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Determination of local hydrodynamic parameters in bubble columns by the electrodiffusion method with oxygen as depolarizer

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An electrodiffusional three-segment probe was developed with which local axial and radial liquid velocities can be determined. Application of this probe in gas–liquid flow yields information on local gas hold-up. In coalescing media the commonly used redox-system $Fe(CN)_6^{3-}/Fe(CN)_6^{4-}$ should be replaced by dissolved oxygen as depolarizer. Measurements of local axial and radial liquid velocity and turbulence intensity in different bubble columns ($D = 150$ and 600 mm) showed good agreement with data obtained by hotfilm anemometry.

List of symbols

a, b, d, e, h, q	coefficients
c	concentration ($mol\,m^{-3}$)
E	potential, voltage (V)
f, g	coefficients (μA, V)
I	current (μA)
I/I_0	relative current
k, l	coefficients (μA, W)
M	measuring quantity (μA, W)
P	power (W)
R	probe resistance (Ω)
S	measuring signal (μA, V)
S_{228}	measuring signal at $u = 228\,cm\,s^{-1}$ (μA, V)
t	time (s)
u	liquid velocity ($cm\,s^{-1}$)
u'	turbulence intensity ($cm\,s^{-1}$)
$\bar{u}$	mean liquid velocity ($cm\,s^{-1}$)
Φ	flow angle (°)
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number

1. Introduction

The electrodiffusion method (EDM) is often used for the determination of local liquid velocity and wall shear stress [1–3] in single phase systems. The possibility of application in two-phase bubble flow has also been proved earlier [4, 5]. Liquid flow in bubble columns is highly turbulent. A probe applied in these reactors must be able to detect the direction of liquid flow. In cooperation with the Institute of Chemical Process Fundamentals in Prague, a three-segment electrodiffusion probe was developed analogous to the triple split-film sensors of hotfilm anemometry (HFA) [6]. This probe is able to detect the direction and the magnitude of liquid velocity. Measurement of liquid velocity, turbulence intensity and Reynolds shear stress is possible.

Since the redox system potassium ferro-ferricyanide, which has usually been employed with EDM, inhibits coalescence in gas–liquid systems it was decided to use dissolved oxygen for the measurements [4]. To suppress migration in the electric field 0.01 M potassium sulphate was added to the electrolyte. The coalescing behaviour of the medium was not influenced by this low salt concentration. With Pt-probes the maximum detectable liquid velocities are about $100\,cm\,s^{-1}$ [4] with oxygen as depolarizer. In bubble columns with diameters of more than ~300 mm and high gassing rates the maximum liquid velocities are much higher; thus silver was used instead of platinum as electrode material.

2. Experimental details

2.1. *Three segment probe*

Three insulated wires of the electrode material of diameter 500 μm were glued together in a triangular arrangement. Then the top part of the probe was ground to cylindrical shape as shown in Fig. 1(b). The electrodes were silver, which is a good catalyst for oxygen reduction [7, 8]. Figure 2 shows that at liquid velocities up to $228\,cm\,s^{-1}$ a plateau occurs in the polarogram so that the requirement for the electrodiffusion method, a diffusion limited current, is fulfilled. The plateau region becomes smaller with increasing liquid velocity. With platinum as electrode material measurements were possible only up to $100\,cm\,s^{-1}$. A voltage of -1.7 V was chosen for the measurements.

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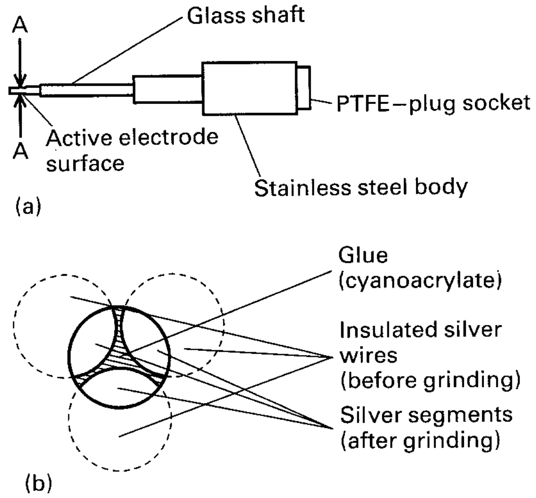

Fig. 1. Three-segment electrodiffusion probe. (a) Setup of the probe, (b) cross section A–A.

2.2. *Two-phase flow*

For application in two-phase flow discrimination between the gas and liquid phases is necessary. This is shown in Fig. 3 where a bubble signal for a single probe segment is given as relative current I/I_0 against time, i.e. as the current, I, related to the current, I_0, before the bubble arrives at the probe. The bubble signals in Fig. 3 were obtained in an airlift reactor with a riser of diameter 90 mm; the probe was placed in the centre of the riser. Since the reactor was aerated at a very low gas rate, interaction of bubbles was avoided and turbulence was low. In Fig. 3 I/I_0 is practically constant up to $t = t_1$, because liquid flow is not disturbed. When a bubble approaches a slight increase of the current is recorded because of the 'front wave' of the bubble. At $t = t_2$ the bubble arrives at the probe producing a rapid decrease of the current down to nearly zero. When the bubble leaves the probe at t_3 the current suddenly rises reaching a maximum at $t = t_4$. During this short interval between t_3 and t_4 the depolarizer concentration in the liquid at and near the probe surface is as high as in the bulk of the liquid with the effect of a high current. But very soon the depolarizer is depleted at the probe surface and the diffusion layer builds up leading to a decrease of the probe current from t_4 up to t_5. From t_5 onwards the probe current is solely determined by diffusion, i.e. depolarizer concentration and flow velocity.

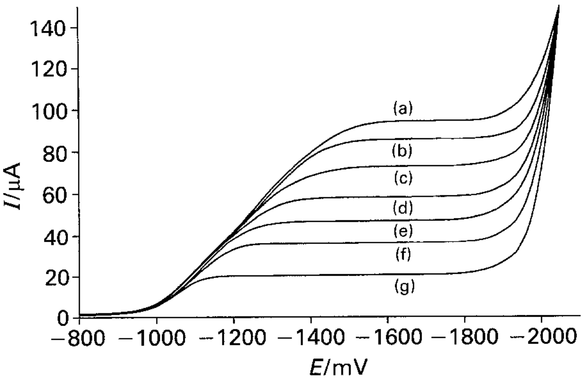

Fig. 2. Polarograms of a three-segment electrodiffusion probe at different liquid velocities, u: (a) 228, (b) 185, (c) 142, (d) 75.5, (e) 45.6, (f) 23, and (g) 4.1 cm s^{-1}.

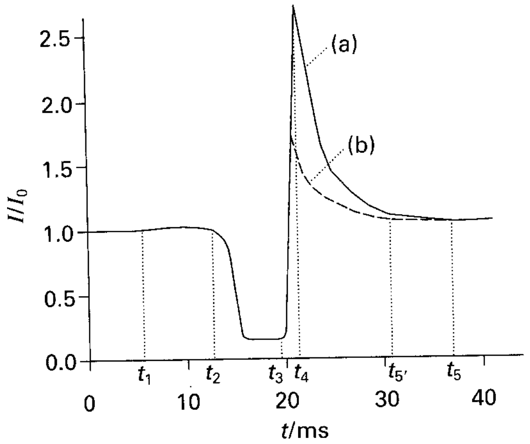

Fig. 3. Bubble signal at two different oxygen concentrations, C_{oxygen}: (a) 0.97, and (b) 0.095 mol m^{-3}.

In Fig. 3 the relative probe current, I/I_0, produced by a rising bubble is shown for two different concentrations of the depolarizer oxygen. At the lower dissolved oxygen concentration, both the current peak at t_4 and the time interval of decreasing current are smaller. This implies that the building up of the diffusion layer is predominant and that information on the wake of the bubble and on its effects on liquid flow cannot be obtained from the current signal between t_4 and t_5. This is a disadvantage of EDM in comparison to hotfilm anemometry.

For the determination of liquid flow parameters (velocity and turbulence) signals which are influenced by bubbles have to be discarded, that is not only from the period when a bubble is in direct contact with the probe ($t_2 < t < t_3$), but the period from t_2 to t_5. The signal filtration has to be done for each segment of the probe. Only if each segment yields a velocity dependent current can the liquid velocity be obtained.

The principle of the determination of the direction of liquid velocity has already been described [4]. Figure 4 shows the relative direction characteristics of the three-segment probe. With these direction characteristics the flow direction is determined by

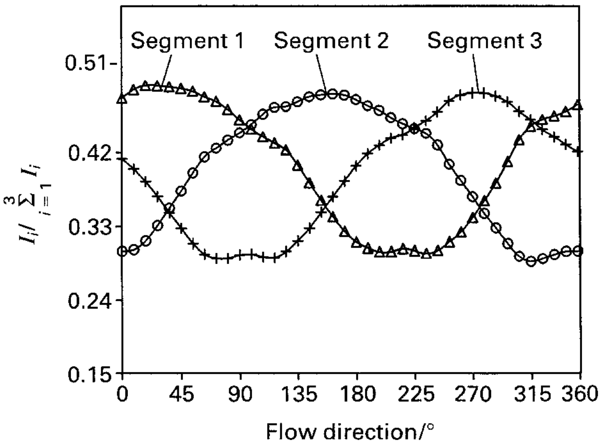

Fig. 4. Directional characteristics of a three-segment probe obtained by stepwise change of flow direction.

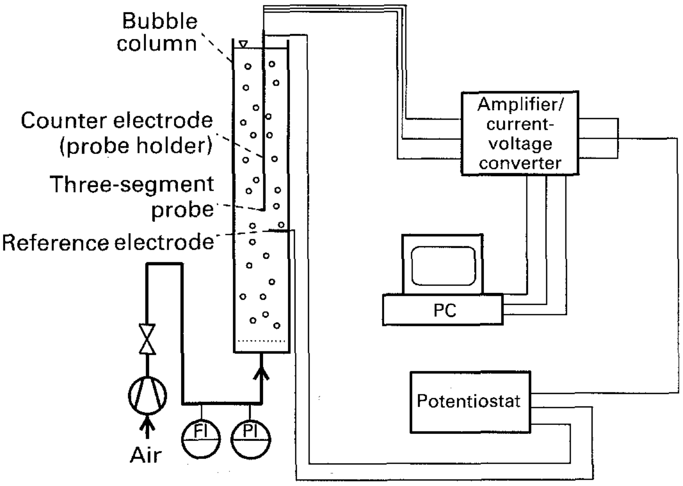

Fig. 5. Experimental setup.

the software. To reduce the time for data treatment a calculation method different to that described in [4] was used for determining the flow angle. Instead of fitting the direction characteristics of the three probe segments by Fourier series, linear interpolation was employed for each angular section of nine degrees of the flow direction, i.e. a total of 40 angular sections were used in the calibration measurements (see Fig. 4).

Because of the nonideality of the probes (e.g. different thickness of insulation films between the segments) total probe current is not independent of flow direction. Deviations in total current of ±5% lead to an error of about 10% in liquid velocity. This deviation of the probe current must be compensated by the treatment software. Experiments were carried out in bubble columns with diameters of 150 and 600 mm. The experimental setup is shown in Fig. 5. A potentiostat was used to ensure the stability of the potential. The data sampling rate was 2.5 kHz for each probe segment. This relatively high frequency must be used in order to ensure correct signal filtration.

3. Results

3.1. *Measurements in bubble columns*

In Fig. 6 the measured mean axial liquid velocity and axial turbulence intensity of the liquid flow are compared with data obtained by hotfilm anemometry in the 600 mm bubble column [9]. The profiles of axial liquid velocity show an asymmetric parabolic shape. There is no significant difference between the results of the two measuring techniques. The agreement in the values for turbulence intensity shows that the frequency response of the probe is sufficient. The electrodiffusion probe is able to follow the change of liquid velocity as fast as the HFA-probe. The limiting factor for maximum detectable frequency of velocity changes should be the dimensions of the EDM probes which are about the same as those of the HFA probes [9]. Likewise comparison of the results obtained by HFA and EDM in the 150 mm bubble column did not show a significant difference between the two measuring methods.

3.2. *Comparison with hotfilm anemometry (HFA)*

To describe the dependence between measuring quantity and liquid velocity the following equation is usually employed for HFA [10]:

$$Nu = aPr^{1/5} + bPr^{1/3}Re^{1/2} \qquad (1)$$

On the basis of the analogy between heat and mass transfer a relation similar to Equation 1 holds for the electrodiffusion method:

$$Sh = dSc^{1/5} + eSc^{1/3}Re^{1/2} \qquad (2)$$

Thus for the dependency of the measuring quantity, M, on liquid velocity, u, a relation of the same type is valid for the two measuring methods:

$$M = k + l(u)^q \qquad (3)$$

where k, l and q can be determined experimentally. u is given in cm s^{-1}. The theoretical value of q is 0.5. In measurements with HFA the heat flow is the measured quantity. The power P needed to

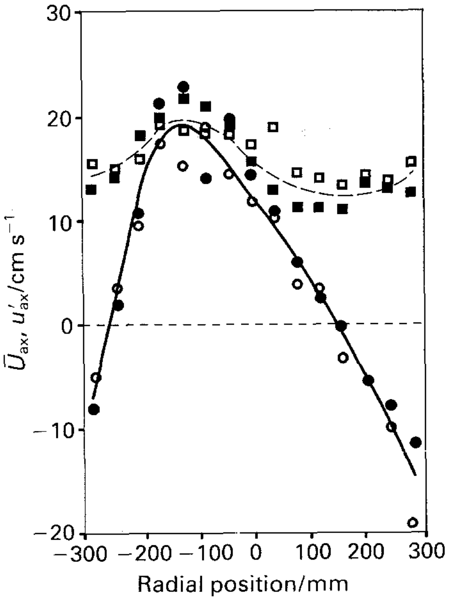

Fig. 6. Radial profiles of mean axial liquid velocity and turbulence intensity at a superficial gas velocity of 2.4 cm s^{-1} in the 600 mm bubble column. Comparison between EDM and HFA. System water/air. Key: (●) $\bar{u}_{ax}$ (EDM), (■) u'_{ax} (EDM), (○) $\bar{u}_{ax}$ (HFA), and (□) u'_{ax} (HFA).

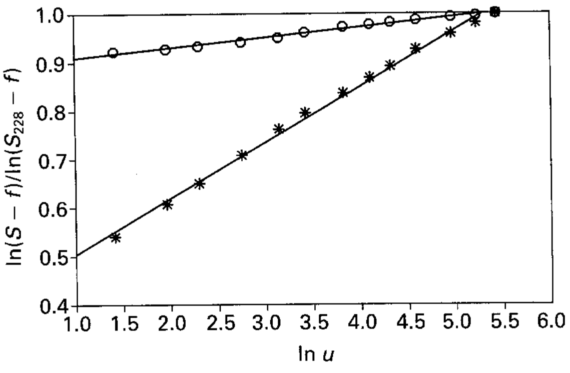

Fig. 7. Dependency of the measuring signal on liquid velocity. Key: (*—*) EDM, (O—O) HFA.

compensate this heat removal is

$$P = EI = E^2/R \tag{4}$$

Therefore the measuring signal S (proportional to E) of the HFA signal is only proportional to $Re^{1/4}$. For EDM the current is directly proportional to the mass transfer rate. This means that for HFA and EDM the following equation is valid (u in cm s^{-1}):

$$S = f + g(u)^h \tag{5}$$

where $h = 0.5$ for EDM and $h = 0.25$ for HFA.

A plot of $\ln(S - f)$ against $\ln u$ yields a straight line with slope h. For a comparison of the signals obtained with the two measuring techniques they were normalized to $u = 228\,\mathrm{cm\,s^{-1}}$. The result is shown in Fig. 7. There is good linearity of $\ln(S - f)$ against the logarithm of liquid velocity for both methods. The experimental value of h obtained with a three-segment electrodiffusion probe was 0.49, which proves that the condition of diffusion limited reaction is fulfilled up to high liquid velocities. Measurements with an HFA dual-splitfilm probe showed a proportionality to $Re^{0.21}$. The difference in dependency of the measuring signal to liquid velocity is demonstrated by the difference of the slopes in Fig. 7. The EDM is more sensitive to changes of liquid velocity than HFA. This is one main advantage of the EDM in comparison to HFA taking into account that drift of the activity and nonideality of the probes (measuring signal $= f(\Phi)$) are problems of both methods.

4. Conclusion

Further development of the electrochemical technique is aimed at the application in three-phase systems with suspended solid particles. In three-phase systems, i.e. aerated liquids containing suspended solids, HFA is difficult to use. The solid particles may damage the thin glass layer on the surface with the consequence that frequent recalibration of probes is required. For the electrodiffusion method the solid particles will reduce one main problem: the limited time of application in electrolytes containing impurities because of the building up of layers at the electrode surface. They consist of hydroxides and sulphides and will reduce the activity of the probes. With abrasive suspended particles these layers will be constantly removed so that it should be possible to use the probes much longer without cleaning.

Application of EDM in media with suspended solid particles may be influenced by mass transfer enhancement dependent on particle diameter and concentration [11]. With very small particles at high concentration this may have significant effects on the probe current.

Acknowledgements

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