FLOW PATTERN IN THE VICINITY OF GAS-LIQUID INTERFACE IN A STIRRED CELL

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Three dimensional turbulent flow was measured in the vicinity of gas-liquid interface using Laser Doppler Anemometer. The measurements were made in a 100 mm i.d. stirred cell with a flat interface. Mean and rms velocities were measured at seven radial and three axial locations. The effect of liquid viscosity on the flow pattern was investigated.

These measurements form a first step in validating the published theories on mass transfer.

Introduction

The value of mass transfer coefficient depends upon the flow field in the vicinity of the interface. However, the present status of the knowledge of flow fields is far from complete. In spite of such incomplete understanding of the flow near the interface, a substantial progress has been made in modeling the process of mass transfer and a number of theories are reported in the published literature. In all these theories, the flow structure in the vicinity of the interface is assumed and, thereupon, the theory is developed. In this manner we have the film theory (Lewis and Whitman, 1924), penetration theory (Higbie, 1935), surface renewal theory (Danckwerts, 1951), film penetration theory (Toor and Marchello, 1958), surface tension damped laminar sublayer model (Levich, 1962; Davies, 1966, 1972), large eddy model (Fortesque and Pearson, 1967) and small eddy model (Scott *et al.*, 1970).

It is likely that one of the models holds under a particular set of conditions and the selection of model depends strongly on the flow structure. Therefore a quantitative understanding of the fluid flow near the interface is desirable. Some interesting data have been given by Luk and Lee (1986). The present paper is an attempt to present some data in the vicinity of the gas-liquid interface. Measurements have been made at the air-water interface as well as in the bulk liquid. The effect of viscosity has also been investigated.

1. Experimental

Measurements were made in an unbaffled 100 mm i.d. stirred cell with a flat gas-liquid interface. The cell was made up of perspex. A paddle stirrer of

Fig. 1 Schematic section of the stirred cell assembly

84 mm diameter and 10 mm width was used. The axle of the paddle was kept vertical by means of a closely fitting perspex disc on a cylindrical support. The lower end of the axle was attached to a magnet that rotated in the cylindrical support. The stirrer was rotated by means of a magnet attached to the shaft of an electric motor with variable speed and placed below the cell assembly as shown in Fig. 1. The cell was filled with the desired liquid so that the surface level was either 10 mm or 50 mm above the impeller. It was then placed in a rectangular perspex tank filled with water.

Measurements were made using laser Doppler anemometer and allied optics supplied by Dantec. Light beam of wavelength 632.8 nm was used from a 15 mW He-Ne laser. Both tangential and axial components of the liquid velocity were measured. The data collection and signal processing was made by the Burst Spectrum Analyser (Dantec), which is also a hard wired Fast Fourier Transform (FFT) analyser, interfaced to a PC-AT 386. "Burstware" software was used for the data processing. The experimental arrangement is shown in Fig. 2. The reproducibility

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Fig. 2 Laser Doppler Anemometer and its associated optics, 2-d traversing system, data acquisition system (Burst Spectrum Analyser)

of measuring mean velocity was within one percent and that for rms was two percent. Time series of the instantaneous velocity was obtained for the required measurement position. The mean velocity was obtained from the data. The deviation of the instantaneous velocity from the mean gave the fluctuating velocity. The square root of the arithmetic mean of the square of the fluctuations gave the root mean square or the rms velocity. Further details pertaining to the laser Doppler anemometer and the data processing have been given by Ranade and Joshi (1990).

Tangential mean and rms velocity measurements were made for three axial distances at levels: 1 mm, 5 mm and 9 mm below the interface when the liquid level was 10 mm above the impeller. Measurements were also made for the axial velocity component at distances of 5 mm, 10 mm and 15 mm below the interface when the water level was increased to 50 mm above impeller. In order to investigate the effect of liquid viscosity on the flow pattern, polyethylene glycol (PEG 6000) was added to water. The physical properties have been reported in **Table 1**. The power consumption was estimated according to

Table 1 Physical properties of liquid used in the experiment

Additive	Viscosity μ [mPas]	Density ρ [kg m ⁻³]
Water	0.9	2000
50% PEG	41	1088

the procedure given by Nagata (1975).

2. Results and Discussions

2.1 Tangential velocity

In a stirred cell with low impeller speeds the tangential component is predominant. **Figure 3** shows the tangential mean velocity profiles for water (0% PEG) and 50% PEG solution. Measurements were made at three values of power consumption: 3.75×10^{-4} , 9.4×10^{-4} and 19.14×10^{-4} W/kg. The corresponding impeller speeds for water and 50% PEG solution are 0.36 and 0.25 r/s (at 3.75×10^{-4} W/kg), 0.5 and 0.36 r/s (at 9.4×10^{-4} W/kg) and 0.66 and 0.5 r/s (at 19.14×10^{-4} W/kg).

Fig. 3 Tangential mean velocity vs. radial distance for water and 50% PEG solution at axial levels of 1 mm, 5 mm and 9 mm below the interface
Liquid level above impeller=10 mm

It can be seen that the tangential mean velocity increases with an increase in the radial distance from the centre, attains a maximum and then decreases with a further increase in the radial distance. The peak of tangential mean velocity is seen to shift nearer the centre in the presence of PEG. The shape of the profiles is very similar at the three axial locations.

The values of the tangential rms velocity are also shown in **Fig. 4**. It can be seen that the behaviour of water and 50% PEG solution is different. In the case of water, the rms velocity increases with an increase in the radial distance. In the case of 50% PEG solution,

the rms velocity obtains a maxima. However, the profiles change the shape as we approach the impeller; at a distance of 9 mm below the interface it can be seen that the maxima shifts suddenly towards the wall. There is a distinctive difference in the nature of the profile shape in the two cases as evident from the figures. It is needless to say that, in both the solutions, the rms velocity increases with an increase in power consumption.

2.2 Axial velocity

In order to understand the mechanism of mass transfer, it is desirable to understand the behavior of

Fig. 4 Tangential rms velocity vs. radial distance for water and 50% PEG solution at axial levels of 1 mm, 5 mm and 9 mm below the interface
Liquid level above impeller=10 mm

the axial velocity with respect to the distance from the interface. **Figure 5** shows the behaviour of axial mean velocity. The flow is upward in the central region and downward near the vessel wall. The values of axial velocity are much higher in water as compared with 50% PEG solution. Further, the nature of velocity profiles is different for water and 50% PEG solution. In the case of water, the values remain practically constant upto 50% radial distance, then increases sharply, attains a maximum and then decreases drastically. In contrast, in the case of 50% PEG solution, the axial velocity decreases continuous-

ly from centre to the wall. These observations are in close agreement with those of Luk and Lee (1986).

The values of axial rms velocity are shown in **Fig. 6**. In water, the turbulence intensity (rms velocity) is practically the same at axial locations of 5 mm and 10 mm below the interface. However, at the interface, there is a reduction in the rms velocity as compared with the bulk. In 50% PEG solution, however, the turbulence was found to decay with a decrease in distance from the interface.

2.3 Eddy life time

The values of average eddy lifetime (T) were

Fig. 5 Axial mean velocity vs. radial distance for water and 50% PEG solution
Liquid level above impeller=50 mm

obtained from the auto correlation (Taylor, 1938) of the experimental data.

The velocity time (time series of velocity) data was obtained for the tangential velocity component, as well as the axial velocity component. The correlation between the fluctuating velocities $u(t)$ and $u(t')$ should depend on the time difference $t' - t = \tau$. The autocorrelation function $C(\tau)$ is then given by the following equation:

$$C(\tau) = \frac{\overline{u(t)u(t+\tau)}}{\overline{u(t)u(t)}}$$

As the value of τ increases $C(\tau)$ decreases. Taylor described the nature of the autocorrelation

function by the following relation:

$$C(\tau) \sim e^{-(\tau/T)}$$

where T is the average lifetime of the eddy and its value can be read from the correlation curve when $C(\tau)$ becomes $1/e$. Turbulence is a three dimensional phenomena. The fluctuating component will usually be different in different directions unless the turbulence is isotropic. The variation of the rms in the tangential and axial directions shows that the energy contained in the eddies in the respective directions is different. This means that the eddies have different sizes in both the directions implying that the turbulence is anisotropic. The difference in the scales of

Fig. 6 Axial rms velocity vs. radial distance for water and 50% PEG solution
Liquid level above impeller=50 mm

turbulence for two different components (radial and tangential) in a stirred tank have already been shown by Cutter (1966). If the turbulence is not isotropic the sizes of eddies will be different in different directions. Thus we redefine the autocorrelation functions in the tangential and axial directions $C_{in}(\tau)$ and $C_{ax}(\tau)$ respectively as given by

$$C_{in}(\tau) = \frac{\overline{u_{in}(t)u_{in}(t+\tau)}}{\overline{u_{in}(t)u_{in}(t)}}$$

$$C_{ax}(\tau) = \frac{\overline{u_{ax}(t)u_{ax}(t+\tau)}}{\overline{u_{ax}(t)u_{ax}(t)}}$$

Thus the values of average eddy life time T for the tangential velocity and axial velocity could be calculated as described earlier.

The values so obtained for the tangential velocity component are shown in Fig. 7 at 3.75×10^{-4} , 9.4×10^{-4} and 19.4×10^{-4} W/kg, respectively. It can be seen that the values of T decrease with an increase in power consumption. Near the impeller the T values are markedly different for water and 50% PEG solution. However, at 1 mm and 5 mm locations, the values are practically the same.

The effect of PEG concentration on the values of average eddy life time T for the axial velocity is shown in Fig. 8. The radial profiles of T for water and 50% PEG solution are quite different. In water, the

Fig. 7 Average eddy life time T of Tangential velocity vs. radial distance for water and 50% PEG solution at axial levels of 1 mm, 5 mm and 9 mm below the interface for water and 50% PEG solution
M Liquid level above impeller=10 mm

profiles are concave with a minima whereas in 50% PEG solution, the profiles are convex with a maxima. The interesting observation is that the values of T decrease as we approach the interface.

Conclusion

1. When the liquid level is 10 mm above the impeller the tangential rms velocity profile shows a different shape for water and 50% PEG solution. The shape of the life time profiles for the tangential velocity component in Fig. 7 suggests that the average

life time of the eddies in the PEG solution is higher than that for eddies in water.

2. When the liquid level is 50 mm above the impeller the eddy life time profiles for the axial velocity component are of a concave shape in the case of water but show a clear maxima in the PEG solution. In the latter case there is a clear indication that the eddy life decreases as one approaches the interface as seen in Fig. 8.

Nomenclature

$C(\tau)$ = autocorrelation function

[—]

Symbol	Power consumption [W/kg]	Symbol	Distance from the interface
A	3.7×10^{-4}	□	5 mm below the interface
B	9.4×10^{-4}	△	10 mm below the interface
C	19.4×10^{-4}	○	15 mm below the interface

Fig. 8 Average eddy life time T of Axial velocity vs. radial distance for water and 50% PEG solution. Liquid level above impeller=50 mm

$u(t)$	= fluctuating component of velocity at an instant t	[m/s]
$u(t')$	= fluctuating component of velocity at an instant t'	[m/s]
τ	= time interval $t'-t$	[s]
μ	= viscosity	[mPa s]
ρ	= density of liquid	[kg m ⁻³ s]
T	= average eddy life time	[s]

<Subscripts>

ax	= axial
tn	= tangential

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