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Vacuum-Spray Stripping of Sparingly Soluble Gases from Aqueous Solutions:

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Part I. Mass Transfer from Streams Issuing from Hydraulic Nozzles

Carbon dioxide, oxygen, Freon 114, and butane were stripped from deionized water, sodium chloride solutions, and freshly acidified seawater in a vacuum-spray chamber using three types of hydraulic nozzle. Purely physical desorption was found for each gas/liquid system.

For both conical-spray and fan-jet nozzles, the bulk of the gas was shown to desorb from the thin liquid sheet issuing from the nozzle, that is, before droplet formation occurs. Behavior was explained semiquantitatively by a mathematical model of the diffusion in the sheet. This model was also shown to predict well the desorption from the laminar liquid sheets formed by jet impingement nozzles. For turbulent flow in jet impingement nozzles, the fit of the model was again semiquantitative.

SCOPE

Oxygen and carbon dioxide must frequently be removed from the feed to desalination plants to minimize corrosion and scaling, respectively. Refrigerant gases must be removed from both the product water and effluent brine streams of some freeze-desalination processes. Vacuum stripping may be used in these cases to avoid the excessive heat load associated with steam stripping, since only one or two equilibrium stages are required for nearly complete removal of a sparingly soluble gas. The purpose of this study was to analyze the mass transfer behavior of sprays during vacuum desorption of sparingly soluble gases. Only aqueous solutions were studied in this work. However, the general principles would be expected to apply equally well to nonaqueous systems.

Of the six major categories of spraying devices (Lapple et al., 1967), hydraulic nozzles are the only type well suited for vacuum-spray stripping, since they use energy relatively efficiently and contain no moving parts. The major types of hydraulic nozzle are fan jet, centrifugal (swirl), and jet impingement. In all three types, the liquid leaves the nozzle as a thin, coherent sheet which then breaks up to form a spray.

Hydraulic nozzles are frequently characterized by the drop size which they produce. The implication is that the important mass transfer takes place after drop formation is completed. However, a number of workers have recognized that rapid mass transfer can occur close to the nozzle before and during drop formation.

It is important to the design of compact, efficient vacuum-spray equipment to determine the region of the spray in which mass transfer is most rapid. One of the goals of this paper was to make that determination by comparing experimental data with contrasting mathematical models. In a second paper a method of designing the equipment for a particular stripping duty will be presented.

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CONCLUSIONS AND SIGNIFICANCE

High rates of mass transfer were observed with each type of hydraulic nozzle tested and for each gas/liquid system investigated. The degree of stripping was in every case considerably greater than could be explained by a rigid sphere model, which only took into account interfacial area available in the spray itself. It was demonstrated experimentally that phenomena occurring close to the nozzles, before droplet formation, were responsible for the observed high rate of mass transfer. It was also found that with centrifugal and fan-spray nozzles, varying the flow rate had little effect on the degree of stripping. The type and design of nozzle, and the diffusivity of the solute gas, were the major factors determining the stripping in the vacuum-spray chamber.

Atomization by hydraulic nozzles is the result of the disintegration (due to instability) of an expanding liquid sheet that issues from the nozzle orifice. Because of the rapid expansion, this sheet becomes very thin before breakup, the thickness near the edge being considerably less than the diameter of the drops formed subsequently. The characteristic length of the diffusion path in the sheet is thus smaller than that in the drops by the ratio of drop diameter to sheet thickness, that is, a factor of 10 to 50. Since the characteristic time for diffusion is inversely proportional to the square of the characteristic length of the diffusion path, the rate of diffusion to the surface of the sheet will be considerably higher than the rate in the drops.

It was found that a transport model developed by Hasson et al. (1964), for heat transfer during condensation on the expanding sheet produced by a fan-spray nozzle, could be adapted to the analysis of the desorption of gases from the liquid sheet issuing from a centrifugal nozzle. Application of this model showed that more than 90% of the observed mass transfer would be expected to occur from the expanding film before drop formation. The assumption of a variable eddy diffusivity, due to turbulence in the sheet, of between three and ten times the molecular diffusivity explains the lack of sensitivity of the stripping to flow rate for the centrifugal and fan-jet hydraulic nozzles.

Jet impingement hydraulic nozzles are of much simpler design than centrifugal and fan-jet nozzles and have a lower pressure drop. They form relatively large liquid sheets which break up into coarse sprays. However, high levels of stripping can be obtained with properly designed jet impingement nozzles. Again, the model of Hasson et al. (1964) can be adapted to explain the stripping occurring during laminar flow in the sheet. Only qualitative agreement with the model is obtained when the sheet is in turbulent flow. Design methods for jet impingement nozzles are presented in a second paper.

Mass transfer to or from a spray may be controlled by either the gas or liquid side resistance. In the case of desorption of sparingly soluble gases at pressures near the vapor pressure of the solvent, it can readily be shown that the gas side resistance is quite negligible and that the surface of the liquid will be in equilibrium with the vapor.

Lapple et al. (1967) provide an extensive review of the six major categories of spraying devices. The effectiveness of each spraying device in promoting mass transfer is intimately associated with the hydrodynamics of atomization and of subsequent droplet motion and so is strongly dependent upon the device used. Hydraulic atomization nozzles are the only types of spraying devices well suited to industrial scale vacuum-spray stripping since they use energy relatively efficiently and contain no moving parts. Lapple et al. (1967) found that drop sizes predicted by the various relationships in the literature for similar hydraulic nozzles are not in good agreement. Very marked disagreement regarding the magnitude of the role played by each variable was noted.

Fraser et al. (1962), Dombrowski et al. (1960), and Dombrowski and Johns (1963) have conducted extensive investigations into the mode of atomization occurring with fan-spray hydraulic nozzles. Their results are specific to fan-spray atomizers but can, with care, be extended qualitatively at least to the other two main types of hydraulic nozzles: centrifugal (swirl) atomizers and jet impingement nozzles. In all three types the liquid leaves the nozzle as a coherent fluid sheet which then breaks up within a short distance due to instability, forming the spray. Essentially the same observation was made by Rayleigh (1878) and Weber (1931) regarding the breakup of fluid jets. The rapid expansion of this fluid sheet as it extends from the nozzle causes it to become very thin, the thickness near the rim being considerably less than the diameter of droplets produced when the sheet breaks up.

The simplest model of the mass transfer process is obtained by assuming that the droplets behave as rigid spheres and that negligible mass transfer occurs until after droplet formation is complete. This model might be expected to be more descriptive of desorption with significant gas-side resistance. It will clearly underestimate vacuum-spray desorption.

Several workers, including Marsh and Heideger (1965), Garner and Lane (1959), and Cheng et al. (1974), have observed rapid mass transfer close to the tips of hydraulic nozzles, occurring before and during drop formation. Their work has been specific to the nozzle used, and they have not attempted to generalize this phenomenon qualitatively so as to make good advantage of the effect. Hasson et al. (1964) and Tamir and Hasson (1970) have observed high transfer rates for steam condensation close to the tip of hydraulic fan nozzles. Tamir and Rachmilev (1972) also observed rapid absorption of carbon dioxide into water close to the tip of fan-spray nozzles. Hasson et al. (1964) developed an analytical model for heat transfer during condensation on the fluid sheet extending from the nozzle. The calculations were in good agreement with their observations. Tamir and Rachmilev (1972) extended this analysis to explain the mass transfer observed in their system.

In this work both the rigid sphere model and the expanding sheet model are compared with experimental data obtained with a centrifugal nozzle. The expanding sheet model is then used to correlate the data obtained with a variety of jet impingement nozzles.

EXPERIMENTAL AND ANALYTICAL

A schematic of the experimental system is shown in Figure 1. The central part of the equipment was the Plexiglas vacuum chamber, which was 1.37 m in height and 0.45 m

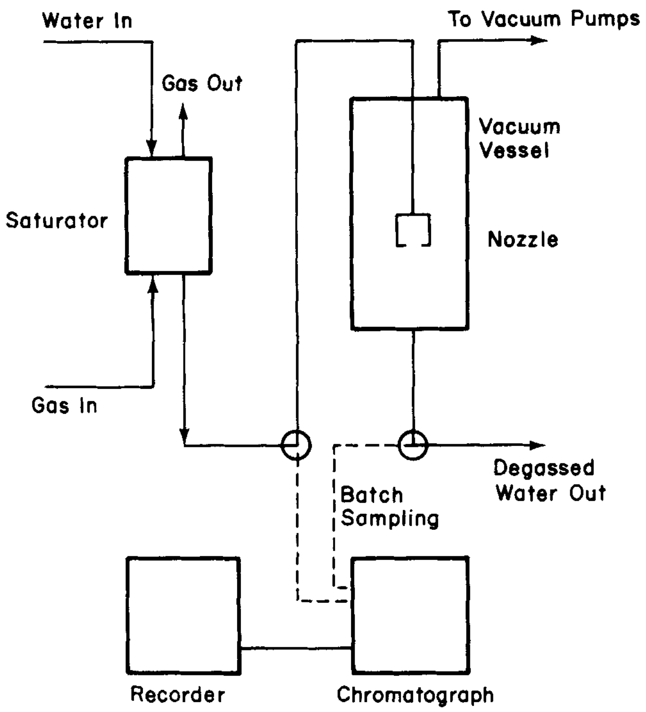

Fig. 1. Overall equipment schematic.

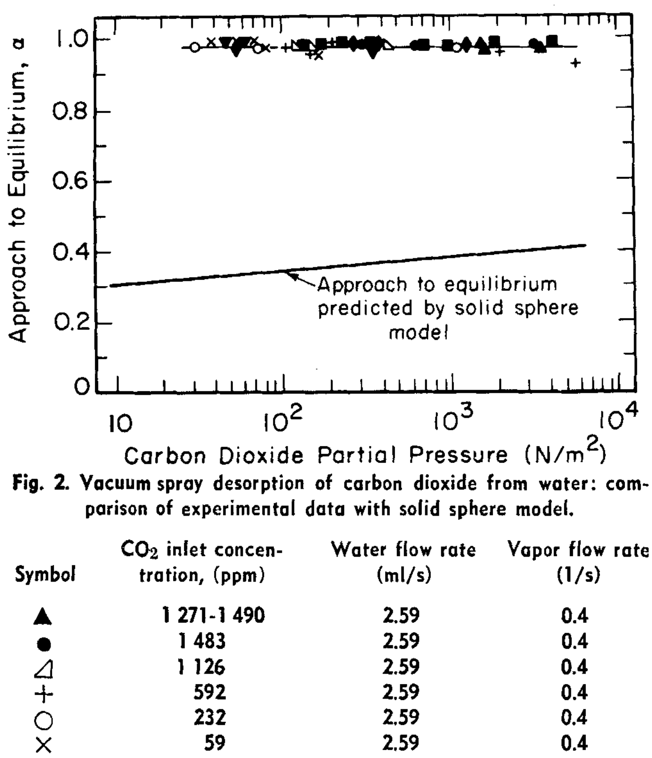

Fig. 2. Vacuum spray desorption of carbon dioxide from water: comparison of experimental data with solid sphere model.

Symbol	CO_2 inlet concentration, (ppm)	Water flow rate (ml/s)	Vapor flow rate (l/s)
▲	1 271-1 490	2.59	0.4
●	1 483	2.59	0.4
◿	1 126	2.59	0.4
+	592	2.59	0.4
○	232	2.59	0.4
×	59	2.59	0.4
■	675	3.57	0.4
▼	89	3.57	0.4
♦	1 418	2.59	0.73

outside diameter. The liquid (deionized water, aqueous sodium chloride solution, or freshly acidified seawater, pH $= 4.2$) was contacted with the gas under investigation in the saturator and pumped from there by a variable speed gear pump through the spray nozzle into the vacuum chamber, where solute gas stripping occurred. Degassed water collected in the sump of the vessel from where it was immediately pumped out by a second variable speed gear pump and was recycled to the saturator or rejected to the drain.

Water temperature measurements at the nozzle and in the sump were made using chromel/alumel thermocouples. The pressure in the vacuum vessel was monitored using both closed-end and open-end mercury manometers. Inlet and outlet water samples were taken by syringe for chromatographic analysis. The analytical technique used was similar to that of Park et al. (1964) and is discussed fully by Simpson (1975). The error in the reported concentrations of dissolved gas in the samples is estimated to be no greater than $\pm 5\%$.

SOLID SPHERE MODEL

Initial vacuum-spray stripping experiments were planned and evaluated in terms of a solid sphere model for mass transfer. The model was simple. Drops in the spray were assumed to behave as solid spheres throughout their trajectory, residence time t, and to be uniform in size, of radius R. By assuming that the interfacial concentration of solute gas is constant throughout droplet motion, in equilibrium with the partial pressure of the gas in the vapor phase, transient diffusion of solute gas out of the drops can be evaluated by the method of Carslaw and Jaeger (1959). The solution for the average dimensionless concentration (approach to equilibrium) in a spherical drop is

$$\alpha = \frac{C_i - \overline{C}_o}{C_i - C_o^*} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{n=\infty} \frac{1}{n^2} \exp\left[-n^2\pi^2 \frac{Dt}{r^2}\right] \quad (1)$$

INITIAL EXPERIMENTAL WORK

A Spraying Systems Company 1/4 LN-2 centrifugal nozzle was used in initial experiments. The nozzle was rated to produce a median drop size of approximately 150 μm (Spraying Systems Company, 1972) and this was confirmed by Arena (1973).

The nozzle was set at a height above the base plate in the vacuum-spray chamber such that a moderate approach to equilibrium would be obtained. The estimate was made by taking the time of flight for a typical droplet calculated by the method of Lapple and Sheppard, 1940) and applying it to the solid sphere model. With a nozzle height of 0.26 m, the predicted approach to equilibrium was sufficiently low that significant deviations from this model would readily be detected.

The results of experiments conducted at nozzle height of 0.26 m with carbon dioxide/distilled water system are shown in Figure 2. During these experiments the partial pressure of the carbon dioxide in the vacuum vessel was varied from approximately 50 N/m^2 (0.4 Torr) up to approximately 10.6×10^3 N/m^2 (80 Torr), the inlet carbon dioxide concentration in the water ranged from 59 to 1 490 p.p.m., and the volumetric vapor-to-liquid rate at chamber conditions was varied from 112 to 282 ml vapor/ml of liquid. It can be seen that the solid sphere model predicted an approach to equilibrium of approximately 35% and so was quite inadequate to explain the high approach to equilibrium, about 97%, which was achieved. Very similar results were obtained for the oxygen/distilled water system (approach to equilibrium approximately 98%) and the Freon 114/distilled water system (about 90%), with the 1/4 LN-2 nozzle at the 0.26 m nozzle height. With each system no significant change was observed in the approach to equilibrium when the following parameters were varied: water flow rate, inlet solute gas concentration, partial pressure of the solute gas in the vapor phase, and vapor flow rate. The approach to equilibrium was, furthermore, only a weak function of the gas/liquid system investigated. It could thus be concluded that the type and design of the nozzle were the major factors controlling the rate of mass transfer in the vacuum-spray stripper.

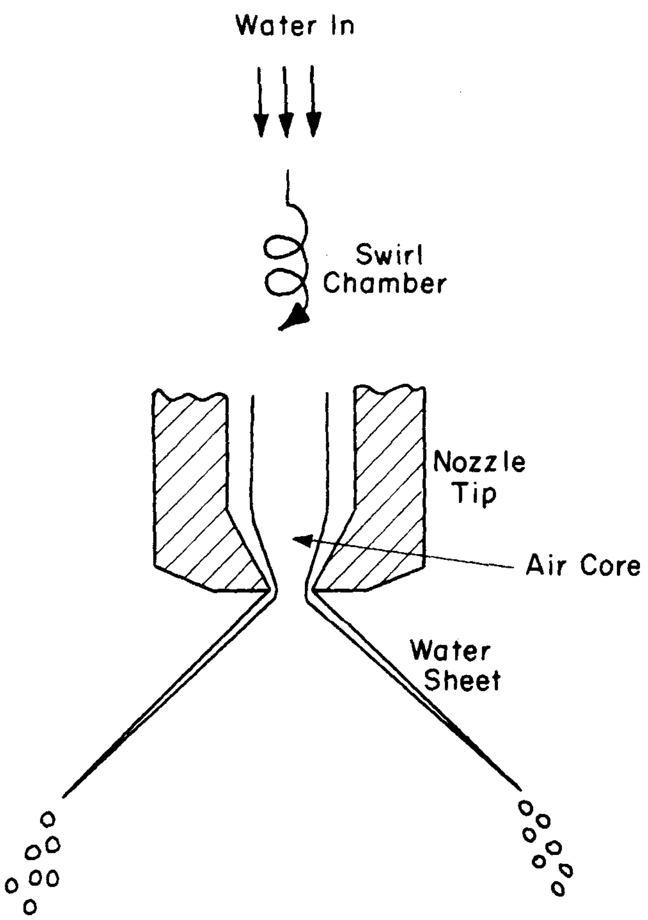

Fig. 3. Mode of action of centrifugal nozzle.

It is apparent that the rate of mass transfer observed is due to phenomena which the solid sphere model does not take into account. There were two possible areas of inadequacy here:

1. The model does not account for the hydrodynamics of the atomization process since it is assumed that droplets are produced instantaneously at the exit of the nozzle.
2. The model ignores internal circulation within the droplets and also interactions between drop trajectories.

Considering the last possibility first, Waslo and Gal-Or (1968) and Happel and Brenner (1965) indicate that the steady (terminal) velocity of a swarm of falling drops is lower than for a single drop of the same dimensions. However, to account for the necessary fortyfold increase in residence time (to make the solid sphere model applicable), a fractional volumetric holdup of dispersed phase (drops) to continuous phase (saturated gas) of approximately 0.6 would be required. Such a fractional holdup, which nearly corresponds to closely packed spheres, is totally unreasonable for the spray generated in these experiments.

Levich (1962) and Waslo and Gal-Or (1968) indicate that departure from a solid sphere to a circulating drop model for desorption is unlikely for droplets in the 150 μm size range, especially since minute concentrations of surface active agents are almost certain to be present. Even rapid circulation within the drops would lead to an increase in mass transfer of only 150% (Kronig and Brink, 1950), far below the fortyfold increase necessary to correlate the data.

It is thus clear that phenomena occurring before droplet formation are responsible for the high rate of mass transfer observed. To show that most of the desorption occurs within a very short distance of the nozzle, a set of experiments at low nozzle heights was carried out with the carbon dioxide/distilled water and oxygen/distilled water systems. At nozzle heights of 20 to 60 mm, the approach to equilibrium was about 90% for both systems (Simpson, 1975).

ATOMIZATION

A centrifugal nozzle imparts a spin component to the fluid, causing it to move in a fast, centrifugal motion down the converging walls of the nozzle upstream of the orifice (Figure 3). The orifice acts as a circular weir over which the water flows in a continuous circular sheet. An air core is thus created inside the nozzle orifice (Darnell, 1953). The radial (centrifugal) velocity component in the fluid causes the sheet to expand into a hollow cone before sheet rupture produces atomization. As the radius of the core increases, the sheet becomes very thin and the surface area per unit volume of liquid in the sheet becomes very high. Fraser et al. (1962) and Dombrowski and Johns (1963) have identified two distinct modes of breakup of the liquid sheet that depend upon the pressure in the chamber. The most significant observation of relevance to the stripping process about the two modes of disintegration is that the drops formed are considerably more coarse than the thickness of the sheet just before breakup (Fraser et al., 1962).

Careful observation of the liquid sheet produced by the 1/4 LN-2 centrifugal nozzle showed that it was 10 to 25 mm in length. The length of the sheet was difficult to estimate more precisely since it was not possible to distinguish easily with the naked eye just where the coherent sheet broke up and droplet flight began. The sheet is about 90 μm thick at the exit of the nozzle and thins to 3 to 6 μm before breakup (Simpson, 1975).

EXPANDING SHEET MODEL FOR MASS TRANSFER

Hasson et al. (1964) provide a theoretical analysis of vapor condensation on expanding water sheets produced by fan-spray nozzles. Sheets produced by fan nozzles are planar. If it is assumed that the curvature of the sheet produced by the centrifugal nozzle can be neglected (this is reasonable since the sheet is so thin), then the sheet can be unfolded and treated as a plane sheet. The analysis of Hasson et al. (1964) can then be adapted. It is assumed that the surface of the sheet is in equilibrium with the vapor and that the sheet is in laminar flow with a constant diffusivity. Allowance is made for the fact that the streamlines converge in the direction normal to the sheet surface as the sheet expands and becomes thinner. The radial velocity of the liquid is assumed constant.

The final result of the analysis is (Hasson et al., 1964; Simpson, 1975)

$$1 - \alpha = \frac{\overline{C}_o - C_o^*}{C_i - C_o^*} = \frac{8}{\pi^2} \sum_{n=1}^{n=\infty} \frac{1}{(2n-1)^2} \exp[-\lambda_n^2 \zeta] \tag{2}$$

where

$$\lambda_n = \frac{\pi}{2}(2n-1)$$

$$\zeta = \frac{4Dx^3\phi^2 u}{3Q^2}$$

ϕ is the enclosed angle in the unfolded sheet, defined by

1. Centrifugal nozzle, $\phi = 2\pi \sin(\beta/2)$, where β is the spray angle.
2. Fan-jet nozzle, ϕ = spray angle.
3. Jet impingement nozzle $\phi = 2\pi$ (see below).

It is found that for values of ζ greater than 0.2, corresponding to α greater than 0.5, the series in Equation (2) converges after one term with less than 0.1% error to give

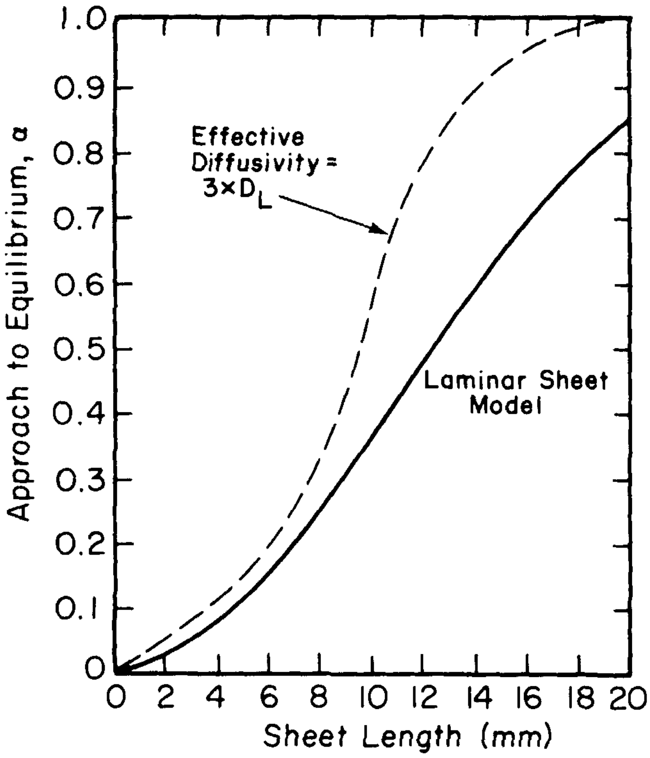

Fig. 4. Stripping efficiency predicted by sheet model s for carbon dioxide/water system using 1/4 LN2 nozzle.

$$1 - \alpha = \frac{\overline{C_o} - C_o^*}{C_i - C_o^*} = \frac{8}{\pi^2} \exp\left(- \frac{\pi^2}{4} \zeta \right) \quad (3)$$

Equation (2) was used to prepare Figure 4 in which the stripping predicted by the expanding sheet model is plotted as a function of sheet length. Two lines are illustrated in Figure 4, the lower for the laminar sheet model [Equation (2)] and the upper (dashed) line for a turbulent sheet model in which an effective diffusivity due to eddy motion in the sheet of three times the molecular diffusivity is assumed.

Fraser et al. (1962) found by high speed photography that the onset of turbulence in the sheet occurs at Reynolds numbers of approximately 10^4. The Reynolds number was based upon the hydraulic mean radius of the orifice; that is

$$Re = \frac{(\text{sheet velocity}) \times (\text{fluid density})}{(\text{fluid viscosity})} \times \frac{(\text{cross-sectional area of sheet at orifice})}{(\text{wetted perimeter of orifice})}$$

Reynolds numbers for sheets produced by the 1/4 LN-2 nozzle were about 1.5×10^4, indicating semiturbulent conditions.

Two points are noteworthy from Figure 4:

1. Both the laminar and turbulent sheet models predict rapid mass transfer for sheets 10 to 25 mm in length by the 1/4 LN-2 nozzle. For a sheet length of approximately 25 mm, the laminar model predicts the approach to equilibrium which was observed.

2. By assuming an effective diffusivity three times the molecular diffusivity, a sheet length of only 14 mm is required to explain the data.

Either assumption is reasonable given the uncertainties of the measurements.

This model can also account simply for the observation that the efficiency of stripping was nearly unaffected by changes in process variables (Figure 2). Darnell (1953) showed that the air core diameter (from which the sheet thickness is calculated) varies only with spray angle for a given nozzle, and that the spray angle is only a weak function of flow rate. The sheet thickness is thus not a strong function of flow rate. Fraser et al. (1962) found that the coherent sheet length remained unchanged over a wide range of liquid flow rate and was only a weak function of gas phase pressure. Hence these process variables cannot be used to change the sheet dimensions. Increasing the nozzle flow rate decreases the residence time of the fluid in the sheet but simultaneously increases the degree of turbulence and hence the effective diffusivity. These two effects tend to offset each other. As a result, stripping performance tends to be independent of liquid flow rate and vessel pressure, as was verified by the experimental data with the 1/4 LN-2 nozzle.

Fan-jet hydraulic spray nozzles were also tested for agreement with the sheet model for gas stripping. The nozzles were operated in the turbulent flow regime. It was found that experimental data could be correlated quite well by assuming an average effective diffusivity up to eight times the molecular diffusivity, agsin implying only a small degree of turbulence. Eddy diffusivities a hundred times greater than molecular diffusivities have frequently been measured (Sherwood and Pigford, 1952).

JET IMPINGEMENT NOZZLES

The expanding sheet model indicates that mass transfer from a liquid sheet before breakup can be very rapid, accounting for a high fraction of the mass transfer observed in vacuum-spray stripping. The small dimensions of the sheets mean that a compact stripper design is possible. However, the centrifugal and fan-spray nozzles discussed above are intricate in design and only operate satisfactorily at relatively high pressure heads; furthermore, they were not specifically designed to produce water sheets but rather to produce sprays.

A *jet impingement* hydraulic nozzle can be very simple in construction (Figure 5). A single jet produced by pumping the liquid through a circular orifice impinges against the flat end of a rod or stud, and a planar circular sheet is produced. At low flow rates the drops fall off the edge of the sheet nearly vertically; at high flow rates the drops fly off the edge horizontally. Relatively large drops are formed when the sheet breaks up. In light of the sheet model, a fully circular planar sheet is of interest because it necessarily exhibits the maximum possible expansion (and so minimum sheet thickness) at any sheet length. If the nozzle orifice and impingement plate are machined carefully, the sheet formed is large and stable. Such nozzles have relatively high flow rates and relatively low pressure

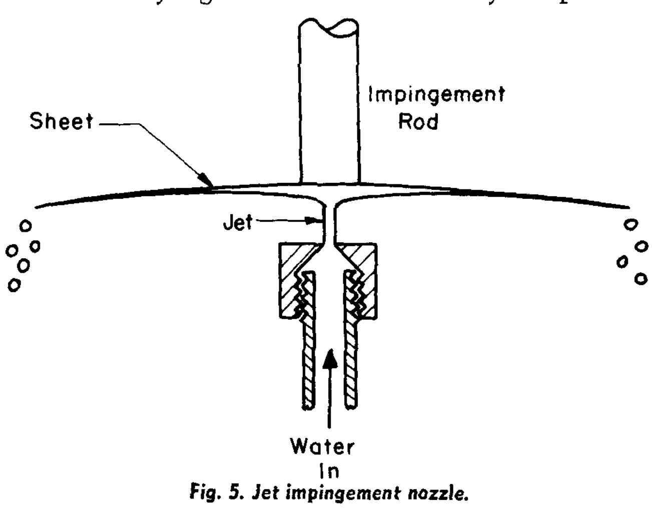

Fig. 5. Jet impingement nozzle.

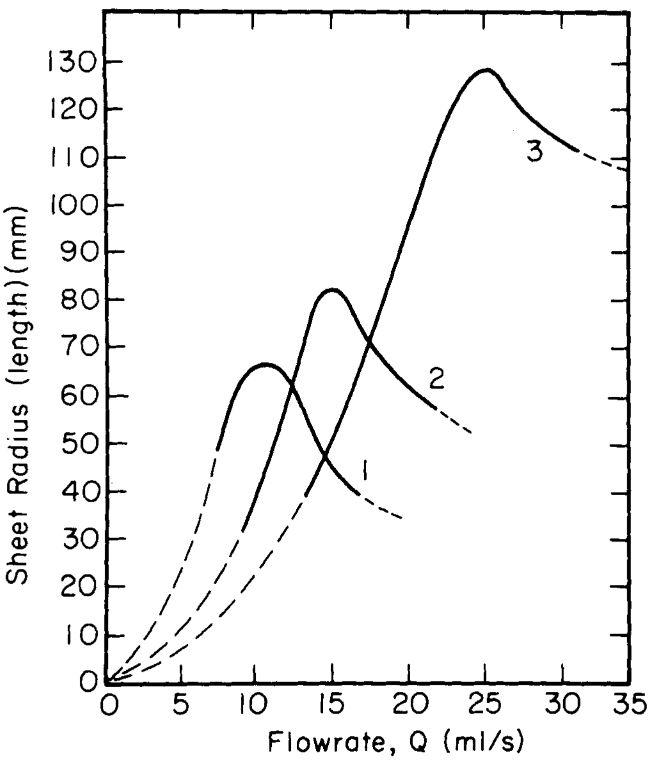

Fig. 6. Typical dimensions of sheets formed by jet impingement nozzles.

Curve	Nozzle	Orifice diam. (mm)	Discharge coefficient
1	1/16 P1	1.05	0.9 -0.96
2	1/16 P1-5	1.55	0.9 -0.93
3	1/16 P2	2.16	0.84-0.88

drops compared to fan-spray and centrifugal-spray nozzles. Several different impingement nozzles, with square edged or convergent orifices with nominal diameters of 1 to 3 mm, were constructed and tested.

SHEET FORMATION BY JET IMPINGEMENT NOZZLES

Radii of typical sheets formed by impingement nozzles are shown in Figure 6. Measurement of the dimensions of the sheets was difficult owing to the frantic motion of the edges of the sheets where drop formation occurred. The dimensions shown are thus considered to be reasonable averages. Figure 6 shows that impingement sheets increase in diameter with increasing flow rate up to a maximum, after which the sheet diameter decreases, at first rapidly, and then relatively slowly. The appearance of the sheets also changes as the flow rate increases. During the phase of sheet growth at low flow rates the sheets are glassy in appearance and transparent. This is the laminar flow phase. At a certain flow rate characteristic of each nozzle the sheet starts to take on a ruffled appearance and becomes translucent. This appearance corresponds to sheet growth becoming less rapid and the sheet passing through its maximum diameter, which is thought to be due to the onset of turbulence. With further flow rate increase the sheet surface becomes increasingly grained in appearance and nearly opaque. This phase, accompanied by a decrease in sheet diameter, corresponds to an increasing degree of turbulence in the sheet.

It was found that the dimensions and characteristics of the sheets were not significantly different when formed by distilled water, seawater, sodium chloride solutions, or distilled water containing 10 p.p.m. Neodel (a surface active agent). Sheets formed by impingement are stable. They

TABLE 1. JET IMPINGEMENT NOZZLE CHARACTERISTICS

Nozzle Designation	Orifice type	Orifice diameter, mm	Discharge coefficient
1/16 P1	Square edged	1.05	0.9 -0.96
1/16 P1.5	Square edged	1.55	0.93-0.96
1/16 P2	Square edged	2.16	0.84-0.88
1/16 P3	Square edged	3.2	0.62
A13C	Convergent	3.21	0.64
SS1.2C	Convergent	1.22	0.98-0.99
8B1.9C	8 Convergent nozzles	0.91 (aver.)	0.94 (aver.)

are unaffected by vibration and can be produced by impingement of the jet in any direction. The most satisfactory sheet formation is effected, however, when the jet is oriented vertically upward or downward. Vertical momentum is not completely dissipated on impingement, and the sheets, particularly at low flow rates, exhibit a slight curvature. This is accentuated by gravity when jets impinge downward. The curvature is so slight, however, that at most flow rates it can hardly be detected with the naked eye, and it can be neglected in making calculations.

VACUUM STRIPPING WITH JET IMPINGEMENT NOZZLES

Laminar Flow Regime

An extensive series of experiments was carried out using impingement nozzles in the vacuum stripper. The nozzles and their characteristics are listed in Table 1. The impingement plates were machined from brass or stainless steel rods 12.7 mm in diameter.

The systems investigated during these experiments were carbon dioxide/distilled water, carbon dioxide/3.5% so-

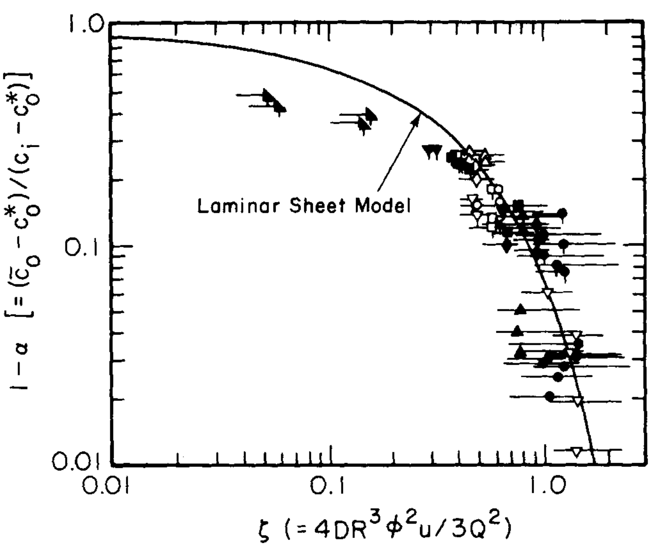

Fig. 7. Fraction of solute remaining in excess of equilibrium: comparison of experimental data with laminar sheet model.

Symbol	System	Nozzle
●	CO_2/distilled water	1/16 P1
▲	CO_2/distilled water	1/16 P1-5
■	CO_2/distilled water	1/16 P2
▽	CO_2/distilled water	1/16 P3
■	CO_2/distilled water	AL3C
×	CO_2/distilled water	SS1-2C
♦	CO_2/distilled water	8B1-9C
○	CO_2/3.5% wt. aq. NaCl	SS1-2C
□	CO_2/7.0% wt. aq. NaCl	SS1-2C
▽	CO_2/seawater (pH 4.2)	SS1-2C
△	Freon 114/distilled water	8B1-9C
◇	n-butane/distilled water	8B1-9C

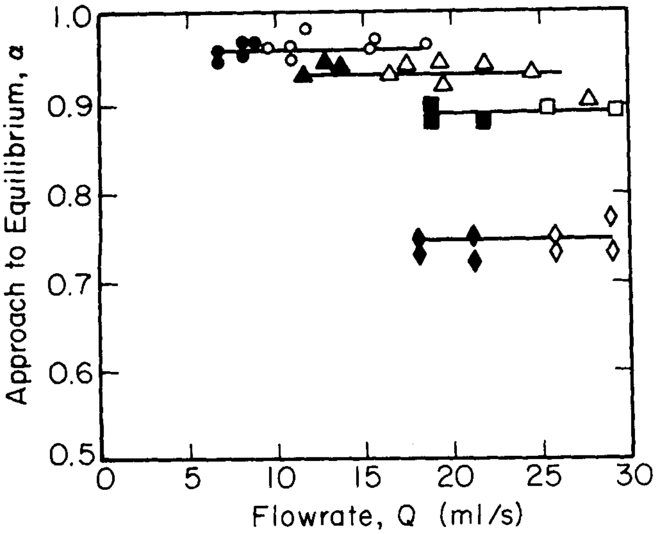

Fig. 8. Stripping efficiency as a function of flow rate for jet impingement nozzles.

Symbol			
Laminar	Semiturbulent	System	Nozzle
●	○	CO_2/H_2O	1/16 P1
▲	△	CO_2/H_2O	1/16 P1-5
■	□	CO_2/H_2O	8B1 9C
♦	◇	Freon 114/H_2O	8B1 9C

dium chloride solution, carbon dioxide/7.0% sodium chloride solution, carbon dioxide/fresh acidified seawater (pH = 4.2), n-butane/distilled water, and Freon 114/distilled water. Results are shown in Figure 7.

The abscissa in Figure 7 is the dimensionless number ζ. This number is proportional to the cube of the sheet length [or sheet radius for a circular sheet, refer to Equation (2)] which, as noted earlier, was a difficult measurement to make accurately. Determining the sheet length was also complicated by the observation that the hydrodynamics close to the edge of the sheet did not appear to be as simple as that assumed in the model. At the edge of the sheet, water tends to accumulate into a rim during both the laminar growth phase and the semiturbulent phase. Drops are formed from nodes created as the rim periodically breaks up owing to instability. Just before the rim there seems to be some evidence of thickening of the sheet towards regions where nodes form. There is thus some question as to the effective sheet length for use in the sheet model. Furthermore, measurements of sheet lengths were made at atmospheric pressure and were never measured under vacuum conditions owing to the difficulty of seeing the edge of the sheet through the walls of the vacuum vessel. It did appear, however, that sheet lengths decreased to a small extent under vacuum conditions. A factor of 0.8 was therefore used to estimate the effective sheet length under vacuum conditions for calculating the prevailing values of ζ. For reasons discussed in detail in Part II of this paper, the radial velocity of the sheet u was assumed to be constant at 0.8 of the velocity of the jet at the vena contracta. The data points in Figure 7 represent the most likely value of ζ. The lengths of the lines attached to the data points represent the estimated uncertainty in the value of ζ.

In order to obtain many of the data points in Figure 7, various diameter cylindrical shields about 30 mm in length were placed concentrically around the nozzles so as to cut off the sheet prematurely. Samples to which this applied are shown as data points with tails. By this means the range of ζ for each nozzle tested was varied by controlling the sheet radius, the nozzle flow rate, and the diffusivity (by using different gas/liquid systems).

Figure 7 shows that agreement with the laminar sheet model was reasonably good. (The sheet model does not fully describe impingement sheets, since it assumes symmetry about the neutral plane in the sheet; however, for sheet lengths of interest it is a very good approximation.) It should be noted that Figure 7 contains data for six different gas/liquid systems, indicating similar behavior for these systems. Data taken with an ensemble of eight nozzles fed by a header (8B1.9C) are also correlated by the model, indicating no loss in performance when impingement nozzles are located close to each other.

At low stripping efficiency ($[1 - \alpha] > 0.5$) (effected by using small diameter shields), mass transfer in excess of that predicted by the laminar sheet model occurred. (In general, data lying to the lower left of the model line in Figure 7 indicate mass transfer greater than predicted by the model.) This additional mass transfer was probably the result of having interfacial area available subsequent to sheet disruption which was not accounted for by the model.

Turbulent Flow Range

Data plotted in Figure 7 were all taken in the laminar flow range of flow rates. Data were also taken in the range of flow rates where the sheets exhibited turbulent appearance. These data were not plotted in Figure 7 since the laminar model takes no account of diffusion enhancement due to eddy motion. Turbulent stripping data, if plotted in Figure 7, would lie well to the lower left of the laminar model line. This occurs because, despite smaller sheet radii and higher fluid velocities in the sheet in turbulent flow, eddy diffusion tends to offset the decrease in ζ so as to maintain an effective value of ζ that is constant for the purposes of the diffusion model. This is shown in Figure 8, where stripping efficiency for various nozzles and solutes is plotted as a function of flow rate, and is seen to be independent of flow rate. Note that the different levels of stripping shown in Figure 8 are due to using different nozzle orifice diameters and to the different diffusivities of the systems tested.

It can be concluded that the expanding sheet model for mass transfer applies for laminar flow in impingement nozzles. The major inadequacies of the model for design purposes are variation of sheet radius with flow rate is not predicted, onset of turbulent behavior is not anticipated, and diffusion enhancement due to eddy motion is not accounted for.

A design model for jet impingement stripping in the turbulent flow range is developed in the second part of this paper.

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NOTATION

C = solute gas concentration, kg/m^3
D = molecular diffusion coefficient, m^2/s
n = integer
Q = liquid flow rate per nozzle, m^3/s
r = radius (droplet), m
t = time, s
u = sheet velocity, m/s
x or R = sheet length or sheet radius, m

Greek Letters

α = approach to equilibrium = $C_i - \overline{C}_o/C_i - C_o^*$
β = enclosed spray angle, rad
ζ = reduced sheet dimension [see Equation 2)] = $4D\,x^3\phi^2 u/3Q^2$
λ_n = eigenvalue [Equation (2)]
ϕ = enclosed sheet angle, rad

Subscripts

i = inlet value
o = outlet value

Superscripts

— = averaged value
$*$ = equilibrium value

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Part II. Stripper Design using Jet Impingement Nozzles

Experimental data on vacuum-spray stripping of sparingly soluble gases from aqueous solution using hydraulic nozzles were presented in part I of this communication. Mass transfer was shown to occur primarily from the thin liquid sheet issuing from the nozzle tip in semiquantitative accordance with an analytical model based on laminar flow behavior.

Jet impingement hydraulic nozzles offer the advantages of simplicity and low operating cost in vacuum-spray stripping. An empirical model for the turbulent flow regime has been developed to facilitate incorporating jet impingement nozzles into a vacuum stripper design. The results of an economic analysis comparing other types of industrial vacuum strippers with the proposed design of a jet impingement vacuum stripper show the latter process to compare very favorably in terms of estimated equipment size and cost and in expected operating cost.

SCOPE

In part I of this paper, experimental vacuum-stripping data for jet impingement hydraulic nozzles operated in the laminar regime were shown to be in satisfactory agreement with a model predicting that mass transfer occurs solely during flow through the thin circular sheets which expand radially from such nozzles. It was thus demonstrated that, owing to the very short diffusional path created in these thin liquid sheets, a high approach to interphase equilibrium is achieved before sheet disruption occurs and subsequent dispersed droplet motion begins. The laminar model does not allow, however, for the development of complex flow patterns within the sheet and so is not capable of predicting the stripping that occurs in the turbulent regime.

In the laminar regime, stripping from the sheets formed by jet impingement nozzles is quite sensitive to flow rate. In the turbulent range of operation, however, as noted

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