DESIGN OF VENTURI-TUBE GAS DISTRIBUTORS FOR BUBBLE-TYPE REACTORS

Milan RYLEK and Jindřich ZAHRADNÍK

Institute of Chemical Process Fundamentals, Czechoslovak Academy of Sciences, 165 02 Prague 6 - Suchdol

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The effect of individual parts of a Venturi-tube gas distributor on quality of the gas–liquid dispersion formed was studied in a bubble-type reactor with forced liquid circulation. Gas holdup (bubble-bed porosity) was used as the dispersion characteristics, type and geometry of nozzles, suction chamber arrangement, and dimensions of the mixing tube and diffuser were chosen as variable design parameters. Experimental data of gas holdup presented in dependence on the rate of energy dissipation in the place of dispersion formation characterized then the dispersion efficiency of the Venturi tube at given conditions. Recommendations for design of Venturi-tube gas distributors are presented based upon the results of the study.

Ejector gas distributors of the Venturi-tube type have been frequently recommended for reactors designed for various chemical and biotechnological processes. For suitably selected construction parameters distributors of this type provide an intensive interfacial contact in two- or three-phase bubble beds. Beside that it is often advantageous from the operational point of view that all the energy needed for gas–liquid bed formation can be supplied solely to the liquid phase. Wider use of these distributors has been however hindered by the lack of sufficiently general routinely applicable relations characterizing the dependence of gas–liquid bed parameters on specific construction parameters of distributors. While numerous papers can be found reporting application of ejector distributors in units for specific chemical and biotechnological processes, more general studies appeared only recently, devoted to description of mechanism of gas–liquid bed formation in units with ejector distributors[1] and/or to optimization of decisive ejector parameters[2]. In our group, the Venturi-tube type ejector distributors and their application in bubble column contactors have been studied systematically for several years[3–6]. Up to now the main attention has been paid to energy aspects of bed formation in analogy to the mechanism of gas dispersion in sieve-tray bubble columns and to the comparison of efficiency of gas–liquid bed formation in these two cases. Our experimental results[4,5] have proved the existence of an unambiguous relation between the rate of energy dissipation in the place of dispersion formation (*i.e.* in the ejector) and quality of gas–liquid dispersion formed and intensity of interfacial mass transfer in the bed characterised by the gas holdup and k_La respectively. It was the aim of our present study to test the effect of selected construction parameters of ejector distributors on quality of resulting gas–liquid dispersion and to obtain quantitative data characterising such effect which could be used as a base for design and scale-up of these distributors. Variable design parameters included type and geometry of ejector nozzles, suction chamber arrangement, and dimensions of mixing tube and diffuser. Mean gas holdup (bubble bed porosity), ε_G, was chosen as the characteristic of the gas–liquid bed in the unit, due to feasibility of its experimental determination. It has been found earlier[7] that there exists direct proportionality between values of gas holdup and specific interfacial area, a. It has been further proved experimentally[4–5] that for a specific way of gas dispersion an unambiguous relation exists even between gas holdup and k_La values. Gas holdup can be thus apparently considered to be a representative characteristics of dispersion eficiency of a distributor used.

EXPERIMENTAL

Schematic chart of the experimental set up is given in Fig. 1. Measurements were performed in a glass-wall column of I.D. 0·3 m. Venturi tube used as the gas-distributing device was mounted to the column bottom by a flange. Details of the Venturi tube can be seen in Fig. 2. Individual construction parts — nozzle *1*, suction chamber *2*, mixing tube *3*, and diffuser *4* — could be easily interchanged due to sectionalized construction of the Venturi tube.

All experiments were performed in a batchwise arrangement at constant clear liquid height $H_0 = 1{\cdot}5$ m, tap water was used as the liquid phase. Liquid flow rate through the ejector, volumetric flow rate of air sucked by the ejector, pressure at the circulation pump outlet, and height of the aerated bed were measured and recorded during experiments. Gas holdup was calculated from the difference of height of aerated bed and clear liquid using the relation

$$\varepsilon_G = (H - H_0)/H\,.$$

Nozzles: Eight different nozzles were used listed in Table I, meaning of their geometrical parameters d_1, d_2, and h is apparent from Fig. 3*a*. In Fig. 3*b* ground plots of outlet nozzle throats are shown, free area of nozzle outlets, A_2, is left unhatched. Inlet cross-sections of all nozzles were circular, corresponding to inlet diameter d_1. Nozzles No 6—8 represented commonly used nozzle types (see *e.g.* Henzler[2] or Zahradník and coworkers[4–5]) with continuous conical transition between inlet and outlet cross-sections, in the case of nozzle 5 a reverse-positioned cone was built in the internal conical space (Fig. 3*c*). Nozzle 4 with smooth continuous transition between circular inlet hole and slot-shaped nozzle outlet was recommended by Zlokarnik[1]. Outlet-throats of nozzles 1—3 were covered by plates with different perforation patterns.

Suction chamber: Two types of suction chambers were used, their construction being obvious from Fig. 4. Type A was the standard type of the chamber used also in our former studies, in arrangement B the chamber was divided to an internal and external zone. The nozzle was located in the inner space which was smoothly connected with the mixing tube. The internal zone was interconnected by eight circular openings with the outer space of the chamber. The total cross-sectional area of interconnecting holes was determined from preliminary experiments so that the additional hole resistance did not influence the flow rate of air sucked into the chamber.

Mixing tube: Experiments were performed with mixing tubes of circular cross-section, tube diameters were 5, 8, 15 and 26 mm, tube lengths were 0·08 and 0·11 m.

Diffuser: Ten diffusers of conical shape were studied. Their lengths were 0·12, 0·18, and 0·50 m, diameters of inlet holes were 0·015 and 0·025 m, angles of wall inclination α (Fig. 2) were 2·5 and 5°. The slot-shaped diffuser recommended by Zlokarnik[1,8] was also tested. Its construction ensured smooth continuous transition between circular inlet hole (D_2 = 0·015 m) and oval-shaped outlet slot. Slot length was 0·045 m, width 0·015 m, radius of oval curvature was 0·0075 m. Outlet to inlet cross-section ratio was practically identical as in the case of the conical diffuser with parameters L_2 = 0·18 m, D_2 = 0·015 m, α = 2·5°.

The effect of flow-orienting bodies was further tested during some experimental runs. Swirl bodies formed by four inclined blades were fixed into the liquid inlet pipe in front of the nozzle or at the mixing tube outlet, their purpose was to bring the stream of liquid or of the gas–liquid dispersion (according to element position) into a rotary motion.

RESULTS AND DISCUSSION

As stated above, the decisive effect of the rate of energy dissipation on quality of gas–liquid dispersion formed by the ejector and on intensity of mass transfer in the bed has been confirmed experimentally in our recent studies[4,5]. Specific rate of energy

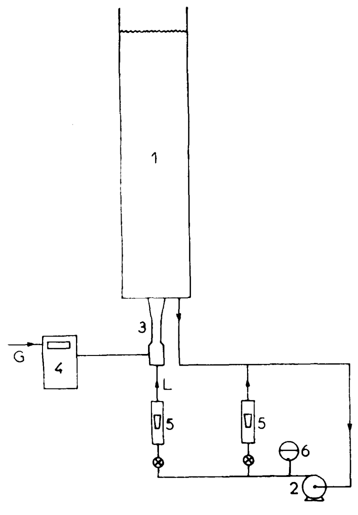

FIG. 1

Experimental set-up. 1 Glass-wall column, 2 pump, 3 Venturi tube, 4 gas-flow meter, 5 rotameters, 6 manometer G gas flow, L liquid flow

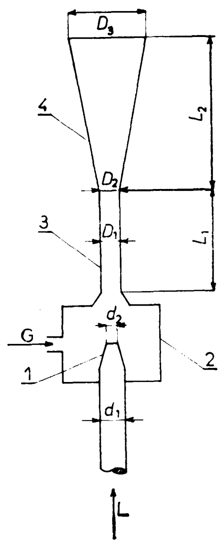

FIG. 2

Venturi-tube ejector distributor. 1 Nozzle, 2 suction chamber, 3 mixing tube, 4 diffuser dissipation related to the unit of liquid mass in the bed, e_d (W/kg), is defined by the relation

$$e_d = \Delta P_e \dot{V}_L / V_L \varrho_L \,, \tag{1}$$

TABLE I

Geometrical parameters of nozzles used in experiments

No	Type	d_1 m	d_2 m	h m	$A_2 \cdot 10^6$ m^2
1	perforated lid on the outlet throat- slot-shaped perforations	0·023	0·013	0·021	30
2	perforated lid on the outlet throat- circular perforations	0·023	0·013	0·021	62
3	perforated lid on the outlet throat- annular free area	0·023	0·012	0·021	59
4	uncovered slot-shaped throat	0·023	$l_1 = 0{\cdot}010$ $l_2 = 0{\cdot}002$	0·025	20
5	in-built cone in the internal space of the nozzle	0·023	0·010	0·020	29
6	free nozzle outlet of circular cross-section	0·023	0·0055	0·020	24
7	free nozzle oulet of circular cross-section	0·023	0·010	0·020	79
8	free nozzle outlet of circular cross-section	0·023	0·0055	0·040	24

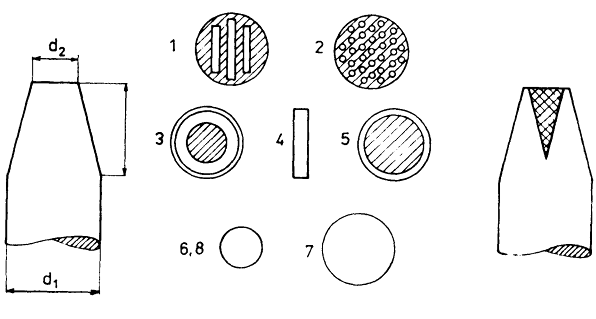

FIG. 3

Ejector-nozzles used in experiments. a) Schematic chart of nozzle geometry; b) Ground plots of outlet nozzle throats (free throat area left unhatched). c) Scheme of the nozzle No 5 (Table I) where ΔP_e is the ejector pressure drop, $\dot{V}_L$ volumetric flow rate of liquid circulated through the ejector and V_L volume of the liquid phase in the bed. Experimental data characterising the effect of design parameters studied on nature of dispersion formed are therefore presented in a generalised form as the dependence of gas holdup on e_d.

In Fig. 5, data ε_G *vs* e_d are presented, obtained for all the nozzles studied at constant values of other construction parameters. As can be seen from the figure these data confirm our former conclusions on the dependence of the character of gas–liquid bed (represented by corresponding gas holdup) on the rate of energy dissipation in ejector. The difference between dependences obtained for the groups of nozzles $1-3$ and $4-8$ respectively has to be apparently ascribed to the construction arrangement of nozzles $1-3$. The outlet throats of these nozzles were covered by perforated lids (Fig. 3*b*) with only area of perforations opened for liquid throughput. Indeed in such a case condition of smooth continuous transition between inlet and outlet nozzle cross-sections was no more fulfilled. Pressure drop of these nozzles was consequently higher in comparison with nozzles $4-8$ (even at constant A_1/A_2 ratios) while only part of the additionally dissipated energy was utilized for dispersion formation. It is thus apparent that nozzles of this type are not suitable for Venturi tubes as gas distributors. Results obtained with nozzles $4-8$ have proved in agreement with our former data that in the case of nozzles with free upper throat *i.e.* with smooth transition between inlet and outlet nozzle cross-sections the bubble-bed gas holdup is unambiguously determined by the specific rate of energy dissipation independently on the ratio of inlet to outlet nozzle cross-sections and on the height and inclination angle of nozzle cone (Fig. 3*a*). It is further obvious from data for nozzles 4 and 5 that no effect of slot-shaped nozzle outlet or in-built internal cone

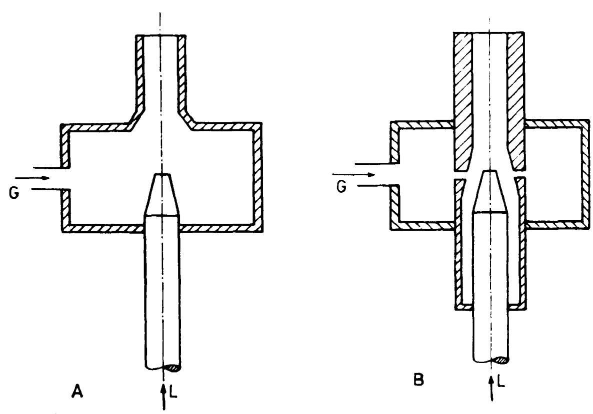

FIG. 4
Suction chambers used. A standard type, B two-zone arrangement

was observed on the dependence ε_G *vs* e_d which was in both these cases identical with that for standard nozzles 6–8.

Study of the effect of other ejector elements (suction chamber, mixing tube, diffusor) was aimed at estimation of the influence of construction arrangement and geometry of these elements on efficiency of utilization of the energy dissipated in the nozzle, *i.e.* on the ratio of dissipated energy directly utilized for gas dispersion[4]. Comparison of data for both suction chambers studied proved no advantages of the more complicated two-zone arrangement (type B). In the case of small total cross-sectional area of interconnecting holes resulting additional resistance reduced substantially the flow rate of gas sucked. When these holes were properly dimensioned ($A_s \geqq 5A_1$) equal suction rate and consequently identical gas holdup were achieved in both cases at comparable conditions. Suctions chambers of the type A can be therefore recommended for both design and manufacturing reasons.

Comparison of dependences ε_G *vs* e_d obtained for different mixing-tube geometries pointed out a significant effect of tube diameter, D_1, or of its ratio to nozzle diameter, D_1/d_2, on character of the dependence and thus on the efficiency of dissipated energy utilisation for dispersion formation *i.e.* for intensive contacting of phases. It is obvious from the graph plotted in Fig. 6 that the experimental dependences of ε_G on D_1 have a maximum at $D_1 \approx 3d_2$ in the whole range of experimental values

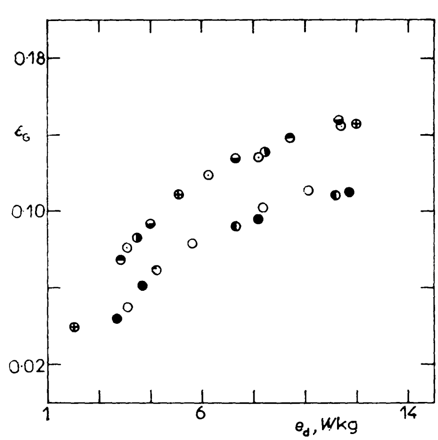

FIG. 5

Gas holdup as a function of specific rate or energy dissipation — the effect of nozzle geometry. $L_1 = 0{\cdot}11$ m, $L_2 = 0{\cdot}18$ m, $D_1 = D_2 = 0{\cdot}015$ m, $\alpha = 5°$ nozzle No: ○ 1, ● 2, ◐ 3, ◑ 4, ◓ 5, ◒ 6, ⊙ 7, ⊕ 8

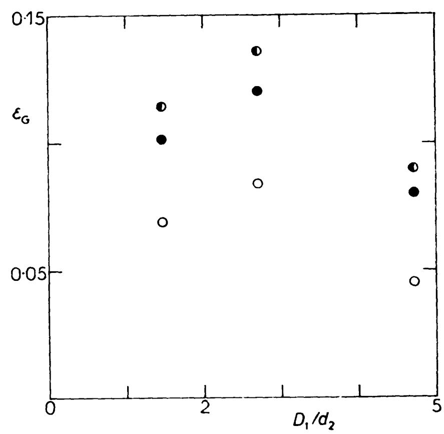

FIG. 6

Dependence of gas holdup on mixing-tube diameter. $L_1 = 0{\cdot}11$ m, $L_2 = 0{\cdot}18$ m, $d_2 = 0{\cdot}0055$ m, $\alpha = 5°$. ○ $e_d = 2{\cdot}0$ W/kg, ● $e_d = 6{\cdot}5$ W/kg, ◐ $e_d = 11{\cdot}0$ W/kg

e_d. Within the range of mixing tube lengths used, $L_1 = 0{\cdot}08 - 0{\cdot}11$ m, no significant effect of L_1 was observed on the character of dependence ε_G *vs* e_d. Regarding the shape of functional relation $(L_1/D_1)_{opt} = f(F)$, $(F = D_1/d_2)^2)$ presented by Henzler[2] for determination of the optimum ratio of mixing tube length to its diameter, our results do not in fact contradict the Henzler's findings. In Fig. 7 experimental dependences ε_G *vs* e_d are plotted obtained for $L_1 = 0{\cdot}11$ m at $D_1 = 0{\cdot}015$ m, $d_2 = 0{\cdot}0055$ m (set A)and at $D_1 = 0{\cdot}025$ m, $d_2 = 0{\cdot}0055$ m (set B), together with data obtained for $L_1 = 0{\cdot}08$ m at $D_1 = 0{\cdot}015$ m, $d_2 = 0{\cdot}010$ m (set C). For corresponding values of factor $F = (D_1/D_2)^2$, $F = 7{\cdot}4$ (A), $20{\cdot}6$ (B), and $2{\cdot}25$ (C), it is possible to estimate appropriate values $(L_1/D_1)_{opt} = 7{\cdot}5$ (for series A and B) or 6 (for set C) from Henzler's graph $(L_1/D_1)_{opt}$ *vs* F and to determine the optimal values of L_1 corresponding to respective mixing tube diameters, $(L_1)_{opt} = 0{\cdot}11$ m (A), $0{\cdot}19$ m (B), and $0{\cdot}09$ m (C). It is obvious from Fig. 7 that for series A and C where $L_{exp} \approx (L_1)_{opt}$ the dependences obtained were almost identical and values ε_G measured at these conditions were significantly higher than for the series B when the mixing-tube length was for the respective diameter value smaller than the corresponding optimal value. Apparently thus these results confirm the conclusions made by Henzler[2] on the effect of (L_1/D_1) ratio on the dispersion efficiency of ejector distributors and

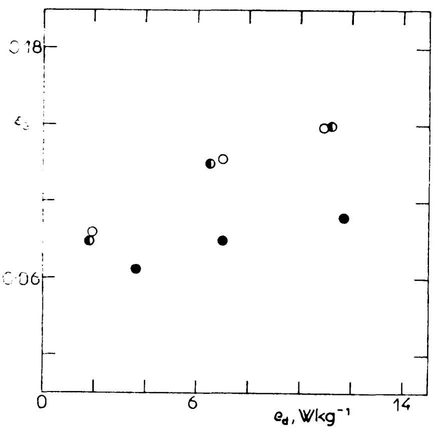

FIG. 7

Gas holdup as a function of specific rate of energy dissipation— comparison of experimental sets A, B, C·○ set A $L_1 = 0{\cdot}11$ m, $D_1 = 0{\cdot}015$ m, $d_2 = 0{\cdot}0055$ m, ● set B $L_1 = 0{\cdot}11$ m, $D_1 = 0{\cdot}025$ m, $d_2 = 0{\cdot}0055$ m, ◐ set C $L_1 = 0{\cdot}08$ m, $D_1 = 0{\cdot}015$ m, $d_2 = 0{\cdot}010$ m

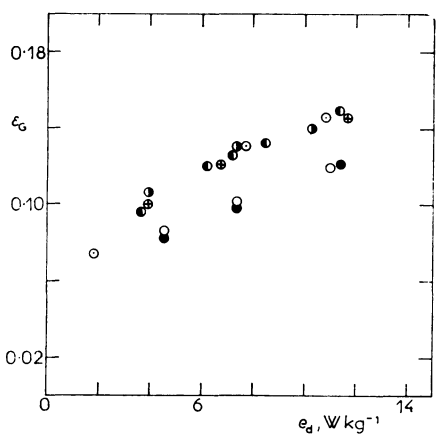

FIG. 8

Effect of diffuser geometry on the dependence ε_G *vs* e_d. $D_1 = D_2 = 0{\cdot}015$ m, $d_2 = 0{\cdot}055$ m, nozzle No 6 conical diffusers: ○ $L_2 = 0{\cdot}12$ m, $\alpha = 5°$; ● $L_2 = 0{\cdot}12$ m, $\alpha = 2{\cdot}5°$; ◐ $L_2 = 0{\cdot}18$ m, $\alpha = 5°$; ◑ $L_2 = 0{\cdot}18$ m, $\alpha = 2{\cdot}5°$; ⊙ $L_2 = 0{\cdot}50$ m, $\alpha = 2{\cdot}5°$; ⊕ slot--shaped diffuser, $L_2 = 0{\cdot}18$ m prove the suitability of the procedure recommended in Henzler's paper[2] for determination of the optimal value of this parameter.

The effect of diffuser geometry on the character of dependence ε_G *vs* e_D is illustrated in Fig. 8 in which the data for conical diffusers of different lengths and angles of wall inclination and foı the slot-shaped diffuser have been plotted. It is obvious from the figure that at comparable conditions the gas holdup increased with the diffuser length in the range $L_2 = 0{\cdot}12-0{\cdot}18$ m, while further increase of the length up to 0·5 m had no effect on bubble bed porosity. Limiting value of diffuser length, $L_2 = 0{\cdot}18$ m, agreed for experimental conditions $(D_1 = D_2 = 0{\cdot}015 \text{ m})$ well with the value $(L_2/D_2)_{crit} \approx 12$ which can be obtained from the graph presented by Henzler[2] for estimation of the diffuser length effect. No influence of wall inclination angle was observed for conical diffusers in the experimental region of α values, $2{\cdot}5-5°$. It is further apparent from Fig. 8 that the dependence ε_G *vs* e_d obtained with the slot-shaped diffuser agreed well with data for conical diffusers of the same length. Regarding the efficiency of dissipated energy utilization both geometrical arrangements can be thus apparently considered to be identical.

Preliminary tests of the effect of swirl bodies proved a positive effect of such elements located at the ejector inlet in front of the nozzle. On the other hand, presence of swirl bodies in the mixing tube influenced negatively the gas holdup values in the whole range of experimental conditions.

CONCLUSIONS

The effect of construction parameters of Venturi-tube gas distributors on their dispersion efficiency was studied in a tower reactor with forced liquid circulation. Experimental results confirmed decisive effect of the rate of energy dissipation in the ejector on the quality of gas dispersion characterised by porosity (gas holdup ratio) of resulting gas–liquid bed. Nozzle type and geometry determined the rate of energy dissipation for a specific liquid throughput, they however did not influence the dependence of gas holdup on energy dissipation rate as long as condition of smooth continuous transition between inlet and outlet nozzle cross-sections was fulfilled. In the case of novel-type perforated-lid nozzles which were also tested the increase of energy dissipation rate due to higher pressure drop of such nozzles did not cause corresponding increase of the flow rate of gas sucked and consequently of the gas holdup. Application of such nozzles in ejector gas distributors thus cannot be recommended. Similarly no advantages of a novel two-zone arrangement of suction chamber were proved in comparison with the standard chamber type the latter thus remaining superior due to its construction and manufacturing simplicity.

While it has been proved that the rate of energy dissipation is determined solely by the nozzle type and geometry it was apparent from our experimental data that the efficiency of dissipated energy utilization *i.e.* the ratio of dissipated energy directly utilized for gas dispersion was dependent on both mixing tube and diffuser geometry. Results of our experiments yielded the optimum value of mixing tube diameter, $D_1 = 3d_2$, while proving validity of Henzler's conclusions[2] on the effect of mixing tube length to diameter ratio, L_1/D_1. Henzler's graph can be recommended for determination of the optimum value of this ratio, $(L_1/D_1)_{opt}$, according to results of our study.

No difference between the data ε_G *vs* e_d for conical and slot-shaped diffusers was observed at constant diffuser length and inlet to outlet cross-sections ratio. Diffuser length influenced the ejector dispersion efficiency up to $(L_2/D_2) \approx 12$ this again being in agreement with results of Henzler's optimization study[2]. No effect of diffuser wall inclination angle, α, on ejector dispersion efficiency was observed in experimental range 2·5 – 5°.

Positive effect of swirl bodies (oriented blades) located in front of the nozzle inlet on the ejector performance was indicated by results of preliminary test experiments. Apparently some further attention should be paid to the use of such elements in future studies.

LIST OF SYMBOLS

A_1 cross-sectional area of nozzle inlet
A_2 free cross-sectional area of the ouzlet nozzle throat
A_S overall cross-sectional area of interconnecting holes between the inner and outer space of two-zone suction chamber (Fig. 4)
D_1 mixing tube diameter
D_2 diameter of diffuser inlet
D_3 diameter of diffuser outlet
d_1 diameter of nozzle inlet
d_2 diameter of outlet throat of a nozzle
e_d specific rate of energy dissipation related to a unit of buble bed mass
h height of conical section of a nozzle
L_1 mixing tube length
L_2 length of diffuser
l_1, l_2 characteristic dimensions of the slot nozzle outlet
ΔP_e ejector pressure drop
V_L volume of liquid phase in the bed
$\dot{V}_L$ volumetric flow rate of liquid through the ejector

Greek symbols

α angle of diffusor walls inclination
ε_G gas holdup (bubble bed porosity)
ϱ_L liquid phase density

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