.33 | 30 |

The agreement of the predicted and experimental data are rather good for runs 29 and 30, and it is safe to say that the

equation can be used to predict efficiency values at points which are not far removed from the range of the variables covered in the original experimental design. The comparison of predicted and observed efficiency for run 31 shows a difference which is significantly greater than one would expect from experimental error. The results of this run might have been predicted to show a decrease in efficiency as the plate was operating at what appeared to be a rather unstable condition. This combination of gas rate, weir height and liquid rate gave an operation which was characterized by surges of liquid in the direction of gas flow which probably resulted in short circuiting a fair portion of the gas, on a time basis, through a shallower depth of liquid, and therefore resulted in a decrease in efficiency.

From these experiments, the statistical study, and preliminary experimental work, it is concluded that the statistically derived equation is valid in the range of operating variables studied and may be used at other operating conditions, if these conditions do not represent a region of unstable plate operation. It is also concluded that this equation is specific for the particular plate design used in this study. Additional experimental work is required on the effects of variations in plate design to enable development of a more general equation that could be used successfully to predict plate efficiency for any of the many possible plate designs.

# DISCUSSION

The statistical program followed in this work leads one to the conclusion that weir height and liquid rate are the two most important factors in determining plate efficiency. It was originally hoped that sufficiently consistent data on froth height could be obtained from this work to develop a second order polynomial expression which would have correlated froth height to the operating variables as has been done for plate efficiency. However, since the physical characteristics of the froth are different at nearly all combinations of the operating variables, it is now felt that this type of quantitative treatment is not possible. It is still, perhaps, valid to compare the general trends in froth height and plate efficiencies to various combinations of the operating variables. This approach has been used to prepare Figures 11, 12 and 13, which present predicted plate efficiencies, froth heights and experimental efficiency at the center of the experimental design. Each figure, therefore, has two of the operating variables fixed and shows the effect of the other variable on efficiency and froth height. The curve representing froth height in each case presents a smooth curve through the $\pm$ 1.682 and 0 coded value observed conditions.

FIGURE 11

PREDICTED MURPHREE PLATE EFFICIENCY AND FROTH HEIGHT AS A FUNCTION OF GAS RATE AT THE DESIGN CENTER

WEIR HEIGHT, $X_2 = 0$; 1.682 in.

LIQUID RATE, $X_1 = 0$; 35 gpm

○ EXPERIMENTAL EFFICIENCY DATA

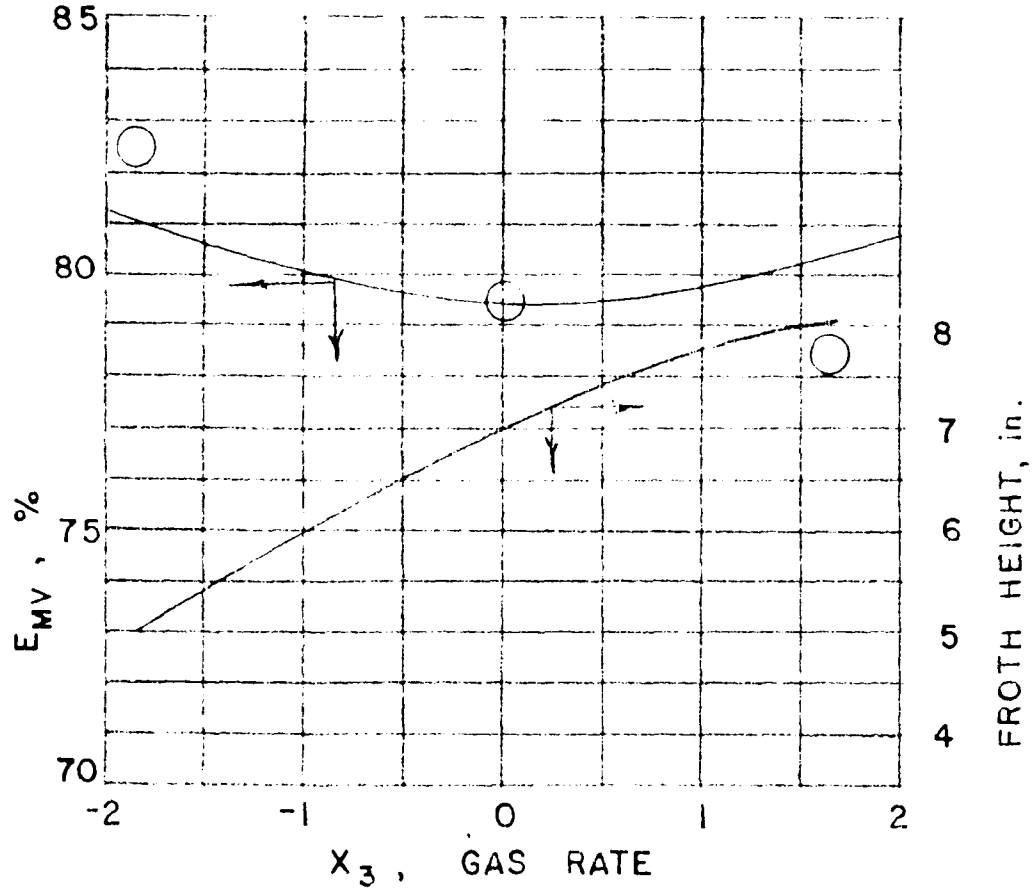


FIGURE 12

PREDICTED MURPHREE PLATE EFFICIENCY AND FROTH HEIGHT AS A FUNCTION OF WEIR HEIGHT AT THE DESIGN CENTER

LIQUID RATE, $X_1 = 0$; 35 gpm

GAS RATE, $X_3 = 0$; 65 fps

○ EXPERIMENTAL EFFICIENCY DATA

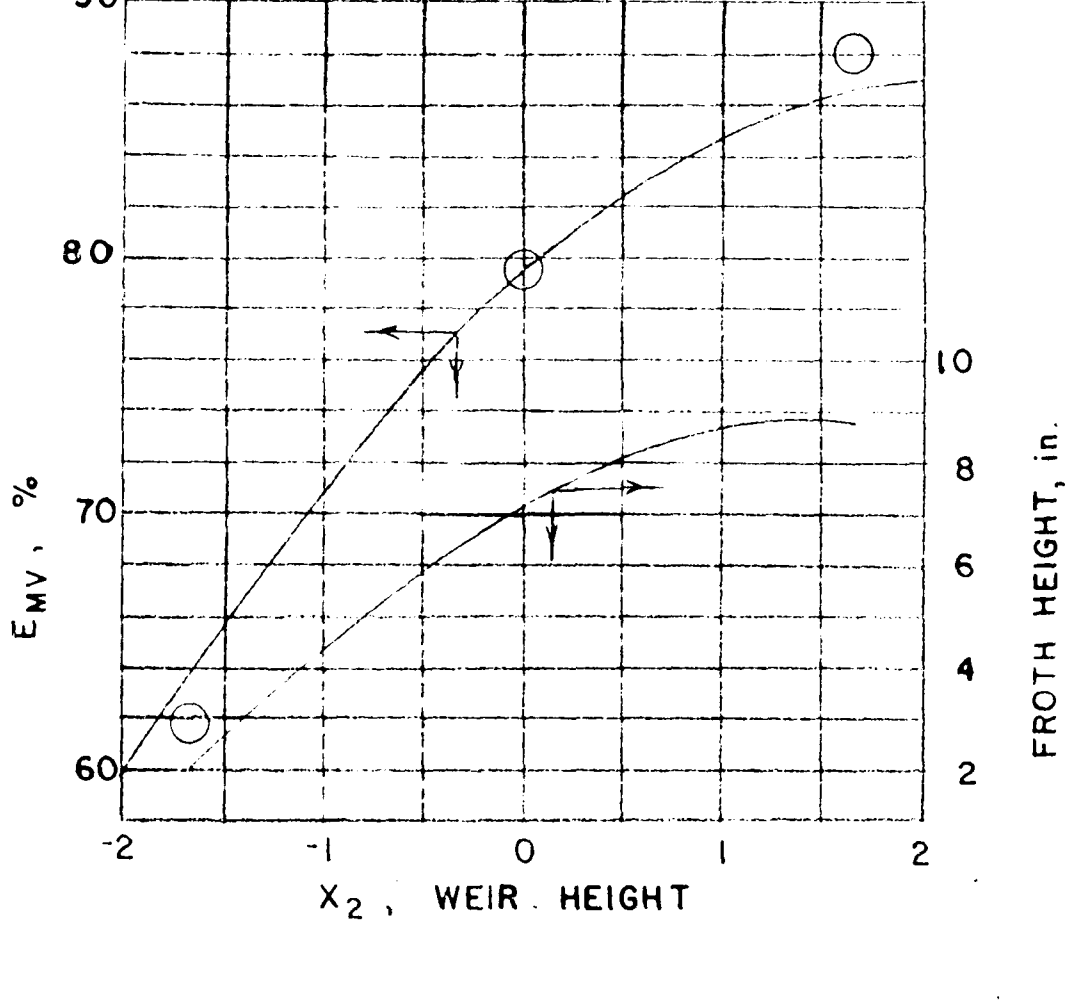


FIGURE 13

PREDICTED MURPHREE PLATE EFFICIENCY AND FROTH HEIGHT AS A FUNCTION OF LIQUID RATE AT THE DESIGN CENTER

WEIR HEIGHT, $X_2 = 0$ ; 1.682 in.

GAS RATE, $X_3 = 0$ ; 65 fps.

○ EXPERIMENTAL EFFICIENCY DATA

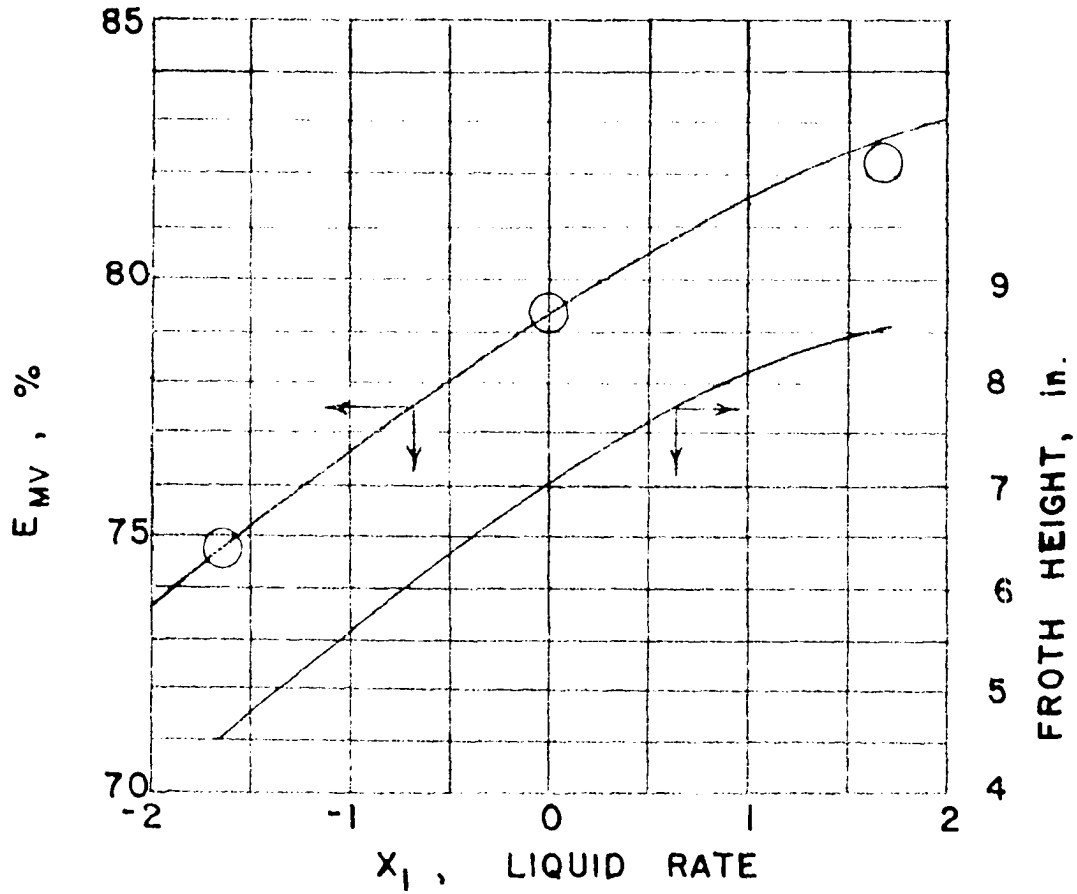


Figure 11 indicates the effect of gas slot velocity, varied from 40 ft./sec. ($X_1 = -1.682$) to 90 ft./sec. ($X_1 = +1.682$), on plate efficiency. The most striking condition that presents itself here is the deviation of the experimental points from the predicted efficiency curve. Although the difference between the experimental points and predicted curve is within the maximum deviation expected by experimental error, it is felt that at the extreme values of gas rate a condition of higher than usual plate leakage (at 40 ft./sec.) and greater than usual entrainment of liquid (at 90 ft./sec.) cause the experimental points to be displaced from the position they would occupy if these aforementioned operating problems did not exist. Thus, if plate leakage were less, it would be expected that one would observe a decrease in efficiency (40 ft./sec.); and, if entrainment were less, one would expect to observe an increase in efficiency (90 ft./sec.). The curve for froth height shows a steady increase in froth as the gas rate is increased. Since the liquid rate and weir height are constant, one would anticipate a slightly increased gas-liquid contact area as the frothing action of the plate increases and therefore, predict an increase in efficiency. The basic assumption in the last statement is: one must truly generate more interfacial area for mass transfer by increasing the gas velocity. Another way of stating this argument is: at higher gas rates, one should observe an increase in the number, but not size, of the gas bubbles rising through the liquid phase, thus maintaining a high interfacial area per unit volume of gas.

In actual operation, however, we find that at the higher gas rates we observe a greater coalescing of the gas bubbles. This effect leads to increasing the surface area of a bubble, but not to an increase in the surface to volume ratio of the active bubbles. It might, therefore, be expected that increased gas rates, although increasing froth height, do not increase mass transfer area and, therefore, we should not anticipate an increase in efficiency. Decreased gas-liquid contact time at higher gas rates would also tend to decrease plate efficiency.

Statistically, we would predict that gas rate itself does not contribute to plate efficiency, but combination of gas rate and liquid rate, and gas rate and weir height, do contribute significantly to plate efficiency.

Figure 12 presents the efficiency curves and froth height curves as weir height was varied from zero in. ($X_2 = -1.682$) to 3.364 in. ($X_2 = +1.682$) at constant gas and liquid rates. The efficiency curve and froth height curves increase markedly as weir height is increased. This increased froth height primarily represents a large increase in gas-liquid contact time, and therefore, results in increased plate efficiency. The nature of the froth in this case changed less markedly than it did in the varying gas rate example. Larger diameter gas bubbles were formed as the depth of liquid on the plate increased but these bubbles always had an increasing contact time for mass transfer, which is not the case as one increases the gas rate.

Figure 13 presents the efficiency curve and froth height data as liquid rate was varied from 9.8 gpm ($X_1$ = -1.682) to 60 gpm ($X_1$ = +1.682). In this case it was observed that the gas bubbles tended to be swept along in the direction of liquid travel and appeared not to coalesce as had been observed as the gas rate and weir height were increased. It appeared that the shearing action of the liquid decreased the average gas bubble size; thus, one obtains a larger gas surface area to volume ratio as liquid rate increases. This effect and the increased froth height results in increased efficiency.

In this discussion, we have not faced the problem of recirculation which occurs at higher gas rates, or the problem of the large liquid drops carried away from the bulk of the froth. It is rather difficult to estimate these effects and, therefore, no attempt has been made to characterize them as variables in the mass transfer operation.

The determination of gas film transfer efficiencies for the corresponding overall plate efficiency has not been computed as no experimental data of the liquid film efficiency were taken during this study. Since we observed large variations in froth characteristics at the various operating conditions, it was felt that $N_L$ data for the tray should be determined experimentally and not by the use of correlations of the type presented by Rush (14) or West (18).

# C O N C L U S I O N S

The principal conclusion to be drawn from this work is that the plate efficiency of a gas-film controlled mass transfer operation is primarily a function of the weir height and liquid rate. It is felt that increased efficiency is observed as one increases these variables because of a complicated relationship of increased gas-liquid contact time and increased interfacial area for mass transfer.

The general correlation developed by the statistical program is valid over the range of variables studied and can be extended to other operating conditions provided one does not have an operating condition which produces unstable plate operation. The correlation is undoubtedly specific for the plate used in the study. It is obvious that a general correlation of the available mass transfer area in the froth is desirable in order to prepare a more general correlation which could then be used to predict efficiencies as a function of operating variables as well as a function of the plate design.

## NOMENCLATURE

| | | |
|---|---|---|
| $b$ | = | general coefficients of statistical equation, subscripts refer to a specific combination of variables |
| $C$ | = | orifice coefficient |
| d.f. | = | degrees of freedom |
| $D$ | = | diffusivity, $cm.^2/sec.$ |
| $E_{MV}$ | = | Murphree plate efficiency, % |
| $E_{OG}$ | = | Transfer efficiency, % |
| $F$ | = | gas column F-factor = $u\sqrt{\rho}$ , ft./sec. $\sqrt{lb./ft.^3}$ |
| $F_S$ | = | gas slot F-factor = $u_S\sqrt{\rho}$ , ft./sec. $\sqrt{lb./ft.^3}$ |
| $g$ | = | conversion constant, (ft.)(lb.mass)/(lb.force)(sec.)(sec.) |
| $G$ | = | gas superficial mass velocity, $lb./(hr.)(ft.^2)$ |
| $G_M$ | = | gas superficial molar mass velocity, $lb.moles/(hr.)(ft.^2)$ |
| $k_Ga$ | = | gas film transfer coefficient, $lb.moles/(hr.)(ft.^3)$ (unit mole fraction) |
| $k_La$ | = | liquid film transfer coefficient, $lb.moles/(hr.)(ft.^3)$ (unit mole fraction) |
| $K_Ga$ | = | overall gas mass transfer coefficient, $lb.moles/(hr.)(ft.^3)$ (unit mole fraction) |
| $L'$ | = | liquid rate, gal./min. |
| $L$ | = | liquid superficial mass velocity, $lb./(hr.)(ft.^2)$ |
| $L_M$ | = | liquid superficial molar mass velocity, $lb.moles/(hr.)(ft.^2)$ |
| $m$ | = | slope of equilibrium curve |
| M.S. | = | mean square |
| $N_G$ | = | number of gas transfer units |

$N_L$ = number of liquid transfer units

$N_{OG}$ = number of overall gas transfer units

$N_{Sc}$ = Schmidt number, $\mu / \rho D$

P = gas pressure, atmospheres

$\Delta P$ = orifice pressure drop, in. $H_2O$ or in. Hg.

$S_2$ = orifice area, $ft.^2$

S.S. = sum of squares

u = superficial column gas velocity, ft./sec.

$u_S$ = gas velocity through perforated area, ft./sec.

W = outlet weir height, in.

$\overline{W}$ = gas rate, lb./min.

$X_1$ = coded liquid rate, (L'-35gpm)/15

$X_2$ = coded weir height, (W-1.682 in.)

$X_3$ = coded gas rate, $(u_S-65)/15$

$X_{AV}$ = average tray liquid composition

$X_{out}$ = outlet tray liquid composition

$Y_{in}$ = column inlet gas composition

$Y_{out}$ = column outlet gas composition

Y = orifice expansion factor

$Y_1$ = point inlet gas composition

$Y_2$ = point outlet gas composition

$Z_v$ = effective liquid depth, ft.

Greek Letters

$\beta$ = general correlating coefficient in general statistical equation

$\mu$ = viscosity, centipoises

$\rho$ = density, lb./ft.$^3$

$\Sigma$ = summation sign

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# A P P E N D I X

## TABLE III

### TABULATION OF EXPERIMENTAL DATA AND CALCULATIONS

| Run | Water[1] Manometer $\Delta P$, in.$H_2O$ | Temperature Inlet Water, °C. | Temperature Outlet Water, °C. | Orifice Manometer, $\Delta P$, in.D.B.P. | Orifice Static Pressure in.Hg. | Temperature of Inlet Gas, °C. | Weir Height in. |
|---|---|---|---|---|---|---|---|
| 9R | 2.80 | 22.0 | 23.0 | 3.40 | 0.63 | 32.0 | 0.682 |
| 10R | 18.80 | 17.5 | 18.5 | 9.04 | 2.00 | 33.0 | 0.682 |
| 11 | 18.80 | 12.5 | 13.0 | 3.20 | 0.56 | 33.0 | 2.682 |
| 12R | 2.80 | 13.5 | 12.5 | 9.03 | 1.95 | 35.5 | 2.682 |
| 13 | 2.80 | 14.5 | 14.5 | 3.20 | 0.55 | 33.0 | 2.682 |
| 14 | 2.80 | 13.5 | 13.5 | 9.00 | 2.00 | 35.0 | 0.682 |
| 15 | 18.80 | 12.5 | 13.5 | 9.03 | 1.95 | 35.5 | 2.682 |
| 16 | 18.80 | 12.5 | 13.5 | 3.20 | 2.30 | 35.0 | 0.682 |
| 17 | 9.05 | 14.0 | 15.0 | 6.00 | 2.20 | 34.0 | 1.682 |
| 18 | 9.05 | 11.0 | 12.5 | 6.02 | 2.13 | 34.0 | 1.682 |
| 19 | 9.00 | 13.4 | 15.0 | 5.80 | 2.20 | 35.0 | 1.682 |
| 20 | 9.00 | 13.0 | 14.5 | 5.75 | 2.20 | 36.0 | 1.682 |
| 21 | 9.00 | 13.0 | 14.5 | 5.75 | 2.20 | 37.0 | 1.682 |
| 22 | 9.03 | 16.0 | 17.3 | 5.92 | 2.10 | 35.0 | 1.682 |
| 23 | 9.05 | 11.5 | 12.5 | 2.61 | 0.63 | 33.0 | 1.682 |
| 24 | 9.00 | 13.0 | 14.5 | 11.24 | 1.80 | 35.5 | 1.682 |
| 25 | 22.20 | 13.0 | 16.0 | 5.75 | 2.20 | 35.5 | 1.682 |
| 26R | 27.00 | 19.7 | 20.3 | 5.85 | 2.20 | 34.5 | 1.682 |
| 27 | 9.03 | 13.9 | 15.0 | 5.95 | 2.10 | 35.0 | 0 |
| 28 | 9.03 | 14.8 | 16.5 | 5.93 | 2.10 | 35.0 | 3.364 |
| 29 | 18.80 | 15.5 | 16.5 | 9.20 | 2.10 | 31.0 | 3.732 |
| 30 | 9.03 | 14.5 | 15.5 | 9.20 | 2.10 | 31.0 | 3.732 |
| 31 | 18.80 | 14.5 | 15.5 | 9.20 | 2.10 | 32.0 | 4.682 |

NOTE: 1 - All data for 2-inch line except Run 25 in which the 1-inch water line was used.

TABLE III (Continued)

| Run | Static Pressure Below Tray, in.Hg. | Static Pressure Above Tray, in.$H_2O$ | Plate Pressure Drop, in. $H_2O$ | Barometric Pressure, mm.Hg. | Room Temperature, °C. | Plate Froth Height, in. (No $NH_3$ in feed gas) | Plate Froth Height, in. ($NH_3$ in feed gas) |
|---|---|---|---|---|---|---|---|
| 9R | 0.1 | 2.20 | 1.75 | 765.1 | 22.0 | 4.0 to 5.0 | 3.0 to 4.0 |
| 10R | 0.1 | 5.00 | 3.62 | 761.0 | 19.0 | 7.0 to 9.0 | 6.0 to 8.0 |
| 11 | 0.1 | 4.00 | 3.00 | 756.3 | 24.0 | 9.0 to 10.0 | 6.0 to 7.0 |
| 12R | 0.1 | 4.80 | 4.00 | 756.3 | 24.0 | 6.0 to 9.0 | 7.0 to 8.0 |
| 13 | 0.1 | 2.80 | 2.45 | 756.3 | 24.0 | 6.0 to 7.0 | 6.0 to 7.0 |
| 14 | 0.1 | 4.40 | 3.85 | 752.6 | 23.5 | 5.0 to 8.0 | 5.0 to 8.0 |
| 15 | 0.1 | 3.30 | 4.40 | 756.3 | 24.0 | >10.0 | 8.0 to 9.0 |
| 16 | 0.1 | 2.70 | 2.20 | 752.6 | 23.5 | >10.0 | 7.0 to 8.0 |
| 17 | 0.1 | 3.20 | 3.25 | 764.8 | 24.5 | 6.0 to 7.0 | 6.0 to 7.0 |
| 18 | 0.1 | 3.70 | 3.20 | 764.8 | 24.5 | 5.0 to 7.0 | 5.0 to 7.0 |
| 19 | 0.1 | 3.90 | 3.15 | 765.0 | 20.0 | 6.0 to 7.0 | 6.0 to 7.0 |
| 20 | 0.1 | 3.60 | 3.15 | 765.0 | 20.0 | 6.0 to 7.0 | 6.0 to 7.0 |
| 21 | 0.1 | 3.50 | 3.10 | 765.0 | 20.0 | 7.0 to 8.0 | 7.0 to 8.0 |
| 22 | 0.1 | 3.80 | 3.10 | 758.0 | 22.0 | 6.5 to 7.5 | 6.0 to 8.0 |
| 23 | 0.1 | 2.50 | 2.26 | 764.8 | 24.5 | 5.0 to 6.0 | 4.5 to 5.5 |
| 24 | 0.1 | 4.50 | 4.20 | 765.0 | 20.0 | 8.0 to 9.0 | 8.0 to 9.0 |
| 25 | 0.1 | 3.70 | 2.80 | 765.0 | 20.0 | 4.0 to 5.0 | 4.0 to 5.0 |
| 26R | 0.1 | 4.00 | 3.30 | 758.0 | 22.0 | ---- | 8.0 to 9.0 |
| 27 | 0.1 | 2.60 | 2.60 | 758.0 | 22.0 | <3.0 | <3.0 |
| 28 | 0.1 | 4.30 | 3.50 | 758.0 | 22.0 | 8.0 to 9.0 | 8.0 to 9.0 |
| 29 | 0.1 | 5.60 | 4.22 | 769.6 | 15.0 | 11.0 to 13.0 | 10.0 to 12.0 |
| 30 | 0.1 | 5.00 | 4.03 | 769.6 | 15.0 | 8.0 to 9.0 | 8.0 to 9.0 |
| 31 | 0.1 | 5.90 | 4.35 | 769.6 | 15.0 | 13.0 to 16.0 | 11.0 to 13.0 |

TABLE III (Continued)

| Run | Gas Feed Rate, lb./min. | Liquid Feed Rate, lb./min. | Mole Fraction $NH_3$ in Inlet Gas | Mole Fraction $NH_3$ in Outlet Gas | Normality of $NH_3$ Liquor Leaving Tray | Material Balance,[2] % | Plate Efficiency, $E_{MV}$, % |
|---|---|---|---|---|---|---|---|
| 9R | 46.01 | 166.60 | 0.0147860 | 0.0051419 | 0.083792 | 90.23 | 71.19 |
| 10R | 76.07 | 416.50 | 0.0128470 | 0.0041390 | 0.048510 | 87.63 | 70.87 |
| 11 | 44.28 | 416.50 | 0.0091626 | 0.0013378 | 0.026760 | 92.22 | 87.83 |
| 12B | 75.46 | 166.60 | 0.0108380 | 0.0027140 | 0.117700 | 92.75 | 83.75 |
| 13 | 44.28 | 166.60 | 0.0097425 | 0.0023750 | 0.061460 | 90.47 | 76.12 |
| 14 | 75.03 | 166.60 | 0.0108100 | 0.0038160 | 0.103000 | 92.96 | 71.46 |
| 15 | 75.34 | 416.50 | 0.0111800 | 0.0016880 | 0.052230 | 89.42 | 88.88 |
| 16 | 45.28 | 416.50 | 0.0914300 | 0.0024850 | 0.023050 | 91.69 | 74.65 |
| 17 | 62.33 | 291.55 | 0.0111800 | 0.0026630 | 0.055070 | 88.00 | 80.39 |
| 18 | 62.40 | 291.55 | 0.0111160 | 0.0026080 | 0.057410 | 90.77 | 80.32 |
| 19 | 61.07 | 292.55 | 0.0152050 | 0.0036690 | 0.074970 | 88.96 | 79.80 |
| 20 | 60.83 | 291.55 | 0.0152200 | 0.0041185 | 0.075360 | 90.40 | 76.88 |
| 21 | 60.68 | 291.55 | 0.0176000 | 0.0043803 | 0.089670 | 93.36 | 79.09 |
| 22 | 61.33 | 291.55 | 0.0168200 | 0.0041050 | 0.083170 | 89.20 | 80.07 |
| 23 | 40.27 | 291.55 | 0.0101480 | 0.0020150 | 0.034490 | 88.42 | 82.65 |
| 24 | 84.26 | 291.55 | 0.0134240 | 0.0035910 | 0.090070 | 90.95 | 78.44 |
| 25 | 60.86 | 81.38 | 0.0152950 | 0.0057435 | 0.250600 | 103.50 | 74.88 |
| 26R | 61.65 | 497.30 | 0.0171100 | 0.0035950 | 0.051630 | 88.40 | 82.26 |
| 27 | 61.52 | 291.55 | 0.0144170 | 0.0058600 | 0.059030 | 93.70 | 61.97 |
| 28 | 61.45 | 291.55 | 0.0136400 | 0.0023265 | 0.073318 | 88.50 | 88.11 |
| 29 | 77.60 | 416.50 | 0.0099030 | 0.0011420 | 0.049900 | 88.17 | 93.58 |
| 30 | 77.58 | 291.55 | 0.0103100 | 0.0015480 | 0.070260 | 86.94 | 91.33 |
| 31 | 77.45 | 416.50 | 0.0102800 | 0.0013810 | 0.051360 | 89.51 | 91.28 |

NOTE: 2 - Material Balance defined as:

$$\text{Material Balance - \%} = \frac{\%NH_3 \text{ in liquid out}}{\%NH_3 \text{ in feed gas} - \%NH_3 \text{ in outlet gas}} \times 100$$

In all runs bottom section of column was wet with water causing a non-measured loss of inlet gas $NH_3$ in this liquid

TABLE III (Continued)

| Run | $m=\frac{Y^*}{X}$ | G, #/hr.ft.$^2$ | L, #/hr.ft.$^2$ | $G_M$, # moles/ hr.ft.$^2$ | $L_M$, # moles/ hr.ft.$^2$ | $\frac{G_M}{L_M}$ |
|---|---|---|---|---|---|---|
| 9R | 0.8224 | 987.74 | 3576.58 | 34.06 | 198.70 | 0.141 |
| 10R | 0.8413 | 1633.08 | 8941.46 | 56.31 | 498.75 | 0.072 |
| 11 | 0.5283 | 950.61 | 8941.46 | 32.78 | 498.75 | 0.035 |
| 12B | 0.5378 | 1619.98 | 3576.58 | 55.86 | 198.70 | 0.148 |
| 13 | 0.5738 | 950.61 | 3576.58 | 32.78 | 198.70 | 0.095 |
| 14 | 0.5528 | 1610.75 | 3576.58 | 55.54 | 198.70 | 0.155 |
| 15 | 0.5373 | 1617.41 | 8941.46 | 55.77 | 498.75 | 0.060 |
| 16 | 0.5409 | 972.08 | 8941.46 | 33.52 | 498.75 | 0.036 |
| 17 | 0.5838 | 1338.11 | 6259.02 | 46.14 | 347.72 | 0.077 |
| 18 | 0.5073 | 1339.60 | 6259.02 | 46.19 | 347.72 | 0.067 |
| 19 | 0.5597 | 1311.06 | 6259.02 | 45.21 | 347.72 | 0.073 |
| 20 | 0.5756 | 1305.90 | 6259.02 | 45.03 | 347.72 | 0.075 |
| 21 | 0.5497 | 1302.68 | 6259.02 | 44.92 | 347.72 | 0.071 |
| 22 | 0.6287 | 1316.64 | 6259.02 | 45.40 | 347.72 | 0.082 |
| 23 | 0.4995 | 864.52 | 6259.02 | 29.81 | 347.72 | 0.043 |
| 24 | 0.5485 | 1809.01 | 6259.02 | 62.38 | 347.72 | 0.098 |
| 25 | 0.5493 | 1306.54 | 1747.01 | 45.05 | 97.06 | 0.255 |
| 26R | 0.7331 | 1323.51 | 10676.09 | 45.64 | 593.11 | 0.056 |
| 27 | 0.5725 | 1320.72 | 6259.02 | 45.54 | 347.72 | 0.075 |
| 28 | 0.6070 | 1319.21 | 6259.02 | 45.49 | 347.72 | 0.079 |
| 29 | 0.6020 | 1665.96 | 8941.46 | 57.45 | 496.75 | 0.070 |
| 30 | 0.5757 | 1665.50 | 6259.02 | 57.45 | 347.72 | 0.095 |
| 31 | 0.5750 | 1662.36 | 8941.46 | 57.32 | 496.75 | 0.066 |

TABLE III (Continued)

| Run | $u_s$ | $a$ | $F_s$ | $F$ |
|---|---|---|---|---|
| 9R | 49.11 | 3.79 | 13.22 | 1.02 |
| 10R | 78.29 | 6.02 | 21.48 | 1.65 |
| 11 | 47.98 | 3.69 | 12.83 | 0.99 |
| 12R | 78.86 | 6.06 | 21.47 | 1.65 |
| 13 | 47.96 | 3.69 | 12.81 | 0.99 |
| 14 | 79.06 | 6.08 | 21.29 | 1.64 |
| 15 | 79.90 | 6.13 | 21.67 | 1.79 |
| 16 | 46.90 | 3.61 | 12.83 | 0.99 |
| 17 | 63.54 | 4.89 | 17.51 | 1.35 |
| 18 | 63.82 | 4.91 | 17.58 | 1.35 |
| 19 | 62.84 | 4.83 | 17.24 | 1.33 |
| 20 | 62.53 | 4.81 | 17.16 | 1.32 |
| 21 | 62.66 | 4.82 | 17.16 | 1.32 |
| 22 | 63.85 | 4.91 | 17.42 | 1.34 |
| 23 | 43.07 | 3.31 | 11.59 | 0.89 |
| 24 | 87.70 | 6.74 | 23.95 | 1.84 |
| 25 | 62.55 | 4.81 | 17.17 | 1.32 |
| 26R | 63.85 | 4.91 | 17.46 | 1.34 |
| 27 | 63.98 | 4.92 | 17.46 | 1.34 |
| 28 | 63.89 | 4.91 | 17.45 | 1.34 |
| 29 | 78.12 | 6.01 | 21.66 | 1.67 |
| 30 | 78.10 | 6.01 | 21.65 | 1.67 |
| 31 | 78.24 | 6.02 | 21.67 | 1.67 |

## Calibrations

The calibration of the water orifices is reported by Scriven (13) and therefore calibration curves for water flow rates will not be included in the present work.

The air flow rates for the standard 4.900-in. diameter orifice in the 10-in. duct were calculated by using the standard orifice equation reported by Perry (12).

$$\bar{W} = CYS_2 \sqrt{\frac{2g\rho_1 \Delta P}{1 - \beta^4}} \times 60 \qquad (13)$$

The air rates determined by use of this equation were then converted to hole velocities and hole F-factors, and plotted as a function of dry plate pressure drop. Figure 14 shows dry plate pressure drop as a function of $F_v$ and compares the data of this work to that of Jones and Pyle (9). In both cases, the data are for 1/8-in. diameter holes on 3/8-in. centers with a 1/8-in. plate thickness used for our present study and a 1/16-in. plate thickness in the Jones and Pyle work.

Figure 15 shows dry plate pressure drop as a function of hole velocity and compares this work to a general correlation of dry plate pressure drop developed by Foss (4). The dry plate pressure drop data are shown in Table IV.

FIGURE 14
DRY PLATE PRESSURE DROP

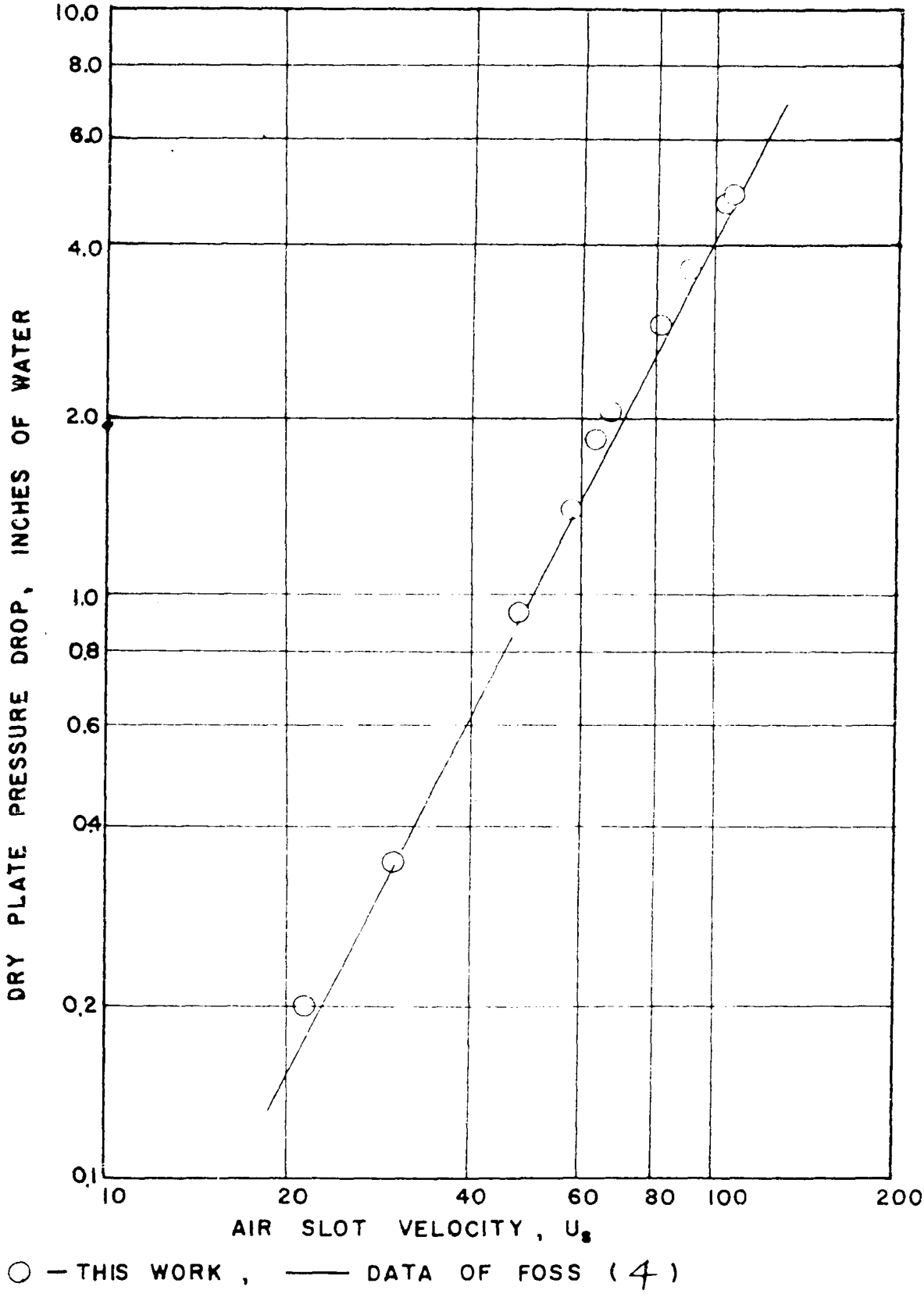

FIGURE 15

DRY PLATE PRESSURE DROP

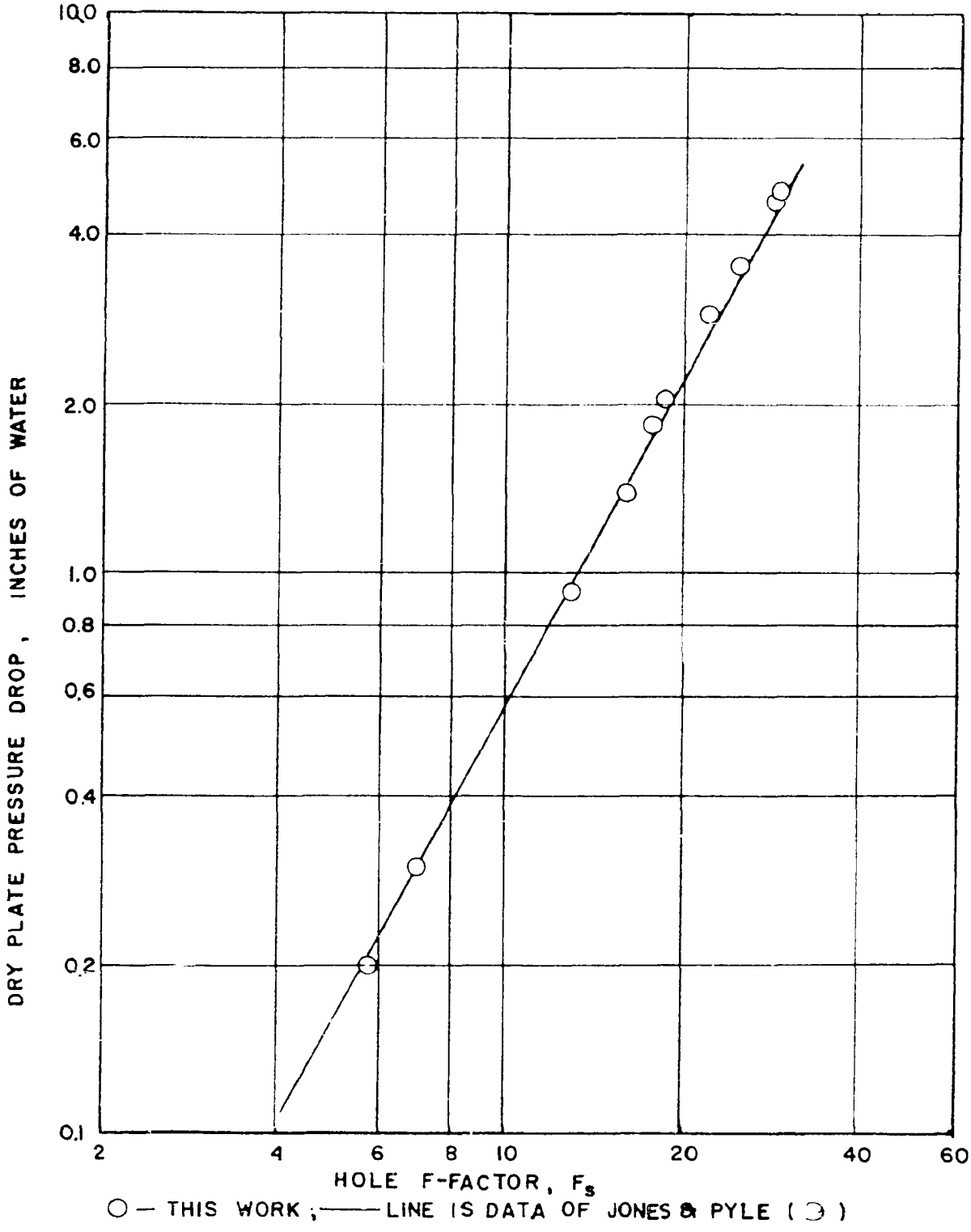

TABLE IV

DRY PLATE PRESSURE DROP RUNS

| Run | Temperature Inlet °C. | Static Pressure Orifice[1] in.Hg. | Pressure Drop Orifice[1] in. D.B.P.[3] | Barometric Pressure mm.Hg. | Temperature Barometric Pressure Manometer, C. | V, lb./min.[2] of Gas | $F_s$, Gag | $v_s$, ft./sec. | Dry Plate Pressure Drop in. $H_2O$ |
|---|---|---|---|---|---|---|---|---|---|
| 3-1 | 33.0 | 1.45 | 16.65 | 755.6 | 20 | 101.60 | 28.75 | 106.50 | 4.80 |
| 3-2 | 33.0 | 1.16 | 0.64 | 755.6 | 20 | 20.05 | 5.72 | 21.27 | 0.20 |
| 3-3 | 33.0 | 0.95 | 1.25 | 755.6 | 20 | 27.77 | 7.99 | 29.70 | 0.35 |
| 3-4 | 33.0 | 0.65 | 3.18 | 755.6 | 20 | 44.26 | 12.78 | 48.70 | 0.93 |
| 3-5 | 33.0 | 1.43 | 4.93 | 755.6 | 20 | 55.76 | 15.90 | 58.48 | 1.40 |
| 3-6 | 33.0 | 2.35 | 6.00 | 755.6 | 20 | 62.17 | 17.55 | 63.87 | 1.85 |
| 3-7 | 33.0 | 1.92 | 9.67 | 755.6 | 20 | 78.41 | 22.18 | 81.10 | 2.94 |
| 3-8 | 33.0 | 2.05 | 6.70 | 755.6 | 20 | 65.58 | 18.50 | 67.40 | 2.06 |
| 3-9 | 33.0 | 1.72 | 12.15 | 755.6 | 20 | 87.50 | 24.65 | 91.00 | 3.60 |
| 3-10 | 33.0 | 1.47 | 16.85 | 755.6 | 20 | 99.79 | 28.42 | 104.50 | 4.65 |

NOTES: 1. Data for 4.9" diameter orifice in a 10" diameter duct

2. Working equation for gas flow (12) $\overline{W} = CS_2Y \sqrt{\frac{2g_c \rho_1 (\Delta P)}{1 - \beta^4}} \times 60$

3. D.B.P. = Dibutylphthalate

Statistical Program

The basic experimental program was planned to permit correlation of experimental data by a second degree polynomial equation. A general correlation of plate efficiency as a function of gas rate, liquid rate and weir height was then developed. The analysis of this basic program is discussed in detail by Cochran and Cox (1).

Table V presents the statistical program, measured Murphree efficiencies, and equations for the solution of the coefficients in the second degree polynomial equation. Table VI presents a summary of the regression coefficients, analysis of variance and the derived polynomial equation. Table VII compares efficiencies calculated from the derived equation and the actual experimental results.

From the analysis of variance (Table VI) and the comparison of the measured experimental efficiencies to the predicted efficiencies (Table VII), it can be seen that the derived second degree polynomial equation is a good representation of the experimental data.

The maximum deviation one can expect by use of the equation is ± 2.55 efficiency percent. This is also the largest deviation observed in the six replicated experiments at the center of the experimental design.

The small mean square value obtained for the six replicated experiments indicates the accuracy of the experimental measurements.

It should be noted (see Table III) that the desired gas slot velocity was not obtained in any of the runs. The maximum deviation between the desired and actually-obtained slot velocity was 6%; the average deviation was about 2.5%. Since the linear and squared terms of gas hole velocity are unimportant in comparison to the liquid rate and weir height, no correction factor was employed to account for these deviations. The deviation is obviously accounted for by the small lack of fit mean square obtained in the variance analysis.

TABLE V

STATISTICAL PROGRAM AND MEASURED EFFICIENCIES

| Run | $X_0$ | $X_1$ | $X_2$ | $X_3$ | $X_1X_2$ | $X_1X_3$ | $X_2X_3$ | $X_1^2$ | $X_2^2$ | $X_3^2$ | Y Exp |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9R | 1 | -1 | -1 | -1 | +1 | +1 | +1 | 1 | 1 | 1 | 71.19 |
| 16 | 1 | +1 | -1 | -1 | -1 | -1 | +1 | 1 | 1 | 1 | 74.65 |
| 13 | 1 | -1 | +1 | -1 | -1 | +1 | -1 | 1 | 1 | 1 | 76.12 |
| 11 | 1 | +1 | +1 | -1 | +1 | -1 | -1 | 1 | 1 | 1 | 87.83 |
| 14 | 1 | -1 | -1 | +1 | +1 | -1 | -1 | 1 | 1 | 1 | 71.46 |
| 10R | 1 | +1 | -1 | +1 | -1 | +1 | -1 | 1 | 1 | 1 | 70.87 |
| 12 | 1 | -1 | +1 | +1 | -1 | -1 | +1 | 1 | 1 | 1 | 83.75 |
| 15A | 1 | +1 | +1 | +1 | +1 | +1 | +1 | 1 | 1 | 1 | 88.88 |
| 25 | 1 | -1.682 | 0 | 0 | 0 | 0 | 0 | 2.828 | 0 | 0 | 74.88 |
| 26B | 1 | +1.682 | 0 | 0 | 0 | 0 | 0 | 2.828 | 0 | 0 | 88.26 |
| 27 | 1 | 0 | -1.682 | 0 | 0 | 0 | 0 | 0 | 2.828 | 0 | 61.97 |
| 28 | 1 | 0 | +1.682 | 0 | 0 | 0 | 0 | 0 | 2.828 | 0 | 88.11 |
| 23 | 1 | 0 | 0 | -1.682 | 0 | 0 | 0 | 0 | 0 | 2.828 | 82.65 |
| 24B | 1 | 0 | 0 | +1.682 | 0 | 0 | 0 | 0 | 0 | 2.828 | 78.84 |
| 17 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 80.39 |
| 18 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 80.32 |
| 19 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 79.80 |
| 20 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 76.88 |
| 21 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 79.09 |
| 22 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 80.07 |

Where:

$X_1 = (L'-35)/15$

$X_2 = (W-1.682 \text{ in.})$

$X_3 = (G-65)/15$

Solutions:

$b_o = 0.166338\ (Oy) - 0.056791 \sum(iiy)$

$b_i = 0.073224\ (iy)$

$b_{ii} = 0.0625\ (iiy) + 0.006859 \sum(iiy) - 0.056791\ (Oy)$

$b_{ij} = 0.125\ (ijy)$

TABLE VI

REGRESSION COEFFICIENTS AND ANALYSIS OF VARIANCE

| | | | |
|---|---|---|---|
| $(0y)$ | 1569.61 | $b_0$ | 79.43 |
| $(1y)$ | 38.32 | $b_1$ | 2.37 |
| $(2y)$ | 92.38 | $b_2$ | 6.76 |
| $(3y)$ | - 1.91 | $b_3$ | - 0.14 |
| $(12y)$ | 13.97 | $b_{12}$ | 1.75 |
| $(13y)$ | -10.65 | $b_{13}$ | - 1.33 |
| $(23y)$ | 12.19 | $b_{23}$ | 1.52 |
| $(11y)$ | 1069.14 | $b_{11}$ | - 0.28 |
| $(22y)$ | 1049.18 | $b_{22}$ | - 1.53 |
| $(33y)$ | 1080.31 | $b_{33}$ | 0.42 |
| $\sum(iiy)$ | 3198.63 | | |

| | SS | d.f. | M.S. |
|---|---|---|---|
| FIRST ORDER TERMS | 701.36 | 3 | 233.79 |
| SECOND ORDER TERMS | 96.59 | 6 | 16.10 |
| LACK OF FIT | 21.27 | 5 | 4.25 |
| EXPERIMENTAL ERROR | 8.88 | 5 | 1.78 |
| Total | 828.10 | 19 | |

$$\hat{y}_{xy} = 79.43 + 2.37x_1 + 6.76x_2 - 0.14x_3 + 1.75x_1x_2 - 1.33x_1x_3 + 1.52x_2x_3 - 0.28x_1^2 - 1.53x_2^2 + 0.42x_3^2$$

## TABLE VII

### COMPARISON OF EXPERIMENTAL EFFICIENCIES AND PREDICTED EFFICIENCIES

| Factor $X_1$ | Factor $X_2$ | Factor $X_3$ | Equation Efficiency, $E_{eq}$, % | Experimental Efficiency, $E_{ex}$, % | Experimental Efficiency Less Equations Predicted Efficiency |
|---|---|---|---|---|---|
| -1 | -1 | -1 | 70.99 | 71.19 | 0.20 |
| 1 | 1 | 1 | 74.89 | 74.65 | -0.24 |
| -1 | 1 | -1 | 77.97 | 76.12 | -1.85 |
| 1 | 1 | -1 | 88.87 | 87.83 | -1.04 |
| -1 | -1 | 1 | 70.33 | 71.46 | 1.13 |
| 1 | -1 | 1 | 68.97 | 70.87 | 1.90 |
| -1 | 1 | 1 | 83.39 | 83.75 | 0.36 |
| 1 | 1 | 1 | 88.98 | 88.88 | -0.10 |
| 1.682 | 0 | 0 | 82.63 | 82.26 | -0.37 |
| -1.682 | 0 | 0 | 74.65 | 74.88 | 0.23 |
| 0 | 1.682 | 0 | 86.47 | 88.11 | 1.64 |
| 0 | -1.682 | 0 | 63.73 | 61.97 | -1.76 |
| 0 | 0 | 1.682 | 80.38 | 78.44 | -1.94 |
| 0 | 0 | -1.682 | 80.86 | 82.65 | 1.79 |
| 0 | 0 | 0 | 79.43 | 80.39 | 0.96 |
| 0 | 0 | 0 | 79.43 | 80.32 | 0.89 |
| 0 | 0 | 0 | 79.43 | 79.80 | 0.37 |
| 0 | 0 | 0 | 79.43 | 76.88 | -2.55 |
| 0 | 0 | 0 | 79.43 | 79.09 | -0.34 |
| 0 | 0 | 0 | 79.43 | 80.07 | 0.64 |
| | | | | TOTAL | 0.01 |

## SAMPLE CALCULATION

## RUN #7

### DESIRED CONDITIONS:

Gas Rate, $X_2$ = 0; 65 fps

Liquid Rate, $X_1$ = 0; 35 gpm

Weir Height, $X_3$ = -1.682; 0 inches

### EXPERIMENTAL DATA:

| | |
|---|---|
| Temp. water in, °C. | 13.9 |
| Temp. water out, °C. | 15.0 |
| Temp. vapor in, °C. | 35.0 |
| Water rate manometer reading, in. $H_2O$<br>1.600-in. diameter orifice in 2-in. pipe | 9.93 |
| Gas Orifice Manometer reading, in. DBP | [illegible] |
| Static Pressure Manometer reading, in. Hg. | 2.10 |
| Barometer reading, mm. Hg. -750.0<br>Hg. - Brass correction at 22°C. -2.7<br>Barometric Pressure corrected, mm. Hg. | 755.30 |
| Pressure Drop across plate and froth, in. $H_2O$ | 2.60 |
| Static Pressure above plate and froth, in. $H_2O$ | 2.61 |
| Static Pressure below tray, in. Hg. | <2.10 |
| Height of froth on plate<br>Without $NH_3$ in vapor stream, in.<br>With $NH_3$ in vapor stream, in. | <3.00<br><3.00 |
| $NH_3$ Rotameter reading | 14.00 |

Inlet Gas Sample:

Bubbler charge - 31.30 ml. of 0.0[illegible]
N HCl plus 20 ml. $H_2O$

2000 ml. of water displaced from aspirator bottle

Temp. of inerts collected over water = 15°C.

Inerts collection pressure = -54.0 mm. Hg.

Caustic required to neutralize the acid bubbler contents = 34.00 ml. of 0.040526 N NaOH

Outlet Gas Sample:

Bubbler charge - 52.30 ml. of 0.048944 N HCl plus 20 ml. $H_2O$

2000 ml. of water displaced from aspirator bottle

Temp. of inerts collected over water = 15°C.

Inerts collection pressure = -54.0 mm. Hg.

Caustic required to neutralize the acid bubbler contents = 52.00 ml. of 0.040526 N NaOH

Outlet Liquid Sample:

| Sample No. | 1322 | 1325 | 1328 |
|---|---|---|---|
| ml. of 0.048944 N HCl to neutralize 25 ml. of sample | 30.65 | 29.95 | 29.65 |

Calculation of Inlet Gas Composition:

Absolute pressure at which inlet gas inerts were collected = barometric pressure + gage pressure of collection - vapor pressure of water at collection temperature = 755.3 - 54.0 - 12.8 = 688.5 mm. Hg.

$$\text{Mole fraction } NH_3 \text{ in Sample} = \frac{\text{moles } NH_3}{\text{moles } NH_3 + \text{moles inerts}}$$

$$\text{Moles } NH_3 = 1.11826 \times 10^{-3}$$

$$\text{Moles inerts} = \frac{PV}{RT} = \frac{(688.5)(2)}{(62.361)(288)} = 0.076445$$

$$\text{mf } NH_3 = \frac{1.11826 \times 10^{-3}}{1.11826 \times 10^{-3} + 0.076445} = 0.014417$$

Calculation of Outlet Gas Composition:

Absolute pressure at which inlet gas inerts were collected = barometric pressure + gage pressure = 755.3 - 64.0 = 691.3 mm. Hg.

Moles $NH_3 = 0.452419 \times 10^{-3}$

Moles inerts = $\frac{(691.3)(2)}{(52.351)(288)} = 0.0767565$

mf $NH_3 = \frac{0.452419 \times 10^{-3}}{0.452419 \times 10^{-3} + 0.0767565} = 0.005860$

Calculation of Composition of Outlet Liquid Sample:

Moles $NH_3$/liter $H_2O$ = $\frac{(N \text{ acid})(\text{ml. acid})}{(\text{ml. sample})}$

Average acid titer = $\frac{30.35 + 29.95 + 29.85}{3} = 30.15$ ml.

N $NH_3 = \frac{(0.048944)(30.15)}{(25.00)} = 0.05903$

Calculation of Vapor Flow Rate:

Vapor flow rate is calculated by the formula

$$W = CYS_2 \sqrt{\frac{2g_c \rho_1 \Delta P}{1 - \beta^4}} \times 60$$

W in lb./min.

$\Delta P = 5.41 \Delta h$, lb./ft.$^2$

$\Delta h$ = pressure drop, in. DBP, = 5.95

$\beta = 4.9/10 = 0.49$

$S_2 = (\pi/4)(4.9/12)^2 = 0.1309$ ft.$^2$

C = 0.614

Y = 0.9957

$\rho_1$ = the density of the inlet gas mixture upstream of the orifice. The temperature of the gas is 35°C., its pressure is 755.3 + (25.4)(2.1) = 808.3 mm. Hg. It contains 0.014417 mole fraction $NH_3$; the balance is air.

$$\rho_i = \frac{[(0.014417)(0.0482) + (0.985583)(0.0808)]}{(273)(808.6)} = 0.074537 \text{ lb./ft.}^3$$

$$\text{Then } \overline{W} = (0.614)(0.9957)(0.1309)\sqrt{\frac{(2)(32.2)(.074537)(5.41)(5.95)}{1-(0.49)^4}}\ (60.0)$$

$$= 61.52 \text{ lb./min.}$$

lb./min. $NH_3$ Entering Column in Gas Stream:

$$\text{lb./min. } NH_3 = \frac{(\text{lb./min. mixture})(\text{mf } NH_3)(17)}{(\text{mf } NH_3)(17) + (\text{mf air})(29)} =$$

$$\frac{(61.52)(0.014417)(17)}{(0.014417)(17)+(0.985583)(29)} = 0.5230 \text{ lb./min.}$$

lb./min. Inerts in Inlet Gas = 61.52 - 0.5230 - 60.9970 lb./min.

lb./min. $NH_3$ Leaving Column in Gas Stream:

$$\text{lb./min. } NH_3 = \frac{(\text{lb./min. inert})(\text{mf } NH_3)(17)}{(\text{mf air})(29)} =$$

$$\frac{(60.9970)(0.00586)(17)}{(0.99414)(29)} = 0.2108 \text{ lb./min.}$$

lb./min. $NH_3$ Leaving Column in Liquid Stream:

$$\text{lb./min. } NH_3 = \frac{(\text{lb./min. } H_2O)(N\ NH_3)(17)}{1000} =$$

$$\frac{(291.55)(0.05903)}{1000}(17) = 0.2926 \text{ lb./min.}$$

Material Balance, as:

$$\% = 100 \times \frac{\text{lb./min. } NH_3 \text{ in liquid}}{\text{lb./min. } NH_3 \text{ in inlet gas} - \text{lb./min. } NH_3 \text{ in outlet gas}}$$

$$= 100 \times \frac{0.2926}{0.5230-0.2108} = 93.70\%$$

Calculation of overall Plate Efficiency on a Vapor Basis:

$$E_{MV} = \frac{Yin - Yout}{Yin - mXout}$$

mX out: average liquid temperature on plate = 14.5°C.
Henry's law constant, K, from Figure 16 , = 7.763

Equilibrium partial pressure of $NH_3$ = (K)(N $NH_3$)
= (7.763)(0.05903) = 0.45825

$$mX\ out = \frac{(equil.\ p.p.\ NH_3)}{(barometric\ pressure)} = \frac{0.45825}{755.3} = 0.000606$$

$$E_{MV} = \frac{0.014417 - 0.005860}{0.014417 - 0.000606} \times 100 = 61.97\%$$

FIGURE 16

HENRY'S LAW CONSTANT FOR $NH_3 - AIR - H_2O$

DILUTE SOLUTIONS DATA FROM SCRIVEN (15)

$$K = \frac{\text{PARTIAL PRESSURE } NH_3 \text{ IN mm Hg.}}{\text{MOLARITY OF } NH_3 \text{ IN AQUEOUS SOLUTION}}$$