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Entropy Analysis in a Bubble Column Based on Ultrafast X-Ray Tomography Data

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***Abstract*—**By means of the ultrafast X-ray tomography facility, data were obtained at different superficial gas velocities U_G in a bubble column (0.1 m in ID) operated with an air-deionized water system at ambient conditions. Raw reconstructed images were treated by both the information entropy (IE) and the reconstruction entropy (RE) algorithms in order to identify the main transition velocities in a bubble column. The IE values exhibited two well-pronounced minima at U_G=0.025 m/s and U_G=0.085 m/s identifying the boundaries of the homogeneous, transition and heterogeneous regimes. The RE extracted from the central region of the column's cross-section exhibited only one characteristic peak at U_G=0.03 m/s, which was attributed to the transition from the homogeneous to the heterogeneous flow regime. This result implies that the transition regime is non-existent in the core of the column.

***Keywords*—**Bubble column, ultrafast X-ray tomography, information entropy, reconstruction entropy.

I. Introduction

Bubble columns are one of the most frequently used gas-liquid contactors. They can operate in the homogeneous, transition and heterogeneous flow regimes. For the successful design and scale-up of bubble columns, it is essential to identify the prevailing flow regime. Different experimental methods (pressure and temperature sensors, particle image velocimetry, laser Doppler anemometry, radioactive particle tracking, computed tomography, electrical capacitance tomography, nuclear gauge densitometry, conductivity wire mesh sensor, etc.), statistical and very sophisticated methods of analysis (chaos analysis, fractal analysis, spectral analysis, wavelet analysis, drift flux analysis, multi-resolutional analysis, stability analysis, computational fluid dynamics, etc.) have been used for flow regime identification.

Some very important parameters for the bubble column operation such as the coefficients of mixing, mass and heat transfer depend on the prevailing flow regime. That is why the clear identification of the boundaries of each flow regime is essential. Flow regime maps are illustrative tools for practitioners to identify the prevailing flow regime in their facility.

There are two main transition velocities in bubble column operation. The first transition velocity indicates the transition from homogeneous (bubbly flow) regime to transition regime. The second transition velocity distinguishes the onset of the heterogeneous (churn-turbulent) flow regime. The first transition velocity is more important since it takes part in the calculation of both the large bubble diameter and large bubble holdup [1]. In the literature, only empirical correlations [2], [3] for prediction of the first transition velocity exist.

The homogeneous regime is characterized by a gentle agitation of the gas-liquid dispersion with relatively small and uniform bubbles. The bubble size distribution is very narrow and it is only influenced by the gas sparger. The bubble streams rise rather rectilinearly and bubble coalescence is insignificant. A relatively uniform gas holdup profile and a rather flat liquid velocity profile are observed.

The transition flow regime is characterized by large flow macrostructures, i.e. large eddies, and widened bubble size distribution due to the onset of bubble coalescence. This regime is formed due to the development of local circulation patterns in the column. The range of the transition regime depends on both the uniformity and the quality of aeration.

The transition from the homogeneous to the heterogeneous flow regime is a gradual process. As the superficial gas velocity U_G increases, larger bubbles start to form whose wakes cause gross circulation patterns in the bubble bed leading to the formation of the heterogeneous regime. The latter is characterized by a wide bubble size distribution and the existence of a pronounced radial gas holdup profile which causes liquid circulation. In this flow regime, coalescence and break-up occur. Bubbles coalesce in the vicinity of the gas distributor to form larger, spherical-cap bubbles. The heterogeneous regime is characterized by vigorous mixing. In this flow regime, the gas distributor has a negligible influence on the main parameters.

The main objective of the current paper is to demonstrate that the new experimental data obtained by ultrafast x-ray tomography combined with an entropy analysis can be used for successful flow regime identification in a bubble column.

II. Information Entropy

The information entropy (IE) is a measure of the amount of information in a certain source (for example, time-dependent signals) and the degree of predictability of the behavior of the system. The IE quantifies the degree of uncertainty involved in predicting the output of a probabilistic event.

In order to apply correctly the IE algorithm, one must divide the cross-section of the column into different semi-rings (with different areas) and to measure the gas (or tracer) content into each of these entities.

According to [4], the probability of the highest gas content

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in every semi-ring can be defined as:

$$P_i(t) = \frac{A_0}{A_i} \frac{A_i\left(signal\ \ value\ (t)\right)_i}{\sum_{i=1}^{N} A_i\left(signal\ \ value\ (t)\right)_i} \quad (1)$$

where N is the length (29,000 points) of the time series signal, A_i is the area of every semi-ring and A_0 is the reference area. As A_0 was used the area of the smallest central semi-ring.

The IE depends not only on the probability but also on the information amount. The latter can be calculated as:

$$I_i(t) = -\log\left(P_i(t)\right) \quad (2)$$

The total IE is a product of both the probability $P_i(t)$ (1) and the information amount $I_i(t)$ (2). It is measured in bits. In this work, the mean information entropy (IE_m) is being used which is the mean of all (29, 000) local IE values.

Since the bubble column had an inner diameter of 0.1 m, the cross-section was divided into 20 semi-rings (see Table I).

TABLE I
DESCRIPTION OF THE DIMENSIONS AND AREAS OF THE SEMI-RINGS

Semi-ring	Dimensions	Area [m^2]
1	IR=0 m, OR=5×10^{-3} m	A=0.3927×10^{-5}
2	IR=5×10^{-3} m, OR=10×10^{-3} m	A=1.1781×10^{-4}
3	IR=10 ×10^{-3} m , OR=15×10^{-3} m	A=1.9635×10^{-4}
4	IR=15×10^{-3} m, OR=20×10^{-3} m	A=2.7489×10^{-4}
5	IR=20×10^{-3} m, OR=25×10^{-3} m	A=3.5343×10^{-4}
6	IR=25×10^{-3} m, OR=30×10^{-3} m	A=4.3197×10^{-4}
7	IR=30×10^{-3} m, OR=35×10^{-3} m	A=5.1051×10^{-4}
8	IR=35×10^{-3} m, OR=40×10^{-3} m	A=5.8905×10^{-4}
9	IR=40×10^{-3} m, OR=45×10^{-3} m	A=6.6759×10^{-4}
10	IR=45×10^{-3} m, OR=50×10^{-3} m	A=7.4613×10^{-4}
11	IR=0 m, OR=-5×10^{-3} m	A=0.3927×10^{-5}
12	IR=-5×10^{-3} m, OR=-10×10^{-3} m	A=1.1781×10^{-4}
13	IR=-10 ×10^{-3} m , OR=-15×10^{-3} m	A=1.9635×10^{-4}
14	IR=-15×10^{-3} m, OR=-20×10^{-3} m	A=2.7489×10^{-4}
15	IR=-20×10^{-3} m, OR=-25×10^{-3} m	A=3.5343×10^{-4}
16	IR=-25×10^{-3} m, OR=-30×10^{-3} m	A=4.3197×10^{-4}
17	IR=-30×10^{-3} m, OR=-35×10^{-3} m	A=5.1051×10^{-4}
18	IR=-35×10^{-3} m, OR=-40×10^{-3} m	A=5.8905×10^{-4}
19	IR=-40×10^{-3} m, OR=-45×10^{-3} m	A=6.6759×10^{-4}
20	IR=-45×10^{-3} m, OR=-50×10^{-3} m	A=7.4613×10^{-4}

IR stands for the inner radius of the semi-ring; OR stands for the outer radius of the semi-ring.

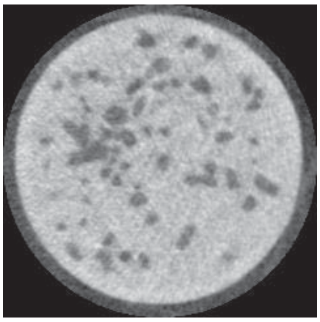

Fig. 1 Typical reconstructed raw image obtained by the ultrafast X-ray tomography at U_G=0.06 m/s

The IE algorithm was applied to reconstructed images (obtained by ultrafast X-ray tomography) as the one exhibited in Fig. 1. Such reconstructed raw images give very good information about the X-ray attenuation in the bubble column cross-section and thus, they are measure for the density distribution and the fraction of the gas phase in different regions (semi-rings) of the cross-section.

III. RECONSTRUCTION ENTROPY

The algorithm for the calculation of the reconstruction entropy (RE) was recently explained by [5]. It aims at extracting the hidden information in the time series. The signal is reconstructed multiple times and the absolute difference between each two sequential elements from the reconstructed parts of the signal is compared. The number of steps b before the absolute difference becomes higher than a preselected threshold value is used to calculate the new RE. As a threshold value, three times the average absolute deviation (AAD) from the signal's mean is used.

RE is a function of the sampling frequency f_s and the parameter b_{av}:

$$\mathrm{RE} = -f_s \ln\left(1 - \frac{1}{b_{av}}\right) \quad (3)$$

The variable b_{av} is the mean of all b values in the time series. Each b value equals the number of sequential pair of points, in which the interpoint distance is for the first time bigger than the specified maximum interpoint distance.

The RE reflects the rate of information loss of the system. RE>0 is a sufficient condition for chaos and the behavior of the chaotic system is only predictable over a restricted time interval.

IV. EXPERIMENTAL SETUP

A plexiglass bubble column (0.1 m in ID) was used for the scans with the ultrafast X-ray tomography facility. The bubble column was equipped with a perforated plate distributor (55 holes with diameter Ø 0.5×10^{-3} m resulting in an open area of 0.14%) and operated with an air-deionized water system (clear liquid height=0.66 m) under ambient operating conditions.

The tomographic facility (see Fig. 2) does not employ rotating objects or source-detector compounds. An electron beam is focused on a circular tungsten target and is at the same time periodically deflected with a high frequency in order to generate a moving focal spot on the target and thus an X-ray source rotating around the object. This source irradiates the object from different viewing angles. A static detector ring surrounding the object measures the radiation passing the object at a high frequency and synchronized with the beam deflection. From the projected data set of one revolution of the electron beam a non-superimposed cross-sectional image of the density distribution within the object can be reconstructed.

The tomographic facility can provide detailed information about the structure of the inherent multiphase flows. The ultrafast X-ray tomography is a powerful noninvasive imaging tool for this purpose. The scans were performed at an axial position of 0.5 m above the gas distributor. The sampling frequency was set at 1000 Hz (1000 cross-sectional images per second) at a spatial resolution of about 1×10^{-3} m, which is the worldwide fastest tomographic imaging technique.

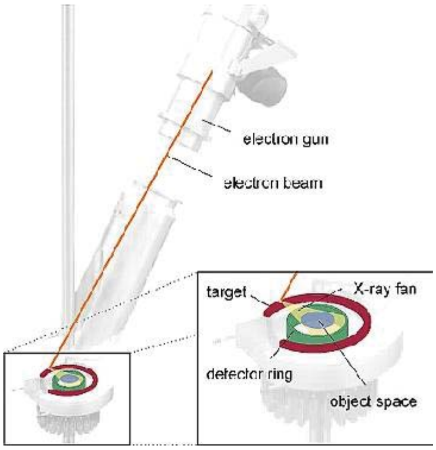

Fig. 2 Schematic of the ultrafast X-ray tomography facility

The superficial gas velocity U_G was varied from 0.01 to 0.15 m/s with increments of 0.01 m/s (in some cases even 0.005 m/s). At each U_G, the scans were performed with a sampling frequency f_s of 1000 Hz for 29 s, which resulted in 29,000 images and points, respectively.

V. Results and Discussion

Fig. 3 shows IE_m, calculated for the whole cross-section, is capable of identifying the two main transition velocities. At U_G=0.025 m/s a minimum occurs, which marks the end of the homogeneous regime and the beginning of the transition regime. It is worth noting that the empirical correlation of [3] predicts that for air-water systems at ambient conditions the first transition velocity should occur at U_G=0.029 m/s, which is a very close value to our result. The second minimum in the IE profile occurs at U_G=0.085 m/s and denotes the onset of the heterogeneous flow regime. Fig. 3 exhibits that the IE_m values in the transition regime decrease monotonously. It is noteworthy that [6] reported similar behavior of the Kolmogorov entropy values in the transition flow regime.

RE extracted from the averaged time-dependent data in the smallest central semi-ring (no. 11 in Table I) from the cross-section of the column, can be also used for identification of the main transition velocity. Fig. 4 shows that at U_G=0.03 m/s the RE value is much higher than the rest of the data. This well-pronounced maximum corresponds to the formation of the first large coalesced bubble (with a spherical-cap shape), which generates strong disturbance in the time-dependent signal due to the enhanced turbulence and liquid circulation. It seems that the transition regime does not exist in this central semi-ring. A second strong peak is not observed. The main transition velocity identified in Fig. 4 is very close to the one extracted from the IE_m values and valid for the whole cross-section (see Fig. 3). The prediction of [3] is also identical with the result shown in Fig. 4.

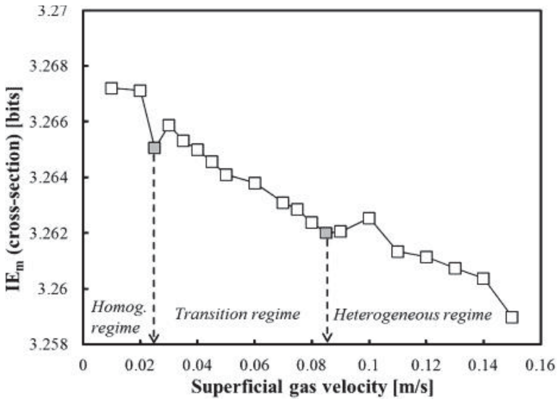

Fig. 3 Values of the IE_m as a function of U_G

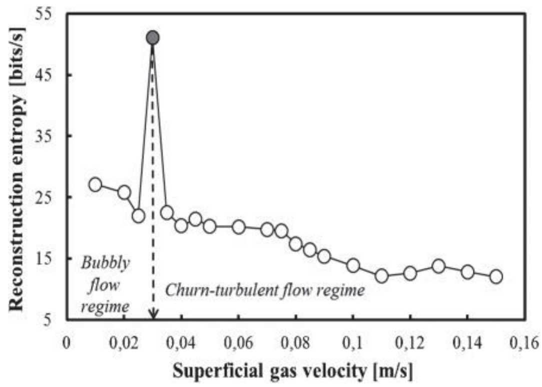

Fig. 4 Values of the RE (in semi-ring 11) as a function of superficial gas velocity U_G

It was found that the RE [5] extracted from data in the central region can be used for validation of the mixing length concept. In the U_G range between 0.08 and 0.11 m/s, the RE can be correlated to the mixing length L (see Fig. 5) calculated by the correlation of [7]. The applicability of the mixing length concept in the transition flow regime of bubble column operation has been already confirmed [6].

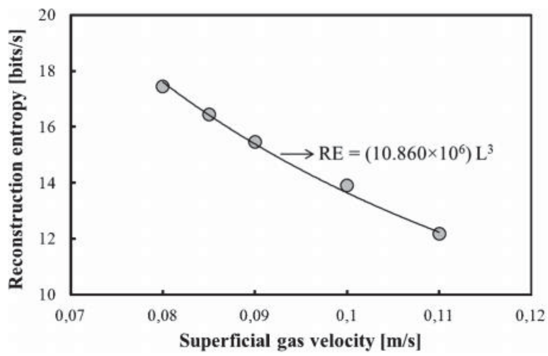

Fig. 5 Correlation between RE and L in the transition regime

Our next goal will be to identify the main transition velocities in every semi-ring and prepare a useful map about the radial distribution of the main transition velocities.

Fig. 6 shows that the average absolute deviations extracted from the data in the central semi-ring (no. 11 in Table I) cannot be used for flow regime identification.

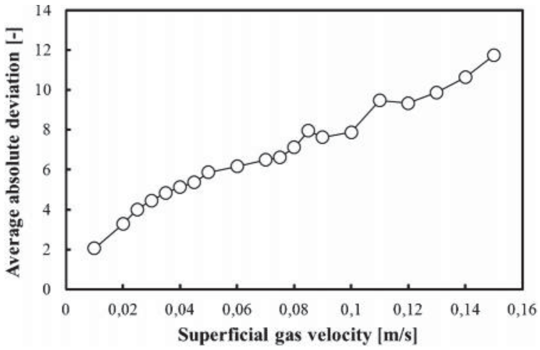

Fig. 6 Values of the average absolute deviation (in semi-ring 11) as a function of superficial gas velocity U_G

VI. Conclusion

A new identification method has been developed for the prediction of the main transition velocities in a bubble column (0.10 m in ID) operated with an air-deionized water system. The new approach is based on experimental ultrafast X-ray tomography data and two different entropies (IE and RE) extracted from this unique time series data.

The IE was capable of identifying the two main transition velocities in the bubble column operation: at U_G=0.025 m/s the end of the homogeneous regime was detected, whereas at U_G=0.085 m/s the onset of the heterogeneous regime was identified. A unified identification criterion (local minimum) was always used.

It was found that the RE in the central semi-ring identifies only the transition velocity (U_G=0.030 m/s) between the homogeneous and heterogeneous flow regimes. In principle, this is the most important transition velocity, which affects both the large bubble diameter and the large bubble holdup.

It is worth noting that the RE values in the transition regime can be correlated to the mixing length values.

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Nomenclature

AAD	average absolute deviation,−
A_0	reference area, m^2
A_i	area of the particular semi-ring, m^2
b	number of sequential pair of points in which the interpoint distance is lower than the cut-off length,−
b_{av}	average number of b values in the time series,−
f_s	sampling frequency, 1/s
$I_i(t)$	information amount,−
IE	(local) information entropy, bits
IE_m	mean information entropy, bits
L	mixing length, m
RE	Reconstruction entropy, bits/s
N	number of data points, −
$P_i(t)$	probability of maximum gas contents in a certain semi-ring, −
t	time, s
U_G	Superficial gas velocity, m/s

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