R & D NOTES

Simulation of a Pilot Scale, Liquid Motivated, Venturi Jet Scrubber by a Laboratory Scale Model

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The scaling of the experimental data carried out in a gas-liquid laboratory scale reactor up to the pilot or industrial scale is an important problem. Indeed, the determination of the solubility and the diffusivity of one or several solutes in a reacting solution with sometimes unknown or complicated kinetics is very often a challenging problem. Moreover, it is not always possible to experiment in reactors of continuously increasing sizes because of time and/or equipment cost. These difficulties have justified the idea of making relatively simple laboratory models with well-defined interfacial areas and gas and liquid phase contact times (Charpentier and Laurent, 1974; Laurent and Charpentier, 1977) and carrying out experiments to obtain information in a form that could be directly applicable to design. The aim is thus to predict the effect of the chemical reaction in an industrial absorber from tests in the laboratory model with the same gas-liquid reactants, or to predict the reactor length for a specified duty using data from the laboratory model, even though the means of agitating both phases in the two types of equipment is quite different. This promising technique, that is, the simulation, has been intensively developed these last years but only in the case of the packed columns, where either a laboratory scale stirred cell can simulate a point in the column, that is, the differential simulation (Danckwerts and Gillham, 1966; Laurent et al., 1974; Danckwerts and Alper, 1975), or a laboratory scale string of spheres can simulate the behavior of the full sized equipment, that is, the integral simulation (Alper and Danckwerts, 1976).

The purpose of this note is to present the use of the simulation in the case of a quite different pilot equipment that is a turbulent Venturi jet scrubber by a laboratory laminar jet used as an integral model. This technique usually requires the equality of two or more of the following interfacial mass transfer and hydrodynamics criteria, k_L, k_G, S/V_L, L/S, and G/S (or G/L), depending on the type of the gas-liquid reaction encountered. So experimental data of the physical liquid side and gas side mass transfer coefficients k_L, k_G in both equipment and of the total interfacial area S in the Venturi jet scrubber will be first presented.

PILOT SCALE, LIQUID MOTIVATED, VENTURI JET SCRUBBER

A schematic diagram of the equipment is presented in Figure 1*a*. The Venturi jet scrubber is a device that permits the pumping of large quantities of gas by the action of the kinetic energy of a jet of liquid at the throat of a Venturi acting as the motive fluid. This simple mode of action has encouraged its more and more frequent use in the fight against air pollution (dust collection, cooling, and absorption). While the first two functions have received considerable attention, data concerning gas-liquid mass transfer are scarce, particularly for units producing a gas flow rate by their own pumping action alone (Barker, 1962; Harris and Haun, 1964; Hoffmann et al., 1973; Krotzsch, 1975; Laurent et al., 1978*a*).

A SAPS Venturi jet scrubber of 50 mm nominal diameter was used which comprises a standard Venturi diffuser of 33 mm throat diameter and 700 mm length. The characteristics of the three ejector nozzles of 3, 4, and 5 mm diameter are presented in Figure 1*b*. The ejector nozzles are designed so that the liquid is injected and pulverized as a conical sheet entirely filling the cross section of the diffuser, giving a good contact between the gas and the liquid and producing a satisfactory aspiration effect by a good conversion of the kinetic energy of the motive liquid. At the exit of the diffuser, the two fluids flowing downwards together are separated in a gravity separator equipped with a jet breaker. The data reported here concern the complete assembly of the scrubber and the separator.

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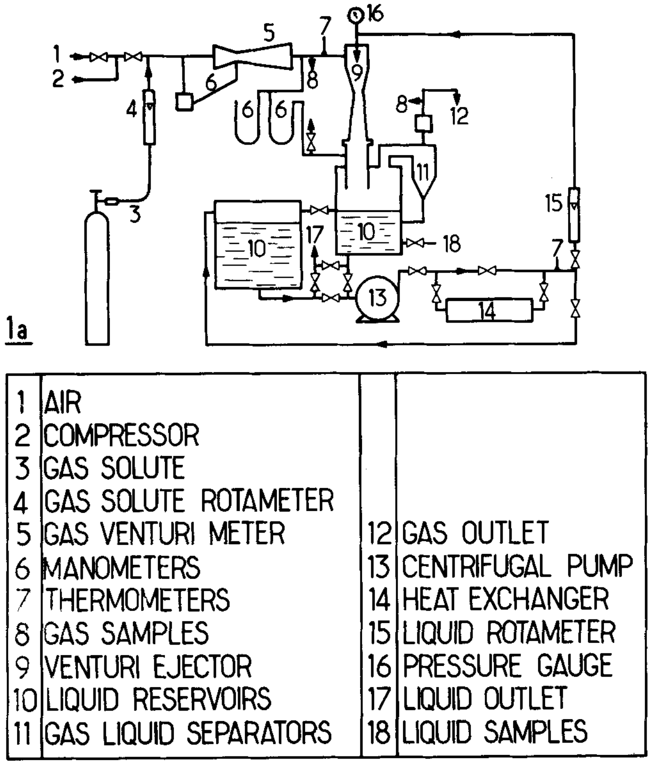


Figure 1*a*. Schematic diagram of the equipment.

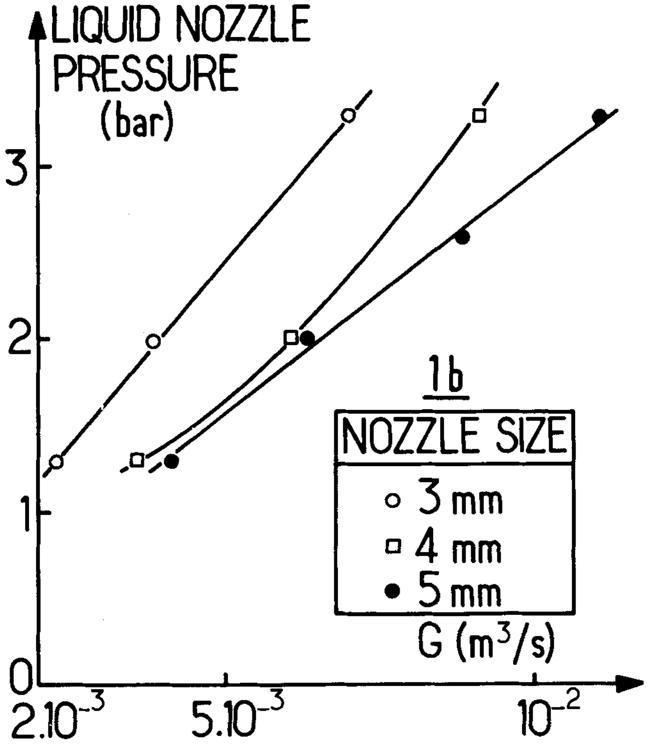


Figure 1*b*. Characteristics of the ejector nozzles.

The characteristic hydrodynamic performance curves of the scrubber showing the suction pressure of the unit as a function of the volumetric gas flow rate G, the different nozzle sizes, and the several liquid supply pressures employed are presented in Figure 2*a*. Such a graph defines the autoaspiration performances of the scrubber.

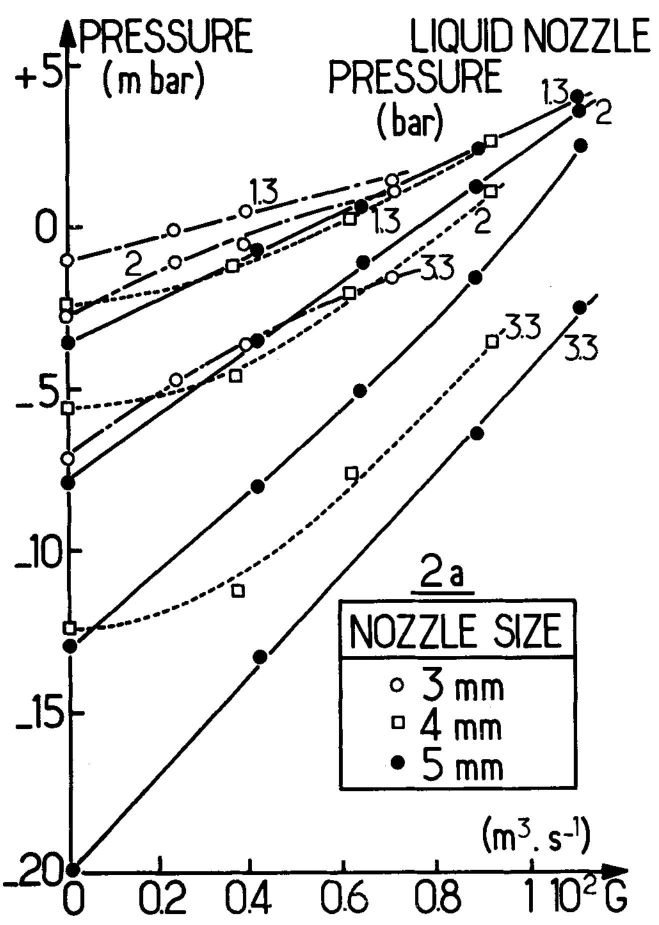


Figure 2*a*. Pumping curves of the Venturi jet scrubber.

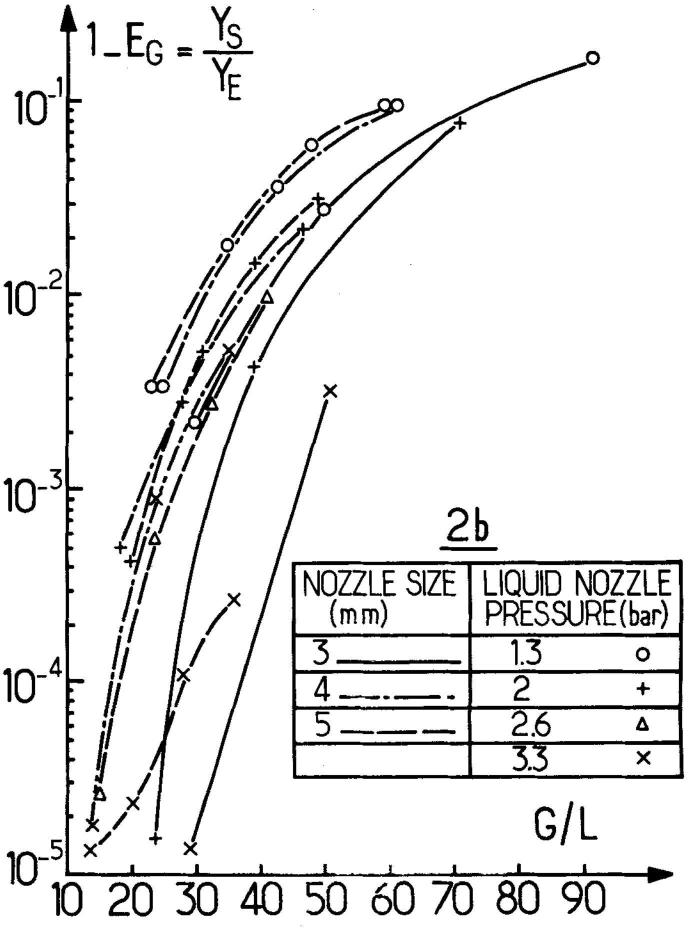
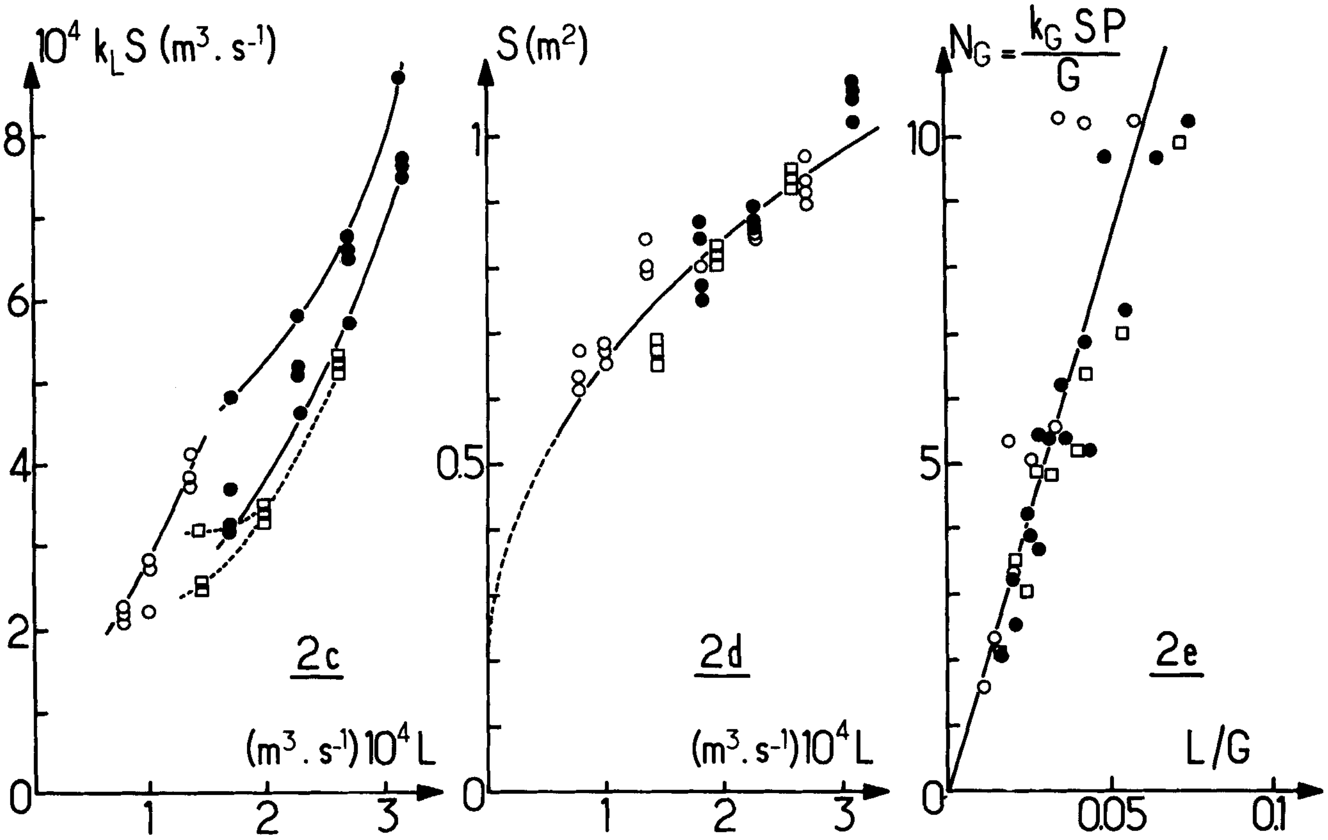


Figure 2*b*. Removal efficiency of the Venturi jet scrubber.



Figures 2c, 2d, 2e. Liquid side mass transfer coefficient (2c), effective interfacial area (2d), and gas side mass transfer coefficient (2e) in the Venturi jet scrubber.

Note also that the volume of liquid inside the contactor varies with the liquid flow rate L in the range 3 to 5% of the total volume of the scrubber.

The mass transfer efficiency and the interfacial parameters were determined with the use of the chemical method at room temperature, and the kinetics of each reaction employed has been previously studied in a laboratory model of known interfacial area and contact time such as a cylindrical wetted wall, a laminar jet, or a mechanically stirred vessel.

The product k_LS was determined in the slow chemical regime by the absorption of dilute carbon dioxide (2%) with air into an aqueous solution of potassium carbonate and bicarbonate in presence of sodium hypochlorite. Figure 2*c* shows the variation of k_LS with L for each nozzle. This parameter varies mainly with L so long as the device acts as an autoaspirator. But when the gas phase is forced through the scrubber, the influence of G becomes significant and more and more important as the nozzle size increases (Fonteix, 1978).

The global interfacial area S in the scrubber and the separator was determined by the absorption with fast pseudo first-order chemical reaction of dilute carbon dioxide (2%) with air into a sodium hydroxide aqueous solution. The variations of S as a function of L, G, and the nozzle size are presented in Figure 2*d*. In the region studied, the interfacial area is independent of gas rate for any given liquid rate. This result agrees with the work of Nagel et al. (1973) carried out in a contactor having a cylindrical body. In fact, when the scrubber is operating in the autoaspiration mode, the mean gas velocity is always less than 10 $m \cdot s^{-1}$. In these conditions, the interfacial area is determined solely by the structure of the liquid jet at the exit of the nozzle. The gas-liquid interactions are too weak to break up the films and streams of the liquid flow into drops and to produce an increase in the interfacial area.

The product k_GS was determined in the surface instantaneous chemical regime by the absorption of dilute sulfur dioxide (1%) with air into a sodium hydroxide aqueous solution. The results are shown in Figure 2*e*, where k_G SP/G is plotted vs. L/G for the three nozzle sizes. These last results are directly indicative of the practical use of the Venturi jet scrubber for the treatment of gaseous effluents to prevent atmospheric pollution. Indeed, the ordinate of Figure 2*e* is directly proportional to the definition of the number of transfer units N_G of the gas phase which is related to the efficiency $E_G = 1 - y_s/y_e$ by the relation $\ln(1 - E_G) = - N_G$. Thus it is possible to conclude from the results shown that the efficiency of the scrubber improves as the ratio L/G is increased. Over the operating range studied here, the removal efficiencies of the scrubber varied from 78 to 99.99%. In practice, for a given liquid injection pressure, a satisfactory scrubbing efficiency will be obtained in the part of the capacity curve corresponding to small gas flow rates as it is shown in Figure 2*b* ($G/L < 15 - 20$). Note that Figures 2*a* and 2*b* characterize completely the scrubber concerning its efficiency and energy (or pressure) need.

LABORATORY SCALE LAMINAR JET

As explained previously, the simulation by a laboratory scale model may need the equality of the criteria k_L, k_G, and S/V_L. From the data presented in Figure 2, it is observed for the scrubber that $3 \cdot 10^{-4} < k_L < 8 \cdot 10^{-4}$ m/s, $5 \cdot 10^{-4} < k_G < 2.6 \cdot 10^{-3}$ k mole/m^2·s·bar, and $S/V_L \simeq 15 \cdot 10^3$ m^{-1} (Fonteix, 1978). Among the various laboratory scale models proposed in the literature (Charpentier,

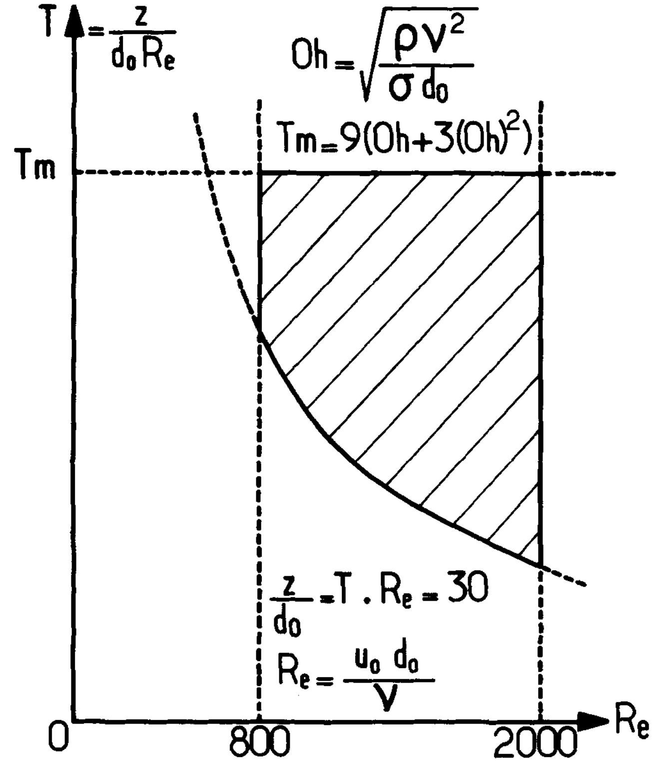


Figure 3. Operating diagram of the laminar jet.

1978), the laminar jet is the only one allowing for the same range of the simulation criteria.

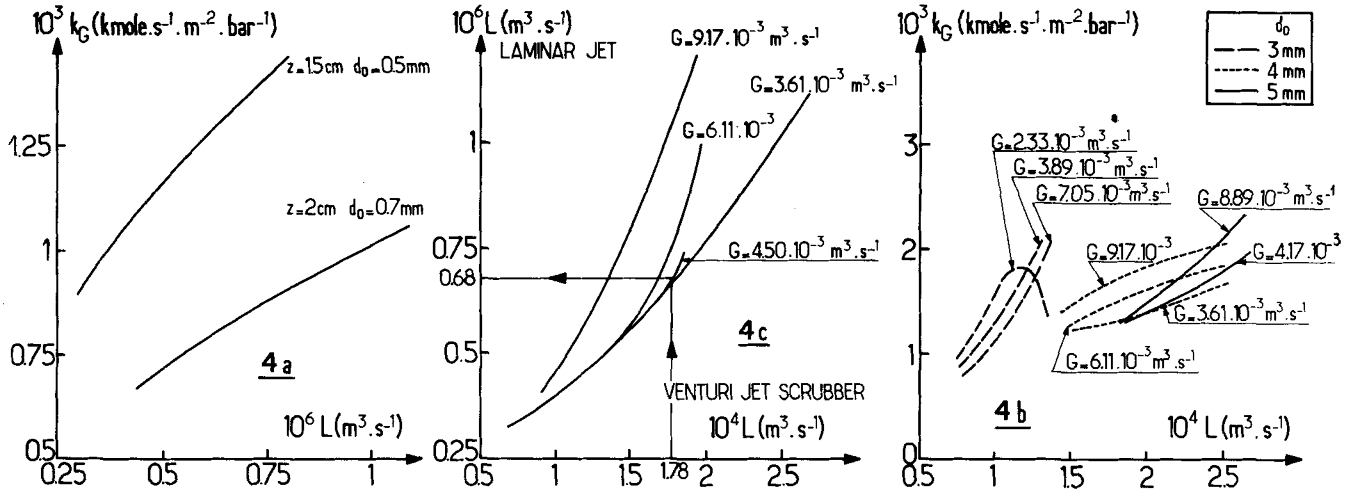
An experimental and theoretical study of this equipment was thus undertaken to determine the limits within which the jet can be regarded as a cylindrical rod in uniform motion of known values of contact times and interfacial area. Several diameter ejector nozzles of the liquid through the gas space are used (d_0 = 0.3, 0.5, 0.7, 0.8, 0.9, 1, 1.5, and 2 mm). The jet receivers are either capillary tubes with an internal diameter slightly greater than the diameter of the jet (0.1 mm) or a vaseline oil pool. Several liquids water, pure isopropanol, pure polyethylene glycol 200, aqueous solution of polyethylene glycol 6 000, aqueous solution of sodium sulfite, and solutions of lauric alcohol in water were tested in presence of stagnant air as the gas phase. The liquid properties are $789 < \rho < 1\,124$ kg/m³, $0.986 \times 10^{-6} < \nu < 19 \times 10^{-6}$ m²·s⁻¹, $21.8 \times 10^{-3} < \sigma < 72.4 \times 10^{-3}$ N/m. Provision is also made for varying the length of the jet $0.013 < Z < 0.15$ m and the liquid flow rate $0.2 \times 10^{-6} < L < 3.2 \times 10^{-6}$ m³/s.

The correct working of the laminar jet is observed by means of a cathetometer and photographs. The net results are represented by the hatched zone on Figure 3 called operating diagram of the laminar jet model that precises the limits of the operating conditions within a 10% accuracy. Practically, the necessary conditions for a good hydrodynamic operations are

$$200\,\pi\,\nu\,d_0 < L < 500\,\pi\,\nu\,d_0 \quad \text{and}$$

$$30\,d_0 < Z < \frac{36\,L}{\pi\,\nu}\,[Oh + 3(Oh)^2]$$

The corresponding values of the mass transfer parameter k_L and k_G are determined by the absorption of pure carbon



VENTURI JET SCRUBBER					LAMINAR JET					DEVIATION
10^4 L	10^3 G	y_E	y_E/y_S	E_G	E_G	y_E/y_S	y_E	10^7 G	10^7 L	
m³ . s⁻¹	m³ . s⁻¹	%	—	%	%	—	%	m³ . s⁻¹	m³ . s⁻¹	%
2.028	4.833	4.4	51	98.04	98.08	52	4.4	1.361	8.472	2
1.861	6.389	4.3	44	97.72	97.87	47	4.4	1.861	8.472	7
1.777	4.500	4.4	57.9	98.27	98.28	58.3	4.4	1.333	6.777	1
2.000	5.694	0.58	178	99.44	99.44	181	0.65	1.667	8.472	2

Figure 4a, 4b. Gas side mass transfer coefficient in the laminar jet (4a) and in the Venturi jet scrubber (4b). Figure 4c. Relation between liquid flow rates in the laminar jet and in the Venturi jet scrubber (couples of simulation criteria k_G).

dioxide into water and the absorption of dilute sulfur dioxide (1.8%) with air into a sodium hydroxide aqueous solution. The experimental results are well represented by the equations

$$k_L = 4\left[\frac{D_{CO_2} L}{\pi^2 d_0^2 Z}\right]^{0.5} \quad \text{and} \quad k_G = \frac{10^{-4}}{d_0}\left[\frac{L}{Z}\right]^{0.5}$$

SIMULATION OF THE VENTURI JET BY THE LAMINAR JET

If now all the simulation criteria k_L, k_G, S/V_L, L/S, and G/S have identical values in both devices, the laboratory model will simulate all the essential features of Venturi jet scrubber, and if the inlet compositions are the same in both equipment, so would be the outlet compositions (Alper and Danckwerts, 1976).

The equality of the criteria S/V_L cannot be fulfilled with any practical laminar jet. Indeed, for the scrubber this ratio is of the order of 15 000 m^{-1} that would correspond to a laminar jet of 0.25 mm diameter. Stable operation in a laminar jet with a vaseline oil pool as jet receiver would be practically impossible, and moreover the values of the criterium k_L would not be compatible with those in the scrubber. Anyway, jet scrubbers are usually employed for rapid or instantaneous reaction that does not need an important liquid holdup but great values of S and k_G and/or k_L.

The values of k_L and k_G in both equipment have been determined by the method of absorption with or without chemical reaction. Then the relation between L and G in the model and in the scrubber giving the same k_L and k_G in both may be established by inspection of the diagrams showing the variation, in each device, of k_L and k_G when changing the flow rates. Thus it has been observed that it is also impossible to achieve simultaneously the same values of k_L and k_G in both equipment (Fonteix, 1978) because these parameters are principally influenced by the liquid flow rate.

Therefore, it is necessary to restrict the integral simulation to operating ranges for which the influence of one or more of the criteria may be neglected. This leads to perform the simulation with the equality of criteria k_G and G/S or k_L and G/S which corresponds, as previously explained, to the potential ordinary uses of the Venturi jet scrubber in gas-liquid absorption with rapid and instantaneous reactions.

Figure 4 gives an example of such a technique of integral simulation in k_G and G/S. Figures 4*a* and 4*b* present the variations of k_G vs. the flow rates and the nozzle diameter in each device. Note that k_G is independent of G in the laminar jet in the range 0 to 10^{-3} m^3/s. Figure 4*c* that is obtained from the two previous curves is the simulation couple that allows for the same values of k_G in the present Venturi jet scrubber fitted with a 4 mm nozzle and in a laminar jet of 0.5 mm diameter and 1.5 cm height. For instance, the scrubber operating with $L = 1.8 \times 10^{-4}$ m^3/s and $G = 4.5 \times 10^{-3}$ m^3/s (L and G are related by Figures 1*b* and 2*a*) has the same k_G as this laminar jet operating with $L = 0.68 \times 10^{-6}$ m^3/s.

If now we want to have an idea of the potential, the validity, and the accuracy of the integral simulation, let us carry out experiments with gas and liquids quite different from those used to establish the values of the mass transfer parameters. The absorption of dilute hydrogen sulfide (0.5 to 4%) with air into a 1.2 N aqueous diethanolamine solute was tested. This is a surface instantaneous reaction necessitating the equality of the criteria k_G and G/S. The gas flow rate in the laminar jet is thus evaluated by

$$G_m = G \times \frac{S_m}{S} = 4.5 \times 10^{-3} \times \frac{\pi d_0 Z}{0.78}$$
$$= 1.361 \times 10^{-7}\ m^3 \cdot s^{-1}$$

As the model simulates all the essential features of the scrubber, the integral simulation predicts that if the inlet composition y_E is the same in both equipment, so will be the outlet composition y_S. The results of the experiments carried out in the model and in the scrubber are presented in the table of Figure 4. The deviations in the prediction is within 10% which is very promising if it is observed that an error of about 5% must be accounted for the accuracy of the analyzer. Note also the ratios of approximately 250 and 34 000, respectively, for the values of L and G encountered in both equipment. Complementary data with the same gas-liquid system tested in the scrubber with different nozzles or with other gas-liquid systems needing the equality of the criteria k_L and G/S in both devices are presented by Fonteix (1978) and Laurent et al. (1978*b*). In spite of the limitations of the present method, the results reported here are representative of the general use of the Venturi jet scrubber and extend the use of the integral simulation to a gas-liquid reactor different from a packed column.

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NOTATION

d_0 = nozzle diameter or laminar jet diameter (L)
D_{CO_2} = diffusivity of carbon dioxide in the liquid phase ($L^2 \cdot T^{-1}$)
E_G = gas absorption efficiency (—)
G = volumetric gas flow rate in the scrubber ($L^3 \cdot T^{-1}$)
G_m = volumetric gas flow rate in the model ($L^3 \cdot T^{-1}$)
k_G = true gas side mass transfer coefficient (kmole $\cdot L^{-2} T^{-1} \cdot$pressure^{-1})
k_L = true liquid side mass transfer coefficient ($L \cdot T^{-1}$)
L = volumetric liquid flow rate ($L^3 \cdot T^{-1}$)
N_G = gas phase number of transfer unit (—)
Oh = Ohnesorge number = $(\rho \nu^2 / \sigma d_0)^{0.5}$ (—)
P = total gas phase pressure ($M \cdot L^{-1} \cdot T^{-2}$)
Re = Reynolds number = $u_0 d_0 / \nu$ (—)
S = total interfacial area in the scrubber (L^2)
S_m = total interfacial area in the model (L^2)
T = parameter = $Z/d_0 Re$ (—)
T_m = maximal value of the parameter T (—)
u_0 = mean superficial liquid velocity at exit of the nozzle ($L \cdot T^{-1}$)
V_L = volumetric liquid holdup in the scrubber (L^3)
y_E, y_S = solute gas phase concentration in mole fraction at entrance and at exit (—)
Z = laminar jet length (L)
ρ = density of liquid ($M \cdot L^{-3}$)
ν = kinematic viscosity of liquid ($L^2 \cdot T^{-1}$)
σ = surface tension of liquid ($M \cdot T^{-2}$)

LITERATURE CITED

Alper, E., and P. V. Danckwerts, "Laboratory Scale-Model of a Complete Packed Column Absorber," *Chem. Eng. Sci.*, 31, 599 (1976).

Barker, P. E., "Performance of a Venturi Atomiser at Low Gas Velocities," *Trans. Inst. Chem. Engrs.*, 40, 221 (1962).

Charpentier, J. C., and A. Laurent, "Some Considerations and Recalls on the Design of Gas Absorbers: Laboratory Apparatus to Simulate Absorber and to Predict the Effect of Chemical Reaction," *AIChE J.*, **20**, 1029 (1974).

Charpentier, J. C., "Gas-liquid Reactors," *Chem. React. Eng. Reviews*, D. Luss and V. W. Weetman, ed., ACS Symposium Series, **72**, 223 (1978).

Danckwerts, P. V., and A. J. Gillham, "The Design of Gas Absorbers: Part I, Method for Predicting Rates of Absorption with Chemical Reaction in Packed Columns and Tests with 1.5 in Raschig Rings," *Trans. Inst. Chem. Engrs.*, **44**, 42 (1966).

———, and E. Alper, "Design of Gas Absorbers; Laboratory Point Model of Packed Column Absorber," *Trans. Inst. of Chem., Engrs.*, **53**, 34 (1975).

Fonteix, C., "Hydrodynamique et Transfert de Matière dans un Laveur Pilote de Type Jet dans un Venturi: Simulation de son comportement par un Modèle de Laboratoire. Intérêt et Limites actuelles de la Technique," Thesis, Institut National Polytechnique de Lorraine, Nancy, France (1978).

Harris, L. S., and G. R. Haun, "The Ejector Venturi Scrubber," *Chem. Eng. Progr.*, **60**, 100 (1964).

Hoffmann, R., H. Kurten, and O. Nagel, "Stoffaustauschfläche und Hydrodynamik in Strahl-bzw. Venturi-Wäschern," *Chemie Ing. Technik*, **45**, 881 (1973).

Krotzsch, P., "Abgasreiningung durch Chemisorption mittels Strahlwäschern am Beispiel der Cl_2—Absorption in wässriger Natriumthiosulfat-Lösung," *ibid.*, **47**, 213 (1975).

Laurent, A., C. Prost, and J. C. Charpentier, "Bestimmung des Stoffübergangs in einem Laborrührwerksbehälter mit Stoffübergangs widerstanden in beiden Phasen," *Chemische Technik*, **26**, 471, réf. 52/74 (1974).

Laurent, A., and J. C. Charpentier, "Le Rôle et l'Utilité des Modeles Expérimentaux de Laboratoire dans la Prévision des Performances d'un Réacteur Gaz-Liquide Industriel," *J. Chimie Physique*, **10**, 1001 (1977).

Laurent, A., C. Fonteix, G. Besson, and J. C. Charpentier, "Pilot-Scale study of Absorption with Chemical Reaction in a Venturi-Jet Scrubber," *Atmosphere Pollution 1978*, M. M. Benarie, ed., *Studies in Environmental Science*, I, 251 (1978*a*).

Laurent, A., C. Fonteix, G. Besson, and J. C. Charpentier, "Gas-liquid Absorption with Chemical Reaction in a Liquid-Motivated Ejector Venturi-Scrubber," Congress CHISA '78, *Section Distillation and Absorption*, Praha, Tchecoslovaquie (Aug. 21-25, 1978*b*).

Nagel, O., H. Kurten, and B. Hegner, "Die Stoffaustauschfläche in Gas-Flüssigkeits-Kontaktapparaten Auswahlkriterien und Unterlagen zur Vegrösserung," *Chemie Ing. Technik*, **45**, 913 (1973).

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A General Criterion to Test the Importance of Diffusion Limitations in Bidisperse Porous Catalysts

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In the analysis of solid catalyzed reactions, it is very important to know whether transport processes within the micro- and macropore regions have any effect on the observed reaction rate. Since the kinetic rate expression is usually nonlinear, it is difficult to determine the regions of kinetic control and diffusion control by solving the controlling differential equations of the model, as was done originally by Thiele (1939) for a first-order reaction. A detailed review of diffusion and reaction processes in porous catalysts was done by Aris (1975).

In order to permit those who work with catalysts to estimate the importance of diffusion limitations on the overall rate, a number of criteria have been derived: Weisz and Prater (1954), Bischof (1967), Narshimhan and Guha (1972). Petersen (1965), Hutchings and Carberry (1966), and Schneider and Mitschka (1966) extended the Weisz-Prater criterion to systems where product inhibition is important. Hudgins (1968) developed a more general criterion for absence of appreciable diffusion effects, applicable for reactions having other than power-type rate expressions

$$\bar{r}_s \frac{R_0^2}{C_0 D} < \frac{1}{C_0} \frac{r_s(C_0)}{r_s'(C_0)} \tag{1}$$

Most of the industrially used catalysts have a bidisperse pore structure. In some cases, the intraparticle diffusion might be at least as important as interparticle diffusion and chemical kinetics. Brown (1972) discussed the intraparticle diffusion effects in branched-pore systems. Örs and Doğu (1979) show that the effectiveness of bidisperse porous catalysts which are formed by the agglomeration of porous particles depends not only upon the Thiele Modulus, but also upon another modulus, that they call α, which is proportional to the ratio of diffusion times in the macro- and micropore regions. In this work, we derive a general criterion for negligible macro- and micro-pore diffusion effects on the observed rate of catalytic reactions in bidisperse porous catalysts.

The effectiveness factor of a spherical bidisperse porous catalyst can be expressed as

$$\eta = \frac{9}{R_0^3 r_0^3 r_s(C_0)} \int_0^{R_0} \int_0^{r_0} [r_s(C_i) r^2 dr] R^2 dR \tag{2}$$

where R_0 and r_0 are the radius of the catalyst pellet and the average radius of the particles which make up the pellet, respectively, and C_i is the concentration of reactant in the micropores.

Following the procedure used by Anderson (1963), the rate is expanded in a Taylor series about the surface concentration of particles, C_a, which is the concentration of reactant in the macropores, and second-order and higher order terms are neglected. The concentration profile within the particles is approximated by a simple parabolic function.
