GAS HOLDUP AND INTERFACIAL MASS TRANSFER IN GAS-LIQUID TOWER CONTACTORS WITH EJECTOR-TYPE GAS DISTRIBUTORS

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The effect of decisive construction parameters of ejectors on gas holdup and on the rate of interfacial mass transport (characterized by k_La values) was studied in a gas–liquid tower reactor (I.D. 0·3 m) with an ejector (Venturi-tube type) gas distributor. The selected ejector characteristics included diffuser length and angle of diffuser walls inclination as well as nozzle type and geometry. Experimental data confirmed validity of our previously published conclusions on the relation between the rate of energy dissipation in the place of dispersion formation (*i.e.* in the ejector) and gas holdup and k_La values. The eficiency of dissipated energy utilization was however significantly influenced by the diffuser geometry. According to our experimental evidence the increase of ejector energy effectiveness with increasing diffuser length can be ascribed solely to its favourable effect on the gas suction rate while the mechanism of phases mixing (dispersion formation) in ejector was apparently independent of diffuser geometry within the whole range of experimental conditions.

Due to their superior gas distribution performance and operational advantages continuous attention has been paid to ejector gas distributors since their application for intensification of mass transfer in bubble column contactors was firstly suggested by Nagel, Kürten, and Sinn[1,2]. Numerous papers have appeared since then reporting the use of ejector distributors in units for specific chemical and biotechnological processes while more general studies devoted to description of mechanism of gas–liquid bed formation in reactors with ejector distributors and/or to optimization of ejector distributors construction were published namely by Zlokarnik[3] and Henzler[4,5]. Despite the long-time effort devoted to studies of ejector distributors there are still some questions left open, hindering wider use of these distributors. According to our opinion there is no convincing experimental data base for decision-making between various construction modifications of ejectors reported in literature (ejectors with or without impulse (mixing) tube, conical or slot-shaped diffusers, secondary liquid-phase suction ect.). Also sufficiently general routinely applicable relations between characteristics of gas–liquid beds and specific construction parameters of ejectors are being missed to be recommended for ejector distributors design and scale-up.

In our group the Venturi-tube type ejector distributors and their application in tower gas–liquid contactors have been studied systematically for several years[6–10]. The results of our recent studies[7,8,10] proved in analogy with sieve-tray bubble column reactors the decisive effect of the rate of energy dissipation in the place of dispersion formation (*i.e.* in the ejector) on the quality of gas–liquid dispersion and consequently on the intensity of interfacial contact. While it was proved[7,8] that the total rate of energy dissipation was determined by nozzle type and geometry it was envisioned on the basis of some preliminary experiments[8] that the efficiency of dissipated energy utilization might depend on other construction parameters of ejectors namely on diffuser geometry[8]. It was therefore the aim of this reported work to obtain experimental data base for estimation of this effect and to evaluate relations between ejector geometry and factors characterizing the quality of gas–liquid dispersion namely gas holdup and k_La. In comparison with some related papers[5,10] our immediate goal was not to optimize the ejector construction but rather to proceed further towards better understanding of the mechanism of dispersion formation in ejector distributors and of the effect of factors determining the quality of dispersion.

EXPERIMENTAL

A single-stage glass-wall column 0·3 m in diameter with an ejector (Venturi-tube) gas distributor was used for experiments. Schematic chart of the experimental set-up can be found in our previous paper[8], details of Venturi tube construction are given in Fig. 1. The experiments were carried out with four conical diffusers, values of their geometrical characteristics are listed in Table I. Three different nozzles[8] of constant diameter ($d_s = 0{\cdot}008$ m) shown schematically in Fig. 2 were used in each experimental set *i.e.* for each diffuser type. All experiments were performed with air–water system in a semibatch arrangement (*i.e.* at zero liquid throughput) at constant clear liquid height, $H_0 = 1{\cdot}6$ m. Rate of liquid phase circulation through ejector was varied between 2·0 and 6·5 m^3/h. Corresponding rates of gas suction ranged between 3 and 28 m^3/h, superficial gas velocity thus being in the region 0·013—0·107 m/s. Gas and liquid flow rates, ejector pressure drop, and aerated bed height were measured and monitored during experiments, gas holdup values were calculated from the difference of clear liquid height and the overall height of aerated bed, $\varepsilon_G = (H - H_0)/H$. The dynamic method was applied for k_La measurements, described in details elsewhere[8].

RESULTS AND DISCUSSION

Data of k_La from all experimental runs are plotted in Fig. 3 against the specific rate of energy dissipation in ejector, e_d, defined as

$$e_d = \Delta P_e Q_L / V_L \varrho_L \,. \qquad (1)$$

In Eq. (*1*) ΔP_e denotes ejector pressure drop and Q_L the rate of liquid circulation through ejector, V_L is the liquid phase volume in the bed and ϱ_L liquid density.

Experimental data clearly prove a significant effect of the diffuser length on the efficiency of dissipated energy utilization for gas dispersion and consequently on the intensity of interfacial contact in the bed. As can be seen from comparison of data for diffusers D2 and D4 no effect of diffuser conus angle was observed in the experimental range of α values. Similarly, no effect of nozzle type on dependence $k_L a$ *vs* e_d was observed for individual diffusers, this being in full agreement with our former results[7,8,10]. The experimental data plotted in Fig. 3 were in the whole range of ex-

TABLE I
Geometrical characteristic of ejector diffusers

Diffuser type	D1	D2	D3	D4
d_0 (m)	0·016	0·016	0·016	0·016
d_1 (m)	0·040	0·040	0·040	0·028
L (m)	0·40	0·20	0·10	0·20
α (°)	1·7	3·40	6·8	1·7

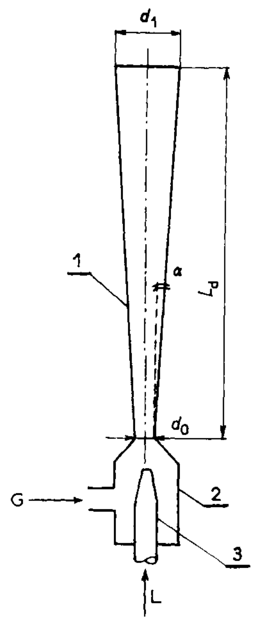

FIG. 1
Schema of Venturi-tube ejector. *1* Diffuser, *2* suction chamber, *3* nozzle. Diffuser characteristics: L_d length, d_0 inlet diameter, d_1 outlet diameter, α wall inclination angle

perimental conditions well described by an exponential type relation

$$k_L a = a_1 e_d^{a_2} . \quad (2)$$

Value of coefficient $a_1 = 0{\cdot}036$ obtained by the least squares method from our experimental data was independent of both nozzle type and diffuser geometry while values of coefficient a_2 varied with diffuser length, $a_2 = 0{\cdot}54$ ($L = 0{\cdot}4$ m); 0·44 ($L = 0{\cdot}2$ m); 0·40 ($L = 0{\cdot}1$ m). Apparently values of a_1 and a_2 corresponding to diffuser D1 agreed well with data obtained in our previous work[8] for an ejector with identical diffuser length ($a_1 = 0{\cdot}04$, $a_2 = 0{\cdot}54$). To evaluate the efficiency of dissipat-

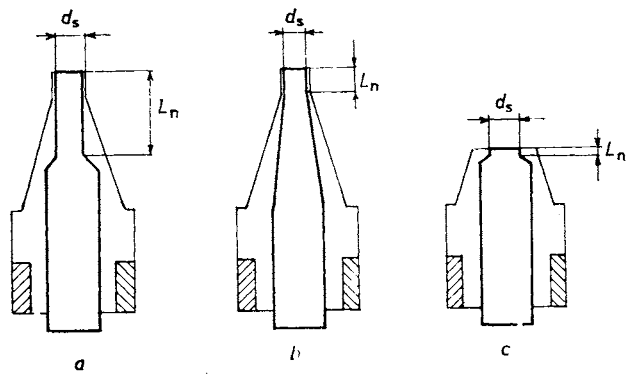

FIG. 2

Ejector nozzles. $d_s = 8$ mm; type *a* $L_n = 25$ mm, type *b* $L_n = 7$ mm, type *c* $L_n = 1{\cdot}5$ mm

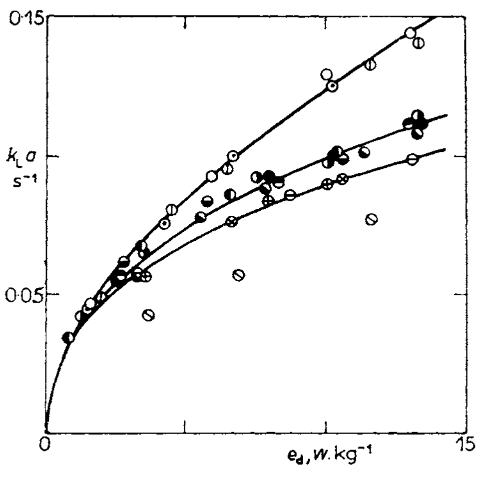

FIG. 3

Dependence of $k_L a$ on the rate of energy dissipation *a*, *b*, *c* — nozzle types (Fig. 2). $L_d = 0{\cdot}4$ m, $\alpha = 1{\cdot}7°$: ○ *a*, ⊙ *b*, ⦶ *c*; $L_d = 0{\cdot}2$ m, $\alpha = 3{\cdot}4°$: ● *a*, ◐ *b*, ◑ *c*; $L_d = 0{\cdot}2$ m, $\alpha = 1{\cdot}7°$: ◓ *a*, ◒ *b*, ◔ *c*; $L_d = 0{\cdot}1$ m, $\alpha = 6{\cdot}8°$: ⊕ *a*, ⊗ *b*, ○ *c*; $L_d = 0$: ⦸ *a*; data calculated from Eq. *2*: ———

ed energy utilization in various types of gas–liquid reactors, an energy effectiveness criterion $\Phi = k_L a / e_d$ was introduced in our former work[7]. Multiplied by the mass transfer driving force the factor Φ yields the amount of oxygen transferred in the bed per a unit of energy dissipated in the place of dispersion formation. In Fig. 4 values of Φ are plotted against corresponding values of $k_L a$ for all types of nozzles and diffusers used in our experiments. Apparently the graph confirms negative effect of decreasing diffuser length on the energy effectiveness of ejector distributors. It is further apparent from the figure that similarly as in sieve-tray bubble columns[7] the energy effectiveness of contactors with ejector gas distributors decreases with increasing demands on intensity of interfacial mass transport.

In following two figures dependence $k_L a = k_L a(e_d)$ was decomposed into two successive steps in an attempt to analyse the effect of diffuser length on the reactor energy effectiveness and consequently to clarify the mechanism of dissipated energy utilization in units with ejector gas distributors. In Fig. 5 the rate of gas suction, $\dot{V}_G$, is presented as a function of the rate of energy dissipation, e_d, while in Fig. 6 $k_L a$ data are plotted against values of superficial gas velocity, w_G, corresponding to appropriate gas suction rates. It is apparent from the two figures that the increase of ejector energy effectiveness with increasing diffuser length can be ascribed solely to the increase of gas suction rate (at identical e_d) while no effect of diffuser length on gas holdup and $k_L a$ values was observed at constant superficial gas velocity (gas suction rate).

Apparently such results seem to suggest that the mechanism of phases mixing (dispersion formation) in diffuser was not influenced by its length. While such an observation may seem a bit surprising it is nevertheless in good agreement with results

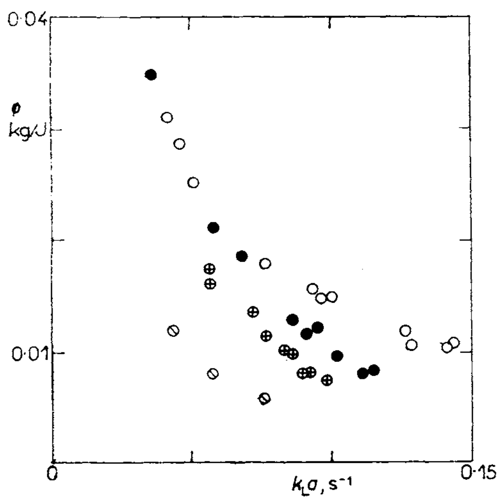

FIG. 4

Relation between the energy effectiveness criterion, Φ, and $k_L a$ at different diffuser lengths. ○ $L_d = 0{\cdot}4$ m, ● $L_d = 0{\cdot}2$ m, ⊕ $L_d = 0{\cdot}1$ m, ⊘ $L_d = 0$

of Zlokarnik's analysis based upon the theory of similarity[3]. It is apparent from his resulting criterial relation that for a given gas–liquid system k_La values in units with ejector-type gas distributors are function of w_G only. For comparison, data obtained at zero diffuser length (*i.e.* when the suction chamber was mounted directly to the column bottom) are also plotted in Figs 3–6. It can be seen from Fig. 6 that at comparable gas flow rates significantly higher k_La values were obtained in this "free jet" arrangement compared to "finite-length" diffusers D1–D4. Apparently this phenomenon can be qualitatively explained by a different mechanism of gas-liquid dispersion formation in the case of ejector without diffuser when due to the position of suction chamber the contact of phases takes place simultaneously with their entrance to the bed. Extremely small rate of gas suction was however observed in the "free-jet" arrangement (Fig. 5) and consequently the overall energy effectiveness was much lower in comparison with Venturi-tube ejector with diffusers D1–D4 (Figs 3, 4). As a result, the arrangement without diffuser cannot be commonly recommended for practical use. Due to the high degree of gas phase utilization (Fig. 6) such arrangement may be however suitable in some cases with forced gas supply, *i.e.* when pressurized gas from a previous technological step can be used as a reactor feed without any additional requirements on energy supply.

We have proved in our former paper[8] that unlike in sieve-tray bubble columns the amount of energy to be dissipated in units with ejector gas distributors

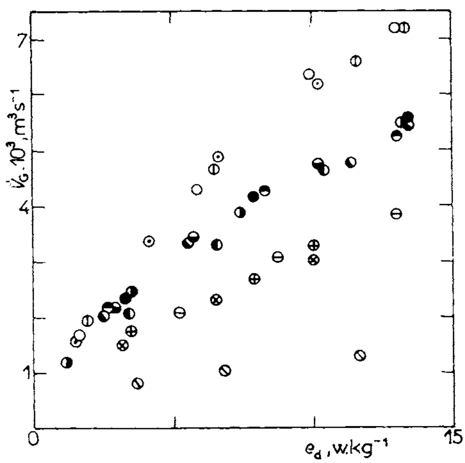

FIG. 5

Gas suction rate as a function of the rate of energy dissipation. Symbol key: ref. to Fig. 3

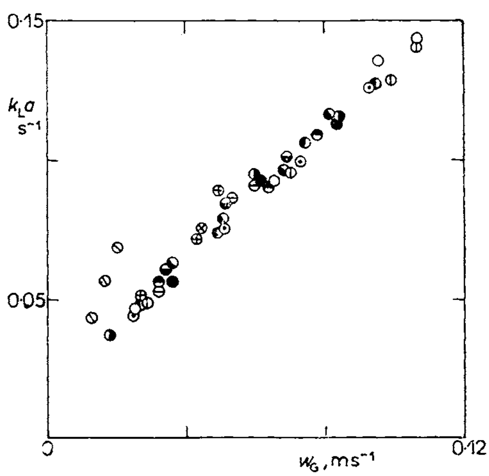

FIG. 6

Dependence of k_La on superficial gas velocity. Symbol key: ref. to Fig. 3

per a unit of gas flow rate increases with increasing demands on gas suction rate. In Fig. 7 the total rate of energy dissipation corresponding to a unit of gas volume sucked and dispersed by the ejector in a time unit, $\Delta P_e Q_L / \dot{V}_G$, is plotted against the gas suction rate, $\dot{V}_G$. Apparently the presented data further confirm the negative effect of diffuser length decrease on the energy effectiveness of ejector distributors.

The conclusions on the independence of mechanism of phase contacting and consequently of dispersion character on the diffuser length have been further confirmed

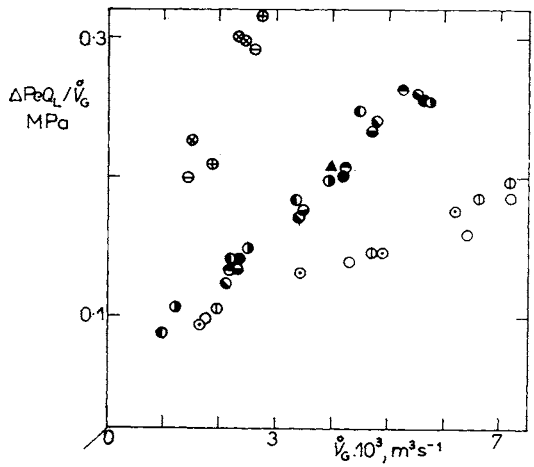

FIG. 7

Energy consumed for dispersion of a gas volume unit as a function of gas throughput. Symbol key: ref. to Fig. 3

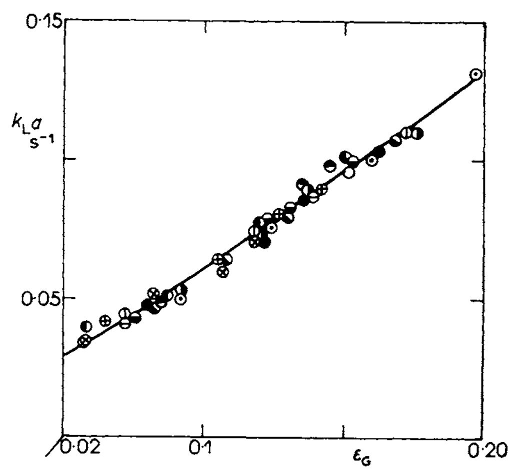

FIG. 8

Dependence of $k_L a$ on gas holdup ratio. Symbol key: ref. to Fig. 3; ——— data calculated from Eq. (3) for $b_1 = 0{\cdot}7, b_2 = 1{\cdot}05$

by the graph presented in Fig. 8, showing mutual relation of k_La and gas holdup data from all experimental runs. The single unambiguous dependence obtained for all diffusers and nozzles used in our experiments apparently proves identical character of gas liquid bed for a given way of dispersion formation independently of construction parameters of an ejector distributor. Experimental data plotted in Fig. 8 thus further prove that the increase of energy effectiveness with increasing diffuser length apparent from Fig. 3 and 4 has been unambiguously caused by increasing rate of gas suction resulting in higher values of gas holdup and k_La for specific rates of energy dissipation while no qualitative changes of mechanism of dispersion formation and bubble bed character occur. As can be seen from Fig. 8 experimental data k_La *vs* ε_G were well correlated by an exponential-type relation

$$k_La = b_1\varepsilon_G^{b_2} \tag{3}$$

for values $b_1 = 0{\cdot}7$, $b_2 = 1{\cdot}05$ obtained from our data by the least squares method. Apparently the value of coefficient b_2 confirms almost linear dependence of k_La on gas holdup observed previously[7] in bubble column reactors with both sieve-tray and ejector gas distributors.

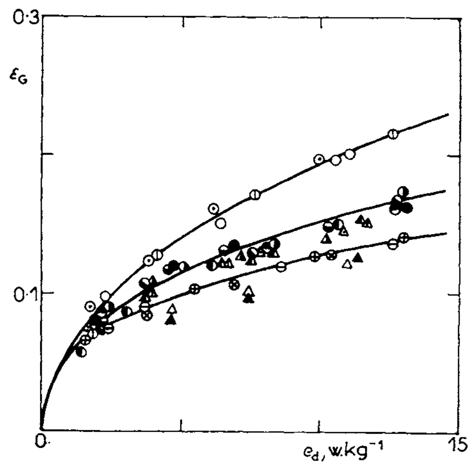

FIG. 9

Gas holdup as a function of the rate of energy dissipation. Ejector E1: $d_0 = 0{\cdot}016$ m, $d_s = 0{\cdot}008$ m; $L_d = 0{\cdot}4$ m, $\alpha = 1{\cdot}7°$: ○ *a*, ⊙ *b*, ⦶ *c*; $L_d = 0{\cdot}2$ m, $\alpha = 3{\cdot}4°$: ● *a*, ◐ *b*, ◑ *c*; $L_d = 0{\cdot}2$ m, $\alpha = 1{\cdot}7°$: ◓ *a*, ◒ *b*, ◐ *c*; $L_d = 0{\cdot}1$ m, $\alpha = 6{\cdot}8°$: ⊕ *a*, ⊗ *b*, ○ *c*. Ejector E2: $L_t = 0{\cdot}11$ m, $d_0 = 0{\cdot}015$ m, nozzle *a*, $d_s = 0{\cdot}006$ m; △ $L_d = 0{\cdot}12$ m, $\alpha = 5°$; ▲ $L_d = 0{\cdot}12$ m, $\alpha = 2{\cdot}5°$; ◭ $L_d = 0{\cdot}18$ m, $\alpha = 5°$; ◮ $L_d = 0{\cdot}18$ m, $\alpha = 2{\cdot}5°$; △ $L_d = 0{\cdot}50$ m, $\alpha = 2{\cdot}5°$; △ $L_d = 0{\cdot}18$ m, slot-shaped diffuser; ——— data calculated from Eq. *4*

In Fig. 9 experimental dependences ε_G *vs* e_d observed for all combinations of nozzle type and diffuser geometry are compared with corresponding data obtained in our recent work[10] for an ejector distributor with cylindrical mixing tube placed between suction chamber and diffuser; diameter of such a tube equals to inlet diffuser diameter. Construction schema of this type of ejector, studied extensively also by Henzler[4,5], can be found elsewhere[5,10]. Experiments with this latter ejector type were carried out[10] at optimum mixing tube length 0·11 m (determined for given conditions from Henzler's graph[5]) both with conical diffusers of different length (L_d = 0·12 to 0·50 m) and wall inclination angle (α = 2·5 and 5°) and with a slot-shaped diffuser recommended by Zlokarnik[3,11] (L_d = 0·12 m). As can be seen in Fig. 9, data for Venturi-tube ejector (E1) used in our present work agreed well with those obtained for ejector with mixing tube (E2) at corresponding diffuser lengths 0·10 and 0·12 m or 0·20 and 0·18 m, respectively. In the latter case however no further increase of gas holdup was observed for L = 0·5 m (in agreement with Henzler's conclusions[5] concerning the optimum diffuser length for this type of ejectors) and consequently ε_G data for this diffuser length were at comparable e_d values significantly lower than those obtained with ejector E1 for L = 0·4 m. As can be also seen from the graph no difference was observed between ε_G *vs* e_d data obtained with ejector E2 for conical and slot-shaped diffuser at constant length and inlet to outlet cross-section ratio. It is further apparent from Fig. 9 that the data ε_G *vs* e_d were for ejector E1 well correlated by an exponential type relation

$$\varepsilon_G = 0{\cdot}057 e_d^n \qquad (4)$$

(n = 0·53 for L = 0·4 m; n = 0·42 for L = 0·2 m; n = 0·35 for L = 0·1 m).

Apparently, results of our comparison suggest that in the case of ejectors without mixing tube (Fig. 1), where the momentum exchange between phases as well as their mixing proceed simultaneously in the diffuser, the ejector performance (and consequently the quality of gas dispersion) can be influenced by diffuser geometry in wider region than in the case of ejectors with mixing tube by variations of both mixing tube and diffuser geometry. Correspondingly, higher efficiency of dissipated energy utilization and consequently higher energy effectiveness of gas distribution can be expected under comparable condition in the former case, being advantageous even due to its simpler construction.

LIST OF SYMBOLS

a	specific interfacial area related to a unit of liquid volume in the bed
a_1, a_2	empirical coefficients (Eq. (2))
b_1, b_2	empirical coefficients (Eq. (3))
d_0, d_1	inlet and outlet diffuser diameters
d_s	nozzle diameter
e_d	rate of energy dissipation related to a unit of bubble bed mass

H_0	clear-liquid height
H	height of aerated gas–liquid bed
k_L	liquid-side mass transfer coefficient
L_d	diffuser length
L_n	characteristic dimension of ejector nozzle (Fig. 2)
L_t	mixing tube length
n	empirical coefficient (Eq. (4))
ΔP_e	ejector pressure drop
Q_L	liquid throughput (rate of liquid circulation through an ejector)
$\dot{V}_G$	gas suction rate
V_L	volume of liquid in bubble bed
w_G	superficial gas velocity
α	angle of diffuser walls inclination (Fig. 1)
ε_G	gas holdup
ϱ_L	liquid phase density
Φ	energy effectiveness criterion ($\Phi = k_L a/e_d$)

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