PERFORMANCE OF THE
KOCH KASKADE TRAY IN HUMIDIFICATION

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

An air humidification study was carried out in a five tray, $13\frac{1}{2}$" i.d. KOCH KASKADE column. The auxiliary equipment and piping were adapted to the special demands of the problem.

The tray spacing was 24" and the weir length 8". Performance data were taken for the two bottom trays only, as nearly complete humidification was obtained with two trays.

Air at different temperatures was blown into the tower below the first tray and water was circulated through the tower. The air velocity was 2.9 to 3.4 feet per second and the water loading ranged from two to ten gallons per minute per square foot of tower cross section.

Absolute air humidities were determined by a gravimetric method, using calcium chloride tubes and a wet test meter. Tray efficiencies were calculated from the air inlet and outlet humidities and the saturated humidity corresponding to the temperature of the water leaving the tray.

The average efficiency for air humidification was found to be 0.73 ± 0.015. Inlet air temperature showed no effect on the efficiency, but a higher water loading yielded increased efficiencies.

The range of air velocities employed was narrow; no appreciable effect on efficiency could be detected.

In the range of air and water loadings used, the pressure drop per tray was rather low, changing mainly with liquid loading. The range of pressure drops was 1.0 to 1.5 inches of water.

The rate of air humidification, expressed as the air film heat transfer coefficient, was found to vary from 1.8 to 2.7 Btu/min-cu.ft.-°F. with a change in water rate from 1.7 to 8.6 lbs/min.

INTRODUCTION

Humidification is a diffusional operation which involves two basic and rigorously correlated phenomena, namely mass transfer from the liquid to the gaseous phase and heat transfer from the gaseous to the liquid phase. The main factors governing diffusional operations are the amount of interfacial surface and the resistance of the transfer films. In the case of adiabatic humidification of air the transfer of water vapor into the air and of heat into the water are controlled by the air film only, as no composition or temperature gradient exists across the water film.

The humification efficiency of any type of equipment used depends on the magnitude of the above factors, which are a function of several variables, as pointed out by W. G. Whitman and J. L. Keats (1). These variables are the character of the equipment, the air velocity, the rate of water flow, and the temperature.

The article by the above mentioned authors is of considerable interest, as it is a survey of all work done up to 1922 on the study of heat and mass transfer in absorption and humidification processes in various types of equipment. Data on heat transfer film coefficients are given for a 1 ft. diameter coke-tower, a McLaurin gas scrubber, spray chambers and a 2 square foot cross-section bubble cap tower. The effect of the different variables is correlated; in all cases, the gas velocity had the most marked effect.

Another, more recent, paper by T. F. Walter and T. K. Sherwood (2) presents data obtained for various diffusional operations in bubble cap columns. Some of the data and results can be compared with those obtained in the present study on humidification. In general, the values of the Murphree plate vapor efficiencies they obtained, lie in the range 0.6 to 0.9, varying relatively little with vapor velocity, but showing a marked increase with increase in liquid depth on the plate. Humidification of air was carried out in a two inch bubble cap tower using a technique similar to that used in this investigation. It is interesting to note that their average efficiency value for humidification ($E^{O}_{MV} = 0.868$) was very close to the average efficiency for the rectification of ethanol-water mixtures in the same equipment ($E^{O}_{MV} = 0.889$).

The claimed superiorities of the KOCH KASKADE tray as compared with the much used bubble cap tray are (3,6):

1. Low pressure drop due to unrestricted flow paths.
2. Good contact as a result of violent mixing and larger surface provided by the perforated baffles.
3. No liquid gradient build-up with increased loading because of the "stair step" arrangement. All liquid must travel the same path and receive the same treatment.
4. Path followed by liquid-laden vapor creates centrifugal action which separates the liquid from the vapor on the baffles. Any entrainment is knocked out by a backward curve on the end of the baffle.

Since the KOCH KASKADE tray is already operating satisfactorily in commercial absorption, distillation and liquid-liquid extraction units (4,5), it was decided to investigate its humidification performance characteristics.

OBJECTIVE

Very little data are available on the performance of the KOCH KASKADE tower and it seems that it has not yet been tried for humidification purposes. Furthermore, only little work has been done on humidification in any other type of plate column.

The present study consisted of:

1. Adaptation of the tower and auxiliaries to the needs of the investigation.
2. Calibration of the air blower and all temperature and flow measuring devices.
3. Determination of heat losses under extreme conditions and their elimination as far as possible.
4. Development of a reliable method for the humidity measurement of the air leaving trays inside the column.
5. Determination of humidification efficiencies of a KOCH KASKADE tray.
6. Determination of the pressure drop per tray as affected by air and water loading.
7. Estimation of mass and heat transfer coefficients.

DESCRIPTION OF EQUIPMENT

1. The column used was $13\frac{1}{2}$ inches in inside diameter and contained five KOCH KASKADE trays. (See Figures 1, 2 and 3).

2. A Buffalo Forge Blower supplied the air to the bottom of the tower through an air heater.

3. The air heater was a shell and tube heat exchanger with steam heating.

4. A Deming Centrifugal pump was used for water circulation.

5. Calcium chloride drying tubes in series with a wet test meter were employed for absolute humidity determinations.

For the general arrangement of equipment, refer to the Flow Diagram, Fig. 4.

Further detailed specifications of equipment and auxiliaries can be found in the Appendix.

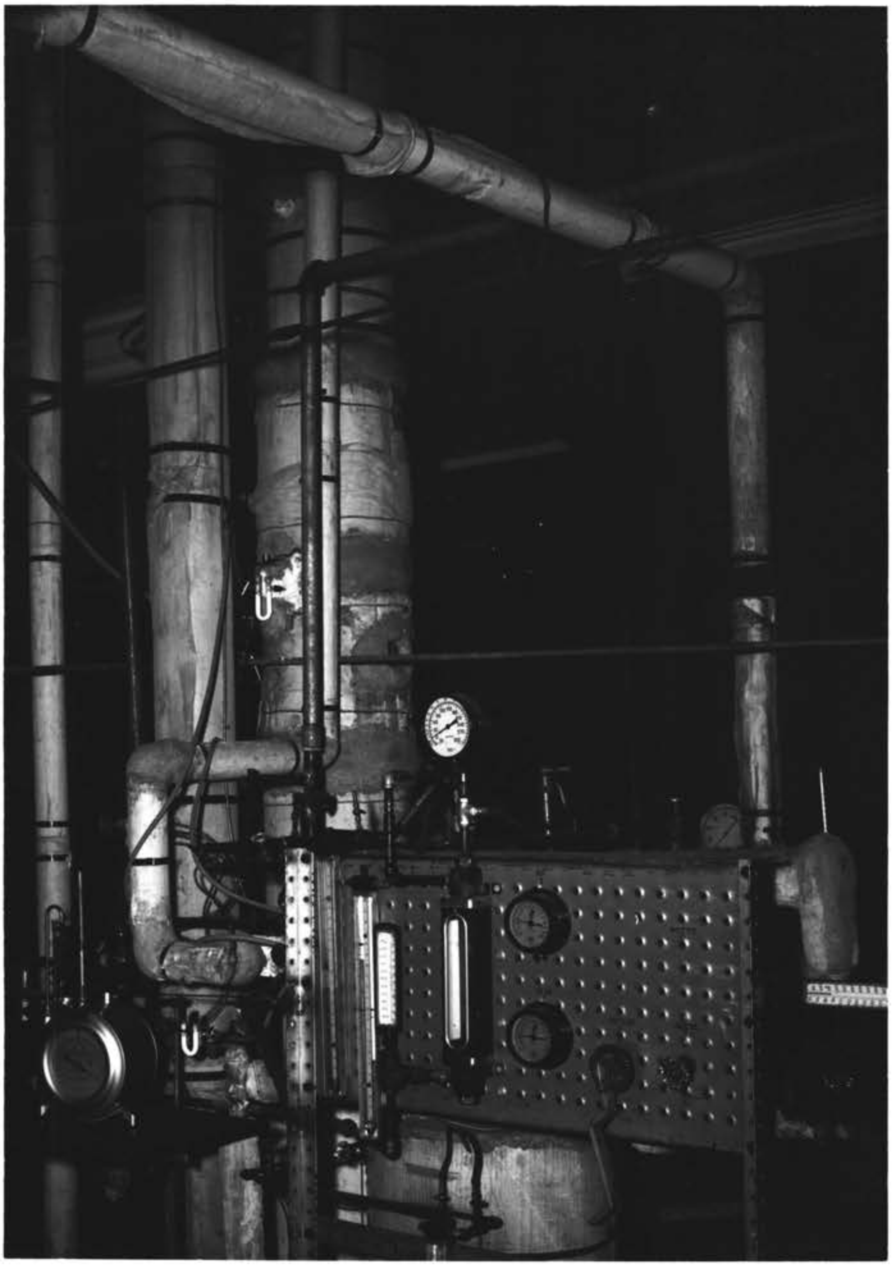


Figure 1.

View of the Column and Auxiliaries

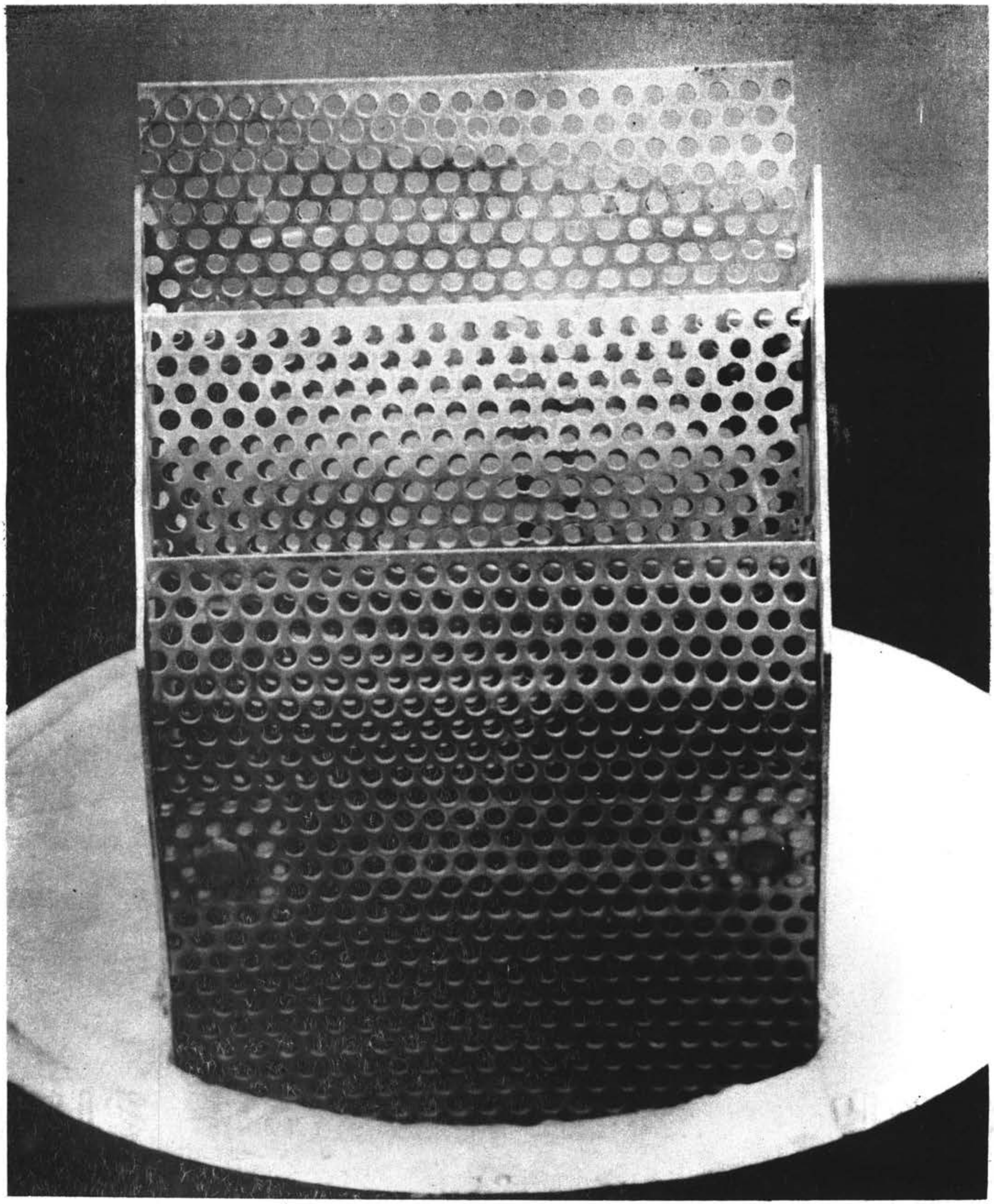


Figure 2. Top View of Tray

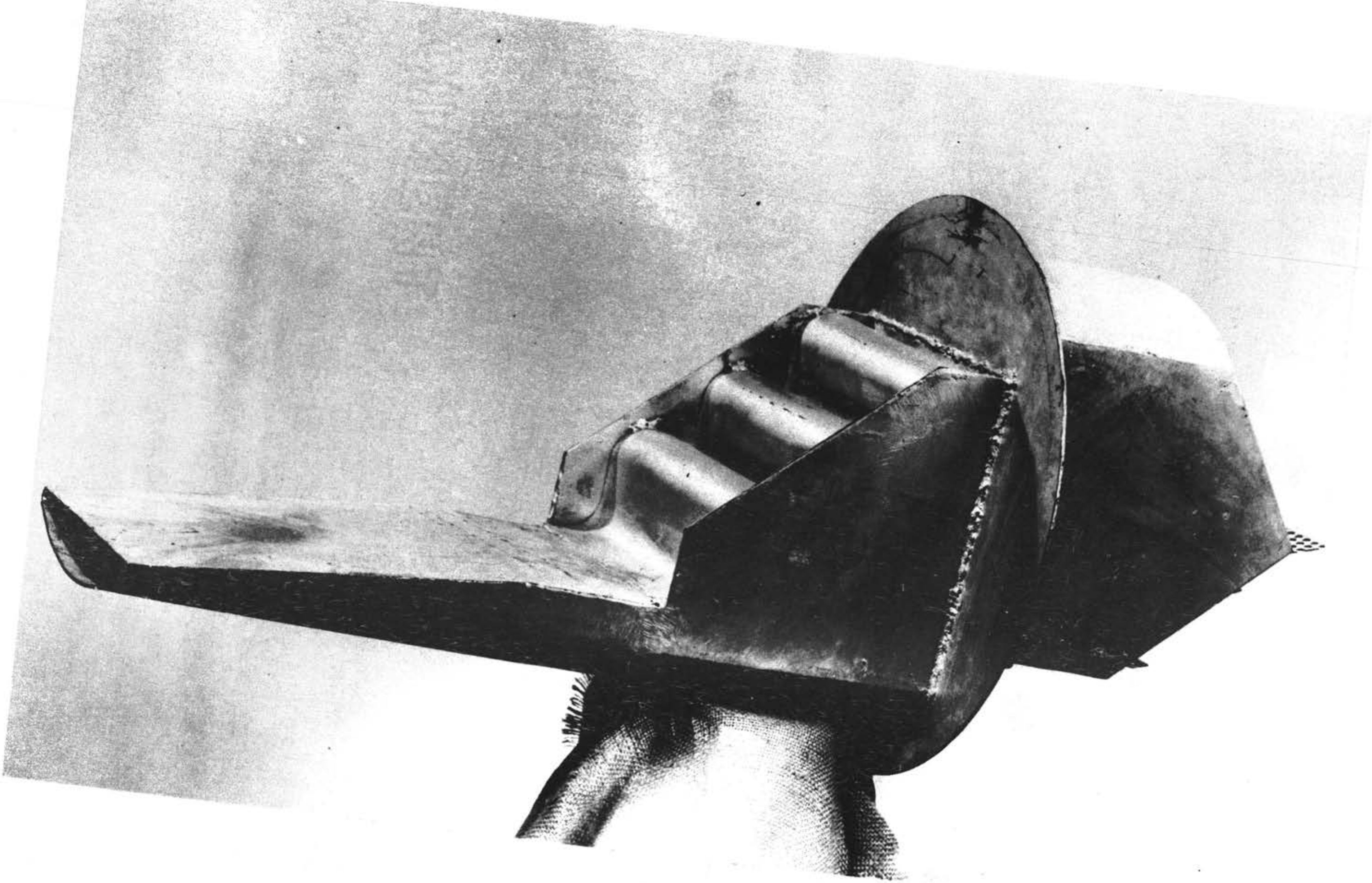


Figure 3. Side View of Tray

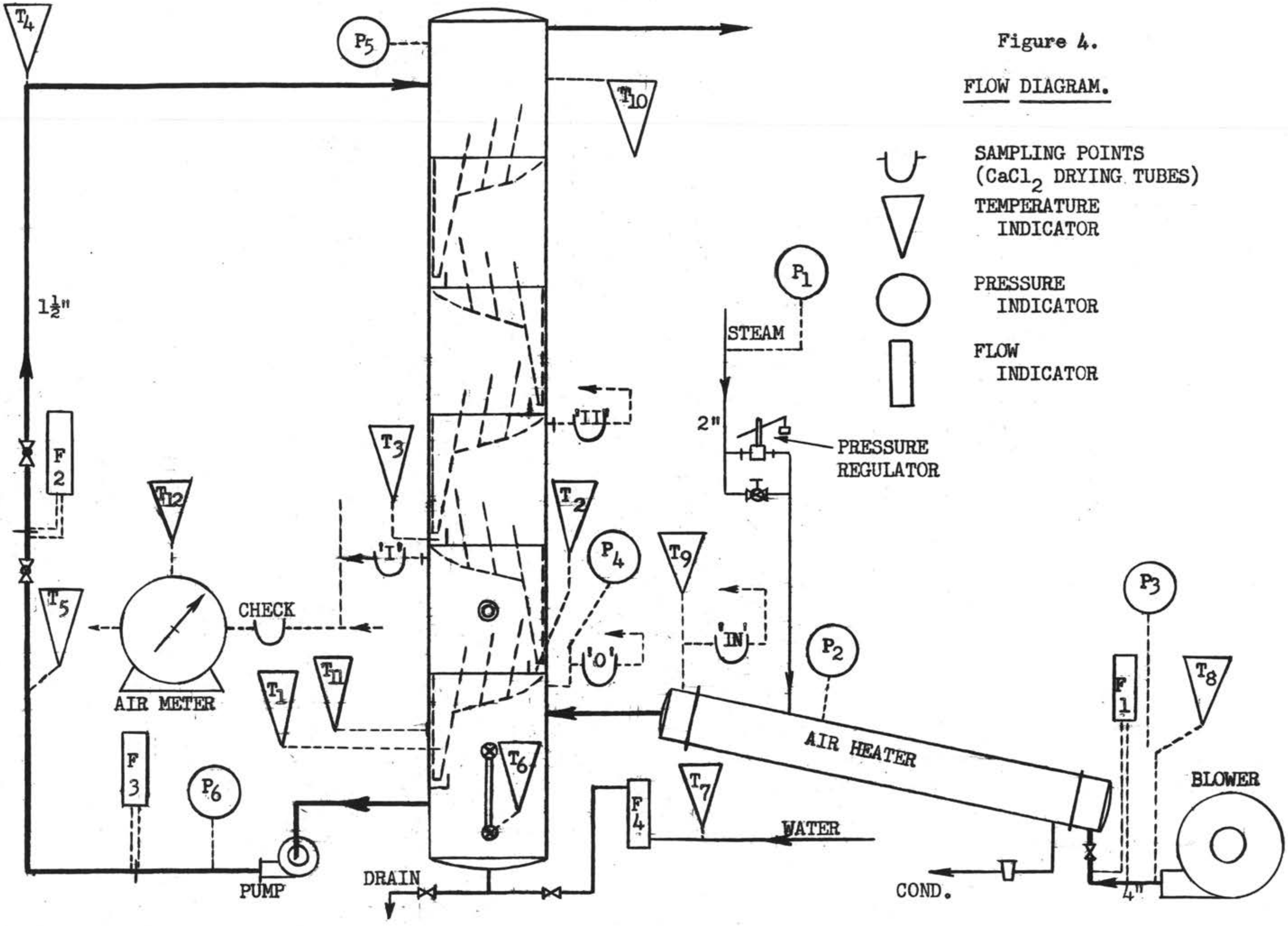


Figure 4.

FLOW DIAGRAM.

PROCEDURE

Air and Water

The air was blown in through the air heater into the tower at different temperatures and the water drawn off at the bottom and recirculated into the top of the tower. A constant water amount was kept in the system by the addition of small quantities of fresh water into the bottom of the tower. The total water charge was approximately twenty gallons, but varied slightly with runs of different water loading in order to keep a constant water level in the bottom of the tower throughout all runs.

The experimental working range was limited by the blower and pump capacities, which were reduced by pressure drops through the equipment and piping and thus reached maximum values of 210 cubic feet per minute of air at 32° F and 14.7 psia and 10.4 gallons per minute of water.

The Runs

Much care was taken to obtain true steady state conditions. This involved constant entering air temperature, constant circulating water temperature and constant water level in the tower bottom, as obtained by regulating the make-up water supply. According to the type of run performed, it took twenty minutes to over an hour to set up steady heat transfer gradients due to the relatively large heat capacity of the equipment as compared with air.

A large number of preliminary runs were carried out in order to study the nature of the system and equipment with regard to air and water loadings, sample-taking and the effect of heat losses.

A series of twelve runs at different elevated air temperatures up to 320° F were performed with the tower completely dry in order to study pressure drops due to air only, heat losses and lagging efficiency.

A few runs were made in order to estimate the effective liquid depth on the trays at different water loadings and maximum air rate. Use was made of the change of the water level in the tower bottom with change of liquid hold-up on the trays. The water level observed at zero water flow indicated zero effective liquid depth on the trays and the extent of level lowering due to hold-up at various water rates served for the estimation of the corresponding liquid depths.

Twelve final runs were performed at four inlet air temperatures, at maximum blower capacity and three different water rates. These runs were designated as follows: The run number contains two figures. The first figure indicates the incoming air temperature; thus "4-" runs were conducted at approximately 327° F, "5-" at 211° F, "6-" at 272° F and "7-" at 172° F. The second figure indicates the water loading used, as follows: "-1" for 10.2 G.P.M., "-2" for 6 G.P.M. and "-3" for 2 G.P.M. For example, run 6-2 was carried out with air heated to 272° F and a water rate of 6 gallons per minute.

Data Taking and Sampling

Air samples were drawn at four points:

1. Tower "IN", a point located in the upper head of the air heater for measurement of atmospheric air humidities.

2. Tower "Zero", a point below the first tray, giving the humidity of the air just before it enters the first tray. This is higher than the tower "IN" humidity because of humidification in the space between the tower water level and the first tray.

3. First tray point, just below the second tray.

4. Second tray point, just below the third tray. (See Flow Diagram, Figure 4).

The air sample was drawn through a short piece of bent glass tubing stuck through well-insulated half-inch fittings, which were in turn reduced to fit ¼ inch drilled and tapped holes in the tower. Entrainment was reduced by using the bent glass tubing. The air was then passed through two calcium chloride drying tubes in series and then through a wet test meter. The second drying tube served as a check tube and took up about 1.0 to 3.5% of the amount of water absorbed by the first tube. Since only one air test meter was available the samples had to be taken in succession after steady state was obtained. About two hours were required for sampling.

Pressure, temperature and flow data were taken shortly after sampling started and checked several times throughout the run. The fluctuations, if any, were negligible.

Water temperatures were taken at six points throughout the system. Because of heat losses and some heat transfer between the water and air without corresponding humidification (i.e., along downcomers), slightly different water temperatures existed at various points under steady state conditions.

For observations made during the development of the sampling method, see Appendix C.

HEAT LOSSES

The effect of heat losses on the system is very pronounced owing to the low heat capacity of air. This may be illustrated by considering that the negligible heat loss of 2000 Btu/hr through the rather large equipment surface would produce a temperature drop of about 10° F in the air flowing up the tower.

Thus, it was advisable to improve the insulation of the entire equipment. The tower originally had a layer of 1" Johns-Manville Asbestocel Insulation on all sections, leaving all the flanges bare. Another 1" layer was added to the lower half of the tower up to the third tray and all flanges were heavily insulated with an asbestos steam pipe insulation cement. Furthermore, all air and water piping, the tower look glasses, and the water circulation pump were covered with $1\frac{1}{2}$ to 2 inch layers of insulation.

A study of heat losses was made for the lower portion of the tower, comprising the section below and the section above the first tray, since it is in this part of the tower that the highest temperature gradients with respect to the atmosphere are encountered. This study was performed by a series of twelve "dry" runs at different air temperatures. Temperature readings were taken at about 15 points. These included inside air, wall, lagging and outside air temperatures (see sketch, Fig. 5). The average lagging efficiency was found as 0.878 ± 0.02, (see Appendix E for formula).

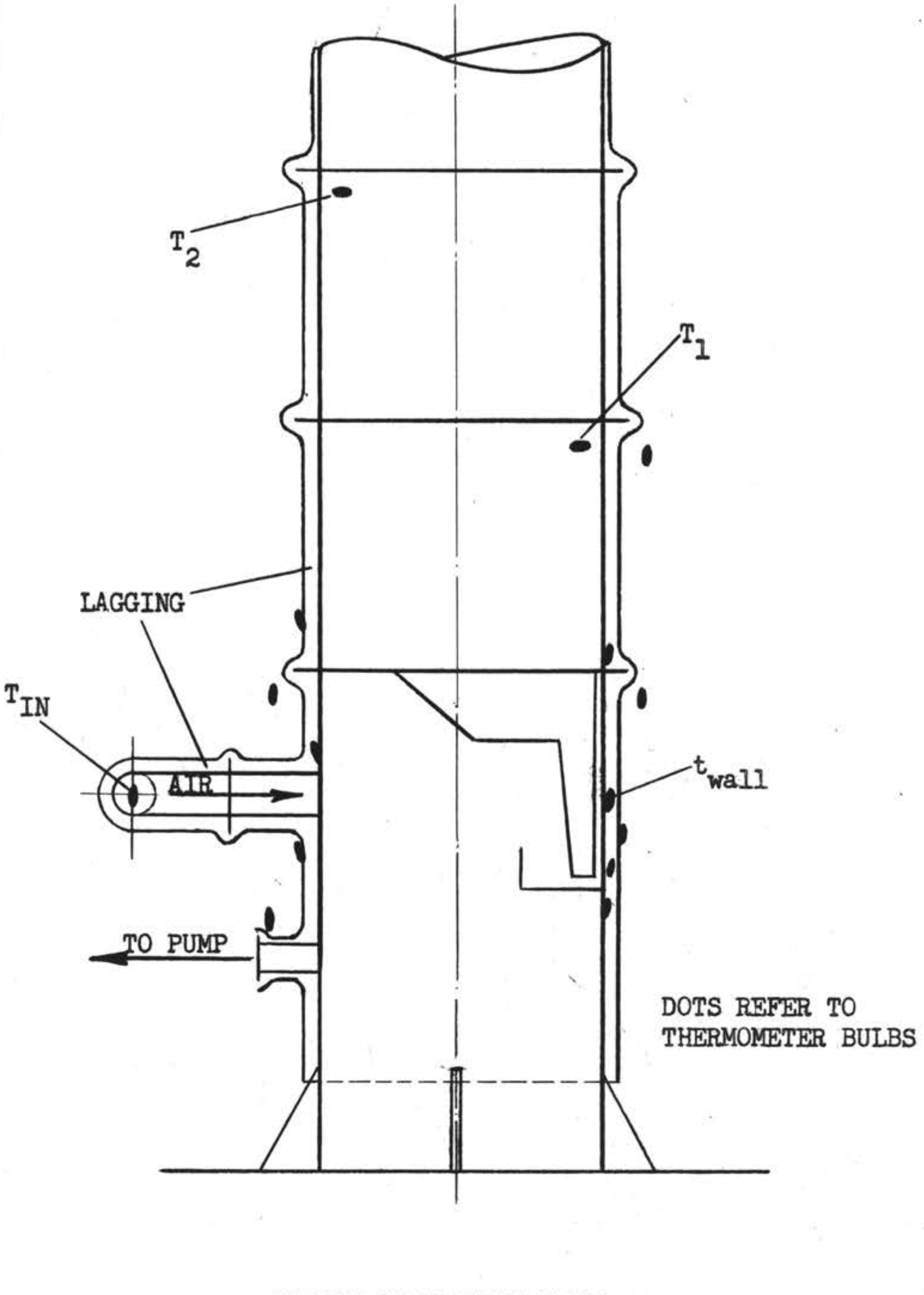
An overall heat transfer coefficient was evaluated for the transfer area between the "AIR IN" point on the top of the air heater and the first tray air point just below the second tray. This coefficient had a value of 9 to 12 Btu/(hr)(°F) for a respective "AIR IN" temperature range of 110 to 350° F.

In actual operation, either with a dry tower or with water flowing, the temperature of the air within the tower below the first tray will always be somewhat lower than the inlet air temperature, T_{IN}, due to heat losses to the outside. This lowering in air temperature, due to external heat losses only, can be evaluated as follows:

The temperature drop between T_{IN} and T_1 (= ΔT), obtained from a series of "dry" runs, was plotted as a function of T_{IN} (see Figs. 5 and 6). In "wet" runs ΔT cannot be observed experimentally. T_1 is lowered to a large extent by wet bulb action and humidification in the first tray. It is known that ΔT for "wet" runs will be smaller than for "dry" runs. The heat losses in "wet" runs are smaller because the incoming air rapidly decreases in temperature due to appreciable humidification below and on the first tray and because of the screening of a large portion of the wall by the water-cooled downcomer of the first tray. The water is heated in the lowest downcomer by about 2° F, and a 1° F rise in water temperature gives an air temperature decrease of 4 to 10° F.

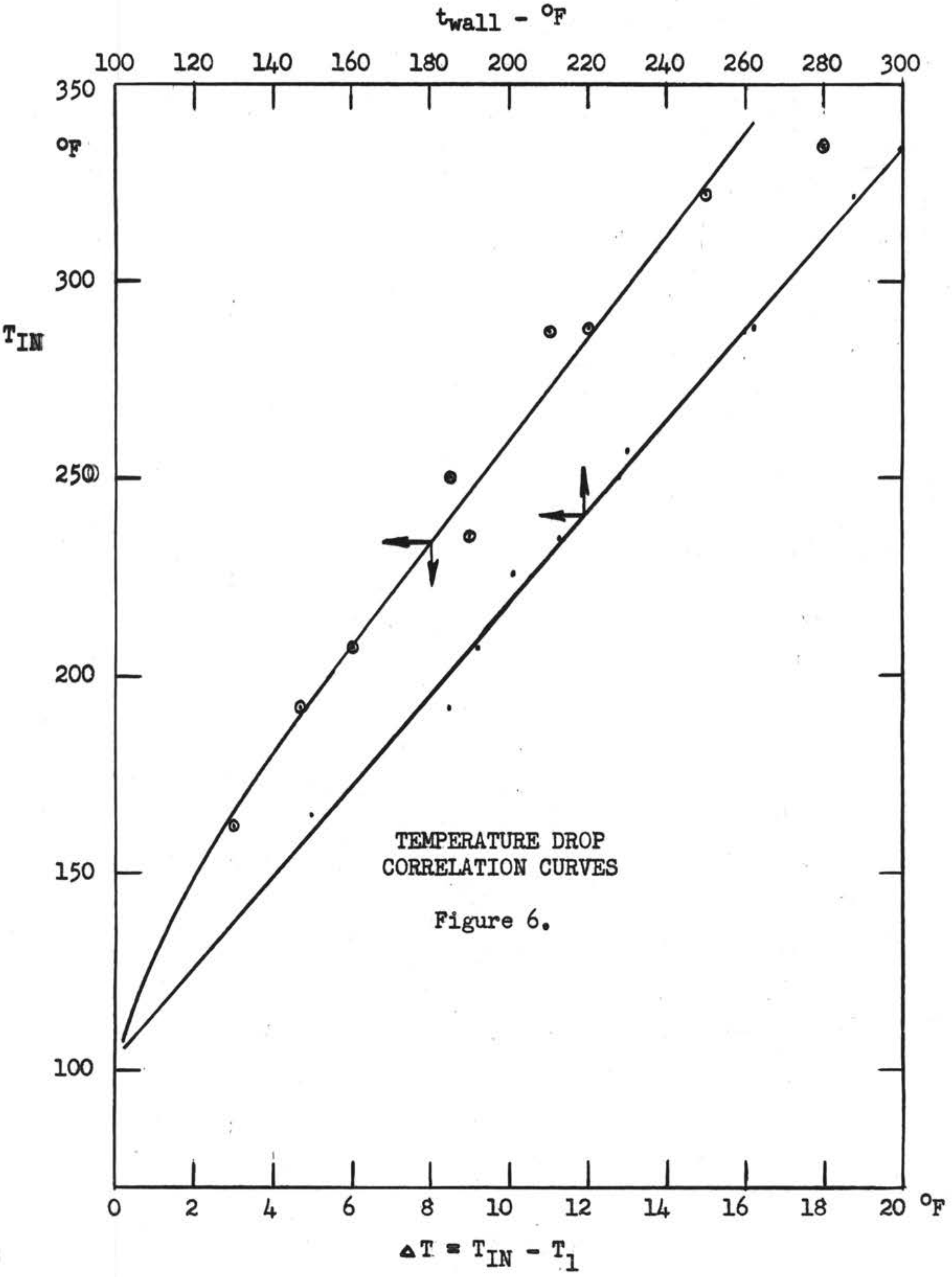
It is apparent, then, that the dry run function ΔT vs. T_{IN} does not apply to "wet" runs. It would be expected however, that a particular tower wall temperature should give a consistent indication of external heat losses for both "dry" and "wet" runs. In the case of "dry" runs, this wall temperature thermometer (see Figure 5) read 5 to 35° F below the incoming air temperature and during "wet" runs it was 50 to 170° F lower. This wall temperature, t_{wall}, was recorded during the dry runs and it is also plotted as a function of T_{IN} in Figure 6. The two curves, ΔT vs. T_{IN} and t_{wall} vs. T_{IN}, are replotted as ΔT vs. t_{wall} with the parameter T_{IN} eliminated (see Figure 7). It is assumed that his curve holds for both "dry" and "wet" runs, and that a reading of t_{wall} during a "wet" run would give a ΔT, from which T_1 can be calculated. It is further assumed that during a "wet" run, essentially all of the heat loss takes place below the first tray; then T_1 is the dry bulb temperature of the air just below the first tray. This T_1 so obtained will be further designated in this study as $T_{IN_{eff}}$.

Although the above method is only an approximate one, it is felt that the ΔT values so obtained are in error by no more than 1 °F.



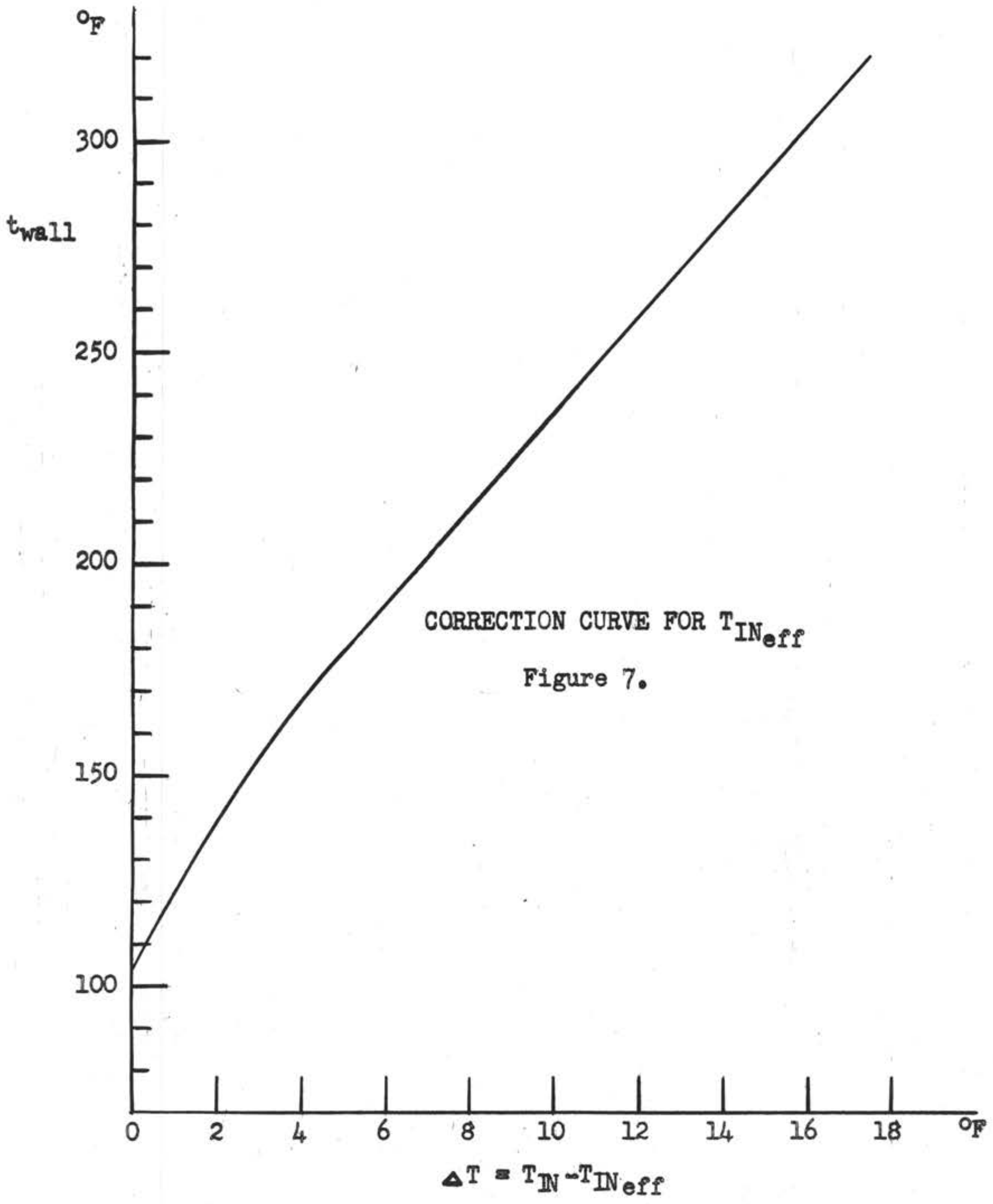
SKETCH OF LAGGING TEST

Figure 5.



TEMPERATURE DROP
CORRELATION CURVES

Figure 6.



CORRECTION CURVE FOR $T_{IN_{eff}}$

Figure 7.

RESULTS

The calibration data for the flow meters are presented in Figs. 9, 10, and 11, and further details on calibration of the instruments used can be found in Appendix B.

The pronounced effect of heat losses from the tower to the outside air was realized and a relation for the correction of the incoming air temperature to that of the unhumidified air below the first tray was found (see preceding section on heat losses). The effective air "IN" temperatures, so obtained, are given in column 4, of Table I.

Before the gravimetric method of humidity determination was adopted, much work was done to study the possible use of wet and dry bulb thermometers. It was found that this instrument did not give consistent and reliable indications of humidity under the prevailing conditions. This is described in detail in Appendix C.

Data were obtained and efficiencies calculated for both the first and second trays, but most of the conclusions are based upon first tray data only, as the second tray data are subject to considerable error (the amount of humidification on this tray was small and a small difference between large numbers is involved). The average efficiency for the first tray, covering thirteen runs over the whole range of operational variables, is 0.728 ± 0.016, the measure of precision being the average deviation of the mean. The average deviation of a single measurement was 0.056. The average efficiency of the second tray was found as 0.750.

Murphree plate vapor efficiencies, air and water loadings and temperatures, and vapor film heat and mass transfer coefficients are summarized in Tables III, and IV. Figures 12 and 13 show the effect of air and water loading on the first tray efficiency, as plotted from Table III. The average efficiency, $(E_{MV_1})_{av}$, as plotted in Figure 13 is the average of the Murphree vapor plate efficiency values obtained for the same water loading, L^o, at different T_{IN} values; for example: The $(E_{MV_1})_{av}$ for runs 4-2, 5-2, 6-2 and 7-2, all involving water rates of $L^o = 6.0$ GPM, is 0.750. For the definition of the various efficiencies given in Table III, see Appendix E.

Figure 14 presents the pressure drop per tray as a function of water loading. This was found to be expressible as follows: $\Delta p = 0.48L^{0.18}$, where Δp is in inches of water and L is the water loading in lbs/(hr)(ft^2). A range of L of 100 to 600 was covered. No effect of air loading was found because of the rather narrow range of air loadings investigated.

The following data were obtained for the effective liquid depths on the trays.

L^o	Tower Water Level	Level lowering	z
GPM	cm	cm	in.
0	75.0		
2	72.9	2.1	0.42
6	69.7	5.3	1.07
10.3	67.7	7.3	1.47

These z values were calculated using the following dimensional data: a 1 cm level difference $\equiv$ 56.4 cu. in., and the crossectional area of the hold-up space on the troughs equals 56 sq.in./tray. The tray and tower dimensions were taken from available drawings (6).

Table II summarizes the humidities and mol fractions obtained in fourteen runs. For the evaluation of humidities, use was made of tables and charts in standard references (8,9).

DISCUSSION

Evaluation of the data shows that although steady state conditions certainly prevailed during all runs, the water temperature varied slightly from tray to tray and was higher than the wet bulb temperature corresponding to the effective incoming air temperature, $T_{IN_{eff}}$. This deviation from adiabatic steady state conditions is of small magnitude and the efficiencies obtained may be somewhat smaller than for absolutely adiabatic humidification. Although slightly higher humidities were obtained for the air leaving the first and second tray, this excessive humidification effect is over-compensated by using a higher saturation humidity corresponding to the water temperature, t_w[1], and not to the wet bulb temperature, $t_{s_{eff}}$. Column 7 of Table I shows the deviation of the steady state first tray water temperature from that related to $T_{IN_{eff}}$ and H_{IN}.

The maximum estimated errors involved in the evaluation of efficiencies were ± 0.12 to ± 0.22 for the first tray and much greater for the second tray. Actually the E_{MV_2} values show high scattering, but it is significant that the average value of E_{MV_2} checks quite closely with the average value of E_{MV_1}.

The efficiency, pressure drop and heat transfer coefficient all increase with increasing water rate. This seems to be due primarily to the larger effective liquid depths built up on the troughs by higher water loadings.

Although the range of air rates used was too narrow to draw conclusions on the effect of this variable upon the performance, it seems that the KOCH KASKADE can work at appreciably higher air loadings before the pressure drop will show an excessive increase.

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[1] The t_w value employed is the average of t_{w1} and t_{w_2}.

Although the runs reported here were performed on a commercial size unit ($13\frac{1}{2}$" in diameter), the results compare quite well with the literature data available for a small laboratory bubble cap column (2) and a commercial coke tower (1). Table V was compiled from the results of T. F. Walter and T. K. Sherwood (2) and summarizes their data on a laboratory one tray, two inch column containing a segment of one slotted two-inch bubble cap. The effective liquid depth on the tray was taken as the distance from the middle of the slots to the top of the tray overflow weir and was kept at $z = 1$ inch. The water temperature was so adjusted that the water leaving the tray was at the wet bulb temperature of the incoming air. The following comparisons may be made (see Tables III, IV and V):

1. The higher efficiencies obtained on a one-plate, two inch column are not indicative of those for a commercial size bubble tray tower. Although they are about 10% higher than those for the comparable runs 4-2, 5-2, 6-2 and 7-2 ($z = 1.07$ in.) of the present study, they might be lower in a fourteen inch bubble cap plate column, as actually found in distillation and absorption (3). Furthermore, the runs of Walter and Sherwood were performed at much higher water rates, and extrapolation of Figure 13 indicates that if these water rates had been employed in the present investigation, appreciably higher efficiencies might have been obtained.

2. Gas film mass transfer coefficients in the present and previous studies (2) show the same values of $K_g''a$ of about 2.5 for runs with $z = 1.07$ inches water depth. The change of active surface with water depth is far from being a linear function and therefore the use by the above authors (2) of a coefficient divided by z is not apt to yield constant values independent of water rate (see Column 9, Table IV). These authors did not observe any effect of liquid rate because in the comparably high range of rates used, the water depth did not increase with

rate and no change in active surface was involved. This further explains why their efficiencies were not subject to water loading changes. Column 9, Table IV summarizes $K''_g a$ values for comparison with Column 6, Table V. $K''_g a$, as defined by the above authors (2), is a mass transfer coefficient per unit liquid depth. For studying the effect of L, it is advantageous to use a coefficient which does not involve z. Therefore, a coefficient $zK''_g a$ is given in Column 10, Table IV. Although at non-adiabatic conditions in the liquid phase, the water temperature gradient involves an appreciable water film heat transfer coefficient, obviously no effect on mass transfer through the one-component liquid can be present under any conditions, and the increase in $zK''_g a$ with water rate or water tray depth can be explained only by the production of more active surface, a, due to splashing and higher entrainment in the air leaving the troughs.

When the data presented by W. G. Whitman and J. L. Keats (1) and used by T. K. Sherwood (7) are compared with those of the present study, the values of h'a as a function of G' are in fair conformity with the results given in Column 6, Table IV. A one foot diameter tower packed with three inch gas coke was used, and the h'a values of 4.2 to 9.1 were found for G' = 7.1 to G' = 18.7 at a constant water rate of L' = 20. It is pointed out (1) that heat transfer is independent of water rate as there is no heat transfer through the water film and increase in active surface with increased liquid rate is negligible in a packed tower. This is not the case in the KASKADE Tray, where the higher the liquid loading the more splashing and entrainment is obtained above the troughs and the more area of the perforated baffle plates is employed in creating active surface. Thus, if water rates of L' = 20 had been used in this study, much higher h'a values would have been obtained, which indicates that the active surface producible in the KASKADE Tray is about as high as the allegedly high amount of surface produced by a packed tower, without involving the drawbacks of high pressure drops at moderate flow rates and maintenance disadvantages.

FUTURE WORK

The following expansion and modifications of the study carried out so far may be suggested:

1. Installation of a blower with a higher capacity in order to study the effect of air velocities of a significantly wider range.

2. Installation of a higher capacity water circulation pump. The tower pressure drops as found in this study were low, and since much higher pressure drops may still be economically employed, it might be desirable to find the maximum efficiency obtainable at higher water loadings (see Figure 13).

3. The method of making measurements may be improved by using three wet test meters or calibrated aspirator bottles simultaneously for air humidity determinations and narrow-range calibrated thermometers with 0.1 °F graduations for tray water temperatures. Furthermore, the water sampling lines should be replaced by thermocouples reading the actual water temperature as it leaves each tray inside the tower.

4. Investigation of air humidification efficiencies and air film transfer coefficients for carefully adjusted adiabatic conditions. This could probably be done by mixing the circulated water with cold tap water and bleeding part of the water from the system so as to regulate the water temperature to the exact value of the wet bulb temperature of the incoming air.

5. Investigation of the efficiencies and water film heat transfer coefficients for non-adiabatic conditions. This can be performed by passing cold or hot water into the top of the tower without circulation, thus setting up a temperature gradient across the water film.

6. Humidification of air with vapor other than water vapor, i. e., a low boiling hydrocarbon.

SUMMARY

The performance characteristics of the KOCH KASKADE Tray have been investigated for the humidification of air.

The average Murphree vapor plate efficiency was found to be 0.73 ± 0.015 varying from 0.65 to 0.80 for corresponding liquid rates of 2 to 10 gallons per sq. ft. per min. In the same range, pressure drops across a single tray were 1.0 to 1.5 inches of water. Thus, the design of the KOCH KASKADE Tray permits high vapor and liquid loadings at moderate pressure drops and produces large contact areas.

The equipment as set up did not allow for higher loadings than those reported. The optimum conditions with regard to efficiency and pressure drop could not be reached with the existing auxiliaries. Extrapolation of the data obtained indicates that appreciably higher efficiencies without unreasonably high pressure drops could be obtained at higher liquid rates and much higher air throughputs.

NOMENCLATURE

a - active surface, sq. ft./cu.ft.

A - interfacial area, sq. ft.

A_{sl} - total slot area per tray, sq. in.; $A_{sl} = 21$ sq. in.

C - heat capacity, Btu/(lb)(°F)

E_{MV} - Murphree plate vapor efficiency

G^{o} - air rate, cu. ft./min. at 32 °F and 14.7 psia.

G - air rate, lbs/(hr)(sq.ft.)

G' - air rate, lbs/(min)(sq.ft.)

ha - gas film heat transfer coefficient, Btu/(cu.ft.)(°F)(hr)

$h'a$ - gas film heat transfer coefficient, Btu/(cu.ft.)(°F)(min)

H - absolute humidity, lbs. water/lb. bone dry air

Kga - gas film mass transfer coefficient, lbs./(cu.ft)(hr)(atm)

$K'_{g}a$ - gas film mass transfer coefficient, lbs/(cu.ft.)(hr)(unit humidity difference)

$K''_{g}a$ - gas film mass transfer coefficient, lb moles/(hr)(atm)(sq.in. slot area)(in. water depth)

L^{o} - water rate, gallons/min.

L - water rate, lbs/(hr)(sq.ft.)

L' - water rate, lbs/(min)(sq.ft.)

M - molecular weight, lbs/lb.mol

p - partial pressure, atm.

P - total pressure atm.

q - heat lost, Btu/hr.

s - humid heat, Btu/(lb dry air)(°F)

$\bar{s}$ - average humid heat, Btu/(lb dry air)(°F)

t - water temperature, °F

T - air temperature, °F

u_{sl} - slot velocity, ft./sec.; (Average temperature taken as 150 °F)

UA - overall heat transfer coefficient, BTU/(hr)(°F)

V - Volume of one tray section, cu. ft.; $V = 2$ cu. ft.

w - rate of mass transfer, lbs/hr

y - mol fraction of water in wet air

z - effective tray liquid depth, in.

ΔT - temp. drop due to heat losses between points "IN" and "1", °F

Subscripts

0 - at zero point, below first tray

1 - at first tray

2 - at second tray

g - bulk of air stream

I - incoming

IN - at "AIR IN" point

L - leaving

lm - logarithmic mean

R - room

S - saturation

w - water

Note: The majority of the above symbols are further defined in Appendix E.

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APPENDIX A.

AUXILIARY EQUIPMENT SPECIFICATIONS

1. Blower:

   Buffalo Forge Type 3RE, Wheel size 21½", direct motor driven at 3450 RPM, 3 phase 2HP induction motor.

   Blower capacity 450 cu. ft. of free air per minute at 31 in. water head and up to 650 CFM at 25 in. WH (see Figure 8).

   Considering the pressure drop due to friction losses in the air heater and fittings a maximum available capacity of 225 CFM was predicted for the blower as installed[2].

2. Air Heater:

   Shell and tube heat exchanger; shell 6-5/8" i.d., 7" o.d.; 28 tubes 19.0 ft. long with 0.50" i.d. and 0.84" o.d., outlets 3" flanged. Installed at an angle of approximately 15° with the horizontal.

3. Water Circulating Pump:

   Deming size 2½ x 2", Fig. 4012 Type 2A, pump capacity 100 GPM at 60 ft. head, 160 GPM at 50 ft. head and 200 GPM at 40 ft., with a bhp of 4.3 HP, 3 phase 7½ HP induction motor.

4. Wet Test Meter (air flow):

   'Precision' (Precision Scientific Co., Chicago)

   0.001 cu. ft. graduations.

5. Thermometers:

   T_5; T_7 : Taylor Binoc Industrial Glass Stem thermometer reading in 2° F graduations.

   T_4 : Tagliabue Dial thermometer reading in 2° F. graduations.

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[2] The pressure drop corresponding to 225 CFM, as calculated, was 31 in. WH which is the maximum static pressure available (see Figure 8).

T_1, T_2, T_3, T_6, T_8, T_{10} : Fisher Scientific Co. Laboratory mercury glass thermometer, 30 to 120° F, 1° F graduations. T_1, T_2 and T_3 were fitted into a piece of 7/8 in. glass tubing with a rubber stopper and the water run over the bulb outside the tower.

T_9, T_{11} : Central Scientific Co. Laboratory glass thermometer, 0 to 220° F, (20 to 400° F for "hot" runs), 2° F graduations.

T_{12} : Part of **Wet** Test Meter, 40 to 110° F; 1° F graduations.

6. Pressure Gages:

P_1 : Marshalltown ammonia gage, 0 to 300 psi. 10 psi graduations.

P_2 : Ashcroft, 0 to 160 psi. 1 psi graduations.

P_3 : U-tube static pressure manometer, 18 inch, manometer fluid-carbon tetrachloride; 0.05 inch graduations.

P_4 : Meriam standard 20" cleanout manometer, manometer fluid-carbon tetrachloride.

P_5 : Marshalltown low pressure gage. 0 to 20 ounces per sq. in., 1.o.s.i. graduations.

P_6 : Ashcroft, 0 to 60 psi., 1 psi graduations

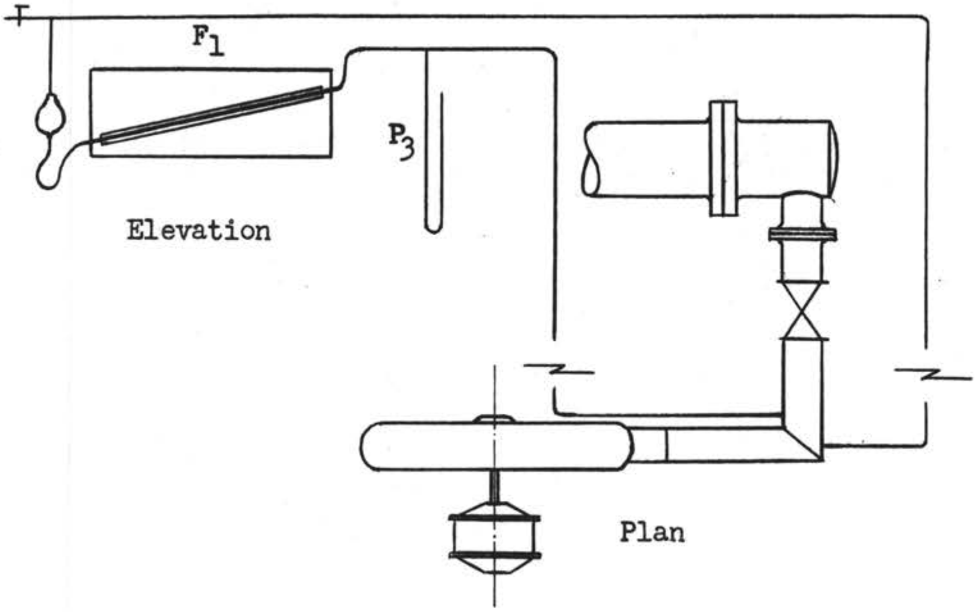
7. Flowmeters:

F_1 : Inclined manometer. Straight glass tube at an angle of 9° to horizontal; lower end connected through fluid bulb to impact pressure tap, located at center of opposite side of 4" sharp angle connected to discharge of blower. Upper end of tube connected to static pressure tap, located at inside of angle, as shown in sketch (page 31).

Manometer scale was a light oil, sp.gr. 0.8373 at 75° F;

Manometer scale graduated in 0.5 inch with subdivisions of 0.05".

F_2 : Low water rate meter; Meriam standard 20" cleanout manometer, orifice dia. 0.35 inch, modified vena contracta taps. Manometer fluid - mercury.



F_3 : High water rate meter; Meriam standard 20" cleanout manometer, orifice dia. 0.95 inch. Vena contracta taps. Manometer fluid - mercury.

F_4 : Fisher & Porter Rotameter; 0.05 to 2.45 gallons per minute; 0.05 GPM graduations.

8. Pressure regulator (steam):

Davis counter-weighted piston, type No. 2, size 2", screwed.

9. Sampling lines:

$\frac{1}{4}$" copper tube brazed onto 1/8" pipe nipples fitted with plug type brass stop-cocks for water lines T_1, T_2 and T_3. No inside lines for air points, but a $\frac{1}{2}$" tee was reduced and fitted to a $\frac{1}{4}$" tapped hole in tower and air drawn through small bent glass tubing.

10. Standard calcium chloride drying tubes fitted with short connecting rubber tubing and tube clamps.

11. Analytical Balances.

APPENDIX B.

CALIBRATION DATA

1. Inclined Air Flow Rate Manometer.

Calibration was performed using a standard Venturi tube (Builder's Foundry Co., Providance, R. I.), throat dia. 1½", up and down stream diameters 3" and discharge coefficient of c = 0.98.

The Venturi manometer liquid was mercury for high capacities and red oil (sp.gr. 1.0) for low capacities.

For the calibration curve, refer to Figure 9.

2. Low and high rate water orifice meters.

The low flow meter covered the range 0 to 7.5 GPM and the high rate flow meter covered the range 3.5 to 17 GPM.

Both meters were carefully calibrated by 44 runs with a platform scale and stopwatch. For the calibration curves, see Figures 10 and 11.

3. Wet Test Meter.

The accuracy of this instrument was checked by displacement of air through the meter with water and weighing the water. The following correction factors were obtained:

Air rate, ft^3/min	0.022	0.088	0.187	0.287	0.368
Factor (multiply reading)	0.943	0.977	0.974	0.968	0.964

4. Thermometers

All thermometers were calibrated and use was made only of instruments with deviations of less than ± 0.5 °F over the entire range, which was less than the experimental error. T_1 and T_2 readings were corrected according to the calibration, as the saturation humidity changes rapidly with slight changes in temperature.

APPENDIX C.

NOTES ON HYGROMETRY

Hygrometers have not been used in this experimental study, their use being discarded after considerable effort to apply them. It seems in place to outline a few of the observations made.

A series of wet and dry bulb thermometers was assembled, using as a chamber, a 5 inch length of 7/8" diameter glass tubing open at both ends and fitted with rubber stoppers. Through the upper stopper were inserted two thermometers, one being covered with a wick immersed in a little tube filled with water. Through the lower stopper was inserted a copper tube. This was connected to the tower "Air Points" through a gas cock. A series of "dry" runs performed gave inconsistent readings. The following was found:

1. Evaporation of water from the wick was too fast, especially in hot runs and the estimation of the true wet bulb temperature was hazardous (10).

2. The amount of air passing through the ¼" test nipples in the tower was too small and the necessary minimum air velocity of 15 feet per second (10) could hardly be obtained in any physical design using two adjacent thermometers.

3. The air velocity through the tower nipple was relatively high and considerable amounts of entrained water were carried through to the instrument during "wet" runs. The air stream might thus undergo additional humidification in the short copper tubing.[3] Although some condensation might have occurred in the tests, especially in the tubes from the first and second tray, it was found that most of the water obtained was due to entrainment. A thermometer stuck into the tower through the test nipples was soon covered with rust, indicating considerable spray in the tower and therefore considerable entrainment when high velocities are employed in the sampling line.

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[3] In the method finally used the air velocities were low (2 ft. per sec.) due to the resistance in the $CaCl_2$ tubes and any possible entrainment was knocked out by using bent glass tube inlets.

APPENDIX D.

Results

TABLE I.

Heat Losses

1	2	3	4	5	6	7
Run	T_{IN}	t_{wall}	$T_{IN_{eff}}$	t_{w_1}	$t_{s_{eff}}$	$t_{w_1}-t_{s_{eff}}$
4-1	327	162	323	110.0	108.6	1.4
6-1	272.5	142	270	104.8	102.2	2.6
5-1	212	120	211	97.6	93.5	4.1
7-1	173	110	173	91.2	86.0	5.2
4-2	328	200	321	110.5	109.0	1.5
6-2	270	172	266	103.9	101.9	2.0
5-2	211	142	209	97.8	95.0	2.8
7-2	166	122	165	87.4	81.1	6.3
4-3	327.5	208	320	109.0	109.0	0.0
6-3	272	180	267	102.6	101.3	1.3
5-3	211	146	209	95.1	94.1	1.0
7-3	178.5	130	177	87.5	86.0	1.5

TABLE II.

Experimental Data

1 Run	2 H_0	3 H_1	4 H_2	5 H_w	6 y_0	7 y_1	8 y_w
3-6	0.01019	0.02258	0.02878	0.0295	0.0162	0.0350	0.0454
3-9	0.01720	0.04290	0.05345	0.0600	0.02755	0.0646	0.0880
4-1	0.01455	0.0510	0.0562	0.0590	0.0229	0.0760	0.0868
4-2	0.01470	0.0495	0.0541	0.0608	0.02313	0.0739	0.0891
4-3	0.01341	0.0436	0.0533	0.0577	0.02113	0.0656	0.0849
5-1	0.01329	0.0348	0.0367	0.0399	0.02095	0.0530	0.0605
5-2	0.01650	0.03445	0.03326	0.0401	0.0259	0.0525	0.0606
5-3	0.01260	0.0289	0.0356	0.0370	0.0199	0.0445	0.0562
6-1	0.01393	0.04263	0.0498	0.0504	0.0219	0.0642	0.0750
6-2	0.01272	0.0396	0.0453	0.0488	0.0201	0.0599	0.0728
6-3	0.01225	0.03575	0.0440	0.0466	0.01936	0.0544	0.0698
7-1	0.01073	0.0274	0.0322	0.0323	0.0170	0.0422	0.0494
7-2	0.00760	0.02321	0.02719	0.0286	0.0121	0.03605	0.0440
7-3	0.00720	0.02008	0.0274	0.0285	0.01146	0.0313	0.0439

TABLE III.

Murphree Plate Vapor Efficiencies

1	2	3	4	5	6	7	8	9	10	11	12
Run	G^o	G	L^o	L	t_{w_1}	t_{w_2}	G/L	E_{MV_1}	E_{MV_2}	E'_{MV_1}	$\bar{E}_{MV}$
3-6	193	794	3.17	158	88.6	88.6	5.02	0.641	0.881	0.644	0.800
3-9	176	725	7.1	354	110.2	110.5	2.05	0.600	0.611	0.614	0.607
4-1	171	710	10.3	514	110.0	110.0	1.382	0.820	0.650	0.831	0.751
4-2	171	702	6.0	299	110.5	110.0	2.408	0.755	0.452	0.770	0.643
4-3	178	731	2.0	99.7	109.0	109.2	7.33	0.681	0.680	0.696	0.684
5-1	184	750	10.3	514	97.6	97.7	1.46	0.807	0.422	0.822	0.652
5-2	185	754	6.0	299	97.8	98.0	2.52	0.760	0.674	0.767	0.718
5-3	194	790	2.0	99.7	95.1	95.2	7.92	0.668	0.849	0.678	0.759
6-1	170	699	10.2	508	104.9	105.1	1.375	0.787	0.974	0.796	0.873
6-2	174	715	6.0	299	103.9	104.0	2.39	0.745	0.620	0.755	0.688
6-3	183	750	2.0	99.7	102.6	102.7	7.54	0.685	0.769	0.695	0.724
7-1	186	765	10.2	508	91.2	91.5	1.505	0.773	0.980	0.778	0.945
7-2	194	794	6.0	299	87.4	87.9	2.655	0.744	0.751	0.751	0.737
7-3	200	818	1.95	99.4	87.5	87.7	8.24	0.604	0.870	0.611	0.777

TABLE IV.

Air Film Heat and Mass Transfer Coefficients

1 Run	2 G	3 G'	4 L'	5 ha	6 h'a	7 u_{sl}	8 z	9 $K''_g a$	10 $zK''_g a$
6-1	699	11.65	8.46	141.6	2.36	24.0	1.46	2.04	2.98
4-1	710	11.83	8.57	158.0	2.63	24.2	1.48	2.24	3.27
5-1	750	12.5	8.57	161.4	2.69	26.0	1.48	2.29	3.35
7-1	765	12.77	8.46	148.1	2.47	26.3	1.46	2.13	3.11
4-2	702	11.7	4.98	129.0	2.15	24.2	1.07	2.51	2.69
6-2	715	11.92	4.98	122.0	2.10	24.6	1.07	2.48	2.66
5-2	754	12.57	4.98	140.2	2.34	26.2	1.07	2.73	2.92
7-2	794	13.22	4.98	141.0	2.35	27.4	1.07	2.74	2.94
4-3	731	12.2	1.66	109.1	1.82	25.2	0.423	5.31	2.24
6-3	751	12.52	1.66	112.9	1.88	25.9	0.423	5.55	2.35
5-3	790	13.18	1.66	113.3	1.89	27.4	0.423	5.51	2.33
7-3	818	13.63	1.65	99.0	1.65	28.3	0.422	4.82	2.08

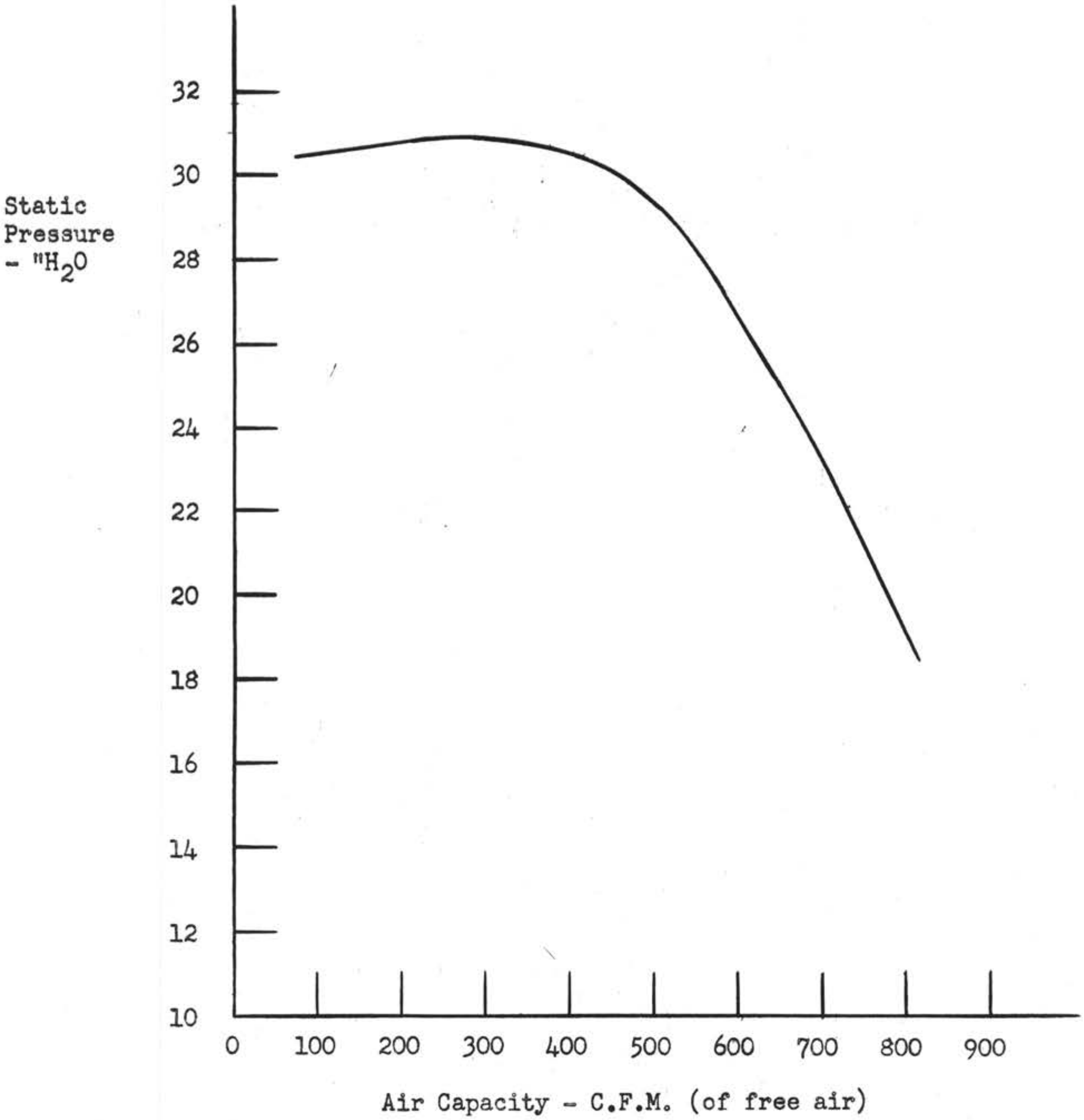
TABLE V.

Literature Data:

Adiabatic Humidification in a 2" Bubble Cap Column (2).

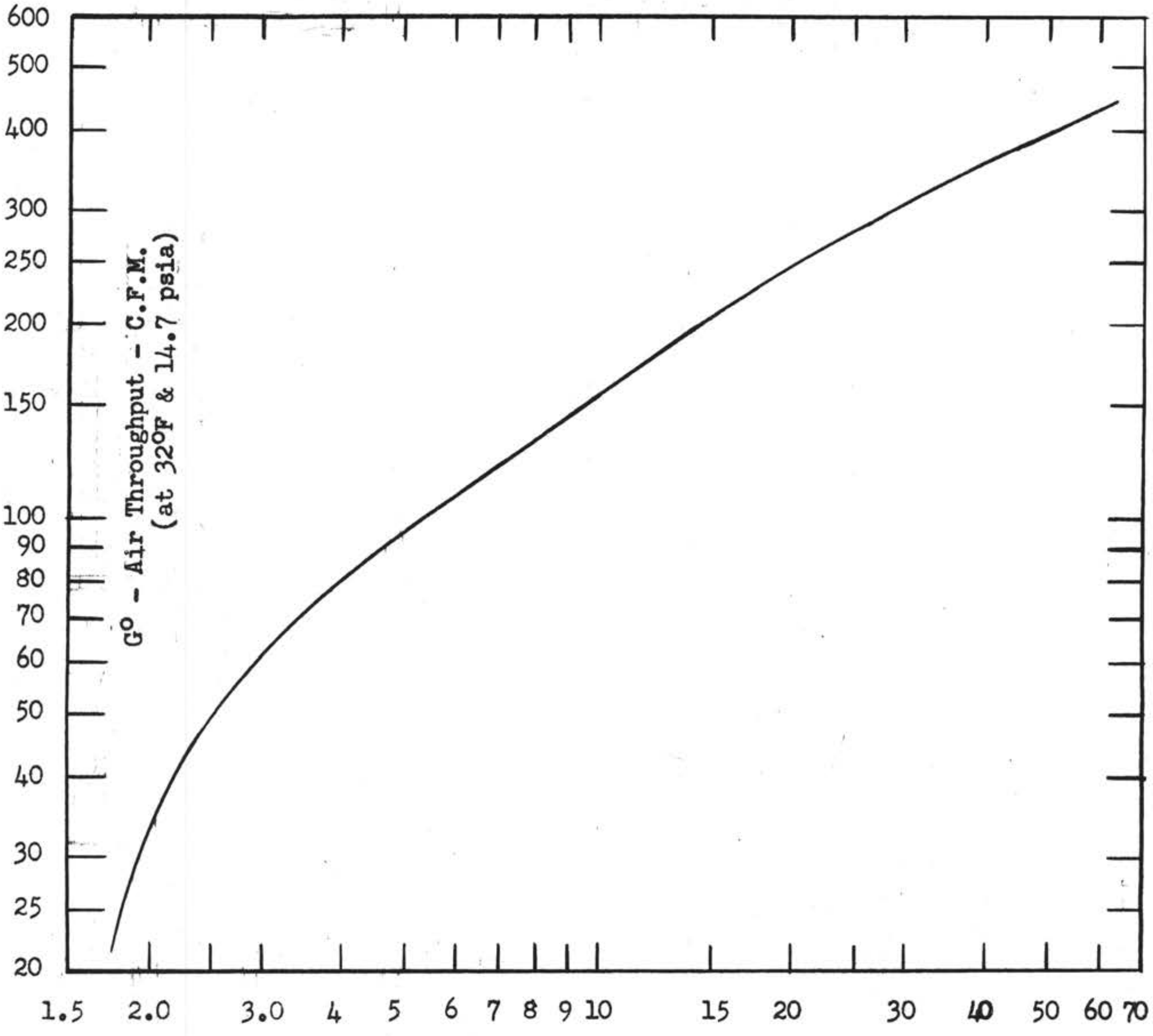
1	2	3	4	5	6
Run	u_{sl}	L'	T_{IN}	E'_{MV}	$K''_g a$ (*)
1	19.9	42.4	204	0.888	2.16
2	19.9	42.4	203	0.878	2.14
3	19.5	35.6	131.5	0.891	2.48
4	19.5	35.6	131.5	0.882	2.38
5	19.7	76.4	181	0.851	1.98
6	19.7	76.4	182	0.852	1.98
7	27.6	44.7	215	0.856	2.69
8	27.5	35.6	181	0.853	2.80

(*) $z = 1.0$ inch.



BLOWER CHARACTERISTICS

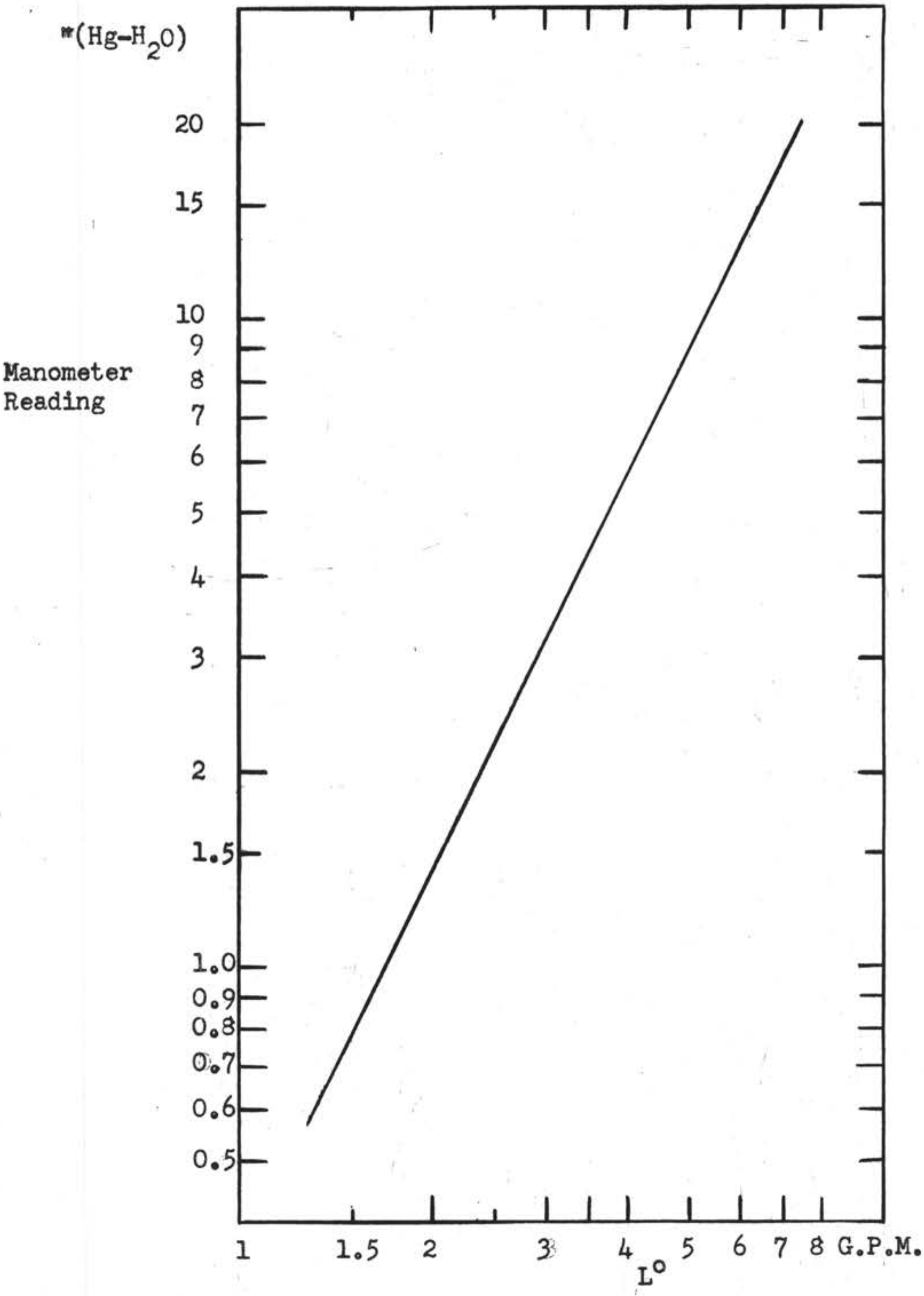
Figure 8.



Angle of Manometer Inclination: 9° with horizontal.
Zero Flow Rate Set Point at 1.4 Manometer Reading.
Sp.Gr. of Manometer Fluid: 0.8373 at 75°F.

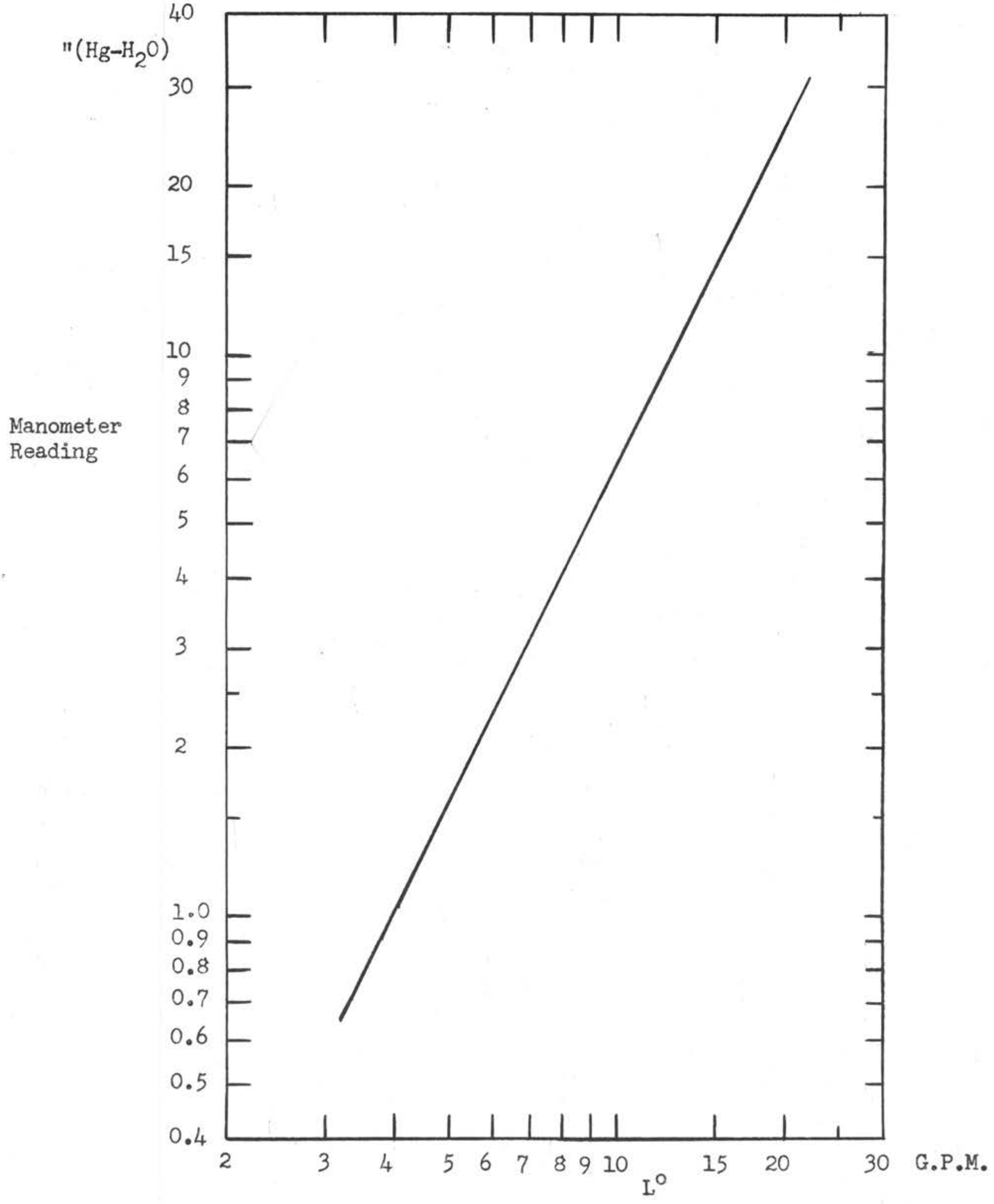
BLOWER CALIBRATION CURVE FOR AIR TAPS - F_1

Figure 9.



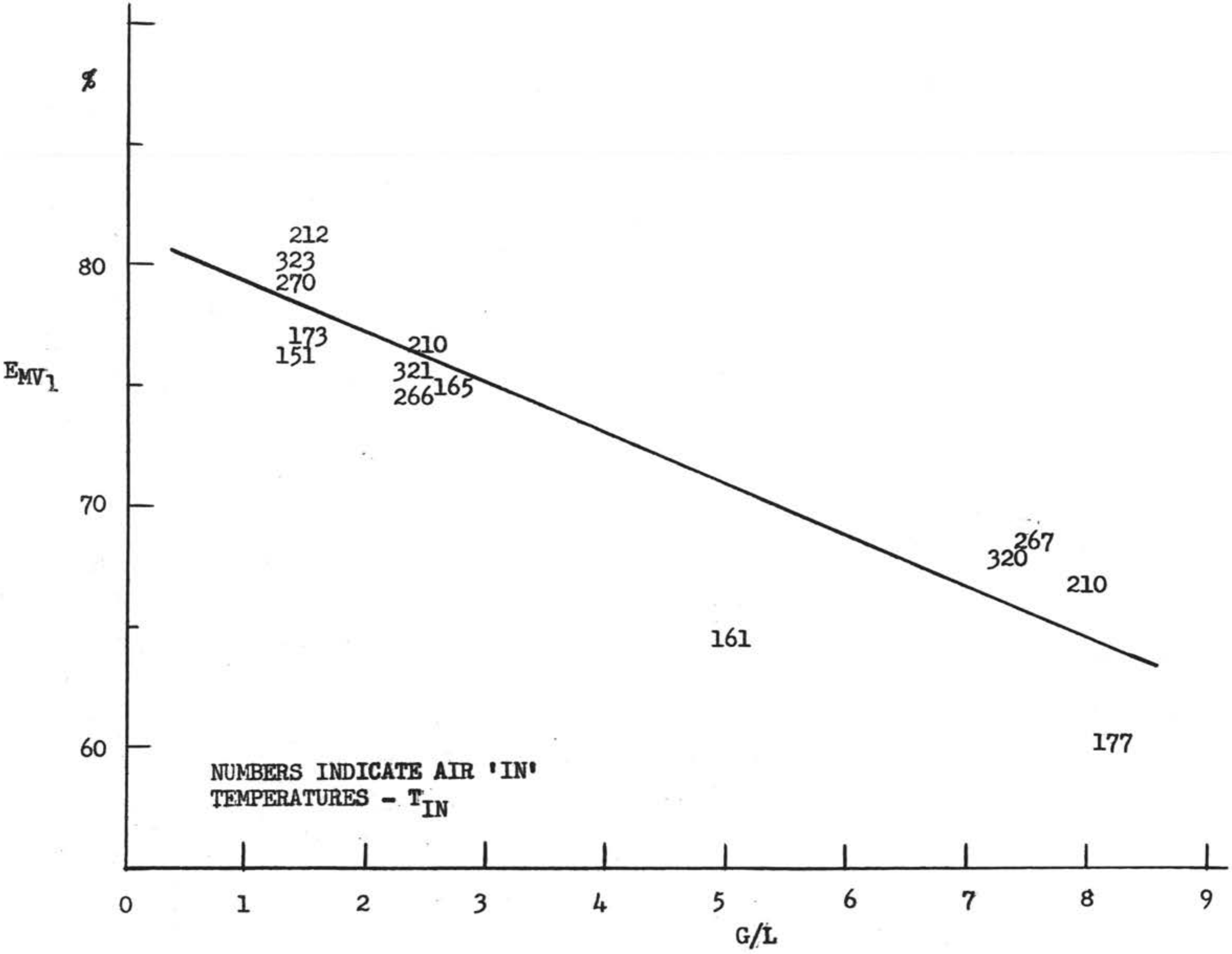
CALIBRATION PLOT OF WATER ORIFICE - F_2

Figure 10.



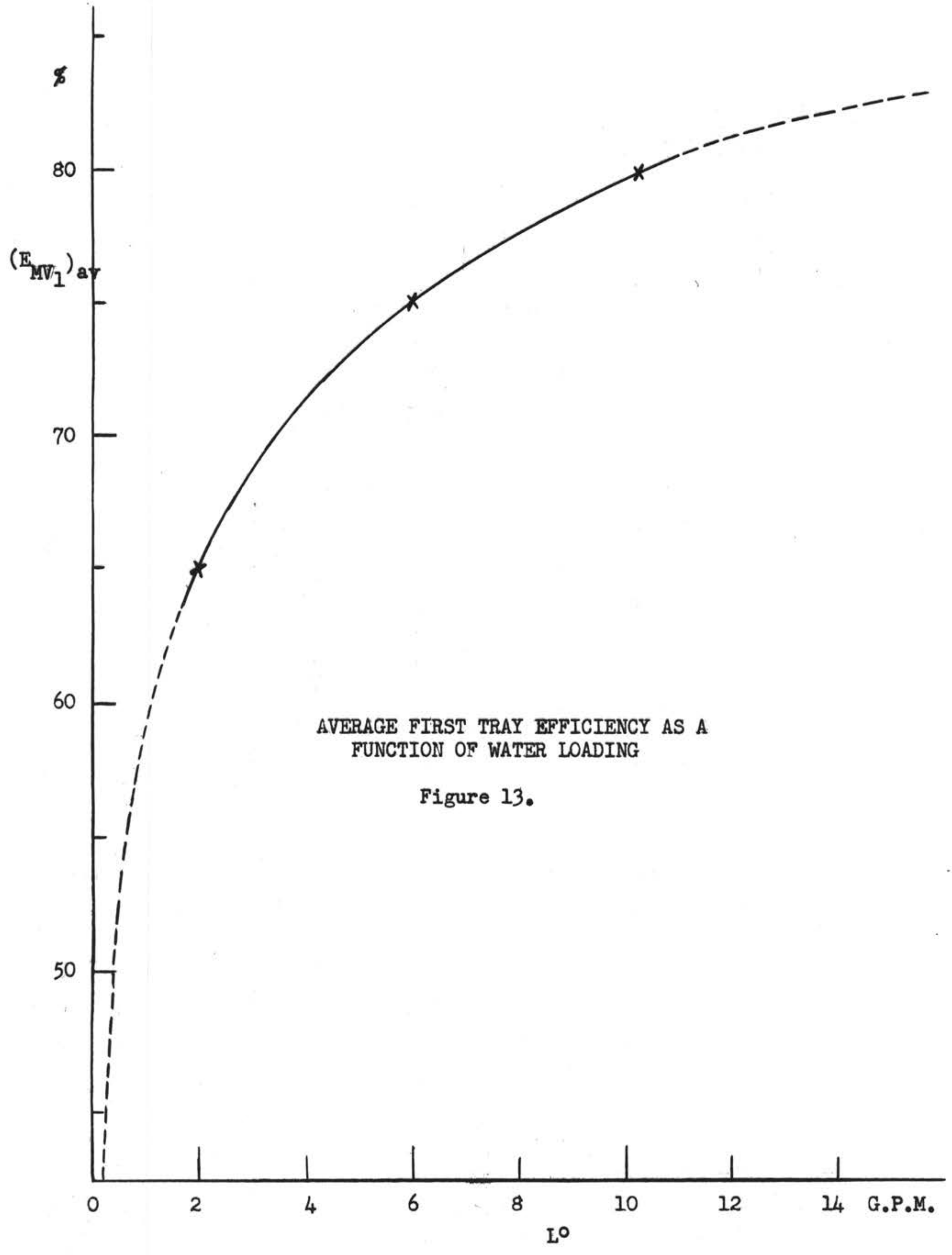
CALIBRATION PLOT OF WATER ORIFICE - F_3

Figure 11.



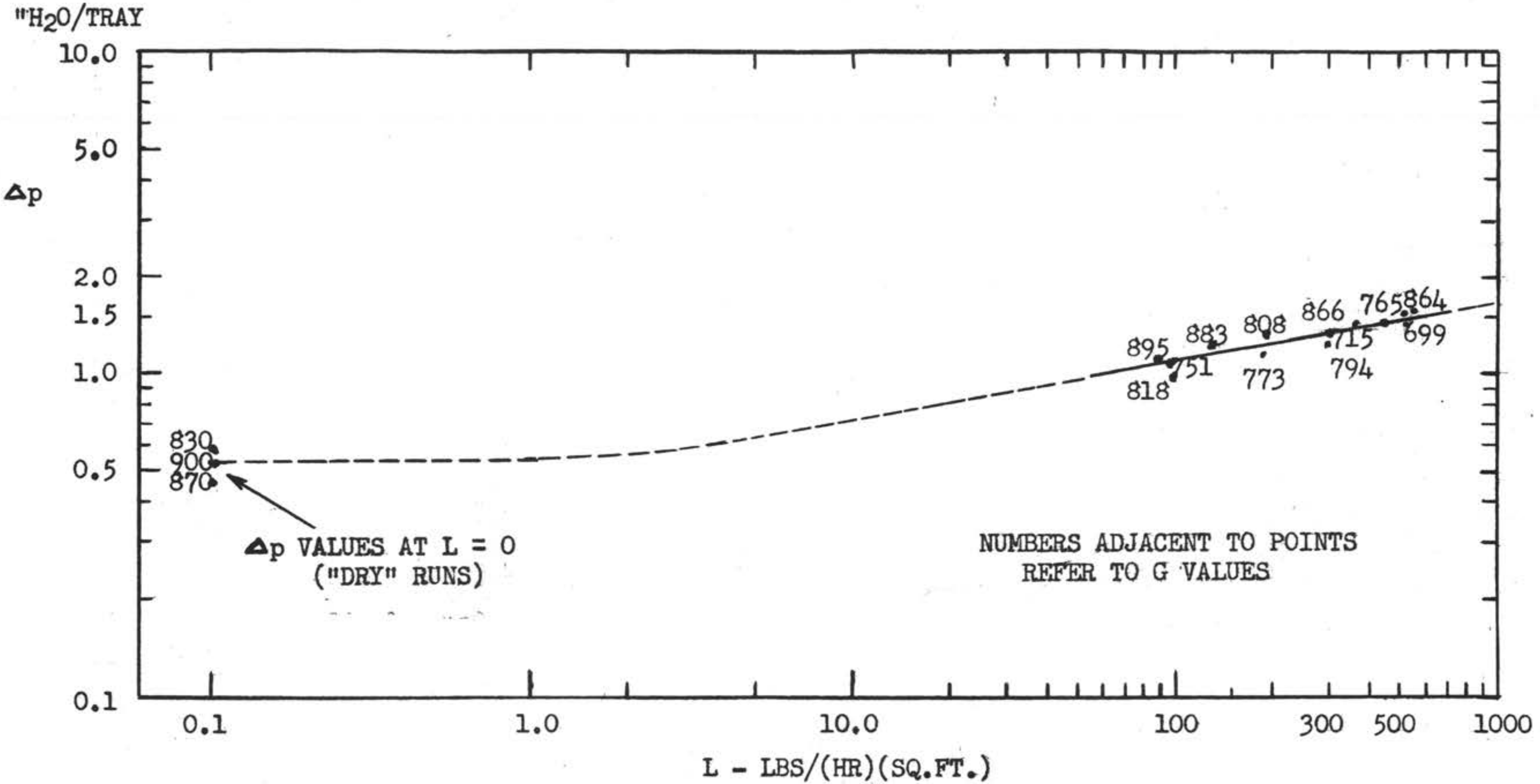
FIRST TRAY EFFICIENCY AS A FUNCTION OF AIR TO WATER LOADING RATIO

Figure 12.



AVERAGE FIRST TRAY EFFICIENCY AS A FUNCTION OF WATER LOADING

Figure 13.



TRAY PRESSURE DROP AS A FUNCTION OF WATER LOADING

Figure 14.

APPENDIX E.

Sample Calculations

1. Murphree plate vapor efficiency.

Substituted values represent run 6-2 data.

a. $$E_{MV} = \frac{H_L - H_I}{H_W - H_I}$$

$$E_{MV_1} = \frac{H_1 - H_0}{H_W - H_0} = \frac{0.03960 - 0.01272}{0.04880 - 0.01272} = 0.745$$

b. $$E'_{MV} = \frac{y_L - y_I}{y_W - y_I}$$

$$E'_{MV} = \frac{y_1 - y_0}{y_w - y_0} = \frac{0.0599 - 0.0200}{0.0728 - 0.0200} = 0.755$$

where:

$$y_L = \frac{H_L/18}{1/29 + H_L/18}; \quad y_L = y_1 = 0.0599$$

$$y_I = \frac{H_I/18}{1/29 + H_I/18}; \quad y_I = y_0 = 0.0200$$

$$y_w = \frac{H_W/18}{1/29 + H_W/18}; \quad y_W = 0.0728$$

c. $\bar{E}_{MV}$ = mean Murphree plate vapor efficiency calculated from both, first and second tray data.

The overall two-plate efficiency is $E_{MV_{1,2}} = \frac{H_2 - H_0}{H_W - H_0}$; assuming equal efficiencies for both plates, the mean single plate efficiency, $\bar{E}_{MV}$, will be:

$$E_{MV_{1,2}} = \bar{E}_{MV} + (1 - \bar{E}_{MV})\,\bar{E}_{MV} = 2\bar{E}_{MV} - \bar{E}_{MV}^{\,2}$$

Solution of this quadratic equation yields:

$$\bar{E}_{MV} = 1 - \sqrt{1 - E_{MV_{1,2}}}$$

$$E_{MV_{1,2}} = \frac{0.04530 - 0.01272}{0.04880 - 0.01272} = 0.903$$

$$\bar{E}_{MV} = 1 - \sqrt{1 - 0.903} = 0.688$$

2. <u>Maximum Error in Efficiency Evaluation</u>.

a. Errors involved in the absolute humidity calculation from the gravimetric $CaCl_2$ method data:

$$H = 2.205 \times 10^{-3}\,(M \pm 5.3\%) \times \frac{v \pm 0.7\%}{V \pm 1.0\%} = 2.205 \times 10^{-3}\,M\,\frac{v}{V} \pm 7.0\%$$

where: M - gr. water absorbed by the $CaCl_2$

v - specific volume, ft^3 wet air / lb dry air

V - ft^3 wet air passed.

b. Errors involved in saturation humidity determination:

Maximum deviations in readings of t_{w1} and t_{w2} : $\pm 0.7^\circ F$.

Corresponding deviation in H_w :

at $t_w = 87.2 \pm 0.7^\circ F$: $H_w = 0.0281 \pm 0.0007$

$t_w = 111.0 \pm 0.7^\circ F$: $H_w = 0.0611 \pm 0.0011$

Maximum error in H_w : $\pm$ 2.5%.

Tray Efficiency :

$$E_{MV} = \frac{(H_L \pm 7\%) - (H_I \pm 7\%)}{(H_w \pm 2.5\%) - (H_I \pm 7\%)}$$

For run 6-2 :

$$E_{MV} = \frac{(0.03960 \pm 0.00278) - (0.01272 \pm 0.00089)}{(0.04880 \pm 0.00122) - (0.01272 \pm 0.00089)} = \frac{0.02688 \pm 0.00367}{0.03608 \pm 0.00211}$$

$$= \frac{0.02688 \pm 13.6\%}{0.03608 \pm 5.9\%} = 0.745 \pm 19.5\% = 0.745 \pm 0.145$$

3. <u>Gas Film Overall Coefficient of Mass Transfer</u> (2, 8, 10).

a. $w = K_g A (p_w - p_g) = K'_g a V (H_w - H_g)$

$$K'_g a = \frac{w}{V (H_w - H_g)_{lm}} = \frac{G (H_L - H_I)}{V (H_w - H_g)_{lm}}$$

where: $$(H_w - H_g)_{lm} = \frac{H_L - H_I}{2.3 \log \frac{H_w - H_I}{H_w - H_L}}$$

Since $V = 2$ cu. ft.,

substitution yields :

$$K'_g a = 1.15 G \log \frac{H_W - H_I}{H_W - H_L} = 1.15 G \log \frac{1}{1 - E_{MV}} .^{4}$$

b. Mass transfer coefficient used by T. F. Walter and T. K. Sherwood (2)

$$G\, dy = K''_g a A_{sl} (p_w - p_g)\, dz = K''_g a A_{sl} P (y_w - y_g)\, dz$$

---

[4] K'_g, being the conventional form of the coefficient, is derived here although it is not used in this study. It serves for comparison with K''_g and for the later conversion into the heat transfer coefficient, h.

Integration and substitution of E'_{MV} gives:

$$K''_g a = \frac{G/M}{A_{sl}\ P\ z} \ \ln\left(\frac{1}{1 - E'_{MV}}\right)$$

A_{sl}, as computed from tray drawing (6) is 3 x 8" x 7/8" = 21 sq. in.

$M = 18.$

$$K''_g a = 0.00608 \frac{G}{z\ \ P} \ \log\left(\frac{1}{1 - E'_{MV}}\right)$$

For run 6-2, first tray values, taking P = 1 atm (see Tables II and III):

$$K''_g a = 0.00608 \frac{715}{1.07} \ \log\left(\frac{1}{1 - 0.755}\right) = 2.48$$

4. Gas Film Overall Coefficient of Heat Transfer.

$$\frac{h}{K'_g} = s = 0.238 + 0.48\ H_g \quad (8)$$

Values of the humid heat, s, were obtained from humidity charts (8, 9).

Substitution in formulas derived for K'_g yields:

$$ha = \frac{\bar{s}\ G\ (H_L - H_I)}{V\ (H_W - H_g)_{lm}} = 1.15\ \bar{s}\ G\ \log\frac{H_W - H_I}{H_W - H_L}$$

$$\text{where :} \quad \bar{s} = \frac{s_I + s_L}{2}$$

$$ha = 1.15\ \bar{s}\ G\ \log\left(\frac{1}{1 - E_{MV}}\right)$$

For run 6-2, first tray values:

$$\bar{s} = \frac{s_1 + s_2}{2} = \frac{0.2565 + 0.2437}{2} = 0.2501$$

$$ha = 1.15 \times 0.2501 \times 715 \times \log\left(\frac{1}{1 - 0.745}\right) = 122.0$$

5. Heat Losses.

Substituted values represent data for a "dry" run.

a. Lagging efficiency

$$E = \frac{t_{wall} - t_{lagging}}{t_{wall} - t_{room}} = \frac{288 - 116}{288 - 91} = 0.872$$

b. Overall heat transfer coefficient, UA, through equipment and lagging between points "AIR IN" and "1st Tray".

$$q = G\, C_{P_{AIR}}\, (t_{IN} - t_1) = 818 \times 0.237 \times (322 - 308) = 2715 \text{ Btu/hr}$$

$$q = UA\, \Delta t_m \quad \text{and} \quad UA = \frac{q}{\Delta t_m} = \frac{2715}{232.5} = 11.7 \text{ Btu/(hr) (}^{\circ}\text{F)}$$

where:

$$\Delta t_m = \frac{t_{IN} - t_1}{\ln \dfrac{t_{IN} - t_R}{t_1 - t_R}} = \frac{322 - 308}{\ln \dfrac{322 - 90}{308 - 90}} = 232.5\ ^{\circ}\text{F}$$

6. Pressure Drop per Tray.

Substituted values represent run 6-2 data.

$$\Delta P = (1.592\, P_4 - 1.73\, P_5) \div 5 = (1.592 \times 10.7 - 1.73 \times 6.0) \div 5$$
$$= 1.33 \text{ inches } H_2O$$

where: ΔP = inches of water

P_4 = bottom tower pressure in inches of CCl_4

P_5 = top tower pressure in ounces per sq. inch.

THESIS TITLE: Performance of the KOCH KASKADE
Tray in Humidification

NAME OF AUTHOR: Arie Yardeni

THESIS ADVISER: Dr. Leo Garwin

NAME OF TYPIST: Lucile Loney & Grace Peebles