August 14, 1950

To the Committee on Graduate Study:

I am submitting to you a thesis written by Jack Bernard Chrisney entitled "Mass Transfer From Granular Beds." I recommend that it be accepted for eighteen quarter hours of credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.

H. J. Garber
Major Professor

We have read this thesis
and recommend its acceptance:

Wm. T. Smith Jr.

Kenneth Boardman

Albert Avery

Accepted for the Committee

C. A. Watts
Dean of the Graduate School

# MASS TRANSFER FROM GRANULAR BEDS

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A THESIS

Submitted to
The Committee on Graduate Study
of
The University of Tennessee
in
Partial Fulfillment of the Requirements
for the degree of
Master of Science

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By

Jack Bernard Chrisney

August 1950

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## ABSTRACT

Experimental data on the mass transfer of four vapors from a packed bed of granular solids to a flowing air stream were obtained in the range of modified Reynolds numbers ranging from 300 to 2200. Three different sizes of porous right circular cylinders were used for packing. A turbulence effect, requiring a variable Schmidt number exponent for correlation of the data is postulated, and evidence for a wall effect, applicable to small beds, is presented. The limited data presented herein are combined with data of Hougen et al (7)(27)(31) to give the following equation:*

$$j'_d = \frac{k_g M_m P_f}{G_{av}} \left(\frac{\mu}{\rho D_v}\right)_f^{.36} = 1.452 \left(\frac{\sqrt{A}G}{\mu}\right)^{-.41}$$

This empirical equation fits the data for a modified Reynolds number range of 300 to 2200 and may apply at higher Reynolds numbers. The data of Wilke and Hougen (31) indicate that another equation applies at lower Reynolds numbers.


* For list of symbols and their meaning see page 38.

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# INTRODUCTION AND THEORY

In the past ten years, experimental study of mass transfer in flow systems has been advanced to a point where many of the physical variables involved in mass transfer have been identified and qualitative empirical relationships determined for many geometrical configurations. Mass transfer to gases flowing through granular beds has many applications. Data on mass transfer coefficients are of value in the design of equipment for such operations as gas absorption by solids, evaporation and drying of granular solids, drying of gases by solid desiccants, chemical reactions between gases and granular solids, and gas reactions catalyzed by granular surfaces, to name a few.

In a flowing fluid stream it is known that laminar or viscous flow occurs in the vicinity of any surface present, even with a high degree of turbulence in the main fluid stream. One point of view considers this laminar layer or "film" of relatively stagnant fluid to be the carrier for the diffusing vapor and the principal resistance to the mass transfer process. The rate of transport of a vapor, A, through a relatively stagnant gas, B, is proportional to the partial pressure gradient of the diffusing vapor $\left(\frac{-dp_A}{dx}\right)$ and inversely proportional to the number of interfering molecules of B (i.e. to the partial pressure of B). This relationship may be expressed by:

$$N_A = \frac{D_M}{P_B} \frac{\partial p_A}{\partial x} \qquad (1)$$

where

$N_A$ is the molal rate of transport of vapor A per unit time per

unit area normal to direction of transport.

$D_M$ is the molal diffusivity (lb. mole/hr.ft.),

$p_A$ is the partial pressure of diffusing gas A,

$P_B$ is the partial pressure of the stagnant gas, B.

x is the distance in the direction of diffusion.

Equation (1) is essentially the definition of $D_M$. At some distance from the surface from which mass transfer occurs, there is a turbulent core where the local gas velocity approaches the mean velocity of the gas stream. Here mass transfer occurs by eddy transport through a velocity gradient. This eddy transport and the molecular transport expressed by equation (1) take place simultaneously in a transition region between the laminar layer and the turbulent core. Since such systems are not conveniently amenable to mathematical analysis, the process is treated as one of pure molecular diffusion of vapor, A, through a hypothetical film of stagnant gas, B. This hypothetical stagnant film is defined as having a resistance to molecular transport equivalent to the total resistance offered by the real laminar layer, transition region, and the turbulent core. While this method of analysis of the problem has the virtue of keeping the analysis relatively simple, it cannot even uncover the fundamental features of the mass transfer processes that occur. Accordingly, it is emphasized that the correlations presented in this discussion are of an empirical rather than fundamental character.

For mass transfer across a gas and a solid or liquid interface, a gas film mass transfer coefficient, $k_g$, is defined by

$$N_A = k_g(p_{A_1} - p_{A_2}) \qquad (2)$$

where $(p_{A_1} - p_{A_2})$ is the partial pressure driving force at a single point. In the equation above $p_{A_1}$ and $p_{A_2}$ are the partial pressures of component A at the interface and in the main gas stream respectively.

In a packed bed where the driving force for mass transfer changes from the bottom to the top of the bed, it is here assumed that the logarithmic mean partial pressure difference will apply. Therefore, the overall mass transfer rate is given by:

$$R_c = k_g \, A \, M\Delta p_{lm} \qquad (2A)$$

where $R_c$ is the mass transfer rate for the entire bed, lbs./hr.

A is the total surface area over which mass transfer occurs.

M is the molecular weight of the diffusing vapor.

$\Delta p_{lm}$ is the logarithmic mean partial pressure difference of the diffusing vapor between the interface and the main gas stream at the terminal boundaries of the bed.

Since the hypothetical film thicknesses in any particular mass transfer flow system are generally unknown, it is customary to correlate experimental data in terms of the arbitrarily defined mass transfer coefficient. In correlating mass transfer data two types of properties are employed. The first includes such process variables as size and shape of the system, mass velocity, and partial pressures. Some of these variables are common to other operations involved in the transfer mechanism, such as heat transfer and fluid flow. Secondly, there are intensive properties of the materials used in the mass

transfer system, such as viscosity, density, and the mass diffusivity of the diffusing component through the stagnant film. Correlation of these variables through the agency of dimensionless moduli permits combination of data from one system of components with those of another composed of entirely different substances.

Colburn (5), by following Prandtl's analysis for heat transfer, developed the equation:

$$\frac{k_g P_f M_m}{G_{av}} = \frac{f}{2\left(1-r+r\ \frac{\mu}{\rho D_v}\right)} \qquad (3)$$

where $M_m$ is the mean molecular weight of the gas stream.

$G_{av}$ is the average mass velocity of the gas stream based on the total cross sectional area of the empty bed lb/hr.ft$^2$. The arithmatic average of the mass velocities just above and below the bed is used.

f is the Fanning friction factor.

r is the ratio of fluid velocity at boundary between laminar and eddy layers, to the average velocity of the main fluid stream = $\frac{V_f}{V_o}$ .

$\mu$ is the average viscosity of the gas film, lb/hr.ft.

$D_v$ is the diffusion coefficient of transferred gas through stagnant gas, ft$^2$/hr.

$\rho$ is the density of the gas film through which the diffusing vapor is transported, lb./ft$^3$.

Then with the assumption that

$$1-r+r\left(\frac{\mu}{\rho D_v}\right) = \left(\frac{\mu}{\rho D_v}\right)^{2/3} \qquad (3A)$$

a diffusional "$j_d$ number" was defined by Chilton and Colburn (4):

$$j_d = \frac{k_g P_f M_m}{G_{av}} \left(\frac{\mu}{\rho D_v}\right)^{2/3} = \frac{f}{2} \qquad (4)$$

Similarly for heat transfer

$$j_h = \frac{h}{C_p G} \left(\frac{C_p \mu}{k}\right) = \frac{f}{2} \qquad (5)$$

where $C_p$ is the constant pressure specific heat of the transferred gas Btu/lb.°F.

k is the thermal conductivity of the transferred gas Btu/hr.ft$^2$°F/ft.

h is the heat transfer coefficient between the surface and the fluid stream Btu/hr.ft$^2$°F.

These "j numbers" are functions of Reynolds number.

$$j_d = \phi \left(\frac{d\,G}{\mu}\right), \quad j_h = \phi' \left(\frac{d\,G}{\mu}\right) \qquad (5A)$$

where d is the characteristic length dimension of the system and the fundamental relationships $\phi$ and $\phi'$ depend upon the mechanical flow arrangement.

Chilton and Colburn (4) showed that $\phi$ and $\phi'$ are numerically similar in the same apparatus for turbulent flow through a circular cylinder. However, these relationships do not necessarily hold for all types of apparatus, although $j_d$ is generally approximately equal to $j_h$.

Since equation (3A) is only an approximation at best, further consideration of this equation is useful. The velocity ratio, r, probably has a low value under conditions of high turbulence. Therefore the Schmidt number is operated upon by a small exponent which fact must be considered for the proper correlation of mass transfer data. Consequently, a variable exponent on the Schmidt number may be necessary for the correlation of data taken from systems having different geometries. A review of the existing data seems to support this conjecture as discussed below.

The following discussion briefly reviews previous investigations by other authors. The Schmidt number exponent may be defined by the following equation:

$$j_d' = \frac{k_g P_f M_m}{G} \left(\frac{\mu}{\rho D_v}\right)^x \qquad (4A)$$

where x is the Schmidt number exponent.

Gamson, Thodos, and Hougen (7) and Wilke and Hougen (30) studied the rates of mass transfer of water vapor in "through circulation drying" of beds of uniformly sized granular solids. The solids used were right circular cylinders with approximately equal heights and diameters and the individual packing sizes varied from 1/8 to 3/4 inch for different beds. The results of these investigations are given in terms of mass transfer "$j_d$ numbers" against a modified Reynolds number in which the diameter term, $d_p$, is taken as the diameter of a sphere having the same surface area as the average particle in the bed. Taecker and Hougen (26) studied the effects of

bed heights and size and shape factors of the individual particles. They found for spheres and cylinders, that the $d_p$ term adequately accounts for packing size, and that the equation of Gamson, Thodos, and Hougen in the Reynolds number range investigated is valid for different bed heights. However, water was the only liquid evaporated in these three investigations, so that the choice of 2/3 for a Schmidt number exponent is open to question.

Gilliland and Sherwood (9) measured the rate of evaporation of water and eight organic liquids in a one inch wetted wall column. Rearrangement of their correlation equation shows a 0.56 exponent on the Schmidt number as a function of the mass transfer "j number". Snoeberger (24) studied the evaporation of water, nitrobenzene, and bromobenzene from single cylinders into a flowing air stream and found a Schmidt number exponent of 0.54. The data of Lohrisch (14) for the absorption of water vapor onto sodium hydroxide cylinders agree with Snoeberger's data.

Hobson and Thodos (13) investigated liquid film coefficients in a two inch diameter bed packed with 0.37 and 0.63 inch porous spheres. They recommended a quadratic function of log $j_d$ vs. log Reynolds number with a 2/3 exponent on the Schmidt number. A plot of their data (13) shows a regular deviation of isobutyl alcohol-water data from methyl ethyl ketone-water data. A 0.56 exponent on the Schmidt number would yield a straight line correlation of their data with the data of Hougen et al (7)(26)(30). However, wall effect differences may nullify the value of any single exponent.

Resnik and White (18) studied the effect of fluidizing the bed, and recommend a 0.1 exponent on the Schmidt number for these conditions. They also made a brief study of stationary granular beds and found a particle size effect, which resulted in higher mass transfer coefficients for larger particles for the same Reynolds numbers. However, their naphthalene pellets were irregularly shaped and varied in size from 14 to 35 mesh, and their choice of basic data is questionable.

The data of Mehta and Parekh (22) for the evaporation of flowing liquids from non porous packing indicate a 0.17 exponent on the diffusivity, but the degree of wetting of the packing area may have varied with the four liquids used (water, methyl alcohol, benzene, and toluene).

McAdams, Pohlenz, and St. John (16) studied heat and mass transfer from a bed similar to that of Mehta and Parekh and found end effects for both heat and mass transfer. However, they imply that not all of the packing area was available for mass transfer because near the bottom of the bed the liquid flowed to the periphery of the packing support and then down the wall to the sump.

Simkin (23), using the same apparatus as the present work, evaporated water, naphthalene, and para-dichlorobenzene into a flowing air stream in order to study the effect of diffusivity on the mass transfer coefficient. Inasmuch as Simkin's exponent of 0.38 was based on 27 points of data with two different particle sizes, and regular deviations from the fitted curve occur for each substance (1.7% for water, 2.1% for naphthalene), and -8.0% for p-dichlorobenzene, it

would be desirable to have many more points, including data for other substances.

The purpose of the present investigation is to supplement the existing data and determine a better Schmidt number exponent for gas phase transfer in granular beds, although it is to be emphasized that the best Schmidt number exponent will be determined only from a huge mass of data on many different substances and several different experimental apparatus assemblies. It must be appreciated that the correlation attempt rests upon but a semi-theoretical basis. Consequently, such methods of correlation indicate trends that are sufficiently good for design purposes. It is too much to expect all experimental points to lie on a single curve instead of a band.

## EXPERIMENTAL

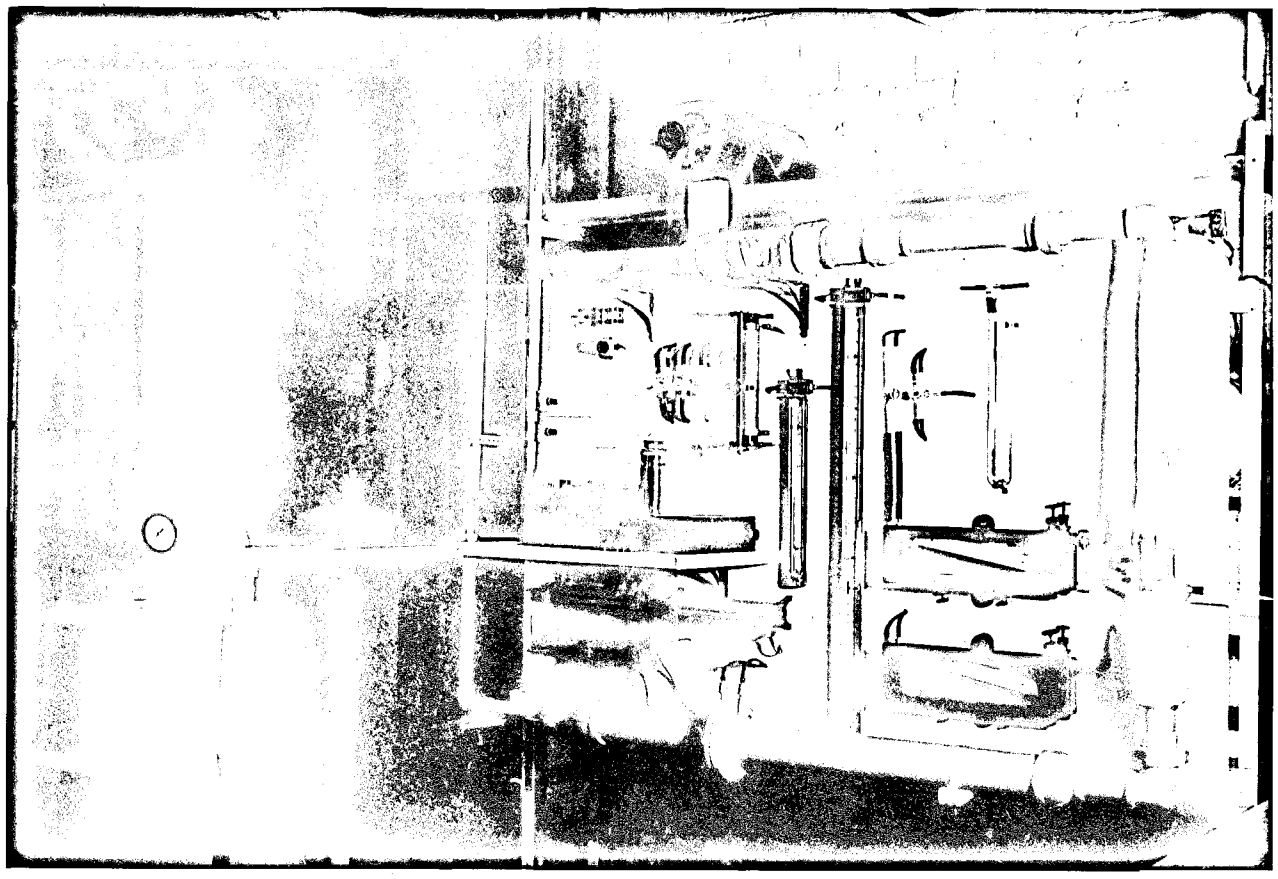
### Plan of Investigation:

Constant velocity air streams were passed through water, aniline, and nitrobenzene-wetted celite cylinder beds and molded naphthalene cylinder beds at constant temperature. The beds were weighed immediately before the run and again after a convenient time interval (3 to 20 minutes). The air stream temperatures approximated room temperatures (17°C-21°C). The air rates varied from 400 to 2000 pounds per hour per square foot of superficial cross section, to give Reynolds numbers ranging from 370 to 2250.

### Equipment:

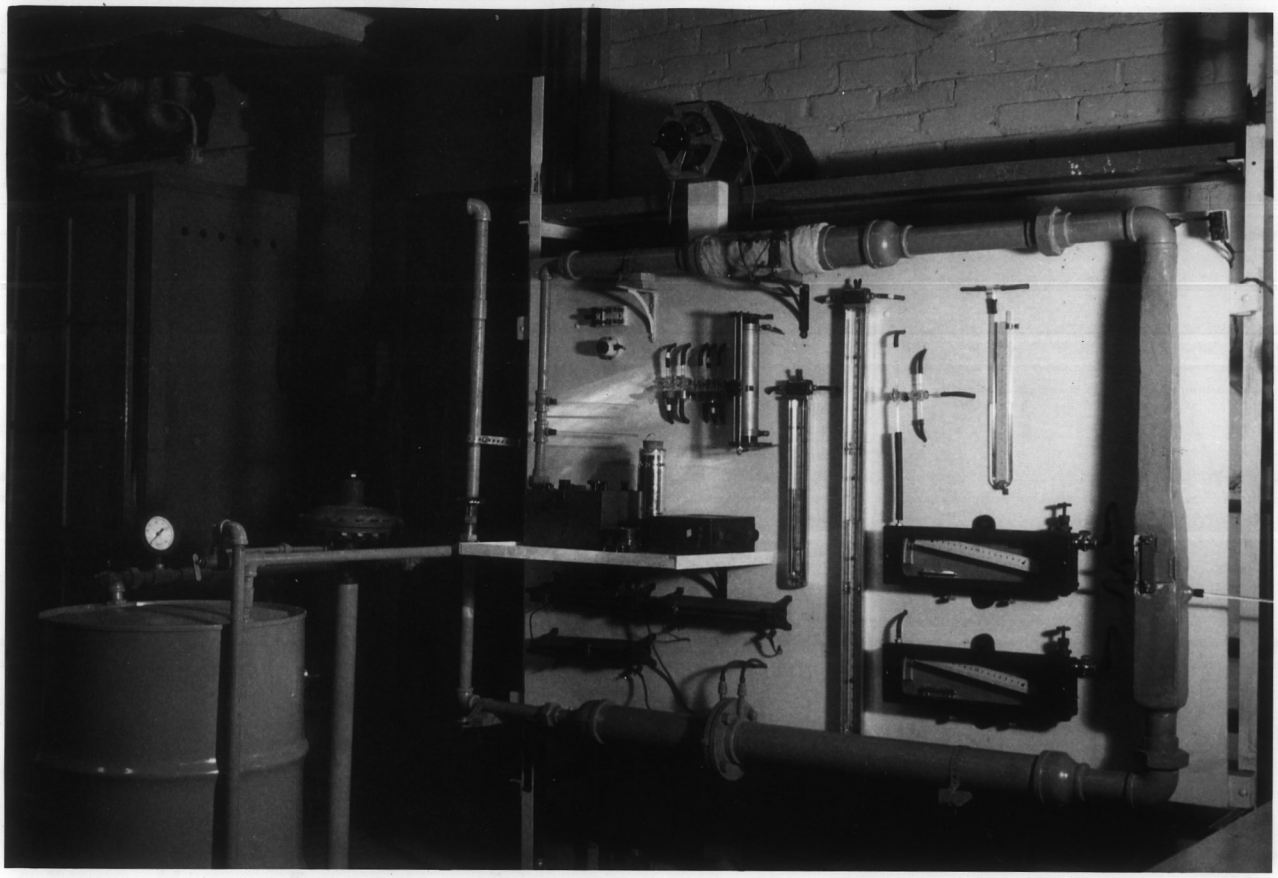
The system as shown in Figures 1 and 2, was used to transport air from a compressor (not shown) at the desired rate through the specimen section containing the bed on which mass transfer studies were made. The essential items of equipment as shown in Figure 1 are a pressure reducing valve, a surge tank, a rate regulating valve, an approximately square test section, and an orifice assembly. The heater and Dekhotinsky regulator shown with the equipment were installed for future work and were not used in these experiments. The thermocouple on the discharge side of the orifice was replaced with a thermometer.

Except for the surge tank and the approximately square test section, the equipment was constructed from standard iron pipe and fittings.



PHOTOGRAPH OF EQUIPMENT

Fig. 1



PHOTOGRAPH OF EQUIPMENT

Fig. 1

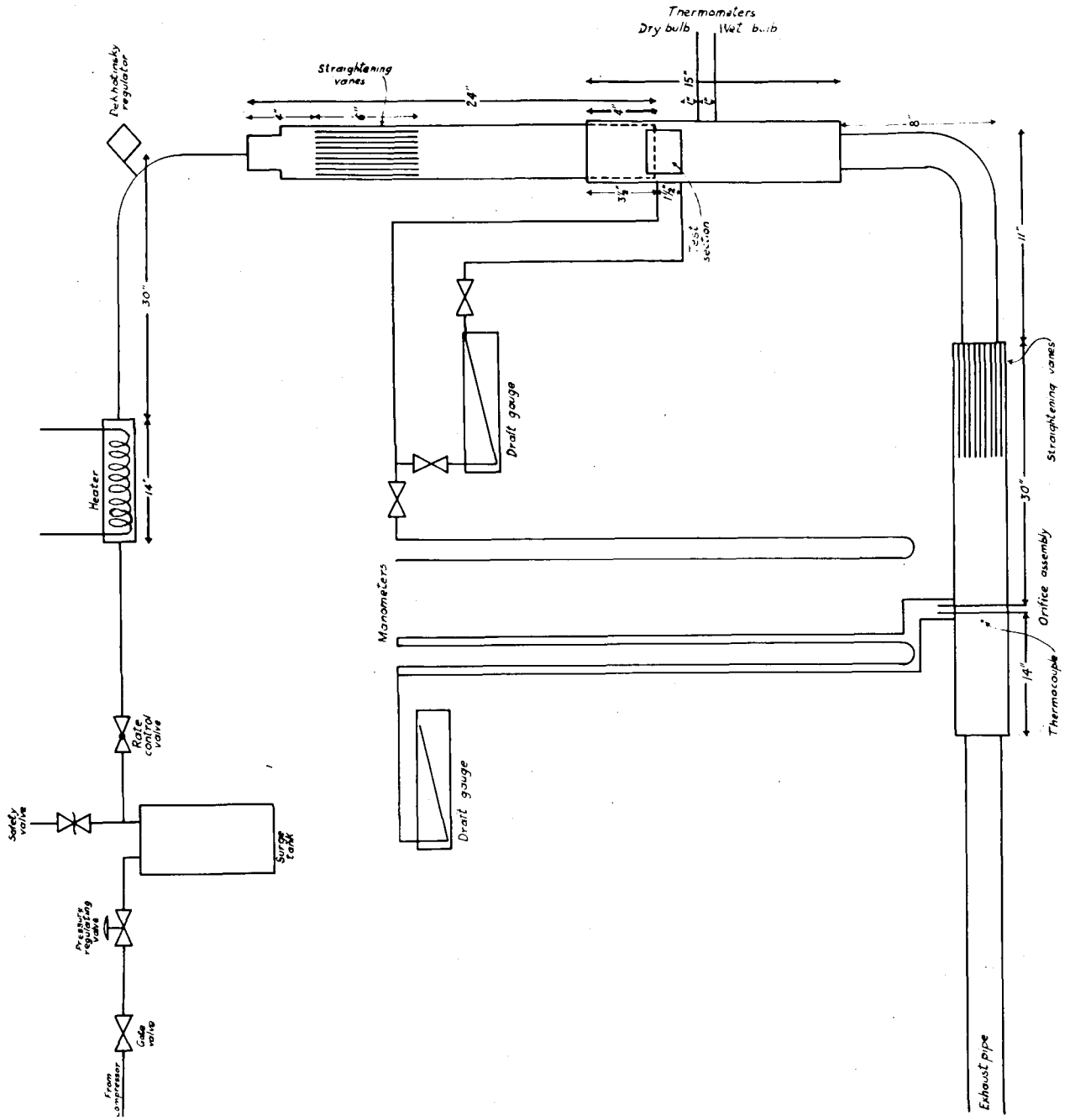



DIAGRAM OF EQUIPMENT

Fig. 2

The reducing valve was a standard Cash type diaphragm reducer which reduced the air pressure from six pounds per square inch to a pressure slightly above that required for the desired flow rate. Final adjustment of the flow rate was made continuously with a 3/4 inch globe valve. The surge tank was a standard type steel drum of 44 gallons capacity. The test section was constructed of 22 gage galvanized iron and had a 1/8 inch thick asbestos insulation. Straightening vanes made of seamless brass tubing with a 1/32 inch wall and 1/2 inch inside diameter were installed as shown in the equipment diagram. The orifice assembly was constructed of standard three inch iron pipe and a 1/16 inch thick stainless steel sharp edged orifice plate with a 0.5412 inch diameter according to the specifications in the A.S.M.E. publication, "Fluid Meters" (6). A previous calibration of this orifice assembly with flowing water showed that the orifice coefficient, K, deviated less than one per cent from the values of K shown in "Fluid Meters". The published values of K for metering air, given on page 111, were therefore used in all calculations.

The thermometers used for all temperature measurements were calibrated against a Bureau of Standards thermometer. These thermometers were installed just below the bed and on the downstream side of the orifice. Temperatures were read to the nearest 0.01°C since all thermometers were graduated in tenths of a degree.

Wet bulb wicks were made of clean muslin and were sewn on the thermometers, covering an inch of stem in addition to the bulb.

The tray holding the bed was made of 26 gage galvanized iron

with a 12 mesh copper screen at the bottom. The tray's dimensions were 1.97 inches by 2.26 inches with a 1.0 inch depth. A 1/4 inch horizontal lip extended completely around the top of the tray. The saddle in the test section on which the tray rested during the experiments was assembled from brass angles. Strips of felt covered the surfaces of the angles on which the tray rested to prevent leakage of air under the tray lip during the experiments.

The door in the test section was lined with sheet rubber to insure a tight fit with the frame and a strip of felt was glued horizontally across the door to fit against the tray lip and to prevent air leakage. The door was clamped shut by a brass cross bar which was held in place by wing-nuts screwed on studs which were brazed to the outside wall of the test section.

A chainomatic balance was used to weigh the bed before and after the runs. A 36 inch water U-tube manometer and a two inch draft gauge filled with Meriam Red Oil in conjunction with the orifice were used to measure the flow rate. A similar two inch draft gauge was used to measure the pressure drop through the bed and the pressure drop from the discharge side of the orifice to the atmosphere. A 12 inch U-tube manometer filled with mercury and another one filled with water were used to measure the pressure drop from the bed to the atmosphere.

Materials:

The celite cylinders used for the gas phase mass transfer experiments on liquids are a form of catalyst carrier manufactured by

the Johns-Manville Corporation. Average heights and diameters were obtained from micrometer measurements of all the pellets. Cylinder properties are tabulated in Table X in the appendix. These pellets were soaked under vacuum with the liquid to be used for each series of runs. The soaking period lasted approximately twenty minutes.

The aniline used for the experiments was the analytical reagent grade material purified by the Mallinckrodt Co. The nitrobenzene used was redistilled at atmospheric pressure from the Eastman grade material. The naphthalene was supplied on special order from the Eastman Kodak Company and was purified by recrystallization from alcohol by the company. Physical properties of all organic materials used are listed in Table XI. Distilled water was used for the water runs.

The naphthalene solid cylinders were molded by heating the purified material to a temperature just above the melting point and pouring the liquid into a steel mold. After the liquid had frozen and cooled the excess material was scraped off the mold with a hot stainless steel spatula. The cylindrical pellets were then stamped out of the molds with a steel rod having a diameter 0.005" less than the mold. Initial average heights and diameters were obtained from micrometer measurements of 50 pellets. All 156 pellets were measured after the third and eighth run. A new bed was used for the three highest velocity runs. A graph was made of the total surface area calculated from the average height and diameter measurements versus the total weight of the bed. The surface areas used in the

calculations were taken from this graph. The maximum decrease in bed area before heights and diameters were remeasured amounted to 2.7 per cent of the total original area. These surface areas are listed in the summary of calculations and in Table X.

Procedure:

The experimental procedure is divided into four divisions.

(A) Preparation of Bed.

The celite cylinders were soaked in the liquid to be used for approximately 20 minutes. The soaking took place inside a vacuum desiccator which was evacuated by the house vacuum line. The pellets were then rolled in cheesecloth to remove the excess liquid from the surface and poured into the tray. The bed was tamped down until a fairly even bed height of approximately 3/4 inch was obtained.

(B) Measurements Preceeding the Run.

In order to determine the humidity, density, and viscosity of the incoming air, wet and dry bulb temperature measurements were taken in the air stream just below the test section at the velocity of the run. For the relatively low velocity water and aniline runs, a radiation correction on the wet bulb temperature was made. Since the local air velocity past the surface of a pellet in the bed is much higher than the air velocity past a thin thermometer in place of the bed, and since the pellets see themselves, the surface temperature of the bed was taken as the true or thermodynamic wet bulb temperature, inasmuch as the process is assumed to be adiabatic. Since the maximum temperature depression with nitrobenzene was only 0.3°C the bed

temperature was taken as the measured wet bulb temperature. Since the maximum wet bulb temperature depression with naphthalene was less than 0.1°C, it was neglected.

(C) The Experimental Run.

The desired air rate was first established with the control valve and orifice meter. The bed was then placed in the air stream for approximately three minutes so that steady state conditions would be achieved. This assumption is not unreasonable inasmuch as the pellets were soaked in liquid very near the wet bulb temperature rather than room temperature and constant rate period had previously been established at several air velocities. After this pre-run the bed was removed and weighed within thirty seconds. After weighing, the bed was quickly placed in the air stream. Placing the bed in the air stream and bolting the door took less than four seconds. The timer was started as soon as the door was shut. During the progress of the run, the following measurements were read and recorded:

$t_2$ - air temperature below the bed, °C

$t_{o2}$ - air temperature on downstream side of the orifice, °C

$\Delta h_o$ - pressure drop across the orifice, inches of water

$\Delta h_{o2-atm}$ - pressure drop from downstream side of orifice to atmosphere, inches of water

$\Delta h_b$ - pressure drop across bed, inches of water

$\Delta h_{b-atm}$ - pressure drop from bed to atmosphere, inches of water or inches of mercury

After the desired time had elapsed, the door was opened and the bed was reweighed. For the water runs, wet and dry bulb temperatures were measured immediately after the bed was removed in order to check the previously measured values. Average humidities from these two sets of measurements were used in all water calculations. The barometric pressure was read between runs and the pressures were corrected to allow for expansion of the brass scale at temperatures above 0°C.

(D) Miscellaneous.

After each naphthalene run the top layer was removed and placed at the bottom of the bed and the other layers were dumped over the new bottom layer to form the higher layers. This procedure was followed so that over a number of runs the cylinders would remain geometrically similar. For the aniline, nitrobenzene, and naphthalene runs, weights were recorded to the nearest 0.0001 gram, but for the water runs the nearest 0.001 gram was sufficient.

## CHOICE OF BASIC DATA

In view of the wide discrepancies existing in the literature concerning such basic data as vapor pressures, diffusivities, etc., the proper choice of data to use in the presentation of other research data often is difficult to make. For the present work, a knowledge of vapor pressures and diffusivities was necessary. A vapor pressure literature survey of the necessary basic data was conducted prior to final choice of organic compounds.

The only recently published values for the vapor pressure of aniline in the temperature range considered (15° - 19°) were the data of Gurevich and Sigalovskaya (15), who covered the range of 0°C to 55°C. The vapor pressure between 15°C and 40°C can be represented by the following equation:

$$\log_{10} p = 4.3936 - \frac{673.63}{120+t} \qquad (6)$$

where p is the vapor pressure in mm. of mercury and t is the temperature in degrees centigrade. A comparison of the vapor pressures observed by Gurevich and Sigolovskaya, and vapor pressures calculated from equation (6) follows:

| t°C | 15.00 | 24.91 | 34.90 | 40.00 |
|---|---|---|---|---|
| P calc. (mm. Hg) | 0.253 | 0.556 | 1.11 | 1.52 |
| P obs. (mm. Hg) | 0.254 | 0.560 | 1.11 | 1.51 |

The diffusivity for aniline-air was taken from the data of Gilliland (8), who reported the value of 0.074 sq. cm./sec. at 25.9°C and one atmosphere pressure.

Three references were considered for the vapor pressure of nitrobenzene. The data of Gurevich and Sigalovskaya (10) were measured by an effusion method and were so low that the actual partial pressures of nitrobenzene in the effluent air stream in these experiments as calculated from weight losses in the bed, were higher than the tabulated vapor pressures at the determined surface temperatures. On the other hand, the data of Bruckner (3) were much too high for a reasonable correlation of the mass transfer data presented here. A dew point method was used by Puck and Wise (18) to determine the nitrobenzene vapor pressure at 25°C. Since the authors considered this method of determination far superior to earlier methods, an Antoine type equation (29) was fitted to this single point and the boiling point to give the following equation:

$$\log_{10} p = 7.036 - \frac{1703.7}{200+t} \qquad (7)$$

The constant in the denominator (200) is known as the Antoine constant and, according to the paper of Thomson (29), may be determined by the empirical equation:

$$c = 240 - 0.19t_B \qquad (8)$$

where $t_B$ is the boiling point in degrees centigrade at one atmosphere pressure. The published values of the vapor pressure of naphthalene at 25°C, as shown in Table I, constitute an example of disagreement of data determined by different investigators and different methods.

The diffusivity of nitrobenzene-air was calculated from the

Arnold equation (22) with the empirical constant adjusted to fit experimental diffusivities of compounds similar to nitrobenzene. Thus, the Arnold equation,

$$D_v = \frac{0.00837\ T^{3/2}}{(1+\frac{C}{T})P\ (V_1^{1/3} + V_2^{1/3})^2}\ \sqrt{\frac{1}{M_1} - \frac{1}{M_2}}\ , \qquad (9)$$

was changed to read

$$D_v = \frac{0.0789\ T^{3/2}}{(1+\frac{C}{T})P\ (V_1^{1/3} + V_2^{1/3})^2}\ \sqrt{\frac{1}{M_1} - \frac{1}{M_2}}\ , \qquad (9A)$$

where

$D_v$ is the diffusivity $\frac{\text{sq. cm.}}{\text{sec.}}$

T is the absolute temperature °K.

P is the total pressure, atmospheres.

$M_1$ and $M_2$ are the molecular weights of components 1 and 2 respectively.

$V_1$ and $V_2$ are the molal volumes of components 1 and 2 respectively.

C is the Sutherland constant, which is a rather complex function of molal volume and the geometric mean of the normal boiling points of the two components in °K.

The empirical constant, 0.0789, was the arithmetrical average of the values of the constant calculated from the published values of $D_v$ for aniline (8), chlorobenzene, ortho chlorotoluene, metachlorotoluene, and parachlorotoluene (14). By this method, the calculated diffusivity of nitrobenzene-air was 0.0622 sq. cm./sec.

Different investigators have published widely divergent values for the vapor pressure of naphthalene. For the temperature range considered there are available the data of the following investigators: Sears and Hopke (21), Winstrom and Kulp (33), Zil'berman and Granovskaya (34), Andrews (1), Swan and Mack (26), Thomas (28), Barker (2), and Schlumberger (20). Table I gives a brief summary of published data.

The data of Zil'berman and Granovskaya (34) were used in the mass transfer calculations. These data were chosen because they fall near the middle of all considered data and, in addition, gave the best mass transfer correlation. For the calculation of the vapor pressure of naphthalene at intermediate temperatures the following equation of Zil'berman and Granovskaya was used:

$$\log_{10} p = 10.3973 - \frac{3429.03}{273+t} \qquad (11)$$

The diffusion coefficient for the naphthalene-air system was taken from the data of Mack (31), who reported a value of 0.0611 sq.cm./sec. at 25.0°C and one atmosphere total pressure.

Table I

VAPOR PRESSURE OF NAPHTHALENE (mm OF Hg)

| t°C | p(21) | p(33) | p(34) | p(1) | p(26) | p(28) | p(2) | p(20) |
|---|---|---|---|---|---|---|---|---|
| 10 | .0154* | | .0192 | .013 | .0174 | .0178 | .0305 | .021 |
| 20 | .0640 | | .0494 | .041 | .0648 | .0512 | .0645 | .054 |
| 30 | .1640 | .12 | .1200 | .119 | .1770 | .1370 | .1630 | .113 |

*extrapolated

## CORRELATION OF DATA

Experimental data are summarized in Tables II through IX with the summaries of calculations. The procedure for development of the general correlation was as follows:

1. The data were plotted as $\frac{k_g P_f M_m}{G}$ versus $\frac{\sqrt{A}\ G}{\mu}$ on logarithmic graph paper as presented in Figures 3 through 5.

2. A best straight line was drawn by eye through the respective points for each packing size and substance evaporated.

3. Colburn numbers were read from each straight line at Reynolds number values of 500, 1000, and 1500.

4. These Colburn numbers at constant Reynolds numbers were plotted versus Schmidt numbers on logarithmic graph paper as shown in Figure 6 for a constant Reynolds number of 1000.

5. The arithmatic average of the slopes of the three plots of log Colburn number versus log Schmidt number was determined and used as the Schmidt number exponent in equation 14.

Schmidt number exponents were determined separately for each packing size. However, the limited data presented herein are combined to yield only a single Schmidt number exponent in equation 15. Less weight was given to the aniline data for the Schmidt number exponent determination since the vapor pressures of aniline are more uncertain than the vapor pressures of water, nitrobenzene, and naphthalene. The data on paradichlorobenzene, as determined by Simkin (24), were completely disregarded because of the large uncertainty of packing area and vapor pressure.

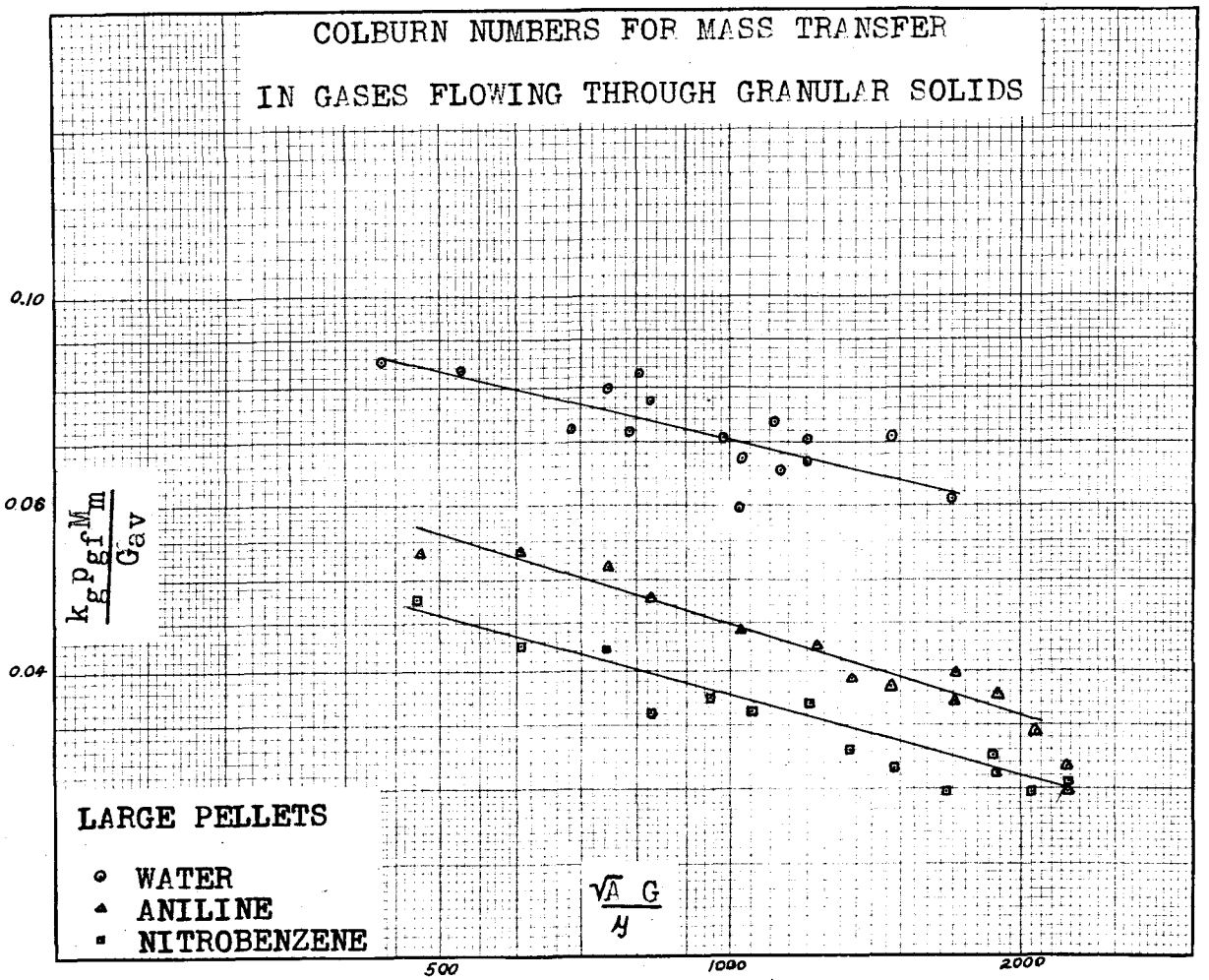

COLBURN NUMBERS FOR MASS TRANSFER
IN GASES FLOWING THROUGH GRANULAR SOLIDS
0.10
0.06
0.04
$\frac{k_g p_{gf} M_m}{G_{av}}$
LARGE PELLETS
WATER
ANILINE
NITROBENZENE
$\frac{\sqrt{A}\ G}{\mu}$
500
1000
2000

Fig. 3

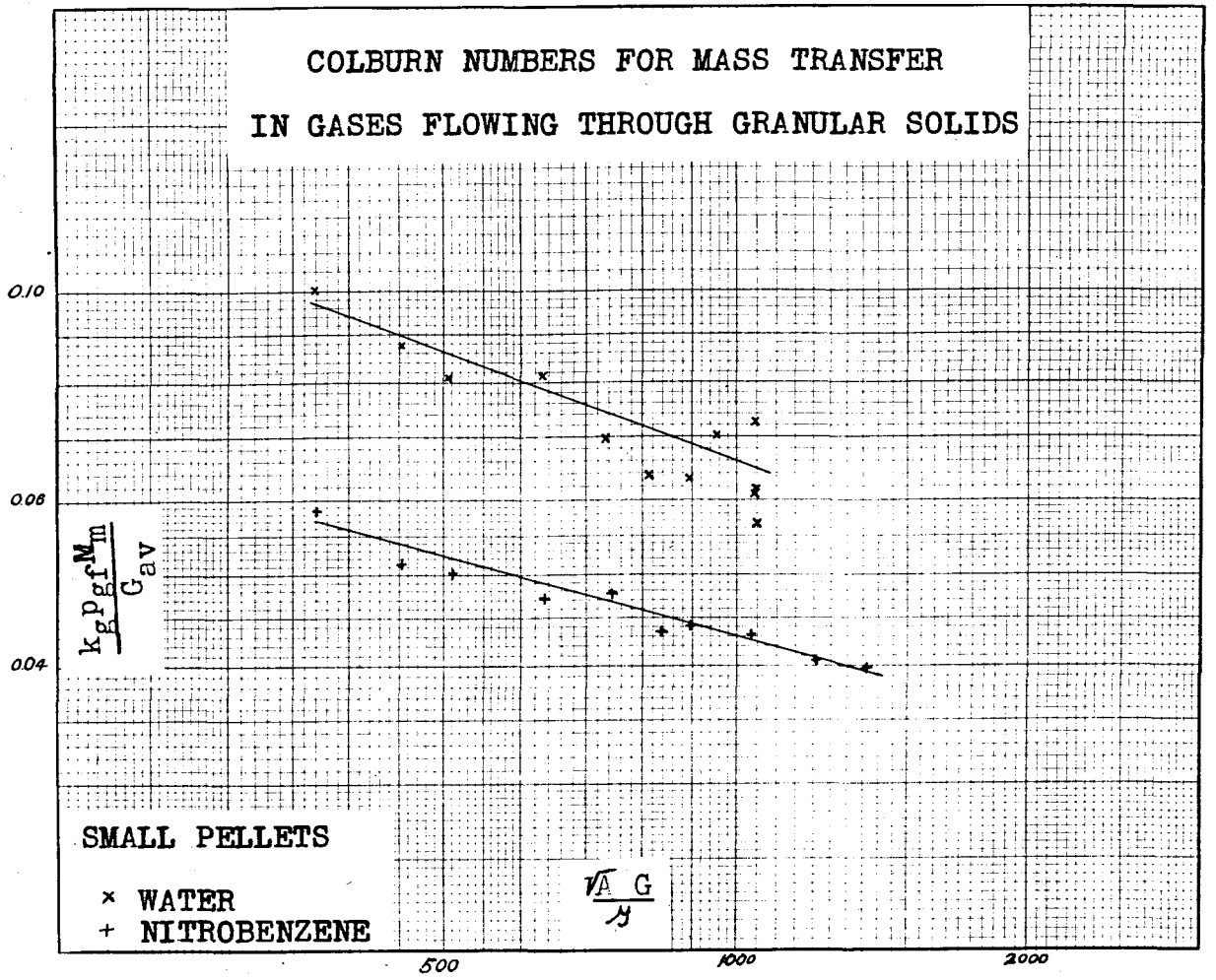

COLBURN NUMBERS FOR MASS TRANSFER
IN GASES FLOWING THROUGH GRANULAR SOLIDS
0.10
0.08
0.04
$\frac{k_g p_{gf} M_m}{G_{av}}$
SMALL PELLETS
× WATER
+ NITROBENZENE
$\frac{\sqrt{A}\,G}{\mu}$
500
1000
2000

Fig. 4

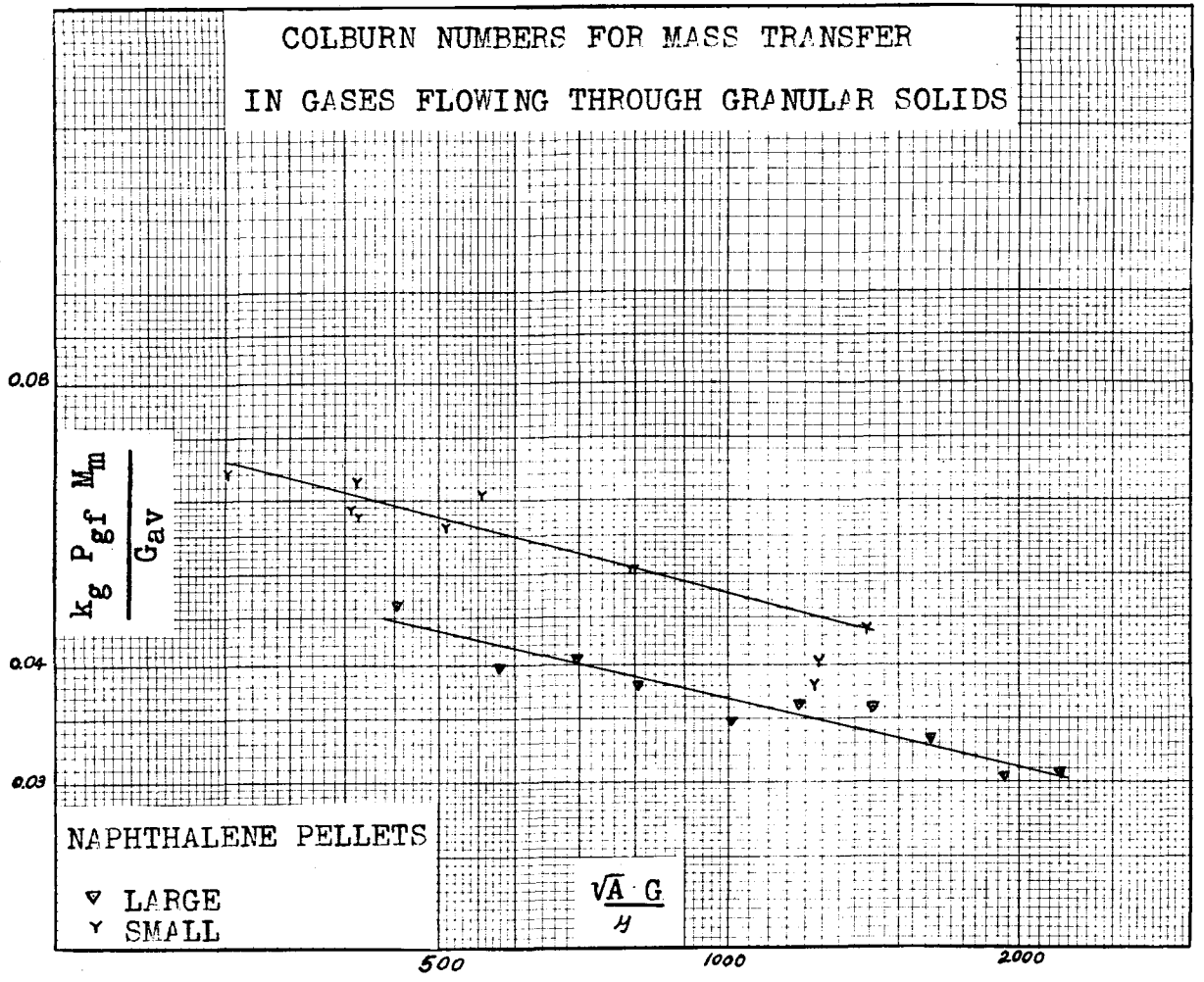
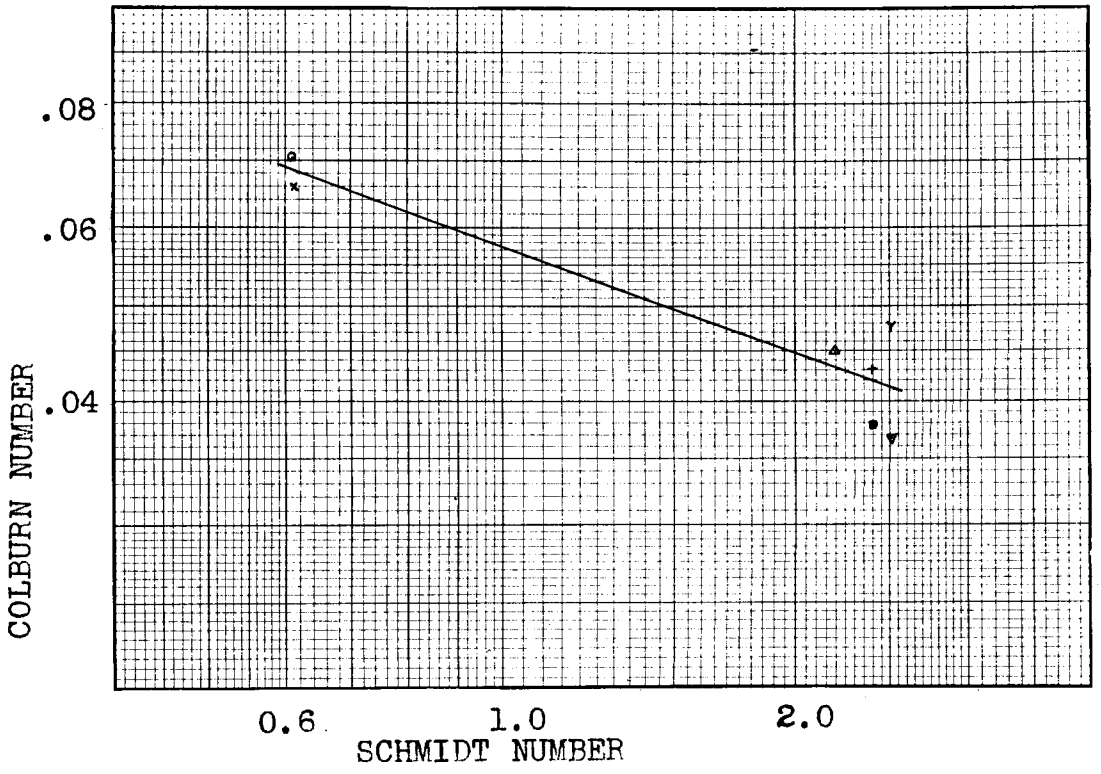

COLBURN NUMBERS FOR MASS TRANSFER
IN GASES FLOWING THROUGH GRANULAR SOLIDS
$\frac{k_g P_{gf} M_m}{G a v}$
0.08
0.04
0.03
NAPHTHALENE PELLETS
LARGE
SMALL
$\frac{\sqrt{A} \cdot G}{\mu}$
500
1000
2000

Fig. 5




LARGE PELLETS

⊙ WATER
▲ ANILINE
⊡ NITROBENZENE
▽ NAPHTHALENE

SMALL PELLETS

× WATER
\+ NITROBENZENE
Y NAPHTHALENE*

*DATA OF SIMKIN

*Fig. 6*

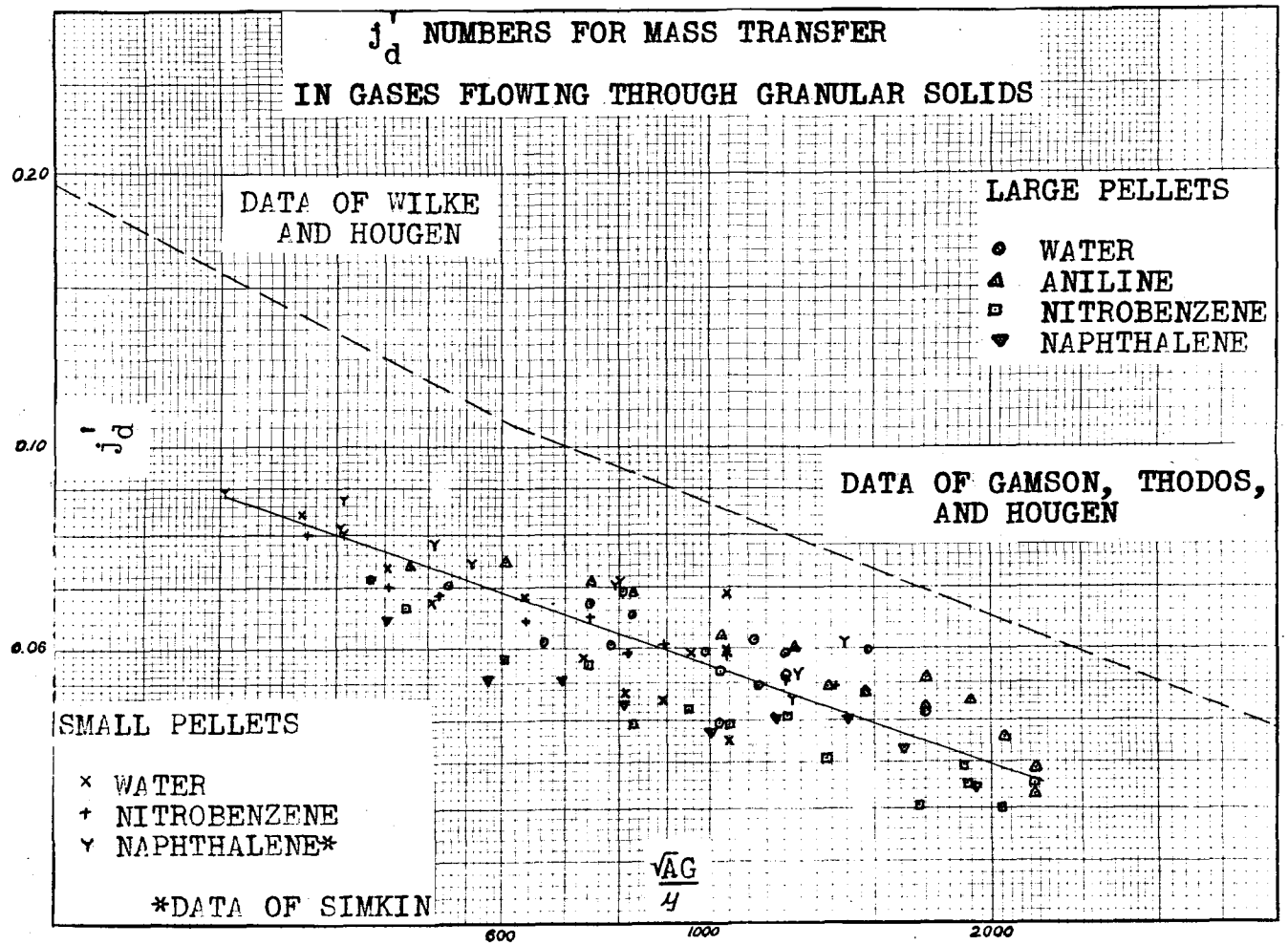

$j_d'$ NUMBERS FOR MASS TRANSFER
IN GASES FLOWING THROUGH GRANULAR SOLIDS
DATA OF WILKE AND HOUGEN
LARGE PELLETS
WATER
ANILINE
NITROBENZENE
NAPHTHALENE
DATA OF GAMSON, THODOS, AND HOUGEN
SMALL PELLETS
WATER
NITROBENZENE
NAPHTHALENE*
*DATA OF SIMKIN
$j_d'$
$\frac{\sqrt{A}G}{\mu}$
0.20
0.10
0.06
600
1000
2000

Fig. 7

## DISCUSSION OF RESULTS

When combined with the data of Simkin (24) on 5/32 inch naphthalene packing, the present granular bed data indicate that a Schmidt number exponent which varies with packing size is necessary for the best correlation of mass transfer data from small beds. The correlations of these data indicate Schmidt number exponents of 0.26 for the 1/6 inch packing and 0.45 for the 9/32 inch packing. For these separate correlations the data from the 1/4 inch naphthalene packing were included with the data of the 9/32 inch packing.

Since these mass transfer data from only two different packing sizes are insufficient for a completely new correlation, they are combined to yield a single Schmidt number exponent of 0.36. Thus, the correlation of these data yields the following equation:

$$j'_d = \frac{k_g M_m P_f}{G_{av}} \left(\frac{\mu}{\rho D_v}\right)^{0.36} = 0.69 \left(\frac{\sqrt{A}\, G}{\mu}\right)^{-.36} \qquad (12)$$

for a Reynold's number range of 300 to 2200. Equation (12) is shown as the solid line of Figure 7.

Since Gamson, Thodos, and Hougen evaporated only water from granular beds, and since the Schmidt number varied only from 0.61 to 0.62, their correlation equation may be rewritten with the same Schmidt number exponent as equation (12).

$$j'_d = \frac{k_g P_f M_m}{G_{av}} \left(\frac{\mu}{\rho D_v}\right)^{.36} = 1.452 \left(\frac{\sqrt{A}\, G}{\mu}\right)^{-.41} \qquad (13)$$

Equation (13) is the recommended design equation for spheres and cylinders in relatively large beds. Equation (13) is shown in Figure (7) as the dashed line at modified Reynold's numbers above 620. This equation is applicable for modified Reynold's numbers of 300 to 2200 and may extend to higher Reynold's numbers but the data of Wilke and Hougen show that another equation will apply at lower Reynold's numbers.

The complete data of the present investigation were not used for the recommended design equation because the $j_d'$ numbers for water lay approximately 30% below those of Hougen et al (7)(27)(31). It is postulated that this difference is due to wall effects since the present research was carried out with a much smaller bed than that of Hougen et al. The difference of modified Reynold's number exponents as found on the two beds is another indication of wall effect. Data from this small bed indicate a Reynold's number exponent of -0.36 while data from the large Wisconsin beds indicate a Reynold's number exponent of -0.41. Since practical use of this design equation will usually be made on relatively large beds the -0.41 Reynold's number exponent was used. If, on the small bed, the air stream channeled around the walls at low mass velocities, a smaller amount of water would be evaporated from the central section of the bed away from the walls than would be evaporated if channelling did not occur. However, at high mass velocities, relatively more air would be forced through the center of the bed, resulting in relatively high mass transfer coefficients. The net effect would be

a decrease in the dependence of the $j_d$ number on the Reynold's number, as was found.

The indication of a variable Schmidt number exponent is not unique with these data. Wilke's recalculation (32) of Snoeberger's data on the evaporation of liquids from a single cylinder shows the same phenomenon. This new correlation on single cylinders shows a 0.56 Schmidt number exponent at low mass velocities and a 0.43 exponent at high mass velocities. It is quite possible that the Schmidt number exponent is itself a function of the Schmidt number as, for example, the effect of Reynold's number on the friction factor, f, is itself a function of Reynold's number. The comparison of Schmidt number exponents for wetted wall columns, (0.56), and fluidized beds, (0.1), also supports the hypothesis of low Schmidt number exponents under conditions of high turbulence and high exponents under conditions of low turbulence.

In the Prandtl analogy extended by Colburn to granular beds the velocity ratio, r, should not depend as much on the Reynold's number in the range considered as it should depend on the geometry of the system. Since it has been shown that a high degree of turbulence will result in a low exponent on the Schmidt number, data on larger beds or smaller particles should correlate better with a low Schmidt number exponent since the degree of turbulence would be higher. In line with this reasoning, the data of Mehta and Parekh as published by Sherwood and Holloway (23) do not seem unreasonable. Although their use of flowing liquids over non-porous packing is

open to criticism because of non-uniform wetting of the packing and spray and end effects, their correlation with a 0.17 exponent on the diffusivity at least qualitatively agrees with this turbulence effect since their packed bed was larger than the bed used here.

The maximum deviation from the best line through all the data reported in this investigation was 22% and the average deviation was 7.8%. In view of the uncertainty of the vapor pressure data, particularly on aniline, these deviations could possibly be smaller if more reliable data were available.

## Recommendations

For further research on this problem it is recommended that:

(1) the wall and turbulence effects be determined on different sized beds and particles by the determination of Schmidt number exponent and subsequent correlation,

(2) other substances be studied,

(3) a dried air supply be used to allow the use of water soluble liquids, and

(4) that vapor pressures and diffusivities be determined more accurately.

# BIBLIOGRAPHY

# BIBLIOGRAPHY


1. Andrews, M.R., J. Phys. Chem. 30, 1497 (1926).
2. Barker, J.T., Z. Physik. Chem. 71, 255 (1910).
3. Bruckner, H., Z. anor. and algem. Chem. 199, 91 (1931).
4. Chilton, T.H., and Colburn, A.P., Ind. Eng. Chem. 26, 1183 (1935).
5. Colburn, A.P., Ind. Eng. Chem. 22, 967 (1930).
6. "Fluid Meters", page 111, A.S.M.E., New York, (1937).
7. Gamson, B.W., Thodos, G., and Hougen, O.A., Trans. Am. Inst. Chem. Engrs. 39, 1 (1943).

7A. Gamson, B.W., Ph.D. Thesis, University of Wisconsin (1943).

7B. Thodos, G., Ph.D. Thesis, University of Wisconsin (1943).

8. Gilliland, E.R., Ind. Eng. Chem. 26, 681 (1934).
9. Gilliland, E.R., and Sherwood, T.K., ibid 26, 516 (1934).
10. Gurevich, V.G., and Sigalovskaya, K.K., J. Gen. Chem. (U.S.S.R.) 9, 1326 (1939).
11. Gurevich, V.G., and Sigalovskaya, K.K., ibid 7, 1805 (1937).
12. Hirshfelder, J.D., Bird, R.B., and Spoty, E.L., J. Chem. Phys. 16, 968 (1948).
13. Hobson, M. and Thodos, G., Chem. Eng. Progress 45, 517 (1949).
14. Internat. Crit. Tab., McGraw Hill, New York V 62, (1929).
15. Lohrisch, W., Forsch. Gebiete Ingenieurw. 322, 46-68 (1929).
16. Mack Jr., E., J. Am. Chem. Soc., 47, 2468 (1925).
17. McAdams, W.N., Pohlenz, J.B., and St. John, R.C., Chem. Eng. Progress 45, 241 (1949).

18. Puck, T.T., and Wise, H., J. Phys. Chem. 50, 329 (1946).

19. Resnik, W., and White, R.R., Chem. Eng. Progress 45, 517 (1949).

20. Schlumberger, Von E., Gasbeleucht. 1257 (1912).

21. Sears, G.W., and Hopke, E.R., J. Am. Chem. Soc. 71, 1632 (1949).

22. Sherwood, T.K., "Absorption and Extraction", page 111, McGraw-Hill Book Co., New York, (1937).

23. Sherwood, T.K., and Holloway, F.H., Trans. Am. Inst. Chem. Engrs. 36, 39 (1940).

24. Simkin, D.J., M.S. Thesis, University of California (1948).

25. Snoeberger, D.F., M.S. Thesis, University of California (1948).

26. Swan, T.H. and Mack, E., J. Am. Chem. Soc. 47, 2112 (1925).

27. Taecker, R.G., and Hougen, O.A., Chem. Eng. Progress 45, 188 (1949).

28. Thomas, J.S.G., J. Soc. Chem. Ind. 35, 506 (1916).

29. Thomson, G.W., Chem. Rev. 38 , 1 (1946).

30. Wile, D.D., Refrig. Eng., October (1944).

31. Wilke, C.R., and Hougen, O.A., Chem. Eng. Progress 45, 188 (1945).

32. Wilke, C.R., Private Communication, Dec. 1949.

33. Winstrom, L.O., and Kulp, L., Ind. Eng. Chem. 41, 2584 (1949).

34. Zil'berman, P., and Granovskaya, A.A., J. Phys. Chem. (U.S.S.R.) 14, 759 (1940).

# APPENDIX

NOMENCLATURE

$A$ = total surface area of packing, ft.$^2$

$\sqrt{A}$ = square root of surface area of a single pellet, ft.

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

$A_t$ = cross sectional area of bed, ft.$^2$

$A_v$ = surface area of packing per unit bulk volume ft.$^2$/ft.$^3$

$(Col) = \frac{k_g P_f M_m}{G_{av}}$ = Colburn number, dimensionless

$C_p$ = specific heat of air stream, Btu/lb.°F.

$c$ = constant in Antoine equation, °C.

$D_M$ = molal diffusivity lb. mol./hr.ft.

$D_v$ = diffusion coefficient, ft.$^2$/hr.

$d$ = characteristic length dimension of a system, ft.

$d_p$ = diameter of a sphere having equivalent surface area to that of a cylinder, ft.

$f$ = Fanning friction factor, dimensionless.

$G$ = mass velocity of gas stream, lb./hr.ft.$^2$

$G_{av}$ = arithmatic average of mass velocities above and below packed bed, lb/hr. per square foot of bed area.

$G_i$ = mass velocity of inert gases, lb./hr.ft.$^2$

$G_o$ = mass velocity at the orifice, lb./hr./ft.$^2$

$g_c$ = conversion factor in Newton's law.

$H$ = humidity, lb.vapor/lb.dry air or gr. vapor/lb. dry air.

$H_s$ = humidity of gas stream in equilibrium with a wetted surface lb. vapor/lb. dry air.

$h$ = heat transfer coefficient, Btu/hr.ft.$^2$°F.

$\Delta h_{bed}$ = pressure drop across the bed, inches of water.

$\Delta h_d$ = pressure drop from downstream orifice tap to atmosphere, inches of water.

$\Delta h_o$ = pressure drop across orifice, inches of water.

$\Delta h_{o2}$ = pressure drop from downstream orifice tap to atmosphere, inches of water.

$\Delta h_1$ = pressure drop from entrance to bed to the atmosphere, inches of water or mm of Hg.

$\Delta h_2$ = pressure drop from exit from bed to the atmosphere, inches of water or mm of Hg.

$j_d$ = mass transfer modulus, dimensionless; the j numbers used are defined as:

$$j_d = \frac{k_g M_m P_f}{G_{av}} \left(\frac{\mu}{\rho D_v}\right)_f^{2/3}$$

$$j_d' = \frac{k_g M_m P_f}{G_{av}} \left(\frac{\mu}{\rho D_v}\right)_f^{.36}$$

$j_h = \frac{h}{C_p G} \left(\frac{C_p \mu}{k}\right)^{2/3}$ = heat transfer modulus, dimensionless.

K = orifice flow coefficient, dimensionless.

k = thermal conductivity, Btu/hr.ft.$^2$ °F/ft.

k' = mass transfer coefficient defined by $R_c = k' A (H_s - H)$

$k_g$ = mass transfer coefficient, lb.mol./hr.ft.$^2$ atm.

$k_g'$ = mass transfer coefficient, lb.mol./hr.ft.$^2$ mm Hg.

M = molecular weight of diffusing vapor, lb./lb.mol.

$M_m$ = arithmatic mean molecular weight of air across mass transfer zone, lb./lb.mol.

$N_A$ = molal rate of transport of vapor A per unit time per unit area normal to direction of transport, lb. mol./hr.ft.$^2$

$n$ = number of pellets.

$P_f$ = arithmatic mean partial pressure of inert gas across the gas film, atm. or mm Hg.

$p$ = partial pressure, mm Hg.

$p_s$ = partial pressure of vapor at packing surface, mm Hg.

$p_1$ = partial pressure of vapor above the bed, mm Hg.

$p_2$ = partial pressure of vapor below the bed, mm Hg.

$\Delta p_1$ = partial pressure driving force above the bed, $p_s - p_1$, mm Hg.

$\Delta p_2$ = partial pressure driving force below the bed, $p_s - p_2$, mm Hg.

$\Delta p_{lm}$ = logarithmic mean partial pressure driving force across mass transfer zone, mm Hg.

$R_c$ = rate of mass transfer, lb/hr.

$Re = \left(\frac{\sqrt{A}\ G}{\mu}\right)$ = Reynold's number, dimensionless.

$r$ = ratio of fluid velocity at boundary between laminar and eddy layer, to the velocity of the main fluid stream, dimensionless.

$Sc = \left(\frac{\mu}{\rho D_v}\right)_f$ = Schmidt number, dimensionless.

$T$ = absolute temperature, °K.

$t$ = temperature, °C or °F.

$t_{dl}$ = dry bulb temperature above the bed, °C or °F.

$t_{do2}$ = dry bulb temperature at the downstream side of the orifice, °C or °F.

$t_w$ = wet bulb temperature, °C or °F.

$t_1$ = dry bulb temperature above the bed, °C or °F.

$t_2$ = dry bulb temperature below the bed, °C or °F.

$\Delta t$ = $t_1 - t_2$, °C or °F.

$\bar{V}$ = specific volume, $ft.^3/lb.$

$w$ = weight of bed and wet pellets before a run, grams.

$w'$ = weight of bed and wet pellets after a run, grams.

$\Delta W$ = loss in weight, lb.

$x$ = film thickness, ft.

$Y$ = expansion factor used in orifice calculation, dimensionless.

$\beta$ = ratio of orifice diameter to inside diameter of pipe.

$\theta$ = time interval, minutes.

$\lambda$ = heat of vaporization, Btu/lb.

$\mu$ = viscosity, lb./hr.ft.

$\pi$ = total static pressure, $lb./ft.^2$ or mm Hg.

$\pi_b$ = atmospheric pressure, $lb./ft.^2$ or mm Hg.

$\pi_{o1}$ = pressure on upstream side of orifice, $lb./ft.^2$

$\pi_{o2}$ = pressure on downstream side of orifice, $lb./ft.^2$

$\Delta\pi_{bed}$ = pressure drop across the bed, $lb/ft.^2$ or mm Hg.

$\Delta\pi_d$ = pressure drop from downstream orifice tap to atmosphere $lb./ft.^2$ or mm Hg.

$\Delta\pi'_o$ = pressure drop across orifice, $lb./ft.^2$ or mm Hg.

$\Delta\pi_1$ = pressure drop from entrance to bed to the atmosphere, $lb./ft.^2$ or mm Hg.

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

Subscripts:

av - refers to arithmatic average of quantity between values above and below the bed.

calc - refers to a calculated rather than a measured value.

f - refers to arithmatic average value or quantity in gas film.

o - refers to value or quantity at orifice.

1 - refers to value or quantity at entrance to bed.

2 - refers to value or quantity at exit from bed.

## Sample Calculations

The complete method of calculation of Colburn and modified Reynold's numbers is given in detail with run number 40 (water vaporized) as an example, modifications necessary for organic compounds are described, and finally the values of $h/k_g$ for aniline are evaluated so that the aniline bed temperatures may be determined.

(1) Steady State (Constant Rate Period) Rate of Mass Transfer

$$R_c = \frac{\Delta W}{\theta} = 0.0601 \text{ lb./hr.}$$

(2) Air Stream Properties

Air viscosities were obtained from charts compiled by Gamson (7A) and Thodos (7B) and, in the temperature and humidity range considered, may be approximated by the equation,

$$\mu = 0.4192 - 0.000108\ t,$$

where $\mu$ has the units of lb./hr.ft. and t is in degrees centigrade.

(a) Mass Velocity

as formulated in "Fluid Meters" (6)

$$G_o = KY\ (2\ g_c\ \rho_{o1}\ \Delta\pi_o)^{1/2}$$

Values of the compressibility factor, Y, may be read in this publication from the graph of Y vs. the ratio of static pressures, $\pi_{o2}/\pi_{o1}$. Values of the orifice constant, K, are given in tables against the Reynold's number value in order to evaluate K. The parameter, $\beta$, appearing on the face of the graph and the table mentioned above is the ratio of the orifice diameter to the pipe diameter.

The calculation follows:

$$\beta = 0.5312/3.068 = 0.173$$

$$Re_o = 18{,}000 \text{ assumed}$$

$$K = 0.604$$

$$\Delta\pi_d = \Delta h_d \times 5.20 = 0.28 \times 5.20 = 1.456 \text{ lb./ft.}^2$$

$$\Delta\pi_o = \Delta h_o \times 5.20 = 2.65 \times 5.20 = 13.78 \text{ lb./ft.}^2$$

$$\pi_b = 756.2 \text{ mm Hg.} = 2106.2 \text{ lb./ft.}^2$$

$$\pi_{o2} = \pi_b + \Delta\pi_d = 2107.7 \text{ lb./ft.}^2$$

$$\pi_{o1} = \pi_{o2} + \Delta\pi_o = 2121.5 \text{ lb./ft.}^2$$

$$\pi_{o2}/\pi_{o1} = \frac{2107.7}{2121.5} = 0.9935$$

$$Y = 0.996$$

From the wet and dry bulb temperatures, and the total pressure at the orifice an approximate humidity is determined from the Carrier Psychrometric Chart (30).

$$t_d = 61.21°F,\ t_w = 49.86°F,\ \pi_{o1} = 2107 \text{ lb./ft.}^2$$

$$H_o = .00510 \text{ lb. water vapor/lb. dry air.}$$

and the specific volume, $\bar{V} = 13.22 \text{ ft.}^3/\text{lb.}$

$$\rho_{o1} = \frac{1}{\bar{V}} = \frac{1}{13.22} = 0.0757 \text{ lb./ft.}^3$$

$$\mu_o = 0.04385 \text{ lb./hr.ft.}$$

$$G_o = (0.604)(.996)\ 2g_c\ (.0757)(13.780)^{1/2}$$

$$= 17{,}747 \text{ lb./hr.ft.}^2$$

$$\text{and } Re_o = \frac{d_o G_o}{\mu_o} = \frac{(05412)\ (17{,}747)}{0.04385} = 17{,}800$$

The value assumed was sufficiently correct.

(b) Humidities and Partial Pressures.

$$G_i = \frac{G_o}{1 + H_o} = \frac{17,747}{1 + 0.0051} = 17,603 \quad \frac{\text{lb. dry air}}{\text{hr. ft.}^2}$$

$t_{dl} = 64.60°F$, $t_{wl} = 47.00°F$, $V = \frac{G}{} = 196$ ft./min.

from Fig. 1 in Wile's paper, (30), $\frac{t_w - t_s}{t_d - t_w} = 0.034$

and $t_s = 46.40°F = 8.00°C$

$H_1 = 18.9$ gr./lb.

$H_1$ must now be corrected for total pressure from the table of corrections with the Carrier Psychrometric Chart.

at $\pi_1 = \pi_b + 1.87\ \Delta h_1 = 756.2 + (1.87)(3.19) = 762.2$ mm Hg.

and corrected wet bulb temperature, $t_s$, $= 46.40°F$.

$H_1$ becomes 18.8 gr./lb. or 0.00268 $\frac{\text{lb. water}}{\text{lb. dry air}}$

$$\text{and } H_2 = H_1 + \frac{R_c}{G_i A_c} = 0.00268 + \frac{.0601}{(17,603)(.00154)}$$

$$= 0.00490 \quad \frac{\text{lb. water}}{\text{lb. dry air}}$$

$$p_1 = \frac{H_1 \pi_1}{H_1 + \frac{18}{29}} = \frac{(.00268)(762.2)}{0.6207 + 0.00268} = 3.28 \text{ mm Hg.}$$

$$\pi_2 = \pi_1 - \Delta\pi_b = 762.2 - 0.45 = 761.8 \text{ mm Hg.}$$

$$p_2 = \frac{H_2 \pi_2}{H_2 + \frac{18}{29}} = 5.97 \text{ mm Hg.}$$

(c) Log Mean Partial Pressure Difference

The surface temperature of the solid was assumed equal to the true wet bulb temperature.

$t_s = 8.00°C$

$p_s = 8.045$ mm Hg.

$$\Delta p_{lm} = \frac{(p_s-p_1) - (p_s-p_2)}{\ln \frac{p_s-p_1}{p_s-p_2}} = \frac{(8.045-3.28)-(8.045-5.97)}{\ln \frac{4.96}{2.08}}$$

$= 3.24$ mm Hg.

(3) Calculation of Dimensionless Groups

$$G_2 = \frac{G_o A_o}{A_t} = \frac{(17,747)\ (0.00154)}{(0.0310)} = 881.6 \frac{\text{lb.}}{\text{hr.ft.}^2}$$

$$G_1 = G_2 - \frac{R_c}{A_t} = 880 \text{ lb./hr.ft.}^2$$

$$G_{av} = 880.8 \text{ lb./hr.ft.}^2$$

at $H_{av} = .00379$, and $t_{av} = 61.46°F$

$\mu_{av} = 0.0439$ lb./hr.ft.

$$\frac{\sqrt{A}\ G}{\mu} = \frac{(0.04926)\ (880.8)}{(.0439)} = 998$$

Total area of pellets = 0.361 ft.$^2$

$$k_g = \frac{R_c}{18\ A\ \Delta p_{lm}} = \frac{(0.0601)\ (760)}{(18)(0.361)(3.24)} = 2.173 \frac{\text{lb. mol.}}{\text{hr.ft.}^2\text{atm.}}$$

$$P_f = 1/4\ (\pi_1 - p_1 + \pi_1 - p_s + \pi_2 - p_2 + \pi_2 - p_s) = 755.6 \text{ mm Hg.}$$

$$\frac{k_g P_f M_m}{G_{av}} = \frac{(2.173)\ (755.6)\ (28.8)}{(760)\ (880.8)}$$

$$\left(\frac{\mu}{\rho D_v}\right) = 0.617$$

$$j_d' = 0.0709\ (0.617)^{0.36} = 0.0596$$

(4) Modifications for Organic Compounds

In general the same method of calculation was used for the determination with organic compounds, taking into account the corresponding changes in molecular weights and the absence of organic vapors in the influent air stream. Another modification considered was the change in bed temperature from top to bottom for substances other than water. This change was calculated for the aniline and large nitrobenzene pellets and is included in the summary of calculations as $t_{s1}$ and $t_{s2}$. However, since the wet bulb depressions were small, the differences in surface temperatures were negligible and were not calculated for the small nitrobenzene pellets. The very small concentration of organic vapors in the gas film and the main gas stream were assumed to have negligible effect on the molecular weight, density, viscosity, and heat capacity of the gas film considered to be pure air.

After the aniline runs had been finished six different determinations of wet bulb depressions were made with an aniline-wet bulb.

With $h_o$ = 8 inches water

$t_d$ = 27.20°C (corrected to standard thermometer)

$t_w$ = 26.01°C

The heat of vaporization of aniline is calculated from the Clausius-Clapeyron equation.

$$\frac{d(\ln p)}{d\ T} = \frac{-\lambda}{R\,T^2}$$

and

$$\ln p = (2.3030)(4.3936) - \frac{(2.303)(673.6)}{T - 153}$$

$\lambda$ becomes 12,880 cal./mole.

= 249.7 Btu/lb.

From the vapor pressure equation, (6),

at $t_w$ = 26.01°C $p_s$ = 0.6034 mm of Hg.,

the saturation humidity,

$$H_s = \frac{p_s M_A}{(\pi_2 - p_s) M_{air}} = \frac{(0.6034)(93.1)}{(766.2-0.6)(29)} = 0.002535 \text{ lb. aniline/lb. air}$$

and

$$\frac{h}{k'} = \frac{\lambda H_s}{t_d - t_w} = \frac{(249.7)(0.002535)}{(1.8)\quad(1.19)} = 0.295$$

The limiting value of h/k at high velocities, as determined by extrapolation, is found to be approximately 0.245. Since this limiting value of h/k' is based on questionable vapor pressures of aniline, its use is intended only for the calculation of surface temperatures for all aniline runs reported here. The use of this h/k' value for other systems or other conditions may easily lead to erroneous results.

Table II

SUMMARY OF CALCULATIONS FOR ANILINE (9/32 INCH PACKING)

| Run | $\Delta h_o$ | $\Delta h_d$ | $\Delta \pi_d$ | $\pi_o$ | $\pi_b$ | $\pi_b$ | $\pi_{o2}$ | $\pi_{o1}$ |
|---|---|---|---|---|---|---|---|---|
| 1. | 0.60 | 0.11 | 0.57 | 3.12 | 755.8 | 2105 | 2106 | 2109 |
| 2. | 1.00 | 0.21 | 1.09 | 5.20 | 755.8 | 2105 | 2106 | 2111 |
| 3. | 1.50 | 0.33 | 1.72 | 7.80 | 755.8 | 2105 | 2107 | 2113 |
| 4. | 1.90 | 0.43 | 2.24 | 9.88 | 757.5 | 2109 | 2111 | 2121 |
| 5. | 3.05 | 0.70 | 3.64 | 15.86 | 757.0 | 2108 | 2112 | 2128 |
| 6. | 4.10 | 0.95 | 4.94 | 21.32 | 757.8 | 2110 | 2115 | 2131 |
| 7. | 5.05 | 1.20 | 6.24 | 26.26 | 757.3 | 2109 | 2115 | 2142 |
| 8. | 6.05 | 1.45 | 7.54 | 31.46 | 756.1 | 2105 | 2113 | 2144 |
| 9. | 6.04 | 1.45 | 7.54 | 31.41 | 753.2 | 2097 | 2105 | 2136 |
| 10. | 8.00 | 1.95 | 10.19 | 41.60 | 753.6 | 2098 | 2108 | 2150 |
| 11. | 8.05 | 1.92 | 9.98 | 41.86 | 753.1 | 2097 | 2107 | 2149 |
| 12. | 10.05 | 2.35 | 12.22 | 52.26 | 757.2 | 2108 | 2120 | 2172 |
| 13. | 12.05 | 2.75 | 14.30 | 62.66 | 757.2 | 2108 | 2122 | 2185 |
| 14. | 14.05 | 3.25 | 16.90 | 73.06 | 757.2 | 2108 | 2125 | 2198 |
| 15. | 14.05 | 3.35 | 17.42 | 73.06 | 753.0 | 2097 | 2114 | 2187 |

SUMMARY OF CALCULATIONS FOR ANILINE (9/32 INCH PACKING)(continued)

| Run | Y | $H_1$ | $t_{do2}$ | $\bar{V}$ | $\rho_{o1}$ | $\mu_o$ | $Re_o$ | K |
|---|---|---|---|---|---|---|---|---|
| 1. | .9996 | 21.0 | 59.05 | 13.12 | .07622 | .0434 | 866 | .613 |
| 2. | .9993 | 21.0 | 59.00 | 13.13 | .07616 | .0434 | 1122 | .609 |
| 3. | .9991 | 21.0 | 59.30 | 13.14 | .07610 | .0434 | 1372 | .607 |
| 4. | .9986 | 31.5 | 65.00 | 13.32 | .07508 | .0437 | 1522 | .606 |
| 5. | .9978 | 39.9 | 65.60 | 13.36 | .07485 | .0437 | 1900 | .604 |
| 6. | .9977 | 27.3 | 63.70 | 13.27 | .07536 | .0436 | 2230 | .602 |
| 7. | .9963 | 35.7 | 65.65 | 13.34 | .07496 | .0437 | 2460 | .603 |
| 8. | .9956 | 31.3 | 61.20 | 13.23 | .07550 | .0435 | 2705 | .601 |
| 9. | .9956 | 26.6 | 61.45 | 13.22 | .07564 | .0435 | 2704 | .601 |
| 10. | .9942 | 21.1 | 58.60 | 13.13 | .07616 | .0434 | 3140 | .600 |
| 11. | .9942 | 26.2 | 61.14 | 13.21 | .07570 | .0435 | 3140 | .601 |
| 12. | .9929 | 28.7 | 61.20 | 13.22 | .07564 | .0435 | 3532 | .600 |
| 13. | .9915 | 28.1 | 61.50 | 13.22 | .07564 | .0435 | 3800 | .599 |
| 14. | .9901 | 27.6 | 61.70 | 13.22 | .07564 | .0435 | 4090 | .599 |
| 15. | .9901 | 25.7 | 60.66 | 13.19 | .07582 | .0438 | 4075 | .599 |

SUMMARY OF CALCULATIONS FOR ANILINE, (9/32 INCH PACKING)(continued)

| Run | $G_o$ | w | w' | $\theta$ | $R_c$ | $10^4 H_2$ | $\Delta h_2$ | $\Delta \pi_2$ | $\pi_2$ | $p_2$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 862 | 82.0430 | 81.4435 | 12.0 | 6618 | 4983 | 0.85 | 1.60 | 757.4 | .1175 |
| 2. | 1102 | 81.349 | 80.722 | 10.0 | 8299 | 4888 | 1.36 | 2.54 | 758.3 | .1154 |
| 3. | 1346 | 82.030 | 81.354 | 9.0 | 9940 | 4800 | 1.92 | 3.95 | 759.4 | .1135 |
| 4. | 1500 | 81.434 | 80.054 | 13.0 | 1406 | 6092 | 2.42 | 4.52 | 762.0 | .1446 |
| 5. | 1870 | 79.869 | 78.621 | 10.0 | 1652 | 5736 | 2.70 | 5.04 | 762.0 | .1361 |
| 6. | 2196 | 81.244 | 79.945 | 10.0 | 1719 | 5085 | 4.86 | 9.10 | 766.0 | .1213 |
| 7. | 2429 | 80.462 | 79.046 | 10.0 | 1874 | 5008 | 6.10 | 11.40 | 768.0 | .1198 |
| 8. | 2639 | 79.428 | 78.160 | 10.0 | 1678 | 4145 | 7.50 | 14.00 | 770.0 | .0994 |
| 9. | 2638 | 81.310 | 80.030 | 10.0 | 1694 | 4162 | 7.51 | 14.00 | 767.0 | .0994 |
| 10. | 3062 | 80.588 | 77.887 | 20.0 | 1783 | 3778 | 9.60 | 17.92 | 771.5 | .0907 |
| 11. | 3062 | 81.427 | 80.438 | 7.0 | 1870 | 3962 | 9.84 | 18.38 | 771.5 | .0952 |
| 12. | 3468 | 81.269 | 79.721 | 10.0 | 2049 | 3895 | 12.14 | 22.70 | 779.9 | .0946 |
| 13. | 3730 | 81.175 | 79.595 | 10.0 | 2091 | 3611 | 14.73 | 27.50 | 784.7 | .0883 |
| 14. | 4020 | 80.984 | 79.220 | 10.0 | 2335 | 3773 | 17.16 | 32.00 | 789.2 | .0927 |
| 15. | 4025 | 81.384 | 80.575 | 5.0 | 2142 | 3455 | 17.54 | 32.75 | 785.8 | .0846 |

SUMMARY OF CALCULATIONS FOR ANILINE (9/32 INCH PACKING)(continued)

| Run | $t_{dl}$ | $t_{dl}-t_s$ | $t_s$ | $p_s$ | $\Delta p_2$ | $\Delta p_{lm}$ | $G_{av}$ | $\frac{\sqrt{A}\,G}{\mu}$ |
|---|---|---|---|---|---|---|---|---|
| 1. | 15.61 | .95 | 14.66 | .245 | .128 | .180 | 428 | 479 |
| 2. | 15.26 | .93 | 14.33 | .239 | .124 | .175 | 538 | 607 |
| 3. | 15.43 | .94 | 14.49 | .243 | .130 | .180 | 669 | 749 |
| 4. | 18.95 | 1.22 | 17.73 | .318 | .173 | .236 | 745 | 828 |
| 5. | 19.14 | 1.24 | 17.90 | .323 | .187 | .248 | 929 | 1032 |
| 6. | 18.04 | 1.21 | 16.90 | .297 | .175 | .228 | 1091 | 1238 |
| 7. | 18.86 | 1.21 | 17.65 | .316 | .193 | .248 | 1207 | 1342 |
| 8. | 16.58 | 1.01 | 15.57 | .266 | .167 | .210 | 1311 | 1465 |
| 9. | 16.56 | 1.01 | 15.55 | .265 | .166 | .209 | 1311 | 1465 |
| 10. | 14.97 | .89 | 14.08 | .234 | .144 | .184 | 1521 | 1707 |
| 11. | 16.47 | 1.00 | 15.47 | .263 | .168 | .209 | 1521 | 1701 |
| 12. | 16.23 | .97 | 15.26 | .259 | .164 | .205 | 1698 | 1899 |
| 13. | 16.38 | .98 | 15.40 | .261 | .174 | .211 | 1853 | 2072 |
| 14. | 16.60 | .99 | 15.59 | .266 | .173 | .214 | 1997 | 2232 |
| 15. | 16.20 | .96 | 15.24 | .258 | .174 | .209 | 2000 | 2237 |

SUMMARY OF CALCULATIONS FOR ANILINE (9/32 INCH PACKING)(continued)

| Run | $k_g$ | $\Delta\pi_1$ | $\pi_1$ | $P_f$ | $\frac{K_g P_f M_m}{G_{av}}$ | $(Col)Sc.^{.45}$ | $j_d'$ |
|---|---|---|---|---|---|---|---|
| 1. | .828 | 1.7 | 757.5 | 757.3 | 0.0557 | 0.0761 | 0.0740 |
| 2. | 1.068 | 2.7 | 758.5 | 758.2 | 0.0563 | 0.0773 | 0.0748 |
| 3. | 1.246 | 3.8 | 759.6 | 759.3 | 0.0537 | 0.0739 | 0.0713 |
| 4. | 1.342 | 4.8 | 762.3 | 760.0 | 0.0521 | 0.0683 | 0.0692 |
| 5. | 1.502 | 5.6 | 762.6 | 762.1 | 0.0467 | 0.0628 | 0.0620 |
| 6. | 1.700 | 9.8 | 767.6 | 766.6 | 0.0453 | 0.0609 | 0.0602 |
| 7. | 1.703 | 12.1 | 769.4 | 768.5 | 0.0412 | 0.0559 | 0.0547 |
| 8. | 1.800 | 14.8 | 770.9 | 770.3 | 0.0402 | 0.0547 | 0.0534 |
| 9. | 1.827 | 14.8 | 768.0 | 767.3 | 0.0406 | 0.0555 | 0.0539 |
| 10. | 2.180 | 19.2 | 772.8 | 771.9 | 0.0420 | 0.0567 | 0.0558 |
| 11. | 2.020 | 19.3 | 772.4 | 771.8 | 0.0389 | 0.0530 | 0.0517 |
| 12. | 2.250 | 23.9 | 781.1 | 780.3 | 0.0394 | 0.0540 | 0.0523 |
| 13. | 2.230 | 29.0 | 786.2 | 785.2 | 0.0360 | 0.0492 | 0.0478 |
| 14. | 2.460 | 34.3 | 791.5 | 790.0 | 0.0332 | 0.0453 | 0.0441 |
| 15. | 2.310 | 34.1 | 787.1 | 787.5 | 0.0311 | 0.0426 | 0.0413 |

$\left(\frac{\mu}{\rho D_v}\right)_f = 2.20$

Table III

SUMMARY OF $\frac{h}{k'}$ CALCULATIONS FOR ANILINE

| $h_o$ | $t_d$ | $t_w$ | $t_d - t_w$ | $\lambda$ | $P_s$ | $\pi_2$ | $H_s$ | $h/k'$ |
|---|---|---|---|---|---|---|---|---|
| 1.0 | 28.28 | 28.15 | 1.13 | 247.6 | .703 | 750.6 | 0.00302 | .367 |
| 1.9 | 28.09 | 26.97 | 1.12 | 248.0 | .6463 | 752.6 | 0.002767 | .340 |
| 4.0 | 27.55 | 26.39 | 1.16 | 249.0 | .620 | 757.2 | 0.002642 | .315 |
| 8.0 | 27.20 | 26.01 | 1.19 | 249.7 | .6034 | 766.2 | 0.00254 | .296 |
| 10.0 | 26.72 | 25.55 | 1.17 | 250.5 | .583 | 770.8 | 0.00244 | .2905 |
| 14.0 | 26.44 | 25.27 | 1.17 | 251. | .571 | 780.4 | 0.002355 | .281 |

Table IV

SUMMARY OF CALCULATIONS FOR NITROBENZENE (9/32 INCH PACKING)

| Run | $\Delta h_o$ | $\Delta h_d$ | $\Delta \pi_d$ | $\Delta \pi_o$ | $\pi_b$ | $\pi_b$ | $\pi_{o_2}$ | $\pi_{o_1}$ |
|---|---|---|---|---|---|---|---|---|
| 16. | 0.60 | 0.22 | 1.114 | 3.12 | 752.7 | 2096 | 2097 | 2100 |
| 17. | 1.00 | 0.32 | 1.664 | 5.20 | 752.6 | 2096 | 2097 | 2102 |
| 18. | 1.50 | 0.48 | 2.496 | 7.80 | 752.8 | 2096 | 2099 | 2106 |
| 19. | 1.90 | 0.65 | 3.380 | 9.88 | 753.1 | 2097 | 2100 | 2110 |
| 20. | 2.50 | 0.71 | 3.692 | 13.00 | 752.9 | 2096 | 2100 | 2113 |
| 21. | 3.05 | 0.79 | 4.108 | 15.86 | 753.0 | 2097 | 2101 | 2117 |
| 22. | 3.05 | 0.90 | 4.680 | 15.86 | 752.8 | 2096 | 2101 | 2117 |
| 23. | 4.05 | 1.08 | 5.616 | 21.06 | 752.8 | 2096 | 2102 | 2123 |
| 24. | 5.05 | 1.31 | 6.812 | 26.26 | 753.2 | 2097 | 2104 | 2130 |
| 25. | 6.05 | 1.52 | 7.904 | 31.46 | 753.3 | 2098 | 2106 | 2137 |
| 26. | 8.05 | 1.95 | 10.140 | 41.86 | 754.0 | 2100 | 2110 | 2152 |
| 27. | 10.05 | 2.40 | 12.480 | 52.26 | 754.0 | 2100 | 2113 | 2165 |
| 28. | 10.05 | 2.45 | 12.740 | 52.26 | 753.1 | 2097 | 2110 | 2162 |
| 29. | 12.05 | 2.80 | 14.560 | 62.66 | 754.0 | 2100 | 2115 | 2177 |
| 30. | 14.35 | 3.02 | 15.704 | 74.62 | 754.0 | 2100 | 2115 | 2190 |
| 31. | 14.35 | 3.04 | 15.808 | 74.62 | 753.9 | 2099 | 2115 | 2189 |

## SUMMARY OF CALCULATIONS FOR NITROBENZENE (9/32 INCH PACKING) (continued)

| Run | Y | $H_1$ | $t_{do2}$ | $\bar{V}$ | $\rho_{o1}$ | $\mu_o$ | $Re_o$ | K |
|---|---|---|---|---|---|---|---|---|
| 16. | .9996 | 27.0 | 64.4 | 13.29 | .07520 | .0437 | 872 | .613 |
| 17. | .9993 | 26.5 | 65.2 | 13.28 | .07530 | .0436 | 1108 | .612 |
| 18. | .9989 | 27.6 | 64.5 | 13.29 | .07570 | .0437 | 1360 | .607 |
| 19. | .9986 | 28.1 | 65.7 | 13.32 | .07508 | .0437 | 1527 | .606 |
| 20. | .9982 | 30.1 | 62.2 | 13.25 | .07547 | .0435 | 1756 | .604 |
| 21. | .9978 | 31.0 | 61.3 | 13.23 | .07559 | .0435 | 1938 | .604 |
| 22. | .9978 | 29.2 | 62.2 | 13.24 | .07553 | .0435 | 1938 | .604 |
| 23. | .9970 | 28.3 | 62.0 | 13.23 | .07559 | .0435 | 2227 | .602 |
| 24. | .9963 | 28.6 | 64.7 | 13.30 | .07519 | .0437 | 2462 | .602 |
| 25. | .9956 | 29.1 | 63.8 | 13.28 | .07530 | .0436 | 2695 | .601 |
| 26. | .9942 | 28.2 | 65.7 | 13.33 | .07501 | .0437 | 3090 | .600 |
| 27. | .9928 | 28.2 | 65.8 | 13.33 | .07501 | .0437 | 3447 | .600 |
| 28. | .9928 | 31.8 | 60.8 | 13.22 | .07564 | .0435 | 3530 | .600 |
| 29. | .9914 | 28.2 | 65.2 | 13.33 | .07501 | .0437 | 3806 | .600 |
| 30. | .9899 | 28.2 | 63.3 | 13.28 | .07530 | .0436 | 4170 | .599 |
| 31. | .9899 | 27.7 | 63.3 | 13.27 | .07536 | .0436 | 4170 | .599 |

SUMMARY OF CALCULATIONS FOR NITROBENZENE
(9/32 INCH PACKING)(continued)

| Run | $G_o$ | w | w' | θ | $R_c$ | $10^4$ $H_2$ | $\Delta h_2$ | $\Delta \pi_2$ |
|---|---|---|---|---|---|---|---|---|
| 16. | 859 | 85.9647 | 85.4340 | 12.0 | .05854 | 4.428 | 1.40 | 2.62 |
| 17. | 1098 | 85.9783 | 85.4659 | 10.0 | .06782 | 4.013 | 1.40 | 2.62 |
| 18. | 1342 | 85.8144 | 85.2389 | 10.0 | .07627 | 3.697 | 2.00 | 3.74 |
| 19. | 1503 | 85.9264 | 85.1698 | 12.0 | .08345 | 3.600 | 2.42 | 4.52 |
| 20. | 1722 | 85.9189 | 85.1132 | 12.0 | .08887 | 3.349 | 3.12 | 5.83 |
| 21. | 1900 | 85.4410 | 84.7654 | 10.0 | .08942 | 3.054 | 3.75 | 7.00 |
| 22. | 1900 | 85.8329 | 85.0986 | 10.0 | .09719 | 3.319 | 3.76 | 7.02 |
| 23. | 2192 | 85.7347 | 84.9147 | 10.0 | .10850 | 3.212 | 5.00 | 9.35 |
| 24. | 2422 | 85.5220 | 84.6142 | 10.0 | .12020 | 3.218 | 6.20 | 11.60 |
| 25. | 2653 | 85.3785 | 84.4507 | 10.0 | .12280 | 3.010 | 7.60 | 14.20 |
| 26. | 3052 | 85.5832 | 84.5370 | 10.0 | .13800 | 2.939 | 9.63 | 18.00 |
| 27. | 3400 | 85.4879 | 84.2032 | 10.0 | .17000 | 3.244 | 12.30 | 23.00 |
| 28. | 3415 | 85.5387 | 84.9353 | 6.0 | .13310 | 2.530 | 12.40 | 23.00 |
| 29. | 3716 | 85.4380 | 84.1728 | 10.0 | .16750 | 2.924 | 15.00 | 28.00 |
| 30. | 4053 | 85.5835 | 84.9400 | 5.0 | .17030 | 2.728 | 18.00 | 33.60 |
| 31. | 4054 | 84.9402 | 84.0252 | 7.0 | .17300 | 2.768 | 18.00 | 33.60 |

## SUMMARY OF CALCULATIONS FOR NITROBENZENE (9/32 INCH PACKING)(continued)

| Run | $\pi_2$ | $P_2$ | $t_{d1}$ | $t_{d1}-t_{s1}$ | $t_{s_1}$ | $P_{s1}$ | $t_2$ |
|---|---|---|---|---|---|---|---|
| 16. | 755.3 | .07878 | 18.49 | .22 | 18.27 | .1701 | 18.44 |
| 17. | 755.4 | .07140 | 18.36 | .22 | 18.14 | .1686 | 18.30 |
| 18. | 756.5 | .08710 | 18.42 | .23 | 18.19 | .1692 | 18.31 |
| 19. | 757.6 | .06424 | 18.74 | .23 | 18.51 | .1736 | 18.59 |
| 20. | 758.7 | .05986 | 17.16 | .22 | 16.94 | .1591 | 17.11 |
| 21. | 760.0 | .05468 | 16.55 | .21 | 16.34 | .1457 | 16.50 |
| 22. | 759.8 | .05941 | 17.00 | .22 | 16.94 | .1520 | 16.97 |
| 23. | 762.1 | .05767 | 16.93 | .23 | 16.70 | .1497 | 16.82 |
| 24. | 764.8 | .05798 | 18.40 | .25 | 18.15 | .1685 | 18.27 |
| 25. | 767.5 | .05442 | 18.00 | .25 | 17.75 | .1632 | 17.83 |
| 26. | 772.0 | .05570 | 18.73 | .28 | 18.45 | .1728 | 18.65 |
| 27. | 777.0 | .05939 | 18.78 | .29 | 18.49 | .1732 | 18.70 |
| 28. | 776.1 | .04624 | 16.12 | .26 | 15.86 | .1402 | 16.08 |
| 29. | 782.0 | .05388 | 18.66 | .31 | 18.35 | .1714 | 18.62 |
| 30. | 787.6 | .05063 | 17.41 | .30 | 17.11 | .1548 | 17.36 |
| 31. | 787.5 | .05136 | 17.50 | .30 | 17.20 | .1560 | 17.46 |

SUMMARY OF CALCULATIONS FOR NITROBENZENE
(9/32 INCH PACKING)(continued)

| Run | $t_2-t_{s2}$ | $t_{s2}$ | $p_{s2}$ | $\Delta p_2$ | $\Delta p_{lm}$ | $G_{av}$ | $\sqrt{\frac{A}{\mu}} G$ |
|---|---|---|---|---|---|---|---|
| 16. | .12 | 18.32 | .1709 | .0921 | .126 | 426.5 | 474 |
| 17. | .12 | 18.18 | .1691 | .0977 | .128 | 545.5 | 607 |
| 18. | .13 | 18.18 | .1691 | .0820 | .120 | 666.7 | 741 |
| 19. | .13 | 18.46 | .1728 | .1086 | .137 | 746.0 | 829 |
| 20. | .12 | 16.99 | .1534 | .0935 | .122 | 855.4 | 955 |
| 21. | .12 | 16.38 | .1462 | .0915 | .115 | 943.9 | 1054 |
| 22. | .13 | 15.84 | .1513 | .0919 | .126 | 943.9 | 1054 |
| 23. | .13 | 16.69 | .1496 | .0919 | .119 | 1088.9 | 1215 |
| 24. | .15 | 18.12 | .1682 | .1102 | .135 | 1203.2 | 1338 |
| 25. | .15 | 17.68 | .1624 | .1080 | .132 | 1317.9 | 1467 |
| 26. | .17 | 18.48 | .1733 | .1176 | .140 | 1516.1 | 1685 |
| 27. | .18 | 18.52 | .1736 | .1142 | .140 | 1689.0 | 1876 |
| 28. | .16 | 15.92 | .1407 | .0945 | .114 | 1696.5 | 1889 |
| 29. | .20 | 18.42 | .1722 | .1183 | .141 | 1846.0 | 2052 |
| 30. | .19 | 17.17 | .1557 | .1051 | .127 | 2013.4 | 2244 |
| 31. | .19 | 17.27 | .1568 | .1054 | .127 | 2013.7 | 2244 |

SUMMARY OF CALCULATIONS FOR NITROBENZENE
(9/32 INCH PACKING) (continued)

| Run | $k_g$ | $\Delta\pi_1$ | $\pi_1$ | $P_f$ | $\frac{k_g P_f M_m}{G}$ | $(Col)Sc^{.45}$ | $j'_d$ |
|---|---|---|---|---|---|---|---|
| 16. | 0.7926 | 1.8 | 754.5 | 754.3 | 0.0478 | 0.0689 | 0.0655 |
| 17. | 0.9043 | 2.8 | 753.4 | 753.2 | 0.0427 | 0.0616 | 0.0585 |
| 18. | 1.0840 | 3.9 | 756.7 | 756.5 | 0.0421 | 0.0607 | 0.0577 |
| 19. | 1.0380 | 4.8 | 757.9 | 757.7 | 0.0361 | 0.0521 | 0.0495 |
| 20. | 1.2420 | 6.3 | 759.2 | 758.8 | 0.0375 | 0.0540 | 0.0514 |
| 21. | 1.3260 | 7.5 | 760.5 | 760.1 | 0.0363 | 0.0523 | 0.0497 |
| 22. | 1.3160 | 7.5 | 760.3 | 760.0 | 0.0361 | 0.0521 | 0.0495 |
| 23. | 1.5520 | 10.2 | 763.0 | 762.5 | 0.0370 | 0.0533 | 0.0507 |
| 24. | 1.5180 | 12.3 | 765.5 | 765.1 | 0.0330 | 0.0476 | 0.0452 |
| 25. | 1.5870 | 15.1 | 768.4 | 767.9 | 0.0316 | 0.0456 | 0.0433 |
| 26. | 1.6810 | 19.0 | 773.0 | 772.4 | 0.0294 | 0.0423 | 0.0403 |
| 27. | 1.0710 | 24.4 | 778.4 | 777.6 | 0.0326 | 0.0470 | 0.0447 |
| 28. | 1.9910 | 24.6 | 777.7 | 776.8 | 0.0311 | 0.0448 | 0.0426 |
| 29. | 2.0250 | 29.5 | 783.5 | 782.6 | 0.0293 | 0.0422 | 0.0401 |
| 30. | 2.2870 | 35.6 | 789.6 | 788.5 | 0.0305 | 0.0440 | 0.0418 |
| 31. | 2.3230 | 35.5 | 789.4 | 788.3 | 0.0310 | 0.0447 | 0.0425 |

$\left(\frac{\mu}{\rho D_V}\right)_f = 2.40$

Table V

SUMMARY OF CALCULATIONS FOR WATER, (9/32 INCH PACKING)

| Run | $\Delta h_o$ | $\Delta \pi_o$ | $\Delta h_d$ | $\Delta \pi_d$ | $\pi_b$ | $\pi_b$ | $\pi_{o2}$ |
|---|---|---|---|---|---|---|---|
| 32. | 0.50 | 2.60 | .04 | 0.208 | 758.0 | 2111.2 | 2111.4 |
| 33. | 0.75 | 3.99 | .25 | 1.300 | 754.5 | 2099.0 | 2100.3 |
| 34. | 1.00 | 5.20 | .09 | 0.468 | 754.0 | 2100.1 | 2100.5 |
| 35. | 1.25 | 6.50 | .11 | 0.572 | 756.2 | 2106.2 | 2106.7 |
| 36. | 1.50 | 7.80 | .18 | 0.936 | 754.5 | 2101.5 | 2102.4 |
| 37. | 1.65 | 8.58 | .16 | 0.832 | 758.0 | 2111.2 | 2112.0 |
| 38. | 1.75 | 9.10 | .16 | 0.832 | 758.0 | 2111.2 | 2112.0 |
| 39. | 1.90 | 9.88 | .60 | 3.120 | 754.5 | 2099.0 | 2102.1 |
| 40. | 2.65 | 13.78 | .28 | 1.456 | 756.2 | 2106.2 | 2107.7 |
| 41. | 2.85 | 14.82 | .37 | 1.924 | 758.0 | 2111.2 | 2113.1 |
| 42. | 2.85 | 14.82 | .37 | 1.924 | 758.0 | 2111.2 | 2113.1 |
| 43. | 3.42 | 17.78 | .33 | 1.716 | 750.4 | 2090.1 | 2109.6 |
| 44. | 3.45 | 17.94 | .33 | 1.716 | 756.2 | 2106.2 | 2107.9 |
| 45. | 4.00 | 20.80 | .28 | 1.456 | 750.4 | 2090.1 | 2091.5 |
| 46. | 4.00 | 20.80 | .29 | 1.508 | 750.4 | 2090.1 | 2091.5 |
| 47. | 6.05 | 31.46 | .65 | 3.380 | 750.3 | 2089.8 | 2093.2 |
| 48. | 8.00 | 41.60 | .85 | 4.420 | 750.3 | 2089.8 | 2094.2 |

SUMMARY OF CALCULATIONS FOR WATER (9/32 INCH PACKING) (continued)

| Run | $\pi_{o1}$ | Y | $t_{do2}$ | $t_{wo2}$ | $H_o$ | $\bar{V}_{o1}$ | $\rho_{o1}$ |
|---|---|---|---|---|---|---|---|
| 32. | 2114.0 | 1.000 | 63.89 | 52.48 | .00582 | 13.35 | .0749 |
| 33. | 2104.2 | 0.999 | 66.70 | 55.48 | .00684 | 13.43 | .0744 |
| 34. | 2105.7 | 0.999 | 66.04 | 55.76 | .00727 | 13.49 | .0741 |
| 35. | 2113.2 | 0.998 | 60.78 | 49.73 | .00510 | 13.28 | .0753 |
| 36. | 2110.2 | 0.998 | 63.73 | 52.02 | .00508 | 13.36 | .0748 |
| 37. | 2120.6 | 0.998 | 62.98 | 52.12 | .00577 | 13.28 | .0753 |
| 38. | 2121.1 | 0.998 | 61.90 | 52.97 | .00650 | 13.27 | .0754 |
| 39. | 2112.0 | 0.997 | 65.96 | 55.00 | .00678 | 13.43 | .0744 |
| 40. | 2121.5 | 0.996 | 61.21 | 49.86 | .00510 | 13.22 | .0757 |
| 41. | 2127.9 | 0.998 | 62.17 | 50.79 | .00531 | 13.21 | .0757 |
| 42. | 2127.9 | 0.998 | 63.41 | 50.88 | .00505 | 13.26 | .0754 |
| 43. | 2109.6 | 0.997 | 64.06 | 51.51 | .00537 | 13.37 | .0748 |
| 44. | 2125.8 | 0.997 | 60.67 | 60.67 | .00502 | 13.20 | .0758 |
| 45. | 2112.3 | 0.996 | 63.84 | 63.84 | .00498 | 13.34 | .0750 |
| 46. | 2112.3 | 0.996 | 63.89 | 63.89 | .00525 | 13.34 | .0750 |
| 47. | 2124.7 | 0.994 | 63.48 | 63.48 | .00522 | 13.26 | .0754 |
| 48. | 2135.8 | 0.992 | 63.66 | 63.66 | .00607 | 13.21 | .0757 |

SUMMARY OF CALCULATIONS FOR WATER, (9/32 INCH PACKING)(continued)

| Run | $\mu_{ol}$ | $Re_o$ | K | $G_o$ | w | w' | θ |
|---|---|---|---|---|---|---|---|
| 32. | .0440 | 7780 | .614 | 7828 | 77.394 | 74.994 | 10.0 |
| 33. | .0442 | 9500 | .612 | 9508 | 77.249 | 74.531 | 10.0 |
| 34. | .0441 | 10940 | .610 | 10932 | 76.635 | 75.375 | 4.0 |
| 35. | .0438 | 12250 | .608 | 12863 | 77.438 | 74.183 | 10.0 |
| 36. | .0441 | 13000 | .607 | 13369 | 78.463 | 74.406 | 10.0 |
| 37. | .0440 | 14070 | .607 | 14067 | 78.545 | 74.906 | 10.0 |
| 38. | .0439 | 14500 | .606 | 14473 | 80.479 | 76.679 | 10.0 |
| 39. | .0442 | 14900 | .605 | 14910 | 76.220 | 73.012 | 8.0 |
| 40. | .0439 | 17800 | .604 | 17747 | 80.120 | 76.486 | 8.0 |
| 41. | .0439 | 18500 | .604 | 18451 | 77.608 | 74.779 | 8.0 |
| 42. | .0440 | 18500 | .604 | 18403 | 77.442 | 74.994 | 10.0 |
| 43. | .0440 | 20250 | .603 | 20038 | 77.696 | 74.489 | 6.0 |
| 44. | .0438 | 20350 | .603 | 20248 | 78.170 | 75.209 | 6.0 |
| 45. | .0440 | 21880 | .602 | 21621 | 80.775 | 77.491 | 6.0 |
| 46. | .0440 | 21880 | .602 | 21615 | 78.354 | 75.514 | 5.0 |
| 47. | .0440 | 26900 | .601 | 26584 | 77.501 | 73.665 | 5.5 |
| 48. | .0440 | 31000 | .601 | 30560 | 80.287 | 76.763 | 5.0 |

SUMMARY OF CALCULATIONS FOR WATER, (9/32 INCH PACKING)(continued)

| Run | $R_c$ | $\Delta h_1$ | $\pi_1$ | $t_{dl}$ | $t_{wl}$ | $t_{dl}$ | $t_{wl}$ |
|---|---|---|---|---|---|---|---|
| 32. | .03175 | 0.60 | 759.1 | 19.08 | 8.75 | 66.35 | 47.74 |
| 33. | .03462 | 1.20 | 756.7 | 20.60 | 11.20 | 69.17 | 52.16 |
| 34. | .04777 | 1.15 | 754.5 | 21.48 | 11.51 | 70.65 | 52.71 |
| 35. | .04306 | 1.58 | 759.1 | 17.65 | 7.80 | 63.79 | 46.03 |
| 36. | .05367 | 1.82 | 757.6 | 19.68 | 9.74 | 67.40 | 49.02 |
| 37. | .04814 | 2.05 | 761.8 | 18.43 | 8.66 | 65.20 | 47.59 |
| 38. | .05027 | 2.05 | 761.8 | 17.33 | 8.36 | 63.20 | 47.04 |
| 39. | .05322 | 2.70 | 759.4 | 20.33 | 10.59 | 68.60 | 51.06 |
| 40. | .06010 | 3.19 | 762.2 | 18.11 | 8.00 | 64.60 | 46.40 |
| 41. | .06332 | 3.40 | 764.3 | 18.98 | 8.69 | 66.18 | 47.65 |
| 42. | .05735 | 3.30 | 764.2 | 18.79 | 8.70 | 65.80 | 47.66 |
| 43. | .07069 | 4.15 | 760.1 | 19.53 | 9.42 | 67.19 | 48.95 |
| 44. | .06529 | 3.33 | 762.4 | 18.11 | 8.04 | 64.60 | 46.48 |
| 45. | .07241 | 4.80 | 759.4 | 19.53 | 9.42 | 67.19 | 48.95 |
| 46. | .07515 | 4.80 | 763.0 | 19.53 | 9.42 | 67.19 | 48.95 |
| 47. | .09227 | 6.38 | 762.2 | 19.63 | 9.58 | 67.35 | 49.26 |
| 48. | .09325 | 9.92 | 768.8 | 19.43 | 9.73 | 67.00 | 49.50 |

SUMMARY OF CALCULATIONS FOR WATER, (9/32 INCH PACKING)(continued)

| Run | $H_1$ | $p_1$ | $G_1$ | $H_2-H_1$ | $H_2$ | $\Delta h_{bed}$ |
|---|---|---|---|---|---|---|
| 32. | .00278 | 3.38 | 7756 | 0.00266 | 0.00544 | .04 |
| 33. | .00445 | 5.38 | 9443 | 0.00238 | 0.00683 | .05 |
| 34. | .00446 | 5.38 | 10805 | 0.00287 | 0.00733 | .08 |
| 35. | .00254 | 3.10 | 12164 | 0.00230 | 0.00484 | .11 |
| 36. | .00316 | 3.85 | 13248 | 0.00263 | 0.00579 | .12 |
| 37. | .00299 | 3.65 | 13938 | 0.00224 | 0.00523 | .16 |
| 38. | .00314 | 3.84 | 14324 | 0.00228 | 0.00542 | .16 |
| 39. | .00398 | 4.85 | 14809 | 0.00233 | 0.00631 | .15 |
| 40. | .00268 | 3.28 | 17603 | 0.00222 | 0.00490 | .24 |
| 41. | .00281 | 3.46 | 18295 | 0.00225 | 0.00506 | .23 |
| 42. | .00283 | 3.47 | 18255 | 0.00204 | 0.00478 | .21 |
| 43. | .00327 | 3.99 | 19867 | 0.00230 | 0.00557 | .29 |
| 44. | .00266 | 3.26 | 20086 | 0.00212 | 0.00478 | .26 |
| 45. | .00327 | 3.98 | 21450 | 0.00219 | 0.00546 | .27 |
| 46. | .00323 | 3.95 | 21435 | 0.00228 | 0.00551 | .27 |
| 47. | .00334 | 4.08 | 26364 | 0.00227 | 0.00561 | .48 |
| 48. | .00346 | 4.26 | 30266 | 0.00200 | 0.00546 | .70 |

SUMMARY OF CALCULATIONS FOR WATER, (9/32 INCH PACKING)(continued)

| Run | $\Delta\pi_{bed}$ | $\pi_2$ | $p_2$ | $p_s$ | $\Delta p_1$ | $\Delta p_2$ | $\Delta p_{lm}$ | $t_{av}$ |
|---|---|---|---|---|---|---|---|---|
| 32. | .07 | 759.1 | 6.59 | 8.44 | 5.08 | 1.87 | 3.21 | 63.07 |
| 33. | .08 | 756.6 | 8.23 | 9.98 | 4.60 | 1.75 | 2.95 | 65.60 |
| 34. | .15 | 754.3 | 8.79 | 10.18 | 4.79 | 1.38 | 2.74 | 64.59 |
| 35. | .21 | 759.0 | 5.87 | 7.94 | 4.84 | 2.07 | 3.27 | 60.95 |
| 36. | .22 | 757.4 | 7.01 | 9.04 | 5.20 | 2.04 | 3.40 | 62.12 |
| 37. | .30 | 761.6 | 6.36 | 8.42 | 4.77 | 2.06 | 3.23 | 61.98 |
| 38. | .30 | 761.6 | 6.59 | 8.25 | 4.41 | 1.66 | 2.83 | 61.21 |
| 39. | .28 | 759.2 | 7.64 | 9.58 | 4.73 | 1.94 | 3.14 | 64.67 |
| 40. | .45 | 762.0 | 5.97 | 8.05 | 4.76 | 2.08 | 3.24 | 61.46 |
| 41. | .43 | 764.1 | 6.18 | 8.44 | 4.99 | 2.26 | 3.45 | 62.38 |
| 42. | .39 | 764.0 | 5.96 | 8.44 | 4.97 | 2.48 | 3.58 | 62.41 |
| 43. | .54 | 759.8 | 6.84 | 8.86 | 4.88 | 2.02 | 3.25 | 62.36 |
| 44. | .49 | 761.9 | 5.82 | 8.06 | 4.80 | 2.24 | 3.36 | 61.69 |
| 45. | .50 | 759.1 | 6.62 | 8.86 | 4.88 | 2.24 | 3.39 | 62.51 |
| 46. | .50 | 762.7 | 6.71 | 8.86 | 4.91 | 2.15 | 3.36 | 62.38 |
| 47. | .90 | 761.3 | 6.82 | 8.95 | 4.87 | 2.13 | 3.32 | 62.10 |
| 48. | 1.31 | 767.5 | 6.69 | 9.05 | 4.79 | 2.36 | 3.44 | 62.52 |

SUMMARY OF CALCULATIONS FOR WATER, (9/32 INCH PACKING)(continued)

| Run | $\mu_{av}$ | $k_g$ | $G_2$ | $G_1$ | $G_{av}$ | $\frac{\sqrt{A}\,G}{\mu}$ | $P_f$ |
|---|---|---|---|---|---|---|---|
| 32. | 0.0439 | 1.16 | 388.9 | 387 | 388 | 435 | 751.7 |
| 33. | 0.0440 | 1.38 | 472.0 | 471 | 472 | 527 | 756.6 |
| 34. | 0.0440 | 2.04 | 543.1 | 542 | 543 | 609 | 754.4 |
| 35. | 0.0439 | 1.55 | 609.2 | 608 | 609 | 683 | 752.5 |
| 36. | 0.0439 | 1.85 | 664.1 | 662 | 663 | 744 | 749.9 |
| 37. | 0.0439 | 1.75 | 699.0 | 697 | 698 | 784 | 754.8 |
| 38. | 0.0439 | 2.09 | 719.0 | 717 | 718 | 806 | 754.7 |
| 39. | 0.0440 | 1.99 | 741.0 | 739 | 740 | 829 | 759.3 |
| 40. | 0.0439 | 2.17 | 881.6 | 880 | 881 | 988 | 755.6 |
| 41. | 0.0439 | 2.15 | 916.6 | 915 | 916 | 1028 | 757.4 |
| 42. | 0.0439 | 1.88 | 914.2 | 912 | 913 | 1024 | 757.3 |
| 43. | 0.0439 | 2.55 | 995.4 | 993 | 994 | 1115 | 752.6 |
| 44. | 0.0439 | 2.28 | 1006.0 | 1004 | 1005 | 1127 | 756.1 |
| 45. | 0.0439 | 2.51 | 1074.0 | 1074 | 1073 | 1204 | 752.0 |
| 46. | 0.0439 | 2.63 | 1074.0 | 1074 | 1073 | 1203 | 755.5 |
| 47. | 0.0439 | 3.27 | 1321.0 | 1321 | 1319 | 1479 | 754.4 |
| 48. | 0.0439 | 3.18 | 1518.0 | 1518 | 1517 | 1700 | 760.8 |

SUMMARY OF CALCULATIONS FOR WATER, (9/32 INCH PACKING)(continued)

| Run | $\frac{k_g P_f M_m}{G}$ | $(Col)\frac{.45}{Sc}$ | $j_d'$ |
|---|---|---|---|
| 32. | 0.0885 | 0.0687 | 0.0718 |
| 33. | 0.0837 | 0.0672 | 0.0703 |
| 34. | 0.1076 | 0.0865 | 0.0904 |
| 35. | 0.0725 | 0.0582 | 0.0609 |
| 36. | 0.0799 | 0.0642 | 0.0671 |
| 37. | 0.0719 | 0.0577 | 0.0604 |
| 38. | 0.0825 | 0.0663 | 0.0693 |
| 39. | 0.0775 | 0.0622 | 0.0651 |
| 40. | 0.0709 | 0.0570 | 0.0596 |
| 41. | 0.0676 | 0.0543 | 0.0568 |
| 42. | 0.0593 | 0.0476 | 0.0498 |
| 43. | 0.0735 | 0.0591 | 0.0617 |
| 44. | 0.0652 | 0.0524 | 0.0548 |
| 45. | 0.0667 | 0.0536 | 0.0560 |
| 46. | 0.0703 | 0.0565 | 0.0591 |
| 47. | 0.0712 | 0.0572 | 0.0598 |
| 48. | 0.0608 | 0.0488 | 0.0511 |

$\left(\frac{\mu}{\rho D_v}\right) = 0.617$

Table VI

SUMMARY OF CALCULATIONS FOR NAPHTHALENE, (1/4 INCH PACKING)

| Run | $\Delta h_o$ | $\Delta \pi_o$ | $\Delta h_d$ | $\Delta \pi_d$ | $\pi_b$ | $\pi_{o2}$ | $\pi_{o1}$ | Y |
|---|---|---|---|---|---|---|---|---|
| 49. | .60 | 1.12 | 0.25 | 0.49 | 753.5 | 754.0 | 755.1 | .9960 |
| 50. | 1.00 | 1.87 | 0.30 | 0.58 | 752.8 | 753.4 | 755.3 | .9930 |
| 51. | 1.45 | 2.71 | 0.35 | 0.68 | 753.6 | 754.3 | 757.0 | .9991 |
| 52. | 1.90 | 3.55 | 0.50 | 0.98 | 752.8 | 753.8 | 757.4 | .9986 |
| 53. | 3.00 | 5.61 | 0.80 | 1.55 | 752.8 | 754.4 | 750.0 | .9978 |
| 54. | 4.00 | 7.48 | 0.96 | 1.86 | 754.4 | 754.3 | 761.8 | .9977 |
| 55. | 6.00 | 11.30 | 1.47 | 2.85 | 754.4 | 754.3 | 768.6 | .9956 |
| 56. | 8.00 | 14.96 | 1.97 | 3.82 | 754.4 | 758.2 | 773.2 | .9942 |
| 57. | 11.00 | 20.50 | 2.55 | 4.95 | 754.2 | 759.2 | 779.7 | .9922 |
| 58. | 14.00 | 26.15 | 3.30 | 6.40 | 754.2 | 760.6 | 786.8 | .9901 |

SUMMARY OF CALCULATIONS FOR NAPHTHALENE (1/4 INCH PACKING)(continued)

| Run | $H_1$ | $t_{do2}$ | $\Delta\pi_1$ | $\pi_1$ | $Re_o$ | K | $G_o$ | $W_i$ |
|---|---|---|---|---|---|---|---|---|
| 49. | 33 | 18.19 | 1.65 | 755.2 | 860 | .613 | 856 | 13.20 |
| 50. | 37 | 17.92 | 2.90 | 755.7 | 1113 | .609 | 1097 | 16.89 |
| 51. | 33 | 17.90 | 4.10 | 755.7 | 1343 | .607 | 1323 | 20.38 |
| 52. | 37 | 17.71 | 5.20 | 758.0 | 1530 | .606 | 1508 | 23.20 |
| 53. | 37 | 17.48 | 8.00 | 760.8 | 1927 | .604 | 1899 | 29.22 |
| 54. | 47 | 19.37 | 10.30 | 764.7 | 2223 | .602 | 2190 | 33.72 |
| 55. | 47 | 19.37 | 15.30 | 769.7 | 2684 | .601 | 2643 | 40.72 |
| 56. | 47 | 19.29 | 20.30 | 774.7 | 3095 | .600 | 3046 | 46.92 |
| 57. | 33 | 17.44 | 26.40 | 780.6 | 3626 | .600 | 3577 | 55.10 |
| 58. | 33 | 17.16 | 34.30 | 788.5 | 4108 | .599 | 4044 | 62.35 |

SUMMARY OF CALCULATIONS FOR NAPHTHALENE (1/4 INCH PACKING)(continued)

| Run | w | w' | θ | $R_c$ | $10^4 H_2$ | $H_2$ | $\Delta\pi_2$ |
|---|---|---|---|---|---|---|---|
| 49. | 63.6933 | 63.5217 | 16.0 | 0.001422 | 1.078 | 0.80 | 1.5 |
| 50. | 63.9642 | 63.7980 | 14.0 | 0.001571 | .932 | 1.45 | 2.7 |
| 51. | 63.8965 | 63.7297 | 12.0 | 0.001841 | .904 | 1.98 | 3.7 |
| 52. | 64.2126 | 64.0338 | 12.0 | 0.001972 | .851 | 2.57 | 4.8 |
| 53. | 64.4254 | 64.2584 | 10.0 | 0.002212 | .757 | 3.91 | 7.3 |
| 54. | 65.5939 | 65.3502 | 10.0 | 0.003225 | .957 | 5.08 | 9.5 |
| 55. | 65.2099 | 64.9277 | 10.0 | 0.003740 | .918 | 7.61 | 14.2 |
| 56. | 64.7805 | 64.5986 | 6.0 | 0.004018 | .855 | 10.13 | 18.9 |
| 57. | 64.9018 | 64.6895 | 8.0 | 0.003515 | .638 | 13.20 | 24.6 |
| 58. | 65.3031 | 65.1255 | 6.0 | 0.003960 | .635 | 17.25 | 32.2 |

SUMMARY OF CALCULATIONS FOR NAPHTHALENE (1/4 INCH PACKING)(continued)

| Run | $\pi_2$ | $10^2 p_2$ | $t_2$ | $\mu_{av}$ | $G_1$ | A | $\sqrt{A}$ | $P_f$ |
|---|---|---|---|---|---|---|---|---|
| 49. | 755.0 | 1.832 | 19.08 | 0.0440 | 426 | .3403 | 0.0466 | 755.1 |
| 50. | 755.5 | 1.585 | 18.58 | 0.0439 | 545 | .3410 | 0.0467 | 755.6 |
| 51. | 757.3 | 1.543 | 18.39 | 0.0439 | 657 | .3408 | 0.0466 | 757.5 |
| 52. | 757.6 | 1.454 | 18.14 | 0.0439 | 755 | .3424 | 0.0468 | 757.8 |
| 53. | 760.1 | 1.298 | 17.76 | 0.0438 | 943 | .3450 | 0.0469 | 760.4 |
| 54. | 763.9 | 1.627 | 19.71 | 0.0441 | 1087 | .3465 | 0.0479 | 764.3 |
| 55. | 768.6 | 1.592 | 19.53 | 0.0441 | 1317 | .3512 | 0.0474 | 769.1 |
| 56. | 773.3 | 1.492 | 19.46 | 0.0440 | 1513 | .3472 | 0.0471 | 774.0 |
| 57. | 778.8 | 1.122 | 17.33 | 0.0437 | 1776 | .3498 | 0.0474 | 779.7 |
| 58. | 786.4 | 1.127 | 17.08 | 0.0437 | 2010 | .3580 | 0.0480 | 787.4 |

SUMMARY OF CALCULATIONS FOR NAPHTHALENE, (1/4 INCH PACKING)(continued)

| Run | $\frac{\sqrt{A}\,G}{\mu}$ | $p_s$ | $\Delta p_2$ | $\Delta p_{1m}$ | $k_g$ | $\frac{k_g P_f M_m}{G}$ | $(Col)Sc^{.45}$ | $j_d'$ |
|---|---|---|---|---|---|---|---|---|
| 49. | 451 | 0.0461 | 0.0278 | 0.0360 | 0.687 | 0.0463 | 0.0700 | 0.0644 |
| 50. | 580 | 0.0449 | 0.0290 | 0.0361 | 0.755 | 0.0398 | 0.0602 | 0.0553 |
| 51. | 697 | 0.0432 | 0.0278 | 0.0346 | 0.928 | 0.0407 | 0.0614 | 0.0566 |
| 52. | 806 | 0.0422 | 0.0277 | 0.0340 | 1.002 | 0.0382 | 0.0577 | 0.0531 |
| 53. | 1010 | 0.0407 | 0.0277 | 0.0334 | 1.138 | 0.0349 | 0.0527 | 0.0485 |
| 54 | 1181 | 0.0488 | 0.0325 | 0.0395 | 1.357 | 0.0362 | 0.0547 | 0.0503 |
| 55. | 1417 | 0.0480 | 0.0321 | 0.0389 | 1.662 | 0.0361 | 0.0545 | 0.0502 |
| 56. | 1621 | 0.0477 | 0.0328 | 0.0392 | 1.725 | 0.0335 | 0.0506 | 0.0466 |
| 57. | 1926 | 0.0392 | 0.0392 | 0.0327 | 1.820 | 0.0304 | 0.0459 | 0.0423 |
| 58. | 2207 | 0.0382 | 0.0382 | 0.0317 | 2.063 | 0.0307 | 0.0464 | 0.0428 |

$\left(\frac{\mu}{\rho D_v}\right)_f = 2.50$

Table VII

SUMMARY OF CALCULATIONS FOR WATER, (1/6 INCH PACKING)

| Run | $\Delta h_o$ | $\Delta \pi_o$ | $\Delta h_{o2}$ | $\Delta \pi_{o2}$ | $\pi_b$ | $\pi_b$ | $\pi_{o1}$ | $\pi_{o2}$ |
|---|---|---|---|---|---|---|---|---|
| 59. | 1.0 | 5.2 | 0.30 | 1.6 | 753.1 | 2097 | 2104 | 2099 |
| 60. | 1.5 | 7.8 | 0.40 | 2.1 | 751.1 | 2091 | 2101 | 2093 |
| 61. | 1.9 | 9.9 | 0.55 | 2.9 | 753.1 | 2097 | 2110 | 2100 |
| 62. | 3.0 | 15.6 | 0.78 | 4.1 | 753.1 | 2097 | 2117 | 2101 |
| 63. | 4.0 | 20.8 | 1.10 | 5.7 | 753.1 | 2097 | 2124 | 2103 |
| 64. | 5.0 | 26.0 | 1.20 | 6.2 | 751.1 | 2091 | 2123 | 2097 |
| 65. | 6.0 | 31.2 | 1.51 | 7.9 | 753.0 | 2096 | 2135 | 2104 |
| 66. | 7.0 | 36.4 | 1.80 | 9.4 | 753.1 | 2097 | 2142 | 2106 |
| 67. | 8.0 | 41.6 | 2.00 | 10.4 | 752.9 | 2096 | 2148 | 2106 |
| 68. | 8.0 | 41.6 | 1.90 | 9.9 | 751.1 | 2091 | 2143 | 2101 |
| 69. | 8.0 | 41.6 | 1.90 | 9.9 | 751.1 | 2091 | 2143 | 2101 |
| 70. | 8.0 | 41.6 | 1.90 | 9.9 | 751.1 | 2091 | 2143 | 2101 |

SUMMARY OF CALCULATIONS FOR WATER, (1/6 INCH PACKING)(continued)

| Run | $t_{dl}$ | $t_{wl}$ | $t_s$ | $H_l$ | $\bar{V}$ | K | Y |
|---|---|---|---|---|---|---|---|
| 59. | 69.77 | 56.37 | 55.60 | .00624 | 13.48 | 0.609 | 0.999 |
| 60. | 69.68 | 56.93 | 56.41 | .00673 | 13.49 | 0.607 | 0.999 |
| 61. | 68.96 | 55.81 | 55.28 | .00628 | 13.46 | 0.606 | 0.999 |
| 62. | 70.93 | 56.42 | 55.94 | .00610 | 13.52 | 0.604 | 0.998 |
| 63. | 65.92 | 51.84 | 51.43 | .00474 | 13.34 | 0.603 | 0.998 |
| 64. | 70.47 | 56.76 | 56.44 | .00645 | 13.50 | 0.602 | 0.996 |
| 65. | 65.78 | 51.92 | 51.63 | .00477 | 13.34 | 0.601 | 0.996 |
| 66. | 71.00 | 55.23 | 54.96 | .00543 | 13.49 | 0.601 | 0.995 |
| 67. | 65.60 | 51.84 | 51.61 | .00474 | 13.34 | 0.600 | 0.994 |
| 68. | 68.60 | 56.39 | 56.18 | .00662 | 13.46 | 0.600 | 0.994 |
| 69. | 68.46 | 55.38 | 55.16 | .00612 | 13.44 | 0.600 | 0.994 |
| 70. | 68.28 | 54.77 | 54.54 | .00583 | 13.44 | 0.600 | 0.994 |

SUMMARY OF CALCULATIONS FOR WATER, (1/6 INCH PACKING)(continued)

| Run | $G_o$ | $G_1$ | $W_i$ | w | w' | θ | $R_c$ |
|---|---|---|---|---|---|---|---|
| 59. | 10880 | 10793 | 16.61 | 68.3616 | 66.8145 | 5.0 | 0.0409 |
| 60. | 13300 | 13200 | 20.33 | 67.5524 | 65.8787 | 5.0 | 0.0443 |
| 61. | 14960 | 14850 | 22.85 | 68.9140 | 67.1058 | 5.0 | 0.0478 |
| 62. | 18630 | 18490 | 28.47 | 67.7393 | 65.4143 | 5.0 | 0.0615 |
| 63. | 21600 | 21460 | 33.05 | 66.0950 | 63.4880 | 5.0 | 0.0619 |
| 64. | 23970 | 23770 | 36.54 | 68.0720 | 65.3810 | 5.0 | 0.0712 |
| 65. | 26350 | 26180 | 43.00 | 65.7952 | 62.8307 | 5.0 | 0.0785 |
| 66. | 28240 | 28030 | 43.20 | 66.7193 | 63.6852 | 4.0 | 0.1003 |
| 67. | 30930 | 30700 | 47.30 | 66.1230 | 62.9384 | 5.0 | 0.0844 |
| 68. | 30850 | 30610 | 47.20 | 67.8532 | 65.7407 | 3.0 | 0.0933 |
| 69. | 30850 | 30610 | 47.20 | 65.7407 | 63.6681 | 3.0 | 0.0914 |
| 70. | 30850 | 30610 | 47.20 | 63.6681 | 61.5310 | 3.0 | 0.0941 |
| | | | | 61.5301 | 59.6627 | 3.0* | |

* This run was the fourth three minute run in a series of runs made to determine the constant rate period. Since the weight loss was abnormally low, the falling rate period had presumably started and this point was discarded.

SUMMARY OF CALCULATIONS FOR WATER, (1/6 INCH PACKING)(continued)

| Run | $(H_2-H_1)$ | $\Delta h_1$ | $t_1$ | $t_s$ | $\lambda$ | $G_{av}$ | $t_{2(calc)}$ |
|---|---|---|---|---|---|---|---|
| 59. | 0.0246 | 2.6 | 69.77 | 55.60 | 1059 | 539 | 59.00 |
| 60. | 0.0218 | 3.7 | 69.68 | 56.41 | 1059 | 658 | 60.12 |
| 61. | 0.0209 | 4.7 | 68.96 | 55.28 | 1060 | 740 | 59.79 |
| 62. | 0.0216 | 7.4 | 70.93 | 55.94 | 1059 | 923 | 61.48 |
| 63. | 0.0209 | 9.7 | 65.92 | 51.43 | 1061 | 1070 | 56.74 |
| 64. | 0.0195 | 12.3 | 70.47 | 56.44 | 1059 | 1187 | 61.96 |
| 65. | 0.0195 | 14.7 | 65.78 | 51.63 | 1061 | 1307 | 57.25 |
| 66. | 0.0232 | 16.7 | 71.00 | 54.96 | 1060 | 1397 | 60.82 |
| 67. | 0.0178 | 19.9 | 65.60 | 51.64 | 1061 | 1530 | 57.77 |
| 68. | 0.0197 | 19.5 | 68.60 | 56.18 | 1059 | 1527 | 59.93 |
| 69. | 0.0192 | 19.5 | 68.46 | 55.16 | 1060 | 1527 | 59.96 |
| 70. | 0.0199 | 19.5 | 68.28 | 54.54 | 1060 | 1527 | 59.54 |

SUMMARY OF CALCULATIONS FOR WATER, (1/6 INCH PACKING)(continued)

| Run | $\pi_1$ | $\Delta h_b$ | $\pi_2$ | $p_1$ | $H_2$ | $p_s$ | $p_2$ | $\Delta p_1$ |
|---|---|---|---|---|---|---|---|---|
| 59. | 755.7 | 0.2 | 755.5 | 7.53 | 8.70 | 11.30 | 10.42 | 3.77 |
| 60. | 754.8 | 0.2 | 754.6 | 8.09 | 8.91 | 11.66 | 10.67 | 3.57 |
| 61. | 757.8 | 0.3 | 757.5 | 7.58 | 8.37 | 11.17 | 10.07 | 3.59 |
| 62. | 760.5 | 0.5 | 760.0 | 7.39 | 8.26 | 11.45 | 9.99 | 2.60 |
| 63. | 762.8 | 0.7 | 762.1 | 5.78 | 6.83 | 9.71 | 8.30 | 3.93 |
| 64. | 763.4 | 0.7 | 762.1 | 7.85 | 8.40 | 11.68 | 10.17 | 3.83 |
| 65. | 767.7 | 1.1 | 766.6 | 5.87 | 6.72 | 9.77 | 8.22 | 3.90 |
| 66. | 769.8 | 0.9 | 768.9 | 6.68 | 7.75 | 11.06 | 9.49 | 4.38 |
| 67. | 772.8 | 1.4 | 771.4 | 5.87 | 6.52 | 9.77 | 8.00 | 3.90 |
| 68. | 770.6 | 1.1 | 769.5 | 8.14 | 8.59 | 11.53 | 10.49 | 3.39 |
| 69. | 770.6 | 1.1 | 769.5 | 7.52 | 8.04 | 11.13 | 9.83 | 3.61 |
| 70. | 770.6 | 1.1 | 769.5 | 7.17 | 7.82 | 10.88 | 9.58 | 3.71 |

SUMMARY OF CALCULATIONS FOR WATER, (1/6 INCH PACKING)(continued)

| Run | $p_2$ | $\Delta p_{lm}$ | $k_g$ | $P_f$ | $G_{av}$ | $\frac{k_g P_f M_m}{G_{av}}$ |
|---|---|---|---|---|---|---|
| 59. | 0.88 | 1.987 | .00252 | 745.5 | 539 | 0.1002 |
| 60. | 0.99 | 2.015 | .00269 | 744.1 | 658 | 0.0877 |
| 61. | 1.10 | 2.100 | .00278 | 747.6 | 740 | 0.0808 |
| 62. | 1.46 | 2.160 | .00347 | 750.3 | 923 | 0.0814 |
| 63. | 1.41 | 2.456 | .00344 | 754.3 | 1070 | 0.0698 |
| 64. | 1.51 | 2.490 | .00350 | 752.7 | 1187 | 0.0639 |
| 65. | 1.55 | 2.548 | .00376 | 758.7 | 1307 | 0.0630 |
| 66. | 1.57 | 2.731 | .00449 | 759.2 | 1397 | 0.0704 |
| 67. | 1.77 | 2.690 | .00394 | 763.8 | 1530 | 0.0566 |
| 68. | 1.04 | 1.990 | .00573 | 759.6 | 1527 | 0.0822 |
| 69. | 1.30 | 2.260 | .00449 | 760.1 | 1527 | 0.0708 |
| 70. | 1.30 | 2.300 | .00500 | 760.4 | 1527 | 0.0716 |

SUMMARY OF CALCULATIONS FOR WATER, (1/6 INCH PACKING)(continued)

| Run | $\mu_{av}$ | $\frac{\sqrt{A}\ G}{\mu}$ | (Col)$Sc^{*.31}$ | $j'_d$ |
|---|---|---|---|---|
| 59. | 0.0440 | 369 | 0.0863 | 0.0842 |
| 60. | 0.0440 | 452 | 0.0755 | 0.0737 |
| 61. | 0.0439 | 506 | 0.0696 | 0.0678 |
| 62. | 0.0441 | 632 | 0.0701 | 0.0684 |
| 63. | 0.0439 | 733 | 0.0601 | 0.0586 |
| 64. | 0.0440 | 812 | 0.0550 | 0.0537 |
| 65. | 0.0439 | 894 | 0.0543 | 0.0529 |
| 66. | 0.0440 | 956 | 0.0606 | 0.0591 |
| 67. | 0.0439 | 1050 | 0.0487 | 0.0475 |
| 68. | 0.0440 | 1043 | 0.0708 | 0.0690 |
| 69. | 0.0440 | 1047 | 0.0610 | 0.0595 |
| 70. | 0.0439 | 1047 | 0.0616 | 0.0600 |

$$\left(\frac{\mu}{\rho D_V}\right)_f = 0.617$$

Table VIII

SUMMARY OF CALCULATIONS FOR NITROBENZENE, (1/6 INCH PACKING)

| Run | $\Delta h_o$ | $\Delta \pi_o$ | $\Delta h_{o2}$ | $\Delta \pi_{o2}$ | $\pi_b$ | $t_s$ | $t_1$ | $\bar{V}$ |
|---|---|---|---|---|---|---|---|---|
| 71. | 1.0 | 5.2 | 0.25 | 1.3 | 749.8 | 19.14 | 19.38 | 13.37 |
| 72. | 1.5 | 7.8 | 0.37 | 1.9 | 749.8 | 18.58 | 18.91 | 13.36 |
| 73. | 1.9 | 9.9 | 0.50 | 2.6 | 749.8 | 18.49 | 18.71 | 13.35 |
| 74. | 3.0 | 15.6 | 0.80 | 4.2 | 749.8 | 18.23 | 18.44 | 13.33 |
| 75. | 4.0 | 21.1 | 1.00 | 5.2 | 749.2 | 16.80 | 16.95 | 13.26 |
| 76. | 5.0 | 26.0 | 1.25 | 6.5 | 749.8 | 19.43 | 19.72 | 13.39 |
| 77. | 6.0 | 31.5 | 1.50 | 7.8 | 749.2 | 16.79 | 17.03 | 13.26 |
| 78. | 8.0 | 41.6 | 1.90 | 9.9 | 749.2 | 16.78 | 16.98 | 13.26 |
| 79. | 11.5 | 57.5 | 2.60 | 13.5 | 749.8 | 17.89 | 18.15 | 13.32 |
| 80. | 14.5 | 73.2 | 3.40 | 17.7 | 749.8 | 17.72 | 17.98 | 13.31 |

Table VIII

SUMMARY OF CALCULATIONS FOR NITROBENZENE, (1/6 INCH PACKING)(continued)

| Run | K | Y | $G_o$ | $W_i$ | W | W' | θ |
|---|---|---|---|---|---|---|---|
| 71. | 0.609 | 0.999 | 10,960 | 16.88 | 69.7720 | 69.3150 | 6.0 |
| 72. | 0.607 | 0.999 | 13,350 | 20.53 | 70.5741 | 70.0043 | 7.0 |
| 73. | 0.606 | 0.999 | 15,050 | 23.17 | 71.1101 | 70.5741 | 6.0 |
| 74. | 0.604 | 0.998 | 18,800 | 28.94 | 71.8855 | 71.3638 | 5.0 |
| 75. | 0.603 | 0.998 | 21,870 | 33.72 | 69.9303 | 69.3880 | 5.0 |
| 76. | 0.602 | 0.997 | 24,120 | 37.18 | 68.7793 | 68.0793 | 5.0 |
| 77. | 0.601 | 0.996 | 26,400 | 40.70 | 70.5502 | 69.9303 | 5.0 |
| 78. | 0.600 | 0.994 | 30,500 | 47.00 | 71.2538 | 70.5502 | 5.0 |
| 79. | 0.600 | 0.992 | 35,650 | 54.40 | 71.9834 | 71.1495 | 5.0 |
| 80. | 0.599 | 0.990 | 40,100 | 61.70 | 71.1495 | 70.2348 | 5.0 |

SUMMARY OF CALCULATIONS FOR NITROBENZENE, (1/6 INCH PACKING)
(continued)

| Run | $10^2 R_c$ | $10^4 H_2$ | $h_1$ | $\pi_1$ | $\Delta h_b$ | $\pi_2$ | $P_2$ |
|---|---|---|---|---|---|---|---|
| 71. | 1.008 | 5.97 | 2.8 | 752.6 | 0.2 | 752.4 | .1057 |
| 72. | 1.076 | 5.25 | 3.9 | 753.7 | 0.3 | 753.4 | .0933 |
| 73. | 1.180 | 5.10 | 4.9 | 754.9 | 0.4 | 754.5 | .0907 |
| 74. | 1.378 | 4.77 | 7.5 | 757.3 | 0.5 | 756.8 | .0850 |
| 75. | 1.433 | 4.25 | 10.5 | 759.7 | 1.0 | 758.7 | .0759 |
| 76. | 1.850 | 4.98 | 12.9 | 762.7 | 1.1 | 761.6 | .0893 |
| 77. | 1.639 | 4.03 | 15.3 | 764.5 | 1.3 | 763.2 | .0724 |
| 78. | 1.860 | 3.96 | 19.3 | 768.5 | 1.5 | 767.0 | .0714 |
| 79. | 2.204 | 4.05 | 27.4 | 777.2 | 1.8 | 775.4 | .0739 |
| 80. | 2.418 | 3.92 | 35.6 | 785.4 | 2.2 | 783.2 | .0723 |

SUMMARY OF CALCULATIONS FOR NITROBENZENE, (1/6 INCH PACKING)
(continued)

| Run | $p_s$ | $\Delta p_2$ | $\Delta p_{lm}$ | $k_g'$ | $P_f$ | G | $\frac{K_g P_f M_m}{G}$ |
|---|---|---|---|---|---|---|---|
| 71. | .1835 | .0788 | 0.1230 | .001462 | 752.3 | 544 | .0584 |
| 72. | .1746 | .0813 | 0.1220 | .001558 | 753.6 | 663 | .0512 |
| 73. | .1737 | .0830 | 0.1228 | .001714 | 754.7 | 747 | .0501 |
| 74. | .1699 | .0849 | 0.1226 | .002007 | 757.0 | 933 | .0471 |
| 75. | .1506 | .0747 | 0.1086 | .002358 | 759.2 | 1087 | .0476 |
| 76. | .1940 | .1033 | 0.1401 | .002355 | 762.2 | 1198 | .0433 |
| 77. | .1521 | .0797 | 0.1118 | .002610 | 763.8 | 1312 | .0441 |
| 78. | .1520 | .0806 | 0.1126 | .002947 | 767.7 | 1517 | .0432 |
| 79. | .1652 | .0913 | 0.1245 | .003163 | 776.3 | 1756 | .0404 |
| 80. | .1631 | .0908 | 0.1233 | .003495 | 784.3 | 1990 | .0398 |

SUMMARY OF CALCULATIONS FOR NITROBENZENE, (1/6 INCH PACKING)
(continued)

| Run | $\mu$ | $\frac{A\ G}{\mu}$ | $(Col)Sc^{.31}$ | $j_d'$ |
|---|---|---|---|---|
| 71. | .0441 | 371 | 0.0751 | 0.0800 |
| 72. | .0440 | 354 | 0.0659 | 0.0701 |
| 73. | .0440 | 511 | 0.0644 | 0.0686 |
| 74. | .0440 | 637 | 0.0605 | 0.0645 |
| 75. | .0439 | 745 | 0.0611 | 0.0652 |
| 76. | .0441 | 819 | 0.0557 | 0.0593 |
| 77. | .0439 | 899 | 0.0567 | 0.0604 |
| 78. | .0439 | 1039 | 0.0554 | 0.0592 |
| 79. | .0440 | 1202 | 0.0519 | 0.0553 |
| 80. | $\left(\frac{\mu}{\rho D_V}\right)_f = 2.40$ .0440 | 1362 | 0.0512 | 0.0545 |

Table IX

SUMMARY OF CALCULATIONS FOR HEAT TRANSFER "J" NUMBERS

| Run | $t_1$ °F | $t_s$ | $\lambda$ | $R_c$ | $G_{av}$ | $t_{2(calc.)}$ | $\frac{h}{C_p G}$ |
|---|---|---|---|---|---|---|---|
| 32. | 66.35 | 47.74 | 1061 | 0.03175 | 387.7 | 54.67 | 0.0850 |
| 33. | 69.17 | 52.16 | 1061 | 0.03462 | 471.5 | 58.70 | 0.0821 |
| 34. | 70.65 | 52.71 | 1061 | 0.04777 | 542.6 | 58.13 | 0.1028 |
| 35. | 63.79 | 46.03 | 1064 | 0.04306 | 609.0 | 53.71 | 0.0719 |
| 36. | 67.40 | 49.02 | 1063 | 0.05367 | 663.0 | 55.88 | 0.0846 |
| 37. | 65.20 | 47.59 | 1064 | 0.04814 | 698.0 | 55.38 | 0.0700 |
| 38. | 63.20 | 47.04 | 1064 | 0.05027 | 718.0 | 53.22 | 0.0823 |
| 39. | 68.60 | 51.06 | 1062 | 0.05322 | 740.0 | 58.38 | 0.0752 |
| 40. | 64.60 | 46.40 | 1064 | 0.06010 | 881.0 | 54.82 | 0.0662 |
| 41. | 66.18 | 47.65 | 1064 | 0.06332 | 916.0 | 56.35 | 0.0649 |
| 42. | 65.80 | 47.66 | 1064 | 0.05735 | 913.0 | 56.83 | 0.0587 |
| 43. | 67.19 | 48.95 | 1063 | 0.07069 | 994.0 | 57.06 | 0.0697 |
| 44. | 64.60 | 46.48 | 1064 | 0.06529 | 1005.0 | 55.34 | 0.0616 |
| 45. | 67.19 | 48.95 | 1063 | 0.07241 | 1073.0 | 57.59 | 0.0642 |
| 46. | 67.19 | 48.95 | 1063 | 0.07515 | 1073.0 | 57.23 | 0.0677 |
| 47. | 67.35 | 49.26 | 1063 | 0.09227 | 1319.0 | 57.41 | 0.0685 |
| 48. | 67.00 | 49.50 | 1062 | 0.09325 | 1517.0 | 58.26 | 0.0595 |

SUMMARY OF CALCULATIONS FOR HEAT TRANSFER "j" NUMBERS (continued)

| Run | $j_h$ | $j_d$ | $j_h/j_d$ | $\frac{\sqrt{A}\,G}{\mu}$ |
|---|---|---|---|---|
| 32. | 0.0697 | 0.0618 | 1.128 | 435 |
| 33. | 0.0674 | 0.0606 | 1.110 | 527 |
| 34. | 0.0843 | 0.0778 | 1.080 | 608 |
| 35. | 0.0589 | 0.0524 | 1.123 | 683 |
| 36. | 0.0694 | 0.0578 | 1.200 | 744 |
| 37. | 0.0574 | 0.0520 | 1.103 | 784 |
| 38. | 0.0675 | 0.0596 | 1.132 | 806 |
| 39. | 0.0617 | 0.0560 | 1.100 | 829 |
| 40. | 0.0542 | 0.0512 | 1.058 | 988 |
| 41. | 0.0533 | 0.0488 | 1.092 | 1028 |
| 42. | 0.0482 | 0.0428 | 1.123 | 1024 |
| 43. | 0.0572 | 0.0532 | 1.074 | 1115 |
| 44. | 0.0505 | 0.0472 | 1.070 | 1125 |
| 45. | 0.0527 | 0.0482 | 1.092 | 1204 |
| 46. | 0.0555 | 0.0508 | 1.092 | 1203 |
| 47. | 0.0562 | 0.0515 | 1.090 | 1979 |
| 48. | 0.0488 | 0.0440 | 1.109 | 1700 |

SUMMARY OF CALCULATIONS FOR HEAT TRANSFER "j" NUMBERS (continued)

| Run | $t_1$ °F | $t_s$ | $\lambda$ | $R_c$ | $G_{av}$ | $t_2$(calc.) |
|---|---|---|---|---|---|---|
| 59. | 69.77 | 55.60 | 1059 | 0.0409 | 539 | 59.00 |
| 60. | 69.68 | 56.41 | 1059 | 0.0443 | 658 | 60.12 |
| 61. | 68.96 | 55.28 | 1060 | 0.0478 | 740 | 59.79 |
| 62. | 70.93 | 55.94 | 1059 | 0.0615 | 923 | 61.48 |
| 63. | 65.92 | 51.43 | 1061 | 0.0619 | 1070 | 56.74 |
| 64. | 70.47 | 56.44 | 1059 | 0.0712 | 1187 | 61.96 |
| 65. | 65.78 | 51.63 | 1061 | 0.0785 | 1307 | 57.25 |
| 66. | 71.00 | 54.96 | 1060 | 0.1003 | 1397 | 60.82 |
| 67. | 65.60 | 51.64 | 1061 | 0.0844 | 1530 | 57.77 |
| 68. | 68.60 | 56.18 | 1059 | 0.0933 | 1527 | 59.93 |
| 69. | 68.46 | 55.16 | 1060 | 0.0914 | 1527 | 59.96 |
| 70. | 68.28 | 54.54 | 1060 | 0.0941 | 1527 | 59.54 |

SUMMARY OF CALCULATIONS FOR HEAT TRANSFER "j" NUMBERS (continued)

| Run | $\frac{h}{C_p G}$ | $j_h$ | $j_d$ | $j_h/j_d$ |
|---|---|---|---|---|
| 59. | 0.0972 | 0.0797 | 0.0725 | 1.098 |
| 60. | 0.0868 | 0.0712 | 0.0634 | 1.122 |
| 61. | 0.0755 | 0.0618 | 0.0584 | 1.058 |
| 62. | 0.0677 | 0.0555 | 0.0588 | 1.058 |
| 63. | 0.0711 | 0.0583 | 0.0505 | 1.153 |
| 64. | 0.0636 | 0.0522 | 0.0462 | 1.130 |
| 65. | 0.0629 | 0.0516 | 0.0456 | 1.131 |
| 66. | 0.0736 | 0.0604 | 0.0508 | 1.188 |
| 67. | 0.0558 | 0.0457 | 0.0409 | 1.118 |
| 68. | 0.0815 | 0.0688 | 0.0594 | 1.158 |
| 69. | 0.0694 | 0.0568 | 0.0512 | 1.108 |
| 70. | 0.0760 | 0.0623 | 0.0517 | 1.203 |

Table X

PACKED BED PROPERTIES

| | Dry weight | Diameter av. | Height av. | No. of Pellets | Total pellet area | $A_V$ |
|---|---|---|---|---|---|---|
| Large Celite Pellets | 31.343g | 0.2722 in. | 0.2716 in. | 149 | 0.361 $ft^2$ | 116 $\frac{ft^2}{ft^3}$ |
| Small Celite Pellets | 23.847g | 0.1683 in. | 0.1638 in. | 500 | 0.4552 $ft^2$ | 287 $\frac{ft^2}{ft^3}$ |
| Naphthalene Pellets | | | | | | |
| *run | | | | | | |
| 54 | 36.475gB** | 0.2672B | 0.2524B | 156 | .3565 | 125 $\frac{ft^2}{ft^3}$ |
| 55 | | ..... | ..... | 156 | .3512 | |
| 56 | 35.480gA** | 0.2651A | 0.2508A | 156 | .3472 | 126 $\frac{ft^2}{ft^3}$ |
| 53 | | ..... | ..... | 156 | .3450 | |
| 52 | | ..... | ..... | 156 | .3424 | |
| 50 | | ..... | ..... | 156 | .3410 | |
| 51 | | ..... | ..... | 157 | .3408 | |
| 49 | 34.403gA** | 0.2620A | 0.2481A | 157 | .3403 | 130 $\frac{ft^2}{ft^3}$ |
| 58 | | 0.2670B | 0.252B | 156 | .3580 | 135 $\frac{ft^2}{ft^3}$ |
| 57 | | ..... | ..... | 155 | .3498 | |

*Listed in chronological order

**A = after the run

B = before the run

Table XI

PHYSICAL PROPERTIES

| | Aniline | Nitrobenzene | Naphthalene |
|---|---|---|---|
| Freezing Point: (°C) | | | |
| Experimental | -5.3 to -6.2 | 5.1 to 5.8 | 80.3 |
| Handbook of Chem. and Physics. | -6.2 | 5.7 | 80.22 |
| Boiling Point: (°C) | | | |
| Experimental | 183.8 -184 at 756.2 mm. | 209.9 at 756.2 mm. | 218.0 -218.2 |
| Handbook of Chem. and Physics | 184.4 at 760 mm. | 210.9 at 760 mm. | 217.9 at 760 mm. |