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Determination of the entropy radial minimum and the various transition velocities in an air-water bubble column

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HIGHLIGHTS

- Analogy between the liquid velocity inversion point and the entropy radial minimum was identified.
- The time series in the stagnation point were characterized with a better order.
- An entropy radial minimum at various gas velocities was observed.
- Similar entropy radial profiles at different gas velocities were identified.
- The radial effect on the transition velocities (based on KE values) was studied.

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ABSTRACT

The bubble column hydrodynamics are complex and the macroscopic flow structure is different in the column core and annulus due to both the bubble coalescence and breakup phenomena as well as the gross liquid circulation. In this work, for the first time the local Kolmogorov entropy (*KE*) minima at different superficial gas velocities U_g were identified. It was found that there is an agreement between the local *KE* minima (occurring around $r/R = 0.63$) and the inversion point (dimensionless radius = 0.7) for the axial liquid velocity reported by both Chen et al. (1994) and Wu and Al-Dahhan (2001).

The *KE* radial profiles were also used to prove the existence of chaotic similarities between the flow patterns in the bubble bed at three different U_g values (0.089, 0.134 and 0.146 m/s) belonging to the heterogeneous regime. This finding implies that the flow patterns and the degrees of turbulence at these U_g values are also identical. The same similarity was also found between the *KE* profiles at $U_g = 0.056$ and 0.067 m/s, which belong to the transition flow regime. These results imply that the flow patterns in the bubble bed repeat (especially at different U_g values falling into the same flow regime).

Based on the KE profiles as a function of U_g, the effect of the dimensionless radial position on the various transition velocities was studied. It was found that the end of the gas maldistribution regime is shifted to slightly higher U_g value in column core and annulus. In most of the cases, the onset of the churn-turbulent regime occurs at $U_g = 0.101$ m/s.

1. Introduction

Bubble columns are characterized with intense liquid mixing and liquid movement due to the rise of bubble swarms through the liquid phase (Walter and Blanch, 1983). These rising bubbles agitate the liquid by the creation of turbulent eddies combined with a steady circulating flow. Walter and Blanch (1983) have argued that the flow in these reactors is highly non-isotropic. Bubble columns are classical gas-liquid contactors, which are widely used in many chemical processes such as oxidation, chlorination, alkylation, carbonylation, carboxylation, hydroformylation, sulfonation, dehydrosulfonation, ammonolysis and ozonolysis, halogenation and hydrohalogenation, polymerization and hydrogenation (Shah et al., 1982).

The bubble column behavior is particularly influenced by the nature of the gas-liquid dispersion. It is difficult to predict the flow patterns in the bubble bed (Walter and Blanch, 1983). There is a lack of understanding of the effect of the gas distributor design on the liquid circulation patterns. Devanathan et al. (1995) have argued that the flow is transient and chaotic even at low gas flow rates. The bubble column performance can be significantly affected by the various flow regimes (Shah et al., 1982) and the transition

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Nomenclature

b	number of steps before the interpoint distance becomes larger than L_0 (–)
$\bar{b}$	mean b value (sum of b values divided by their number) (–)
f_s	sampling frequency (1/s)
KE	Kolmogorov entropy (bits/s)
k	parameter (varying between 0 and $m-1$) in the KE algorithm (–)
L_0	maximum distance (cut-off length) (–)
m	embedding dimension (–)
U_g	superficial gas velocity (m/s)
U_{trans}	transition gas velocity (m/s)
r	radial coordinate (m)
R	column radius (m)
r/R	dimensionless radius (–)
x	respective data points in the time series (%)
X	state vector (using delay time of unity) (–)

Subscripts

i	number of elements in the first arbitrary generated state vector (–)
j	number of elements in the second arbitrary generated state vector (–)

points between them. The demarcation criteria of the flow regimes may vary with design or operating variables such as column diameter, distributor type and liquid properties (Chen et al., 1994).

The homogeneous (bubbly) flow regime is encountered at low superficial gas velocities U_g. It is characterized by relatively small and uniform bubbles. The bubble size distribution is very narrow and it is mainly influenced by the gas distributor. Relatively uniform gas holdup profiles along with rather flat liquid velocity profiles are observed. If the gas distributor is not effective, the homogeneous regime is replaced by a gas maldistribution regime which is characterized by the existence of both preferentially aerated zones and dead zones.

The transition from homogeneous to heterogeneous regime is a gradual process. Olmos et al. (2003a, 2003b) have reported the existence of two transition sub-regimes. The flow structure is not well established in the first transition sub-regime. The large bubbles are formed only in the vicinity of the gas distributor. The authors argue that in the first transition sub-regime the flow is still homogeneous despite some predominating bubble paths in the column core. The individual bubble plumes are transformed into an oscillating plume of gathered bubbles. However, this central plume is unstable and beyond a certain liquid height, the flow structure returns to the existing one in the homogeneous flow regime with individual trajectories. In the second transition sub-regime, the bulk region coalescence and breakup, together with the development of gross liquid circulation effects begin to dominate. Olmos et al. (2003a) reported the appearance of a global liquid flow macrostructure. The distributor effects become less important.

The heterogeneous (churn-turbulent) flow regime is characterized by the wide bubble size distribution and by the existence of a parabolic radial gas holdup profile, which causes gross liquid circulation. The latter gives rise to a radial velocity distribution. The liquid rises in the middle portion of the bubble bed and descends adjacent to the walls. The column core is rich on bubbles, while the column annulus is lean on bubbles. This causes differences in the buoyancy forces (Ueyama and Miyauchi, 1979). The gross liquid circulation gives rise to a radial velocity distribution. Chen et al. (1994) argued that the downward liquid streams (adjacent to the wall) move either in a straight or spiral manner depending on the U_g value.

In many cases, this gross liquid circulation pattern determines the boundary between both column core and column annulus. In the region close to the column wall (annulus), a descending liquid flow can always be found due to the lack of bubble motion. Chen et al. (1994) have argued that in the region between the central bubble stream and the column wall tiny bubbles are observed to move up and down, which also indicates the dynamic nature of this region. The liquid flows downward in a spiral manner adjacent to the wall and at the same time demonstrates a vortical flow pattern. The vortical flow structure in the vortical-spiral flow regime is analogous to the turbulent Taylor vortices structure (Chen et al., 1994). For the frequently used low viscosity fluids, a recirculation type of flow is observed, when the U_g value is in excess of 0.04–0.05 m/s (Ueyama and Miyauchi, 1979).

1.1. Liquid velocity inversion point

Both the liquid velocity profile and the average liquid circulating velocity are important for the performance of bubble columns. In the center of the column the liquid rises with the gas bubbles. The highest liquid velocity is found at the column's core, and there is a decrease of liquid velocity with increasing the distance from the column center. In the column annulus the liquid flows downwards. A transition region (radius = 0.6–0.8) is formed between these two sections characterized by steep velocity gradients and large velocity fluctuations. Within this section appears a flow transition or inversion point, at which the average liquid velocity is zero (Walter and Blanch, 1983). The inversion point between an upward flow in the column core and a downward stream along the wall is usually located between 0.5 and 0.7 of the dimensionless column radius (Walter and Blanch, 1983). Crabtee and Bridgewater (1969) and Rietema and Ottengraf (1970) indicated that the flow transition point occurred at a dimensionless radius of 0.5 and a maximum downward velocity was observed at a dimensionless radius of 0.7. Later, Chen et al. (1994) and Wu and Al-Dahhan (2001) demonstrated that the inversion point of the average axial velocity occurs at 0.7. In fact, Ueyama and Miyauchi (1979) and Walter and Blanch (1983) stated also that for inviscid systems the transition point occurs at a dimensionless radial coordinate of 0.7. The authors referred also to a previous work, which reported both local and average axial and radial dispersion coefficient measurements. The highest local dispersion coefficients were observed around a dimensionless radius of 0.7, i.e. in the transition point of the column, where the velocity gradients are the greatest. According to Walter and Blanch (1983), the inversion point is very unstable (due to large-scale velocity fluctuations) and moves outward with increasing gas holdup and decreasing liquid viscosity. In low viscosity liquids, at high U_g values, large liquid velocities were recorded very close to the column wall. On the contrary, in very viscous liquids (0.1 and 0.15 % carbopol solution), a significant velocity gradient and very low liquid velocities were measured near the column wall.

Wu and Al-Dahhan (2001) have argued that the inversion point of the axial liquid velocity and the liquid circulation velocity in an air-water system occurs at a dimensionless radius of about 0.7. It is