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EFFECT OF PRESSURE ON MASS TRANSFER IN THE GAS PHASE

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Robert Joseph Fallat
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March 1959

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ABSTRACT

The work of E. J. Lynch on mass transfer in packed columns with countercurrent liquid-gas systems[1] suggested that the height of a transfer unit (HTU_G) might be expressed as a function of a $\sqrt{\rho u^2}$ parameter (ρ = density, u = gas velocity) in place of the more commonly used Reynolds number, and further suggested the use of the Schmidt number raised to the 1/2 power instead of the more commonly used 2/3 power.

Further work was carried out by Lynch and Wilke with packed beds of solid napthalene and nitrobenzene or water-saturated alundum spheres over which hydrogen, Freon-12, helium, and air were passed.[2] The systems of air-napthalene and helium-napthalene were further used by the author at pressures up to 37.8 atmospheres. The work of Lynch and Wilke along with the high-pressure studies presented here substantiated the Reynolds number, Re, rather than $\sqrt{\rho u^2}$, in two ways. First, the low-pressure data of Lynch and Wilke could not be correlated with any accuracy when the $\sqrt{\rho u^2}$ parameter was used, but gave, with Re, the equation

$$a_v HTU_G = 1.344\ Sc^{0.666}\ Re^{0.322}$$

where the standard deviation of the ln $a_v HTU_G$ is 0.078. Secondly, the high-pressure data scattered very little from the above equation utilizing Re, but exhibited considerably variation when plotted versus $\sqrt{\rho u^2}$, the variation with pressure being exactly that expected if Re were the correct correlating modulus.

With this strong experimental evidence, it was concluded that $\sqrt{\rho u^2}$ is inadequate as a parameter in correlating mass-transfer data in the absence of liquid flow over the packing; however, countercurrent liquid-gas flow systems will have to be more thoroughly studied to establish the use of either Re or $\sqrt{\rho u^2}$ more conclusively.

The following final equation for the low-pressure data of Lynch and Wilke on packings without liquid flow was shown to be in generally good agreement with others in the literature:

$$J_D = \frac{Sc^{2/3}}{a_v HTU_G} = 0.626 \left(\frac{D_P G}{\mu}\right)^{-0.322}$$

Finally, it was pointed out that the use of a fugacity gradient as the mass-transfer driving potential was not so satisfactory to correlate the high-pressure data as the commonly accepted concentration gradient.

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INTRODUCTION

The study on this subject by Lynch considered mass-transfer rates between a liquid and a gas stream in countercurrent flow in a packed column containing 1-inch Raschig rings.[1] Water was vaporized into three gases, helium, air, and Freon-12. A psychrometric study was run concurrently on the same three systems.

The results of this experiment indicated the Reynolds number, Re, to be inadequate as a correlating parameter in two important respects. First, the loading points of the three systems did not occur at the same value of Re, and second, to correlate the three systems on a single plot, the Re parameter required the use of the Schmidt number, Sc, to the 0.9 power, a conclusion hardly justified in view of the poor agreement with the 0.5 power obtained from the psychrometric study and similar values reported by several other investigators (see Discussion, below). Therefore in place of Re the "inertia group," ρu^2, was proposed, based on a qualitative analogy to momentum transfer in packed beds which had been shown to be a function of ρu^2 and independent of Re at high Re.[1] This new group corrected both of the difficulties found with Re; the loading points occurred at one value of $\sqrt{\rho u^2}$ for all three systems, and the 0.47-power dependence on Sc was in good agreement with the other investigations.

Although this experiment indicated the possible usefulness of the $\sqrt{\rho u^2}$ group in mass-transfer correlations, more corroborating evidence was needed to substantiate its validity. In addition, some uncertainty was introduced into the results by the presence of a flowing liquid, since the wetted area available might vary with the gases used as well as with the flow rates. In an effort to obviate these difficulties

and to collect further evidence for the use of $\sqrt{\rho u^2}$, Lynch and Wilke carried out experiments at atmospheric pressure using packed-bed systems with no liquid flow.[2] These data are presented in this report, as they provided the initial arguments against the use of $\sqrt{\rho u^2}$ and further served as a useful baseline in a comparison with my high-pressure data.

These "no liquid flow" experiments of Lynch and Wilke utilized a bed of porous pellets which were thoroughly soaked with the liquid to be vaporized. The vaporization rate was measured in the "constant rate" drying period. Nitrobenzene was the liquid selected for these experiments. The use of an organic liquid, however, restricted the investigations to inert gases; Freon-12, helium, hydrogen, and air were used. Water-air was another system used in order to compare these experiments with the extensive data already reported in the literature on the air-water system.

It is also possible to measure the sublimation rate of an organic solid in a packed bed. This technique was not only used in the low-pressure work of Lynch and Wilke but also was especially well suited to the high-pressure studies that I undertook to further confirm the use of either Re or $\sqrt{\rho u^2}$ as explained in Theory. The use of solid packing seemed desirable when it appeared that the various pressures might be influencing the liquid feed to the surface of the ceramic pellets. Napthalene was chosen for this group of experiments since the molded, cylindrical pellets proved rugged enough to withstand handling and pressures and also had a sufficiently low vapor pressure so that change in pellet size during a run and the wet-bulb temperature depression were minimized. Air, helium, and Freon-12 gases were used by Lynch and Wilke at atmospheric pressure, whereas I used only air and helium for the high-pressure studies.

THEORY

For flow in pipes, annular spaces, and other streamlined shapes, where only skin friction is involved, the velocity distribution has been well defined and several satisfactory theories have been proposed for the correlation of mass-transfer data based on the analogy between transfer of heat, mass, and momentum and the known velocity distribution. A survey of these is given by Lynch.[1] These theories may all be expressed by the same general form,

$$S_t = \frac{h}{C_p G} = \frac{\frac{f}{2}}{\Theta\,(Pr)} \tag{1}$$

for heat transfer, and

$$S'_t = \frac{k_g\, M_m\, p_{BM}}{G} = \frac{\frac{f}{2}}{\Theta'\,(Sc)} \tag{2}$$

for mass transfer.

The development of an equally successful theory in packed beds has been prohibited by the extremely irregular flow patterns, which have not as yet been satisfactorily represented mathematically. However, Chilton and Colburn[3] found empirically that the packed-tube data on heat transfer could be correlated by using $(Pr)^{2/3}$ for $\Theta\,(Pr)$ in Equation (1) and suggested that, by analogy, it should be possible to represent mass-transfer data by a similar equation with $Sc^{2/3}$. Using these equations they defined two new terms,

$$J_H = \frac{h}{C_p\, \rho\, u_{av}}\,(Pr)^{2/3} = \psi\,(Re), \tag{3}$$

$$J_D = \frac{k_g\, M_m\, p_{BM}}{G}\,(Sc)^{2/3} = \psi'\,(Re). \tag{4}$$

However, the use of 2/3 or any other single-power function of Sc has never been shown to be fully satisfactory over extensive ranges of Sc, and the latest work of Lynch and Wilke using a modified form of the Lin, Moulton, and Putnam equations,[4] indicates the necessity of a

function that varies with both Re and Sc numbers and may account for the various values reported in the literature ranging from 0.15 to 1.0.

Furthermore, the ψ (Re) is found experimentally to approximate f/2 for streamlined shapes, but for flow past bluff objects such as packed beds of spheres or cylinders, the assumption of a uniform boundary layer throughout the area of mass transfer and the further assumption that the friction factor adequately describes the energy transfer are no longer valid. As a result, the use of any Re number function has been questioned, and the group $D_p \sqrt{\rho u^2}$ has been proposed as a substitute, as explained in Introduction.

A study of the pressure effects on J_D is one simple and effective method of confirming either ψ (Re) or ψ ($D_p u \sqrt{\rho}$) in Eq. 4. For the systems used and the range covered in this experiment, these parameters may be satisfactorily used as simple negative fractional-power functions; that is,

$$J_D = C_1 \left[\frac{D_p u \rho}{\mu}\right]^{-Y}$$

or

$$J_D = C_2 \left[D_p u \sqrt{\rho}\right]^{-Y} ,$$

where Y equals approximately 0.4, as found by several investigators using Re.

Since D_p of the solid pellets is independent of pressure and also since the viscosities (μ) of vapors and gases exhibit relatively little change with pressure, it is clear that, as a constant mass rate of flow ($u \rho$), there should be no change of J_D with pressure if Re is correct, but a variation equivalent to $\rho^{Y/2}$ and therefore approximately to $P^{Y/2}$ if $D_p u \sqrt{\rho}$ is the correct parameter. Conversely, if $u \sqrt{\rho}$ were kept constant while the pressure was varied, there should be no change in J_D if $D_p u \sqrt{\rho}$ were correct but a change proportional to $\rho^{-Y/2}$ or $P^{-Y/2}$ if Re were the correct parameter. Since Y is approximately 0.4, a 30-fold variation in pressure should give an approximate twofold variation in Sc if one or the other parameters is correct.

For correlation of packed-bed design Chilton and Colburn[5] further defined the following terms:

$$h = HTU_G \; NTU_G, \tag{5}$$

where h = height of the packed bed, HTU_G = height of a transfer unit

$$= \int_0^h \frac{G_M}{k_g \; a_v \; P_{BM}} = \frac{Sc^X}{(a_v \; J_D)}, \tag{6}$$

NTU_G = number of transfer units

$$= \int_0^h \frac{-y_{PM} \; d\,y}{(1 - y/2)\;(y - y_w)} . \tag{7}$$

These integral forms are taken from Wilke.[6]

In this work, where the materials used have very low vapor pressures, the NTU_G may be calculated from the integrated form

$$NTU_G = \ln \frac{(y_w - y)_o}{(y_w - y)_h}, \tag{8}$$

where y_w and y are the saturated and bulk stream concentrations respectively.

EQUIPMENT

The equipment used for my high-pressure studies is shown in Figs. 1, 2, and 3. The high-pressure gas was supplied from a bank of six cylinders feeding into a common manifold. The pressure in the system was kept constant by use of a specially made two-stage Victor regulator capable of handling outlet pressures accurately from 0 to 1000 psig. Slight variation in outlet pressure due to a drop in the cylinder pressure occurred at the higher pressures, but this was controlled by the valves V_2 and V_3 or V_4. With this multiple control, the maximum pressure deviation from the mean value of a run was less than 1%.

To heat the gas after expansion from the cylinder and to keep a constant temperature in the bed, the gas was sent through two 100-foot coils of 1/4-inch refrigerator-type copper tubing, C_1, placed in a constant-temperature water bath. A mercury-switch-relay-heater system kept the bath temperature constant to within 0.1°C.

One-half-inch insulated copper tubing carried the gas to the bed tube, which was made from 2-inch o.d. stainless steel pipe. The bed was made of a light aluminum alloy tubing (1.93-inch i.d.) with a fine-mesh screen floor for supporting the 1-inch-deep bed of 150 randomly packed, cylindrical napthalene pellets (1/4 x 1/4 inch). The bed was held in a removable section of the same 2-inch o.d. stainless steel pipe as the rest of the bed tube. The short bed used in the experiment is shown in Fig. 3 being inserted into the bed tube from behind, while a similar but longer (8-inch pellet depth) aluminum bed and its stainless steel holder are shown standing beside the assembly in the same photograph. The longer bed was used to determine the saturated vapor pressure values for napthalene at high pressures. To properly seat the bed-holding mechanism required a turn of approximately 200° of the section shown between Plates 1 and 2 by using the rod shown in Fig. 3. Since Plate 2 is fixed in the tube, the screw action forces Plate 1 up and this in turn pulls Plate 3 and the bottom part of the tube tightly up against the bed section via the three preset bolts. O-ring rubber gaskets proved an excellent high-pressure gas seal.

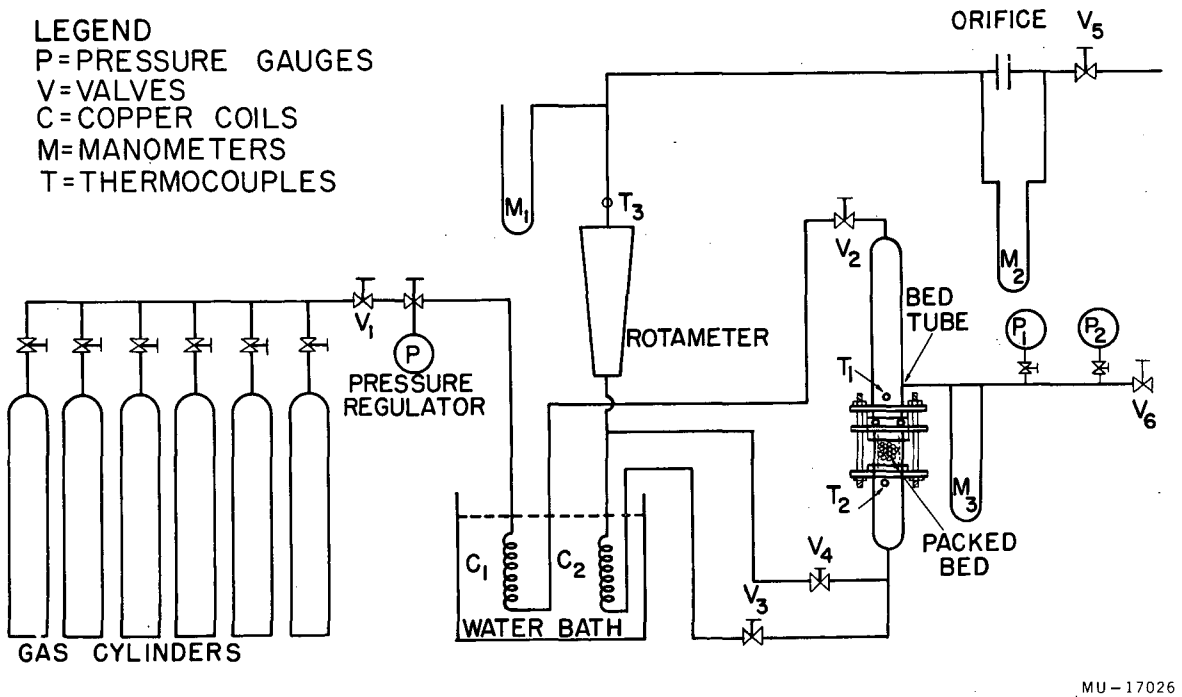

Fig. 1. High-pressure equipment.

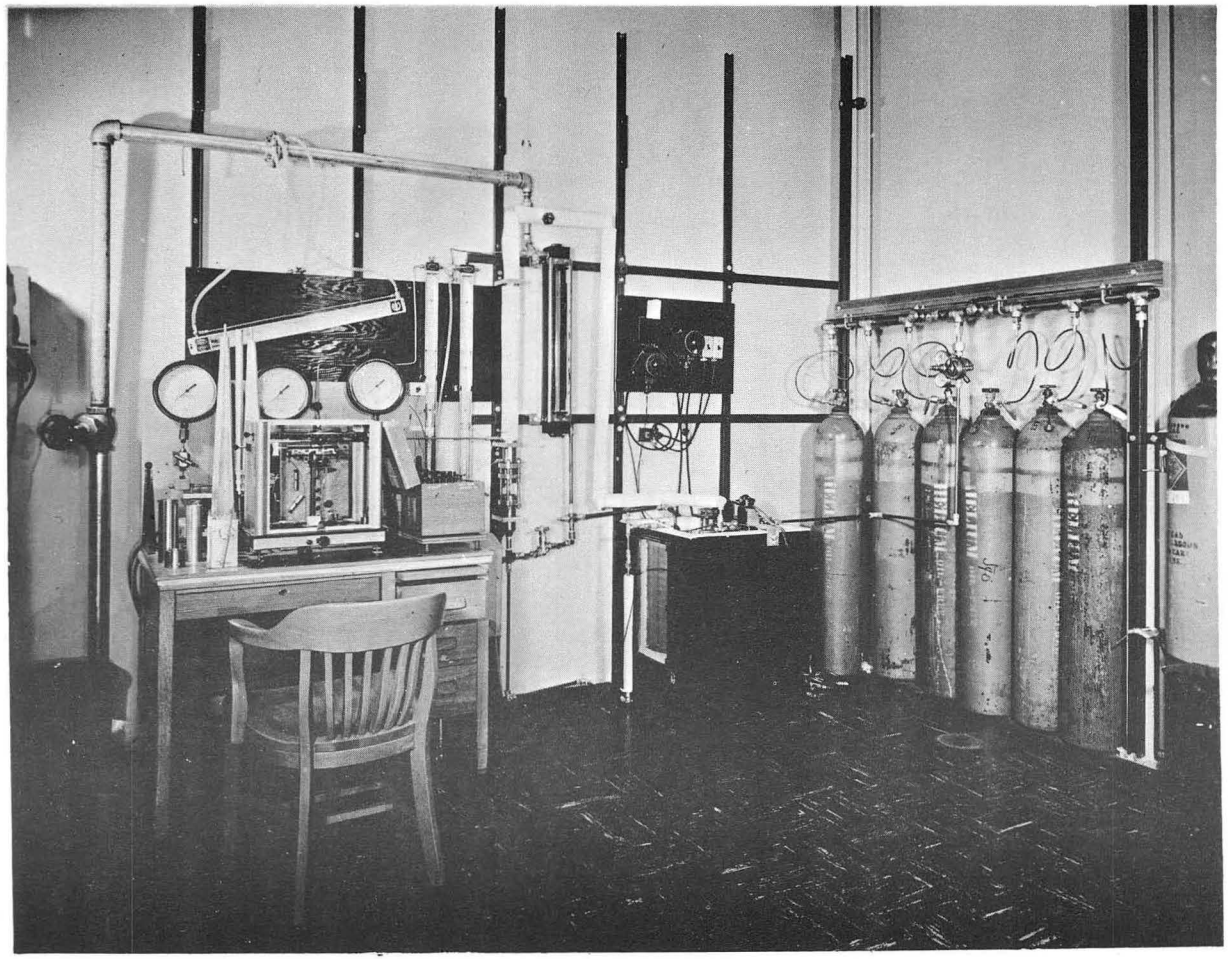

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Fig. 2. High-pressure equipment.

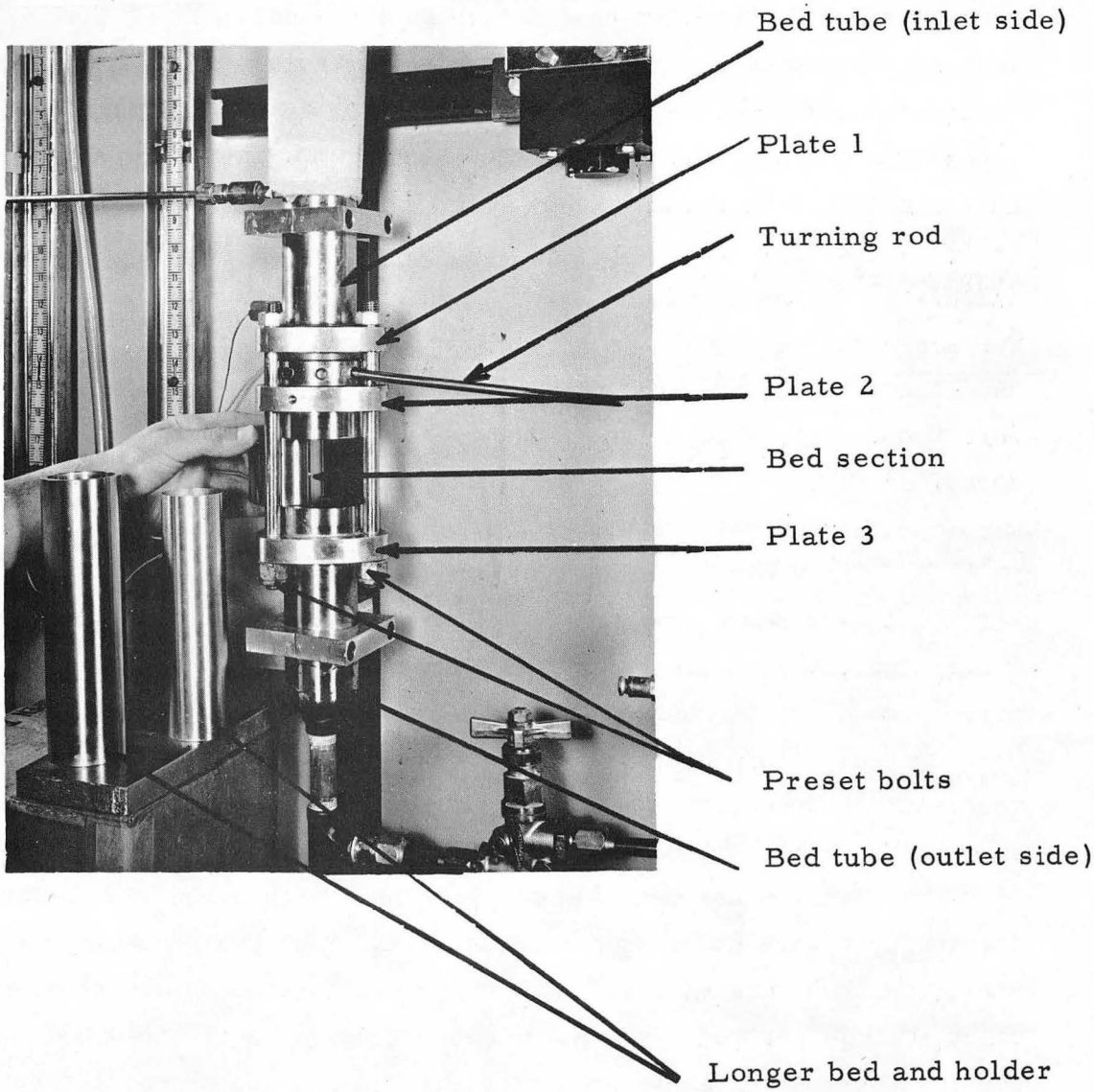

Fig. 3. Detail photograph of high-pressure bed-holding mechanism.

After passing through the bed the gas was throttled down through valve V_3 and then passed through a 50-foot coil, C_2, of 5/8-inch copper tubing in the same constant-temperature water bath previously used. For runs at the lowest pressures it was necessary to bypass the cooling coils and needle valve V_3 to minimize pressure drop in the exit piping. This was done through the lower control valve V_4.

The flow rate was measured by a two-float Brooks Co. Rotameter calibrated by the company to within 1% for air at 1 atmosphere and 70°F. The scale ranged from 0.4 to 3.4 cfm and from 3.0 to 20.0 cfm for the two floats. Pressure and temperature corrections were supplied but were found negligible in the range used. For the helium runs, an ASME-specified flange-tap orifice was used; with a draft guage, the orifice was found accurate to within 2% by calibration with the air rotameter.

The pressure within the bed was measured on a mercury manometer for the low-pressure runs and on two United States Co. Bourdon-type guages for the high pressures. The guages were calibrated with a mercury dead-weight guage to within the scale reading accuracy of 0.1%. Pressure was also measured at the rotameter outlet with a water manometer to determine the density of the gas and also to determine any correction that might have been necessary on the meter.

Temperature measurements were made with number 30 Cu-constantan thermocouple wire and a precision Leeds and Northrup portable potentiometer. Calibrations at 0 and 32.4°C (crystallization temperature of $Na_2SO_4 \cdot 10\ H_2O$), assured temperature determination to within ± 0.1°. Readings were taken above and below the bed and at the rotameter outlet.

PROCEDURE

Generally, the procedure in the high-pressure study was to make a series of four runs, one at each bed pressure of approximately 540, 440, 300, and 150 psig, while the mass rate of flow, G, and all temperature and pressure conditions were kept as constant as possible. The bed was weighed on a Chainomatic balance to 0.1 mg at the beginning and end of each run to determine the napthalene vaporized. The time of each run was set to give approximately the same weight loss of 0.1 gm per run. The difficulties involved in startup and shutdown at the higher pressures accounted for the major errors encountered in this operating procedure.

The first step in a run was to preset the regulator at the pressure desired under flow conditions, in order to set the pressure more accurately and quickly during the run. Valve V_2 was then closed, keeping the desired operating pressure in coil C_1. The next step was to determine the error involved in the startup and shutdown. It was found that if the pressure in the bed tube was allowed to build up too rapidly during startup, the sudden burst of gas into the bed tube and especially into the packed bed of solid napthalene pellets produced unexpectedly high temperatures. In fact, at the higher pressures the temperature rose to the melting point of napthalene, as evidenced by the fusion of the top layers of pellets. To overcome this difficulty, valve V_2 was cracked open very slowly while valves V_3 and V_4 were closed, allowing the pressure to build up at a rate predetermined for that pressure and flow rate to give a minimum temperature rise in the pellets and at the same time not have too great a loss of napthalene from the bed. For all but the low-pressure (7 psig) runs, 4 minutes were allowed for the pressure to build up, then valve V_3 was opened and 1 minute was allowed for adjustments of valves V_2 and V_3 to obtain the desired pressure and flow rate and to allow the system to come to equilibrium. For the 7-psig runs both the regulator and valve V_4 were preset (V_3 kept closed throughout the run) and V_2 was quickly opened, allowing only a 0.25-minute startup time in order to minimize the

napthalene vaporization. The shutdown was also standardized. The procedure was to close valve V_2 as quickly as possible at the end of a time run and open the vent valve V_6 as soon as V_2 was fully closed. This procedure of startup and shutdown was carried out twice before each run and an average value of the napthalene weight loss from the two was used to correct the weight loss for that run. This correction was as high as 8.8% of the total napthalene weight change, but the maximum difference found between any of the pairs of correction runs was only 0.5 mg or 0.43% of the total weight change.

The time of the runs varied from 3 minutes for the high-flow-rate, low-pressure runs to 60 minutes for the 540-psig, Re = 943 run. This kept the total napthalene weight change at a value high enough for accuracy and low enough to prevent the bed characteristics from changing throughout the experiment, as the average dimensions of the pellets did not change after several runs. Readings of the rotameter, bed pressure (P_B), and rotameter pressure (P_F), temperatures above and below the bed (T_1,T_o), and rotameter temperatures (T_F) were taken every 5 minutes for all but the 7-psig runs, for which readings were taken either every minute or every 2.5 minutes. Average values of these readings were then used in the calculations.

Fluctuations in flow rate were controlled by the needle valves V_3 and V_4. The variation in readings was never more than 0.4 cfm at 70°F. 1 atmos); this represented a maximum deviation from the average reading of 2.3%, while the average deviation for all runs was less than 1%, well within the accuracy of the rotameter. The pressure was controlled mainly by valve V_2 during a run. The maximum deviation encountered was 0.98%.

By far the most significant error in the experiment was in the bed temperature. Even with the care taken to allow a very slow buildup of pressure, the bed temperature gave evidence of some undesirable temperature variations that could have been eliminated only by an elaborate redesign of the equipment. The temperature effect manifested itself not only by a change in temperature during a run of as much as

1.50°C, but also by as much as 0.3°C difference in temperature between the top and bottom of the bed for a given reading. However, these extreme variations occurred only for a short time interval at the starts of the runs, and average differences between top and bottom readings were less than 0.05°C. For all but three of the air runs the maximum bed-temperature deviation from the average value of all readings during a run was less than 0.3°C. These measurements were quite precise enough for the deviations to have a negligible effect on the calculations, correlations, and conclusions.

Additional difficulties were encountered when other gases such as helium were used in the equipment. Since the bed had to be removed from the equipment for weighing, attempts were made at purging the bed with air before removal, but this resulted in large weight losses that were difficult to standardize. As a result the bed was simply removed and weighed in air, and the startup-shutdown weight corrections were relied on to account for the uncertainties in this weighing procedure. The total weight of napthalene was large enough to keep uncertainties in the calculation of a_v HTU_G within the range of ± 10%. In spite of this large error, two high-pressure and two low-pressure runs were made with helium in the same manner as the air runs to obtain at least a qualitative confirmation of the air data.

RESULTS

The values of a_v HTU_G collected at atmospheric pressure by Lynch and Wilke are shown in Figs. 4 and 5 plotted versus a modified Reynolds number, $Re' = D_p G/\mu(1-\epsilon)$, and the "inertia" group $\sqrt{\rho\ u^2}$, respectively. Straight parallel lines are used, as the precision of the data and the relatively short range of Re' and $\sqrt{\rho\ u^2}$ precluded the use of curves with any accuracy. The slope of 0.34 was found to be most satisfactory on both the plots. The two plots are essentially the same, as within any one system the velocity of the gas is the only significant variable in each plot. Consequently, these two plots alone offer no criterion for judging the two parameters, but are useful to determine the variation of HTU_G with Schmidt number (Sc) with the two alternate parameters.

A more thorough test of the two parameters is shown in Figs. 6 and 7, which are cross plots of the a_v HTU_G (taken from Figs. 4 and 5 at specified Re' and $\sqrt{\rho\ u^2}$ values) versus Sc of the systems. These cross plots indicate the Sc function necessary to bring about a vertical alignment of the curves in Figs. 4 and 5. The points taken from the Re' plot are well fitted with a line of slope 2/3, in agreement with the value originally proposed by Chilton and Colburn's analogy and since extensively used. Only the helium-nitrobenzene and the helium-napthalene systems give deviations unexplained by experimental error.* It is interesting to note that a least-squares determination of the best possible exponent for Sc including the helium data turned out to be 0.666, while the over-all equation for the data is

$$a_v\ HTU_G = 1.344\ Sc^{0.666}\ Re^{0.322}. \tag{9}$$

The standard deviation of ln a_v HTU_G is 0.078. The points taken at $\sqrt{\rho\ u^2} = 3000$ are shown in Fig. 7, and it is seen that the correlation is not nearly so satisfactory as that obtained with Re.

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*As shown by Lynch and Wilke,[2] a modified form of the Lin, Moulton, and Putnam equation apparently represents the Schmidt-number dependence more satisfactorily for wider ranges of Sc. However, the 2/3-power function is satisfactory for present purposes.

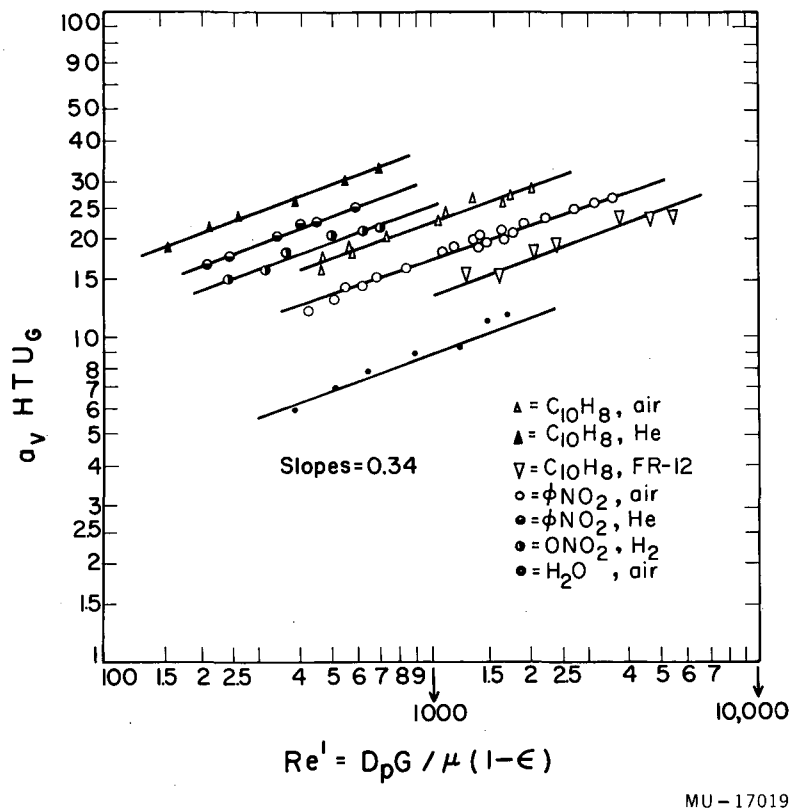

Fig. 4. Data of Lynch and Wilke, collected at 1 atmosphere, correlated by using Reynolds Number.

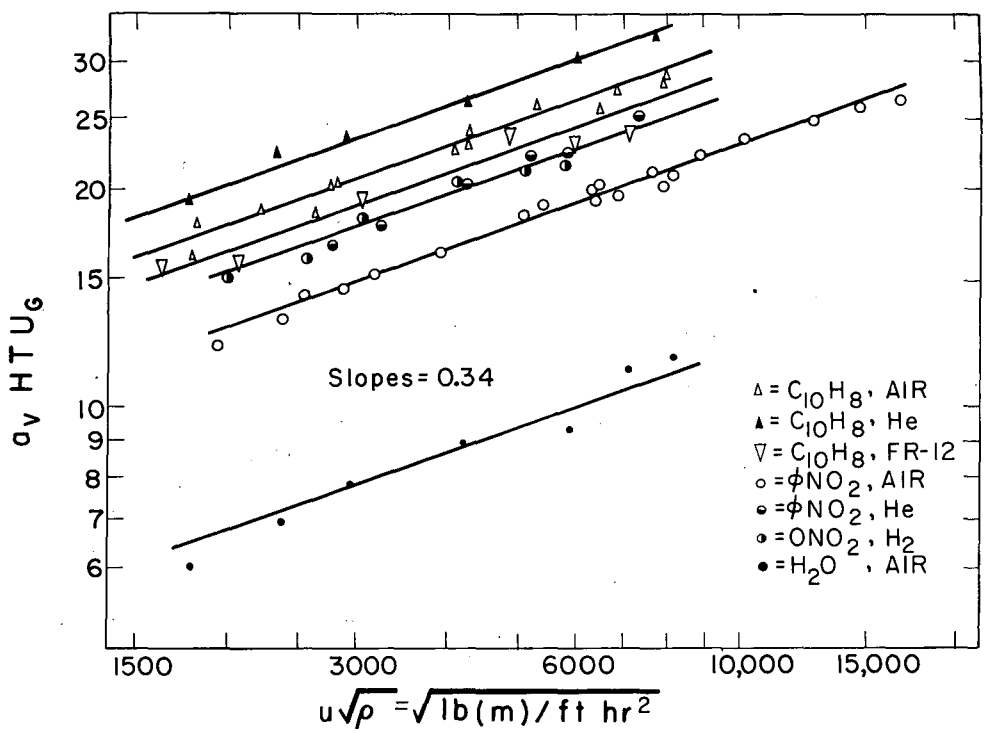

Fig. 5. Data of Lynch and Wilke, collected at 1 atmosphere, correlated by using $\sqrt{\rho u^2}$.

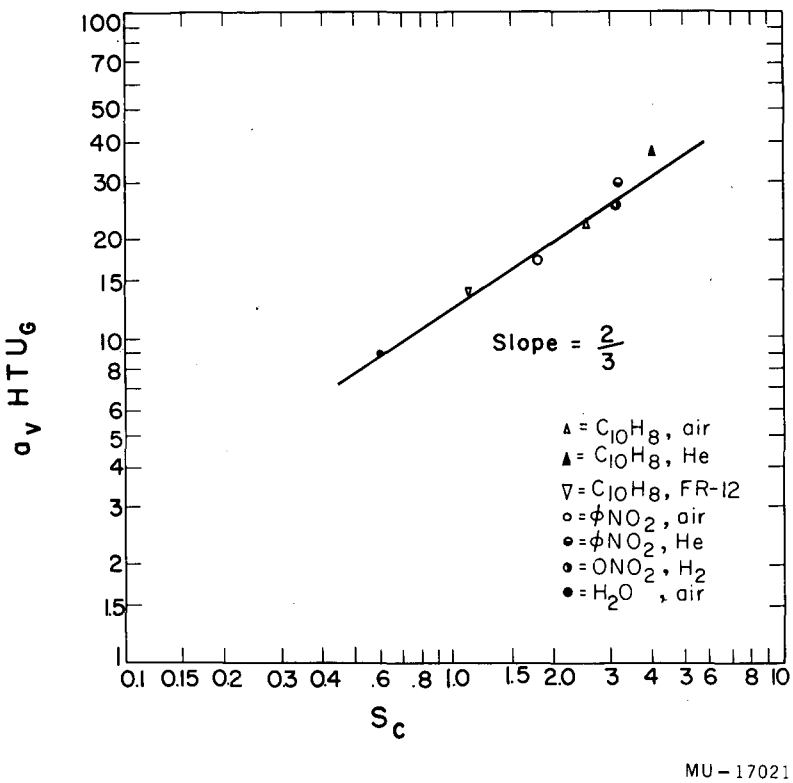

Fig. 6. Schmidt-number cross plot from Fig. 4 at Re' = 1000.

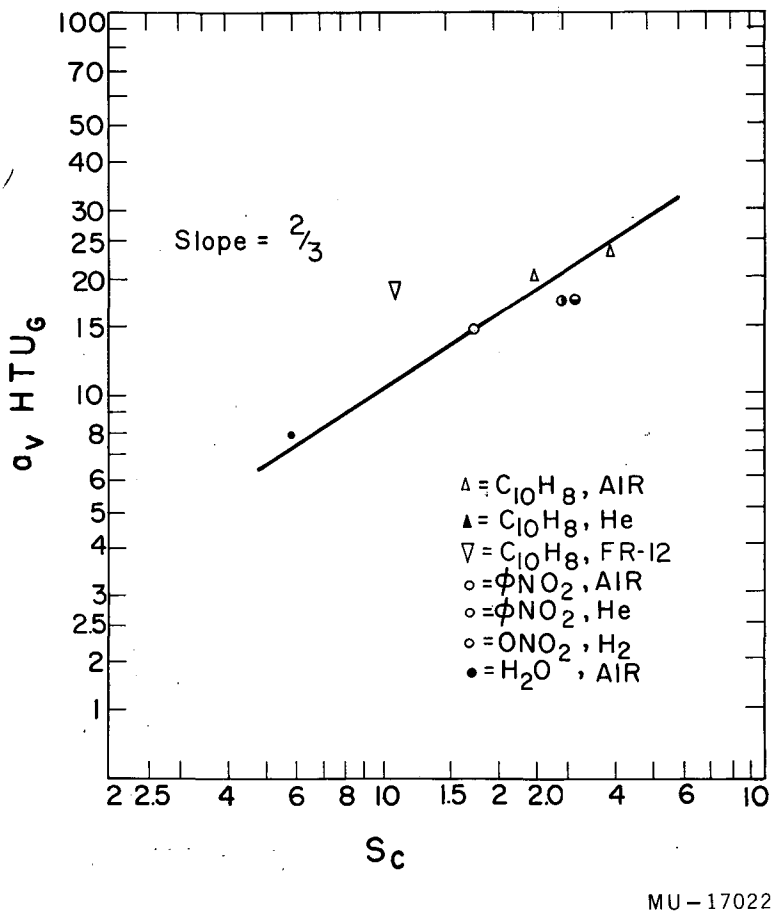

Fig. 7. Schmidt-number cross plot from Fig. 5 at $u\sqrt{\rho}=3000$.

In the second phase of the experiment started by Lynch and Wilke, I investigated the effect of pressure on J_D in an effort to further clarify and substantiate the use of one or the other of the two parameters, Re and $\sqrt{\rho e^2}$. The bulk of this investigation was carried out using an air-napthalene system, and the results are shown in Figs. 8, 9, and 10. Throughout these experiments the same bed of pellets was used so that the pellet diameter (D_p) and the void fraction (ϵ) did not vary and were therefore omitted from the plots. The data ranged from 542 psig to 4.9 psig, the lowest pressure possible on the high-pressure equipment. However, the atmospheric pressure lines of slope 0.34 obtained for the air-napthalene system (see Figs. 4 and 5) were again used here for comparison. Two other general points should be noted. First, the viscosity of air in the pressure range studied varied less than 6%,[7] and since it enters only to the 0.35 power in Re the viscosity effect on J_D is never more than 2%. Second, the density of air was found to be directly proportional to pressure to within 1% accuracy.[15] Within the limitations of these two insignificant effects, therefore, it was explained in the theory that if $u\sqrt{\rho}$ is the correct combination of variables and not $u\rho$ as found in Re', then J_D should show a variation with P to the 0.34 x 1/2 or 0.17 power when plotted versus Re; conversely, if $u\rho$ is correct and not $u\sqrt{\rho}$, J_D should show no variation with P when plotted versus Re but should show a variation with $P^{-0.17}$ when plotted versus $u\sqrt{\rho}$. That the latter is true is clearly seen from Figs. 8, 9, and 10.

It is apparent from Fig. 8, in which essentially Re is used, that the atmospheric pressure line fits all the high-pressure points within experimental tolerance. The points fall on either side of the line and show no marked trend with pressure. Furthermore, the same high-pressure values of J_D that correlate so well with Re in Fig. 8 show great deviations from the atmospheric line when plotted versus $u\sqrt{\rho}$ in Fig. 9. Lines parallel to the atmospheric one are drawn through each group of points at the same pressure with the exception of the 31.0-atmos and 37.7-atmos groups, which were combined owing to their indiscernible

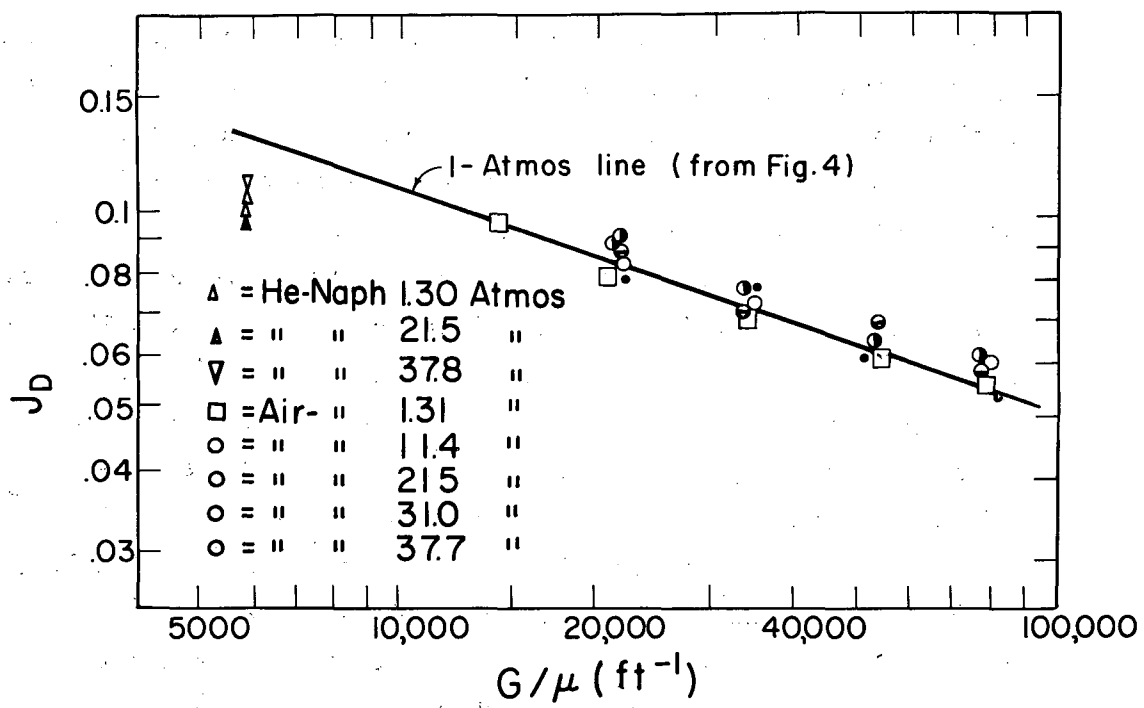

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Fig. 8. Air-naphthalene and helium-naphthalene data collected at higher pressures.

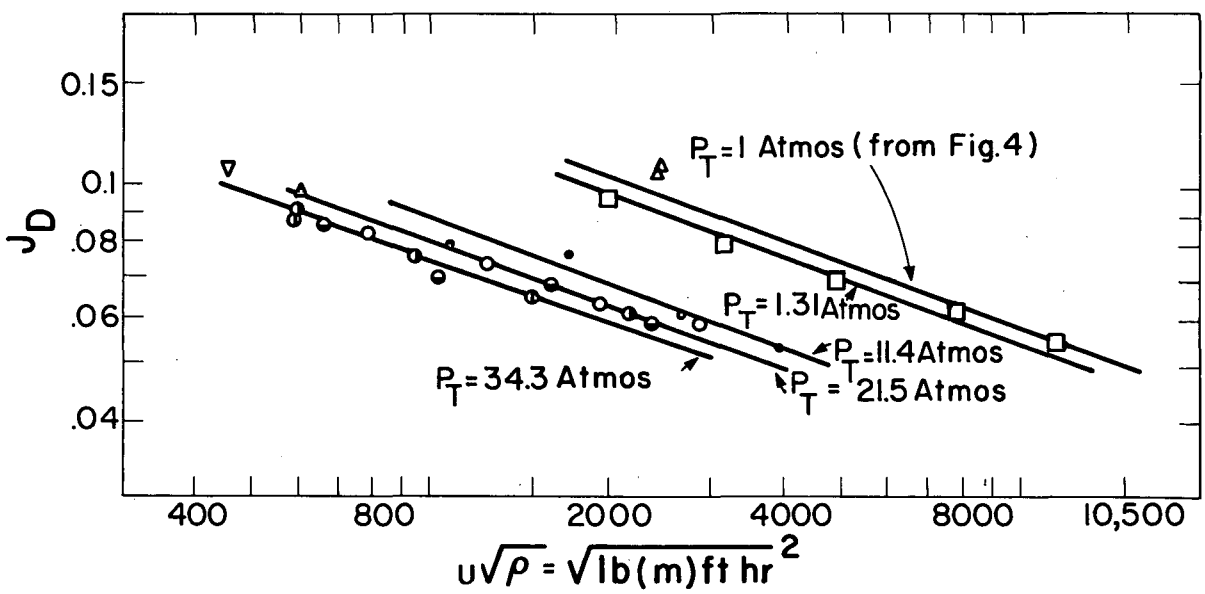

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Fig. 9. Air-naphthalene and helium-naphthalene data collected at higher pressures.

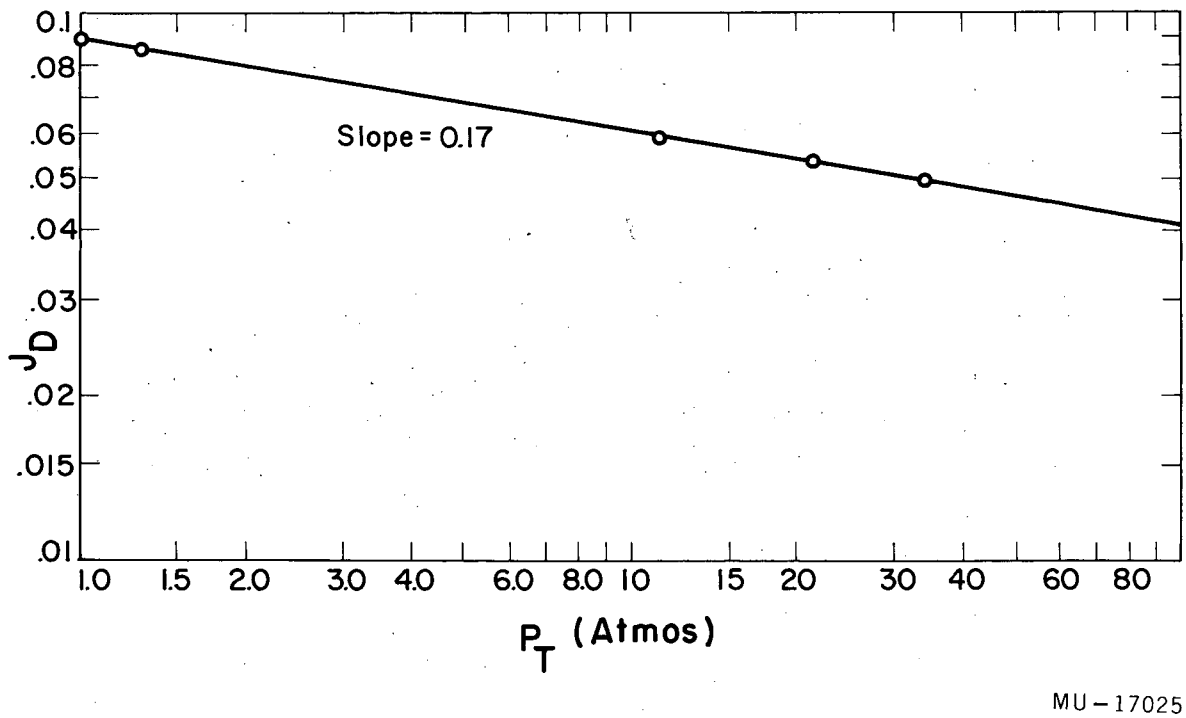

Fig. 10. Cross plot from Fig. 9 at $u\sqrt{\rho} = 3000$.

difference. Figure 10 is a cross plot of the average pressure of each group versus J_D taken from Fig. 9 at the specified value of $u\sqrt{\rho}$. The slope of -0.17 found in Fig. 10 is an excellent confirmation of the validity of $Re^{-0.34}$.

A further confirmation of these results was obtained with the helium-napthalene system, the results of which are also shown in Figs. 8 and 9. As with the air-napthalene system, a_v HTU_G shows no noticeable dependence on pressure when Re is used, while the use of $u\sqrt{\rho}$ leads to variations of the same order of magnitude as found with the air-napthalene system. Because of the additional experimental difficulties and errors introduced with the helium runs, nothing more than this qualitative confirmation was attempted.

The lack of a Schmidt-number function to correlate the $\sqrt{\rho u^2}$ data, and the conclusive evidence offered by the pressure studies, very well establish the use of Re in packed beds with no liquid flow. It must be remembered, however, that the use of $\sqrt{\rho u^2}$ group postulated by Lynch was based on data collected in beds with countercurrent gas and liquid flow where the mass-transfer system is much more complex, owing to the possible influence of additional factors such as the liquid holdup and wetting characteristics, which have a profound effect on the effective interfacial area available. These factors are undoubtedly influenced by gas-liquid interactions and may well demand the use of parameters in addition to or perhaps different from the commonly used Reynolds and Schmidt numbers.

DISCUSSION

My data were collected mainly for the purpose of clarifying the effect of pressure, and particularly the use of the $\sqrt{\rho u^2}$ parameter, in the correlation of mass-transfer data. The range of Re and Sc numbers covered and the precision of the data in comparison with the low-pressure studies were limited in this investigation by the experimental restrictions imposed by the high-pressure operation. In view of these limitations on the high-pressure data, and since my data are in close agreement with the more extensive low-pressure data of Lynch and Wilke (see Fig. 8), and furthermore, since the low-pressure data were not presented by Lynch and Wilke in the usual manner using a single-power function of Sc, these data are presented here for comparison with the other packed-bed investigations in the literature.

The final correlations of all the low-pressure data are shown in Figs. 11 and 12. The plots are essentially identical except for the addition of the void fraction, $(1-\epsilon)$, in calculating a modified Re in Fig. 11. This variation was necessary to properly compare these data with the others in the literature which have been reported in either of the two ways. The final least-squares equations for each are

$$J_D = \frac{Sc^{2/3}}{a_v \, HTU_G} = 0.744 \, Re'^{-0.322} \tag{10}$$

and

$$J_D = 0.626 \, Re^{-0.322}. \tag{11}$$

The standard deviation of ln J_D from Eqs. (10) and (11) are ± 0.078 and ± 0.076, while the correlation coefficients are 0.920 and 0.923 respectively. The effective equality of these figures and of the Re exponent is expected in view of the small range of void fractions, from 0.40 to 0.42, encompassed by the systems.

The only outstanding deviations seen in these data are with the helium systems. It is apparent from the plots that the two helium systems are separated from the rest of the data and account for much of

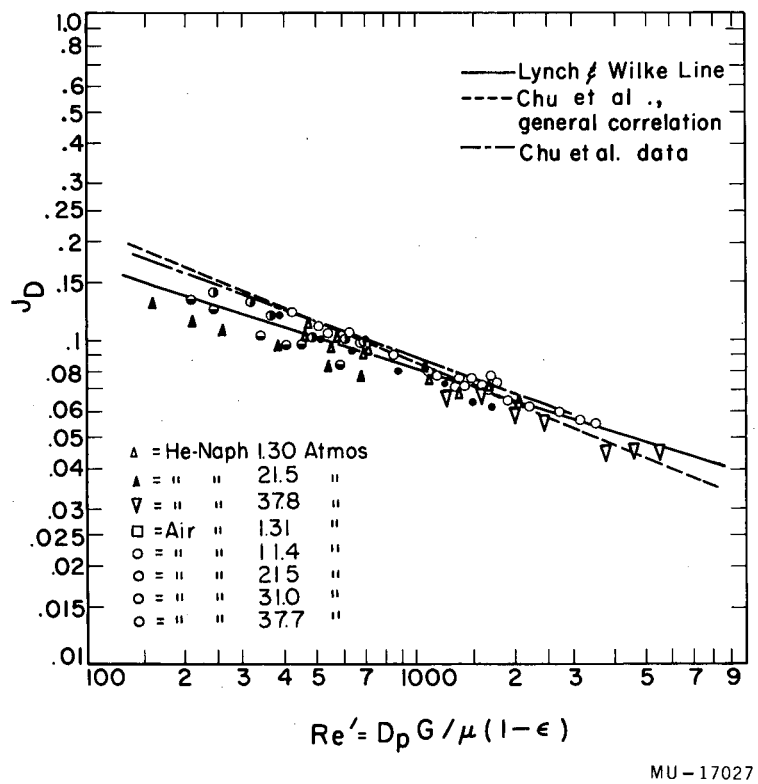

Fig. 11. Comparison of data with other correlations.

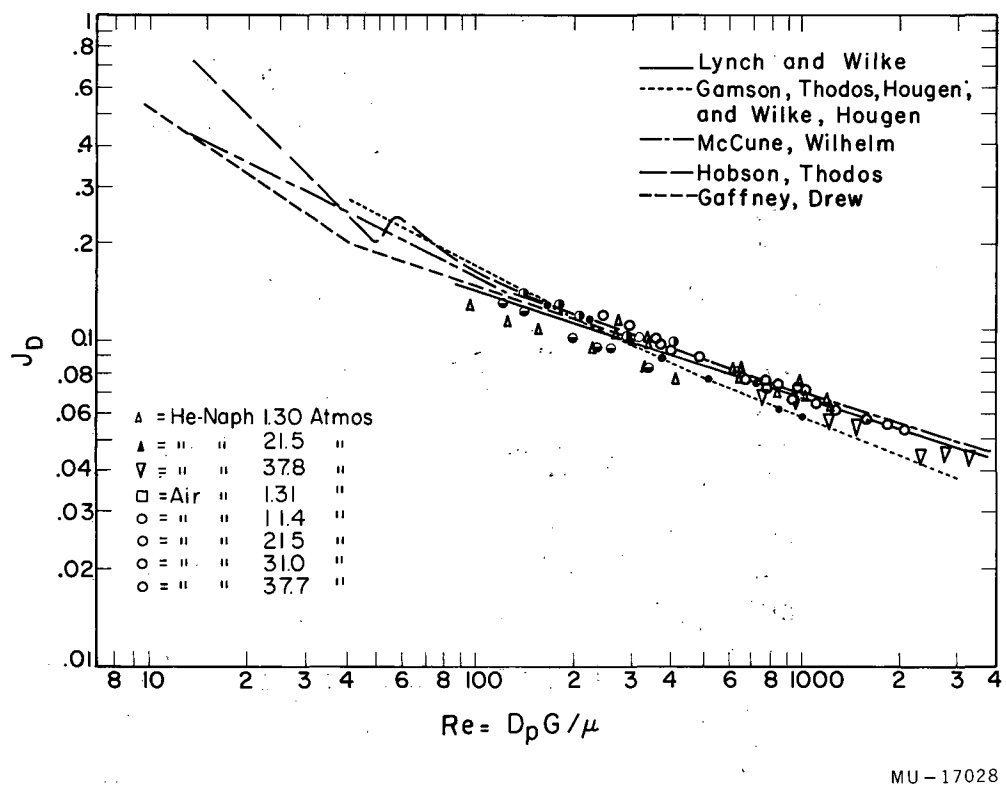

Fig. 12. Comparison of data with previous correlations.

the deviation from other investigations. A least-squares calculation using all but the helium data gives the equations

$$J_D = 0.912\ Re'^{-0.373} \tag{12}$$

and

$$J_D = 0.881\ Re^{-0.371}. \tag{13}$$

The standard deviations of ln J_D dropped to 0.050 when these equations were used, whereas the correlation coefficients improved to 0.97. More important is the fact that plots of Eqs. (12) and (13) clearly show much better agreement with the other investigations. The reason for the deviation of the helium data is not known.

The several other investigations shown in Figs. 11 and 12 cover a wide variety of systems and conditions; however, all investigators worked with a single fluid flowing over fixed or fluidized beds of solids or liquid-saturated carrier solids. The data of Gaffney and Drew[8] and McCuen and Wilhelm[9] are for liquid-solid systems, including 2-naphthol into water, succinic acid into acetone and butyl alcohol, and salicylic acid into benzene. These workers covered a Sc range from 150 to 10,700 and Re from 0.8 to 1500. Considering the wide range of the variables and the differences in properties from the gas systems of this work, the agreement is believed to be very satisfactory.

Hobson and Thodos[10] vaporized water, n-butanol, toluene, n-octane, and duedecane into air, N_2, O_2, and H_2 covering a Sc range from 0.6 to 5.0 and Re from 3 to 325. The agreement is good with this experiment within the limited range of Re where the two overlap, but the scatter of their data is so large that the agreement might well be just fortuitous.

The extensive air-water data of Gamson, Thodos, and Hougen[11] and Wilke and Hougen[12] fall exactly on the air-water data of this experiment, but in general lie slightly below the rest of these data as well as those of others in the higher-Re region.

The extensive data of Chu, Kalil, and Wetteroth,[13] using fixed and fluidized beds of napthalene vaporized into air, is an excellent

confirmation of the use of Re' (the modified Re) to eliminate the divergence due to bed porosity. Both a line of their own data and their general correlation including the data of Refs. 8, 9, 10, 11, and 12 show good agreement with these data.

In general the over-all agreement of the various investigators is remarkable considering the wide variety of materials, shapes, and flow ranges covered. The most significant discrepancy in this report is found with the helium data, as noted previously. In addition, the extensive air-water data are slightly lower than the data for other fixed-bed systems in the higher Re region. Beyond these differences, however, there lies a much more significant dissension among the various workers as to the proper exponent to be used with the Sc number, a problem which the latest work of Lynch and Wilke[2] may help to clarify.

Another interesting facet of the high-pressure studies concerns the use of concentrations as the driving force for mass transfer. For gaseous solutions at atmospheric pressure, concentration is the proper driving force; but at increased pressures, where partial pressures differ markedly from fugacity, there is some question whether or not fugacity should be used in place of concentration. This newly defined J number would be

$$J_f = \frac{\dfrac{k_f M_m P_{BM}}{G}}{\psi \left(\dfrac{\mu}{\rho D_f}\right)} = \frac{\dfrac{k_g M_m P_{BM}}{\phi G}}{\psi \left(\dfrac{\mu \phi}{\rho D}\right)} \tag{14}$$

where k_f and D_f are based on fugacity rather than concentration and ϕ is the fugacity coefficient. If the Schmidt number enters to the 2/3 power, we have

$$J_D \approx J_f \, \phi^{1/3}. \tag{15}$$

In this experiment, the solubility* of napthalene was measured over the same range of pressures as the mass-transfer data, and is shown in Figs. 14 and 15 in the Appendix. The details of the experimental measurements and the derivation of the theoretical equations for solubility based on Van der Waal's constants are also given in Appendix A of this report. As seen in Fig. 15, the pressure range covered was sufficiently large to give a marked difference between the fugacity and partial pressure and thereby adequately differentiate the correct use of one or the other in mass-transfer correlations.

The values of J_D and J_f are shown in Fig. 13 plotted versus Re. The plot of J_D is the same as Fig. 8 presented in Results, with the data adequately fitted by the atmospheric pressure line of Lynch. The values of J_f, on the other hand, show considerable spread of the high-pressure points suggesting that the concentration potential is preferable to the fugacity potential.

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*At higher pressures there is some question as to the use of the term "vapor pressure" for the quantity yP, and therefore the more general term "solubility" is used.

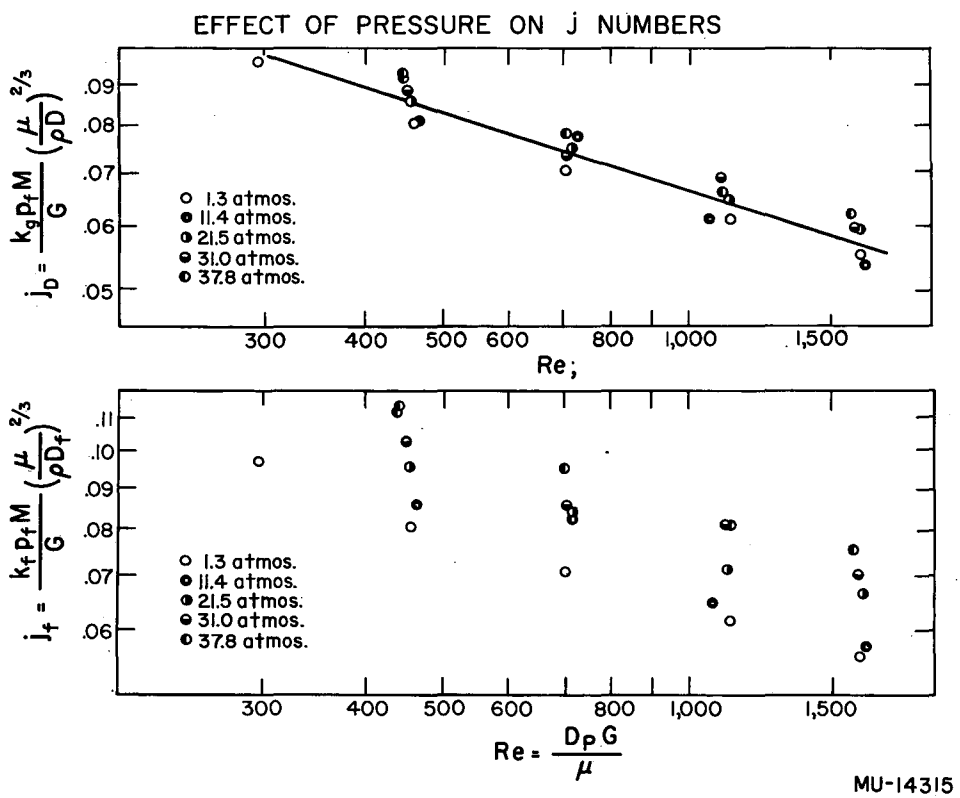

Fig. 13. Comparison of j numbers based on fugacity and concentration gradients.

ACKNOWLEDGMENT

I wish to express my gratitude to Professor Charles R. Wilke for his guidance, encouragement, and patience, and to Professors Harold A. Johnson and LeRoy A. Bromley for their critical review of the text.

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Appendix A. Physical Properties of Materials

Gas Specifications

The helium used was supplied by the U. S. Navy at a purity of 99.9%. The major impurity was water vapor. The compressed air used in the high-pressure work was supplied by Stuart Oxygen Company.

Liquid and Solid Specifications

Naphthalene was used directly as supplied by Baker (C. P. Grade). The melting point of naphthalene was measured and found to be $80^{\circ} \pm .05^{\circ}C$.

Viscosity

The viscosities of air and helium were taken from a review article by F. G. Keyes[14] in which available literature data for several gases are collected and formulated by means of an empirical equation. The high-pressure viscosity corrections for helium and air were taken from Kestin and Pilarcyzk.[15]

Diffusivity

The diffusivity for the system helium-naphthalene was calculated by the equation of Hirschfelder, Bird, and Spotz.[16] The diffusivity for the system air-naphthalene is taken from the International Critical Tables (ICT).[17] Diffusivities were corrected for changes in pressure by use of Slattery and Bird correlations.[18]

Density

Gas densities were taken from the Lange Physics and Chemistry Handbook[19] with ideal gas pressure and temperature corrections. Compressibility-factor corrections to ideality as reported in the ICT[20] were found to be less than 0.7% for air and less than 0.1% for helium, therefore, they were not used.

Vapor Pressure and Solubility*

The vapor pressure of water was taken from Perry's Handbook.[21]

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*At higher pressures there is some question as to the use of the term "vapor pressure" for the quantity yP, and therefore the more general term "solubility" is used.

The vapor pressure of naphthalene at atmospheric pressure was taken from the ICT.[22] The equation given is:

$$\log_{10} p = 11.450 - \frac{3729.3}{t + 273.16} \tag{16}$$

At elevated pressures, the solubility of naphthalene was measured by using the same equipment and procedure as for the mass transfer runs except that a longer bed of naphthalene was used in order to obtain saturation of the gas stream. The bed length was varied by 40% to check for saturation. The data are shown in Tables I and II and plotted in Figs. 14 and 15. All the helium data, including the high-pressure points, were within experimental tolerance of the atmospheric line, therefore the ICT equation was used throughout the helium calculations. However, with air, the vapor pressure exhibits an extensive variation with pressure. A series of lines, parallel to the ICT line, correlate the data well. To facilitate the mass-transfer calculations, the following equations were developed from the data at pressures which represent the average pressure used for each group of mass-transfer runs in that pressure vicinity. This "average" equation was then used for all the runs in that range as the variations in pressure in any group of mass-transfer runs was well within the experimental tolerance of the solubility data.

$$\log p = 11.547 - \frac{3729.3}{t + 273.16} \quad (11.4 \text{ atmos}) \tag{17}$$

$$\log p = 11.631 - \frac{3729.3}{t + 273.16} \quad (21.5 \text{ atmos}) \tag{18}$$

$$\log p = 11.714 - \frac{3729.3}{t + 273.16} \quad (31.0 \text{ atmos}) \tag{19}$$

$$\log p = 11.773 - \frac{3729.3}{t + 273.16} \quad (37.7 \text{ atmos}) \tag{20}$$

Unexpectedly good agreement was found between these experimental results and the theoretically predicted values obtained in the following way:

At a constant temperature T, the pressure variation of fugacity

Table I

Air-naphthalene vapor pressure data and tabulation of calculations
(Bed length=8 in., bed diameter=2.0/in., bed=1/4 in. cylindrical pellets)

Run	t_i (°C)	t_o (°C)	t_F (°C)	P_B (mm Hg)	P_F (mm Hg)	V_E (cfm)	θ (min)	W (gm)	$1/T_B$ (1/°K)	P_N (mm Hg)
1	22.90	23.08	22.60	28,714	756.3	4.25	20.0	.0670	33756	.1522
2	22.30	22.42	21.97	28,767	757.5	4.25	35.0	.1100	33834	.1434
3	22.55	22.52	22.10	28,710	756.9	1.142	80.0	.0705	33820	.1486
4	22.63	22.70	22.20	23,542	756.3	4.29	35.0	.1214	33800	.1278
5	22.50	22.58	22.30	16,449	"	4.28	25.0	.0994	33814	.1026
6	21.82	21.80	21.50	8,614	"	4.38	20.0	.1190	33904	.07838
7	22.23	22.15	21.95	8,578	"	1.158	75.0	.1259	33863	.08347
8	21.65	21.95	21.50	993.7	753.8	1.116	12.5	.1418	33887	.06790
9	22.05	22.23	21.85	996.5	"	1.122	"	.1430	33854	.06840
10	23.72	23.47	23.15	28,737	756.4	4.27	30.0	.1061	33712	.1603
11	24.20	23.98	23.42	23,555	756.0	4.19	25.0	.0960	33654	.1456
12	24.02	23.88	23.50	16,372	756.1	3.070	35.0	.1163	33665	.1196
13	25.18	25.00	24.45	28,631	759.0	4.22	25.0	.1008	33539	.1845
14	25.45	25.20	24.75	23,526	759.4	4.27	20.0	.0871	33517	.1619
15	25.10	24.92	24.58	16,390	759.0	3.041	30.4	.1110	33548	.1328
16	23.80	23.70	23.75	8,590	758.1	3.037	30.2	.1534	33686	.09679
17	23.92	23.70	23.28	993.5	757.9	1.145	12.5	.1718	33686	.08020
18	23.75	23.65	23.20	997.8	"	1.157	10.0	.1468	33692	.08512
19	22.08	22.15	21.90	987.9	759.7	1.102	10.0	.1128	33863	.06755
20	25.32	24.97	24.90	28,590	757.7	4.22	26.3	.1077	33543	.18767
21	25.90	25.63	25.40	23,157	758.2	4.30	26.0	.1216	33468	.1706
22	25.42	25.10	24.80	16,335	758.5	3.079	30.0	.1138	33528	.1360
23	25.15	24.90	25.70	8,718	758.7	3.080	25.2	.1465	33550	.1115
24	23.95	24.03	24.37	983.8	757.3	0.994	7.75	.0971	33648	.0838
25	23.50	23.45	23.35	989.6	752.8	0.999	12.5	.1465	33714	.07865
26	23.40	23.52	23.25	990.4	752.6	0.985	"	.1426	33707	.07770
27	23.30	23.65	23.22	989.4	752.3	.979	"	.1423	33692	.07795
28	23.32	23.50	23.20	991.1	752.5	.984	"	.1408	33708	.07684
29	23.17	23.40	23.10	996.5	752.6	.994	"	.1392	33720	.07559
30	23.12	23.42	23.00	996.7	"	.993	"	.1443	33718	.07841

Table II

Helium-naphthalene vapor-pressure data and tabulation of calculations
(Bed length=8 in., bed diameter=2.0/in., bed=1/4 in. cylindrical pellets)

Run	ϵ_i (°C)	ϵ_o (°C)	ϵ_F (°C)	P_B (mm Hg)	P_F (mm Hg)	V_F (ft^3/min)	θ (min)	W (gm)	$1/T_B$ (1/°K)	P_N (mm Hg)
1-H	25.32	25.10	24.22	28,667	760.0	5.698	26.5	.0649	33528	.08288
2-H	24.62	24.37	24.37	16,415	760.7	5.596	30.0	.1217	33611	.07996
3-H	25.40	25.32	"	980.3	759.0	5.196	2.40	.1633	33503	.08652
4-H	25.42	25.40	24.30	984.9	759.1	5.194	2.25	.1552	33495	.08810
5-H	24.35	24.30	23.32	16,281	755.8	5.535	30.0	.1204	33618	.07957
6-H	24.25	24.32	23.25	983.8	757.4	5.882	2.25	.1591	33616	.07955
7-H	24.25	24.22	"	991.4	757.8	6.022	2.00	.1437	33630	.07950
8-H	22.05	22.13	21.62	28,134	754.7	8.645	30.0	.0900	33866	.06560
9-H	"	22.20	21.50	28,155	754.1	5.229	43.7	.0790	33858	.06530
10-H	23.00	22.95	23.08	998.5	756.5	5.788	2.0	.1160	33770	.06736
11-H	23.40	23.40	23.15	996.4	756.4	5.764	"	.1260	33720	.07334
12-H	22.25	22.28	22.05	991.1	756.0	5.696	"	.1090	33849	.06364
13-H	22.30	22.35	21.95	996.2	"	5.738	"	.1082	33842	.06300

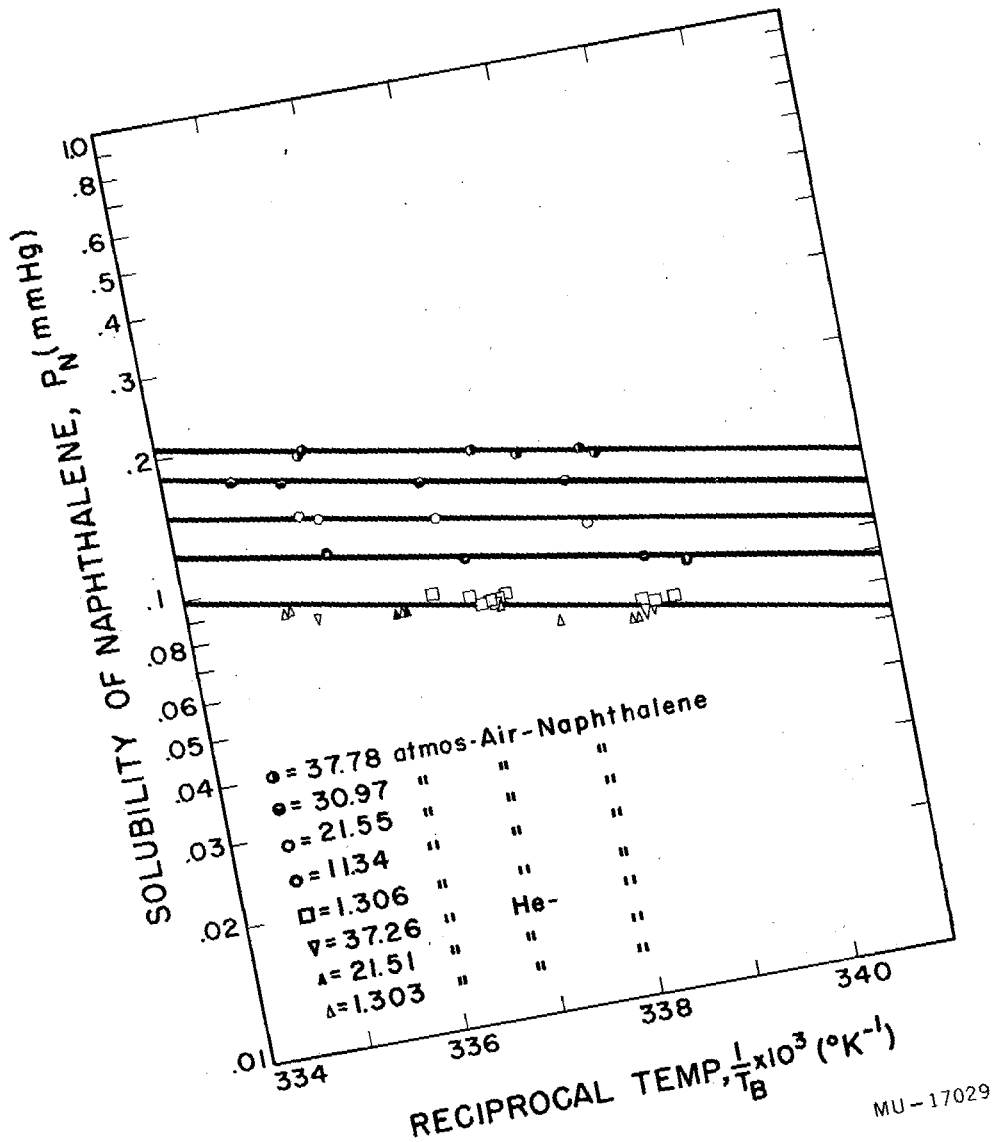

Fig. 14. Solubility of naphthalene in air and helium.

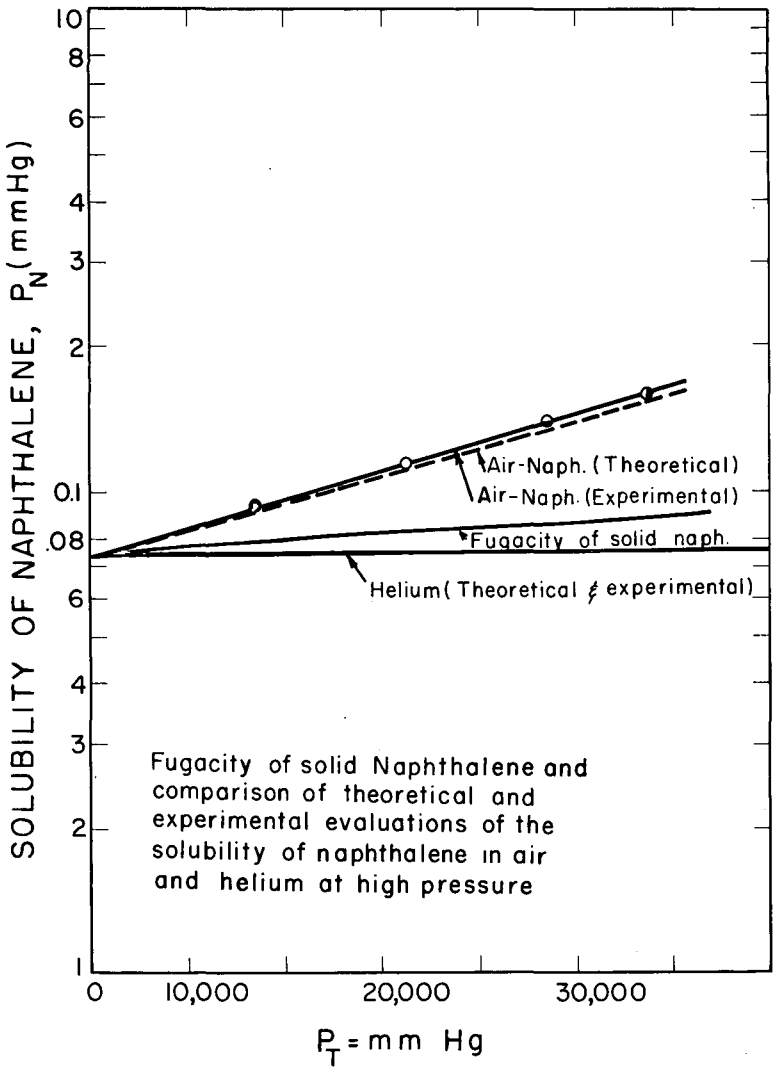

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Fig. 15. Fugacity of solid naphthalene and comparison of theoretical and experimental evaluations of the solubility of naphthalene in air and helium at high pressure.

f of a gas, liquid, or solid is given by

$$\left[\frac{\partial \ln f}{\partial p}\right]_T = \frac{v}{RT} \quad . \tag{21}$$

If we apply Eq. (21) to solid naphthalene and assume the specific molal volume, v, to remain constant with P, we obtain, upon integration,

$$\ln\left(\frac{f_2^o}{f_1^o}\right)_s = \frac{v_s}{RT}(P_2 - P_1), \tag{22}$$

where superscripts ^{o} refer to fugacity of the pure component and subscript s refers to the solid state.

If the reference pressure, P_1, is selected sufficiently low so that the fugacity of the solid, $f_{s_1}^o$, is equal to the vapor pressure p_1 of the solid, then Eq. (22) may be written

$$\ln f_{s_2}^o = \frac{v_s}{RT}(P_2 - P_1) + \ln p_1 . \tag{23}$$

For the vapor phase a virial form of the van der Waals equation may be used* to relate the molal volume v and the pressure P of the pure vapor:

$$\frac{Pv_v}{RT} = 1 - \left(\frac{a_v}{RT} - b_v\right)\frac{P}{RT} + \frac{a_v}{RT}\left(2b_v - \frac{a_v}{RT}\right)\frac{P^2}{RT} + \ldots , \tag{24}$$

where a_v and b_v are van der Waals constants for the vapor.

Using a two-term approximation of the above series for v in Eq. (21) and integrating gives

$$\ln\left(\frac{f_2^o}{f_1^o}\right)_v = \ln\frac{P_2}{P_1} - \left(\frac{a_v}{RT} - b_v\right)\frac{P_2 - P_1}{RT} . \tag{25}$$

Again, if the reference pressure is chosen low enough, the fugacity, $f_{v_1}^o$, and P_1 will be equal, and the equation may be written

*Other equations of state could be used, provided the constants of the equations are available.

$$\ln f^{o}_{v_2} = \ln P_2 - \left(\frac{a_v}{RT} - b_v\right) \frac{P_2 - P_1}{RT} \quad . \tag{26}$$

Hildebrand and Scott[23] have shown, for binary gaseous mixtures,

$$\ln f_v = \ln y_v f^{o}_v + \frac{P\Delta}{RT} (y)^2_g \ , \tag{27}$$

where $$\Delta = \frac{(a_v^{1/2} - a_g^{1/2})^2}{RT} \ , \tag{28}$$

f^{o}_v = fugacity of pure vapor at total pressure P and temperature T,

y_v, y_g = mole fraction of vapor and gas respectively.

The significant point about Eq. (28) is the second term, $\frac{P\Delta}{RT} y_2^2$, which is not included in the more frequently used Lewis-Randall fugacity rule, which simply states

$$f_2 = y_v(f^{o}_v). \tag{29}$$

Now, substituting from Eq. (26) into Eq. (27), one has

$$\ln f_{v_2} = \ln y_{v_2} + \ln P_2 - \left(\frac{a_v}{RT} - b_v\right) \frac{P_2 - P_1}{RT} + \frac{P_2\Delta}{RT} y_g^2. \tag{30}$$

The pressure P_1 is very small compared with P_2 and may be neglected. At equilibrium, the fugacity of the solid, $f^{o}_{s_2}$, and the fugacity fits vapor, f_{v_2}, are equal; therefore Eqs. (23) and (30) may be equated to give an expression for the vapor pressure of a solid at any pressure and temperature:

$$\ln \frac{p_2}{p_1} = \frac{v_s}{RT} (P_2 - P_1) + \left(\frac{a_v}{RT} - b_v\right) \frac{P_2}{RT} - \frac{P_2\Delta}{RT} \ y_g^2 \ , \tag{31}$$

where $p_2 = y_{v_2} P_2$.

In application of this equation to the vaporization of solid naphthalene into compressed air and helium the following constants[24] were used:

$a_{naphthalene} = 39.82 \times 10^6$ cc^2 - atmos. mol.$^{-2}$,

$a_{air} = 1.377 \times 10^6$ " ,

$a_{helium} = 3.418 \times 10^4$ " ,

$b_{naphthalene} = 193.9$ cc mol^{-1},

$v_s = 112.0$ cc mol^{-1},

$T = 296.7^{\circ}$K.

By use of these constants Eq. (31) can be reduced to

$$\ln \frac{p_2}{p_1} = 0.0147\ P_2 + 0.0046\ (P_2 - 1) \quad \text{for air} \tag{32}$$

and

$$\ln \frac{p_2}{p_1} = -0.0041\ P_2 + 0.0046\ (P_2 - 1) \quad \text{for helium.} \tag{33}$$

Figure 15 shows a plot of Eqs. (32) and (33) as well as a cross plot at $T = 296.7^{\circ}$K ($1/T = 3.37 \times 10^{-3}$) of the experimental data shown in Fig. 14. For helium the experimental points are adequately fitted by the ICT atmospheric pressure line, and the theoretical equation likewise indicates a negligible change in vapor pressure in the range covered up to 40 atmos. for the air-naphthalene system, the agreement between the theoretical and experimental values also proved very satisfactory, as seen in Fig. 15.

Appendix B. Sample Calculations

1. Mass-Transfer Factor, HTU_G

From Eq. (5) we have $HTU_G = \frac{h}{NTU_G}$;

From Eq. (8), $NTU_G = \ln \frac{(y_w)_i - y_i}{(y_w)_o - y_o}$.

At the gas-solid interface, the gas is assumed to be saturated with the vapor (y_w) at the wet-bulb temperature calculated at the bed inlet and outlet. However, for the high-pressure study, the vapor-pressure data were not precise enough to warrant the use of different y_w values for inlet and outlet streams, therefore only the measured outlet temperature was used to obtain y_w throughout the bed.

Therefore, for air-naphthalene run No. 4 (see Table III):

$$y_w = \frac{p_w}{P_B} = \frac{1}{P_B} \text{ antilog } \left(11.547 - \frac{3729.3}{t_o + 273.16}\right),^*$$

$$y_w = \frac{1}{8{,}638 \text{ mm Hg}} \times \text{antilog } \left(11.547 - \frac{3729.3}{24.03 + 273.16}\right),$$

$$y_w = \frac{0.0997}{8{,}638} = 1.1542 \times 10^{-5}.$$

The bulk stream concentration at the inlet of the bed, y_i, was always zero, as the gas came directly from the high-pressure cylinders.

The bulk stream outlet concentration, y_o, is simply that amount of naphthalene added to the gas by vaporization. For run No. 4:

$$\text{Moles of naphthalene vaporized per minute} = \frac{0.1141 \text{ gm}}{128.16 \frac{\text{lb}}{\text{lb-mole}} \times 11.2 \text{ min} \times 453.6 \frac{\text{gm}}{\text{lb}}}$$

$$= 1.752 \times 10^{-7} \frac{\text{lb-mole}}{\text{min}} .$$

---

*The measurement and calculation of the solubility of naphthalene at high pressures are discussed in Appendix A.

Table III

Air-naphthalene and helium-naphthalene mass-transfer data at various pressures

Run	t_i (°C)	t_o (°C)	t_F (°C)	P_B (mm Hg)	P_F (mm Hg)	V_F (ft^3/min)	θ (min)	W (gm)	$(Pw)_o$ (mm Hg)	NTU_G	a_vHTU_G	Sc	J_D	J_F	G/μ (ft^{-1})	$\sqrt{\rho u^2}$ ($lb^{1/2}, ft^{-1/2}hr$)	$Re = \frac{D_pG}{\mu}$
1	24.65	24.60	18.30	28,138	756.4	16.20	25.0	.1498	0.1750	.501	31.6	2.76	.0623	.0754	77,300	2,180	1595
2	24.42	24.40	19.08	23,546	756.6	16.29	20.0	.1214	0.1517	.485	32.7	2.73	.0598	.0703	78,200	2,390	1615
3	24.25	24.10	20.15	16,379	759.1	16.35	"	.1410	0.1216	.488	32.4	2.68	.0596	.0665	79,400	2,870	1638
4	24.15	24.03	21.52	8,638	758.9	16.34	11.2	.1141	0.0997	.447	35.4	2.63	.0538	.0570	80,100	3,930	1650
5	23.25	23.22	22.65	993.7	757.9	16.0	3.0	.1978	0.0736	.467	33.9	2.56	.0552	.0555	79,200	11,270	1635
6	23.27	"	22.75	996.7	758.3	11.0	"	.1473	"	.520	30.4	"	.0615	.0618	54,500	7,740	1125
7	23.18	23.20	22.77	995.2	758.0	6.89	"	.1015	0.0734	.592	26.7	"	.0702	.0705	34,100	4,850	705
8	23.27	23.30	"	"	757.9	4.44	5.0	.1213	0.0741	.679	23.3	"	.0803	.0805	22,000	3,130	455
9	23.42	23.42	23.85	998.0	758.8	2.888	10.25	.1846	0.0752	.814	19.4	"	.0965	.0968	14,300	2,030	296
10	23.72	23.72	19.28	28,728	757.8	11.22	30.0	.1191	0.1626	.536	29.5	2.76	.0666	.0810	53,500	1,490	1105
11	23.75	23.75	18.92	23,536	758.1	11.08	25.0	.1064	0.1392	.562	28.2	2.73	.0693	.0812	53,400	1,630	1100
12	23.47	23.42	21.02	8,587	757.8	11.06	20.0	.1447	0.0940	.509	31.1	2.63	.0612	.0650	51,500	2,670	1063
13	23.72	23.70	20.47	16,349	758.1	11.15	25.0	.1220	0.1171	.524	30.2	2.68	.0639	.0713	54,000	1,950	1115
14	23.72	23.57	23.03	28,705	757.3	7.22	45.0	.1263	0.1604	.631	25.1	2.76	.0783	.0950	34,000	945	703
15	23.77	23.72	23.25	23,529	"	7.25	40.0	.1156	0.1420	.588	26.9	2.73	.0726	.0852	34,400	1,050	710
16	"	23.75	23.45	16,352	757.5	"	35.0	.1245	0.1177	.614	25.8	2.68	.0749	.0836	34,800	1,260	720
17	23.03	22.75	22.50	8.642	757.4	7.20	20.0	.1038	0.0879	.645	24.5	2.63	.0778	.0825	35,200	1,720	727
18	23.00	23.03	22.25	28,754	757.0	4.52	45.0	.0839	0.1521	.741	21.4	2.76	.0919	.1118	21,400	592	443
19	22.42	22.45	22.28	28,739	"	4.53	60.0	.1061	0.1437	.746	21.2	2.76	.0928	.1126	21,400	592	443
20	"	22.42	"	16,365	757.2	4.55	45.0	.0971	0.1033	.700	22.6	2.68	.0854	.0953	22,000	789	455
21	21.95	21.87	21.65	8,679	757.4	4.56	35.0	.1081	0.08050	.761	23.6	2.63	.0807	.0855	22,400	1,090	463
22	22.67	22.70	22.18	23,478	"	"	55.0	.1056	0.1287	.724	22.1	2.73	.0883	.1035	21,800	661	450
1-H	23.80	23.87	23.03	28,746	756.1	9.387	30.0	.0556	0.0785	.667	23.6	4.25	.1120	.1055	5,930	456	123
2-H	23.00	23.00	22.70	988.7	"	9.331	3.0	.1453	0.0721	.651	24.2	4.05	.1048	.1048	5,910	2,440	123
3-H	23.05	22.95	22.70	986.9	756.0	9.286	"	.1415	0.0717	.635	24.6	4.05	.1020	.1020	5,890	2,430	121
4-H	23.03	23.25	22.95	16,350	757.7	9.344	40.0	.1154	0.0739	.614	25.8	4.16	.1000	.0968	5,920	602	123

$$\text{Moles of air per min.} = 16.34\ \frac{ft^3}{min} \times 0.08071\ \frac{lb}{ft^3} \times \frac{1}{29\ \frac{lb}{lb\text{-}mole}}$$

$$\times \frac{760}{758.9} \times \frac{294.68}{273.16} = 0.04209\ \frac{lb\text{-}mole}{min}\ .$$

$$y_o = \frac{1.752 \times 10^{-7}}{0.04209}\ ,$$

$$\therefore\ y_o = 0.4162 \times 10^{-5}.$$

NTU_G may now be calculated:

$$NTU_G = \ln \frac{y_w}{y_w - y_o} = \ln \frac{1.1542 \times 10^{-5}}{(1.1542 - 0.4162) \times 10^{-5}}\ ,$$

$$NTU_G = 0.447.$$

Finally,

$$HTU_G = \frac{h}{NTU_G}$$

where h = height of packed bed = 0.0833 ft.

$$HTU_G = \frac{0.0833\ ft}{0.477}$$

$$HTU_G = 0.1747.$$

2. Mass-Transfer Factor J_D

From Eq. (6) we have $J_D = \dfrac{Sc^x}{a_v\ HTU_G}$

The value of a_v given in Table IV was calculated from the average value of the micrometer measurements of a random sampling of the pellets and an accurate measurement of the bed diameter.

The least-squares determination of x from the low-pressure data of Lynch was 0.666; this commonly used value of 2/3 was therefore used throughout the high-pressure experiment, as it involved the same flow range and systems as those used in the low-pressure studies.

For run No. 4, then,

$$J_D = \frac{(2.63)^{0.666}}{189.7\ \frac{ft^2}{ft^3} \times 0.1747\ ft}\ , \qquad J_D = 0.00538.$$

Table IV

For high-pressure mass-transfer runs with 1/4-inch (nominal size) napthalene pellets

D_B	=	1.929 inches
D_P	=	.02609 feet
$\sqrt{A_P}$	=	.04625 feet
ϵ	=	0.400
a_v	=	189.7 feet^2/feet^3

150 pellets in bed of 1-inch length

NOMENCLATURE

a_v	area available for mass transfer per unit volume of packing (ft^2/ft^3).
A_p	area of a single piece of packing (ft^2).
$a_v HTU_G$	mass-transfer factor defined by Eq. (6).
C_p	heat capacity (BTU/lb, ^oF).
D_p	diameter of a sphere having the same surface area as packing (ft).
D_B	diameter of the bed (ft).
D_v	diffusivity (lb/hr, ft).
f	fanning friction factor or fugacity of mixture.
f^o	fugacity of pure substance.
G_M	molar gas flow rate (lb mole/hr ft^2).
G	gas flow rate (lb/hr ft^2).
G_B	gas-flow rate through bed (lb/min).
HTU_G	hight of a transfer unit defined by Eq. (6) (ft).
h	coefficient of heat transfer.
h_B	height of packed bed.
J_H, J_D	Chilton-Colburn J numbers for heat and mass transfer. defined by Eqs. (3) and (4) respectively.
k_g	coefficient of mass transfer for gas film (lb moles/hr, ft^2).
M, M_m	molecular weight and mean molecular weight (lb/lb mole).
NTU_G	number of transfer units (defined by Eq. (7).
p_{BM}	film pressure factor (atmos).
p_w	saturated partial vapor pressure (mm Hg).
p	partial pressure (mm Hg).

P	total pressure (mm Hg).
R	gas constant (atmos ft^3/lb mole ^oF).
Re	dimensionless Reynolds number, D_pG/μ
Re'	dimensionless Reynolds number, $D_pG/\mu\ (1-\epsilon)$.
Sc	dimensionless Schmidt number, $\mu/\rho D_v$.
St, St'	dimensionless Stanton numbers defined by Eqs. (1) and (2).
t	temperature (^oC or ^oF).
T	absolute temperature (^oK).
u	velocity (ft/min).
V_F	flow rate of gas (ft^3/min).
v	specific molal volume (ft^3/lb mole).
y	vapor concentration.
w	weight of substance vaporized from packed bed during run.
ϵ	bed voidage.
θ	time (min).
Θ (Pr), Θ (Sc)	functions to be determined experimentally, defined in Eqs. (1) and (2).
ρ	density (lb/ft^3).
ϕ	fugacity coefficient.
ψ (Re), ψ' (Re)	functions to be determined experimentally, defined in Eqs. (3) and (4).
μ	viscosity (lb/ft hr).

Subscripts

B	packed-bed conditions.
c	conditions in condenser.
F	conditions in flowmeter.
f	fugacity.
g	refers to gaseous state.
i	inlet of bed.
L	refers to liquid state.
N	refers to napthalene.
o	outlet of bed.
s	refers to solid state.
v	refers to vapor.
w	saturation conditions.

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