JOURNAL OF APPLIED ELECTROCHEMISTRY **21** (1991) 1073–1076

Electrodiffusional direction-specific probe for measuring local velocity of aerated aqueous systems*

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Received 1 February 1991; revised 20 May 1991

A three-segment direction specific probe based on the electrodiffusion measuring technique was used to measure local liquid velocities in gas-liquid flow. Dissolved oxygen was employed as depolarizer instead of the usually applied redox system ferro-ferricyanide in water. The concentration of the auxiliary electrolyte K_2SO_4 was so low that coalescence behaviour of the gas-liquid system was not influenced. It was possible to measure liquid velocities up to ca $100\,\mathrm{cm\,s^{-1}}$. The probe showed satisfying sensitivity to flow direction. Furthermore, unequivocal discrimination between signals from the liquid and gas phases was achieved.

Notation

a_{ij}, b_{ij}	Fourier coefficients
D	diameter (cm)
E	potential (V)
I_i	single segment current (A)
k	number of probe segment
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
t	time (s)
T	temperature (° C)
u, v	liquid velocity ($\mathrm{m\,s^{-1}}$)
θ	flow angle (°)

1. Introduction

The electrodiffusion measuring technique based on polarography is widely used to determine hydrodynamic parameters, for instance local liquid velocities and wall shear stresses [1, 2]. Apart from a few investigations of gas-liquid flow, for example [3–5], only measurements in single phase liquid systems and flow with preferential direction, such as tubular flow, were carried out. In systems where flow from any direction may occur, i.e. in bubble columns, it is necessary to detect the local velocity vector. For these applications a three-segment electrodiffusional probe has been developed [6], which is in close analogy to triple-split film probes used in hot-film anemometry. With these cylindrical probes the projection of the velocity vector into the plane perpendicular to the cylinder axis can be measured.

Furthermore, a clear distinction between signals from liquid and the gas phase is required, since otherwise the liquid velocity cannot be determined correctly. Using the electrodiffusional method bubbles can be identified either by electrical conductivity measurement by means of a superposed high frequency voltage [7] or by analyzing the probe current. The latter method does not require special hardware and was used here.

Since, on the one hand, the usually applied redox system potassium ferro-ferricyanide inhibits coalescence in gas-liquid systems and since on the other hand it is not suited for measurements in microbial cultures, it was necessary to use another depolarizer for flow measurements in fermenters. In 1958 Ranz [8] showed that, in principle, it should be possible to measure liquid velocities by using oxygen as depolarizer. First experiences with local measurements of liquid velocity using a three-segment direction-specific probe in oxygen-water two-phase flow are reported in this paper.

2. Experimental details

Whereas in polarography the depolarizer concentration has to be determined and flow conditions near the working electrode have to be controlled, in electrodiffusion the anemometry liquid velocity and its gradients and fluctuations are determined at known depolarizer concentration. The monitored quantity is

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* This paper was presented at the Workshop on Electrodiffusion Flow Diagnostics, CHISA, Prague, August 1990.

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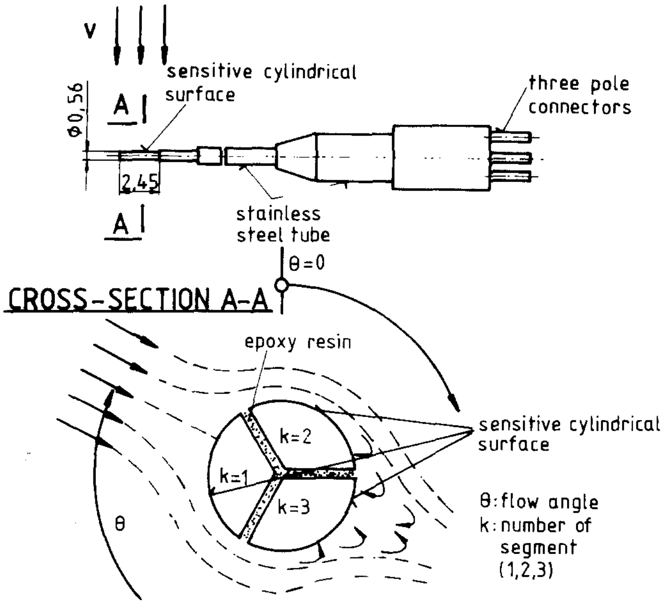

Fig. 1. Three-segment velocity probe.

the limiting diffusion current caused by the diffusion of dissolved oxygen to the surface of the cathode. If the electrode reaction

$$O_2 + 4e^- + 2H_2O \longrightarrow 4OH^-$$

is very fast and migration of the active ions is prevented, mass transfer is controlled by liquid velocity. In order to keep migration low, a solution of 0.01 M potassium sulphate was added to the aqueous solution as auxiliary electrolyte; thus coalescence behavior of the two-phase system did not change.

The measuring probe is shown in Fig. 1. It consists of three platinum segments, isolated by epoxy resin. The sensitive area of the cathodes consists of the outer surface of the segments. The velocity vector perpendicular to the cylindric axis of the probe can be determined.

The probe was calibrated in front of a nozzle in water saturated with oxygen at 1 bar and 20° C. A platinum sheet with an area of approximate 20 cm^2 was applied as counter electrode. Details of the experimental set-up have been described elsewhere [9]. The dependence of the diffusion current on liquid velocity was measured. Furthermore the directional characteristics of the probe, i.e. the relative currents of the single segments, $I_i/\Sigma I$, were determined as a function of flow direction.

The limiting diffusion currents were recorded with an A/D-converter and a personal computer at a measuring frequency of 700 Hz for each segment of the working electrode. During these experiments the measuring time for a single determination was 10 s.

To discover whether the probe is able to discriminate between liquid and gas phase signals, measurements were carried out in a bubble column of 2.57 m height and 0.15 m diameter. Aeration was performed by a perforated plate (hole diameter 0.5 mm) with pure oxygen. Here the measuring frequency was 2.5 kHz for each probe segment with a measuring time of 180 s.

3. Results and discussion

3.1. *Liquid velocity measurement in front of a nozzle*

In Fig. 2 polarographic curves for different liquid velocities are shown. Compared to results obtained in ferro-ferricyanide aqueous solutions [6] it is obvious that total sum of currents

$$\Sigma I = I_1 + I_2 + I_3 \qquad (1)$$

is independent of the applied voltage at low liquid velocity only, which means that only at these conditions does a plateau of limiting diffusion current exist. For liquid velocities smaller than 15 cm s^{-1} this basic requirement is absolutely fulfilled. With increasing flow velocity the slope of the linear region of the polarographic curves also increases. The electrode reaction is not absolutely diffusion controlled but

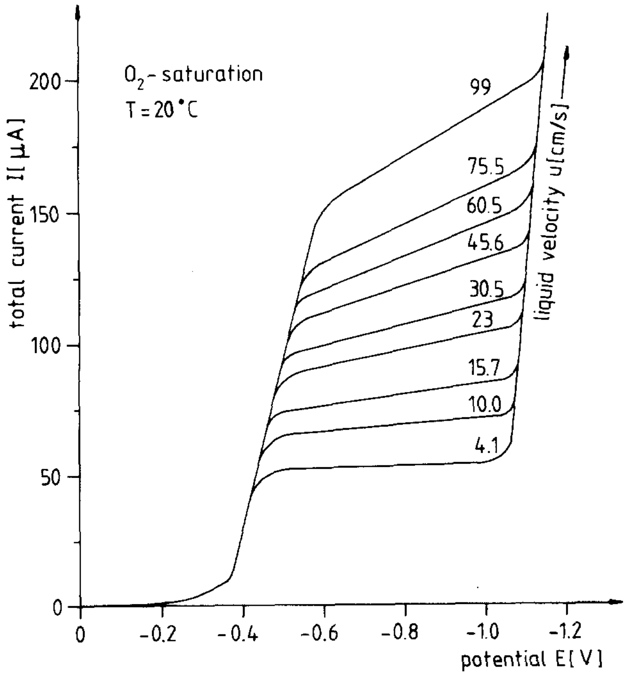

Fig. 2. Current-voltage curves at different liquid velocities.

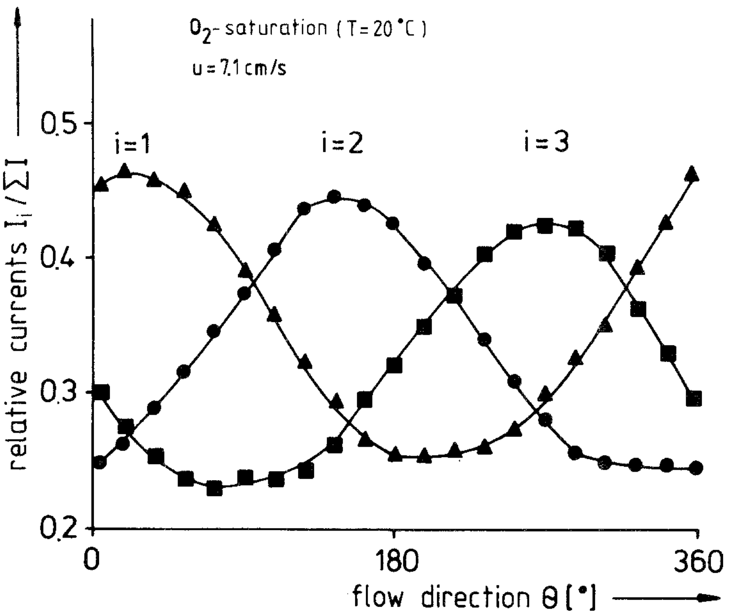

Fig. 3. Directional characteristics.

becomes more and more kinetically obstructed. This means the basic requirement of the electrodiffusion measuring technique is fulfilled. At a velocity of 99 cm s^{-1} the slope $\Delta I/\Delta E$ reaches a value of 95 μA V^{-1}. Here the deviation in current is about ± 16% related to the limiting current in the middle of the plateau at a voltage of -0.8 V. Nevertheless it is possible to correlate the dependence of the total current at a potential of 1.0 V on flow rate by the relation

$$Sh = 1.47 Sc^{0.33} Re^{0.5} \qquad (2)$$

within an error of 10%.

Typically directional characteristics of the individual currents are shown in Fig. 3. The directional characteristics are recorded in the plane perpendicular to the cylinder axis. To reduce the influence of flows not occurring in this plane relative currents are concerned. The currents of the individual electrode segments are strongly affected by the flow direction, whereas the sum of currents is almost independent of this parameter with a maximum deviation of 5%

The directional characteristics can be described by a Fourier series of fourth order

$$I_i/\Sigma I = a_{i0} + \sum_{j=1}^{4} a_{ij} \sin j\theta + \sum_{j=1}^{4} b_{ij} \cos j\theta \qquad (3)$$

The Fourier coefficients are dependent on liquid velocity. Details of the calculation of flow direction have been presented elsewhere [10]. In order to detect the flow angle with an error smaller than 3° the velocity range between 4.1 cm s^{-1} and 99 cm s^{-1} must be divided into seven intervals with different Fourier coefficients.

3.2. *Filtration of gas phase signals*

To determine liquid velocity correctly it is important to discriminate between signals from the gas and liquid phases. The total current of the three-segment probe during contact with a bubble is shown in Fig. 4. Before t_0 the bubble is not in the neighbourhood of the electrode and does not influence the measuring signal. Between t_0 and t_1 liquid velocity rises as the probe is within the sphere of influence of the bubble. At t_1 the probe pierces the bubble. During the interval between t_2 and t_1 the sensor is surrounded by gas. At t_2 the bubble leaves the sensor and a very steep rise in current occurs. In the very short interval between t_3 and t_2 the probe pierces the bubble again. The following decay of the current until t_4 can be explained as a transient process following the stepwise potential application. During this process the limiting diffusion-layer is built up at the probe surface. During the time interval between t_5 and t_4 the signal is influenced by the bubble to a diminishing extent.

4. Discussion and conclusions

The experiments described above have shown that it is possible to employ the electrodiffusion measuring technique without the usually applied redox system potassium ferro-ferricyanide, by using oxygen as depolarizer. However there are some restrictions. As the limiting current region is not completely perfect (Fig. 2), the dependence of current on voltage becomes larger with increasing velocity; increasing deviations occur at higher velocities. If a measuring accuracy of only 30% is sufficient measurements of liquid velocities up to 1 m s^{-1} are possible. To estimate how important these restrictions are, one has to consider which local liquid velocities might occur. For example in industrial bubble columns values up to 3 m s^{-1} are assumed [9]. In such a case electrodiffusional velocity measurements would not be sufficiently sensitive, whereas in smaller columns, for instance with a diameter of 15 cm, only values up to 1 m s^{-1} are detected [11]. For a wide applicability of the electrodiffusion method with oxygen as depolarizer additional investigations are required. On the one hand it is possible to reach higher measureable liquid velocities by using another electrode material. Gold electrodes may be better suited than platinum since, due to hydrogen

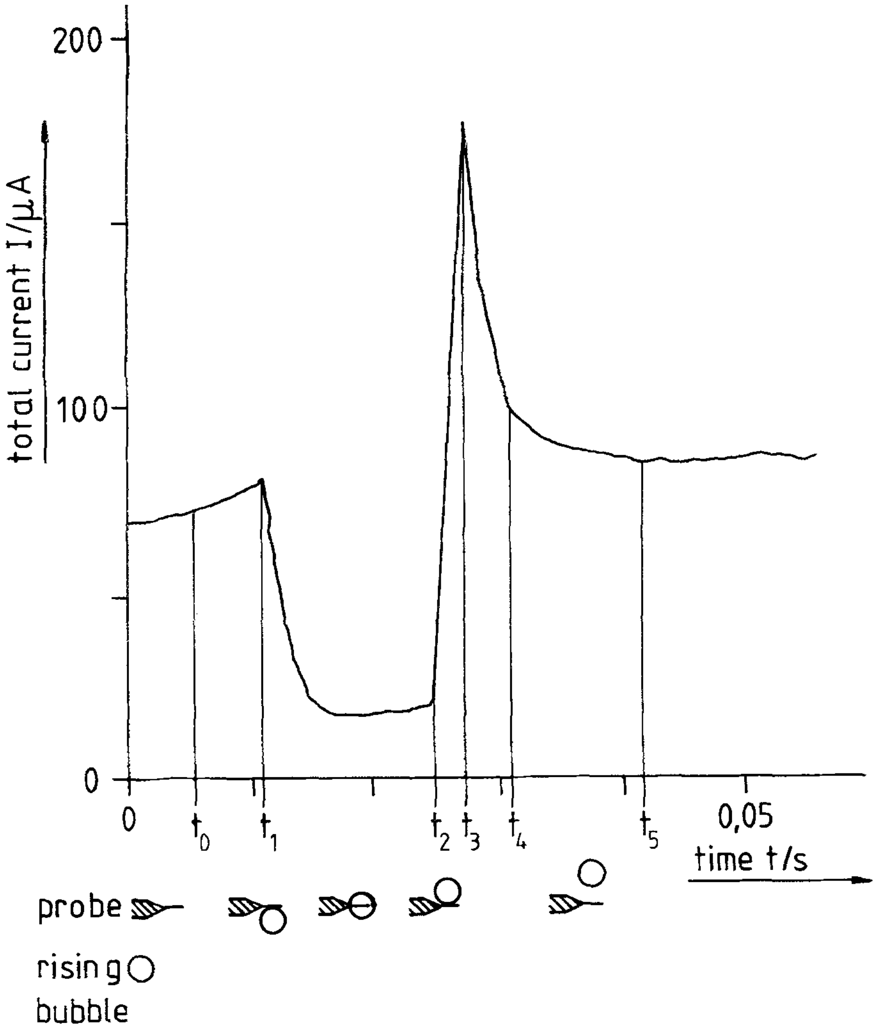

Fig. 4. Bubble signal.

evolution at higher potentials, the limiting current region and, hence, the working range is larger. On the other hand measurements of liquid velocities in gas-liquid two-phase flow must show that the electrodiffusion method is sufficiently fast for measurement of velocity fluctuations and turbulence intensities. Regarding the very good bubble detection (Fig. 4) it appears that the response time of the probe is sufficient.

Acknowledgements

We thank Mr Cand.-Ing. S. Pannek and Mr. Dipl.-Chem. F. Kurrek for experimental work. Moreover, we express our thanks to DECHEMA for an 'Applied biology and biotechnology grant for Mrs Dipl.-Ing. J. Pauli and also we thank the Alexander von Humboldt Foundation for a grant to Dr V. Sobolik. Fond der chemischen Industrie is also gratefully acknowledged for its contribution.

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