

PERFORMANCE CHARACTERISTICS  
OF A SPRAY COLUMN

by

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## ABSTRACT

Performance characteristics of a liquid-liquid spray column 2" in diameter and with an effective length of 6.08' were investigated using heat transfer, instead of mass transfer, between the two liquids. Dispersed phase (benzene) rates were varied from 1.0 to 4.0 cu.ft./hr. and continuous phase (water) rates were varied from 1.5 to 6.0 cu.ft./hr. Drop sizes were obtained by a photographic procedure and were found to be independent of the water rate. Velocities of rise were measured and the actual surface area for heat transfer evaluated. Area transfer coefficients were calculated and found to be a function of holdup only, for a particular direction of heat transfer. The coefficients first remained constant and then decreased with increased holdup. It is reasonable to suppose that partial obstruction of the available area by closely packed drops is responsible for the latter effect. Volumetric coefficients showed the usual increase with holdup. The end effect at the bottom of the column (point of drop formation) was found to be negligibly small. No coefficients were calculated for the top end (point of coalescence) due to the small driving force occurring there.



## INTRODUCTION

There are many processes in the field of chemical engineering which defy quantitative analysis. This is due to a host of independent variables whose measurement and control are difficult if not impossible. A good example of such a case is the liquid-liquid spray column.

Despite the large amount of work done with these columns, data for design purposes have accumulated slowly. The main reason for this is the inability to evaluate operating characteristics in terms of equipment variables and the physical properties of the solvents and solutes involved. This difficulty is enhanced by the often unpredictable effect on physical properties caused by the mixing of the solutes and solvents. It has been and still is better to actually test a system in the type of unit to be used rather than to try to predict behavior from the results of other systems and column types.

Enough work has been done, however, to describe and predict certain effects in a spray column. Often, due to differences in the systems and columns used, the results reported by different workers are difficult to relate. The variation in the transfer coefficient with column length is an example of this. Sherwood, Evans, and Longcor<sup>(12)</sup>, Nandi and Viswanathan<sup>(10)</sup>, and Johnson and Bliss<sup>(8)</sup>, found that an appreciable amount of the extraction occurs within the first 0.5 foot from the disperser tips. Geankoplis and Hixson<sup>(6)</sup> found a similar effect at the continuous phase inlet and none

at the disperser.

Elgin and Browning<sup>(4)</sup> give the following factors as influencing drop size:

1. Densities of the two phases.
2. Viscosities of the two phases.
3. Interfacial tension.
4. Tip diameter and velocity.

They found that changing the solute from one phase to the other, and thereby changing the physical properties, produced an effect much larger than that due to entering velocity. Sherwood, Evans and Longcor found the range of drop diameters quite small compared with the range of nozzle diameters used. Johnson and Bliss report that no noticeable difference in drop size occurred with changing dispersed phase flow rates. Appel and Elgin<sup>(1)</sup> considered the linear dependence of holdup on dispersed phase flow rate as evidence of constant drop size. Hayworth and Treybal in some work devoted entirely to drop size prediction<sup>(7)</sup>, give an empirical equation for predicting the size of liquid drops formed from a single tip into a stagnant phase.

The drop size partially determines the drop velocity,<sup>(16)</sup> and through the velocity, the shape of the drop. Lower velocities give greater holdup. Holdup is a function of drop size and velocity of rise and is therefore greatly affected by flow rates<sup>(1, 8, 2)</sup>. Johnson and Bliss, and Appel and Elgin found the holdup to be practically a linear function of the dispersed phase rate. Blanding and Elgin<sup>(12)</sup>, in their work on flooding velocities found holdup to be no criterion of flooding

since holdup varied widely with the number of drops and their spacing along with drop size and flow rates. Holdup was the greatest when the column was flooded at low continuous phase rates.

It has been postulated by Appel and Elgin and borne out by Elgin and Browning, Nandi and Viswanathan<sup>(11)</sup>, and others, that both the volumetric coefficient for mass transfer,  $Ka$ , and holdup depend on the same variables.

Many writers have suggested that the actual surface coefficient,  $K$ , and the area per unit of column volume,  $a$ , might not change in the same direction as the holdup increases. The change in area may very well mask the change in  $K$ . Sherwood, Evans, and Longcor evaluated the contact area formed by drops from a single tip rising through an essentially stagnant phase. They were able to plot  $K$  versus drop size. The coefficient,  $K$ , was found to increase with drop size and to vary for drops of the same size but of different liquids. The larger convection currents in the larger drops caused by the surface drag of the continuous phase was offered as an explanation of the former effect. Differences in physical properties between the two liquids and their effect upon the convection currents would account for the different  $K$ 's in the latter case.

The use of a volumetric transfer coefficient,  $Ka$ , which can be evaluated only after the column has been built and operated makes column design rather uncertain. If the designer of a spray column had available means of predicting,

for a given type of disperser, the number of tips working for a given dispersed phase rate, the drop sizes produced, the velocity of rise, and transfer coefficients based on unit area, then such column design would be much less hazardous than it is now.

It is the purpose of this paper to present such data for the system benzene-water. To simplify the experimental work, heat transfer instead of mass transfer between the two phases was measured. This, in itself, has some immediate practical possibilities in the use of a spray column for direct heat transfer between two immiscible liquids without the interposition of a metal wall. Since the two phases were clear, direct observation of nozzle performance and a photographic method of determining the drop sizes were possible. By measuring the velocity of rise of the drops, accurate values of the holdup were obtained and with these data the transfer coefficient was divorced from the area. The end effect at the disperser end of the column was also investigated.

## EXPERIMENTAL EQUIPMENT

The apparatus consisted of a spray column and its attendant storage vessels, flow meters, and interface regulator. Compressed air was used as the means of forcing the liquids through the column.

To these usual devices were added a steam heater with which either feed stream could be heated to any desired temperature, a cooler for the benzene leaving the column, and a potentiometer which could be connected to any one of the twelve thermocouples positioned throughout the column.

To furnish more detail each unit will be described briefly. Schematic drawings of the setup are shown in Figures 3 and 4. A photograph of the column appears in Figure 5.

Column Proper: The column was constructed of eight pyrex tees like the one shown in Figure 1. The inside diameter of the tees was  $2 \pm 1/32$ ". Bell-shaped pyrex enlargers (2" to 4") were used at both ends of the column in order to duplicate Blanding and Elgin's design. At the top, a calming section of 4" pyrex pipe 6" long was added, all of which gave an overall length of  $84\frac{1}{2}$  inches and an effective length (nozzle to interface) of 73".

All sections were held together with cast aluminum flanges. A gasket material of an asbestos-rubber composition was used satisfactorily both in the joints and as a cushion between flanges and glass.

Dispersal Unit: The 20 tips were made of  $3/16$ " outside

diameter capillary copper tubing drilled to an inside diameter of 0.125". Each tip was 0.500  $\pm$  0.005" long and was silver-soldered into a piece of 1/4" copper plate 2 5/8" in diameter so as to be flush with the bottom of the plate. This bottom side was polished to give a perfectly smooth juncture between plate and tips. The top end of the tips were then beveled (approximately 45°) and final drilling to 0.125" carried out to insure a constant cross-section.

A short piece of 2" copper pipe was used as the dispersal cylinder. The top plate described above and a bottom plate were fastened to it in the manner shown in Figure 2. A layer of small glass beads was placed in the disperser cylinder to break up the entering liquid jet and further insure uniform flow through each tip. Pieces of screen wire, soldered to the cylinder above and below the beads, held them in place. The entire unit was positioned in the bell-shaped enlarger at the lower end of the column with the tips approximately 1 1/2" below the 2" diameter column proper.

Overflow Weir: A piece of 2" copper pipe 2 1/2" long was machined down until it sat well in the top bell-shaped end section. It was then cemented in place with High Pyseal cement. (The liquid-liquid interface was maintained about 1" above the top of this weir.)

End Plates: Galvanized plate approximately 1/8" thick was used. Brass fittings for the feed and drain lines were soldered into these plates.

Heater: A steam chest containing different lengths (1.5', 2.0', and 3.0') of 3/8" copper tubing was constructed.

Either the water or the benzene feed streams could be passed through any one of these lengths or any combination thereof. Provisions were made for maintaining a constant steam pressure in the chest from 0 to 35 psig.

Reservoirs: Two twelve gallon pyrex glass carboys were used as the primary feed reservoirs. Their liquid levels were maintained constant by feeding in fluid as fast as it was withdrawn to feed the column. These carboys operated under about one-half atmosphere of gauge pressure. The benzene make-up came from a 35 gallon drum under 10 psig. while the water needed to maintain a constant carboy level came directly from the water main. Exit water from the column was sent to the drain while the benzene, after cooling, was collected in a second 35 gallon drum.

Benzene Cooler: This consisted simply of a coil of  $3/8$ " copper tubing 21' long immersed in a cooling water bath.

Flow Meters: Two laboratory rotameters, manufactured by the Fischer-Porter Company were used. Each contained two spherical floats; a glass one for low flow rates and a steel one for high flow rates. Calibration curves appear in the Appendix (Figure 24). Flow through the meters was controlled by means of pinch clamps acting on short sections of Tygon tubing inserted in the feed lines just before the rotameters. The rotameters were used only to approximate the desired flow rates and to indicate constancy of flow. The actual flow was obtained by measuring timed portions of the exit streams.

Pressure System: Compressed air varying from 80 to 120 psig. was reduced in pressure to 10 psig. This air was piped

directly to the 35 gallon storage drums. Air for the glass carboys was further reduced in pressure by means of a globe valve. This air was maintained at a constant pressure by means of a leg of mercury through which the excess air was constantly bubbled. A layer of water on top of the mercury helped decrease fluctuations of the mercury surface.

This arrangement provided a very constant pressure for the feed streams. This was evidenced by constancy of the water rotameter readings. There was some difficulty with a slowly decreasing benzene rate, but this was not due to pressure variations. The Tygon tubing under the pinch clamp used to control the flow rate had a tendency to swell when in contact with benzene. This swelling gradually constricted the passage for flow and caused a decreasing benzene flow.

Temperature Indicating Devices: Chromel-constantan couples were used since this combination gives one of the highest e.m.f.'s per degree of any pair listed in the literature. One was installed in each of the eight column tees and two at each end of the column to get inlet and outlet stream temperatures. The couples were installed in the tees as shown in Figure 1. Small diameter glass tubing and neoprene rubber stoppers were used to hold the thermocouple in position. The tubing turned upward upon leaving the stopper on the inside of the column and projected about 1/4" into the column. The couple junction, which projected very slightly from the glass tubing came into contact only with the continuous phase flowing down the column. Leakage from the column through the glass tube was prevented by means of a short



section of small rubber tubing. This tubing fitted tightly over the glass tubing and was pressed down firmly by a pinch clamp over the couple leads as they came out of the glass tubing on the outside of the column.

The leads to couples #1, #2, #11, and #12 which were situated at the ends of the column were brought out through small holes in the gaskets under the end plates. Pressure between the plate and the column end section prevented any leakage. The inlet benzene thermocouple (#12) was positioned inside the disperser just below the tip openings. (See Figure 2).

The chromel leads of all couples were run together to form a common lead to the cold junction (ice and water were used). The constantan leads were kept separate and were connected to a twelve pole gang-switch which permitted connection of the potentiometer to any single couple.

Each glass tube holding a couple in the column was rotated  $120^{\circ}$  from a position directly over the couple below it. This was done to minimize whatever turbulence the couple installations might have caused (this was observed to be negligible) and to get a good sampling of the column. The approximate locations of the couples in the column are shown in Figure 3.

A Leeds and Northrup student's potentiometer, No. 7651, furnished the means of measuring e.m.f.'s. The instrument was read to the smallest division, 0.005 millivolt. This corresponded to slightly more than  $0.1^{\circ}\text{F}$ . Calibration data for all the couples appear in the Appendix (Table XI).

Lines: Copper tubing of 3/8" diameter was used except for the vented leg of the interface level controller. Tygon was used here to secure greater flexibility.

Photographic Equipment: Photographs were taken with a 35 mm. camera. Lighting was accomplished by placing an ordinary light bulb behind the column and masking it with a large piece of filter paper.

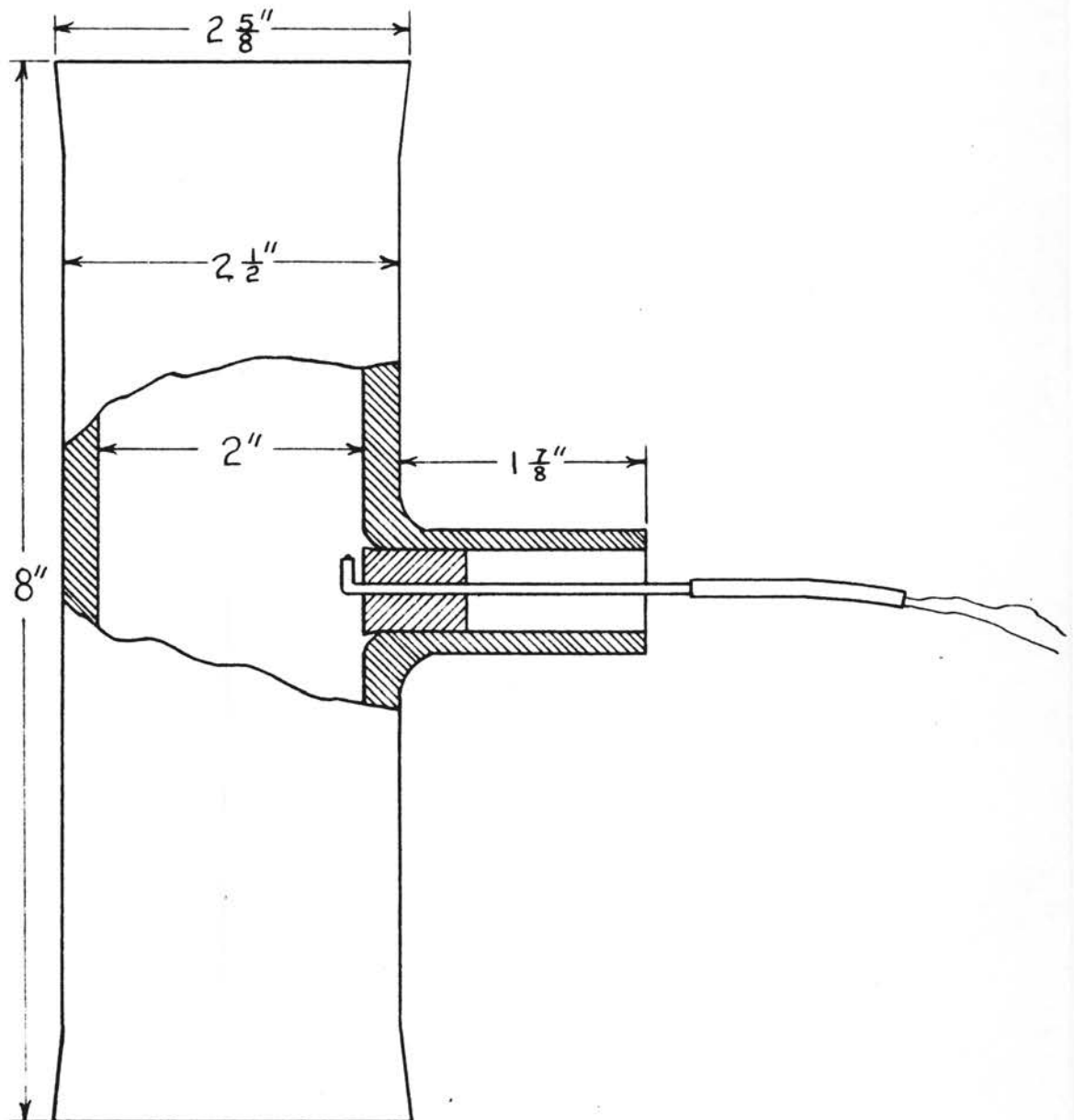


FIG. 1—TYPICAL COLUMN SECTION  
SHOWING COUPLE INSTALLATION.

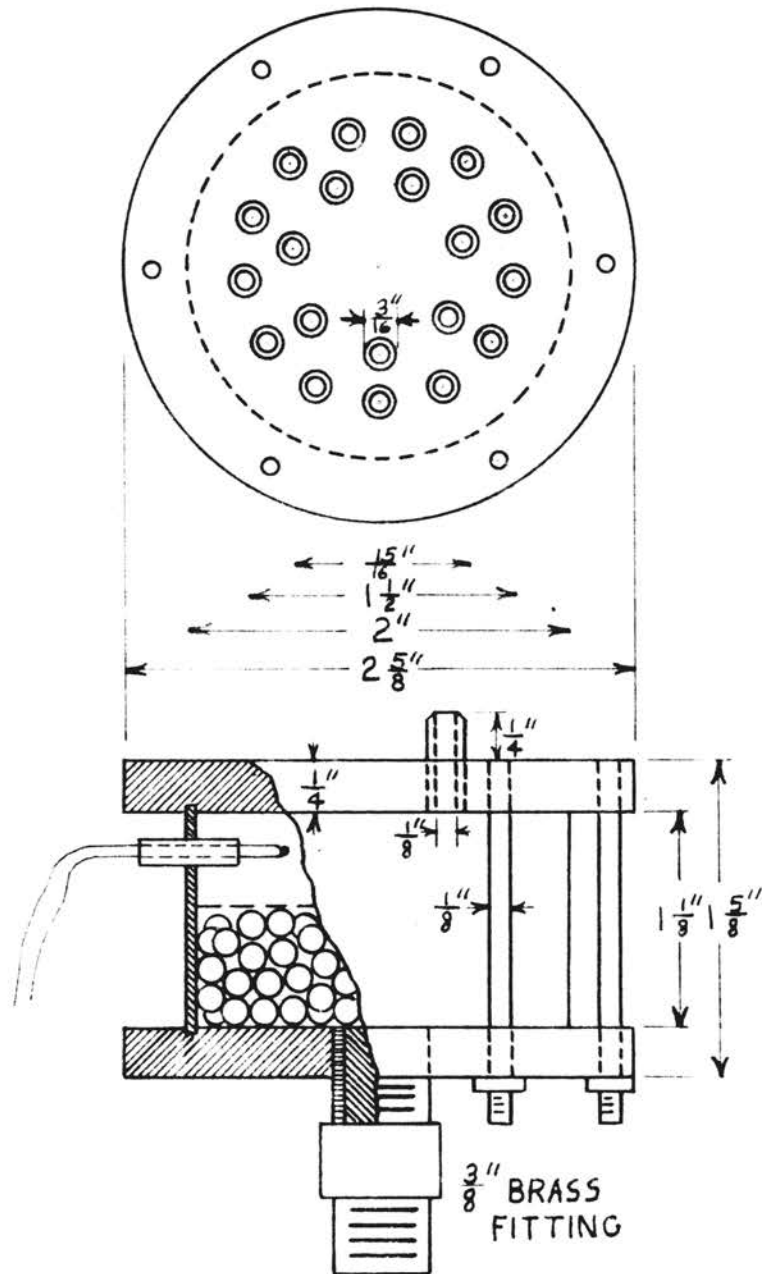
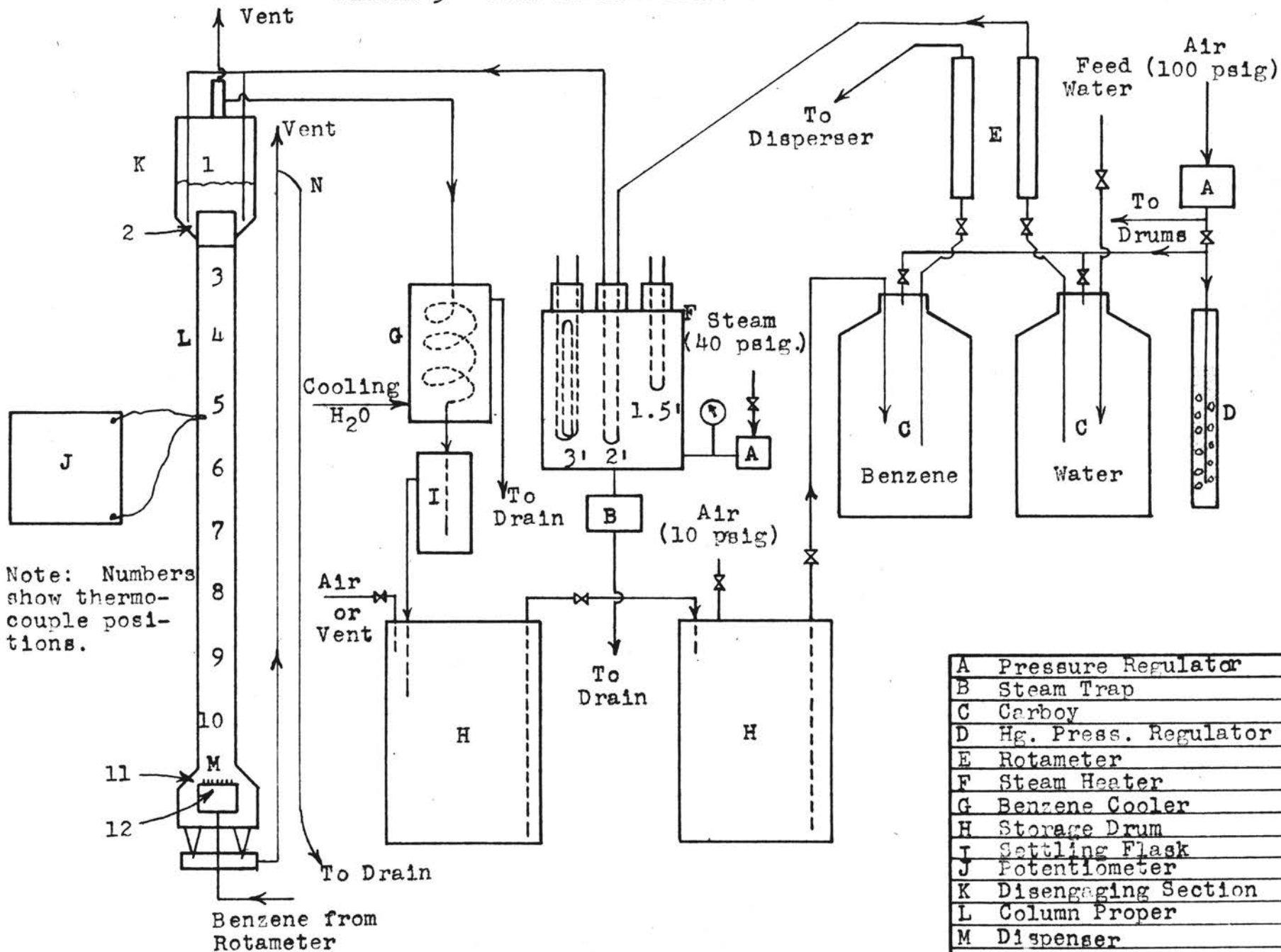


FIGURE 2 - DISPERSER ASSEMBLY

FIGURE 3 - FLOW DIAGRAM FOR WATER-HOT RUNS



Note: Numbers show thermocouple positions.

A	Pressure Regulator
B	Steam Trap
C	Carboy
D	Hg. Press. Regulator
E	Rotameter
F	Steam Heater
G	Benzene Cooler
H	Storage Drum
I	Settling Flask
J	Potentiometer
K	Disengaging Section
L	Column Proper
M	Dispenser
N	Interface Control

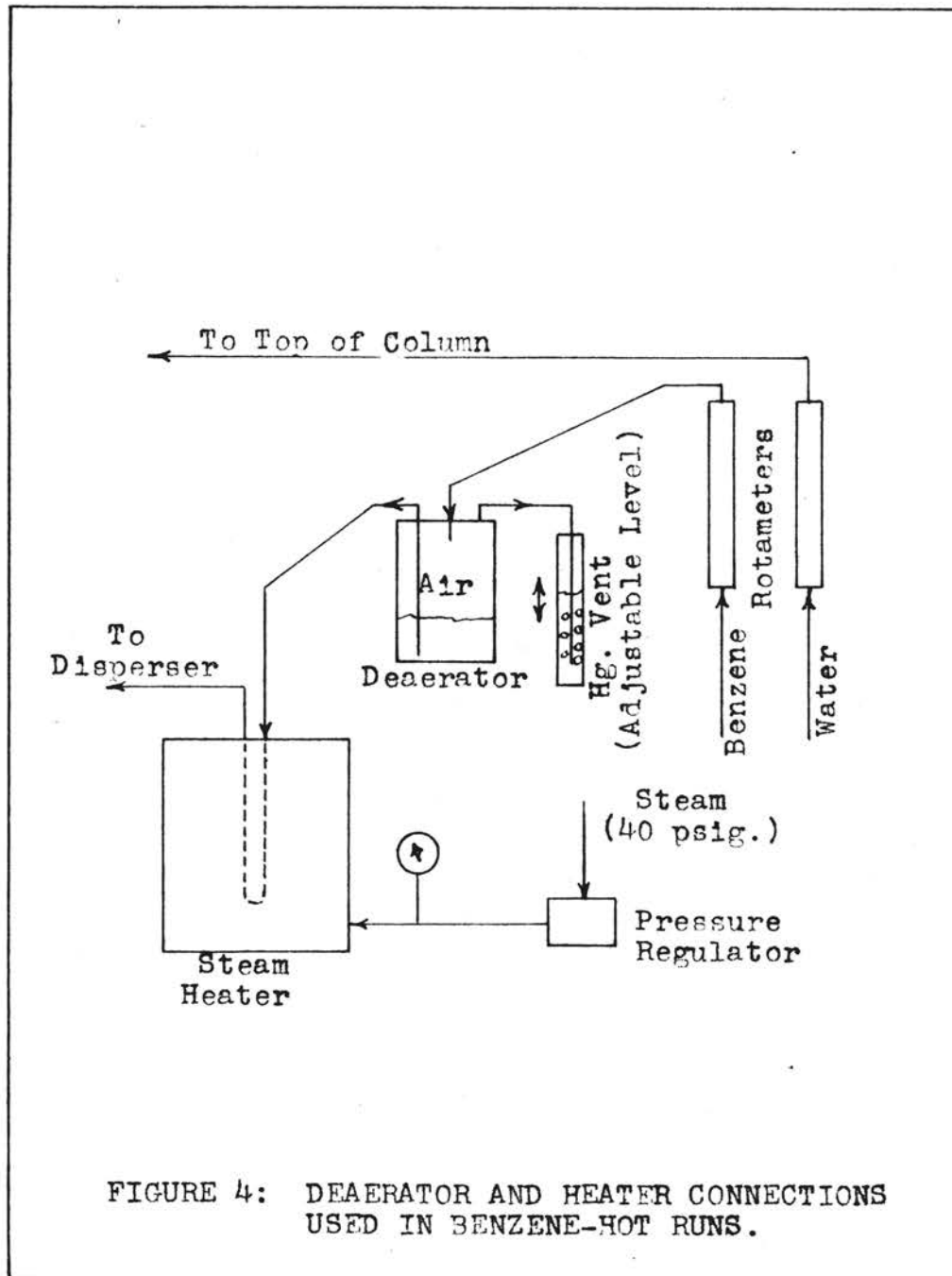


FIGURE 4: DEAERATOR AND HEATER CONNECTIONS USED IN BENZENE-HOT RUNS.

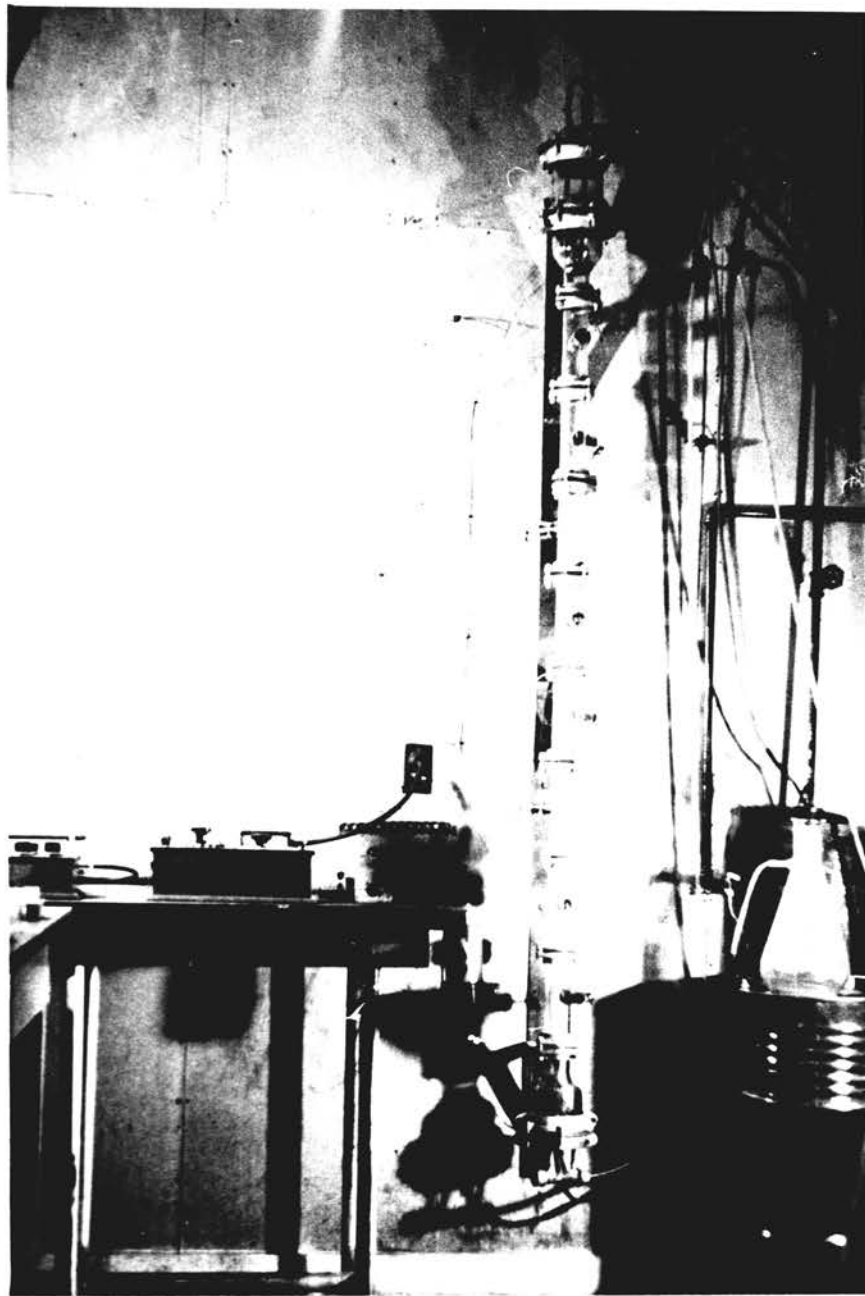


FIGURE 5: Column and Some of the Auxiliaries

## MATERIALS USED

Benzene and water were chosen as the immiscible pair of liquids to be used. The benzene was a technical grade. The water used was ordinary tap water.

## EXPERIMENTAL PROCEDURE

The experimental procedure varied somewhat depending on whether the water or the benzene feed stream was to be heated. Figure 3 shows the layout used when the water was heated and this arrangement will be presumed for the first part of the discussion. In all cases the water was the continuous phase.

For some time before any runs were to be made, water was drawn from the main to ensure a constant feed temperature to the heater. All condensate and non-condensibles were flushed out of the heater. These steps were taken in order that a constant temperature would be maintained in the heated feed stream. After this, pressure in the carboys was increased until a steady bubbling occurred through the mercury leg. Water was turned into the column at the desired rate (as shown by the rotameters) and at the same time the exit stream from the carboy was matched by one from the water main to the carboy. This ensured a constant level and, therefore, a constant head between the carboy level and the top of the column. Once the water rate was established, steam was turned on in the



heater. Time was allowed for the heater and the column to come to thermal equilibrium, usually about thirty minutes, before any benzene flow was started. Similarly to the water, the benzene exit stream from the carboy was balanced by an entering stream from the 35 gallon storage drum. Water leaving the column went to the drain, but the benzene was cooled to approximately 80°F, then passed through a settling flask which removed any water accidentally entrained in it, and finally sent to the storage drum. Between runs the benzene was transferred by means of compressed air from this drum to the drum feeding the benzene carboy.

After starting the flow of benzene to the column, the column was allowed to reach a new thermal equilibrium. The interface was adjusted to a level about one inch over the top of the weir. The time required for attaining steady state operation varied from about twenty-five to ten minutes depending upon whether the water rate was low or high, respectively. When steady state had been attained, the following were obtained:

1. Velocity of rise of the benzene drops.
2. Photograph of the drops in the section containing couple #8.
3. Number of disperser tips working.
4. Flow measurements at three different times during the run. These were taken by simply catching some of the exit streams.
5. E.m.f.'s of all twelve couples.
6. Room temperature.

Velocity of Rise: Velocity of rise could be measured

only over a six-inch distance. A drop was timed from the instant of its appearance over one flange to its disappearance behind the flange above. This was done at the same section where the photographs were taken. Twenty drops were timed during each run and the average time obtained. The velocity of rise in ft./sec. was then the reciprocal of twice the average time.

Photographs: To secure a good approximation of surface area available for transfer in the column, photographs of all the runs were taken. To correct for the distortion of the drop image due to the curved column surface and the water, distortion factors were obtained from photographs of glass marbles of known size taken under the same conditions. The prints when enlarged showed distinct distortion depending upon the marble's position in the column. (See Figures 6, 7, 8 and Table X.)

The marbles used were about twice as large as the drops. Since the camera sees a flat projected area it can probably be assumed that the curvature of the drop (as compared with the curvature of the marble) has no effect on the distortion. Therefore, the difference in size would cause no significant error. In fact, since the distortion factor had to be applied over a greater portion of the column cross-section than that occupied by the standard object, the larger size probably gave factors closer to a true average for that portion.

The photographs were enlarged to natural size in all dimensions by printing on a curved surface having the same

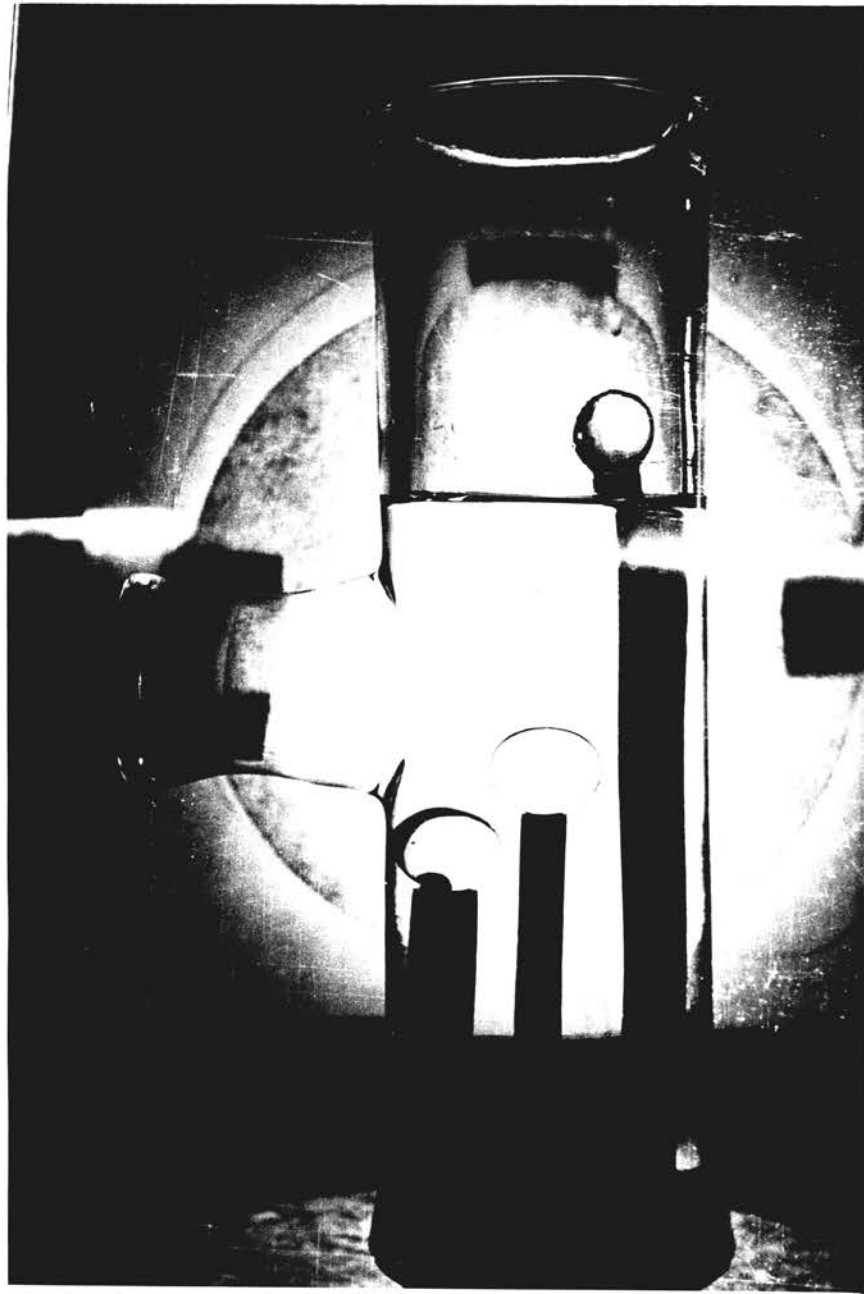


FIGURE 6: Effect of Water on the Distortion of the Glass Marbles.

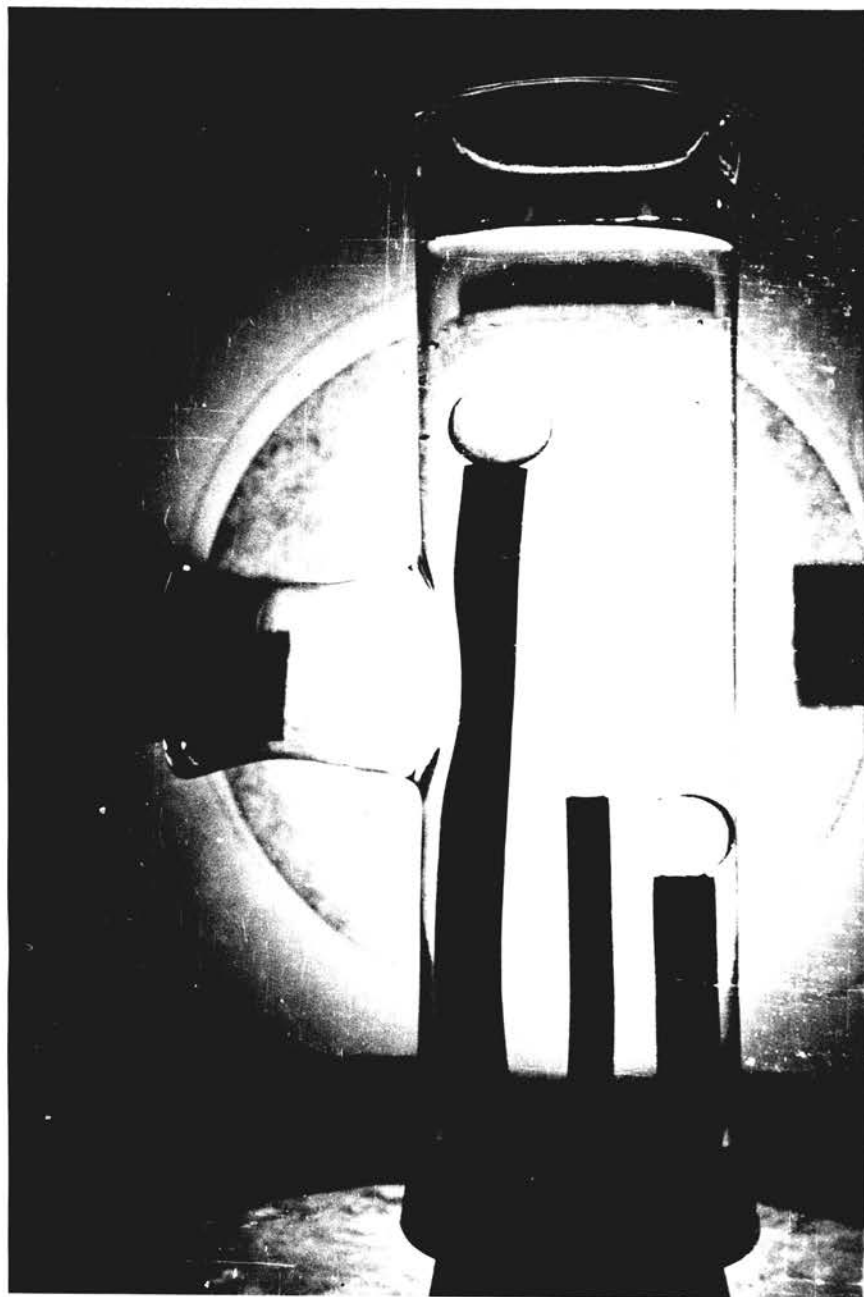


FIGURE 7: Distortion in Positions A and B.

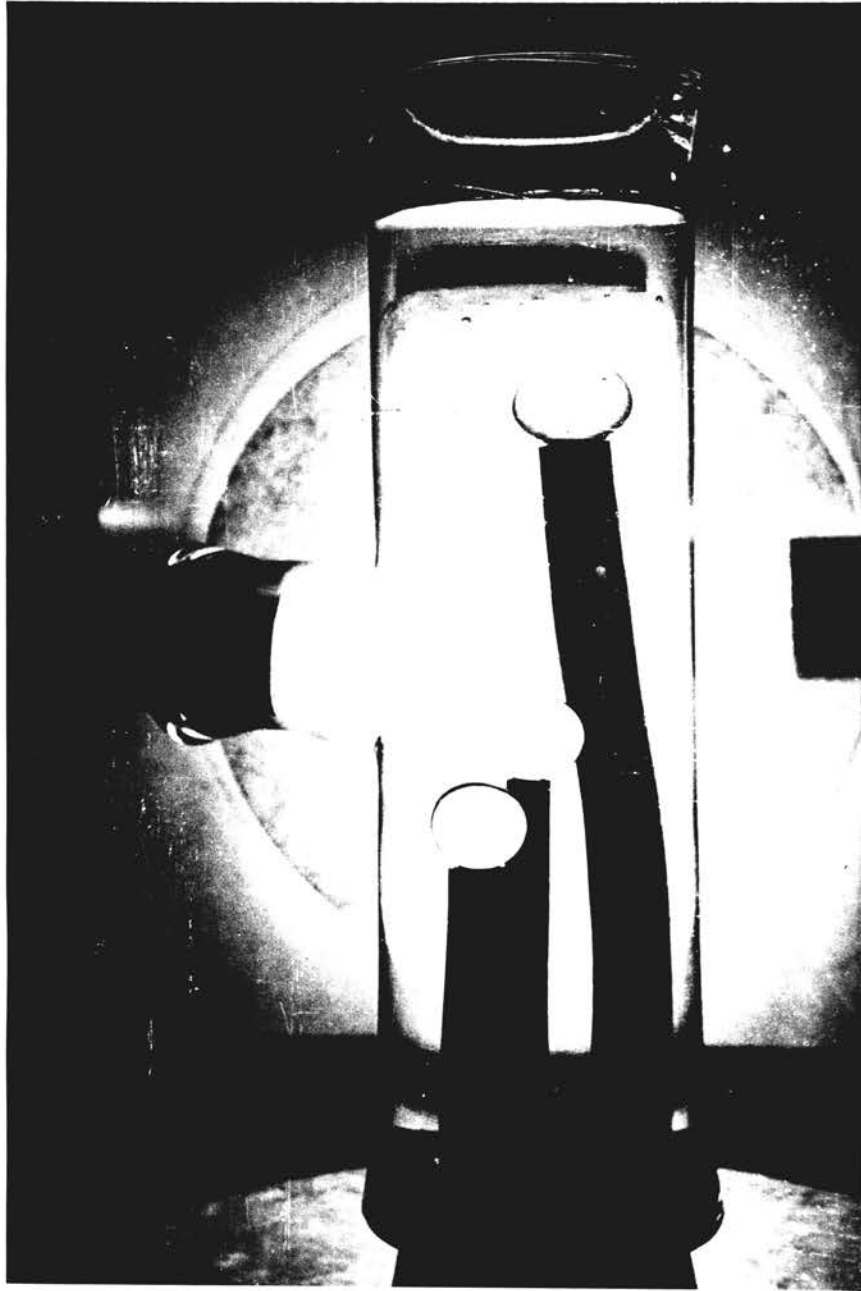


FIGURE 8: Distortion in Positions C, A, and D.

radius of curvature as the column itself. The marble photographs and the drop photographs were taken with the same camera distance and enlarged to the same size. Therefore, it is reasonable to expect that a distortion factor obtained by ratioing the actual marble diameter to the measured image diameter for a certain location in the column cross-section could be applied to a drop image in the same part of the column cross-section to obtain the actual drop size.

Distortion factors for the vertical and horizontal directions were obtained. Also, the distortion in a diagonal direction ( $45^\circ$ ) was found from the marbles to permit the measuring of drops that happened to be tilted at the instant when the photograph was taken. (See Table X, Appendix.)

The average drop size was obtained from each photograph by measuring twenty-four images to the closest one-hundredth of an inch. To apply the appropriate correction factor (see Table X) the position of the drop in the column had first to be ascertained. At low benzene rates when all of the drops were visible (see Figure 9) it was assumed that those drops not in one of the two B positions were evenly distributed between positions C, A, and D, and the distortion factor for A was applied to all of them. As the benzene rate was increased, drops in D were masked from view and were no longer measurable. Distinction between A and C was easily made here by noting the drop's position relative to drops behind or in front of it. At the highest benzene rates only positions C and B were used because only the drops closest to the column wall could be seen. (See Figure 10.)

Number of Tips Working: Since at the lower benzene rates not all the twenty tips formed drops it was necessary to record the actual number working in order to calculate the tip velocity. The number working was very much affected by the extent to which water had penetrated into and had wetted the tips. Good reproducibility, that is, the same number working for the same benzene rate, could be obtained by turning the benzene rate up high enough to force benzene out of all tips, thus removing the water and wetting all the tips with benzene. (See Figure 11.)

Flow Measurements: The rotameters were used only as an indication of the amount and constancy of flow. When the hot benzene from the column passed through the cooler, part of its small amount of dissolved water separated out causing the benzene to become cloudy. This water was very highly dispersed and required several hours to settle out. These small water particles would preferentially wet the glass rotameter ball, increasing the viscous drag on it considerably. This tendency of the water to cling to the glass ball in the benzene rotameter caused this rotameter's reading to be high and unreliable. The water did not affect the steel ball in this manner. Also, a temperature change of  $10^{\circ}\text{F}$ . would cause a 2 or 3% deviation of the rotameters from their calibration curves when the glass ball was used. Therefore, at three different times during each run, timed portions of both the exit streams were measured in a graduated cylinder and their temperatures taken to enable the calculation of the actual gravimetric flow rates.

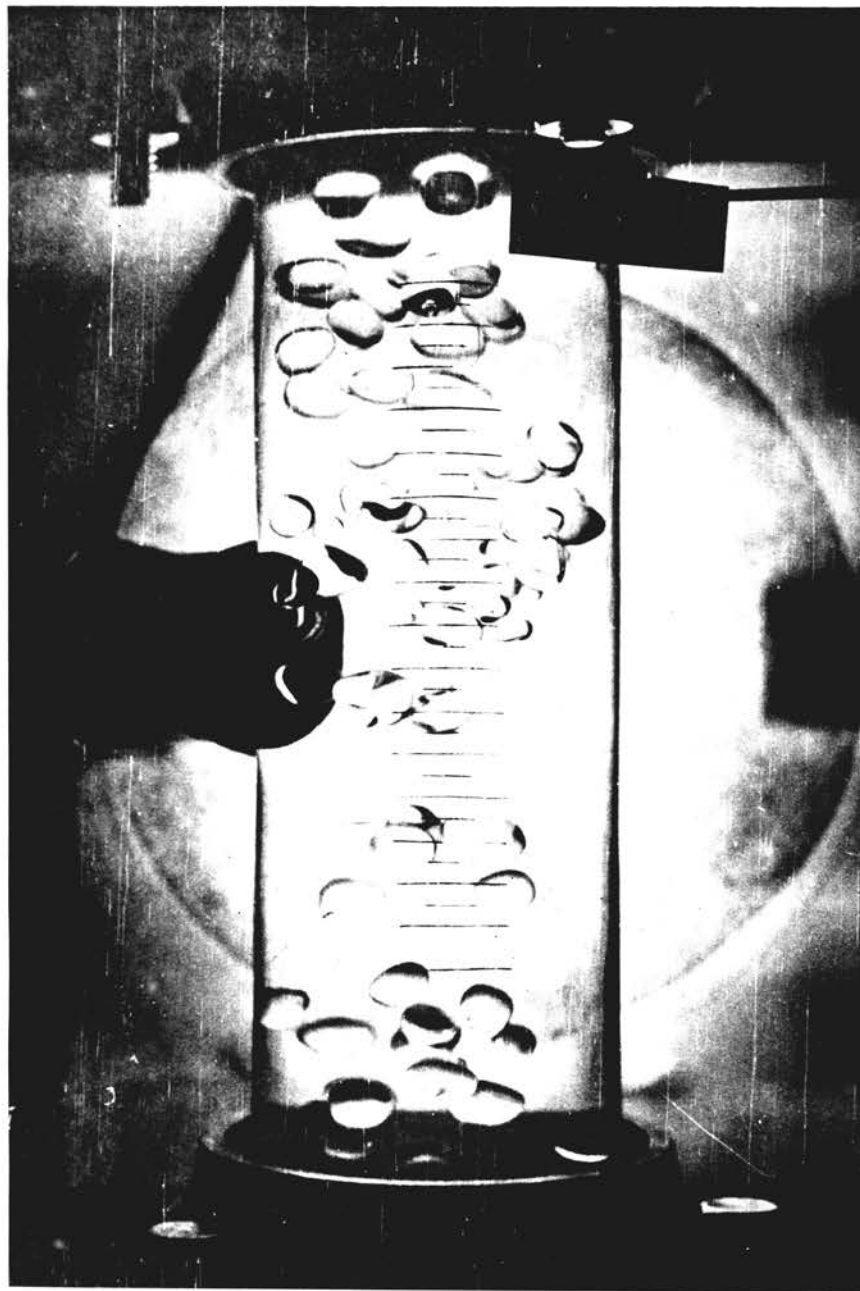


FIGURE 9: Low Holdup and Drop Sizes in a Water-hot Run.





FIGURE 10: High Holdup and Drop Sizes in a Benzene-hot Run.

E.m.f. Measurement: After steady state in the column had been attained, e.m.f. measurements were made with the four end couples first. These were read first since the entering stream temperatures had to be constantly checked to make sure that they were constant. By the previously-mentioned precautions (drawing out the water main, elimination of non-condensibles in the steam heater, and maintenance of a constant flow rate), the inlet temperatures could usually be controlled quite closely for a length of time sufficient to take all the e.m.f. readings. If either stream changed in temperature more than a few tenths of a degree Fahrenheit, or if the interface level changed appreciably, the e.m.f. measurements were repeated after column conditions had settled down again.

Room Temperature: The temperature of the surrounding air was taken in order to be able to make allowance for the heat loss. The thermometer was halfway between the two ends and about four inches from the column.

When the benzene was the heated stream, difficulty was encountered due to the decreased solubility of air as the temperature of the benzene was raised. Sufficient air would be dissolved at the temperature and pressure in the carboy to completely disrupt drop formation at the nozzle once the air was forced out of solution by the heating. A small deaerator had to be included between the heater and the column. (See Figure 4). This device consisted of a flask having a vent through a variable head of mercury. The benzene came in

the top and was taken out of the bottom below the liquid level. The level was positioned by regulating the pressure under which the air was removed from the flask through adjustment of the head of mercury over the vent.

The same difficulty tended to occur in the column itself when the benzene came in cold. As it heated up on its course through the column, a small vapor bubble would form at the top of the drop, which bubble, if allowed to become large, would materially affect the velocity of rise and the drop shape. To minimize this, the inlet water temperature was held low enough to prevent excessive heating of the benzene drops as they passed upward through the column.

## METHODS OF CALCULATION

The liquid densities used in calculating the gravimetric flow rates corresponded to the temperature of the flow measurements. Since the benzene leaving the cooler was approximately 80°F., the density usually used for it was 54.3 #/cu.ft.

The specific heat of water was taken to be 1.00 at all experimental temperatures. The specific heat of benzene was not considered constant. The value used was entered in the tabulation of data even though in most cases the variations were negligible. When the temperature of the benzene changed, the  $C_p$  corresponding to the average temperature was used.

The runs were numbered in such a manner as to furnish information on the approximate flow rates and which entering stream was heated. For example, the designation W1.53.5 means the water entered hot and flowed at the rate of 1.5 cu.ft./hr., while the benzene rate was 3.5 cu.ft./hr. B32 means the benzene was initially heated and flowed at a rate of 2 cu.ft./hr. while the water rate was 3 cu.ft./hr. The water rate is always the first number (including the decimal fraction, if any) after the letter. The actual flows usually differed slightly from the nominal rates given by the designation.

When the letter "f" appears in the run designation, it means that it was a flooding run. The column was considered to be at flooding when the benzene drops began to back up into the lower conical section just above the disperser but had not yet progressed far enough downward to interfere with the

drop formation.

The heat gained or lost by a stream was calculated by the usual relationship:

$$Q = M \times C \times \Delta t$$

The  $Q$  used in calculating the transfer coefficient,  $U = \frac{Q}{A \Delta t_m}$ , was in every case the heat gain or loss of the benzene. This was done because of the effect of heat loss on the enthalpy change of the continuous phase (water).

The driving force used was the conventional logarithmic mean temperature difference even though conditions deviated slightly from adiabatic. The transfer coefficient,  $U$ , was assumed to be constant over the column length.

To check on the accuracy of the log mean driving force, a rigorous expression was derived in the following manner: Let " $t_w$ " represent the water temperature, " $t_b$ " the benzene temperature, and " $t_a$ " the air temperature. For the sake of simplicity, the water is taken as the hot phase, although the method is applicable to transfer in either direction.

$$(1) \int dQ_w = M_w C_w dt_w$$

$$(2) \int dQ_b = M_b C_b dt_b$$

By making use of a heat loss coefficient based on the outside area of the column,  $U_L A_L$ , the differential heat loss  $dQ_L$  can be expressed in terms of the effective column length,  $L_e$ :

$$(3) U_L a'_L = \frac{U_L A_L}{L_e} = \frac{U_L dA_L}{dL_e}$$

$$(4) dQ_L = U_L a'_L (t_w - t_a) dL$$

The same thing can be done for the heat transferred to

the benzene,  $Q_b$ :

$$(5) \quad d = \frac{A}{L_e} = \frac{dA}{dL}$$

$$(6) \quad dQ_b = U(t_w - t_b) a' dL$$

Then,

$$(7) \quad dQ_w = \int_{t_w}^{t_{w2}} M_w C_w dt_w = \int_0^L U_L a'_L (t_w - t_a) dL + \int_{t_b}^{t_{b1}} M_b C_b dt_b$$

where  $t_{w2}$  and  $t_{b1}$  refer to the water temperature at couple #2 and the benzene temperature at couple #1, respectively, ( $L =$  zero at these points), and  $t_w$  and  $t_b$  refer to the water and benzene temperatures at the position in the column corresponding to  $L$ .

Since e.m.f. readings were taken all along the column length,  $t_w$  is known experimentally as a function of length. Also, as shown below,  $U_L a'_L$  can be rigorously calculated from the experimental values of heat loss from the column. (See Heat Loss Calculations). Therefore, the first two integrals in (7) can be evaluated. The first integral is simply the enthalpy gain (or loss) equation, while the second one can be found graphically. The third integral is then the difference between the first two. From the third integral the temperature change in the benzene in going from any point in the column (position  $L$ ) to the top can be found. This in turn gives the benzene temperature at that point.

By repeating the above procedure from point to point, the benzene temperature is then known as a function of length. Since, also,

$$\int_{t_b}^{t_{b1}} M_b C_b dt_b = \int_0^L U(t_w - t_b) a' dL = U \int_0^L (t_w - t_b) a' dL$$

then,

$$U = \frac{\int_{t_b}^{t_{b1}} M_b C_b dt_b}{\int_0^L (t_w - t_b) a' dL} = \frac{M_b C_b (t_{b1} - t_b)}{\int_0^L (t_w - t_b) a' dL}$$

where the denominator is obtained by graphical integration. If this is evaluated over the entire column length ( $L = L_e$ ) an average  $U$  is obtained.

The coefficient was calculated in this manner for two runs, W1.51.5 and W1.53.5. The  $U$  calculated by the rigorous method was 52.5 in the first case and 45.5 in the second case. (See Table VII, Appendix.) The corresponding  $U$ 's from the use of a log mean temperature difference were 53.0 and 42.8. These results show small differences and evidently the log mean driving force is sufficiently accurate in these two cases. Due to a lack of time, it was impossible to investigate rigorously runs at other flow rates. However, it is intended to apply the rigorous calculation just described to enough runs to definitely determine the applicability of the log mean driving force under all the experimental conditions.

The calculation of the transfer area was based on the obtaining of average drop sizes from photographs of each run. Since the drops assume a form other than spherical as they rise (see Figure 9), both the major and minor diameters were measured and the volume and surface area evaluated on the assumption of an ellipsoidal shape. This assumption is not exactly correct even for drops that are not distorted by collision. As pointed out by Miyagi,<sup>(9)</sup> a drop or bubble

tends to follow the line of least resistance. This changes continually because as the drop flattens during its rise, it tends to slip sideways to take advantage of a decreased frontal area and consequently rises in a helical course. Therefore, the major and the minor axes are continually changing their positions in the drop. This effect is, of course, much smaller for liquid drops than for gas bubbles.

Despite this effect, the assumption of an ellipsoid was considered much more accurate than that of a sphere. The volume of a sphere calculated from the average of the two diameters varied by 10.5% for the largest and 6.5% for the smallest drops from the volume of the corresponding ellipsoid. The difference in the surface area was slightly larger, 13.8% and 8.3%, respectively.

The following equations were used in the calculation of drop surface area and volume: (14)

$$V_D = \frac{4}{3} \pi m^2 r$$

$$S_D = 2\pi m \left[ m + \frac{m^2}{\sqrt{m^2 - r^2}} \ln \frac{m + \sqrt{m^2 - r^2}}{r} \right]$$

The average deviation of an individual measurement from the mean was found in all runs for both the velocity of rise and the drop diameter by the following equations: (13)

$$\text{a.d.} = \frac{|N_1| + |N_2| + |N_3| + \dots + |N_n|}{n}$$

The average deviation of the mean was then found by,

$$\text{A.D.} = \frac{\text{a.d.}}{\sqrt{n}}$$



The holdup,  $H$ , which is the volume of benzene in the column, was calculated from the velocity of rise,  $v$ , the effective column length,  $L_e$ , and the volumetric benzene rate,  $B$ , in the following manner:

$$H = \frac{L_e}{v} \times \frac{B}{3600}$$

The interfacial area in the column,  $A$ , neglecting the interface, was found by using the average drop characteristics  $V_D$  and  $S_D$ :

$$A = \frac{H}{V_D} \times S_D$$

where  $H/V_D$  corresponds to the number of drops in the column.

The following equation was used to calculate the tip velocity,  $v_t$ :

$$v_t = \frac{B}{3600} \times \frac{30.48}{\text{Tips Working}} \times \frac{1}{0.785d_t^2}$$

Heat Loss Calculation: An average heat loss coefficient,  $U_L A_L$ , which lumped together the surface coefficient and the column wall area was calculated from the experimental values of heat loss occurring during the water-hot runs. The heat loss was usually negligible in the benzene-hot runs. Since  $U_L A_L$  was needed in the calculations checking the accuracy of the log mean temperature difference, it had to be obtained rigorously and not through the use of a log mean driving force. With the water temperatures known as a function of column length, a rigorously correct  $U_L A_L$  can be found by the following calculation:

$$U_L a'_L = \frac{U_L A_L}{L_e} = \frac{Q_L}{\int_0^{L_e} (t_w - t_a) dL}$$

Since the experimental  $Q_L$  was the relatively small difference between  $Q_w$  and  $Q_b$ , and therefore subject to considerable error, care had to be exercised in selecting values of  $Q_L$  for these calculations. The water-hot runs were divided into groups having approximately the same temperature difference between the water and the air. The average  $Q_L$  for each group was found by averaging the individual values. A run whose  $Q_L$  compared well with the average for its group could then be used with some degree of assurance as to the accuracy of the  $Q_L$  value. The actual experimental value of  $Q_L$  was used, not the group average. Nine runs were selected and used in this manner. The heat loss coefficients for these runs and the average  $U_L A_L$  calculated from them are shown in Table IV, Appendix. This  $U_L A_L$  based on nine runs was found to be 3.9. It was used in all the calculations. The  $U_L A_L$  calculated by the use of a log mean temperature difference and based on 31 runs was 4.5. Because of the small magnitude of the heat losses, the latter value could have been used without serious error.

Besides the checking of the applicability of the log mean temperature difference, the  $U_L A_L$  was also used in the calculation of the transfer coefficients for the bottom section of the column (approximately the bottom fifth of the effective length). In these calculations the temperature

change of the benzene in passing through the bottom section was found by the following calculation:

$$\Delta t_b = \frac{Q_b}{M_b C_b}$$

where  $Q_b$  is for the section between couples #11 and #9. To calculate the benzene temperature at #9,  $\Delta t_b$  was either added to or subtracted from the experimentally measured benzene temperature at couple #12 depending upon whether the benzene was heated or cooled in going from #12 to #9.

Since in some cases (only benzene-hot runs) the temperature of the continuous phase was below that of the surrounding air, the  $Q_L$  does not always represent heat lost from the column. Depending upon the direction of heat flow through the column wall, the  $Q_b$  for the benzene-hot runs was calculated by one of the following equations:

$$Q_b = Q_w + Q_L \quad \text{when heat was lost from the column.}$$

$$Q_b = Q_w - Q_L \quad \text{when heat flowed into the column.}$$

For all the water-hot runs,  $Q_b = Q_w - Q_L$ .

In Table III, for those few runs where heat flowed into the column, the value of  $Q_L$  is preceded by a negative sign to distinguish it from heat lost from the column.

## DISCUSSION OF RESULTS

DETERMINATION OF THE TRANSFER AREA:

Calculation of the area for transfer depended upon two things, a knowledge of the dispersed phase holdup in the column and a value of the average drop size.

Dispersed Phase Holdup: By getting the velocity of rise, the benzene holdup in the column could be calculated as shown previously. Although the velocity of rise is primarily a function of drop size and flow rates, it also depends upon the temperatures of the two phases. Two properties which affect the velocity of rise and which show some change with temperature are viscosity and interfacial tension. The viscosity of the dispersed phase is probably of less importance than that of the continuous phase.

The interfacial tension is important in that it not only affects the size of the drop during formation but also controls the drop shape. It is the force tending to pull the drop into a spherical shape, and it opposes the flattening effect of the continuous phase on the drop as the latter rises. The situation was complicated here because the liquids on either side of the interface were not in thermal equilibrium, the temperature at the interface being at some intermediate value between the temperatures of the two phases.

Since determinations of rise velocity were not the primary purpose of this work, the change in velocity as the

phases changed temperature was not thoroughly investigated. A few observations, some of which are listed in Table I, show an approximate variation of from 6 to 11% in velocity from the bottom to the top for fairly small continuous phase temperature changes. These data were taken when the water came in hot and the benzene drops heated as they rose.

Table I: Effect of Temperature of Continuous Phase on Rise Velocity.

Position in Column ↓	Run Number					
	W41		W41.5		W52.5	
	Temp. (°F.)	v	Temp. (°F.)	v	Temp. (°F.)	v
Bottom	136.7	0.297	135.0	0.278	131.1	0.176
1/3 of way up*	-	0.305	137.2	0.295	135.0	0.183
Top	139.5	0.314	139.6	0.312	137.6	0.200

\* Position where photographs were taken and the velocity of rise timings were made.

For lower water rates the temperature change of the continuous phase was much greater, being 52°F. for the extreme case in the run W1.54. However, while the increasing temperature decreases the viscous drag on the drop, it also decreases the interfacial tension. This causes a more flattened drop which offers more resistance to movement through the water. Therefore, a proportionate increase in rise velocity is probably not to be expected with larger changes in temperature from bottom to top.

For the benzene hot runs where both the benzene and the water became colder toward the top, the increased viscosity

would tend to slow the drop down while the increased interfacial tension would tend to make its rise easier through the maintenance of a more spherical drop. No measurements of the velocity were made in different parts of the column for the benzene-hot runs so no quantitative discussion can be offered. It was observed, however, that for both the benzene-hot runs and the water-hot runs, the holdup was always slightly greater at the bottom end of the column and flooding always began there.

To minimize the error caused by making a point determination of a quantity that changed over the length of the column, all velocity of rise measurements were made at the section containing couple #8. This was approximately one-third of the way up the column and probably represented more closely than any other position an average of conditions between the top and bottom.

Other difficulties in the velocity of rise measurements were the short distance over which the ascent was timed and the large variation among the individual drops. This non-uniformity of velocity of rise became increasingly evident as flooding was approached. However, by taking a large number of timings (twenty) for each run, a good average value was obtained. (See average deviation data in Tables II and III, Appendix.)

Since it was possible to observe the drop formation at the tips, the fraction of the tips working (see Figure 11) and the point at which the formation changed from "pulsing" (single drop formation) to formation from a jet was easily

marked. All the tips would be working at a benzene rate of about 2.45 cu.ft./hr. (or 0.12 cu.ft./hr.-tip). Jet formation would begin simultaneously in all tips at a benzene rate of about 2.6 cu.ft./hr. which corresponded to a tip velocity of about 13 cm./sec. At this point there was a rather abrupt decrease in drop size and a change of slope in the velocity of rise curve. (See Figures 12a and 12b.)

**Average Drop Sizes:** As in the case of the velocity of rise, these figures are based on a large number of measurements (twenty-four for each photograph). The data and the average deviations are shown in Tables II and III in the Appendix. The small average deviation values and the good grouping of points in Figures 14a and 14b indicate that these determinations were probably quite accurate.

Tip velocity, tip size, nozzle temperature, and water rate might be expected to be the most important variables affecting the drop size. From Figure 14c, it can be seen that the drops formed at an average benzene temperature of 150°F. were considerably smaller than those formed at an average benzene temperature of 85°F. The change in the interfacial tension between these two temperatures was probably the biggest factor causing the different drop sizes.

Figure 14b and the listings of the diameters in Table II show that water rate had practically no effect on drop size. However, the shape of the larger size drops was apparently affected by the water rate. (See Figure 15.) This effect of water rate on the drop shape was very likely

partially caused by a temperature effect. In the water-hot runs, as the water rate increased, the temperature of the water dropped less as it went down the column. The higher the temperature, the lower the interfacial tension, and the drop tended to flatten out more. Some of the scattering in Figures 14a and 14b is undoubtedly due to this phenomenon. The effect was more pronounced in the larger drop-size range and these larger drops were formed in the water-hot runs. In the benzene-hot runs, the drops formed were smaller and therefore subject to less flattening. Another factor affecting the ratio of drop diameters is the greater turbulence in the column caused by the higher water rate. More of the drops were distorted and this would affect the average diameters which were measured.

For a given set of liquids, tip size, and temperature, the drop size is determined by the tip velocity. For this reason, the major diameters were plotted against tip velocity for the two different ranges of benzene tip temperature. (Figure 14c.) As was pointed out above, a decrease in drop size occurred as the type of formation changed from that of successive single drops at the tip to formation at the end of a jet of benzene. Finally, after the jets had reached a certain length, the drops became somewhat more independent of tip velocity, and the curve of major diameter versus tip velocity flattens out.

#### AREA TRANSFER COEFFICIENT:

The area transfer coefficient,  $U$ , was found to be



constant and then drop off as the flow rates were further increased. The rate at which  $U$  drops off is affected more by the benzene rate than by the water rate. This is shown in Figures 16 and 17.

In Figures 17, for the lowest benzene rates of 1.5 and 2.0 cu.ft./hr., changing the water rate from 1.5 to 6.0 cu. ft./hr., a fourfold change, decreases  $U$  by only 6%. The same thing occurs for 2.5 cu. ft./hr. of benzene until flooding is approached at about 4.5 cu. ft./hr. of water. On the other hand, at a water rate of 1.5, changing the benzene rate from 1.5 to 4.0 causes a 31% decrease in  $U$ . At the higher benzene rates where flooding is approached, the water rate becomes much more important.

This decrease in  $U$  as the flow rates increase is believed due to a decreased efficiency of contact between the phases as the holdup increases. Each drop begins to shield the drops below so that the water does not impinge upon each drop. Drops begin to touch one another as nearly as their coating film of water will allow. Small pockets of water are undoubtedly carried along with the drops for a short distance while often the drops themselves back up. This recirculation causes a departure from true countercurrent action.

Although holdup is the primary factor affecting the  $U$  for a given set of liquids at a given temperature (see Figures 21 and 22), plots of  $U$  versus holdup show some scattering. This is due to the fact that for a given holdup the factors mentioned in the previous paragraph do not necessarily enter

to the same degree in all cases. For instance, for a given holdup with large drops, the degree of "touching" of drops would not be the same as for the same holdup with small drops. The shielding would also be different. It is probably true that, just as holdup can be no criterion of flooding<sup>(2)</sup>, so it also cannot be used for an absolute prediction of  $U$ . Nevertheless, the plots show a fairly good relationship, sufficiently good for most practical purposes. Also, they furnish a means of tying drop size, velocity of rise, and flow rates together and expressing  $U$  as a function of the combined variables.

The  $U$  is somewhat higher when the heat transfer takes place from the drops to the continuous phase, the difference being about 25% for the lower rate runs (far removed from flooding). (Compare Figures 16 and 17; see also Figure 23). This effect of direction of transfer may be an artificial one caused by the possible non-applicability of the log mean temperature difference. This will be checked more completely later.

A plot of the more conventional volumetric coefficient,  $U_a$ , against flow rates shows the same relative effect of the continuous and discontinuous rates as in the case of  $U$ . The small effect of water rate is forcibly shown in Figure 20, where the transfer was from the continuous to the discontinuous phase. Water rate was more important, however, when transfer was from the drops to the continuous phase. This is shown by Figure 19 which is a cross-plot of Figure 18.

Much higher values of  $U_a$  were obtained when the benzene entered hot. This was due not only to the larger values of  $U$  in these cases but also the the fact that the hot benzene formed smaller drops which resulted in a larger holdup and greater interfacial surface. The larger effect of water rate in Figure 19 as compared to Figure 20 may also be due to this small drop size. Small drops rise less rapidly and are subject to more recirculation when the holdup increases.

It was originally intended to determine whether or not an end effect occurred at either end. However, in almost all cases the driving force at the top was too small to permit any degree of accuracy in such calculations. An error in a temperature measurement of a few tenths of a degree coupled with the uncertainty in applying a heat loss coefficient based on the entire column length to the bell-shaped end could amount to a large percentage error when the water temperature change was only  $1^{\circ}\text{F}$ . or less. Also, allowance would have to be made for the presence of the interface (about 0.1 of a square foot of plane area) which was neglected in computations based on the entire column length.

For these reasons the end effect at the top was not calculated. At the bottom end where the water temperature change was larger and the heat loss a small percent of the heat transferred between the liquids, such calculations were more feasible. Also, the complication of the interface did not exist. The values obtained for  $U$  in this bottom fifth of the column showed no marked change from those based on

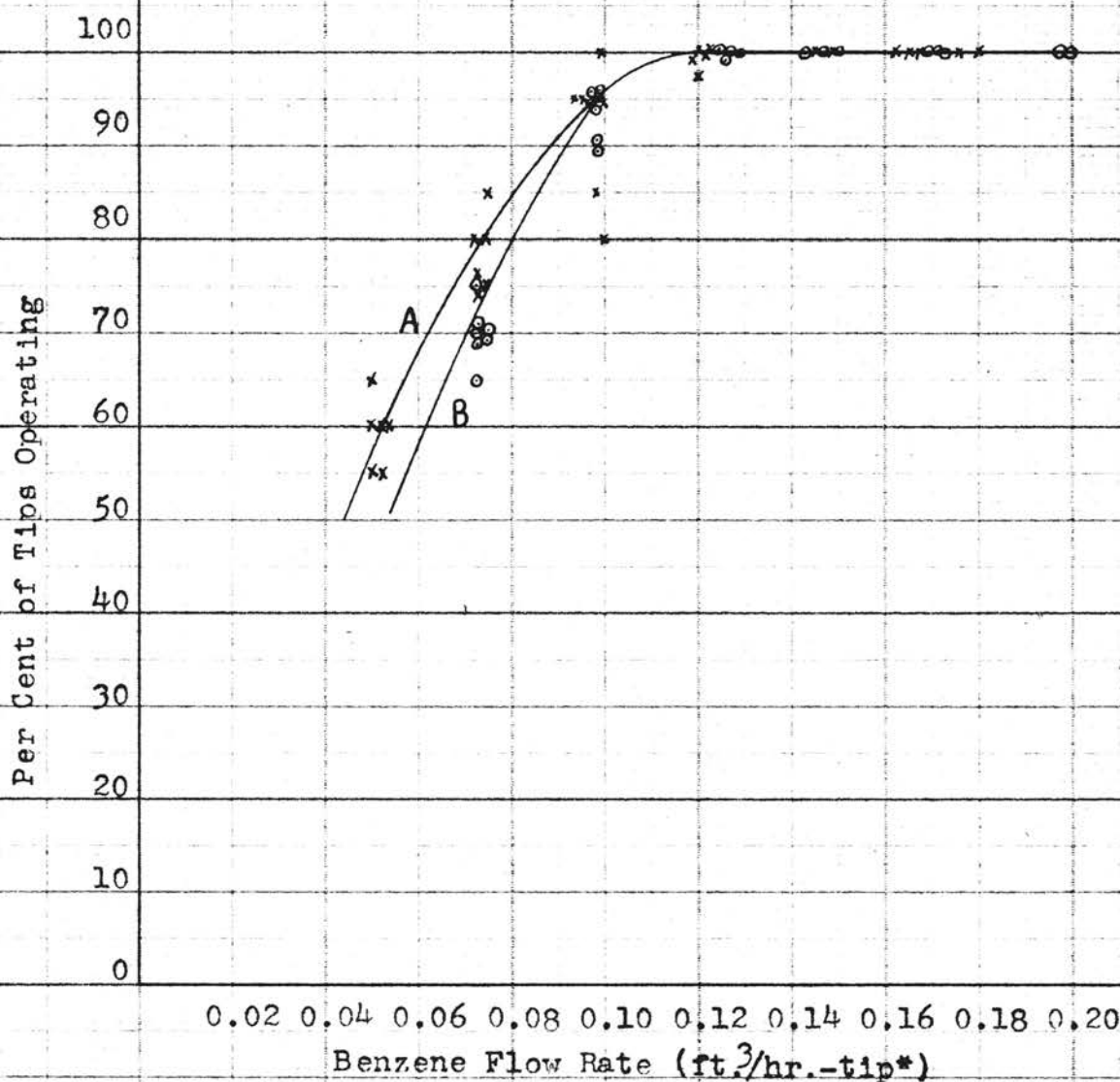
the entire column. (See the last two columns of Tables V and VI).

FIGURE 11: Nozzle Characteristics

Number of Nozzles = 20  
 Inside Nozzle Diameter = 0.125"

Range of Temperatures at Tips (°F.)  
 (For runs below 100% operation.)

Curve	Symbol	Benzene	Water
A	X	76-91°F.	125-135°F.
B	○	133-161	85-110

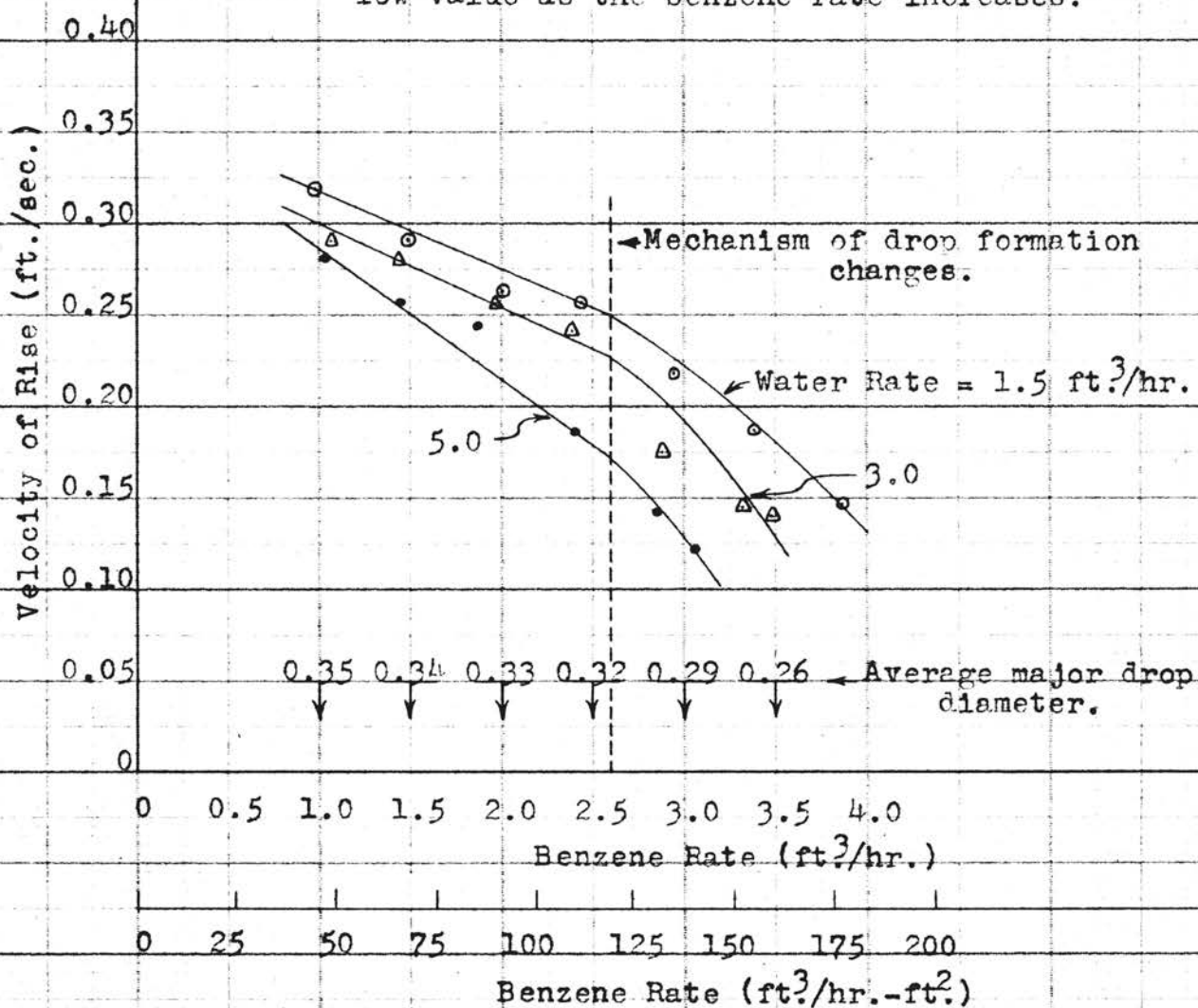


\*Based on total number of tips in nozzle.

FIGURE 12a: Velocity of Rise for the Water-hot Runs.

Symbol	Water Temp. at Point of Measurement (°F.)	Benzene Temp. During Drop Formation (°F.)
○	133-101	80-91
△	138-135	81-84
•	140-135	76-80

Note: Water temperature goes from the high to the low value as the benzene rate increases.



100-101-102-103-104-105-106-107-108-109-110-111-112-113-114-115-116-117-118-119-120-121-122-123-124-125-126-127-128-129-130-131-132-133-134-135-136-137-138-139-140-141-142-143-144-145-146-147-148-149-150-151-152-153-154-155-156-157-158-159-160-161-162-163-164-165-166-167-168-169-170-171-172-173-174-175-176-177-178-179-180-181-182-183-184-185-186-187-188-189-190-191-192-193-194-195-196-197-198-199-200-201-202-203-204-205-206-207-208-209-210-211-212-213-214-215-216-217-218-219-220-221-222-223-224-225-226-227-228-229-230-231-232-233-234-235-236-237-238-239-240-241-242-243-244-245-246-247-248-249-250-251-252-253-254-255-256-257-258-259-260-261-262-263-264-265-266-267-268-269-270-271-272-273-274-275-276-277-278-279-280-281-282-283-284-285-286-287-288-289-290-291-292-293-294-295-296-297-298-299-300-301-302-303-304-305-306-307-308-309-310-311-312-313-314-315-316-317-318-319-320-321-322-323-324-325-326-327-328-329-330-331-332-333-334-335-336-337-338-339-340-341-342-343-344-345-346-347-348-349-350-351-352-353-354-355-356-357-358-359-360-361-362-363-364-365-366-367-368-369-370-371-372-373-374-375-376-377-378-379-380-381-382-383-384-385-386-387-388-389-390-391-392-393-394-395-396-397-398-399-400-401-402-403-404-405-406-407-408-409-410-411-412-413-414-415-416-417-418-419-420-421-422-423-424-425-426-427-428-429-430-431-432-433-434-435-436-437-438-439-440-441-442-443-444-445-446-447-448-449-450-451-452-453-454-455-456-457-458-459-460-461-462-463-464-465-466-467-468-469-470-471-472-473-474-475-476-477-478-479-480-481-482-483-484-485-486-487-488-489-490-491-492-493-494-495-496-497-498-499-500-501-502-503-504-505-506-507-508-509-510-511-512-513-514-515-516-517-518-519-520-521-522-523-524-525-526-527-528-529-530-531-532-533-534-535-536-537-538-539-540-541-542-543-544-545-546-547-548-549-550-551-552-553-554-555-556-557-558-559-560-561-562-563-564-565-566-567-568-569-570-571-572-573-574-575-576-577-578-579-580-581-582-583-584-585-586-587-588-589-590-591-592-593-594-595-596-597-598-599-600-601-602-603-604-605-606-607-608-609-610-611-612-613-614-615-616-617-618-619-620-621-622-623-624-625-626-627-628-629-630-631-632-633-634-635-636-637-638-639-640-641-642-643-644-645-646-647-648-649-650-651-652-653-654-655-656-657-658-659-660-661-662-663-664-665-666-667-668-669-670-671-672-673-674-675-676-677-678-679-680-681-682-683-684-685-686-687-688-689-690-691-692-693-694-695-696-697-698-699-700-701-702-703-704-705-706-707-708-709-710-711-712-713-714-715-716-717-718-719-720-721-722-723-724-725-726-727-728-729-730-731-732-733-734-735-736-737-738-739-740-741-742-743-744-745-746-747-748-749-750-751-752-753-754-755-756-757-758-759-760-761-762-763-764-765-766-767-768-769-770-771-772-773-774-775-776-777-778-779-780-781-782-783-784-785-786-787-788-789-790-791-792-793-794-795-796-797-798-799-800-801-802-803-804-805-806-807-808-809-810-811-812-813-814-815-816-817-818-819-820-821-822-823-824-825-826-827-828-829-830-831-832-833-834-835-836-837-838-839-840-841-842-843-844-845-846-847-848-849-850-851-852-853-854-855-856-857-858-859-860-861-862-863-864-865-866-867-868-869-870-871-872-873-874-875-876-877-878-879-880-881-882-883-884-885-886-887-888-889-890-891-892-893-894-895-896-897-898-899-900-901-902-903-904-905-906-907-908-909-910-911-912-913-914-915-916-917-918-919-920-921-922-923-924-925-926-927-928-929-930-931-932-933-934-935-936-937-938-939-940-941-942-943-944-945-946-947-948-949-950-951-952-953-954-955-956-957-958-959-960-961-962-963-964-965-966-967-968-969-970-971-972-973-974-975-976-977-978-979-980-981-982-983-984-985-986-987-988-989-990-991-992-993-994-995-996-997-998-999-1000

FIGURE 12b: Velocity of Rise for the Water-hot Runs.

Symbol	Water Temp. at Point of Measurement (°F.)	Benzene Temp. During Drop Formation (°F.)
□	137-126	79-84
x	138-135	77-85
+	142-139	83-85

Note: Water temperature goes from the high to the low value as the benzene rate increases.

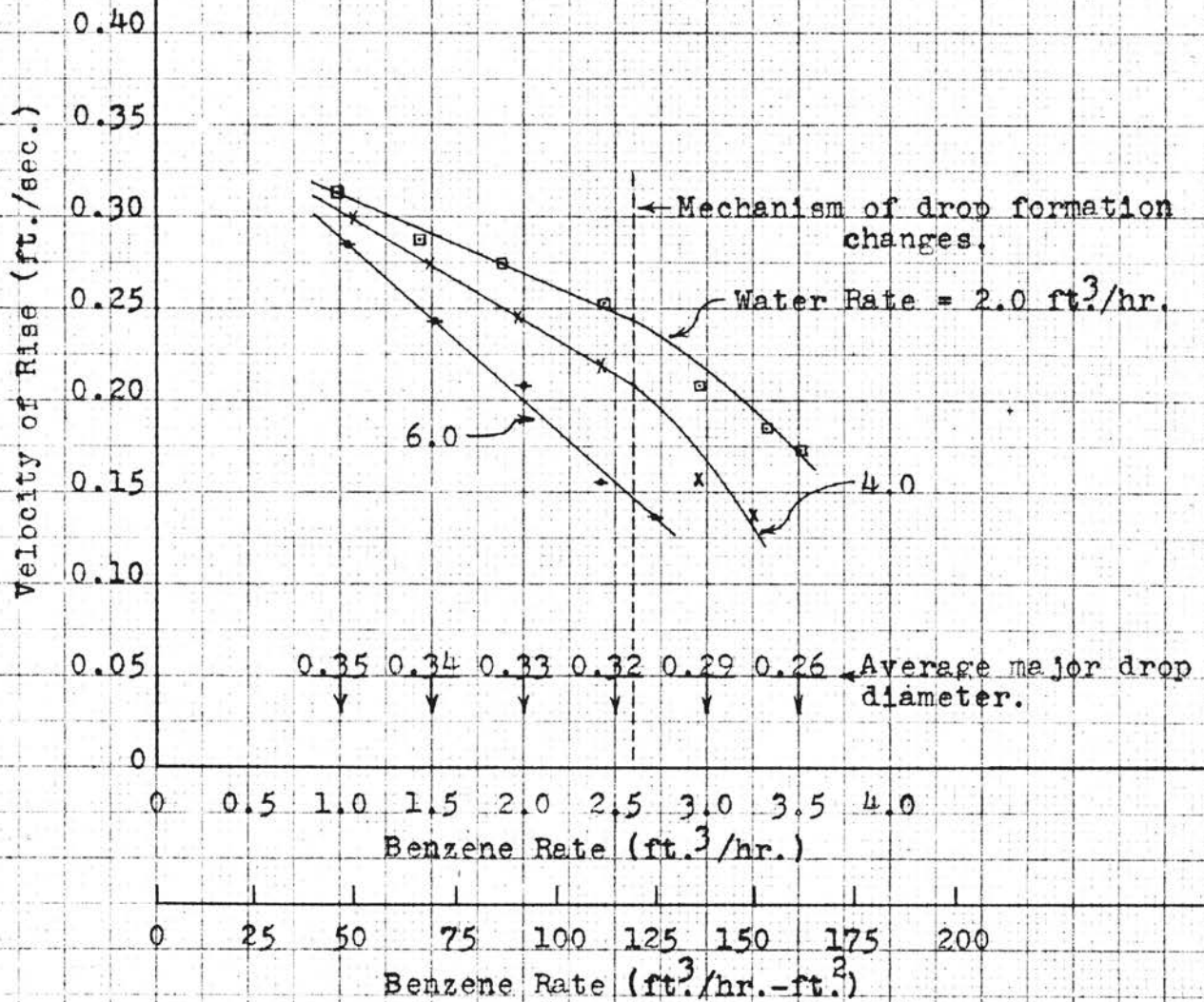


FIGURE 13a: Velocity of Rise for the Benzene-hot Runs.

Symbol	Range of Properties		
	Major Drop Diameter	Water Temp. at Point of Measurement (°F.)	Benzene Temp. During Drop Formation (°F.)
⊖	0.28-0.31	87-76	133-142
△	0.28-0.29	99-76	150-161
■	0.22-0.25	114-79	158-161

Note: The water temperature goes from the high value to the low value as the water rate goes from 1.5 to 6.0.

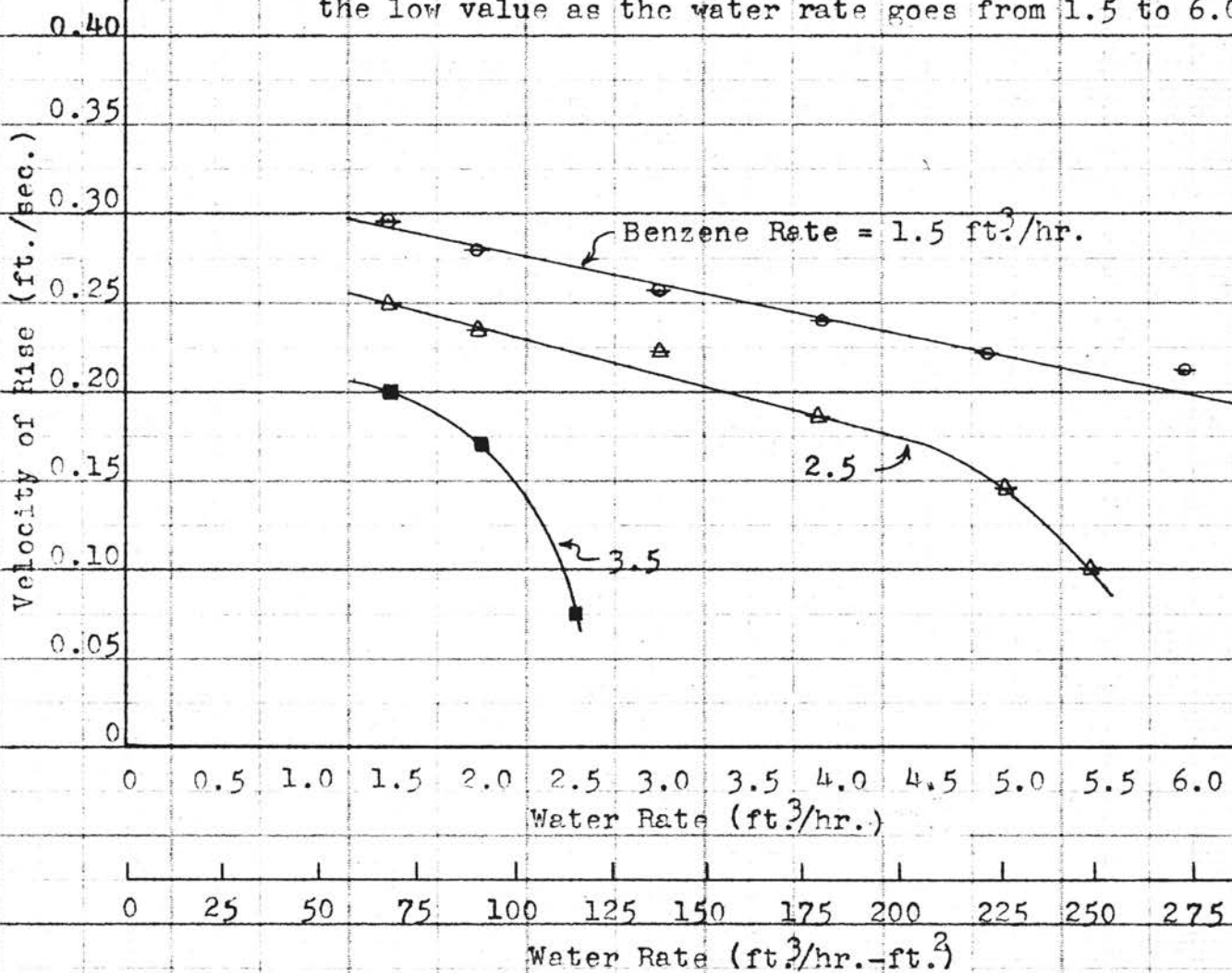




Figure 13b: Velocity of Rise for the Benzene-hot Runs.

Symbol	Range of Properties		
	Major Drop Diameter	Water Temp. at Point of Measurement (°F.)	Benzene Temp. During Drop Formation (°F.)
⊖	0.29-0.30	95-75	138-151
+	0.24-0.25	106-76	156-166
▲	0.23-0.24	125-100	160-161

Note: The water temperature goes from the high value to the low value as the water rate goes from 1.5 to 6.0.

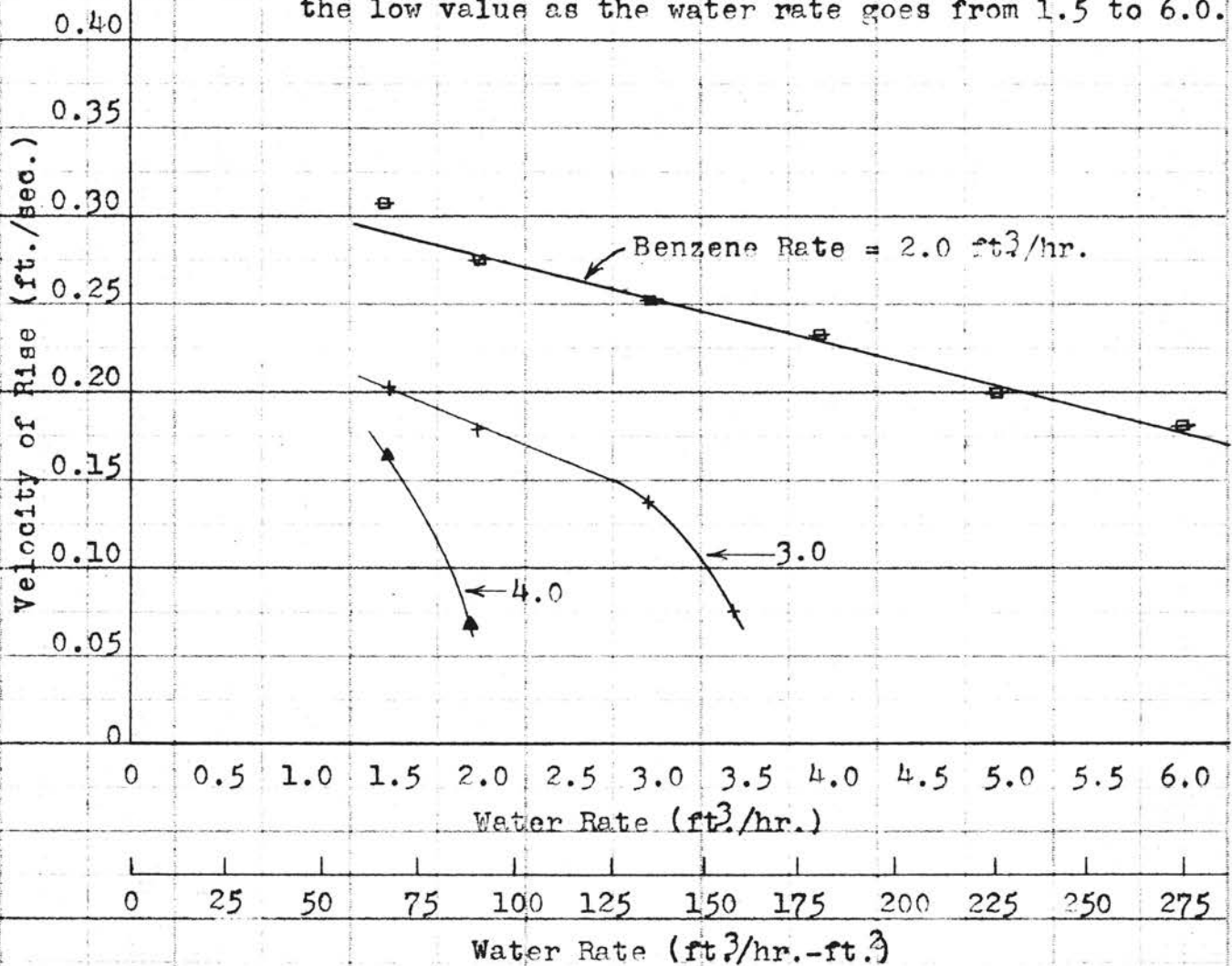


FIGURE 14a: Drop Sizes in the Water-hot Runs.

Symbol	Water Rate (ft. <sup>3</sup> /hr.)	Water Temp. at Tips (°F.)	Benzene Temp. During Drop Formation (°F.)
⊙	1.5	127-87	80-91
⊠	2.0	133-103	79-84
△	3.0	132-110	81-83
×	4.0	135-122	78-85
•	5.0	132-126	76-80
+	6.0	140-131	83-85

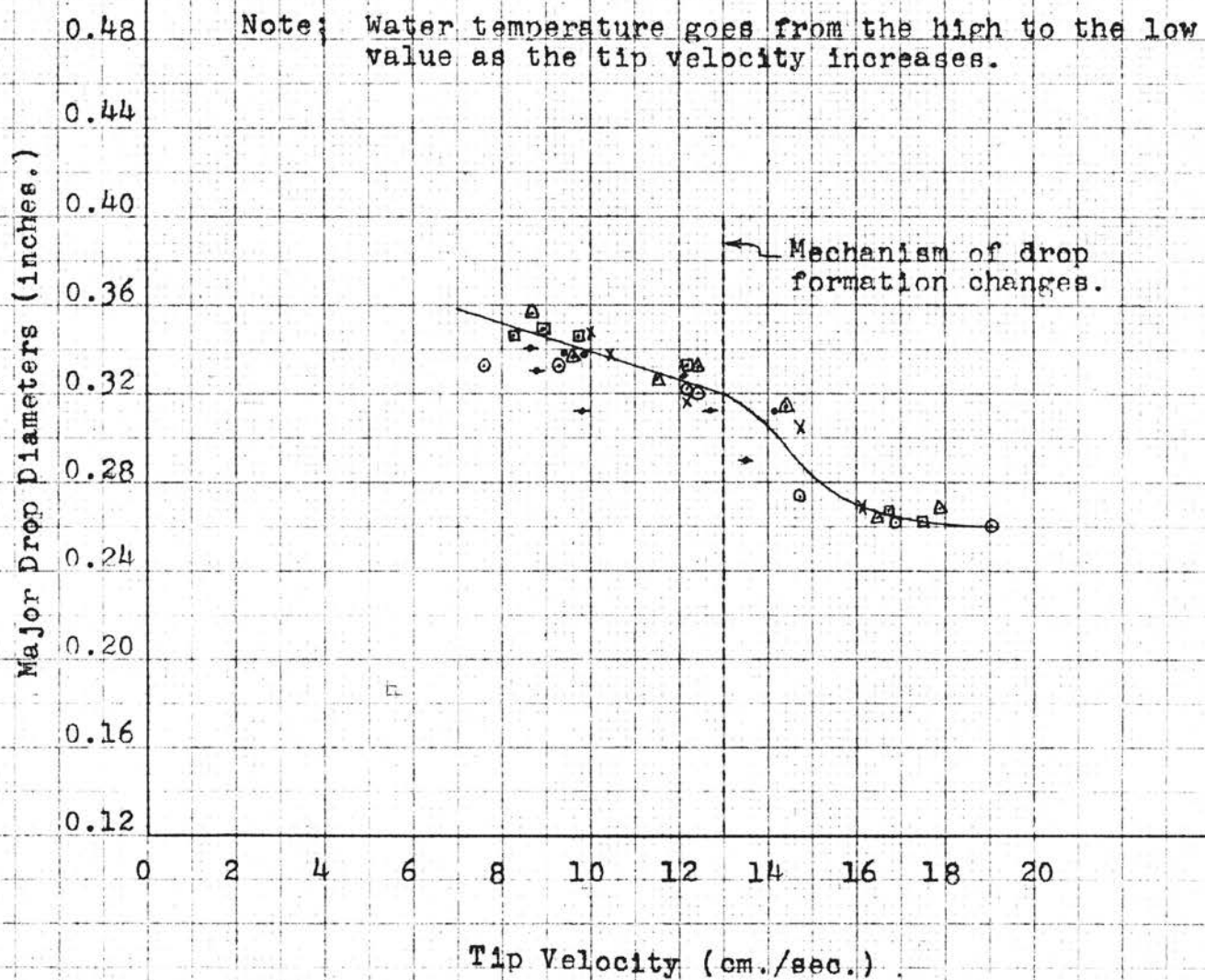


FIGURE 14b: Drop Sizes in the Benzene-hot Runs.

Symbol	Water Rate (ft. <sup>3</sup> /hr.)	Water Temp. at Tips (°F.)	Benzene Temp. During Drop Formation (°F.)
⊕	1.5-6.0	100-87	133-142
⊞	1.5-6.0	111-86	138-151
△	1.5-5.4	118-88	150-161
+	1.5-3.5	132-101	156-166
■	1.5-2.5	140-117	158-161
▲	1.5-2.0	147-140	160-161

Note: Water temperature goes from the high to the low value as the water rate increases.

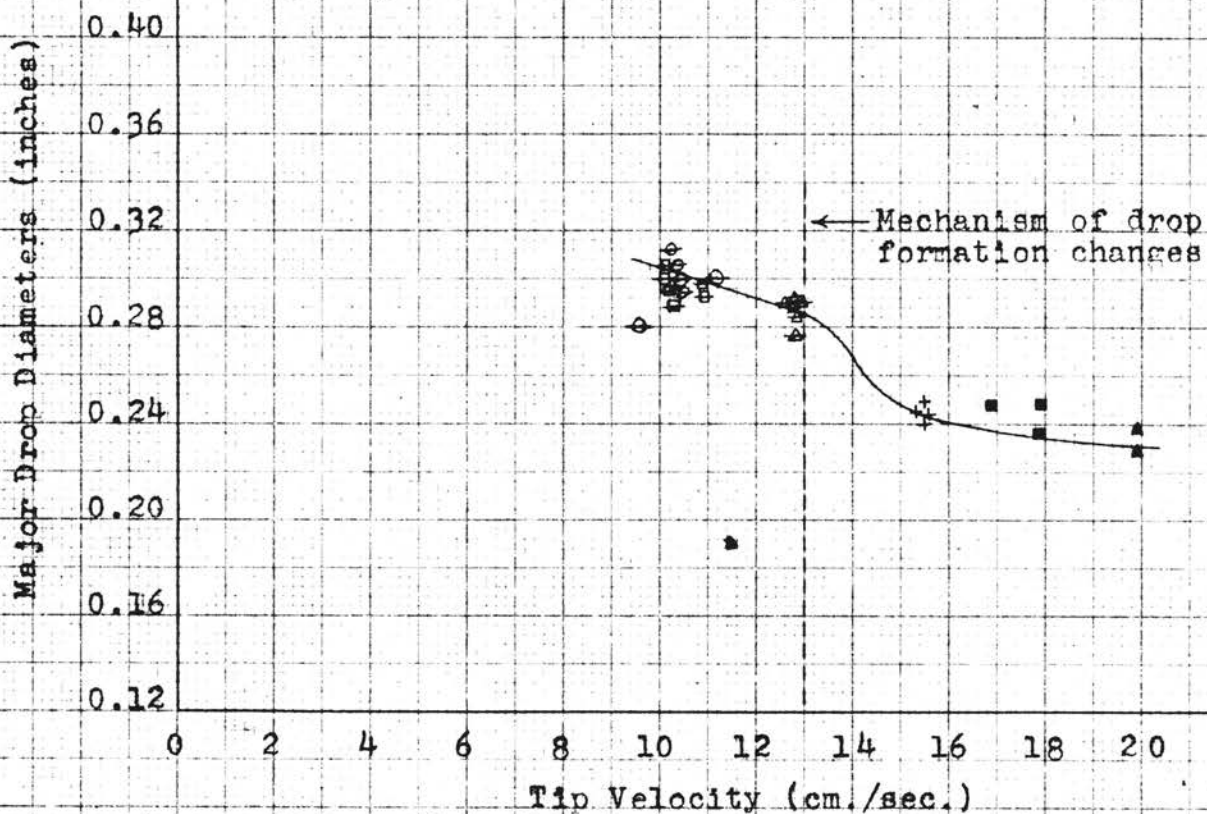


FIGURE 14c: Effect of Temperature on Drop Sizes.  
(Re-plot of Figures 14a and 14b)

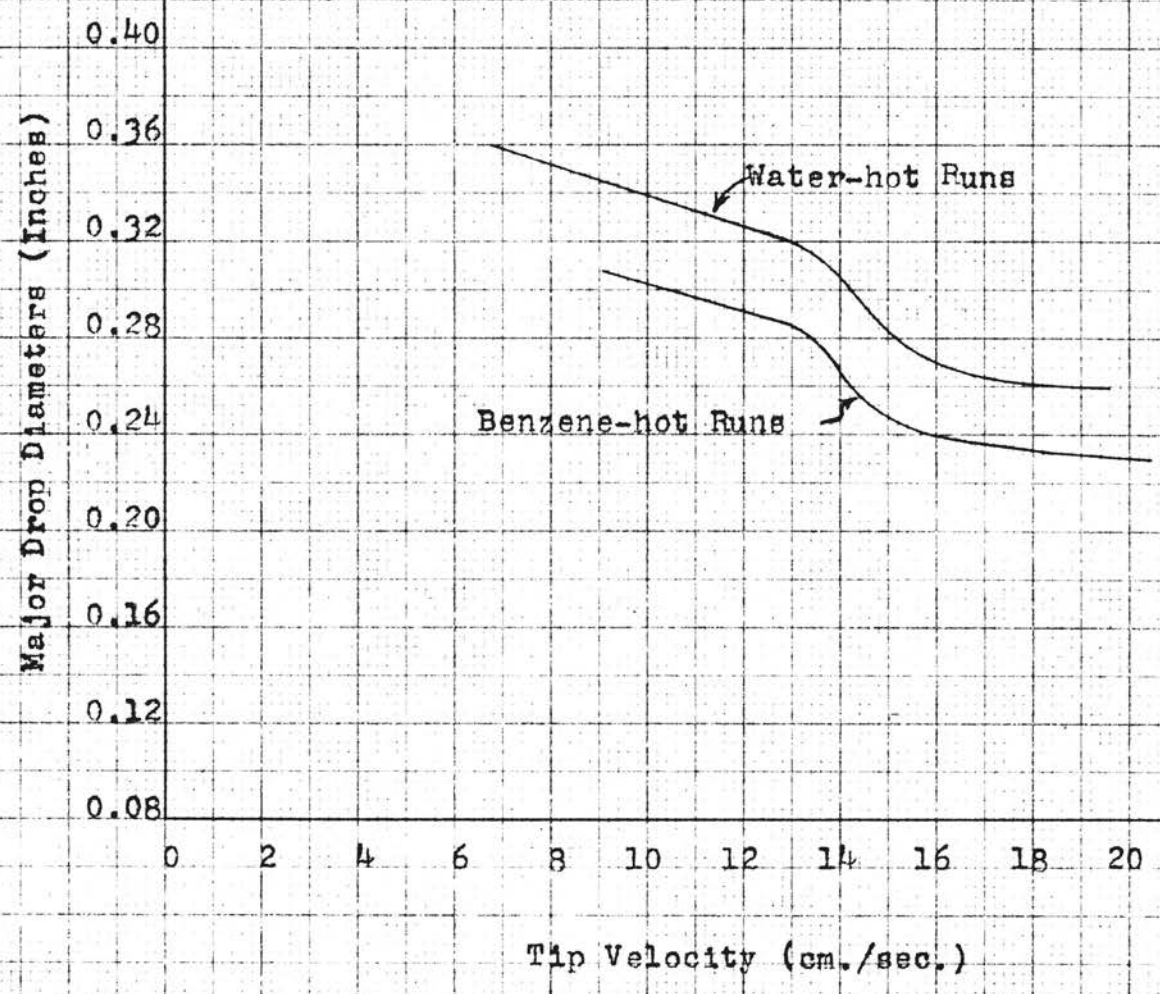


FIGURE 15: Relation Between Major and Minor Diameter and the Effect of Continuous Phase Temperature. (Both the water-hot and the benzene-hot runs.)

Symbol	Water Rate (ft <sup>3</sup> /hr.)	Range of Water Temperatures for major diameter > 0.27. (Water-hot runs)
○	1.5	100-133
□	2.0	125-136
△	3.0	130-138
X	4.0	135-139
•	5.0	135-140
→	6.0	139-142

Note: For a given water rate, the higher water temperature corresponds to the larger major diameters, the lower temperature to the smaller diameters.

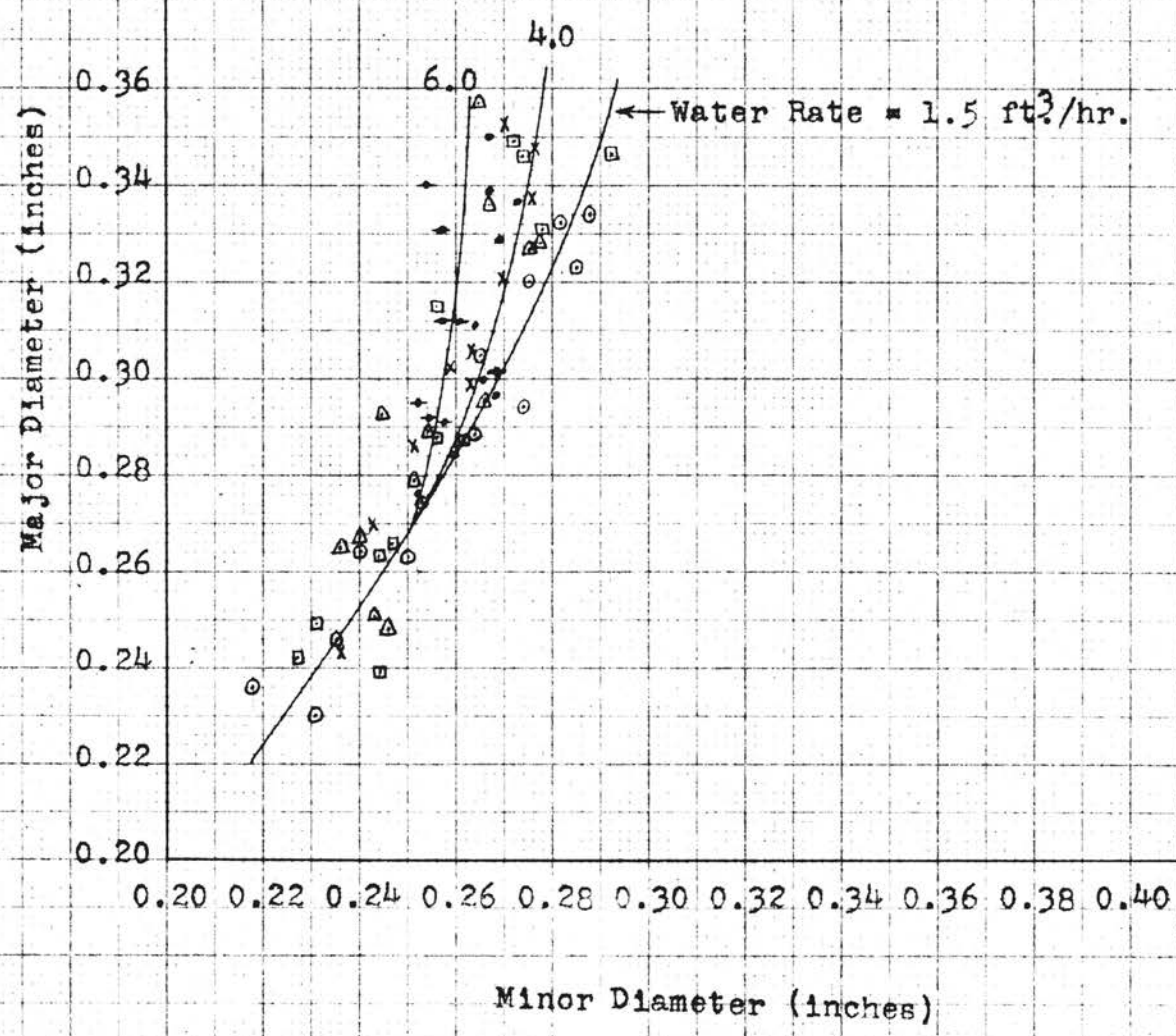


FIGURE 16: Area Coefficients for Transfer from the Continuous to the Discontinuous Phase.

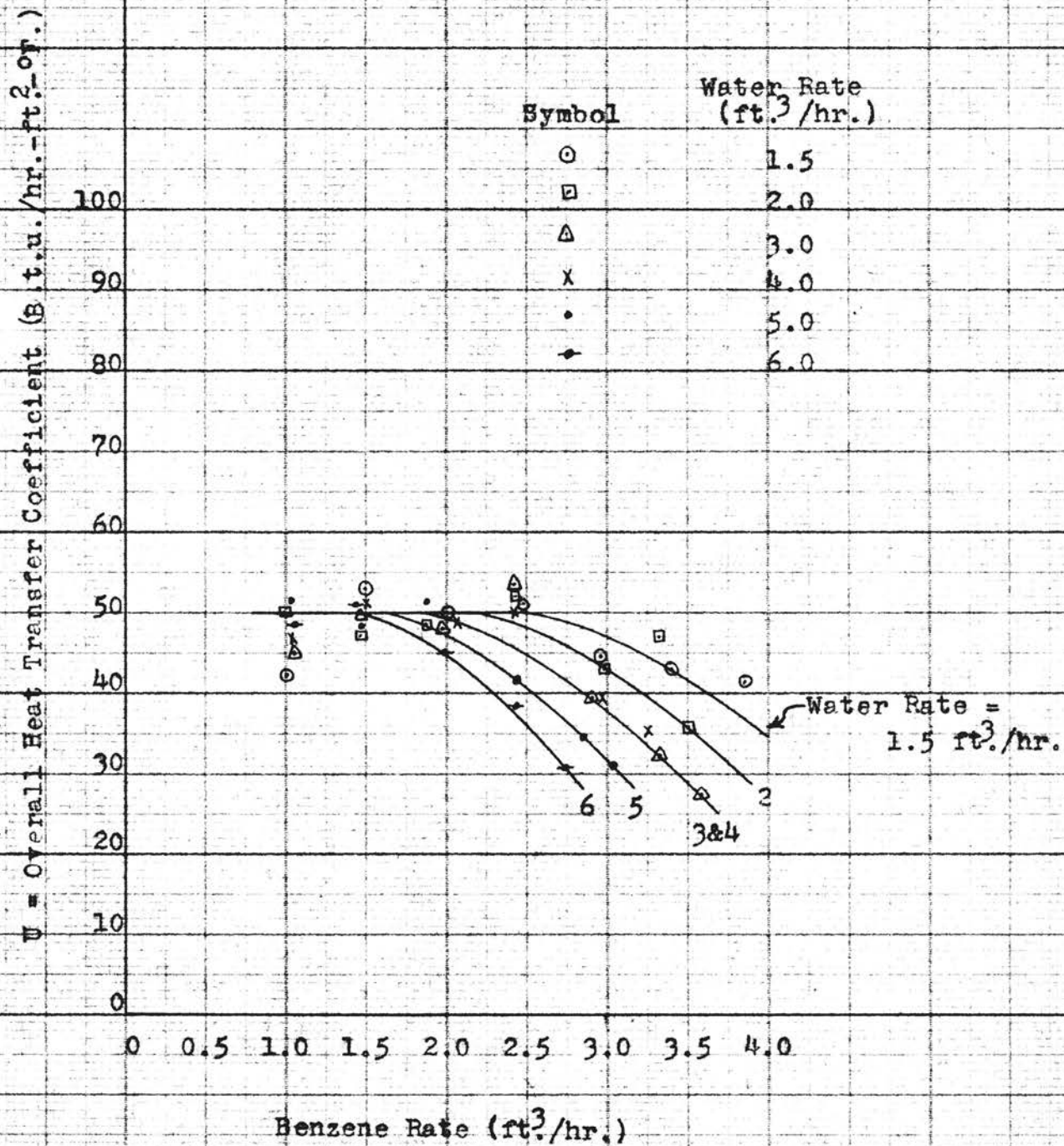
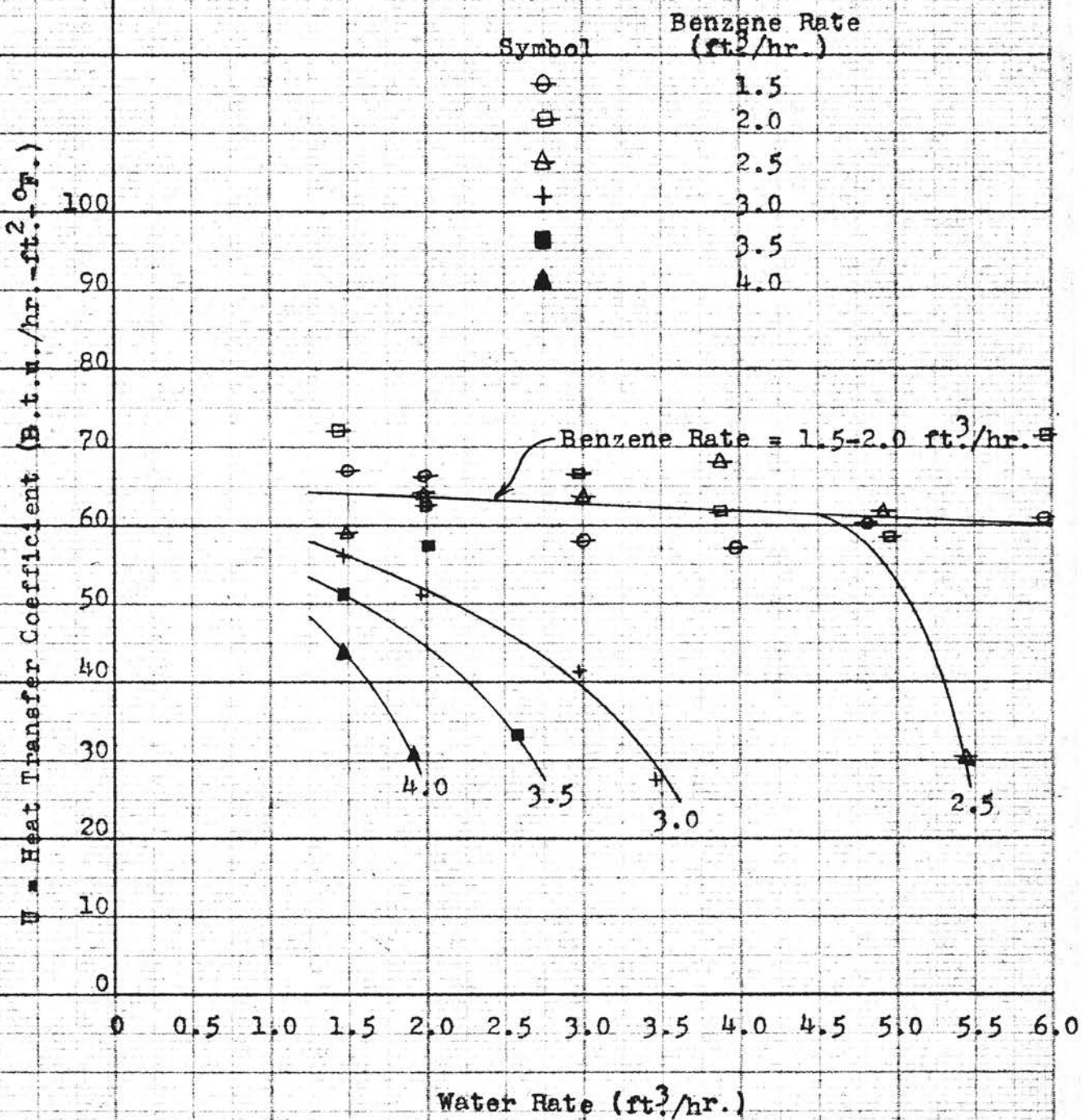


FIGURE 17: Area Coefficients for Transfer from the Discontinuous to the Continuous Phase.



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FIGURE 18: Volumetric Coefficients for Heat Transfer from Discontinuous to Continuous Phase.

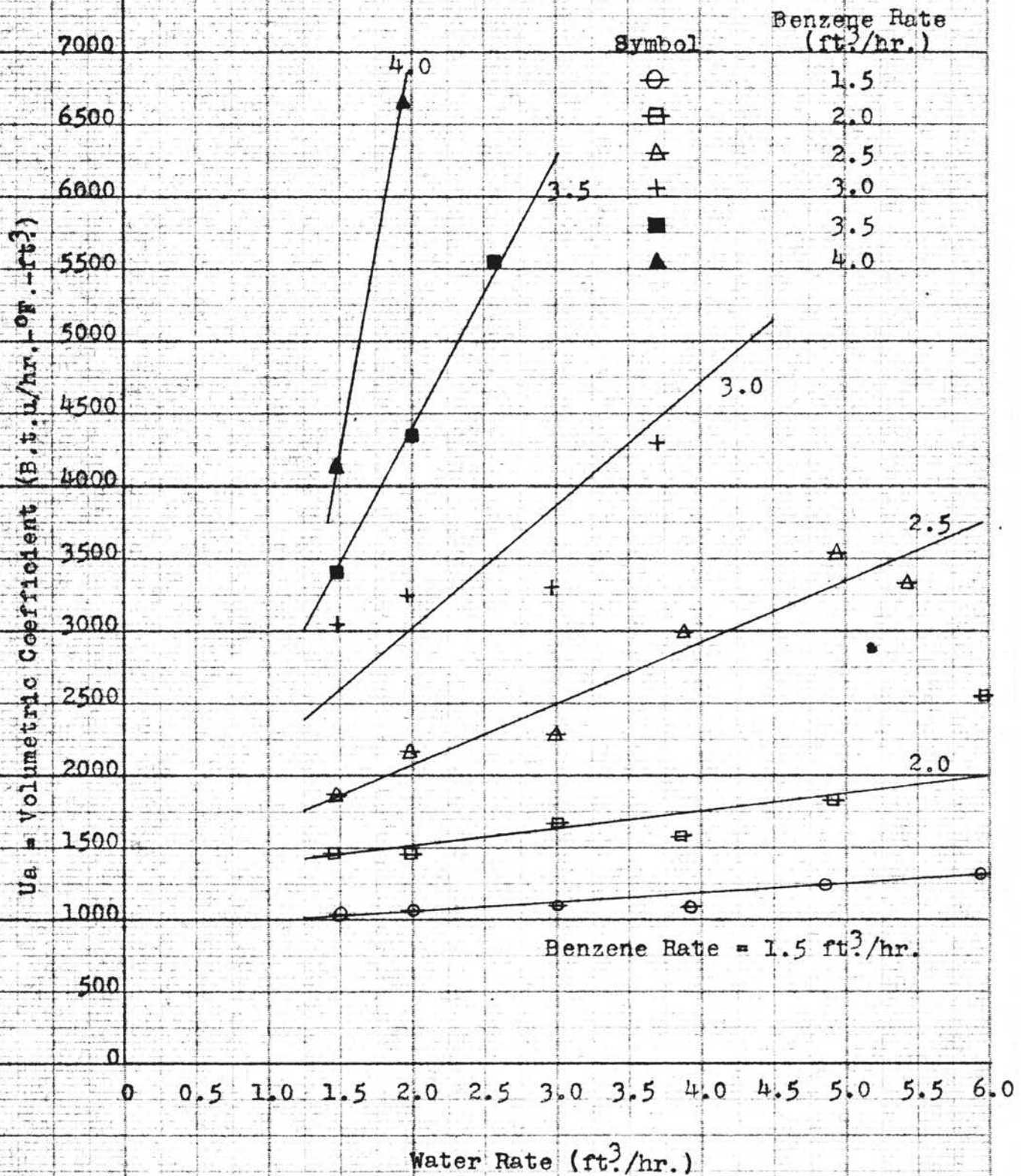




FIGURE 19: Volumetric Coefficients for Heat Transfer  
from Discontinuous to Continuous Phase  
(Cross Plot of Figure 18)

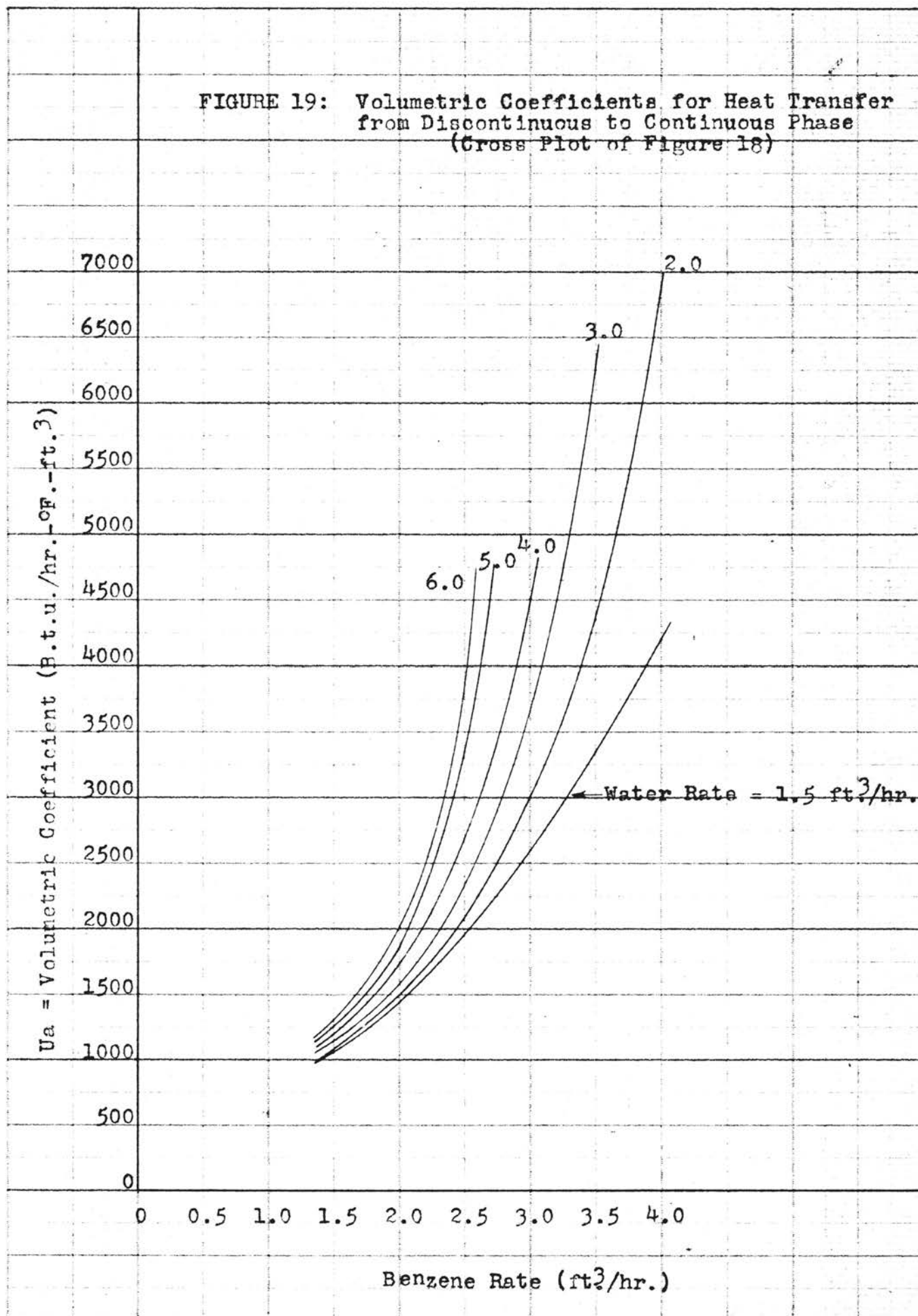


FIGURE 20: Volumetric Coefficients for Heat Transfer from the Continuous to the Discontinuous Phase.

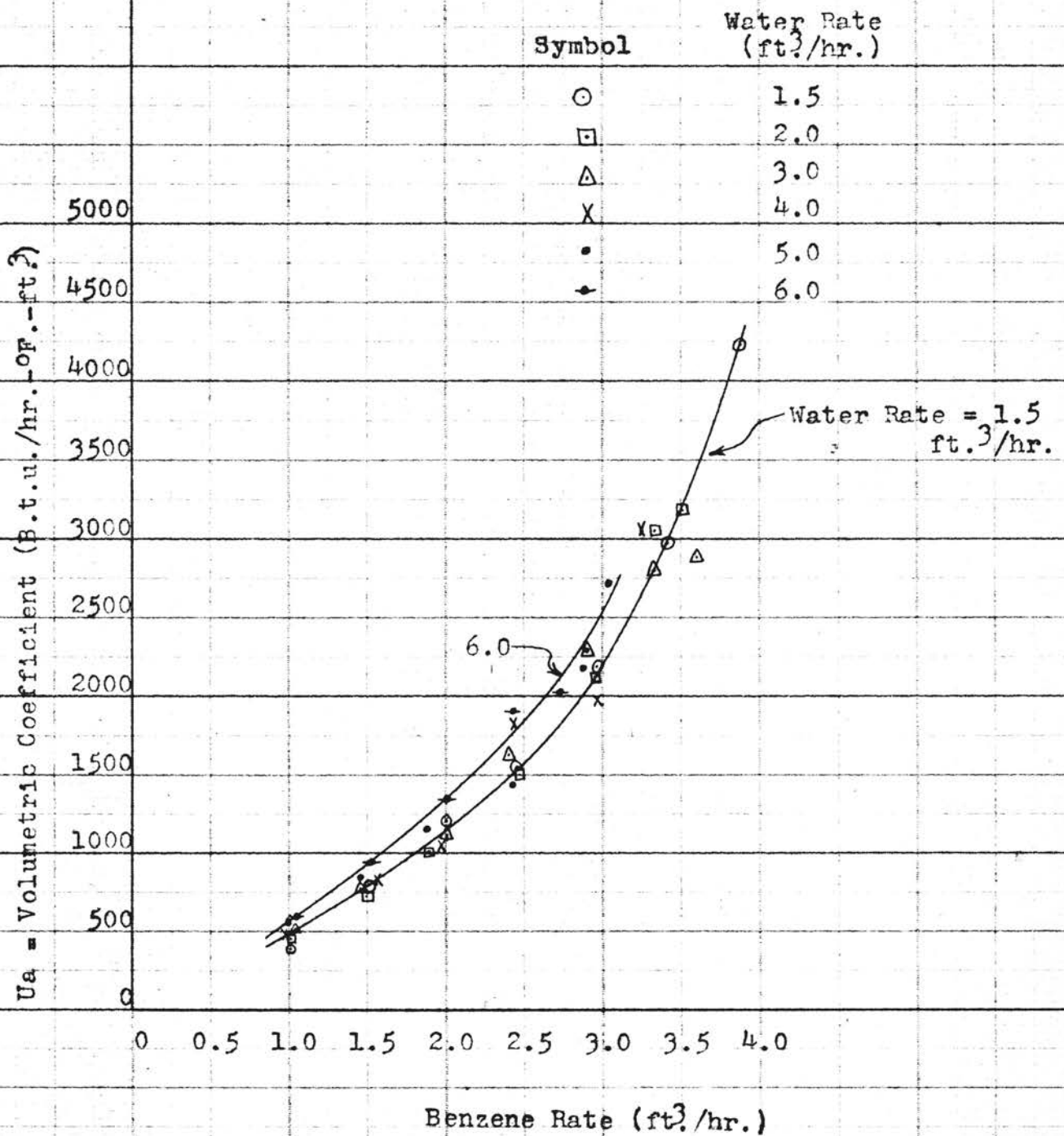


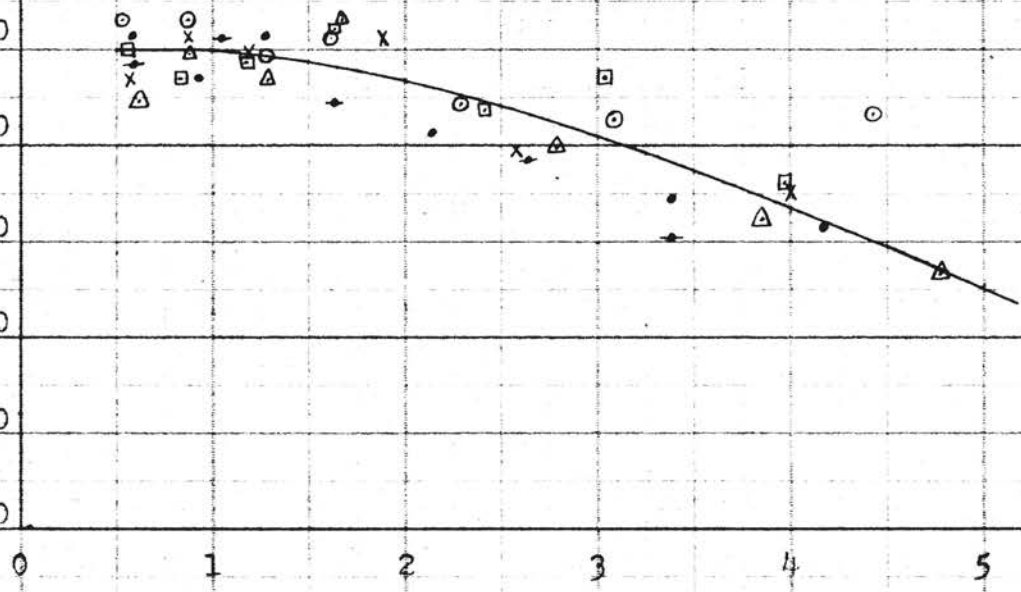
FIGURE 21: Relation Between Area Transfer Coefficient and Holdup for Heat Transfer from the Continuous to the Discontinuous Phase.

Symbol	Water Rate (ft. <sup>3</sup> /hr.)	Major Drop Diameters (inches)
○	1.5	0.26-0.33
□	2.0	0.26-0.35
△	3.0	0.26-0.36
×	4.0	0.27-0.35
•	5.0	0.28-0.35
→	6.0	0.29-0.34

U = Overall Heat Transfer Coefficient

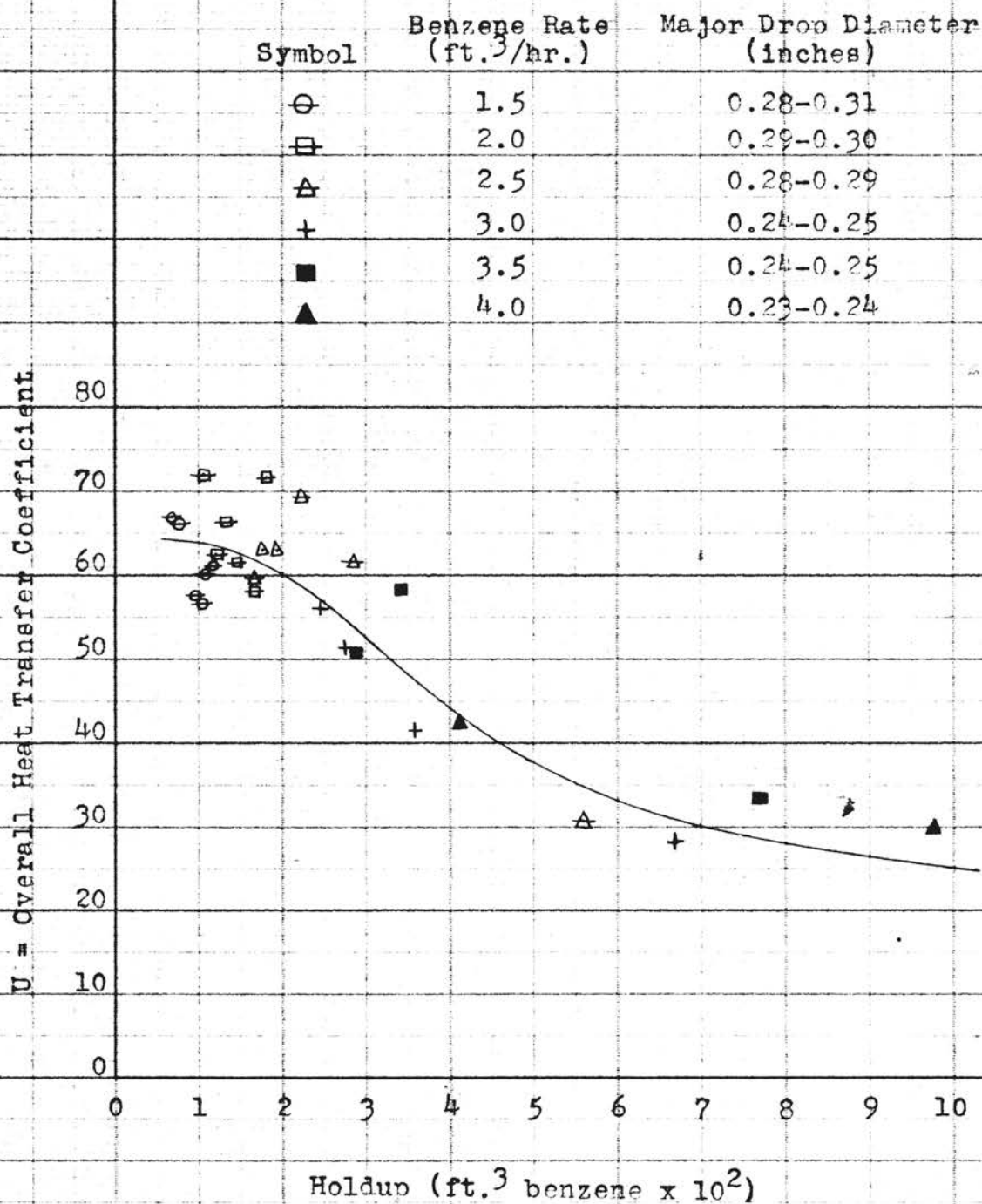
80  
70  
60  
50  
40  
30  
20  
10  
0

Note: Larger drop sizes correspond to smaller values of holdup; smaller drop sizes to larger values of holdup.



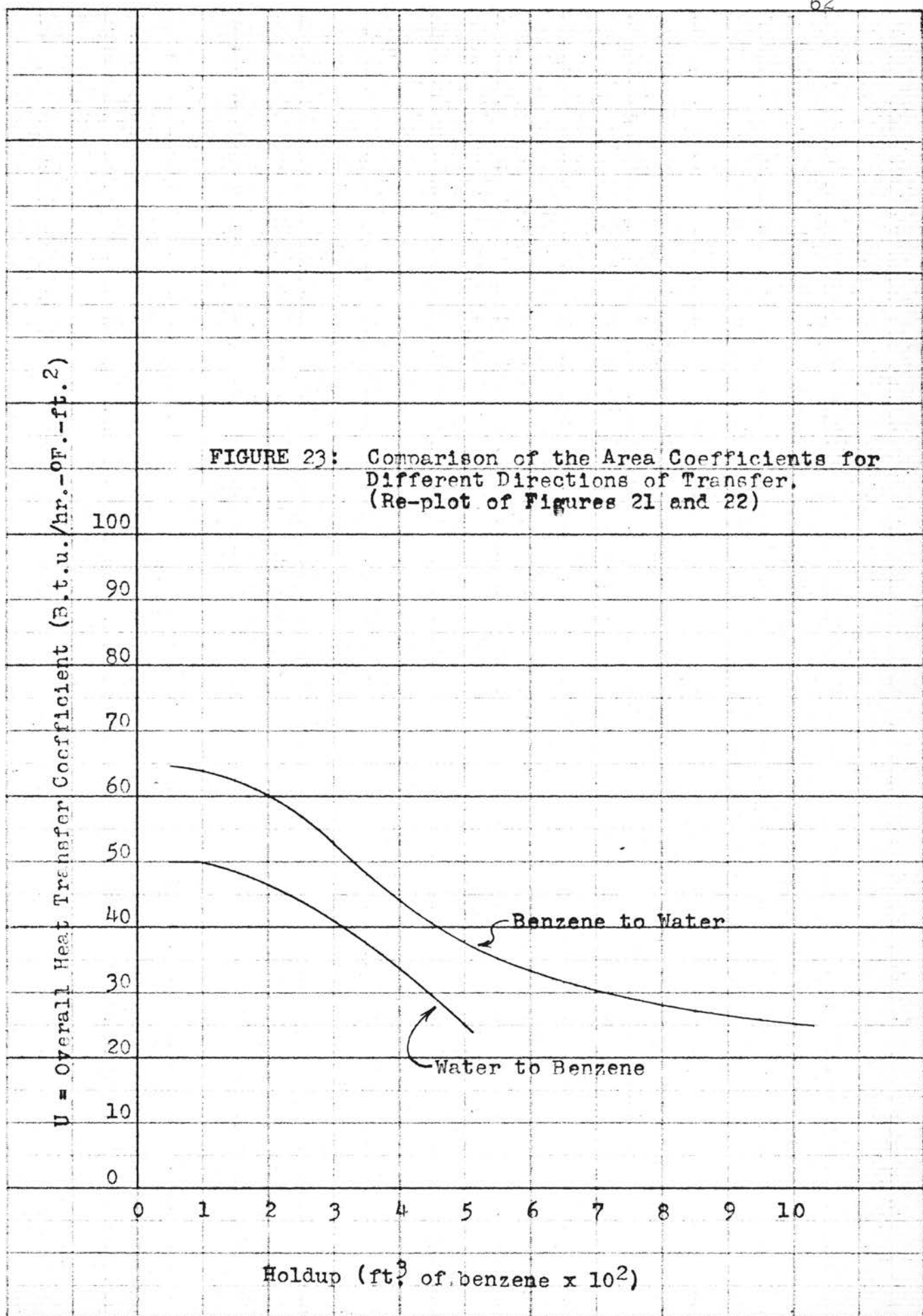
Holdup (ft.<sup>3</sup> benzene x 10<sup>2</sup>)

FIGURE 22: Relation Between Area Transfer Coefficient and Holdup for Heat Transfer from the Discontinuous to the Continuous Phase



U = Overall Heat Transfer Coefficient (B.t.u./hr.-sq.ft.-ft.<sup>2</sup>)

FIGURE 23: Comparison of the Area Coefficients for Different Directions of Transfer. (Re-plot of Figures 21 and 22)



Holdup (ft<sup>3</sup> of benzene x 10<sup>2</sup>)

## CONCLUSIONS

It has been demonstrated that data can be obtained for a liquid-liquid spray column which makes possible the calculation of a heat (or mass) transfer coefficient on a unit area basis. The methods outlined are simple in principle but rather laborious. In this work alone, approximately 2500 drops were measured and distortion corrections applied. It is believed that the data obtained are of fundamental importance.

It is planned to use the procedures outlined for other systems. As more and more data of this type accumulate, it should be possible to develop correlations of drop size and velocity of rise with the physical properties of the phase. Enough data are given in this paper to test the Hayworth and Treybal equation for the prediction of drop size. Another interesting possibility is the Colburn "j" factor<sup>(3)</sup> as used by Gamson, Thodos and Hougen,<sup>(5)</sup> and Taecker and Hougen<sup>(15)</sup>. These calculations are planned for the immediate future.

Four basic conclusions which have been discussed previously might well be repeated for emphasis. These are as follows:

1. The water rate has practically no effect on drop size. This is a valuable extension of the Hayworth-Treybal correlation, which was obtained for a stagnant continuous phase.
2. There is no appreciable end effect at the point of

drop formation. No calculations were made for the end where the continuous phase entered.

3. The area coefficient,  $U$ , was found first to be constant and then to decrease with increased phase rates. This is believed due to a decreased efficiency of contact between the two phases due to partial obstruction and shielding. Increased recirculation may also be a factor.

4. The area coefficient,  $U$ , was found to be a function of holdup only, for a particular direction of extraction.

## SUMMARY

Data were obtained to permit the calculation of transfer coefficients for spray columns on a unit area basis. This entailed the calculation of holdup and transfer area from measurements of the average drop characteristics and the velocity of rise.

Drops were found to assume a non-spherical shape (assumed to be ellipsoidal) as they rose, the major diameter of which, for a benzene temperature of approximately 85°F., varied from 0.35 inch at the tip velocity of 8 cm/sec. to 0.26 inch at a tip velocity of 19 cm/sec. At a higher benzene temperature of approximately 150°F. the major diameter varied from 0.31 to 0.23 inch between the same limits of tip velocity. Water rate was found to have very little effect on drop size. The ratio of major diameter to minor diameter was found to be mainly a function of drop size, particularly in the small drop size range.

Two types of drop formation were witnessed, single or "pulsing" formation and jet formation. Drop sizes were smaller in the latter case.

The transfer coefficient based on unit area,  $U$ , was found first to remain constant and then to decrease with increasing flow rates (increasing holdup) while the "volumetric" coefficient  $U_a$  showed the usual increase. Higher values of  $U_a$  and  $U$  were found for transfer from the benzene drops



to the water than for the case of transfer in the opposite direction. In the case of  $U_a$  this difference is believed to be partially due to the smaller drop size obtained in the benzene-hot runs.

The  $U$  calculated for the bottom of the column showed no significant variation from the  $U$  based on the entire column length. This indicates no end effect at the disperser.

The logarithmic mean temperature difference was found to be applicable for two low water rate runs despite departure from adiabatic operating conditions. The  $U$ 's calculated by means of a rigorous driving force obtained by graphical integration varied from the  $U$ 's based on the log mean temperature difference for these runs by 1 and 6%. The enthalpy change of the benzene was used as the amount of heat transferred between the two phases.

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NOMENCLATURE

A	total transfer area between drops and continuous phase, ft. <sup>2</sup> . The interface area was neglected.
a	transfer area between drops and continuous phase per cubic foot of effective column volume, ft. <sup>2</sup> /ft. <sup>3</sup>
a'	A/L <sub>e</sub> , transfer area between drops and continuous phase per foot of effective column length, ft. <sup>2</sup> /ft.
a' <sub>L</sub>	area for heat loss per foot length of the column, ft. <sup>2</sup> /ft.
A.D.	average deviation of the mean.
a.d.	average deviation from the mean of an individual measurement.
B	volumetric flow rate of benzene, ft. <sup>3</sup> /hr. When used in a run designation it means the benzene entered the column hot.
C	specific heat at constant pressure, B.t.u./#-°F.
d <sub>t</sub>	inside tip diameter, ft.
f	used in the run nomenclature to denote flooding.
H	holdup, volume of dispersed phase in column, ft. <sup>3</sup>
K	overall area mass transfer coefficient.
Ka	volumetric mass transfer coefficient.
L	limit of integration corresponding to any desired portion of L <sub>e</sub> , ft.
L <sub>e</sub>	effective column length. Distance from disperser tips to interface, ft.
M	mass flow rate, #/hr.
m	one-half the major diameter of an ellipsoid, inches.
N	absolute difference between an individual measurement and the mean.
n	number of measurements.

Q	enthalpy change, B.t.u./hr.
r	one-half the minor diameter of an ellipsoid, inches.
$S_D$	average single drop surface area, ft. <sup>2</sup>
t	temperature, °F.
$\Delta t$	temperature change of a phase, °F.
$\Delta t_m$	logarithmic mean temperature difference, °F.
U	overall heat transfer coefficient between liquids, B.t.u./hr.-ft. <sup>2</sup> -°F.
Ua	volumetric heat transfer coefficient, B.t.u./hr.-°F.-ft. <sup>3</sup>
$U_L A_L$	heat loss coefficient based on entire column length, B.t.u./hr.-°F.
$U_L a'_L$	heat loss coefficient for unit column length = $U_L A_L / L_e$ , B.t.u./hr.-ft.-°F.
$V_D$	average single drop volume, ft. <sup>3</sup>
v	drop velocity of rise, ft./sec.
$V_t$	linear velocity of dispersed phase through the disperser tips, cm./sec.
W	volumetric flow rate of water, ft. <sup>3</sup> /hr. When used in a run designation it means the water entered the column hot.

Subscript:

a	refers to air outside the column wall.
b	refers to benzene.
D	refers to the single drop characteristics.
e	refers to the effective column length from the interface to the disperser tips.
L	refers to heat transferred through the column wall.
t	refers to the disperser tips.
w	refers to water.
1	refers to couple #1
2	refers to couple #2.

## APPENDIX

## SAMPLE CALCULATIONS

$$\text{Effective column volume} = 0.785 \times \frac{(2)^2}{144} \times 6.08 = 0.133 \text{ ft.}^3$$

$$\text{Tip cross-section} = 0.785 \times \frac{(0.125)^2}{144} = 8.52 \times 10^{-5} \text{ ft.}^2$$

1. Calculation of heat loss coefficient,  $U_L A_L$ .

For Run W22 (Table IV):

$$Q_L = \int_0^{L_e} U_L a'_L (t_w - t_a) dL = U_L a'_L \int_0^{L_e} (t_w - t_a) dL$$

$$U_L A_L = U_L a'_L \times L_e = \frac{Q_L}{\int_0^{L_e} (t_w - t_a) dL} \times L_e$$

From a plot of  $(t_w - t_a)$  versus  $L$ ,  $\int_0^{L_e} (t_w - t_a) dL = 351 \text{ }^\circ\text{F.-ft.}$

$$U_L A_L = \frac{280}{351} \times 6.08 = 4.8 \text{ B.t.u./hr.-}^\circ\text{F.}$$

The average value of  $U_L A_L$  used was that obtained from nine such calculations.

2. Calculation of overall heat transfer coefficient,  $U$ , for the entire column.

(a) Based on log mean temperature difference,  $\Delta t_m$ . (See Tables II and III.)

For Run W1.51 (Table II.)

$$Q_w = M_w C_w \Delta t_w = 90.7 \times 1.0 \times (144.1 - 127.0) = 1550 \text{ B.t.u./hr.}$$

$$Q_b = M_b C_b \Delta t_b = 54.2 \times 0.430 \times (135.3 - 90.7) = 1140 \text{ B.t.u./hr.}$$

$$\Delta t_m = \frac{(127.0 - 90.7) - (144.1 - 135.3)}{\ln \frac{(127.0 - 90.7)}{(144.1 - 135.3)}} = 19.9^\circ\text{F.}$$

$$\begin{aligned} \text{Tip velocity} = v_t &= \frac{B}{3600} \times \frac{30.48}{\text{Tips Working}} \times \frac{1}{0.785d_t^2} \\ &= \frac{0.995}{3600} \times \frac{30.48}{13} \times \frac{1}{8.52 \times 10^{-5}} = 7.60 \text{ cm./sec.} \end{aligned}$$

$$\text{Time of drop in column} = \frac{L_e}{\text{Rise Velocity}} = \frac{6.08}{0.318} = 19.12 \text{ sec.}$$

$$\begin{aligned} \text{Benzene holdup in column} = H &= \frac{B}{3600} \times \text{time of drop in} \\ \text{column} &= \frac{0.995}{3600} \times 19.12 = 52.8 \times 10^{-4} \text{ ft.}^3 \end{aligned}$$

$$\text{Number of drops in column} = \frac{H}{V_D} = \frac{52.8 \times 10^{-4}}{0.923 \times 10^{-5}} = 573$$

$$\begin{aligned} \text{Area} = A = \text{Drops in column} \times S_D &= 573 \times 2.155 \times 10^{-3} \\ &= 1.24 \text{ ft.}^2 \end{aligned}$$

$$U = \frac{Q_b}{A \Delta t_m} = \frac{1040}{(1.24)(19.9)} = 42.0 \text{ (B.t.u./hr. - ft.}^2\text{-}^\circ\text{F.)}$$

$$U_a = \frac{UA}{0.133} = \frac{(42.0)(1.24)}{0.133} = 392$$

(b) Based on rigorous integrated driving force. (See Table VII.)

The method used to calculate Table VII is explained fully in "Methods of Calculation."

3. Calculation of overall heat transfer coefficient in bottom section of column. (See Tables V and VI.)

For Run W1.51.5 (See Table V):

Between couples #11 (or #12) and #9:

Total heat lost by water minus  $Q_L$  = Heat gained by benzene  
 $535 - 27 = 508 \text{ B.t.u./hr.}$

$$\begin{aligned} \text{Temperature change of benzene} = \Delta t_b &= \frac{Q_b}{C_b M_b} \\ &= \frac{508}{0.420 \times 81.2} = 14.9^\circ\text{F.} \end{aligned}$$

$$\begin{aligned}\text{Benzene Temperature at \#9} &= \text{Temperature at \#12} + \Delta t_b \\ &= 89.4 + 14.9 = 104.3^\circ\text{F.}\end{aligned}$$

$$\Delta t_m = \frac{(124.4 - 89.4) - (130.3 - 104.3)}{\ln \frac{(124.4 - 89.4)}{(130.3 - 104.3)}} = 30.4^\circ\text{F.}$$

$$\begin{aligned}\text{Area (in bottom section)} &= A \times 0.212 = 1.97 \times 0.212 \\ &= 0.418 \text{ ft.}^2\end{aligned}$$

$$U = \frac{Q_b}{(0.418) (\Delta t_m)} = \frac{508}{9.418 \times 30.4} = 40.0 \text{ (B.t.u./hr.-ft.}^2\text{-}^\circ\text{F.)}$$

For Run B61.5 (See Table VI):

$$Q_b = Q_w + Q_L$$

$$Q_b = 1810 + (-10) = 1800$$

Remainder of the calculation is the same as for Run W1.51.5.

For Run B1.52.5 (See Table VI):

$$Q_b = Q_w + Q_L = 1225 + 17 = 1242.$$

Remainder of the calculation is the same as for Run W1.51.5.



Diameters(in.)				Average Drop Characteristics				Column Condition				U***	Ua
Major	A.D.( $\pm$ ) (Major)	Minor	(A.D.( $\pm$ )) (Minor)	Volume (ft. <sup>3</sup> x10 <sup>5</sup> )	Surface Area (ft. <sup>2</sup> x10 <sup>3</sup> )	Rise Velocity (ft./sec.)	A.D.( $\pm$ ) (Rise Velocity)	Time in Column (sec.)	Benzene in Column (ft. <sup>3</sup> x10 <sup>4</sup> )	Drops in Column	Area (ft <sup>2</sup> )		
0.296	0.006	0.275	0.003	0.736	1.837	0.297	0.008	20.45	82.4	1120	2.05	66.9	1035
0.315	0.003	0.256	0.002	0.759	1.870	0.280	0.005	21.71	87.5	1152	2.16	66.5	1080
0.279	0.005	0.252	0.004	0.593	1.591	0.256	0.006	23.75	95.7	1613	2.57	57.9	1120
0.304	0.005	0.259	0.003	0.710	1.782	0.242	0.006	25.10	101.2	1429	2.54	57.6	1100
0.300	0.006	0.265	0.004	0.710	1.782	0.221	0.007	27.50	110.8	1561	2.78	60.3	1260
0.301	0.005	0.268	0.003	0.736	1.837	0.213	0.006	28.55	115.0	1562	2.87	60.8	1310
0.305	0.006	0.264	0.005	0.710	1.782	0.308	0.006	19.75	107.0	1507	2.69	72.0	1460
0.288	0.005	0.262	0.004	0.663	1.712	0.274	0.008	22.20	120.3	1813	3.11	62.6	1465
0.295	0.005	0.266	0.004	0.683	1.750	0.251	0.005	24.20	131.2	1920	3.36	66.5	1680
0.300	0.005	0.264	0.003	0.710	1.782	0.232	0.006	26.20	142.0	2000	3.57	61.5	1580
0.297	0.004	0.267	0.003	0.736	1.837	0.199	0.006	30.55	165.5	2250	4.13	58.5	1820
0.295	0.005	0.252	0.003	0.640	1.670	0.182	0.008	33.40	181.0	2830	4.72	71.9	2560
0.288	0.004	0.263	0.004	0.663	1.712	0.251	0.006	24.20	164.8	2485	4.25	59.1	1890
0.288	0.004	0.256	0.003	0.663	1.712	0.235	0.005	25.90	176.3	2680	4.59	63.1	2180
0.289	0.005	0.254	0.003	0.640	1.670	0.224	0.005	27.15	184.9	2890	4.83	63.1	2290
0.286	0.006	0.251	0.003	0.640	1.670	0.187	0.005	32.50	221.3	3460	5.77	69.2	3010
0.276	0.004	0.252	0.004	0.593	1.591	0.146	0.004	41.70	284.0	4790	7.63	61.5	3540
0.291	0.004	0.256	0.003	0.663	1.712	0.074	0.002	82.20	560.0	8445	14.45	30.7	3340
0.246	0.005	0.236	0.003	0.454	1.329	0.203	0.004	29.95	243.5	5365	7.12	56.7	3040
0.242	0.005	0.227	0.003	0.402	1.220	0.180	0.005	33.80	278.0	6920	8.45	51.3	3260
0.251	0.004	0.243	0.004	0.454	1.329	0.139	0.003	43.70	359.5	7910	10.51	41.8	3310
0.244	0.004	0.236	0.004	0.418	1.257	0.075	0.003	81.10	667.0	15950	20.05	28.5	4290
0.236	0.005	0.218	0.004	0.384	1.187	0.201	0.006	30.25	287.0	7480	8.88	51.0	3410
0.249	0.005	0.231	0.005	0.436	1.289	0.169	0.003	36.00	342.0	7850	10.12	57.2	4350
0.248	0.005	0.246	0.004	0.473	1.363	0.079	0.002	81.10	770.00	16300	22.25	33.2	5550
0.230	0.006	0.231	0.003	0.369	1.155	0.167	0.004	36.40	404.5	10960	12.65	43.4	4130
0.239	0.004	0.244	0.003	0.419	1.257	0.069	0.002	88.10	979.0	23400	29.40	30.1	6650

\*\*\*U = Q/A( $\Delta t$ )<sub>m</sub> = B.t.u./hr.-ft.<sup>2</sup>-OF

Transfer of Heat from Discontinuous Phase to Continuous

Flow Rate Benzene ft <sup>3</sup> /hr #/hr	Stream Temperatures (°F)				Room Temp.	C. Benzene	Q (B.t.u./hr.)		Delta t* (l.m.)	No. of Tips Working	Tip Velocity (cm/sec)	Diameters (in.)				Volume (ft. <sup>3</sup> x 10 <sup>5</sup> )	Surface (ft. <sup>2</sup> x 10 <sup>5</sup> )	
	Water #2	Water #11	Benzene #1	Benzene #12			Water	Benzene				Major	A.D. (±) (Major)	Minor	A.D. (±) (Minor)			
1.450	78.9	77.9	99.5	81.2	138.5	86.0	0.430	1985	1980	14.4	14	10.30	0.296	0.006	0.275	0.003	0.736	1.83
"	"	77.3	93.4	80.0	133.2	88.0	0.428	1980	1800	13.8	14	10.30	0.315	0.003	0.256	0.002	0.759	1.87
"	"	76.4	87.7	77.7	141.1	91.0	0.430	2105	2100	14.1	15	9.60	0.279	0.005	0.252	0.004	0.593	1.59
"	"	80.0	87.9	81.2	138.2	91.0	"	1920	1930	13.2	14	10.30	0.304	0.005	0.259	0.003	0.710	1.78
"	"	77.4	84.3	78.1	139.4	91.0	"	2080	2080	12.4	13	11.07	0.300	0.006	0.265	0.004	0.710	1.78
"	"	74.3	81.3	74.9	142.2	91.5	"	2580	2285	13.1	14	10.30	0.301	0.005	0.268	0.003	0.736	1.83
1.95	106.0	77.0	111.3	81.7	150.9	88.0	0.431	3060	3160	16.3	19	10.18	0.305	0.006	0.264	0.005	0.710	1.78
1.94	105.0	75.3	99.5	78.3	143.6	89.0	0.431	2990	2960	15.2	19	10.18	0.288	0.005	0.262	0.004	0.663	1.71
1.96	106.4	74.6	89.8	75.9	137.6	91.5	0.429	2810	2820	12.8	18	10.75	0.295	0.005	0.266	0.004	0.683	1.75
"	"	74.1	86.2	75.2	143.6	92.0	"	2910	3120	14.2	19	10.18	0.300	0.005	0.264	0.003	0.710	1.78
"	"	74.5	84.0	75.1	139.7	92.0	"	2890	2950	12.2	19	10.18	0.297	0.004	0.267	0.003	0.736	1.83
"	"	77.4	86.5	77.5	148.6	92.0	0.430	3390	3260	9.6	18	10.75	0.295	0.005	0.252	0.003	0.640	1.67
2.45	133.3	78.7	118.1	84.1	152.0	90.0	0.430	3600	3890	15.5	19	12.80	0.288	0.004	0.263	0.004	0.663	1.71
"	"	77.4	110.5	80.1	153.9	89.5	"	4070	4225	14.6	"	"	0.288	0.004	0.256	0.003	0.663	1.71
"	"	75.9	98.1	77.2	149.5	90.0	"	4135	4145	13.6	"	"	0.289	0.005	0.254	0.003	0.640	1.67
"	"	74.9	93.8	75.2	156.6	91.0	"	4450	4670	11.7	"	"	0.286	0.006	0.251	0.003	0.640	1.67
"	"	73.5	89.7	73.6	160.9	92.0	0.432	4970	5020	10.7	"	"	0.276	0.004	0.252	0.004	0.593	1.59
"	"	75.2	87.9	75.3	160.8	84.5	"	4280	4920	11.1	"	"	0.291	0.004	0.256	0.003	0.663	1.71
2.925	159.0	80.3	132.1	85.1	156.5	88.0	0.430	4750	4880	12.1	19 (Jet)**	15.3	0.246	0.005	0.236	0.003	0.454	1.32
2.96	161.0	78.0	121.1	80.3	157.9	88.0	"	5250	5375	12.4	" "	"	0.242	0.005	0.227	0.003	0.402	1.22
"	"	75.8	104.7	76.7	156.2	89.0	"	5300	5500	12.5	" "	"	0.251	0.004	0.243	0.004	0.454	1.32
"	"	73.3	101.0	73.5	165.7	88.5	"	5930	6400	11.2	" "	"	0.244	0.004	0.236	0.004	0.418	1.25
3.415	185.8	77.1	139.6	85.5	158.4	90.5	0.432	5710	5850	12.9	19 (Jet)	17.85	0.236	0.005	0.218	0.004	0.384	1.18
"	"	76.5	128.4	78.8	160.4	90.0	0.432	6380	6550	11.3	" "	"	0.249	0.005	0.231	0.005	0.436	1.28
"	"	74.2	116.9	74.6	161.4	90.0	0.430	6730	6920	9.37	20 (Jet)	17.93	0.248	0.005	0.246	0.004	0.473	1.36
4.00	217.5	77.6	147.2	88.8	160.4	92.0	0.434	6350	6750	12.3	20 (Jet)	19.85	0.230	0.006	0.231	0.003	0.369	1.15
"	"	75.6	140.6	78.3	161.4	90.5	0.432	7760	7800	8.8	" "	"	0.239	0.004	0.244	0.003	0.419	1.25

\*For heat transfer to water.  
 \*\*Mechanism of drop formation changed from single, pulsing formation to formation at the end of a jet of benzene.

Transfer of Heat from Continuous Phase to Discontinuous

Flow Rates			Stream Temperatures (°F)				Room Temp.	C Benzene	Q (Btu/hr)		Delta t* (l.m.)	No. of Tips Working	Tip Velocity (cm/sec)	Diameters (in.)				Volume (ft³ x 10⁵)	Surface (ft² x 10⁵)
#/hr	Benzene ft³/hr	#/hr	Water #2	Water #11	Benzene #1	Benzene #12			Water Benzene	Benzene Benzene				Major	A.D. (±) (Major)	Minor	A.D. (±) (Minor)		
90.7	0.995	54.2	144.1	127.0	135.3	90.7	92.5	0.430	1550	1040	19.9	13	7.60	0.332	0.006	0.282	0.004	0.923	2.15
"	1.493	81.2	144.1	124.4	138.2	89.4	94.0	"	1787	1705	16.3	16	9.27	0.334	0.005	0.288	0.004	0.956	2.18
"	2.00	108.8	143.7	118.5	137.6	90.9	94.5	"	2285	2180	14.2	16	12.40	0.320	0.004	0.275	0.004	0.840	2.01
"	2.44	132.9	142.2	107.6	134.1	82.7	88.0	"	3140	2935	15.0	20	12.10	0.323	0.005	0.285	0.004	0.869	2.06
"	2.96	161.0	142.4	103.3	134.6	84.0	91.0	"	3545	3500	12.6	20 (Jet)**	14.70	0.274	0.004	0.253	0.002	0.553	1.51
"	3.40	185.0	141.7	98.1	133.7	85.5	88.0	"	3955	3830	10.2	20	16.85	0.264	0.005	0.240	0.003	0.493	1.40
1.2	3.86	210.0	138.9	86.9	129.2	80.0	80.0	"	4730	4450	8.2	20	19.16	0.263	0.004	0.250	0.003	0.512	1.41
8.3	0.995	54.2	146.1	132.9	138.9	82.2	80.5	0.430	1560	1320	22.2	12	8.23	0.347	0.005	0.292	0.003	1.076	2.38
9.6	1.44	78.3	146.4	127.9	139.1	82.5	81.0	"	2210	1890	20.8	16	8.93	0.349	0.004	0.272	0.003	1.004	2.28
8.9	1.87	101.7	147.7	124.5	140.5	83.8	81.5	"	2760	2480	19.3	19	9.75	0.346	0.006	0.274	0.004	1.004	2.28
0.0	2.44	132.8	144.1	114.0	138.0	78.6	84.0	"	3680	3350	17.4	20	12.10	0.332	0.004	0.278	0.004	0.923	2.14
2.8	2.96	161.0	144.1	111.9	138.7	83.9	85.0	"	3950	3790	13.7	20 (Jet)	14.65	0.285	0.005	0.259	0.003	0.617	1.63
0.2	3.33	181.0	144.7	105.6	140.0	82.5	85.5	"	4760	4480	11.5	20	16.55	0.266	0.005	0.247	0.003	0.553	1.51
2.8	3.51	191.0	144.8	102.6	139.0	83.1	85.5	"	5170	4580	11.3	20	17.42	0.263	0.004	0.244	0.004	0.4925	1.40
3.7	1.06	57.5	141.6	132.3	135.7	82.9	85.0	0.430	1710	1310	20.3	12	8.77	0.357	0.007	0.265	0.005	0.990	2.33
"	1.45	78.7	141.3	129.3	136.5	83.4	85.0	"	2205	1800	18.1	15	9.60	0.337	0.006	0.267	0.005	0.947	2.18
"	1.97	106.9	142.3	126.8	137.5	81.0	87.0	"	2850	2600	18.0	17	11.48	0.327	0.005	0.275	0.004	0.892	2.10
"	2.40	130.2	144.0	125.3	140.5	82.4	90.5	"	3435	3260	15.6	19	12.22	0.329	0.005	0.277	0.002	0.923	2.11
"	2.90	157.3	143.5	121.5	140.8	83.4	88.5	"	4040	3880	13.3	20 (Jet)	14.38	0.293	0.006	0.245	0.004	0.612	1.62
"	3.32	180.0	143.1	116.5	140.0	82.9	90.0	"	4820	4430	13.1	20	16.45	0.265	0.005	0.236	0.003	0.493	1.40
2.5	3.60	196.0	139.2	112.2	135.7	81.6	88.0	"	4925	4560	12.4	20	17.85	0.267	0.002	0.240	0.004	0.530	1.47
5.0	1.024	55.8	140.2	134.6	134.7	84.1	88.0	0.430	1316	1215	20.2	11	9.25	0.353	0.005	0.270	0.004	1.004	2.28
"	1.505	82.0	140.3	132.1	135.9	85.0	88.0	"	1925	1790	18.0	15	9.95	0.348	0.005	0.276	0.003	1.040	2.31
"	1.99	108.1	139.4	128.3	134.4	80.0	87.5	"	2610	2580	19.2	19	10.40	0.338	0.005	0.276	0.004	0.985	2.27
8.0	2.44	132.3	140.8	126.3	138.6	77.8	83.0	"	3450	3460	14.9	20	12.10	0.321	0.005	0.269	0.004	0.840	2.01
5.0	2.96	161.0	138.1	121.5	134.8	81.2	87.0	"	3900	3710	14.7	20 (Jet)	14.70	0.306	0.005	0.262	0.004	0.759	1.87
8.0	3.25	176.2	142.0	122.0	139.8	79.2	80.5	"	4640	4590	11.7	20	16.11	0.270	0.004	0.243	0.003	0.530	1.47
2.0	1.028	55.8	136.6	132.1	132.5	76.4	88.5	0.430	1360	1350	19.7	11	9.27	0.350	0.007	0.267	0.004	1.004	2.28
"	1.45	78.6	142.0	134.9	138.2	77.1	82.5	"	2145	2035	19.7	15	9.56	0.337	0.005	0.273	0.003	0.947	2.11
"	1.88	102.0	140.9	131.4	138.0	77.4	92.5	"	2850	2670	17.4	19	9.81	0.338	0.006	0.267	0.004	0.947	2.18
1.0	2.43	132.1	138.4	127.3	135.0	79.8	87.5	"	3340	3140	16.6	20	12.05	0.329	0.006	0.269	0.004	0.892	2.10
2.0	2.86	155.0	141.6	127.3	139.8	77.8	84.0	"	4320	4125	14.3	20 (Jet)	14.20	0.312	0.007	0.264	0.003	0.759	1.87
"	3.03	164.3	140.5	126.0	139.5	79.5	84.0	"	4380	4240	11.8	20	15.00	0.282	0.006	0.254	0.003	0.593	1.59
2.0	1.038	56.2	143.4	139.5	140.9	83.8	90.0	0.430	1410	1355	17.0	12	8.60	0.340	0.006	0.254	0.004	0.875	2.44
"	1.505	81.6	142.6	136.9	140.5	84.9	91.0	"	2065	1950	15.5	17	8.78	0.331	0.007	0.267	0.003	0.892	2.10
"	1.98	107.4	144.3	136.3	142.6	84.1	92.0	"	2900	2685	15.3	20	9.81	0.312	0.006	0.261	0.004	0.759	1.87
"	2.43	131.8	141.7	132.7	140.5	84.0	89.5	"	3260	3200	12.7	19	12.70	0.312	0.005	0.257	0.003	0.759	1.87
"	2.73	148.9	141.2	131.0	140.4	83.2	93.5	"	3690	3640	13.3	20 (Jet)	13.53	0.291	0.005	0.254	0.003	0.640	1.67

\*For heat transfer to benzene.  
 \*\*Mechanism of drop formation changed from single, pulsing formation to formation at the end of a jet of benzene.

Average Drop Characteristics				Column Conditions				
Area (ft <sup>2</sup> )	Rise Velocity (ft./sec.)	A.D. (±) (Rise Velocity)	Time in Column (sec.)	Benzene in Column (ft <sup>3</sup> x 10 <sup>4</sup> )	Drops in Column	Area (ft <sup>2</sup> )	U***	Ua
35	0.318	0.007	19.12	52.8	573	1.24	42.0	390
35	0.292	0.007	20.83	86.4	903	1.97	53.0	785
35	0.261	0.006	23.30	129.4	1540	3.10	49.6	1210
35	0.257	0.006	23.67	160.4	1850	3.83	51.2	1540
35	0.218	0.007	27.90	229.3	4150	6.27	44.3	2180
35	0.186	0.006	32.70	309.0	6270	8.78	42.8	2960
35	0.147	0.003	41.30	443.0	8660	12.43	43.2	4220
35	0.313	0.006	19.42	53.7	500	1.19	50.0	468
35	0.289	0.005	21.04	84.2	838	1.91	47.5	712
35	0.273	0.005	22.30	115.8	1152	2.63	48.8	1010
35	0.253	0.008	24.00	162.8	1763	3.70	52.0	1510
35	0.208	0.007	29.20	240.0	3890	6.32	43.8	2160
35	0.185	0.005	32.90	304.0	5500	8.30	47.0	3060
35	0.149	0.004	40.80	398.0	8080	11.30	36.0	3200
35	0.292	0.009	20.85	61.3	620	1.44	44.8	507
35	0.281	0.008	21.65	87.2	920	2.01	49.6	782
35	0.257	0.007	23.65	129.3	1450	3.05	47.3	1135
35	0.242	0.007	25.10	167.3	1810	3.90	53.6	1640
35	0.175	0.005	34.75	279.5	4570	7.40	39.5	2300
35	0.145	0.004	41.90	386.5	7850	11.00	32.4	2800
35	0.127	0.004	47.90	479.0	9040	13.33	27.6	2890
35	0.305	0.007	19.95	56.7	565	1.29	46.7	473
35	0.295	0.009	20.63	86.3	830	1.93	51.3	780
35	0.281	0.005	21.65	119.5	1215	2.72	49.4	1057
35	0.218	0.009	27.90	189.1	2250	4.52	51.3	1820
35	0.193	0.003	31.50	258.8	3410	6.37	39.6	1980
35	0.137	0.003	44.30	400.0	7550	11.13	35.3	3090
35	0.284	0.009	21.40	58.2	579	1.32	51.8	546
35	0.258	0.006	23.57	94.9	1002	2.18	47.3	777
35	0.246	0.007	24.75	129.2	1365	2.98	51.5	1155
35	0.183	0.006	33.20	214.8	2290	4.60	41.2	1425
35	0.143	0.006	42.55	338.1	4460	8.33	34.6	2170
35	0.123	0.004	49.40	416.0	7010	11.28	31.9	2710
35	0.284	0.006	21.40	58.2	665	1.63	48.8	598
35	0.243	0.009	25.00	104.5	1170	2.46	51.2	947
35	0.208	0.005	29.23	161.0	2120	3.96	44.6	1330
35	0.155	0.007	39.20	264.5	3485	6.52	38.3	1880
35	0.136	0.006	44.70	339.0	5300	8.85	30.6	2040

$$***U = Q/A (\Delta t)_m = \text{B.t.u./hr.} - \text{ft}^2 - \text{of.}$$

Table IV --Calculation of Heat Loss Coefficient,  $U_{L A_L}$ .

Note: Since the experimental  $Q_L$  was the relatively small difference between  $Q_w$  and  $Q_b$ , care had to be exercised in selecting values of  $Q_L$  for the calculation of  $U_{L A_L}$ . The water hot runs were divided into groups having approximately the same log mean temperature difference between the water and the air. The average  $Q_L$  was calculated for each group. A run whose  $Q_L$  compared well with the average for its group could then be used with some degree of assurance as to the accuracy of the  $Q_L$  value. Since the heat loss was usually negligible in the benzene-hot runs, none of them was used in these calculations.

THERMOCOUPLES

		2	3	4	5	6	7	8	9	10	11
	L	0	0.75	1.42	2.08	2.75	3.42	4.08	4.75	5.42	6.08
Run: W22	$t_w \rightarrow$	147.7	145.9	144.2	142.3	140.5	138.2	135.9	134.5	132.1	124.5
$t_a = 81.5$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	49.2	91.8	133.1	172.9	211.5	248.7	284.5	319.0	351.0
$Q_L = 280$											
$U_{L A_L} = 280/351 \times 6.08 = 4.8$											
Run: W32	$t_w \rightarrow$	142.3	141.3	140.5	139.5	138.0	136.7	135.5	134.1	131.3	126.8
$t_a = 87.0$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	41.4	77.6	113.0	147.5	181.1	213.9	246.1	277.0	305.4
$Q_L = 250$											
$U_{L A_L} = 250/305 \times 6.08 = 5.0$											
Run: W32.5	$t_w \rightarrow$	144.0	143.0	142.2	141.2	139.8	138.5	137.1	134.6	131.0	125.3
$t_a = 90.5$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	39.6	74.4	108.6	142.2	174.9	206.7	237.2	265.8	291.3
$Q_L = 175$											
$U_{L A_L} = 175/291 \times 6.08 = 3.6$											
Run: W33	$t_w \rightarrow$	143.5	142.2	141.4	-	-	-	135.5	132.8	128.5	121.5
$t_a = 88.5$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	40.7	76.3	111.1	145.3	178.8	211.1	241.7	270.2	295.0
$Q_L = 160$											
$U_{L A_L} = 160/295 \times 6.08 = 3.3$											
Run: W52	$t_w \rightarrow$	140.9	140.4	140.0	139.5	138.7	138.6	138.1	136.9	135.2	131.4
$t_a = 82.5$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	43.6	82.2	120.5	158.5	196.1	233.5	270.5	307.1	341.1
$Q_L = 180$											
$U_{L A_L} = 180/341 \times 6.08 = 3.2$											
Run: W52.5	$t_w \rightarrow$	138.4	137.5	137.2	136.9	135.7	135.6	135.0	134.0	132.1	127.3
$t_a = 87.5$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	37.9	71.4	104.6	137.4	169.8	201.9	233.5	264.2	292.6
$Q_L = 200$											
$U_{L A_L} = 200/293 \times 6.08 = 4.1$											
Run: W53	$t_w \rightarrow$	141.6	141.1	140.8	140.1	139.4	139.1	138.3	136.9	133.7	127.3
$t_a = 84.0$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	43.0	81.1	118.9	156.3	193.2	229.9	265.9	300.3	331.9
$Q_L = 195$											
$U_{L A_L} = 195/332 \times 6.08 = 3.6$											
Run: W62	$t_w \rightarrow$	144.3	144.0	143.9	143.3	-	-	142.2	141.5	139.8	136.3
$t_a = 92.0$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	39.2	74.0	108.5	142.7	176.7	210.4	243.8	276.4	307.2
$Q_L = 200$											
$U_{L A_L} = 200/307 \times 6.08 = 4.0$											
Run: W1.53.5	$t_w \rightarrow$	141.7	136.1	132.3	127.7	123.2	118.4	114.2	109.0	103.5	98.1
$t_a = 88.0$	$\int_0^L (t_w - t_a) dL \rightarrow$	0	38.4	69.5	97.5	122.5	144.1	163.3	179.1	191.2	200.0
$Q_L = 125$											
$U_{L A_L} = 125/200 \times 6.08 = 3.8$											

Average  $U_{L A_L} = 3.9$  B.t.u./hr.-°F.

Calculation of Heat Transfer Coefficient in Bottom Section for  
Heat Transfer from Continuous to Discontinuous Phase.

Section =  $\frac{15.5}{73}$  or 0.212 of the effective column length.

Rates (#/hr)	Water Temp.		Room Temp.	Heat Loss to Air		Heat Lost by Water (B.t.u.)		C Benzene	Temp. Changes		Benzene Temp.		Delta t (l.m.)	Area (ft <sup>2</sup> )	U = Q/AΔt <sub>m</sub>	U*****	
	#11	#9		Delta t (l.m.)	Q <sub>a</sub> (B.t.u./hr.)	Total	To Benzene**		Water	Benzene***	#12(Exp.)	#9(Calc.)					
2	90.7	127.0	-	92.5	-	-	-	-	-	-	90.7	-	-	0.262	-	42.0	
2	"	124.4	130.3	94.0	33.3	27	535	508	0.420	5.9	14.9	89.4	104.3	30.4	0.418	40.0	53.0
8	"	118.5	127.0	94.5	28.0	23	771	748	"	8.5	16.4	90.9	107.3	23.6	0.657	48.2	49.6
9	"	107.6	117.7	88.0	24.4	20	916	896	"	10.1	16.1	82.7	98.8	21.9	0.812	50.3	51.2
0	"	103.3	113.1	91.0	16.7	14	888	874	"	9.8	12.9	84.0	96.9	17.7	1.332	37.0	44.3
0	"	98.1	109.2	88.0	14.9	12	1007	995	"	11.1	12.8	85.5	98.3	11.7	1.864	45.5	42.8
0	91.2	86.9	95.7	88.0	-	-	-	-	-	-	-	-	-	-	2.540	-	43.2
2	118.3	132.9	137.0	80.5	54.4	45	485	440	0.420	4.1	19.3	82.2	101.5	42.8	0.252	40.8	50.0
3	119.6	127.9	134.5	81.0	50.1	11	790	749	"	6.6	22.8	82.5	105.3	36.4	0.405	50.8	47.5
7	118.9	124.0	132.5	81.5	47.1	39	1010	971	"	8.5	22.8	83.8	106.6	32.8	0.558	53.0	48.8
8	120.0	114.0	125.5	84.0	35.8	30	1380	1350	"	11.5	24.2	79.0	103.2	28.1	0.785	60.4	52.0
0	122.8	109.5	123.0	85.0	30.8	25	1660	1635	"	13.5	24.2	82.6	106.7	21.2	1.343	57.2	43.8
0	120.2	105.6	120.6	85.5	26.9	22	1805	1783	"	15.0	23.4	82.5	105.9	18.7	1.760	54.0	47.0
0	122.8	102.6	118.3	85.5	24.1	20	1930	1910	"	15.7	23.8	83.1	106.9	15.1	2.395	52.7	36.0
5	183.7	132.3	136.6	85.0	49.5	41	790	749	0.423	4.3	30.8	82.9	113.7	34.5	0.305	71.2	44.8
7	"	129.3	135.6	85.0	47.5	39	1158	1119	"	6.3	33.6	83.4	117.0	30.3	0.425	87.0	49.6
9	"	126.8	134.1	87.0	43.0	35	1340	1305	"	7.3	28.9	81.0	109.9	34.1	0.647	59.1	47.3
2	"	125.3	134.6	90.5	39.4	33	1708	1675	"	9.3	30.4	82.4	112.8	30.9	0.827	65.8	53.6
3	"	121.5	132.8	88.5	37.0	31	2080	2049	"	11.3	30.8	83.4	114.1	27.2	1.570	48.0	39.5
0	"	116.9	131.9	90.0	34.0	28	2760	2732	"	15.0	35.8	82.5	118.3	22.4	2.335	52.3	32.4
0	181.5	112.2	127.4	88.0	30.9	25	2780	2755	"	15.2	33.2	81.6	113.4	21.7	2.828	47.7	27.6
8	235.0	134.6	137.4	88.0	48.0	40	658	618	0.420	2.8	26.4	84.1	110.5	37.9	0.274	59.5	46.7
0	"	132.1	136.3	88.0	46.2	39	987	948	"	4.2	27.5	85.0	112.5	34.5	0.410	67.0	51.3
1	"	128.3	133.9	87.5	43.5	36	1318	1282	"	5.6	28.2	80.0	108.2	36.2	0.577	61.3	49.4
3	238.0	126.3	134.9	83.0	47.5	39	2045	2006	"	8.6	36.0	77.8	113.8	33.1	0.957	63.3	51.3
0	235.0	121.5	-	-	-	-	-	-	-	-	-	81.2	-	-	1.320	-	39.6
2	238.0	122.0	135.0	80.5	47.9	40	3095	3055	0.430	13.0	40.9	79.2	120.1	26.4	2.380	48.5	35.3
8	302.0	133.2	135.9	88.5	45.5	38	815	777	0.420	2.7	33.1	77.0	110.1	40.1	0.280	69.2	51.8
6	"	134.9	139.1	82.5	54.7	45	1270	1225	"	4.2	37.1	77.1	114.2	39.3	0.463	67.3	47.3
0	"	131.4	136.9	82.5	51.8	43	1660	1617	"	5.5	37.7	77.4	115.1	35.6	0.632	71.8	51.5
1	"	127.3	134.0	87.5	43.0	36	2025	1989	"	6.7	35.8	80.2	116.0	30.3	0.975	67.3	41.2
0	301.0	127.3	136.9	84.0	48.0	40	2890	2850	0.423	9.6	43.5	77.8	121.3	29.7	1.766	54.2	34.6
3	302.0	126.0	136.6	84.0	47.2	39	3200	3161	"	10.6	45.5	79.5	125.0	25.3	2.390	52.3	31.9
2	362.0	139.5	141.7	90.5	50.0	41	796	755	0.420	2.2	32.0	83.8	115.8	39.4	0.346	55.3	48.8
6	362.0	136.9	139.8	91.0	47.8	40	1050	1010	"	2.9	29.4	84.9	114.3	37.3	0.522	51.8	51.2
4	"	136.3	141.5	92.0	47.0	39	1882	1843	0.427	5.2	40.2	84.1	124.3	31.7	0.840	69.2	44.6
8	"	132.7	138.7	89.5	46.0	38	2170	2132	"	6.0	37.8	84.5	122.3	29.5	1.382	52.2	38.3
0	"	131.0	138.4	93.5	41.2	34	2680	2646	"	7.4	42.0	83.2	125.2	26.7	1.877	52.8	30.6

2 x 3.9 x Delta t (l.m.)

\*\*The heat gain of the benzene = total heat lost by water minus Q<sub>a</sub>.  
\*\*\*Temperature change in benzene = heat gain of the benzene divided by (#/hr of benzene x C of benzene).

\*\*\*\*Area = 0.212 x total area in column.  
\*\*\*\*\*Coefficient based on entire column. (From Table II)

Calculation of Heat Transfer Coefficient in Bottom Section for  
Transfer from Discontinuous to Continuous Phase.

Section =  $\frac{15.5}{73}$  or 0.212 of the effective column length.

Benzene Rates (#/hr)	Water Temp.		Room Temp.	Heat Loss to Air		Enthalpy Changes ( $\frac{B.t.u.}{hr}$ ) C.			Temp. Changes		Benzene Temp.		Delta t (l.m.)	Area**** (ft <sup>2</sup> )	U = Q/A <sub>at,m</sub>	U*****	
	Water	#11		#9	Delta t (l.m.)	Q <sub>L</sub> * (B.t.u./hr.)	Water	Benzene**	Benzene	Water	Benzene***	#12					#9(Calc.)
78.9	91.9	99.5	90.2	86.0	-	-	855	855	0.440	9.3	24.6	138.5	113.9	30.9	0.436	63.5	66.9
	122.9	93.4	85.2	88.0	-	-	1007	1007	0.435	8.2	29.4	133.2	103.8	27.7	0.458	79.4	66.5
	186.1	87.7	81.5	91.0	-	-	1153	1153	0.440	6.2	33.2	141.1	107.9	37.9	0.545	55.9	57.9
	242.5	87.9	-	91.0	-	-	-	-	-	-	-	138.2	-	-9	0.538	-	57.6
	301.0	84.3	79.9	91.0	-	-	1324	1324	0.435	4.4	38.6	139.4	100.8	35.4	0.590	63.5	60.3
	369.5	81.3	76.4	91.5	-12.5	-10	1810	1800	0.433	4.9	52.7	142.2	89.5	31.2	0.608	94.8	60.8
06.0	89.5	111.0	97.7	88.0	15.4	13	1190	1203	0.445	13.3	24.9	154.8	129.9	37.8	0.570	54.5	72.0
05.5	123.3	99.5	-	89.0	-	-	-	-	-	-	-	143.6	-	-	0.659	-	62.6
06.4	185.0	89.8	-	91.5	-	-	-	-	-	-	-	137.6	-	-	0.712	-	66.5
	240.0	86.2	78.9	92.0	-	-	1752	1752	0.440	7.3	37.5	143.6	106.1	40.2	0.756	57.5	61.5
	304.0	84.0	77.9	92.0	-10.8	-9	1855	1846	0.435	6.1	39.9	139.7	99.8	36.3	0.876	58.0	58.5
	372.0	86.5	79.6	92.0	-13.8	-11	2570	2559	0.438	6.9	54.9	155.7	100.8	40.3	1.000	63.5	71.9
33.3	91.4	118.1	104.7	90.0	20.6	17	1225	1242	0.448	13.4	20.9	152.0	131.1	30.0	0.900	46.2	59.1
	122.8	108.9	94.3	89.5	10.6	9	1792	1802	0.445	14.6	30.4	152.4	122.0	35.2	0.973	52.8	63.1
	187.2	98.1	85.1	90.0	-	-	2435	2435	0.440	13.0	41.5	149.5	108.0	35.3	1.024	67.4	63.1
	235.1	93.8	80.9	91.0	-	-	3160	3160	0.440	12.9	53.9	156.6	102.7	39.0	1.223	66.2	69.2
	306.5	89.7	77.9	92.0	-	-	3620	3620	0.440	11.8	61.8	160.9	99.1	41.3	1.618	54.2	61.5
	336.7	87.9	76.5	84.5	-	-	3840	3840	0.440	11.4	65.4	160.8	95.4	40.0	3.065	31.3	30.7
59.0	91.5	132.1	114.7	88.0	35.0	29	1593	1622	0.450	17.4	22.7	156.5	133.8	21.7	1.510	49.6	56.7
61.0	121.8	121.1	100.1	88.0	20.7	17	2555	2572	0.450	21.0	35.5	157.9	122.4	28.8	1.791	50.0	51.3
61.0	183.4	104.7	-	89.0	-	-	-	-	-	-	-	156.2	-	-	2.230	-	41.8
61.0	214.0	101.0	77.9	88.5	-	-	4950	4950	0.440	23.1	69.8	165.7	95.9	36.7	4.250	31.8	28.5
35.8	91.3	140.2	122.4	90.5	40.0	31	1626	1657	0.450	17.8	19.9	159.4	139.5	18.1	1.880	49.0	51.0
	123.0	128.4	105.2	90.0	25.1	21	2855	2876	0.450	23.2	34.4	160.4	126.0	26.0	2.145	51.6	57.2
	157.7	116.9	84.6	90.0	-	-	5095	5095	0.440	32.3	62.3	161.4	99.1	26.7	4.720	40.4	33.2
17.5	91.2	147.2	132.2	92.0	47.0	39	1368	1407	0.450	15.0	14.4	160.4	146.0	13.5	2.680	39.2	43.4
	119.3	140.6	110.2	90.5	32.8	27	3625	3652	0.450	30.4	37.4	161.4	124.0	17.1	6.230	34.2	30.1

0.212 x 3.9 x Delta t (l.m.). Heat loss is considered positive,  
by column is considered negative. Q(Loss) was neglected when  
numerically less than 10.

\*\*Enthalpy change of benzene = Algebraic sum of enthalpy change  
of water and Q<sub>L</sub>.

\*\*\*Temperature change of benzene = Enthalpy change of benzene  
divided by (#/hr of benzene x C. of benzene).

\*\*\*\*Area = 0.212 x total drop  
area in column.

\*\*\*\*\*Coefficient based on the  
entire column. (From Table III)

Table VII--Investigation of Applicability of Logarithmic Mean Temperature Difference.

Run: W1.51.5  
 Water Rate =  $M_w = 90.7 \text{ \#/hr.}$   
 Benzene Rate =  $M_b = 81.2 \text{ \#/hr.}$   
 $A = 1.973 \text{ ft}^2$   
 $a' = A/L_e = \frac{1.973}{6.08} = 0.325 \frac{\text{ft}^2}{\text{ft}}$   
 Room temperature =  $94.0^\circ\text{F}$

Couple	Exp. t	Smoothed** t	L (ft)	$(t_{w2}-t_w)$	$\int_{t_w}^{t_{w2}} M_w C_w dt_w$	$(t_w-t_a)$	$\int_0^L (t_w-t_a) dL$	$U L a' \int_0^L (t_w-t_a) dL$	$C_b$	$\int_{t_b}^{t_{b1}} M_b C_b dt_b$	$(t_{b1}-t_b)$	$t_b^{***}$	$(t_w-t_b)$	$a'(t_w-t_b)$	$\int_0^L a'(t_w-t_b) dL$
1	138.2*	-	0	-	-	-	-	-	-	0	0	138.2	-	-	-
2	144.1	144.1	0	0	0	50.1	0	23	-	0	0	138.2	-	-	0
3	142.3	142.4	0.75	1.7	154	48.4	36.0	43	0.444	131	3.6	134.6	7.8	2.53	1.66
4	140.8	140.6	1.42	3.5	318	46.6	68.0	63	0.443	275	7.6	130.6	10.0	3.25	2.60
5	138.7	138.7	2.08	5.4	490	44.7	98.8	82	0.442	427	11.9	126.3	12.4	4.03	5.00
6	136.7	136.8	2.75	7.3	662	42.8	128.0	100	0.440	580	16.2	122.3	14.5	4.71	7.95
7	134.7	134.8	3.42	9.3	844	40.8	156.3	117	0.439	744	20.8	117.4	17.4	5.66	11.43
8	133.1	132.7	4.08	11.4	1035	38.7	183.5	133	0.438	918	25.8	112.4	21.3	6.93	15.53
9	130.2	130.2	4.75	13.9	1260	36.2	208.0	148	0.438	1127	31.7	106.5	23.7	7.80	20.35
10	126.8	127.4	5.42	16.7	1515	33.4	231.5	161	0.436	1367	38.6	99.6	27.8	9.04	25.97
11	124.4	124.4	6.08	20.7	1880	30.4	252.5	-	0.434	1719	48.7	89.5	34.9	11.33	32.73
12	89.4*	-	6.08	-	-	-	-	-	-	-	-	89.5	-	-	-

\*Benzene temperatures at the ends of the column.  
 \*\*This water temperature was obtained from the best curve on a plot of  $t_w$  versus L.  
 \*\*\*Calculated benzene temperatures.

By rigorous method:  $U = \frac{1719}{32.7} = 52.5$   
 By use of  $\Delta t_m$ :  $U = 53.0$

Run: W1.53.5  
 Water Rate =  $90.7 \text{ \#/hr.}$   
 Benzene Rate =  $185 \text{ \#/hr.}$   
 $A = 8.78$   
 $a' = \frac{A}{L_e} = \frac{8.78}{6.08} = 1.443$   
 Room Temperature =  $88.0^\circ\text{F}$

1	133.7*	-	0	-	-	-	-	0	-	0	0	133.7	-	-	-
2	141.7	141.5	0	0	0	53.5	0	24	-	0	0	133.7	-	-	0
3	136.1	136.6	0.75	4.9	444	48.6	38.4	44	0.440	419	5.1	128.6	8.0	11.5	8.5
4	132.3	132.0	1.42	9.5	862	44.0	69.5	62	0.439	818	10.1	123.6	8.4	12.3	16.3
5	127.7	127.7	2.08	13.8	1252	39.7	97.5	78	0.438	1190	14.7	119.0	8.7	12.6	24.5
6	123.2	123.1	2.75	18.4	1670	35.1	122.5	92	0.437	1592	19.7	114.0	9.1	13.1	33.2
7	118.4	118.5	3.42	23.0	2090	30.5	144.1	104	0.436	1998	24.8	108.9	9.6	13.9	42.1
8	114.2	114.0	4.08	27.5	2495	26.0	163.3	114	0.435	2390	29.7	104.0	10.0	14.4	51.5
9	109.0	109.0	4.75	32.5	2950	21.0	179.1	122	0.434	2835	35.3	98.4	10.6	15.3	61.5
10	103.5	103.7	5.42	37.8	3430	15.7	191.2	128	0.432	3308	41.4	92.3	11.4	16.5	72.1
11	98.1	98.1	6.08	43.4	3940	10.1	200.0	-	0.438	3812	48.0	85.7	12.4	17.9	83.6
12	85.5*	-	6.08	-	-	-	-	-	-	-	-	85.7	-	-	-

By rigorous method:  $U = \frac{3812}{83.6} = 45.5$   
 By use of  $\Delta t_m$ :  $U = 42.8$



Table VIII--Point Temperatures for Runs in which Heat was Transferred from the Continuous Phase to the Discontinuous Phase (°F.)

	THERMOCOUPLES											
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
W1.51	135.3	144.1	142.0	140.8	-	-	-	-	-	129.6	127.0	90.7
W1.51.5	138.2	144.1	142.3	140.8	138.7	136.7	134.7	133.1	130.3	127.0	124.4	89.4
W1.52	137.6	143.7	141.3	139.3	137.1	134.6	132.4	130.0	127.0	123.1	118.5	90.9
W1.52.5	134.1	142.2	138.1	135.4	132.2	128.6	125.1	122.1	117.7	112.9	107.6	82.7
W1.53	134.6	142.4	137.3	134.2	130.5	-	-	-	113.1	109.0	103.3	89.0
W1.53.5	133.7	141.7	136.1	132.3	127.6	123.2	118.4	114.2	109.2	103.5	98.1	85.5
W1.54	129.2	138.9	129.0	123.1	116.3	110.5	105.4	100.9	95.7	90.9	86.9	80.0
W21	138.9	146.1	144.7	143.9	142.8	-	-	-	137.0	135.3	132.9	82.2
W21.5	139.1	146.4	144.4	143.6	142.1	140.2	138.3	136.4	134.5	132.1	127.9	82.5
W22	140.5	147.7	145.9	144.2	142.3	140.5	138.2	135.9	134.5	132.1	124.5	83.8
W22.5	138.0	144.1	141.8	140.0	137.8	135.0	132.5	129.4	125.5	120.6	114.0	78.6
W23	138.7	144.1	141.9	139.3	136.7	133.8	130.7	127.3	123.0	119.0	111.9	83.9
W23.5	140.0	144.7	141.8	139.5	136.7	133.2	129.3	125.9	120.6	113.9	105.6	82.5
W24	139.0	144.8	141.2	138.7	-	-	-	-	118.3	111.6	102.6	83.1
W31	135.7	141.6	140.9	140.3	139.5	138.5	-	137.9	136.6	134.9	132.3	82.9
W31.5	136.5	141.3	140.8	140.1	139.5	138.1	137.4	136.7	135.6	133.5	129.3	83.4
W32	137.5	142.3	141.3	140.5	139.5	138.0	136.7	135.5	134.1	131.3	126.8	81.0
W32.5	140.5	144.0	143.0	142.2	141.2	139.8	138.5	137.1	134.6	131.0	125.3	82.4
W33	140.8	143.5	142.2	141.4	-	-	-	135.5	132.8	128.5	121.5	83.4
W33.5	140.0	142.9	141.8	140.9	139.6	138.0	136.5	134.7	131.9	126.9	116.5	82.9
W3f	135.7	139.2	137.8	137.1	135.7	134.3	132.5	130.7	127.4	124.4	112.2	81.6
W41	134.7	140.2	139.4	139.0	-	-	-	-	137.4	136.4	134.6	84.1
W41.5	135.9	140.3	139.7	139.3	138.3	137.5	137.5	137.2	136.3	135.1	132.1	85.0
W42	134.4	139.4	138.7	138.3	137.5	136.3	136.1	135.3	133.9	131.9	128.3	80.0
W42.5	138.6	140.8	140.1	139.7	139.0	-	-	-	134.9	132.1	126.3	77.8
W43	134.8	138.1	137.4	135.9	136.1	-	-	-	-	-	121.5	81.2
W43.5	139.8	141.5	141.1	140.3	139.4	138.9	138.5	137.6	135.0	131.0	122.0	79.2
W51	132.5	136.6	136.0	135.8	135.4	134.9	135.4	135.3	135.9	134.2	132.1	76.4
W51.5	138.2	142.0	142.0	141.7	141.2	139.9	140.0	139.6	139.1	137.7	134.9	77.1
W52	138.0	140.9	140.4	140.0	139.5	138.7	138.6	138.1	136.9	135.2	131.4	77.4
W52.5	135.0	138.4	137.5	137.2	136.9	135.7	135.6	135.0	134.0	132.1	127.3	79.8
W53	139.8	141.6	141.1	140.8	140.1	139.4	139.1	138.3	136.9	133.7	127.3	77.8
W5f	139.5	140.5	140.1	139.7	138.9	138.4	138.4	137.8	136.6	132.5	126.0	79.5
W61	140.9	143.4	143.0	142.9	142.6	-	142.6	142.1	141.7	140.7	139.5	83.8
W61.5	140.5	142.6	142.0	141.8	141.4	-	-	140.3	139.8	139.0	136.9	84.9
W62	142.6	144.3	144.0	143.9	143.3	-	-	142.2	141.5	139.8	136.3	84.1
W62.5	140.5	141.7	141.2	140.8	140.5	139.9	140.3	139.9	138.7	136.7	132.7	84.0
W6f	140.4	141.2	140.8	140.5	140.0	139.7	139.7	139.3	138.4	136.7	131.0	83.2

Table IX--Point Temperatures for Runs in which Heat was Transferred from the Discontinuous Phase to the Continuous Phase. (°F.)

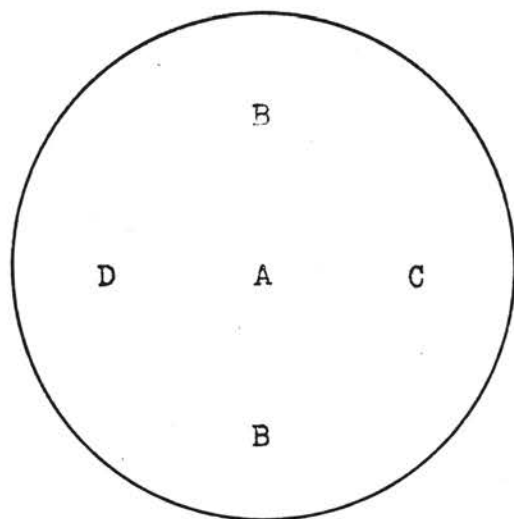
Run	THERMOCOUPLES											
	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
B1.51.5	81.2	77.9	79.3	80.1	-	-	-	86.9	90.2	94.3	99.5	138.5
B21.5	80.0	77.3	77.8	78.6	78.9	79.9	81.3	82.8	85.2	88.3	93.4	133.2
B31.5	77.7	76.4	76.5	77.0	80.1	77.8	78.9	79.7	81.5	84.4	87.7	141.1
B41.5	81.2	80.0	-	-	-	-	-	-	-	85.3	87.9	138.2
B51.5	78.1	77.4	77.5	77.7	77.8	78.1	78.7	79.0	79.9	81.5	84.3	139.4
B61.5	74.9	74.3	74.4	74.6	74.7	75.1	75.5	75.8	76.4	78.0	81.3	142.2
B1.52	81.7	77.0	79.4	80.7	-	-	-	-	97.7	103.2	113.3	150.9
B22	78.3	75.3	-	-	-	-	-	-	-	93.5	99.5	143.6
B32	75.9	74.6	75.0	75.5	75.9	-	-	-	-	83.8	89.8	137.6
B42	75.2	74.1	74.3	74.6	74.7	75.1	76.5	77.4	78.9	82.1	86.2	143.6
B52	75.1	74.5	74.6	-	-	-	76.3	76.5	77.9	80.3	84.0	139.7
B62	77.5	77.4	77.2	77.4	77.3	77.4	78.3	78.9	79.6	81.9	86.5	148.6
B1.52.5	84.1	78.7	81.5	83.9	86.8	90.0	94.1	98.6	104.7	111.9	118.1	152.0
B22.5	80.1	77.4	78.2	-	-	-	-	-	94.3	102.6	110.5	153.9
B32.5	77.2	75.9	76.0	76.7	77.3	78.1	79.8	81.8	85.1	90.8	98.1	149.5
B42.5	75.2	74.9	75.0	75.4	75.4	76.1	77.3	78.3	80.9	85.7	93.8	156.6
B52.5	73.6	73.5	73.5	73.9	73.8	74.2	75.2	75.8	77.9	81.9	89.7	160.9
Bf2.5	75.3	75.2	75.3	75.5	75.6	75.8	-	-	76.5	78.7	87.9	160.8
B1.53	85.1	80.2	83.8	87.4	91.6	95.1	100.9	106.6	114.7	123.8	132.1	156.5
B23	80.3	78.0	79.4	80.9	82.7	85.1	89.5	93.3	100.1	109.9	121.1	157.9
B33	76.7	75.8	76.2	77.0	77.5	78.9	80.4	-	-	93.2	105.7	156.3
Bf3	73.5	73.3	73.5	73.9	74.0	74.3	75.2	75.9	77.9	83.8	101.0	165.7
B1.53.5	85.5	77.1	84.4	89.1	95.6	101.8	109.0	115.9	122.1	130.9	139.6	158.4
B23.5	78.8	76.5	78.0	80.2	83.0	86.4	92.0	97.2	105.2	116.1	128.4	160.4
Bf3.5	74.6	74.2	74.4	64.9	75.3	76.0	77.9	80.2	84.6	95.9	116.9	161.4
B1.54	88.8	77.6	89.0	95.9	103.2	-	-	124.9	132.2	139.4	147.2	160.4
Bf4	78.3	75.6	78.1	80.3	83.3	86.6	92.6	99.5	110.2	124.9	140.6	161.4

Table X -Distortion Factors by which Drop Images were Multiplied to give Actual Size.

Diameter of glass marbles = 0.61  $\pm$  0.005 inches

Position	Vertical Image*	Vertical Factor	Horizontal Image*	Horizontal Factor	Diagonal Image*	Diagonal Factor
A	0.55	1.11	0.72	0.847	0.63	0.968
B	0.53	1.15	0.84	0.726	0.66	0.925
C	0.56	1.09	0.68	0.897	0.61	1.00
D	0.56	1.09	0.79	0.772	0.66	0.925

\*This is the measured diameter of the marble image.



Top View of Column  
Cross-Section

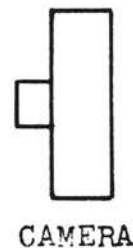


Table XI--Calibration Values for Chromel-constantan Thermocouples (Millivolts).

Temp. (°C)	Thermocouple Number											
	1	2	3	4	5	6	7	8	9	10	11	12
70	1.235	1.235	-	-	-	-	-	-	-	-	-	1.225
80	1.580	1.580	-	-	-	-	-	-	1.585	1.580	1.570	1.570
90	1.925	1.925	1.925	1.920	1.920	1.915	1.920	1.920	1.925	1.920	1.915	1.915
100	2.270	2.270	2.270	2.270	2.265	2.260	2.270	2.270	2.270	2.265	2.265	2.260
110	2.615	2.615	2.620	2.615	2.610	2.605	2.615	2.615	2.615	2.610	2.615	2.605
120	2.965	2.960	2.965	2.965	2.955	2.950	2.965	2.960	2.960	2.955	2.960	2.950
130	3.315	3.315	3.320	3.320	3.310	3.310	3.300	3.315	3.310	3.310	3.310	3.300
140	3.675	3.675	3.675	3.675	3.670	3.665	3.680	3.675	3.665	3.670	3.660	3.660
150	4.035	4.030	4.030	4.035	4.030	4.025	4.035	4.030	4.020	4.025	4.005	4.020
160	4.395	4.390	4.390	4.390	4.390	4.385	4.390	4.385	4.375	4.385	4.355	4.395
170	-	-	-	-	-	-	-	-	-	-	-	-

Note: All thermocouples were calibrated in place in the column. Water was passed through the column at a high flow rate so as to obtain as small a temperature drop as possible from one end to the other. This small drop, due to heat loss, ranged from 0.5 to 1.1°F. and was considered to be linearly distributed along the column. Two thermometers graduated to the nearest 0.2°F. and reading to the nearest 0.1°F were placed at the column ends to act as standards. The error due to the inversion of one thermometer was found to be negligible. Both thermometers had been previously checked against a thermometer bearing a National Bureau of Standards Certificate.

A separate curve was drawn and used for each couple.

FIGURE 24: Rotameter Calibration Curves

READ THE BOTTOM OF THE BALL

Rotameter Reading

16  
14  
12  
10  
8  
6  
4  
2  
0

Water (glass ball)  
(82°F.)  
(97-102°F.)

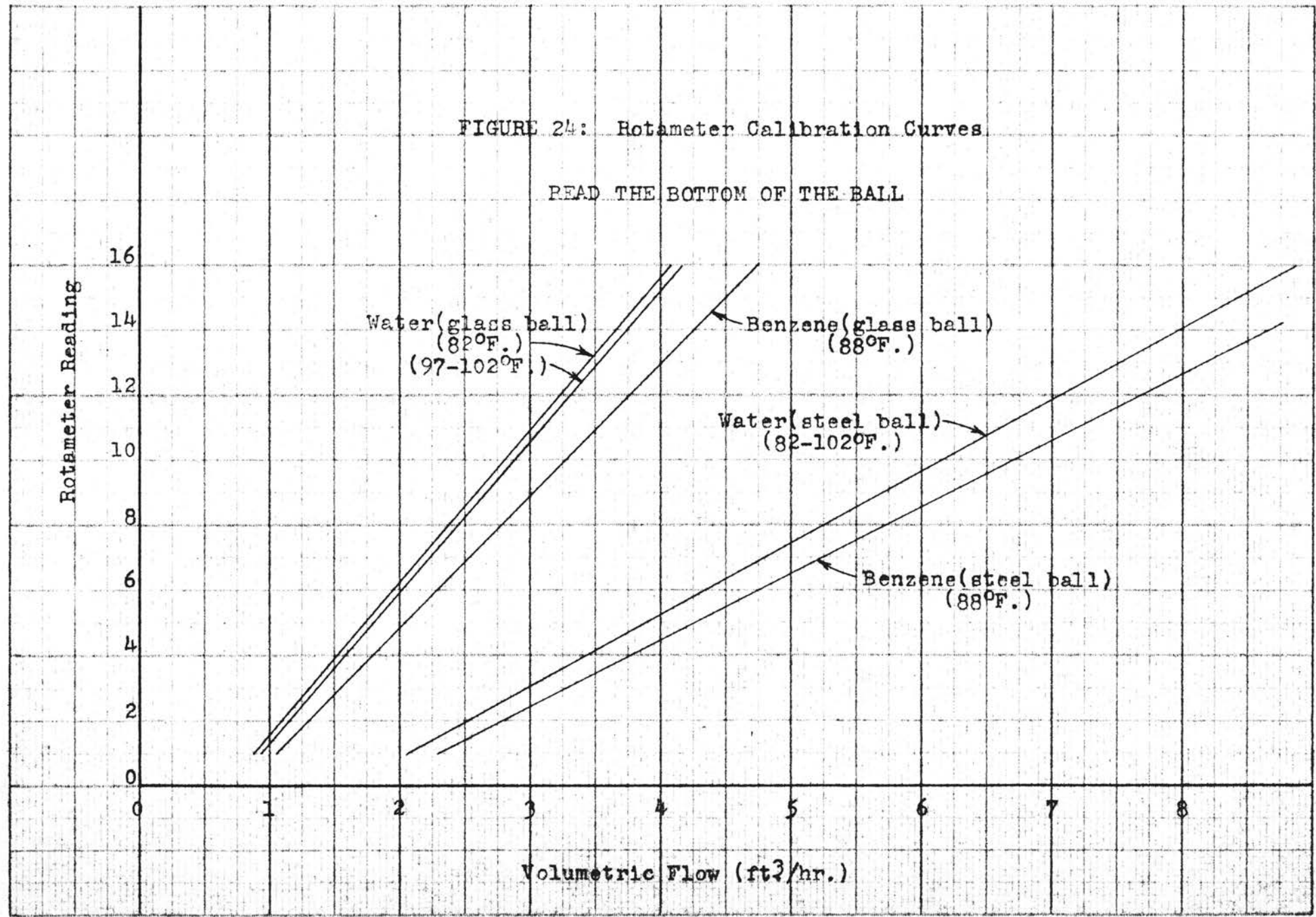
Benzene (glass ball)  
(88°F.)

Water (steel ball)  
(82-102°F.)

Benzene (steel ball)  
(88°F.)

Volumetric Flow (ft<sup>3</sup>/hr.)

0 1 2 3 4 5 6 7 8



THESIS TITLE: PERFORMANCE CHARACTERISTICS  
OF A SPRAY COLUMN

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