Early Detection of Foam Formation in Bubble Columns by Attractor Comparison

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Introduction

Bubble column reactors have many industrial applications such as biological conversions, direct and indirect coal liquefaction, and hydrogenation reactions. In many of these applications, unwanted formation of foam can take place, which leads to a reduction in working volume, loss of product, fouling of sensors, and limitation in aeration rate. Therefore, foam control is an important issue. In most cases, foaming occurs unexpectedly and irregularly in time. Therefore, it is very important to have the possibility of anticipating the foaming and to avoid all the problems associated with excessive foaming. Many research reports discuss foam *control* (for example, Kunii et al., 1994; Takesono et al., 1994; Guitián and Joseph, 1998, Deshpande and Barigou, 2000), but to our best knowledge, no information is available in literature about the *early detection* of foam formation.

Van Ommen et al. (2000) recently developed a monitoring method that was successfully used for the early detection of agglomeration in fluidized beds. This article shows that this monitoring method is more generic and can also be applied for early detection of foam formation in bubble columns. Knowing that dilute alcohol solutions simulate reasonably well the liquid-phase behavior in bioreactors (Bukur and Patel, 1989), and can also lead to foaming (Pugh, 1996), the system water/ethanol was chosen as a model system. Experiments were carried out both in the homogeneous and the heterogeneous regime.

Monitoring by Attractor Comparison

The monitoring method is based on pressure fluctuation measurements. It compares the pressure fluctuation time-series measured in the bubble column at a certain desired reference state (that is, without foaming) to the pressure time-series subsequently obtained during operation of the column (so-called evaluation time-series), using a statistical test developed by Diks et al. (1996). A short description of the procedure is given below; refer to Van Ommen et al. (2000) for a more detailed description.

The state of a bubble column at a certain time can be determined by projecting all variables governing the system in a multidimensional space (the "state space"); the collection of the successive states of the system during its evolution in time is called the "attractor". However, it is practically impossible to know all governing variables of a bubble column. Takens (1981) proved that the dynamic state of a system can be *reconstructed* from the time-series of only one *characteristic* variable (such as the local pressure in a bubble column). Suppose we have a reference pressure time-series $p_k = (p_1, p_2, \ldots, p_{N_p})$ consisting of N_p values. To make the test less sensitive to the superficial gas velocity, we want to remove the influence of the standard deviation by normalizing the pressure time-series: the average value is subtracted from all values and they are divided by the standard deviation of the time-series. In this way, we obtain a time-series x_k with a mean of zero and a standard deviation of unity. In the same way, we can convert an evaluation time-series into a normalized evaluation time-series y_k.

Using so-called time-delay coordinates, it is possible to convert the pressure time-series $(x_1, x_2, \ldots, x_{N_p})$ consisting of N_p values into a set of $N_p - m + 1$ delay vectors $\boldsymbol{X}_k$ with m elements, where $X_k = (x_k, x_{k+1}, \ldots, x_{k+m-1})^T$. The subsequent delay vectors can be regarded as points in an m-dimensional state space yielding a reconstructed reference attractor, which we will denote as $\rho_x(\boldsymbol{X}_i)$. The reconstructed evaluation attractor will be denoted as $\rho_y(\boldsymbol{Y}_i)$. The extent to which two attractors differ can be expressed by the squared

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distance Q between them

$$Q = \left(2d\sqrt{\pi}\right)^m \int \left(\rho_x(\boldsymbol{R}) - \rho_y(\boldsymbol{R})\right)^2 d\boldsymbol{R}$$

Diks et al. (1996) have given a procedure to calculate an unbiased estimator $\hat{Q}$ of the squared distance for two given time-series. The larger the difference between two attractors, the larger their squared distance Q will be. However, we will need to know whether or not a certain value of the estimator $\hat{Q}$ indicates a *significant* difference between the two delay vector sets, and, thus, between the two hydrodynamic states of the bubble column from which they originate. Therefore, we also need an estimate for the variance V of $\hat{Q}$. Diks et al. (1996) also derived an expression to calculate this variance for two given time-series. Subsequently, we can define a statistic S as

$$S = \frac{\hat{Q}}{\sqrt{V(\hat{Q})}}$$

The dimensionless squared distance S is a random variable with a zero mean and standard deviation equal to unity when the two time-series originate from the same hydrodynamic situation. When $S > 3$, we know with more than 95% confidence that the two hydrodynamic situations differ. The reason to choose this method for monitoring bubble column hydrodynamics is that it provides us with a quantitative, mathematically founded tool to judge whether a difference is significant or not. Moreover, the method evaluates the pressure signal as a whole and not just one property of the pressure signal (such as, the standard deviation or the main frequency) as other methods do. This makes the monitoring method based on attractor comparison more generic than other methods.

Experimental Studies

The experiments were carried out in a PMMA column of 0.19 m of internal diameter and 4 m in height. Air was blown through a stainless steel porous plate distributor. The column was filled with water to a height of 0.60 m. At certain times, small ethanol additions were made to simulate the foam formation process. At different heights, four pressure probes of 0.18 m long and 4 mm internal diameter were inserted in the column; the probe tips were located on the column axis. Three piezoelectric pressure sensors of Kistler type 7261 connected to probes located at 0.13, 0.33, and 0.53 m above the distributor were used to measure pressure fluctuations. A Validyne pressure sensor connected to a probe located at 0.43 m above the distributor was used to measure the hydrostatic pressure of the system. The signals were sampled at 400 Hz and low pass filtered at 200 Hz to avoid aliasing. The length of the time-series used for evaluation by the monitoring method was 2 min. An embedding dimension, bandwidth, and segment length of 20, 0.5, and 2.5 s, respectively, were used to compute the S-statistic. For more information about the monitoring method parameter settings, refer to Van Ommen et al. (2000). Digital video recordings were made to follow the formation of the foam layer.

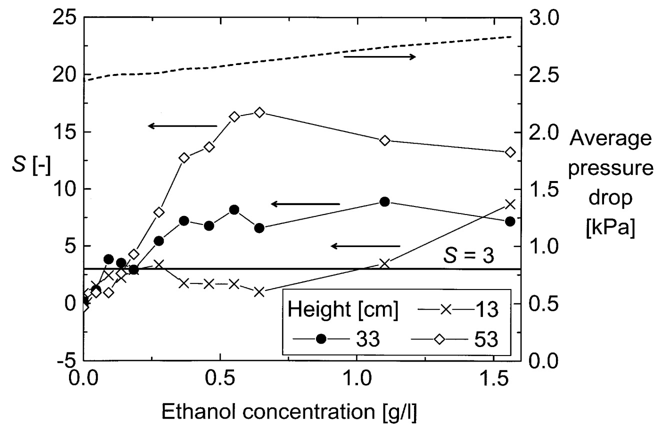

Figure 1. Average S-value and the average pressure drop (dashed line) as a function of the ethanol concentration in the homogeneous regime.

The S-values are calculated for pressure fluctuations measured at three different heights; the average for eight values is given. The average pressure drop is measured over the upper part of the column.

Results and Discussion

Foam detection in the homogeneous regime

The experiments in the homogeneous regime were performed at a fixed superficial gas velocity of 0.029 m/s. The ethanol concentration was increased step by step to slowly induce foaming. We applied the monitoring method to the system using a pressure time-series measured with pure water as the reference state. At a certain ethanol concentration, the method calculates an S-value larger than three (Figure 1). At this point, both time-series, reference, and evaluation differ significantly and the method detects a change in the hydrodynamics of the system as a result of the addition of the surfactant. Figure 1 also shows that the average pressure drop over the upper part of the column is not very sensitive to that change. In the homogeneous regime, the pressure signal measured at a height of 0.53 m resulted in the most sensitive S-value (see Figure 1). This might be due to the accumulation of surfactant in the upper part of the column.

To determine if the monitoring method could be used as an early warning indicator, we used the video recordings made during the experiments to observe the amount of foaming for each ethanol concentration. Figure 2 shows the S-values for pressure fluctuation measurements at 0.53 m together with pictures of the top of the column at several ethanol concentrations. It can be seen that only at the highest concentration serious foaming takes place. However, the monitoring method already exceeds the value three at much lower values. This indicates that the hydrodynamics already changes before foaming gives serious problems.

Foam detection in the heterogeneous regime

Similar experiments were carried out in the heterogeneous regime at a superficial gas velocity of 0.16 m/s. Figure 3 shows that already at low ethanol concentrations the S-value becomes larger than three. The change is sharper than in the homogeneous regime and the concentration where the change appears is lower. Again, the pressure drop does not clearly

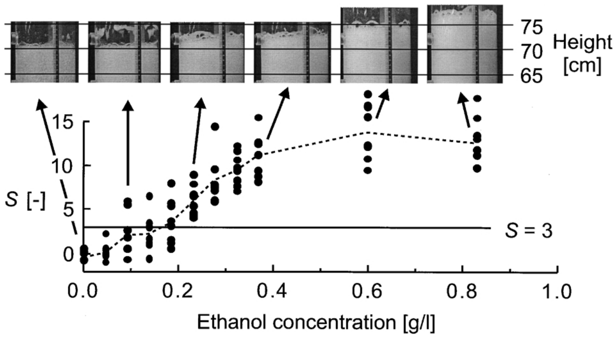

Figure 2. *S*-values and pictures from digital video recordings for the homogeneous regime.

The *S*-values are calculated for the pressure signal measured at 0.53 m above the distributor. The dashed line gives the average *S*-value. The photos give an indication of the upper liquid/foam level.

indicate a change in the hydrodynamics. Figure 3 shows that the pressure signals measured at 0.33 m yield the most sensitive *S*-values. This result was duplicated in various experiments; it was checked that it was not due to a difference in the sensors. Up to now, we do not yet have a clear explanation for the difference in the result for different measurement height. When the concentration of ethanol reaches 0.05 g/L, the *S*-value becomes larger than three, although no foam layer is yet visible. Therefore, we conclude that the monitoring method can be used as an early warning indicator for foam formation both in the homogeneous and the heterogeneous regime.

Conclusions

The monitoring method based on attractor comparison has been used for monitoring bubble column hydrodynamics. The method is based on reconstruction of the attractor from a pressure fluctuation signal measured in the bubble column; the attractor gives a representation of the dynamic state of the bubble column.

Experiments have been performed in which foaming was induced by adding small increasing amounts of ethanol to the water in the bubble column. The average pressure drop over the upper part of the bubble column does not give a clear indication of foaming. The monitoring method based on attractor comparison gives a warning before foaming gets serious (that is, before a growing foam layer has been observed) both in the homogeneous and the heterogeneous regime.

In future work, other foaming systems and more realistic situations will have to be considered. Moreover, the influence of the position of the pressure measurements on the outcomes of the monitoring method needs more investigation.

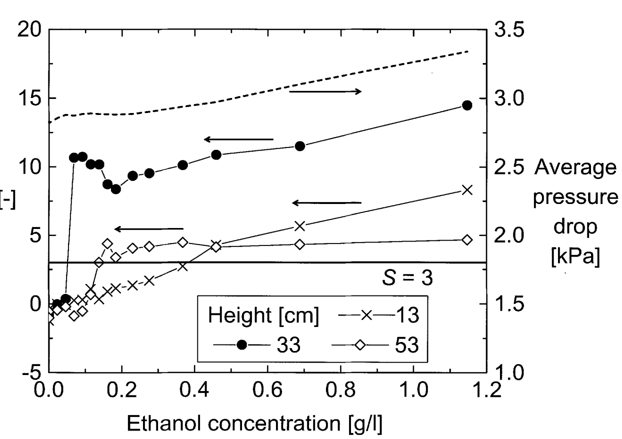

Figure 3. The average S-value and the average pressure drop (dashed line) as a function of the ethanol concentration in the heterogeneous regime.

The *S*-values are calculated for pressure fluctuations measured at three different heights; the average for eight values is given. The average pressure drop is measured over the upper part of the column.

Notation

d = band width for smoothing of points in the state space
m = embedding dimension
N_p = number of values in pressure time-series p
p_i = pressure value, Pa
Q = squared distance between two attractors
$\hat{Q}$ = estimator for Q
$\boldsymbol{R}$ = point in the state space
S = estimator for the normalized squared distance between two attractors
V = variance
x_k = normalized pressure value in reference time-series
$\boldsymbol{X}_i$ = vector of normalized pressure values in reference time-series
y_k = normalized pressure value in evaluation time-series
$\boldsymbol{Y}_i$ = vector of normalized pressure values in evaluation time-series
$\rho_x(\boldsymbol{X}_i)$ = distribution of set $\boldsymbol{X}$

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