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SORPTION CHARACTERISTICS OF SLOT INJECTORS AND THEIR DEPENDENCY ON THE COALESCENCE BEHAVIOUR OF THE SYSTEM

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Abstract—For the design of injectors serving as gas dispersion devices in gas–liquid contacting, data are needed which describe the influence of material, geometrical and process-related parameters on the absorption rate In this article these data will be presented for a new type of injector, the so-called slot injector, in the form of sorption characteristics To vary the coalescence behaviour of the system, common salt and/or solids (cellulose, activated carbon) were added The shape of the slot injector has proved particularly advantageous in overcoming the problems associated with scale-up This is verified by an industrial size slot injector which is characterized by high efficiency of mass transfer and which is likely to prove almost entirely free from blocking

INTRODUCTION

For the enhancement of the mass transfer in gas–liquid contacting two-phase nozzles are being increasingly used These nozzles include ejectors, injectors, Venturi nozzles, jet aerators etc Common to these devices is the utilisation of the kinetic energy of the liquid jet to disperse the gas throughput into very fine bubbles The gas–liquid dispersion leaves the device in the form of a free jet, which having penetrated a certain distance into the surrounding liquid, loses its energy and breaks up into a cloud of bubbles This rises in the liquid and causes the mass transfer As a consequence the use of two-phase nozzles is not restricted to certain liquid depths, on the contrary, the liquid depth is a parameter which can be chosen freely The two-phase nozzles are therefore particularly suitable as gas distributors in bubble columns and in biological waste-water treatment plants

For the design and optimisation of two-phase nozzles for a required mass transfer rate, reliable data are necessary These will be introduced later in the form of sorption characteristics for a very efficient type of injector, the so-called slot injector These sorption characteristics were obtained by evaluating absorption measurements on both semi-industrial and industrial sizes using the theory of similarity

It is known that the primary formed fine gas bubbles tend to coalesce to larger ones The bubble coalescence is favoured by some geometrical and material parameters, but can also be prevented by certain additives In industry the absorption process is rarely carried out in a pure liquid In most cases suspended particles (e g bacterial culture) and dissolved inorganic and/or organic material is present which decisively influences the bubble coalescence The absorption measurements were therefore carried out not only in pure water but also in aqueous solutions with defined coalescence behaviour differing greatly from that of pure water

CHARACTERISTIC FEATURES OF THE SLOT INJECTOR

The two-phase nozzles, used as gas distributors, should utilize the kinetic energy of the liquid jet as efficiently as possible for the gas dispersion For this purpose a large proportion of the energy must still be present in the free jet to enable the gas-liquid dispersion to mix rapidly with the surrounding liquid thus inhibiting the bubble coalescence As the two-phase nozzles inject the gas–liquid dispersion in the surrounding liquid, they are often referred to as injectors

This study is concerned with the so-called slot injector, Fig 1 Its characteristic feature is the shape of the

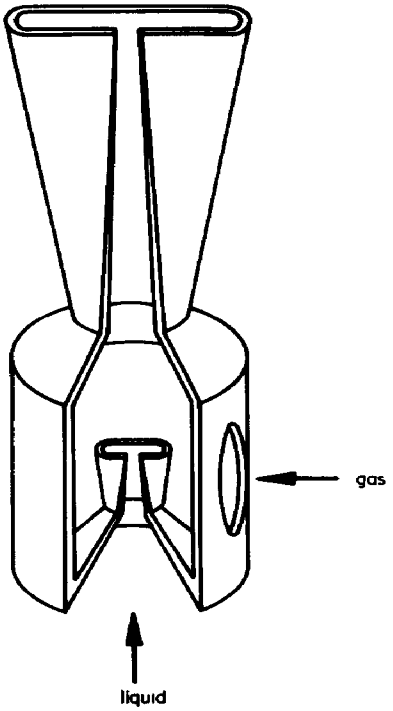

Fig 1 Diagram of the slot injector

mixing chamber, which is originally circular and gradually becomes slot shaped, the cross-sectional area not necessarily being changed[1]. This slot shape offers two advantages. Firstly the mixing chamber consists largely of convergent surfaces along which the shear rate increases. This results in a lower pressure drop compared with an accelerated flow and implies that a fine gas dispersion is produced with the free jet retaining a large amount of its kinetic energy. Secondly the free jet leaves the injector as a relatively flat band which mixes more rapidly with the surrounding liquid thus suppressing the bubble coalescence.

The shape of the liquid nozzle is adapted to that of the mixing chamber in order to ensure that the slot shaped outlet is entirely filled with the gas-liquid dispersion.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The sorption characteristics discussed in this study were obtained for two slot injectors (types A and B) being geometrically dissimilar. The principal dimensions of the liquid nozzle and of the mixing chamber are given in Table 1.

Table 1. Principal dimensions of the investigated slot injectors

	Type A	Type B
Liquid nozzle		
Cross-sectional area at the outlet, mm^2	113	452
Slot width, mm	8	16
Mixing chamber		
Cross-sectional area at the outlet, mm^2	314	1256
Slot width, mm	10	20

Two vessels with semi-ellipsoidal bottoms and having a diameter of 1.60 m in the one case and of 2.80 m in the other were used to obtain the measurements for the injectors of Type A and B respectively. Liquid levels of up to $H = 8$ m were obtainable in both vessels.

In all experiments air was used as the gas and water as the liquid and the coalescence behaviour of the system was varied by adding common salt in various concentrations between 0 and 20 g/l. The absorption measurements were carried out under steady-state conditions, while hydrazine was fed continuously into the system to remove the absorbed oxygen.

Details of this experimental procedure, which has the advantage of not changing the material composition of the system and hence its physical and chemical nature, are given in[2]. Due to the steady-state absorption conditions, the mass transfer coefficient k_La, as defined by the absorption rate equation

$$k_La = G/(V\Delta c) \tag{1}$$

is determined by the mass of hydrazine G introduced in unit time (which equals the oxygen flow rate through the interface, as the molecular masses of hydrazine and oxygen are the same), the liquid volume V (without gas) and the mean logarithmic concentration difference Δc_m. The last quantity is defined by the relationship

$$\Delta c_m = (c' - c'')/\ln[(c' - c)/(c'' - c)] \tag{2}$$

which accounts for no back-mixing of the gas phase and compete back-mixing of the liquid. c' and c'' represent the oxygen saturation concentrations in the liquid at the gas inlet and outlet respectively, c being the concentration of oxygen dissolved in the liquid. In all the experiments c was measured and recorded with two oxygen electrodes, one being positioned near the bottom of the vessel and the other near the surface of the liquid. Both electrodes indicated similar oxygen concentrations in the liquid, thus confirming the assumption of the complete back-mixing of the liquid phase.

Whereas the saturation concentration at the gas inlet

$$c' = c_s x(1 + 0.1\,H) \qquad (x = 0.21 \text{ for air}) \tag{3}$$

depends only on the system temperature and the height of the liquid, H (in metres) above the injector, the saturation concentration at the gas outlet

$$c'' = c_s x'' \tag{4}$$

also depends on the mole fraction x'' of the oxygen in the outflowing gas, which is calculated from the absorption rate G and the air throughput q according to the relationship

$$x'' = (qx' - G/\rho_{O_2})/(q - G/\rho_{O_2}), \tag{5}$$

the gas throughput q and the gas density of oxygen ρ_{O_2} must be related to identical conditions (e.g. standard conditions).

The dependence of the 0_2 saturation concentration on the system temperature $c_x(\vartheta)$, was taken from[3].

As the system temperature was not constant from measurement to measurement, but varied in the range $\vartheta = 15$–30°C, the measured k_La values were converted to k_La at 20°C by using the equation proposed by Calderbank[4] to determine k_L in the case of bubbles with diameters > 2.5 mm.

FORMULATION OF THE PROBLEM IN ACCORDANCE WITH THE THEORY OF SIMILARITY

When formulating the absorption process in accordance with the theory of similarity one must bear in mind that the definition of k_La as a volume-related intensive quantity implies the following three consequences.

(a) No dependence on the geometrical parameters (owing to the assumption that the gas–liquid system is quasi-uniform).

(b) No dependence on the material parameters of the gas phase (owing to the assumption $k_G \gg k_L$).

(c) formulation of the process parameters as intensive quantities[2, 5].

The following material parameters of the liquid phase can be involved in the mass transfer

ρ—liquid density

ν—liquid kinematic viscosity

$\mathbf{D}$—diffusivity of the gas in the liquid

σ—surface tension of the liquid

S_i—material parameters which describe the coalescence behaviour of the system and are expressed in this study by means of the NaCl concentration.

With injectors the gas throughput q and the liquid throughput q_L are involved as extensive process parameters. As the hydrodynamic behaviour in bubble columns depends on the gas load, i.e. the gas throughput divided by the cross-sectional area q/A, these two process parameters could be intensively formulated in the form q/A and q/q_L. However, the parameter q/q_L has the disadvantage, that it occurs only in two-phase nozzles. An evaluation of the experimental material with the aid of this parameter would therefore give expressions which could not be compared with those of other absorption devices. Therefore, by analogy with the sorption characteristics for stirrers[5], not the liquid throughput q_L, but its power P_L

$P_L = \Delta p_L q_L$ (Δp_L—pressure drop in the liquid nozzle)

is introduced as a process parameter which, however, requires a knowledge of the pressure drop characteristic of the liquid nozzle. The extensive process parameters q and q_L are thus converted into the intensive quantities q/A and P_L/q. The third process parameter is the gravitational constant g, which exerts an important influence on the hydrodynamics of the process because of the large density differences in the gas–liquid system.

Thus the functional dependency for k_La reads as follows

$$k_La = f(\rho, \nu, \mathbf{D}, \sigma, S_i, q/A, P_L/q, g) \qquad (6)$$

This dependence on nine dimensional quantities can be reduced, in accordance with the theory of similarity, to a dependence on $9-3=6$ dimensionless numbers. This is due to their dimensions consisting of the three fundamental units (mass, length, time).

(Concerning the quantities termed S_i, which describe the coalescence behaviour of solutions, of which the definitions are still not clear, it may be pointed out that regardless of their dimensions they can always be transformed into the pure material numbers by means of the parameters ρ, ν and g.)

It follows

$$(k_La)^* = \psi\{Sc, S_i^*, \sigma^*, (q/A)^*, (P_L/q)^*\}, \qquad (7)$$

where

$(k_La)^* \equiv k_La(\nu/g^2)^{1/3}$

$\mathrm{Sc} \equiv \nu/\mathbf{D}$—Schmidt number

$\sigma^* \equiv \sigma(\rho^3\nu^4 g)^{-1/3}$

$S_i^* \equiv$ dimensionless material parameters S_i

$(q/A)^* \equiv (q/A)(g\nu)^{-1/3}$

$(P_L/q)^* = (P_L/q)/[\rho(\nu g)^{2/3}]$

When the absorption process is carried out in a given system and at constant temperature, the numbers Sc, σ^* and S_i^* remain constant and the process is described by

$$(k_La)^* = \psi_1\{(q/A)^*, (P_L/q)\} \qquad (8)$$

Let us assume that the average bubble size in the bubble cloud remains constant when the gas load is increased but the power per unit gas throughput is kept constant. In that case, a doubling of the gas load will double the number of gas bubbles and hence the interfacial area, k_La is thus directly proportional to the gas load.

$$(P_L/q)^* = \text{const} \quad (k_La)^* \propto (q/A)^* \rightarrow (k_La)^*/(q/A)^* = \text{const} \qquad (9)$$

This assumption, which will of course need to be confirmed below, reduces the three-dimensional π-space (8) to a two-dimensional one

$$(k_La)^*/(q/A)^* = \psi_1\{(P_L/q)^*\}, \qquad (10)$$

but the meaning of the number produced in (10) is difficult to visualize. However, if we recall the definition of k_La (1) and replace V by HA, the following expression is obtained

$$\frac{G}{HA\Delta c_m}\left(\frac{\nu}{g^2}\right)^{1/3}\frac{A}{q}(\nu g)^{1/3} \equiv \frac{G}{Hq\Delta c_m}\left(\frac{\nu^2}{g}\right)^{1/3} \qquad (11)$$

The form of this number shows that the mass transfer rate G is proportional to the liquid height H, the gas throughput q and the logarithmic mean concentration difference Δc_m.

Where high bubble columns are concerned it is to be expected that the influence of the gas throughput q on G is taken into account more accurately when it is related to the mean pressure of the system

$$q_1 = q/(1+0.05H) \qquad (12)$$

In contrast, the power P_L of the liquid jet effects the gas throughput which is subjected to the pressure exerted by the liquid head above the injector

$$q_2 = q/(1+0.1\,H) \qquad (13)$$

In view of these circumstances the two numbers are defined as follows

$$Y \equiv \frac{G}{Hq_1\Delta c_m}\left(\frac{\nu^2}{g}\right)^{1/3} \quad \text{sorption number} \qquad (14)$$

$$X \equiv \frac{P_L/q_2}{\rho(\nu g)^{2/3}} \quad \text{dispersion number} \qquad (15)$$

The object of the experiments is thus to determine the functional dependence

$$Y = \phi_1(X),$$

which in the following text is referred to as the *sorption characteristic* of the injector

DISCUSSION OF THE EXPERIMENTAL RESULTS

Influence of the liquid height above the injector on the degree of coalescence

It may be seen from the structure of the sorption number Y that the mass transfer rate G is directly proportional to the liquid height above the injector This statement need not be generally true for any value of H, because the coalescence of the gas bubbles is not necessarily complete once the free jet has broken up into a bubble cloud It was therefore necessary to determine the lowest height of the liquid above the injector at which H ceases to influence $Y(X)$

Figure 2 shows the results of the measurements, for which a slot injector of Type A was attached to the wall of the vessel at a distance of 1 metre from the base and directed downwards at an angle of 25° from the horizontal It can be seen that the liquid jet of the slot injector begins to produce fine and therefore coalescence-inclined gas bubbles only when $X > 2 \times 10^4$ The degree of the bubble coalescence is greater the longer the bubble path in the liquid Only at $H = 3$ m is the coalescence in the bubble cloud complete, i e the size of the bubbles produced by the coalescence remains constant The different slopes of the straight lines show clearly how the dispersing effect of the liquid jet is destroyed by the bubble coalescence

Influence of the salt concentration on the the degree of coalescence

It is known that the coalescence of the primary gas bubbles can be decisively influenced in solutions of various inorganic salts or organic liquids such as lower fatty alcohols[5] The reasons for this will not be considered here, but they are connected with the changing of the water structure ("cluster formation"), which is reflected at the interface by the value of $d\delta/dc$[6]

In this work the degree of coalescence was varied by adding common salt to water, the concentrations of which are expressed in g NaCl/l Figure 3 presents the results of corresponding absorption measurements for which a slot injector of Type A was positioned centrally at the bottom in such a way that the jet was directed vertically upwards, the height of the liquid in the vessel was $H = 8$ m It can be seen that the coalescence is already inhibited to a small extent at 3 g NaCl/l, at 5 g NaCl/l, however, the inhibition is very marked—so much so that it cannot be substantially increased by raising the NaCl concentration further

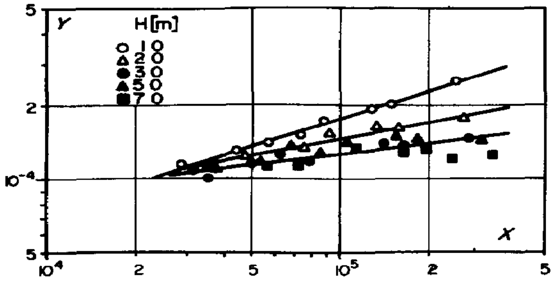

Fig 2 Dependency of the sorption characteristics $Y(X)$ on the liquid height above the injector $D = 1\ 6$ m, jet direction 25°↘, system water/air

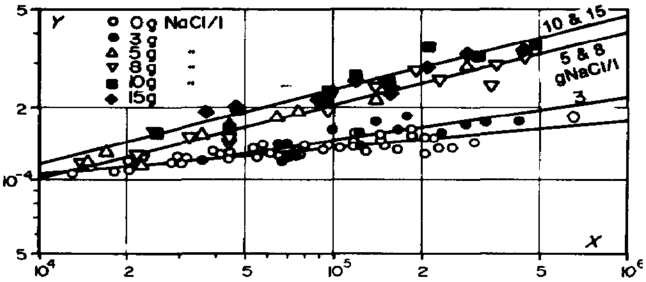

Fig 3 Dependency of the sorption characteristics $Y(X)$ on the degree of coalescence $D = 1\ 6$ m, $H = 8$ m, jet direction ↑, system water/air

This effect is certainly not attributable to the salt concentration alone and is principally connected to the device used to disperse the gas experiments with injectors of different designs have produced different types of $Y(X, c)$ behaviour The smaller the size of the gas bubbles produced by an injector and the more coalescence suppressing the hydrodynamic conditions in both the free jet and the bubble cloud, the greater is the ability of the salt concentration to favour the "preservation" of the primary bubbles The shape of the slot injector under discussion was optimized with regard to obtaining the best possible sorption characteristic in solutions of *low* salt concentrations A design which would give very small primary bubbles, which later coalesce to form larger ones, thus wasting the energy used in their formation, was deliberately avoided The work expended on the design of the injector was evidently quite successful, since otherwise the salt concentration would have a considerably greater influence on the coalescence behaviour of the system

The dominating influence of a gas dispersing device on the coalescence behaviour of the system is best illustrated by comparing the results presented in Fig 3 with the sorption characteristics of a mixing vessel with a hollow stirrer[5] For this purpose the enhancement factor $m = (k_L a)_{\text{solution}}/(k_L a)_{\text{water}}$ is plotted for both devices

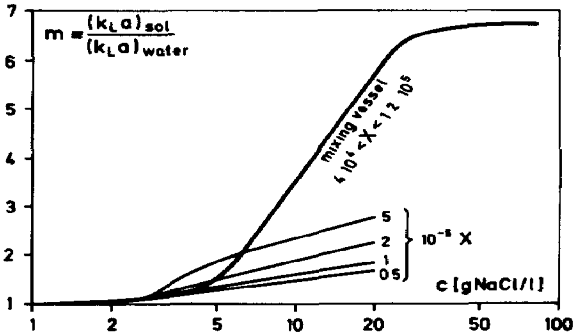

Fig 4 Enhancement factor m as a function of the degree of coalescence, the dispersing action and the type of the gas distributor

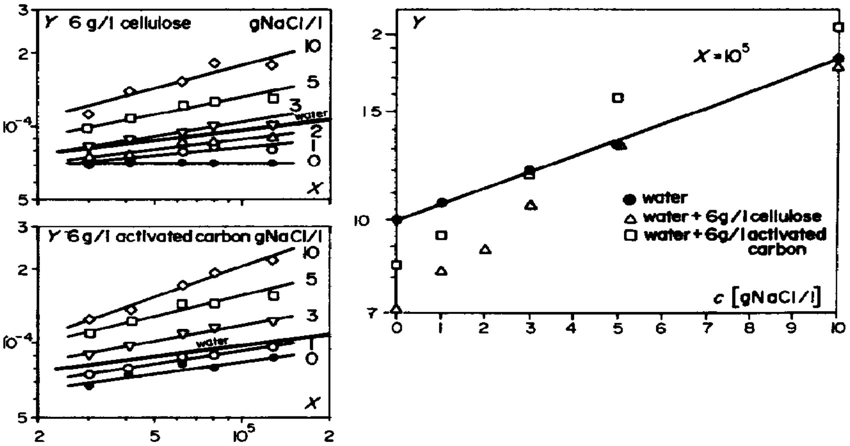

Fig 5 Dependency of the sorption characteristics $Y(X)$ on the presence of different solids and salt concentrations $D = 0.6$ m, $H = 2.5$ m

as a function of the salt concentration in Fig 4. With the mixing vessel there is a single dependence $m(c)$ over the range $4 \times 10^4 < X < 1.2 \times 10^5$ and $P/V = 100$–600 W/m^3, with the injector, however, m also depends on X. This is comprehensible in view of the fact that the injector produces each gas bubble once only. A gas bubble, once formed, is left to itself and—as a result of the coalescence—can only become larger. In the mixing vessel, however, dispersion and coalescence of the gas bubbles take place simultaneously, the mean size of the bubbles therefore reflects the position of the steady-state between these two processes. The fact that the injector may be more effective than the stirrer in the range of salt concentrations which offers little resistance to coalescence ($c < 5$ g NaCl/l) can be explained with reference to the hydrodynamics of the bubble cloud in the column, at the gas loads likely to be encountered here, the bubbles rise essentially parallel to one another. The tendency to coalesce is therefore small when compared with that in mixing vessels.

From what has been said above, it is clear that the coalescence behaviour of a system cannot be described by means of a material-parameter alone. On the contrary, the enhancement factor m depends on the interaction of material and process-related parameters and on the type of the gas dispersing device. Hence there is no physical justification for the so-called "α-value", which is still widely used in waste-water treatment and is regarded as a material parameter.

Coalescence behaviour of a system containing suspended solids

Most absorption processes of technical interest are applied to gas–liquid–solid systems, the solid phase being a bacterial culture, a catalyst, one of the reactants etc. As the injectors are of particular interest in the biological waste-water treatment, it was necessary to determine the extent to which a solid, acting as a "crystallization nucleus", promotes coalescence.

In these lab-scale experiments, the slot injector of Type A was positioned vertically upwards in the bubble column of diameter 0.6 m and of liquid height 2.5 m. Cellulose and activated carbon at concentrations of 6 g/l were used. The cellulose was fibrous with a mean fibre length of 1 mm, its mean settling velocity was 2 cm/min. The activated carbon had a mean particle size of 0.1 mm. Despite these differences the two solids behaved similarly with regard to the coalescence behaviour of the system. As may be seen from the two diagrams in the left-hand side of Fig 5, the presence of the solids lowers the $Y(X)$ values to about 30% below those for pure water. This undesirable effect can be compensated by adding salt at 2–3 g NaCl/l the absorption rates are the same as those measured in pure water.

On the right-hand side of Fig 5, Y is shown as a function of c. This diagram shows that at $c > 5$ g NaCl/l there is practically no difference between systems with and without solids. Of course, this statement applies only to the two solids under consideration and should not be generalized until measurements have been performed with other systems. Experiments using sludge from the biological waste-water treatment plant have given a bubble coalescence that is actually audible and Y values

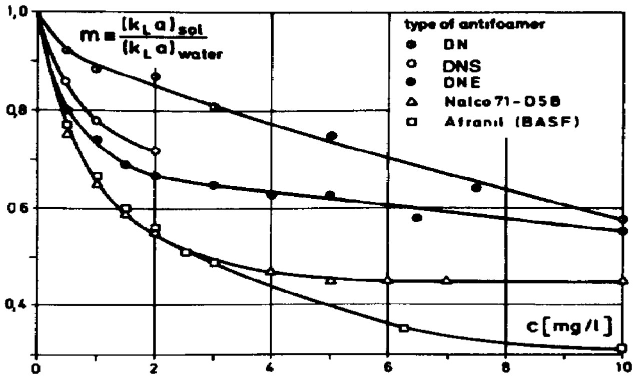

Fig 6 Enhancement factor m as a function of the concentration of different antifoamers $D = 0.6$ m, $H = 1.8$ m, Bayer injector 8/14, $X = 4.5 \times 10^4$

only about half as high as that of pure water It seems likely that this behaviour is less attributable to the presence of the flocs than to their particular nature Apparently the sludge, even after being watered several times, retained such large amounts of organic matter in the absorbed state that it was responsible for the vigorous coalescence of the bubbles

It may be seen from Fig 6 that certain antifoamers, added in minute concentrations of 3 mg/l, are sufficient to reduce the enhancement factor m to 0 5[1]

Coalescence behaviour and scale-up

Larger injectors are known to be considerably less efficient than smaller ones[7, 8] This is due to the outer regions of the liquid jet making a larger contribution to the gas dispersion than the core of the jet When the diameter of the nozzle is increased, the cross-sectional area of the jet increases with the square of the diameter, whereas the circumference of the jet increases linearly only It follows that, as the diameter of the liquid jet increases, a correspondingly decreasing part of the liquid jet throughput utilizes its kinetic energy to disperse the gas This effect is undoubtedly present and can be comprehended quantitatively by measuring the mass transfer rate in a non-coalescent system (e g as in the oxidation of sodium sulphite) In a coalescent system the efficiency of a larger injector is further reduced, because the coalescence is enhanced by the increased gas load of the bubble cloud

These effects can be seen clearly in Fig 7 where the sorption characteristics of the injectors Type A and Type A2 (geometrically similar to Type A but doubled in size) are compared We see that when the injectors are positioned vertically upwards (black symbols in both diagrams), the injector which is twice the size produces 50% lower $Y(X)$-values This deterioration in effectiveness is undoubtedly partly due to the increased gas load in the resulting bubble cloud This being true the performance of the larger injector can be improved by positioning it in such a way as to favour the spreading out of the free jet in order to lower the gas load in the bubble cloud

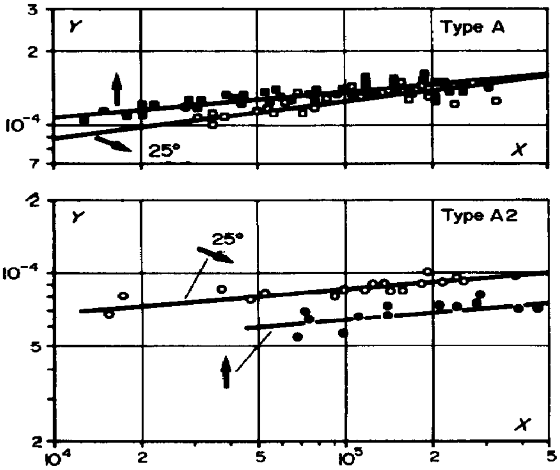

Fig 7 Sorption characteristics $Y(X)$ for the slot injectors Type A and A2 as functions of the jet direction $D = 1\ 6$ and $2\ 8$ m resp , $H = 7$ and 8 m respectively, system water/air

As can be seen from Fig 7, the direction of the jet has an insignificant effect with the smaller injector, due to the low gas load in the bubble cloud formed here However, the direction of the jet results in an unexpectedly high improvement of the $Y(X)$-characteristic for the large injector when the injector A2 is directed downwards at 25° from the horizontal, there is a 30% enhancement of the $Y(X)$-values when compared to the vertical direction

When the spreading out of the free jet results in such a large suppression of the coalescence in the bubble cloud, further means should be applied to favour it One such way is to increase the divergence of the walls of the mixing chamber This was done by reducing the dimensions of Type A2 in the vertical direction only, thus producing the injector Type B

In Fig 8 the sorption characteristics for Type B are presented for different directions of the injector We see that the angle of 35° towards the base results in such a large lowering of the gas load in the bubble cloud that the bubble coalescence is strongly suppressed and the energy of the jet utilized for the bubble production is highly preserved This can be seen from the slope of the $Y(X)$-line which is 0 33 compared with that of Type A2 working under similar conditions where the slope is only 0 1, see Fig 7

In Fig 9 the sorption characteristics for Type B, positioned at the favourable angle of 35°, are presented for different salt concentrations which, as shown previously, has a remarkable effect on the suppression of the bubble coalescence Due to the low gas load in the bubble cloud in Type B, a concentration of only 3 g NaCl/l has already a considerable coalescence suppress-

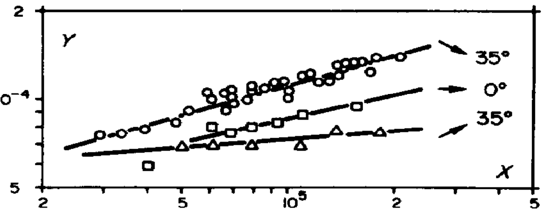

Fig 8 Sorption characteristics $Y(X)$ for the slot injector Type B as a function of the jet direction $D = 2\ 8$ m, $H = 7$ m, system water/air

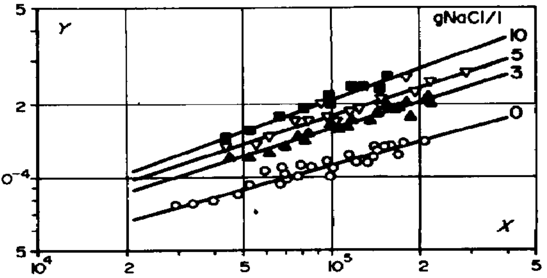

Fig 9 Sorption characteristics $Y(X)$ for the slot injector Type B as a function of the degree of coalescence $D = 2\ 8$ m, $H = 7$ m, jet direction 35°↘

ing effect which cannot be greatly improved by further increase in salt concentration (In Type A for a marked coalescence suppression 5 g NaCl/l was needed)

The analytical expressions for the sorption characteristics in Fig 9 read as follows

g NaCl/l	
0	$Y = 2\ 4 \times 10^{-6} X^{1/3}$
3	$2\ 2 \times 10^{-6} X^{0\ 37}$
5	$2\ 0 \times 10^{-6} X^{0\ 39}$
10	$1\ 5 \times 10^{-6} X^{0\ 43}$

CONCLUSIONS

The experimental results obtained with slot injectors as gas distributors in gas–liquid contacting show the strong influence of the bubble coalescence conditions on the effectiveness of the gas dispersing device The coalescence conditions of the system as a whole result from the interaction between the coalescence behaviour of the liquid and the hydrodynamic behaviour in the free jet and the bubble cloud as produced by the type of injector and the flow pattern of the surrounding liquid Due to the antagonism between the dispersing action of the injector and the bubble coalescence in the gas–liquid dispersion produced, lab-scale measurements do not allow a reliable scale-up of the injectors for coalescent conditions In this case measurements on the industrial scale are indispensable This paper shows how comprehensive studies are necessary to achieve an effective injector for coalescent conditions (e g biological wastewater treatment)

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NOTATION

A	cross-sectional area of the bubble column, m^2
c	dissolved oxygen concentration, g/m^3
c_s	oxygen saturation concentration, g/m^3
c', c''	oxygen saturation concentration as defined by eqns (3) and (4)
Δc_m	log mean concentration difference as defined by eqn (2)
D	diffusivity of the gas in the liquid, m^2/s
G	oxygen flow rate through the interface, kg O$_2$/s
H	liquid height over the injector, m
k_La	mass transfer coefficient as defined by eqn (1)
P_L	power of liquid jet, W
Δp_L	pressure drop of the jet in the nozzle, N/m^2
q, q_L	gas and liquid throughputs respectively, m^3/s
q_1, q_2	gas throughputs as defined by eqns (12) and (13)
S_i	material parameters describing coalescence behaviour
x', x''	mole fractions of oxygen in the gas, see eqns (4) and (5)
X	gas dispersion number as defined by eqn (15)
Y	sorption number as defined by eqn (14)

Greek symbols

ρ	liquid density, kg/m^3
ν	liquid kinematic viscosity, m^2/s
σ	liquid surface tension, N/m

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