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Measurements of local interfacial area: application of bi-optical fibre technique

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Abstract

Local mean interfacial area in gas–liquid bubbly flow is experimentally investigated; data is obtained from the experiments carried out with a double optical sensor intrusive probe and analysed by statistical methods. Local variables are measured in the riser of an external loop airlift reactor in air/water medium. The results are presented in the form of the radial profiles of void fraction, bubble diameter and local average interfacial area at superficial gas velocities ranging from 0.003 to 0.11 m/s. The axial variations of the same parameters are also investigated. The values of local interfacial area obtained from the classical equation ($\bar{a}_i^t = 6\varepsilon_g/d_{32}$) and from bubble velocity statistical treatment methods agree reasonably well. This shows that the double optical probe is a reliable method for local measurements of interfacial area. Eventually, the maximum angle α_0 between the probe vertical direction and bubble velocity vector at the piercing point is evaluated and the influence of gas superficial velocity on α_0 is demonstrated.

Keywords: Bubbly flow; Local mean interfacial area; Bubble diameter; Void fraction; Optical probe; Airlift

1. Introduction

Gas–liquid mass transfer in multiphase reactors is generally characterised by an overall volumetric transfer coefficient $k_L a$. The specific interfacial area a (m^{-1}) varies significantly when hydrodynamic conditions change. Currently, refined local two fluid models are increasingly in use in computational fluid dynamics (CFD) and interfacial terms are the weakest links in the constitutive equations. Thus, experimental data on the local distribution of interfacial area in the entire reactor would be of great interest for two fluid models validation and for locating zones of weak mass transfer in real reactors. In the same perspective, other local parameters such as bubble size, bubble velocity, and local gas hold-up are investigated.

Several methods exist for interfacial area measurements in gas–liquid mixtures. These are photographic, light attenuation, ultrasonic attenuation, double-optical probes and chemical absorption methods. Detailed reviews of these methods are given elsewhere (Veteau &

Morel, 1981). These methods are effective under certain conditions only. To measure local interfacial areas at high void fractions (more than 20% as in our case), intrusive probes are indispensable.

This work presents an experimental study of the local mean volumetric interfacial area \bar{a}_i^t (m^{-1}) in the riser column of an external loop airlift reactor. The measurements are carried out with a double optical probe. The spatial variations of \bar{a}_i^t are analysed and the influence of superficial gas velocity is investigated. Different methods to calculate \bar{a}_i^t from the literature are tested and discussed and a simplified way is suggested.

2. Double optical probe method

2.1. Measuring technique

In bubbly flows, electrical and double optical probes are widely used to measure the local void fraction, bubble size and frequency, bubble velocity, interfacial area density and its spatial distributions (Chen, Zheng, Feng, & Hofman, 1998; Utiger, Stüber, Duquenne, Delmas, & Guy, 1999; Kang, Cho, Woo, Kim, & Kim, 2000). With double optical probes, an infrared light beam is emitted

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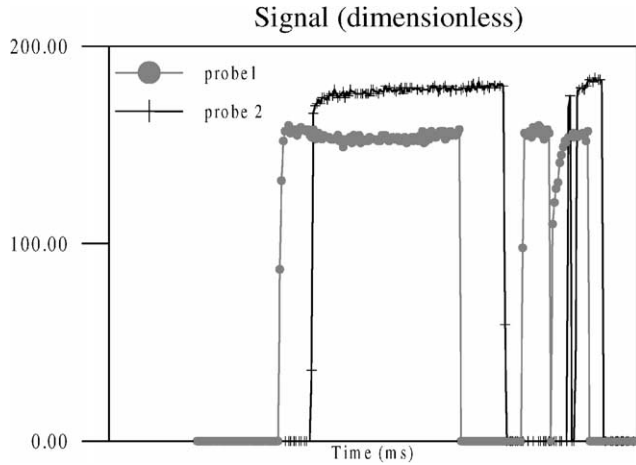


Fig. 1. Output signals delivered by double tip optic probe (sampling frequency 6 kHz).

from a phototransistor into the optical fibres. The probe, when inserted in a bubbly flow, pierces the dispersed gas bubbles and senses the phase change around its tip because of the differences in optical refraction indexes of fluids. Emitted light hitting the tip surface is either refracted into the medium when surrounded by liquid or reflected back via the fibre to the electronic device when in contact with gas. The reflected light beam is converted into voltage and the voltage signal fluctuates between V_{\max} (gas) and V_{\min} (liquid). Fig. 1 is an example of the output signal. The measuring frequency has to be sufficient to describe properly the bubble passages on the probe tips (Cartellier & Achard, 1991). Since there are two optical sensors, each sensor is connected to its own measuring circuit and therefore each is used as an independent phase identifier.

The gas part of the signal gives the local gas hold-up (Liu, 1993) and the local bubbling frequency. A statistical analysis based on cross correlation of both signals (Roig, Suzanne, & Masbernat, 1998) identifies bubbles pierced by both probe tips and for these bubbles, the rising velocity is obtained from the time that each bubble takes between the two probe tips. The distance between the two probe tips is 3.2 mm. By multiplying the bubble velocity with its passage time at the first probe tip, the bubble chord can be obtained.

2.2. Measurement of volumetric local mean interfacial area

Two statistical methods of calculating the experimental interfacial area were used and compared with the classical method as described in the following section.

2.2.1. Classical method

At the measuring point, axial component of the bubble velocity and the bubble chord can be obtained for

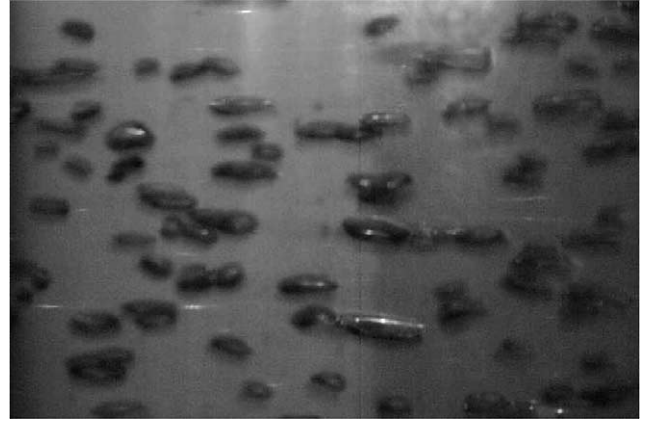


Fig. 2. An example of the photograph of bubbles rising in the riser column ($U_G = 0.03$ m/s).

each identified bubble as explained before, which yields the local bubble rising velocity and bubble chord distributions. Assuming a log-normal diameter distribution and a spherical or an ellipsoidal shape for the bubbles (Kamp, Colin, & Fabre, 1995), the bubble size probability density function is derived from bubble chord distribution by statistical analysis (Liu & Clark, 1995; Liu, Clark, & Karamavruc, 1998). Hence, each local optical probe measurement leads to either a spherical or an ellipsoidal shaped bubble Sauter's mean diameter \bar{d}_{32} . In this work, bubbles are assumed to have an ellipsoidal shape and this has been confirmed with photographs of the gas-liquid dispersion (see Fig. 2 for instance). Bubbles can be reasonably considered as ellipsoids of approximate size of 2–9 mm.

The time averaged local interfacial area density \bar{a}_i^t may then be evaluated: the exact (classical) equation for interfacial area is

$$\bar{a}_i^t = 6\varepsilon_g/\bar{d}_{32}. \quad (1)$$

Values of local gas hold-up are considered to be exact if the sampling period is sufficiently small (see Fig. 1). The authors consider values of \bar{a}_i^t determined from Eq. (1) as the reference.

2.2.2. Statistical method based on bubble velocity

In a two phase bubbly flow, several forces due to liquid velocity fluctuations resulting from liquid turbulence and fluid-bubble interactions impose on bubbles a spatial trajectory motion also known as *zigzag* motion. Therefore, when a bubble rises through the column (riser) it intersects the probe (which is vertical) under an angle sometimes called *entrance angle*. Furthermore, the probe does not always intersect a bubble at its centre. Based on the above considerations, detailed studies of local mean interfacial area evaluation have been carried out (Delhaye, 1976; Kataoka, Ishii, & Serizawa, 1986). The

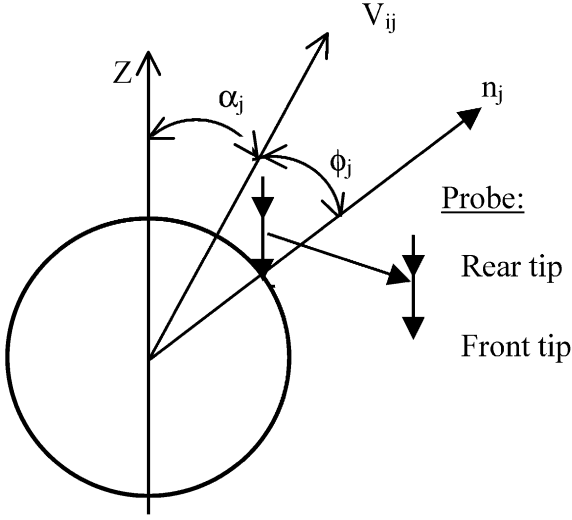


Fig. 3. Bubble passage through the probe.

time averaged local interfacial area is given by

$$\bar{a}_i^t = \frac{1}{\tau} \left(\frac{1}{|V_{ij}| \cos \phi_j} \right), \quad (2)$$

where ϕ_j is the angle between the velocity of the j th interface, V_{ij} , and the direction of the normal surface vector n_j (Fig. 3). Index j stands for any interface passing during the averaging period. τ is the averaging time interval between interfaces. If the number of bubbles that pass through a measuring point per unit time is denoted by N_t , then τ can be given by $\tau = 1/(2N_t)$. The factor of 2 indicates that a bubble has two interfaces (the front and rear part) associated to it.

V_{ij} and the normal unit vector of the j th interface are expressed by normal unit vectors and by angles linked to the x -, y - and z -axis. By considering that there is no statistical correlation between V_{ij} and ϕ_j , the angle ϕ_j can be evaluated through statistical integration of the density probability functions of these angles. This procedure assumes that the interfaces are composed of spherical bubbles and that the probe passes every part of the bubble with an equal probability. The assumption of spherical shape of bubbles is disputable and its implication on results will be discussed later. Considering that the main flow is in the Z direction, \bar{a}_i^t can be related to the velocity axial component $V_{ij,z}$ and to an angle α_j described by interfacial bubble velocity direction and z -axis, where α_j is considered to be random and described with an equal probability within a maximum angle α_0 ($0 < \alpha_k < \alpha_0$). Revankar and Ishii (1992) gave an equation for local mean interfacial area as

$$\bar{a}_i^t = \frac{4N_t \left[\sum_j \frac{1}{|V_{ij,z}|} / \sum_j \right]}{1 - \cot(\alpha_0/2) \ln(\cos \alpha_0/2) - \tan(\alpha_0/2) \ln[\sin(\alpha_0/2)]}, \quad (3)$$

where α_0 , as explained above, is the maximum angle that a bubble interface makes with the probe surface. By knowing the value of α_0 , the time averaged local interfacial area concentration can be calculated from the measured value of N_t and from values of $V_{ij,z}$.

Considering the turbulent motion of bubbles, Kataoka et al. (1986) evaluated the maximum angle α_0 from statistical parameters of the interfacial velocity values as

$$\frac{\sin(2\alpha_0)}{2\alpha_0} = \frac{1 - [\sigma_z^2 / |\overline{V_{ij,z}}|^2]}{1 + 3[\sigma_z^2 / |\overline{V_{ij,z}}|^2]}. \quad (4)$$

In this relation, the bubble velocity RMS fluctuations are considered to be equal in all directions. This assumption is questionable, as turbulence isotropy in airlift columns is not verified.

Based on similar considerations, Dias, França, and Rosa (2000) approximated the same maximum angle α_0 by

$$\alpha_0 \cong \sqrt{\frac{4(\sigma_{iz} / \overline{V_{ij,z}})^2}{1 + 3(\sigma_{V_{iz}} / \overline{V_{ij,z}})^2}}. \quad (5)$$

In this work, the maximum solid angle α_0 is evaluated at each measuring point by the two methods (Eqs. (4) and (5)) and \bar{a}_i^t is evaluated by relation (3). Reference values of \bar{a}_i^t are computed by Eq. (1).

3. Experimental set-up

The experiments are carried out in a 15 l external loop airlift reactor in an air/water medium. The riser is 0.094 m in diameter and 1.2 m in height; the disengagement section is 0.6 m wide (Fig. 4). The superficial gas velocity was varied between 0.003 and 0.09 m/s. The gas is fed through a series of parallel-perforated stainless tubes with pore diameter of 0.6 mm.

The double optical probe used in this work (RTI Instrumentation and Measure) has a distance of 3.2 mm between the two fibre tips and a sensor tip diameter of 40 μ m. Sampling frequencies of 2–6 kHz were used; these frequencies proved to be adequate to describe precisely bubble passages on the fibre tip (Fig. 1) and the resulting statistical data were validated through repeatability tests. The measurements were obtained for signal length of 70–700 s and observations of 300–3000 bubbles depending on gas superficial velocity and location of probe in the reactor. Data acquisition was conducted with a PC with the help of an analog/digital converter (RTI 820, Analog Device).

The numerical routine used to calculate bubble parameters was able to classify the bubbles either into spherical or ellipsoidal shapes based on bubble eccentricity. As mentioned above, ellipsoidal shape has been considered and satisfactorily investigated in this work. The routine

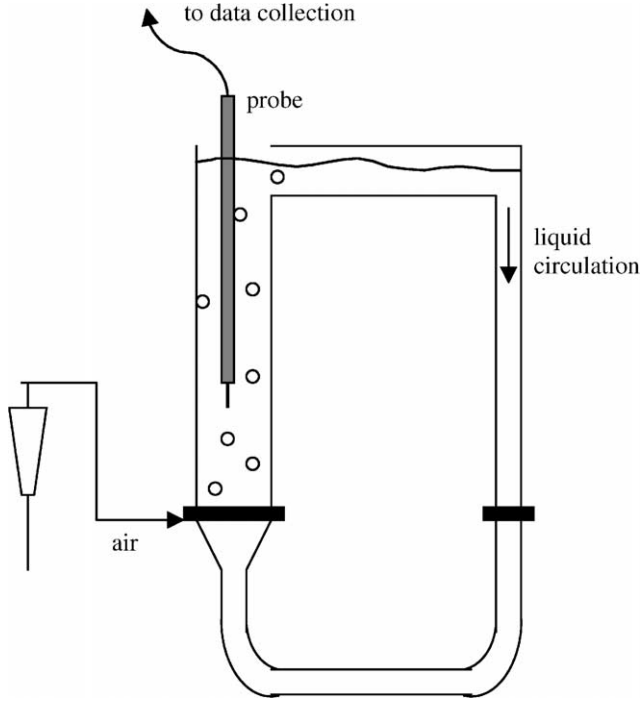


Fig. 4. Experimental set-up.

follows Liu and Clark's (1995) chord length to bubble diameter transformation.

4. Results and discussion

4.1. Previous work

The double optical probe technique has been previously applied to the airlift apparatus (Utiger, 1998; Utiger et al., 1999) together with the hot film anemometry technique. A detailed investigation of local hydrodynamic parameters such as gas hold-up (up to 20%), bubble size distribution and bubble velocities were performed. It was shown that for both phases, local hydrodynamic parameter profiles were fully established at a 0.5 m position above the gas sparger and that the radial distribution of liquid velocity turbulence was homogeneous beyond this axial position.

4.2. Experimental study of local mean interfacial area

4.2.1. Variations of \bar{a}_i^t in the airlift apparatus

Radial profiles of local mean interfacial area \bar{a}_i^t are shown in Fig. 5 at axial position $z = 0.75$ m and at three gas superficial velocities corresponding to homogeneous, transition and heterogeneous bubbling regime. Fig. 6 shows radial profiles of \bar{a}_i^t for three axial positions at $U_G = 0.069$ m/s. The values of \bar{a}_i^t are obtained from the classical equation $6\epsilon_G/\bar{d}_{32}$.

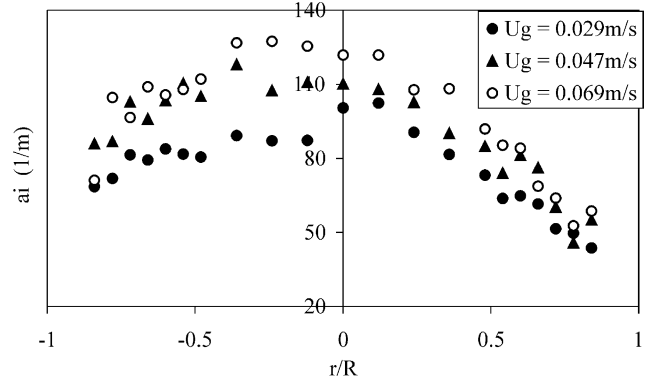


Fig. 5. Radial profiles of mean interfacial area for various superficial gas velocities at $z = 0.75$ m.

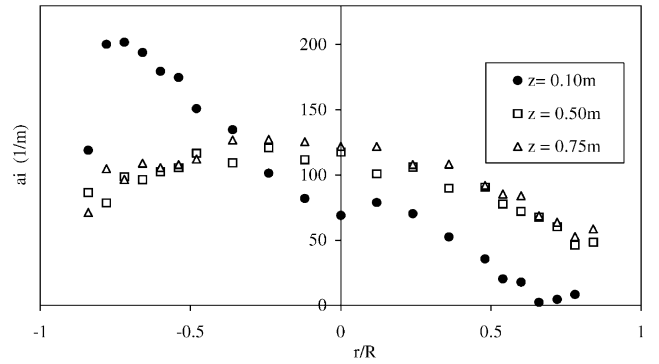


Fig. 6. Radial profiles of mean interfacial area for various axial positions.

It can be seen that \bar{a}_i^t is disturbed by flow loop circulation near the gas distributor and that it reaches a smooth bell shape above $z = 0.50$ m (Fig. 6). \bar{a}_i^t increases with superficial gas velocity U_G , see Fig. 5. In the same apparatus, Utiger et al. (1999) showed that the local gas hold-up ϵ_G increases with gas superficial velocity in the range of 6–18%. Under high gas flow rate, ϵ_G is also strongly inhomogeneous near the distributor, as is shown in Fig. 7 at $z = 0.1$ m. The same authors proved that the profiles of local bubble Sauter mean diameter d_{32} do not vary much beyond 0.5 m above the gas sparger. Hence, the similar shape is observed between radial profiles of \bar{a}_i^t and ϵ_G (Figs. 6 and 7).

The effect of superficial gas velocity on local mean interfacial area was further investigated as shown in Fig. 8. From the series of measurements of \bar{a}_i^t , performed at $z = 0.75$ m and $r = 0$, it is obvious that variations of \bar{a}_i^t are large for low gas superficial velocities. These variations show a change of slope at $U_G > 0.03$ m/s. It is interesting to note that this change in slope corresponds to transition regime in bubbling regime development (Kiambi, 1999).

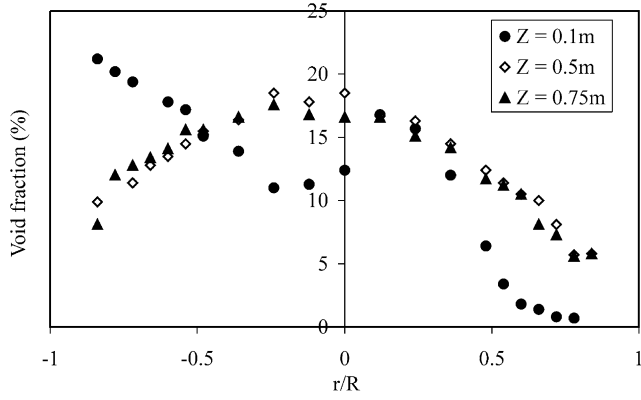


Fig. 7. Radial profiles of void fraction for various axial positions ($U_G = 0.067$ m/s).

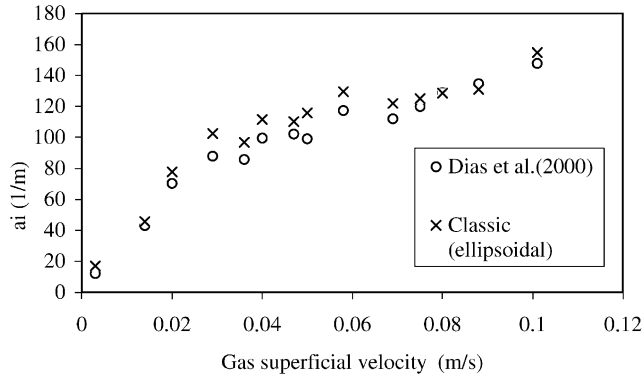


Fig. 8. Evolution of mean interfacial area with gas superficial velocity ($r = 0$, $z = 0.75$ m); data are evaluated according to relations (1) and (3).

4.2.2. Statistical methods for evaluation of \bar{a}_i^t : comparison

Values of \bar{a}_i^t have been calculated from Eq. (1) based on ellipsoidal shape assumption, and also from relation (3), where the maximum angle α_0 has been evaluated by the methods of Revankar and Ishii (1992) and Dias et al. (2000) on the basis of Eqs. (4) and (5). The corresponding radial profiles of \bar{a}_i^t are plotted for $z = 0.75$ m and at $U_G = 0.069$ m/s, see Fig. 9.

Maximum variations are observed at high gas superficial velocity (about 22%, see Fig. 9). Values from both methods are found to be always smaller than the reference values. This can be explained by the fact that the bubble frequency N_t is underestimated: some bubbles pierced by front tip are deviated before reaching rear tip. These discrepancies may also be due to inadequacies of models (4) and (5) specifically on the assumption of spherical bubble shape in their derivations. Another source of error could be the experimental data treatment inaccuracies in evaluations of d_{32} and of bubble velocity distributions. Method of Dias et al., gives values closer to reference

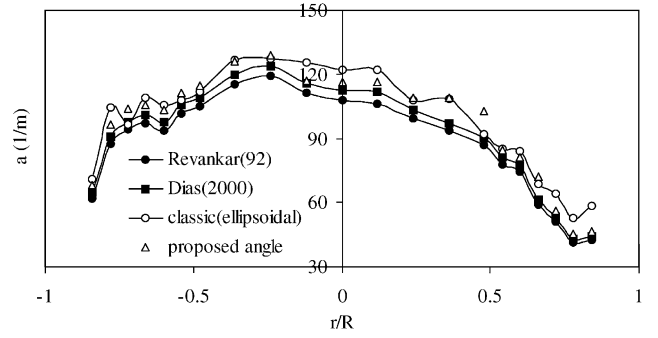


Fig. 9. Comparison of various methods for local mean interfacial area evaluation ($U_G = 0.069$ m/s, and $z = 0.75$ m).

Table 1
Results at $U_G = 0.003$ m/s

	Revankar	Dias	Classic
a_i (1/m)	11.16	12.05	17.19
α_0 (°)	26.94	21.51	1.0

values (Eq. (1)) than Revankar and Ishii method, but the difference is rather small (3–6%).

4.2.3. Analysis of maximum angle α_0

For further comparison, we performed a measurement at very low gas superficial velocity of 0.003 m/s; this test enabled us to impose the ellipsoidal shape to all bubbles and to check the order of magnitude of evaluated bubble Sauter's mean diameter (Table 1). The bubble velocity fluctuations, observed at this very low gas superficial velocity, are probably due to typical helicoidal motion of bubbles in the riser, and not due to plain liquid turbulence, and so the maximum angle of the bubble should be small (estimated to be 1°); the value of α_0 is clearly overestimated by Eqs. (4) and (5) (Table 1). For higher gas flow rates, where the three estimations of \bar{a}_i^t are in good agreement, radial profiles of α_0 are plotted at $U_G = 0.069$ m/s and $z = 0.75$ m (Fig. 10). These angles are evaluated from Eqs. (4) and (5) as described above. The profiles are almost flat; this is in good agreement with the RMS liquid velocity fluctuation profiles (Utiger et al., 1999); turbulence level is quite homogeneous along the riser diameter. The maximum angle between bubble motion and probe axis depends probably on gas superficial velocity and axial position at high gas superficial velocities. A single value α , as shown in Fig. 10 ($\alpha = 20^\circ$ for $U_G = 0.069$ m/s) is then proposed. This value is induced from Eq. (5) with reference to Eq. (1). α depends on U_G and axial position as mentioned above and since α is stable for $z > 0.50$ m the evolution of the proposed (identified angle) α was investigated as a function of U_G only.

This identified angle α is plotted with U_G (Fig. 11). As expected, the evolution of the curve changes around

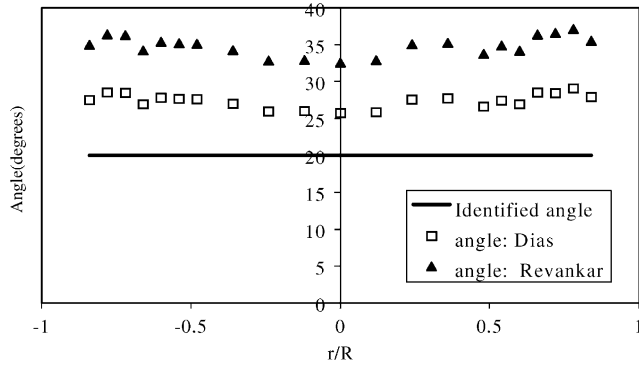


Fig. 10. Radial profiles of probable limiting angle between bubble velocity vector and probe direction.

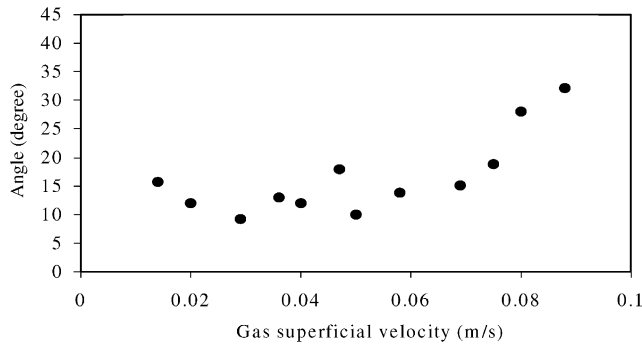


Fig. 11. Evolution of probable limiting angle with gas superficial velocity.

$U_G = 0.03$ m/s for transition regime and again at 0.05 m/s for heterogeneous bubbling regime; the identified angle α increases drastically with gas superficial velocity, indicating that the turbulence conditions intensify in the column.

5. Conclusions and perspectives

In this work, the experimental investigation of time averaged local interfacial area has been performed in the riser column of an external loop airlift reactor operated in an air–water medium. The classic equation $\bar{a}_i^t = 6\epsilon_g/\bar{d}_{32}$ has been used. Influence of gas hold-up, Sauter's bubble diameter, and gas superficial velocity on \bar{a}_i^t has been analysed, together with the spatial distribution of these values.

Various statistical methods for evaluation of \bar{a}_i^t have been tested and compared. A direct method is suggested, which involves the maximum angle α_0 described by bubble velocity vector and probe direction, and for which only local bubble frequency and local bubble velocity distribution are needed. In the literature, correlations are found to evaluate α_0 (Revankar & Ishii, 1992; Dias,

França, & Rosa, 2000), these correlations give a rather good estimation of \bar{a}_i^t .

An identified value of α_0 , called α , offers information on bubbling regime and turbulence level in the liquid phase. For further analysis of α , studies are to be performed for other gas–liquid media and in other types of gas–liquid contactors.

Notation

\bar{a}_i^t	time averaged local mean interfacial area, m^{-1}
\bar{d}_{32}	bubble Sauter's mean diameter, m
N_t	bubbling frequency
V_{ij}	velocity of the j th bubble interface, m/s
$V_{ij,z}$	bubble velocity in Z direction

Greek letters

α	identified angle
α_0	limiting (solid) angle
ϵ_g	local gas fraction
σ_{iz}^2	RMS in the Z direction
τ	averaging time interval between interfaces
ϕ_j	angle between the velocity of the j th interface V_{ij} and the direction of the normal surface vector n_j

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