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)] = $4D\,x^3\phi^2u/3Q^2$
λ_n = eigenvalue [Equation (2)]
ϕ = enclosed sheet angle, rad

Subscripts

i = inlet value
o = outlet value

Superscripts

— = averaged value
* = equilibrium value

LITERATURE CITED

Arena, J., III, "Measurement of Flow and Droplet Size Distribution for Spray Nozzles," M.S. thesis, Univ. Calif., Berkeley (1973).

Carslaw, H. W., and J. C. Jaeger, *Conduction of Heat in Solids*, 2 ed., p. 234, Oxford Univ. Press, England (1959).

Cheng, Y-S., A. J. Barduhn, and P. A. Rice, "The vacuum stripping of butane from water in sprays," *Syracuse Univ. Dept. Chem. Eng. and Mat. Sci., Report F-10*, O.S.P. No. 6707 (1974).

Darnell, W. H., Ph.D. thesis, Univ. Wisc., Madison (1953).

Dombrowski, N., D. Hasson, and D. E. Ward, "Some Aspects of Liquid Flow Through Fan Spray Nozzles," *Chem. Eng. Sci.*, **12**, 35 (1960).

Dombrowski, N., and W. R. Johns, "The Aerodynamic Instability and Disintegration of Viscous Liquid Sheets," *ibid.*, **18**, 203 (1963).

Fraser, R. P., P. Eisenklam, N. Dombrowski, and D. Hasson, "Drop Formation from Rapidly Moving Liquid Sheets," *AIChE J.*, **8**, 672 (1962).

Garner, F. H., and J. J. Lane, "Mass Transfer to Drops of Liquid Suspended in a Gas Stream," *Trans. Inst. Chem. Engrs.*, **37**, 162 (1959).

Happel, J., and H. Brenner, *Low Reynolds Number Hydrodynamics with Special Applications to Particulate Media*, p. 389, Prentice-Hall, Englewood Cliffs, N.J. (1965).

Hasson, D., D. Luss, and R. Peck, "Theoretical Analyses of Vapor Condensation on Laminar Liquid Jets," *Int. J. Heat Mass Trans.*, **7**, 969 (1964).

Kronig, R., and J. C. Brink, "On the Theory of Extraction from Falling Droplets," *Appl. Sci. Res.*, **A2**, 142 (1950).

Lapple, C. E., J. P. Henry, and D. E. Blake, "Atomization—A Survey and Critique of the Literature," *SRI Technical Report No. 6* (1967).

Lapple, C. E., and C. B. Shepherd, "Calculation of Particle Trajectories," *Ind. Eng. Chem.*, **32**, 605 (1940).

Levich, V. G., *Physicochemical Hydrodynamics*, p. 426, Prentice-Hall, Englewood Cliffs, N.J. (1962).

Marsh, B. D., and W. J. Heideger, "Mass Transfer from Free Drops," *Ind. Eng. Chem. Fundamentals*, **4**, 129 (1965).

Park, K., G. H. Kennedy, and H. H. Dobson, "Comparison of Gas Chromatographic Method and pH Alkalinity Method for Determination of Total CO_2 in Water," *Anal. Chem.*, **36**, 1686 (1964).

Rayleigh, Lord, *Proc. London Math. Soc.*, **10** (1878).

Sherwood, T. K., and R. L. Pigford, *Absorption and Extraction*, p. 46, McGraw-Hill, New York (1952).

Simpson, S. G., "Vacuum Stripping of Sparingly Soluble Gases from Water," Ph.D. thesis, Univ. Calif., Berkeley (1975).

Spraying Systems Co., Bellwood, Ill., Private communication (1972).

Tamir, A., and D. Hasson, "Evaporation and Condensation Coefficient of Water," *Chem. Eng. J.*, **2**, 200 (1970).

Tamir, A., and I. Rachmilev, "Absorption of Carbon Dioxide in a Rapid Laminar Fan-Shaped Water Sheet," *ibid.*, **4**, 85 (1972).

Waslo, S., and B. Gal-Or, "Hydrodynamics of an Ensemble of Drops (or Bubbles) in the Presence or Absence of Surfactants," *Chem. Eng. Sci.*, **23**, 1431 (1968).

Weber, C., *Z. angew. Math. u. Mech.*, **11**, 136 (1931).

Manuscript received June 30, 1976; revision received June 2, and accepted June 22, 1977.

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

Correspondence concerning this paper should be addressed to Scott Lynn. Stuart G. Simpson is with Union Carbide Corporation, Tarrytown, New York.

in part I, this sensitivity is not observed. This change is thought by the authors to be caused by diffusion enhancement, due to turbulent eddy motion, which increases with flow rate and so counteracts the decreased residence time of fluid in the sheet before atomization occurs. Since it is important to stable plant operation that stripping performance be independent of throughput over a reasonable range of flow rates, industrial jet impingement strippers would be operated in the turbulent regime.

One goal of this work was to develop a design model to predict turbulent stripping performance of jet impingement nozzles. The purpose of the model is to provide a conservative prediction of the stripping efficiency attainable with any impingement nozzle and, conversely, to provide a method of nozzle design for any duty such that flexible plant operation would be possible while the specified stripping performance is maintained.

A second goal was to compare vacuum stripping of sparingly soluble gases from aqueous solution using an industrial scale impingement stripper with other available processes. Accordingly, a configurational design has been proposed and evaluated that would meet Office of Saline Water specifications for degassing seawater feed to desalination plants. Fixed capital investment and total annual operating costs for the proposed jet impingement vacuum stripper have been compared with those for more conventional equipment designed to the same specifications.

CONCLUSIONS AND SIGNIFICANCE

The model developed by Hasson et al. (1964) for transport to a laminar expanding sheet of liquid has been extended to include gas stripping from sheets created by jet impingement hydraulic nozzles throughout their normal range of flows, that is, turbulent and semiturbulent as well as laminar. The model developed predicts sheet radius as a function of flow rate, jet diameter, and liquid properties during the laminar range of operation. Turbulent stripping performance is predicted by using the empirical observation that the degree of stripping remains approximately constant when Re_{jet} exceeds the critical value for transition to turbulent flow.

This model provides a convenient procedure for designing impingement nozzles for any required stripping duty. The model is felt to be conservatively valid for aqueous systems for the range of orifice diameters and flow rates tested (which would include most cases of practical interest). It would serve as a useful point of departure for other systems.

The model developed has been used to design jet impingement nozzles for a vacuum-spray deaerator for a 50 MGD (2 100 kg/s product rate) desalination plant. A prototype of the design has been built and tested satisfactorily. The design is more compact than a conventional packed column using steam stripping and would be expected to have lower operating costs.

Degassing is an important operation in the chemical process industries. A specific example of its significance is in the control of dissolved oxygen and carbon dioxide in the seawater feed to multistage flash and multieffect evaporation desalination plants. These gases must be removed to protect process equipment from corrosion and scale formation due to deposition of insoluble carbonates. In this case, process economics dictates reduction of dissolved oxygen and carbon dioxide to less than 5 p.p.b. and 1 p.p.m., respectively (Hunter et al., 1967).

Sulfuric acid may be used to adjust the pH of seawater to 4.2 so as to convert more than 99% of the bicarbonate ion to free carbon dioxide that may be removed in a degassing tower. Acid costs for this method are low (Elliott, 1969), and hence economic feasibility depends upon very efficient degassing. Simultaneous oxygen removal may also be achieved, and since oxygen removal is a problem equal in importance to scale control, the method has significant potential advantage over the processes.

Di Luzio et al. (1965) have demonstrated virtually complete degasification of acidified seawater by countercurrent vacuum steam stripping under partial vacuum in a 200 mm diameter tower packed with two 1.5 m beds of 25.4 mm porcelain Berl saddles. However, Hunter et al. (1967), in reviewing this and other deaerator designs submitted to the Office of Saline Water, considered them to be unsuitable because of high stripping steam requirements and/or high pressure drop.

The high rate of mass transfer attainable in the expanding liquid film which extends a short distance from the outlet of a hydraulic nozzle (as reported in part I of this paper) make this form of contacting the basis for an interesting design alternative to conventional stripping processes. A simple, compact stripper design may be visualized in which a three-dimensional matrix of expanding liquid films is produced by a set of aligned, closely packed nozzles. Spray formation would not be important in such a device; with proper design there would be sufficient mass transfer occurring within the expanding films of liquid. High specific capacity could thus be achieved. Jet impingement nozzles are particularly suited to this application because of their simple construction and low operating cost.

The stripping performance of an impingement nozzle increases with increasing flow rate to a maximum coincident with the onset of turbulent flow in the expanding liquid film. Subsequent performance is relatively insensitive to flow rate increase. This latter phenomenon is particularly relevant to the design of a stripping process, since a high turn down ratio may be attained without loss of design performance and without creating equipment redundancy. The transport model developed by Hasson et al. (1964) and used in part I to analyze the performance of jet impingement nozzles operating in the laminar regime cannot be applied in any straightforward manner to predict turbulent stripping behavior. Their model relies upon a prior knowledge of the length (radius) of the liquid film and accounts for mass transfer solely by molecular diffusion. Thus, in order to facilitate design of an impingement stripping process, complete modeling of all transport processes occurring in the expanding liquid film created by jet impingement is needed.

The objectives are: modeling of the fluid mechanics of sheet formation so that the radius of an impingement sheet

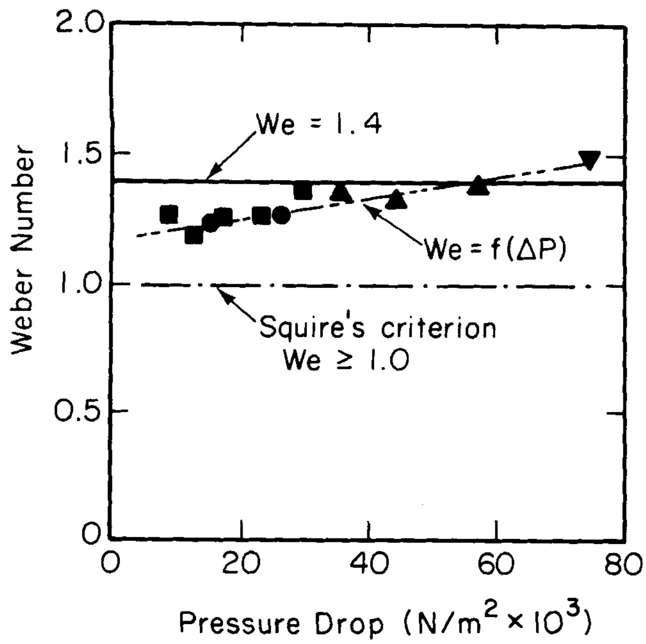

Fig. 1. Weber number at atmospheric pressure for impingement sheets in laminar flow:

Symbol	Nozzle
▼	1/16 P1
●	1/16 P1-5
■	1/16 P2
▲	SS1-2C

can be predicted as a function of flow rate, liquid properties, and nozzle parameters; modeling of the stripping efficiency in both laminar and turbulent flow as a function of the same variables; and devising a procedure for nozzle design for use in a process to achieve a desired stripping duty.

MODELING OF JET IMPINGEMENT SHEET FORMATION

Sheets produced by impingement nozzles show three distinct types of flow (laminar, transitional, and turbulent) which were discussed in part I.

In the laminar range, in theory, sheet breakup occurs (Squire, 1953) because of hydrodynamic instability at the rim when the surface energy approaches the kinetic energy.

$$We \left(\equiv \rho \frac{u^2 \delta_{\rm rim}}{2\sigma} \right) \geqq 1.0 \qquad (1)$$

Fraser et al. (1962) examined this criterion for sheets formed by fan-spray nozzles. They found that We was 1.6 to 3 for sheets formed in air at atmospheric density (1.2 kg/m^3). At lower air densities the value of the Weber number increased gradually until, at an air density of approximately 2×10^{-2} kg/m^3, the value of the Weber number increased rapidly up to about 5. Fukui and Sato (1972) also observed that sheets formed by direct impingement of two jets did not achieve the theoretical maximum length, indicating the Weber number for such sheets was greater than 1. Taylor (1959), however, found that $We = 1.0$ fit his data for laminar sheets produced by single jet impingement nozzles.

Taylor (1959) also found that approximately 20% of the jet velocity is lost by kinetic energy dissipation in the impingement process. The radial velocity of the sheet u was observed to be constant and is thus approximately 80% of the jet velocity. The thickness of the sheet can therefore be related to its radius and the velocity of flow through the nozzle by the equation of continuity:

$$Q = C_D \frac{\pi d_o^2}{4} \cdot \frac{u}{0.8} = 2\pi R \delta_{\rm rim} u \qquad (2)$$

Combination of Equation (1) with Equation (2) gives

$$We = \frac{0.8\, \rho Q^2}{\pi^2 C_D d_o^2 \sigma R} \qquad (3)$$

The value of We is thus a measure of the sheet radius for a given nozzle, flow rate, and set of fluid properties.

Figure 1 shows Weber number defined by Equation (3) for laminar jet impingement sheets plotted against pressure drop (a measure of the flow velocity) for four nozzles. A design criterion of $We = 1.4$ was selected, in preference to one of the form $We = f(\Delta P)$ indicated by the dashed line in Figure 1, as a conservative approximation. The characteristics of the nozzles listed in Figure 1 are given in Table I of part I. It should be noted that the dependence of We on ρ and σ that is predicted by Equation (3) was not effectively tested. All of the aqueous solutions had very similar densities. The addition of 10 p.p.m. Neodol did not appear to affect R for a given value of Q, but the time of flight may have been too short for the surfactant to affect the surface tension.

This correlation of laminar sheet size is applicable up to the point where the transition to turbulent flow begins. The transition is assumed to start when the sheet first takes on a ruffled appearance. This occurs at a particular flow rate for each nozzle and corresponds to an increased Weber number. Ranz (1959) discussed a gas-phase Weber number to account for aerodynamic instability causing the transition. A similar approach was

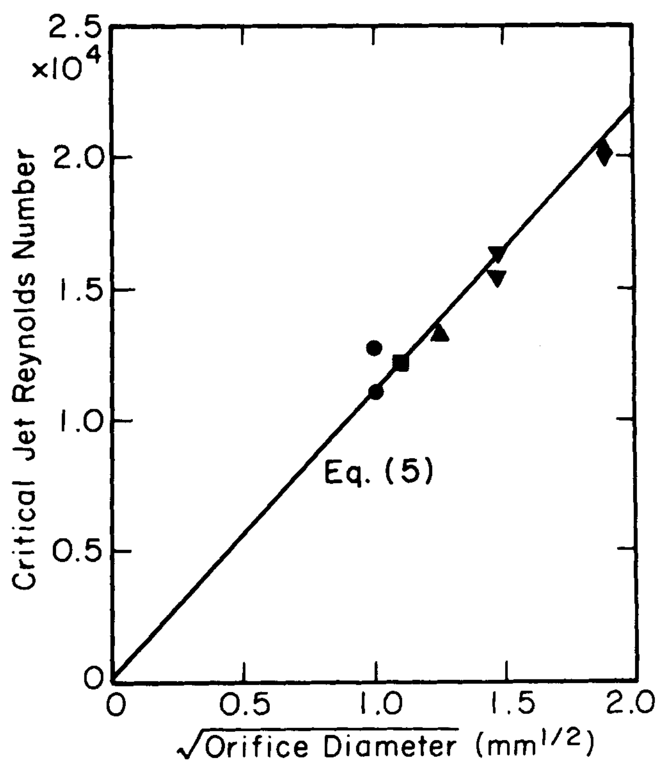

Fig. 2. Correlation of Re_{jet} at onset of sheet turbulence with orifice diameter for jet impingement nozzles:

Symbol	Nozzle
●	1/16 P1
▲	1/16 P1-5
▼	1/16 P2
♦	1/16 P3
■	SS1-2C

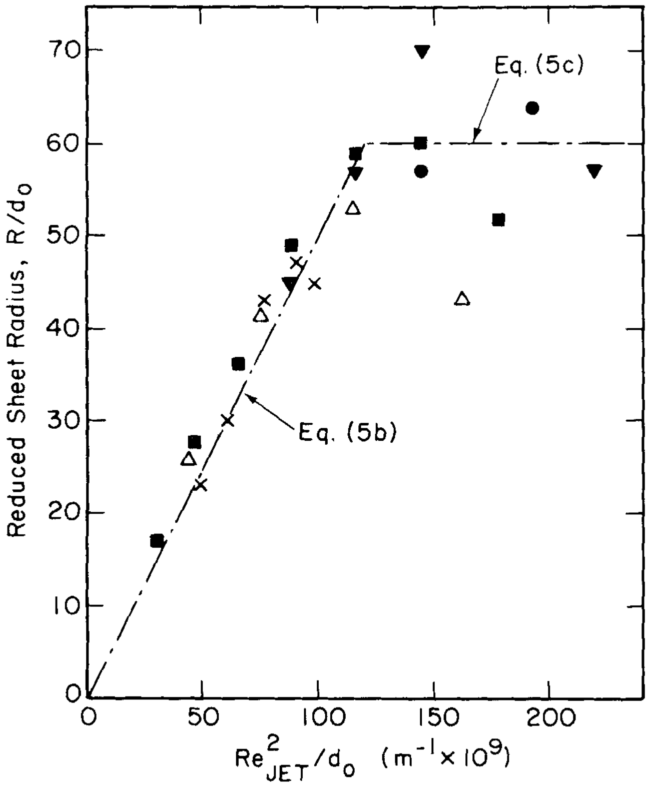

Fig. 3. Correlation of sheet size with flow rate and nozzle diameter:

Symbol	Nozzle	Orifice diameter
●	1/16 P1	1.05 mm
△	1/16 P1-5	1.55 mm
■	1/16 P2	2.16 mm
×	1/16 P3	3.2 mm
▼	SS1-2C	1.22 mm

found to give very poor correlation with data in this work. Further investigation did reveal a correlation between the jet Reynolds number at the onset of turbulence and the nozzle diameter. The jet Reynolds number was defined as

$$Re_{\text{jet}} = \frac{4Q\rho}{\sqrt{C_D}\pi d_o \mu} \tag{4}$$

The results of this correlation are shown in Figure 2, from which the criterion for transition to semiturbulent behavior in the sheet is given by the dimensional equation

$$Re_{\text{jet,crit}} = 3.5 \times 10^5\, d_o^{1/4} \tag{5}$$

The critical Reynolds numbers determined are in good agreement with those observed by Fraser et al. (1962) for fan-spray nozzles.

By rearranging Equation (3) and substituting the definition of Re_{jet} [Equation (4)], one obtains

$$\frac{R}{d_o} = \frac{0.8\,\mu^2 Re_{\text{jet}}^2}{16\sigma\rho We d_o} \tag{6a}$$

For $\mu = 1.0 \times 10^{-3}$N s/m², $\sigma = 72 \times 10^{-3}$ N/m, $\rho = 1.0 \times 10^3$ kg/m³, and $We = 1.4$

$$\frac{R}{d_o} = 0.50 \times 10^{-9}\, Re_{\text{jet}}^2/d_o \tag{6b}$$

Equation (6b) would be expected to hold for aqueous solutions having physical properties near those of water and for flow rates up to the point where turbulence begins, as indicated by Equation (5). At that point, by substituting Equation (5) into Equation (6b), one obtains

$$\frac{R}{d_o} = 60 \;(Re_{\text{jet}} \geq Re_{\text{jet,crit}}) \tag{6c}$$

For flow rates above Q_{crit}, it was found experimentally that the extent of stripping remained constant. For modeling purposes it was decided to assume that the sheet radius also remained constant at flow rates above Q_{crit}, despite the fact that this was a gross over simplification of the fluid mechanics of sheet formation. Sheet dimensions calculated using Equations (6b) and (6c) are compared with actual sheet measurements in Figure 3. It is seen that for all of the nozzles Equation (6a) is followed quite well until the value of Re_{jet}^2/d_o is reached at which $R/d_o = 60$. At higher flow rates the sheets become turbulent, and the value of R begins to decrease.

MODELING OF THE EFFICIENCY OF STRIPPING WITH IMPINGEMENT NOZZLES

In the laminar regime of sheet behavior the laminar transport model for vacuum stripping (Hasson et al., 1964) applies well, as shown in part I of this paper, with the assumptions that $u_{\text{sheet}} = u_{\text{jet}}$ and that the effective sheet radius is 0.8 of the radius at atmospheric pressure. The approach to equilibrium is given by the expression

$$\alpha = \frac{C_i - \overline{C}_o}{C_i - C_o^*} = 1 - \frac{8}{\pi^2}\exp\left\{\frac{-68\,DR^3}{C_D Q d_o^2}\right\} \tag{7a}$$

By substituting Equation (4) and the physical properties of water, one obtains

$$\alpha = 1 - \frac{8}{\pi^2}\exp\left\{-86 \times 10^6 \frac{D\left(\frac{R}{d_o}\right)^3}{C_D^{3/2} Re_{\text{jet}}}\right\} \tag{7b}$$

Equations (7a) and (7b) apply up to $Q \leq Q_{\text{crit}}$. The sheet radius is calculated from Equation (6b).

Consider now the stripping occurring during turbulent sheet behavior, that is, at flow rates above Q_{crit} as de-

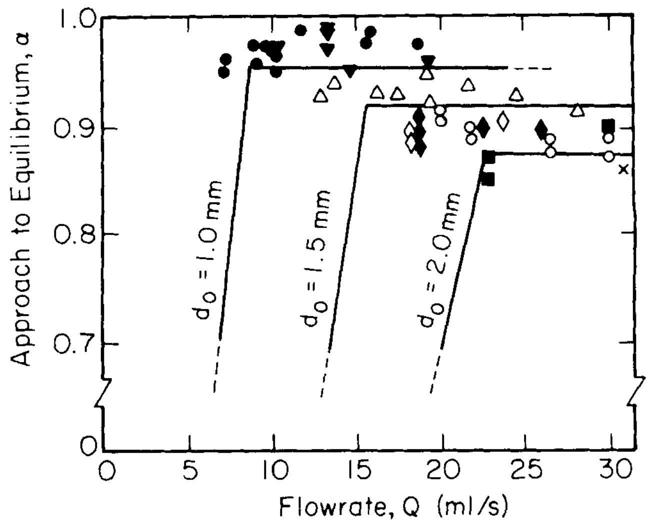

Fig. 4. Vacuum stripping from turbulent sheets formed by jet impingement nozzles. Experimental data compared with turbulent sheet model:

Symbol	System	Nozzle	Orifice diameter (mm)
●	CO_2/H_2O	1/16 P1	1.05
△	CO_2/H_2O	1/16 P1-5	1.55
■	CO_2/H_2O	1/16 P2	2.16
×	CO_2/H_2O	1/16 P3	3.2
◆	CO_2/H_2O	8B1-9C	1.9(avg)
▼	CO_2/seawater	SS1-2C	1.22
◐	Freon 114/H_2O	8B1-9C	1.9(avg)
◇	n-butane/H_2O	8B1-9C	1.9(avg)

fined by Equation (4). It has been found empirically that the stripping remains constant at a value corresponding to the critical flow rate; thus it can be concluded that the effective values of R/d_o and Re_{jet} remain constant at the values corresponding to Q_{crit}. Thus, by substituting for R/d_o and $Re_{jet,crit}$ in Equation (7b) the values from Equations (6c) and (5), one obtains

$$\alpha = \frac{C_i - \overline{C}_o}{C_i - C_o^*} = 1 - \frac{8}{\pi^2} \exp\left\{ -53 \times 10^6 \frac{D}{C_D^{3/2} d_o^{1/2}} \right\} \tag{8}$$

Equation (8) applies for supercritical flows. Note that the term $D/d_o^{1/2}$ is dimensional, so that the value of the numerical constant within the brackets depends upon the units used.

In Figure 4 the impingement stripping model summarized in Equations (7b) and (8), evaluated for the carbon dioxide/distilled water system at 20°C for 1.0, 1.5, and 2.0 mm impingement nozzle orifice diameters, is compared with stripping data for carbon dioxide/distilled water, carbon dioxide/seawater, Freon 114/distilled water, and n-butane/distilled water systems. Data for systems other than carbon dioxide/distilled water were normalized for differences in the molecular diffusion coefficient using Equation (8) and the diffusivities in Table 1, so that direct comparison could be made. The extent of this adjustment can be seen by comparing Figure 4 with Figure 8 in part I of this paper.

The ability of the model to correlate data for varying nozzle orifice diameters and liquid diffusivities is shown in Figure 4. The model provides a conservative design estimate of the performance of jet impingement nozzles in vacuum stripping. It is felt to be valid for any aqueous system from which a physically dissolved gas is to be stripped but should be used with caution outside the range of orifice sizes and liquid flow rates tested in part I. The model has not been tested for nonaqueous systems.

NOZZLE DESIGN

Equations that can be used for nozzle design follow directly from the stripping model developed above. By inverting Equation (8), the orifice diameter required for a particular efficiency of stripping α for an aqueous system with diffusion coefficient D is

$$d_o = \sqrt{\frac{53 \times 10^6 D}{-\ln\left[\frac{\pi^2}{8}(1-\alpha)\right] C_D^{3/2}}} \tag{9}$$

Equation (9) holds for flow rates

TABLE 1. DIFFUSION DATA FOR SYSTEMS IN FIGURE 4

System	$D_{25°C}$	References
CO_2/H_2O	2.0×10^{-9} m²/s	Vivian and King (1964) Duda and Vrentas (1968) Tham et al. (1967)
n-C_4H_{10}/H_2O	1.1×10^{-9} m²/s	Wise and Houghton (1966) Tham et al. (1967) Witherspoon and Bonoli (1969)
Freon 114/H_2O	1.0×10^{-9} m²/s	Wilke and Chang (1955)*

* Correlation. Diffusivities at other temperatures were calculated by assuming $D\mu/T$ = constant.

$$Q \geq 0.27\, C_D^{1/2} d_o^{3/2} \tag{10}$$

The approximate spray radius from the model is found from Equation (6c)

$$R \approx 60\, d_o \tag{11}$$

and the minimum pressure drop to produce this level of operation can be determined from Equation (2), noting that

$$Q = C_D \frac{\pi d_o^2}{4} \sqrt{\frac{2\Delta P}{\rho}} \tag{12}$$

so that

$$\Delta P_{\min} = \frac{8 Q^2_{crit} \rho}{C_D^2 \pi^2 d_o^4} \tag{13}$$

Equation (9) thus provides a rational, conservative model for designing an impingement nozzle for any duty in an industrial vacuum stripper. Equations (10), (11), and (13) provide operating information.

PROCESS DESIGN AND ECONOMICS

The design of a stripping process that uses impingement nozzles was undertaken firstly to compare the purchased cost of the proposed equipment with that for other available designs for a 50 MGD (2 100 kg/s) desalination plant, and secondly to estimate the total annual operating costs for such a deaerator. Design specifications for the deaerator for the 4 460 kg/s seawater feed to the desalination plant are given by Hunter et al. (1967).

Conceptual Design of the Stripper

Full details of the design proposed for the impingement-nozzle deaerator are given by Simpson (1975). Salient points are summarized here. The design envisioned uses a conventional vacuum vessel set horizontally. Inside the vacuum vessel, arranged on a triangular pitch, are pipes running parallel to the axis of the vessel, similar to those in a shell-and-tube heat exchanger. The pipes are set into a tube sheet at one end and capped at the other. Nozzles are set in rows along the tops and bottoms of the pipes, at a sufficient distance apart (0.2 m) to allow coherent sheet formation, so that at each nozzle location one nozzle points vertically upward and another vertically downward. Water is fed to the pipes and thence to the nozzles from a header. Degassed water collects in the bottom of the shell and is pumped out from there. Alternative designs might be imagined. Various polymeric materials were specified for nozzles, impingement plates, and pipes. All other materials would be of plastic-coated mild steel.

Staging of the Process

The design specifications call for oxygen and carbon dioxide remaining in the degassed seawater to be reduced by 99.93 and 99.0% of their feed concentrations, respectively. Oxygen is the limiting component despite the fact that it is stripped more efficiently than carbon dioxide. Thus, by stripping oxygen to the required level, carbon dioxide is simultaneously removed to a greater extent than required.

Impingement nozzles of a practical design cannot achieve the specified removal level for oxygen in one stage under normal operating conditions. The maximum oxygen stripping that can be achieved with nozzles of practical diameters in a single stage at 32°C (the seawater feed temperature) is approximately α = 0.99, which is not adequate to meet the above specifications. The deaeration must therefore be staged. It can readily

TABLE 2. DETAILS OF PROCESS STEAMS FOR A TWO-STAGE DEAERATOR FOR A 50 MGD DESALINATION PLANT

	Feed seawater	First stage sump	Outlet seawater	First stage vapor		Second stage vapor	
				Mole fraction	Flow rate	Mole fraction	Flow rate
Water (kg/s)	4 460.4	4 458.0	4 455.5	0.916	2.43	0.994	2.47
Oxygen (g/s)	32.1	0.857	0.025	6.65×10^{-3}	31.3	1.88×10^{-4}	0.83
Nitrogen (g/s)	54.1	1.03	0.025	0.013	53.0	5.58×10^{-3}	1.01
Carbon dioxide (g/s)	449	35.4	1.39	0.064	413	2.61×10^{-4}	34.0
Argon (g/s)	2.14	0.103	2.52×10^{-3}	3.24×10^{-4}	2.02	1.28×10^{-5}	0.10
Temp. (°C)	32.0	31.7	31.4		31.7		31.4
Pressure (kN/m²)	—	—	—		5.13		4.65

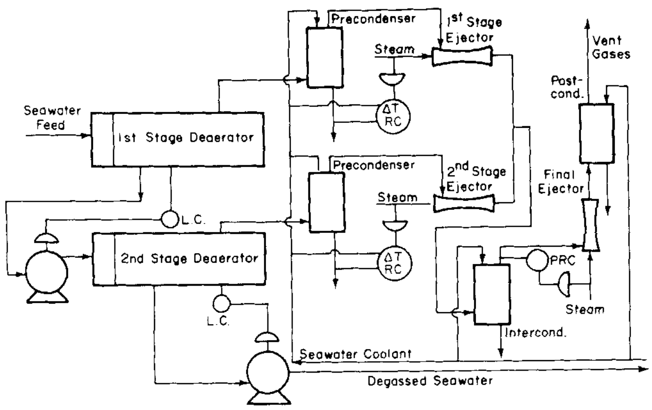

Fig. 5. Process flow sheet.

be shown, however, that the design that can meet product specifications with the fewest number of stages will be the most economical to build and operate. Taking the same approach to equilibrium for the limiting component, oxygen, in each stage of a two-stage deaeration requires α to be 0.974. The resulting nozzle orifice diameter, assuming a discharge coefficient of 0.9, is $d_o = 1.5$ mm [Equation (9)], and the impingement sheet radius is $R \leq 80$ mm [Equation (11)]. This orifice diameter was considered reasonable, since prefiltering is carried out in all desalination plants. A process flow sheet is shown in Figure 5. Note that a two-stage steam ejector vacuum pumping system with appropriate condensers is used. Full specifications for all process equipment are given by Simpson (1975).

Enthalpy and Material Balances

A range of operating pressures exists for achieving the desired two-stage stripping. As the pressure in either stage is reduced, there is a resultant flow of water vapor and desorbed gases from that stage. Sensible heat loss by the processed seawater rises as the vapor flow from each stage is increased, due to increased rate of water evaporation. Optimum operating conditions were found to correspond to the lowest total vapor load and occur when the amount of water vaporized in each stage is about the same (Simpson, 1975). Details of process streams for optimum operating conditions are presented in Table 2.

Selection of Nozzle Flow Rate

For design purposes it was assumed that feed seawater was available at 100 kN/m² absolute (1 bar). Under steady state operation, with the total pressure in the vacuum chambers being approximately 5 kN/m² absolute, a natural differential pressure of 95 kN/m² is available, whereas the value of $\Delta P_{\min}$ is 40 kN/m². Taking a pressure drop across the nozzles of 67 kN/m² to allow for possible entry losses results in a flow rate per nozzle of 18 ml/s (0.3 gal/min).

A one-stage prototype of a jet impingement nozzle deaerator of the design described above was built and tested by Rasquin (1977). The deaerator contained twelve nozzles and operated at a flow rate of about 240 ml/s (3.8 gal/min). The oxygen content of the feed was 5 p.p.m. Oxygen stripping was 92 to 94% for feed at temperatures of 19° to 20°C when the chamber pressure was 3.7 to 4.9 kN/m². The approach to equilibrium exceeded 97%, the design value.

The proposed design is more compact, by about a factor of 2, than most of the commercial designs utilizing packed columns that were proposed for the same service (Hunter et al., 1967). The most important cost improvement is the elimination of the stripping steam for the packed column designs. A recent study has shown, however, that it is also advantageous to carry out vacuum stripping with packed columns operated in two stages without stripping steam (Rasquin et al., 1977).

ACKNOWLEDGMENT

This project was funded by the U.S. Department of the Interior, Office of Saline Water, Contract No. 14-30-2949.

NOTATION

C = solute gas concentration, kg/m³
C_D = nozzle discharge coefficient
D = molecular diffusion coefficient, m²/s
d_o = orifice diameter, m
ΔP = pressure drop across nozzle, N/m²
Q = liquid flow rate per nozzle, m³/s
Q_{crit} = liquid flow rate per nozzle at onset of turbulence, m³/s
R = sheet radius, m
Re_{jet} = jet Reynolds number [see Equation (4)]
u = flow velocity in expanding sheet, m/s
We = Weber number (defined in text)

Greek Letters

α = approach to equilibrium, $= (C_i - \overline{C}_o)/(C_i - C_o^*)$
δ = sheet thickness, m
μ = viscosity, N s/m² (kg/m s)
ρ = density, kg/m³
σ = surface tension (energy), N/m (J/m²)

Subscripts

i = inlet value
o = outlet value

Superscripts

— = averaged value
* = equilibrium value

LITERATURE CITED

Di Luzio, F. C., E. N. Sieder, and E. A. Cadwallader, "Desorption of Carbon Dioxide and Oxygen from Sea Water," Office of Saline Water R. and D. Prog. Rept. No. 158 (1965).

Duda, J. L., and J. S. Vrentas, "Laminar Liquid Jet Diffusion Studies," *AIChE J.*, 14, 286 (1968).

Elliott, M. N., "The Present State of Scale Control in Sea Water Evaporators," *Desalination*, 5, 87 (1969).

Fraser, R. P., P. Eisenklam, N. Dombrowski, and D. Hasson, "Drop Formation for Rapidly Moving Liquid Sheets," *AIChE J.*, **8**, 672 (1962).
Fukui, N., and T. Sato, "The Study of Liquid Atomization by the Impingement of Two Jets," *Bull. Jap. Soc. Mech. Eng.*, **15**, 83, 609 (1972).
Hasson, D., D. Luss, and R. Peck, "Theoretical Analyses of Vapor Condensation on Laminar Liquid Jets," *Intern. J. Heat Mass Trans.*, **7**, 969 (1946).
Hunter, J. A., E. N. Sieder, and P. G. Tomalin, "Deaerators for Desalination Plants," Office of Saline Water R. and D. Prog. Rept. No. 314 (1967)
Ranz, W. E., "Some Experiments on the Dynamics of Liquid Films," *J. Appl. Phys.*, **30**, 1950 (1959).
Rasquin, E. A., "Vacuum Desorption of Gases and Volatile Organic Liquids from Water in Packed Columns," M.S. thesis, Dept. of Chem. Eng., Univ. Calif., Berkeley (1977).
———, S. Lynn, and D. N. Hanson, "Vacuum Degassing of Carbon Dioxide and Oxygen from Water in Packed Columns," *Ind. Eng. Chem. Fundamentals*, (Feb., 1977).
Simpson, S. G., "Vacuum Stripping of Sparingly Soluble Gases from Water," Ph.D. thesis, Univ. Calif., Berkeley (1975).
Squire, H. B., "Investigation of the Instability of a Moving Liquid Film," *Brit. J. Appl. Phys.*, **4**, 167 (1953).
Taylor, G. I., "The Dynamics of Thin Sheets of Fluids," *Proc. Royal Soc.*, **A253**, 389 (1959).
Tham, M. J., K. K. Bhatia, and K. E. Gubbins, "Steady State Method for Studying Diffusion of Gases in Liquids," *Chem. Eng. Sci.*, **22**, 309 (1967).
Vivian, J. E., and C. I. King, "Diffusivities of Slightly Soluble Gases in Water," *AIChE J.*, **10**, 220 (1964).
Wilke, C. R., and P. Chang, "Correlation of Diffusion Coefficients in Dilute Solutions," *ibid.*, **1**, 265 (1955).
Wise, D. L., and G. Houghton, "The Diffusion Coefficients of Ten Slightly Soluble Gases in Water at 10-66°C," *Chem. Eng. Sci.*, **21**, 999 (1966).
Witherspoon, P. A., and L. Bonoli, "Correlation of Diffusion Coefficients for Paraffin Aromatic and Cycloparaffin Hydrocarbons in Water," *Ind. Eng. Chem. Fundamentals*, **8**, 589 (1969).

Manuscript received June 30, 1976; revision received June 2, and accepted June 22, 1977.

Pyrite Oxidation in Aqueous Ferric Chloride

W. E. KING, JR.
and
D. D. PERLMUTTER
Department of Chemical and Biochemical Engineering
University of Pennsylvania
Philadelphia, Pennsylvania 19174

The rate of pyrite oxidation in aqueous ferric chloride was determined for two distinct solid particle systems: industrial grade pyrite and coal particles containing pyrite. The oxidation rate for the pyrite particle system was found to increase significantly with increasing temperature (40° to 100°C), ferric chloride concentration (0.1 and 1.0 M), and pyrite loading (2 to 20 g/l); the rate decreased with increasing particle size (−325 to 140 mesh). Agitation did not have a significant effect, and a kinetic model was developed and fit to the experimental data.

For the coal particle system used in this study, the most important variable was particle size. The oxidation rate of pyrite in coal smaller than 325 mesh was much greater than in larger coal particles. The effect of temperature (80° to 100°C) on the oxidation of pyrite in coal was not significant, nor was the effect of pretreatment with 0.1N hydrochloric acid. Approximately half of the detected ferric iron reduction was attributable to pyrite oxidation; the balance arises from other coal reactions.

SCOPE

The chemical treatment of pulverized coal with aqueous solutions of iron salts is reported (Hamersma et al., 1973) to be capable of almost complete removal of inorganic sulfur (pyrite) in residence times of the order of hours. Detailed kinetic studies are needed to provide a basis for optimum reactor design.

In the study reported here, oxidation rates in aqueous solutions of ferric chloride were measured for two distinct solid particle systems: industrial grade pyrite and coal particles containing pyrite. For the former, the effects of temperature, ferric chloride concentration, reactor agitation, particle size, and solid loading were investigated. For the coal particle system, the effects of temperature, particle size, and dilute acid pretreatment were examined.

All experiments were carried out isothermally in a well-stirred batch reactor. Samples were taken at selected time intervals and analyzed for ferric and ferrous iron. The kinetic data for the pyrite particle system were used to develop a kinetic rate model.

CONCLUSIONS AND SIGNIFICANCE

The oxidation rate for the pyrite particle system was found to increase significantly with temperature, ferric chloride concentration, and pyrite loading; the rate decreased with increasing particle size, while agitation did not have a significant effect. The experimental data for the pyrite particle system were empirically correlated over a wide range of operating conditions by the simple two-parameter kinetic model

W. E. King, Jr. is at the University of Maryland, College Park, Maryland 20742.