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Effect of Sampling Frequency and Surfactants on Regime Transitions in Bubble Columns Using Differential Pressure Signals

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Abstract. In this paper, the influence of data sampling frequency and the inclusion of surface active agent on the flow pattern in bubble columns is investigated. The study is based on applying statistical, spectral and fractal metrics on recorder differential pressure measurements of air-water system. It is found that a highly sampled pressure signals can provide useful information using spectral and statistical tools, whereas a slowly sampled signal can only deliver meaningful details when spectral analysis is employed. Moreover, the addition of 5% polyethylene, which acts as coalescence inhibitor, to the air-water system showed a similar statistical and spectral behavior to that of sole air-water system. However, the averaged-frequency of the power spectra and the Hurst exponent managed to unfold the characteristics of flow regimes in both media and to disclose the discrepancy between coalescing (air-water) and the non-coalescing (5% polyethylene in air-water) solutions.

Keywords*:* Differential pressure, Bubble column, Hydrodynamics, Regime transition, Hurst analysis.

Introduction

Bubble columns are multiphase reactors that are widely used in the chemical and petrochemical industries. The success of bubble columns is attributed to the advantages they offer over the other kind of multiphase reactors. For example, they have simple construction, minimum mechanically vibrating parts, good heat and mass transfer properties, good mixing, low power requirements and high thermal stability [1]. Bubble columns are known to have complex hydrodynamic properties. Up to this point in time, it is found that three hydrodynamic flow patterns exist in these columns. The first is the homogeneous regime which occurs at low gas velocity followed by the transition region and then the heterogeneous regime which occurs at high gas velocities [2]. The bubble properties (such as bubble size, shape and velocity) play an important role in the column hydrodynamics. Other factors that influence the hydrodynamics of the column are the column geometry, sparger design, operating conditions, and physico-chemical properties of the gas-liquid phases. The variation of those parameters strongly affects the three flow regimes making the hydrodynamics more complicated. Consequently, further research and analysis to deeply understand the hydrodynamic behavior of bubble columns and its sources will enhance its operation, design and scale-up. For this reason, several techniques to measure the bubble size, shape and velocity were developed and tested. A review of these methods can be found elsewhere [3].

Recently, most of the work dealing with studying the bubble properties and/or flow transitions is centered on the measurement of gas hold up, pressure fluctuation and acoustic sound [4-10]. Several types of analysis tools were successfully applied to extract useful information from the previously mentioned measurements. Among these tools are statistical [8, 11, 12], spectral [8, 11, 12], fractal [8, 13], time series [8, 9] and deterministic chaos [4, 8, 11]. Al-Masry *et al.* [3] have employed the spectral analysis to acoustic sound measurements in air-water system to determine the bubble characteristics such as the bubble size, bubble distribution, and damping factor of the bubble oscillation. Al-Masry *et al.* [5] and Al-Masry and Ali [14] have extended the work to include the addition of coalescence and non-coalescence agents to air-water system. The influence of such surfactant compounds on the overall bubble characteristics was investigated. It is found that acoustic measurements and spectral tools are helpful to unfold valuable information about the bubble properties, especially the bubble size and its frequency of oscillation.

According to the various investigations mentioned above, the pressure fluctuation inside bubble columns has attracted a lot of attention. Unlike the gas holdup measurement, the pressure signals can provide more local (detailed) information. In fact, pressure fluctuation signals found to be strongly related to the gas holdup and liquid-phase circulation. Consequently, pressure fluctuation and/or differential pressure measurements were used to identify the flow regimes and transition points in bubble columns. Another attractive point is that such pressure transducers are commonly utilized in process industries because it is robust, cheap and well developed. A major difference between the pressure signals and acoustic signals is that the former is not used to infer information about the bubble size.

In the literature, the pressure signal was sampled at various frequencies ranging from 50 Hz to 800 Hz. No explanation was given upon how to select the suitable sampling rate. In another upcoming work [15], a sampling frequency of 10000 Hz was used to record the differential pressure signal from which the transition points were identified. In this paper, these results will be compared with that obtained from differential pressure signal sampled at 100 Hz in an attempt to explore the effect of the sampling rate. Moreover, the influence of injecting 5% by volume polyethylene in air-water system on the overall hydrodynamic properties will be investigated. In this regard, statistical, spectral and Hurst analysis will be applied.

Equipment and Experimental Methods

Schematic diagram of the experimental setup is shown in Fig. 1. Details of the experimental setup, and analysis can be found elsewhere [3, 5, 14]. In this work, pressure fluctuations were measured using two different techniques: form inside the column using miniature hydrophone, and from outside the column using differential pressure meter between two points at the column wall.

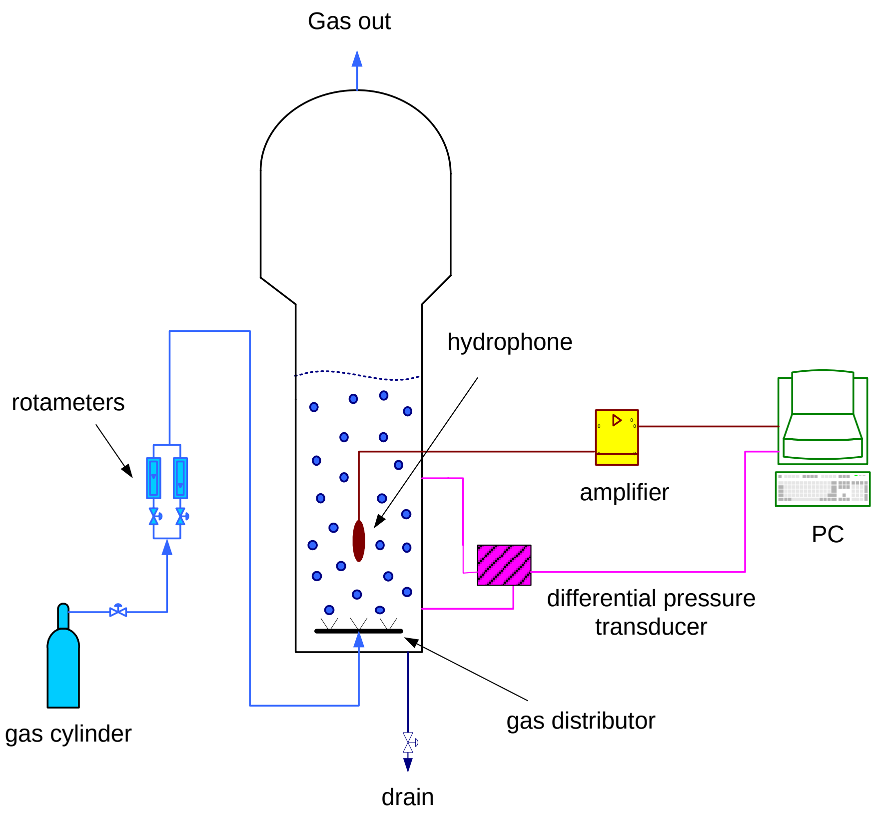

Fig. 1. Schematic diagram of the experimental setup.

Analysis Tools

Statistical tools

The third and fourth moments of the probability distribution (skewness and kurtosis) are used to analyze the pressure signals. In probability theory and statistics, skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable. Roughly speaking, a distribution has positive skew (right-skewed) if the right (higher value) tail is longer and negative skew (left-skewed) if the left (lower value) tail is longer. Skewness can be calculated from the following relation:

$$skewness = \frac{n}{(n-1)(n-2)} \sum_{i=1}^{n} \left(\frac{x_i - \bar{x}}{\sigma} \right)^3 \quad (1)$$

On the other hand, kurtosis is a measure of the "peakedness" of the probability distribution of a real-valued random variable. A high kurtosis distribution has a sharper peak and fatter tails, while a low kurtosis distribution has a more rounded peak and wider shoulders. The mathematical definition of kurtosis is given as follows:

$$kurtosis = \frac{n(n-1)}{(n-1)(n-2)(n-2)} \sum_{i=1}^{n} \left(\frac{x_i - \bar{x}}{\sigma} \right)^4 \frac{3(n-1)^2}{(n+2)(n+3)} \quad (2)$$

Hurst analysis

The rescaled range (Hurst exponent, ***H***) was initially proposed by Hurst [16] and was first applied by Fan *et al*. [17] to identify flow pattern in fluidized beds. Interested reader may refer to these references for details and background. The fractal method is usually employed to extract information about stochastic behavior of time series. When the time series contains both a rapidly and a slowly varying trend, Hurst exponent is able to distinguish the following situations:

- Long term trend: the future of a time series trends is similar to its past. In this case, the system is called persistent or positively correlated.
- Short term memory: the future of time series tends to oppose its past. In this case, the system is called anti-persistent or negatively correlated.

To compute the value of ***H***, the following procedure is usually adopted. The discrete random signal is divided into a set of sub-records of equal length, τ denoted as lag. For each sub-record, the standard deviation, *S* and cumulative range, *R* are calculated. The average of the two terms gives the rescaled value (R/S). Repeating the procedure for different values of the lag produces a series of values for R/S as a function of τ. The algorithm for computing the rescaled value is given in the appendix. Plotting R/S versus τ on a log scale gives a straight line. The Hurst exponent is thus the slope of the straight line.

According to Darhos *et al*. [13], for $H > 0.5$ denotes a persistent process, i.e. the process exhibits significant trend. For $H < 0.5$, the process behavior is anti-persistent, i.e. large positive value tend to be followed by large negative values. For the singular case $H = 0.5$, the process corresponds to uncorrelated Gaussian white noise. Despite the effectiveness of Hurst method in analyzing timer series signals, it suffers from a drawback such that it is sensitive to probe type and that calculations are highly time consuming [18]. It should be noted that Hurst analysis was used successfully to detect the effect of sparger design and surfactant solution on the bubble characteristic in bubble columns using acoustic sound measurements [14]. Here, Hurst effectiveness to detect the impact of sampling frequency and surface active solution using differential pressure measurements will be examined.

Results and Discussion

It is well known that the hydrodynamics of bubble columns can be described by three distinguished flow patterns [4]. The first flow pattern is the homogeneous regime which occurs at very low gas velocity and is characterized by uniform bubble size distribution. The coalescence and breakup of bubbles as well as liquid-phase circulation are negligible. As the gas velocity increases the system undergoes the transition regime where larger bubble formation and liquid-phase circulation starts. At high gas velocity, the liquid circulation becomes violent and larger bubble sizes are produced due to coalescence. At this stage, the homogeneous regime can not be maintained and thus wide bubble-size distribution is observed, i.e. the flow regime is heterogeneous. This phenomenon is observed by many researchers using wall pressure and differential pressure fluctuation. Statistical and spectral tools were applied to pressure signals. Negative peaks (valleys) or sudden changes in the statistical and/or spectrum trends are believed to indicate regime transition.

The effect of sampling frequency

Two signals of the differential pressure for air-water system are recorded. One pressure signal is sampled at 10 kHz frequency over a period of 10 sec. Another signal is sampled at 100 Hz over a period of 10 sec. In the literature, it is reported that various sampling frequencies ranging from 50 to 800 Hz were used. The pressure trends in this paper are mean removed for fair comparison. First, the effectiveness of the two signals will be compared using statistical tools. The 100 Hz signal can capture any fluctuation with a frequency less than 50 Hz. On the other hand, the 10 kHz signal provides information up to 5000 Hz. Although the source of high frequency components in the pressure signal is not known, it is found to provide useful information as discussed in the next sections.

The second, third and fourth moments of the differential pressure is demonstrated in Fig. 2. It is expected that the deviation of the pressure signal from its mean will increase as gas flow increase because of growing fluid circulation and bubble-induced level fluctuation. Therefore, the standard deviation is expected to increase monotonically. Moreover, Gourich *et al.* [1] have shown that for air-water system, the standard deviation for differential pressure is constant at velocity below 4 cm/s, gradually increasing between 4 and 7 cm/s and then remain constant above 7 cm/s. They concluded that σ increase rapidly in the transition region and slowly in the heterogeneous regime. The dotted line in Fig. 2 represents the pressure signals sampled at 100 Hz while the solid line represents the pressure signal sampled at 10 kHz. As far as the standard deviation is concerned, the trend for 100 Hz and 10 kHz agrees with that reported by Gourich *et al*. [1]. Unlike the trend using 100 Hz that shows smooth increasing curve, the trend for 10 kHz provides interesting information with respect to regime transition. For example, a sudden drop in σ is observed at 3.7 cm/s and another at 5.8 cm/s. This variation in the data structure could be the result of a change in the flow behavior. These values coincide with the critical velocities found in the literature [1, 13] and with that found be chaos analysis [14].

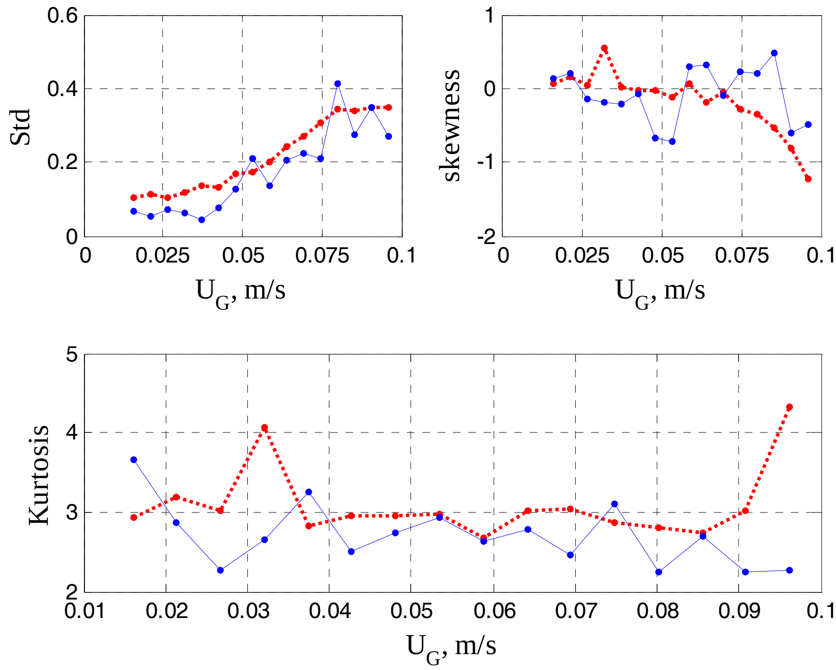

Fig. 2. Statistical analysis of the differential pressure signals; (dotted) 100 Hz, (solid) 10 kHz.

The superiority of the 10 kHz signal over the 100 Hz in the sense of providing useful details continues even for the second and third moments. Skewness for 10 kHz, for example, maintain a negative value between 2.7 cm/s and 5.3 cm/s and almost a positive value afterward except at very high gas flow. Interestingly, a pronounced change from negative to positive skew value occur between 5.3 and 5.8 cm/s which complements the result obtained from the standard deviation. The kurtosis moment delivered oscillating trend, but again with distinct peaks at 3.7 cm/s and 5.3 cm/s. These peaks in kurtosis indicate that the pressure signal has a distinct distribution in the transition region that distinguish it form the other regimes. Conversely, the skewness and kurtosis for the 100 Hz signal delivered no significant details. The ability of the 10 kHz signal to have distinguished peaks and valleys can be attributed to the combined effect of high and low frequencies that exist in the signal. This observation is more obvious when the spectral analysis of these signals is discussed.

The spectral analysis of the two signals is shown in Figs. 3 and 4. In Fig. 3, slow sampling frequency is used, thus only low frequency component can be captured and displayed. The figure does not show frequencies higher than 10 because no significant peaks were observed. In this figure, two dominant frequencies can be observed. A peak at very small frequency of around 0.5 Hz and another peak at small frequency of around 3 Hz is reported. The first peak is attributed to liquid level fluctuation and the second is due to fluid circulation known also as macro-structure. In the literature, the level circulation fluctuates at 0.1 Hz and the liquid circulation at 3-5 Hz [8]. Both peaks grow up as the gas velocity increases with the first peak being greater in magnitude than the second peak up to gas velocity of 6.9 cm/s. Interestingly, the intensity of the first peak drops at 2.6 cm/s and again at 5.3 cm/s and the second peak becomes greater than the first peak starting from 7.4 cm/s. These critical values may designates regime transition points and agree well with what was mentioned earlier. On the other hand, Fig. 4 shows the result when high sampling frequency is used. It is clear that low frequency components are overshadowed by the peaks that occur at high frequencies which are primarily due to noise or other high frequency components.

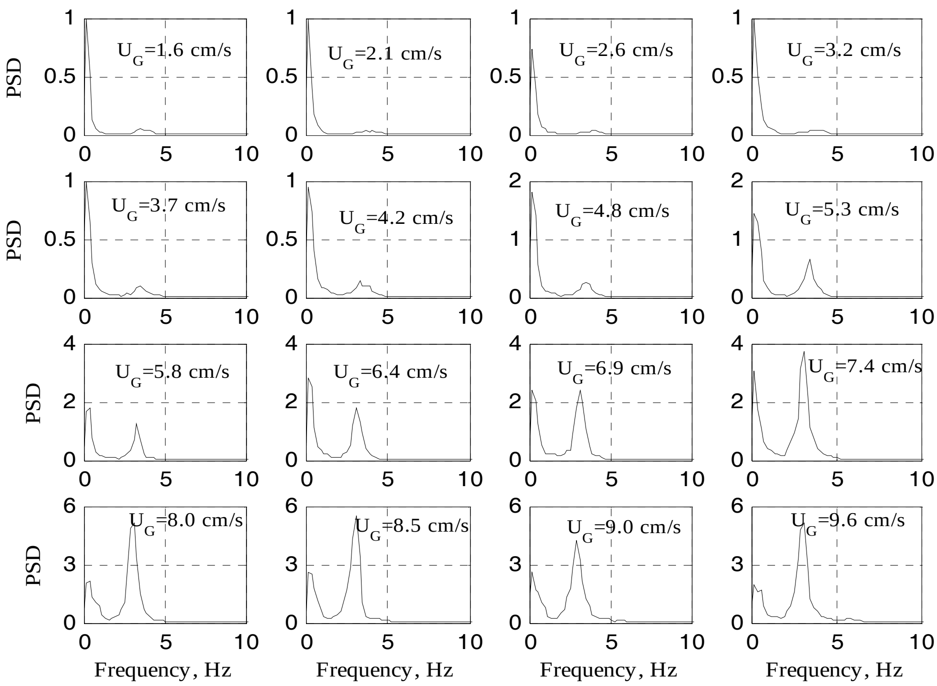

Fig. 3. Spectral density for water using 100 Hz sampling frequency.

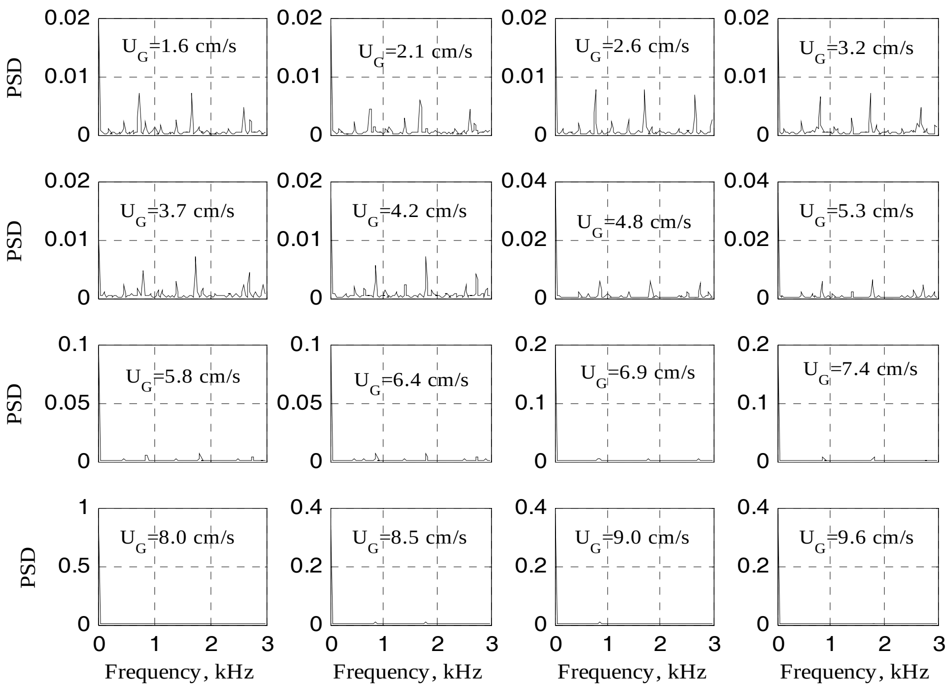

Fig. 4. Spectral density for water using 10 kHz sampling frequency.

It can be argued that spectral analysis can deduce useful information for both slowly and rapidly sampled pressure signals. However, the statistical analysis is only helpful for rapidly sampled signals. Letzel *et al*. [11] used a sampling frequency of 200-800 Hz and Drahos *et al*. [12] used a sampling frequency of 50 Hz and they both have reported that no significant information about regime transitions can be obtained using the statistical tools.

For further investigation, the fractal analysis of the pressure fluctuation signals is considered. Figure 5 depicts the evolution of *H* as a function of the superficial velocity. In this case, Hurst analysis showed that the slowly sample pressure signals is highly persistent and that it becomes even more persistent as gas velocity increases. In the opposite anti-persistent character is recorded for the highly sampled pressure fluctuation. This is consistent with the shape of the power spectra shown in Fig. 4. The very high frequency components of the spectra resembled a random noise to the trend. Hence, the signals behaved more stochastic or equivalently anti-persistent. The pronounced persistent character of the slowly sampled signal at elevated gas velocity can be attributed to the presence of large bubbles. This is because large bubbles induce high fluctuation in the level surface and consequently pressure fluctuations become progressively more correlated [1]. This phenomenon can also be observed for the highly sampled pressure signals, however, the randomness of the high frequency band weaken the correlations.

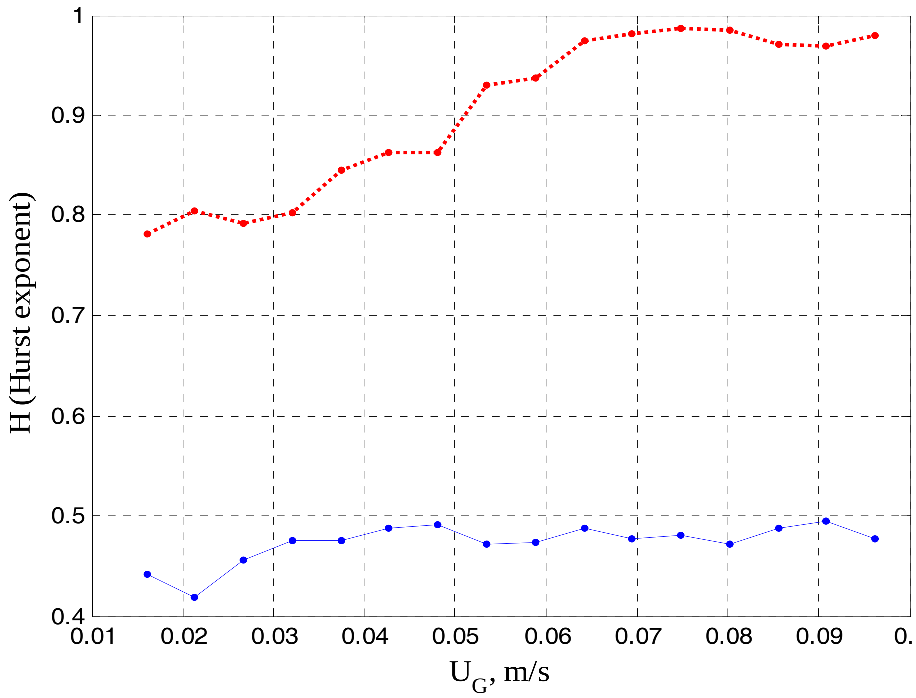

Fig. 5. Hurst exponent; (solid): 10 kHz, (dash): 100 Hz

Effect of surfactant agents

As mentioned earlier, the physico-chemical properties of the liquid phase influence the hydrodynamic characteristics. Here, the effect of adding 5% polyethylene to the air-water system is studied. For all cases, 100 Hz sampling frequency will be utilized because it is within the range of values used in the literature. Traces of polyethylene should act as a coalescence inhibitor and thus the system should exhibits a prolonged homogeneous regime. The comparison of the statistical moments of the air-water system with the air-water-polyethylene solution is shown in Fig. 6. Obviously, the standard deviation and skewness delivered almost the same trend for both systems. Although kurtosis showed slightly different results, no valuable signs can be extracted from the entire statistical parameters.

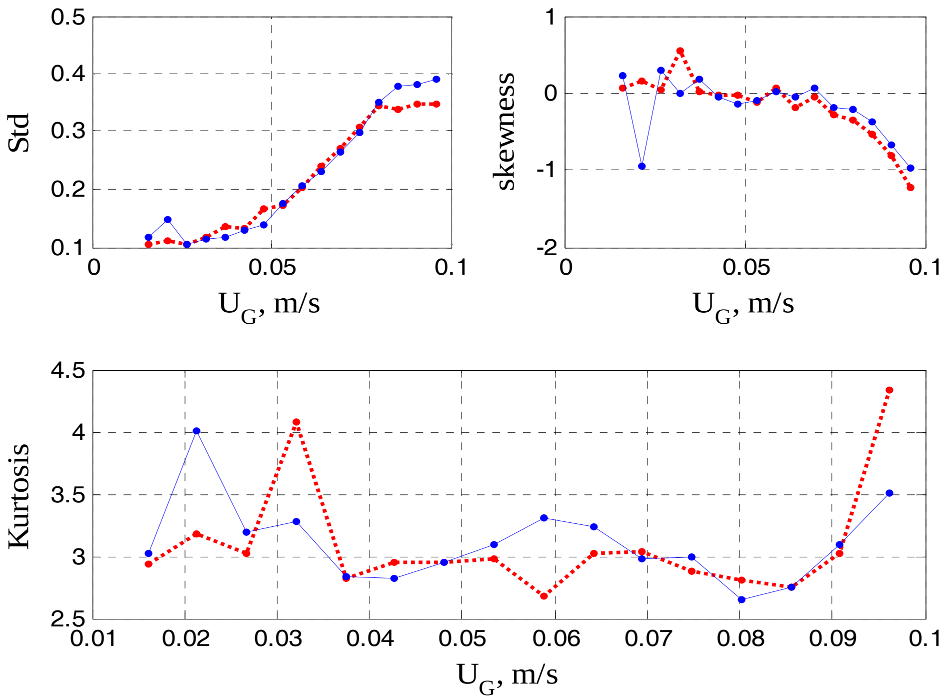

Fig. 6. Statistical moments of the differential pressure signals; (dotted) water, (solid) 5% polyethylene.

Next, Fig. 7 shows the power spectrum of the pressure fluctuation for the 5% polyethylene solution. To assess the impact of the tensioactive agent, the power spectrum of Fig. 7 should be compared to that of Fig. 3. It is clear that the spectral densities are almost the same. The only observation is that in the presence of surface active species, the intensity of the liquid circulation propagates rapidly starting from 4.8 cm/s. Because polyethylene traces degrade coalescence behavior, the gas holdup increases in the homogeneous region. The latter may cause higher bubble-induced circulation. As mentioned, comparing the spectrum for differences is somewhat tricky. Therefore, the average dominant frequency can be computed using the following rule:

$$f_m = \frac{\sum_{i=1}^{nc} f_i n(f_i)}{\sum_{i=1}^{nc} n(f_i)} \tag{3}$$

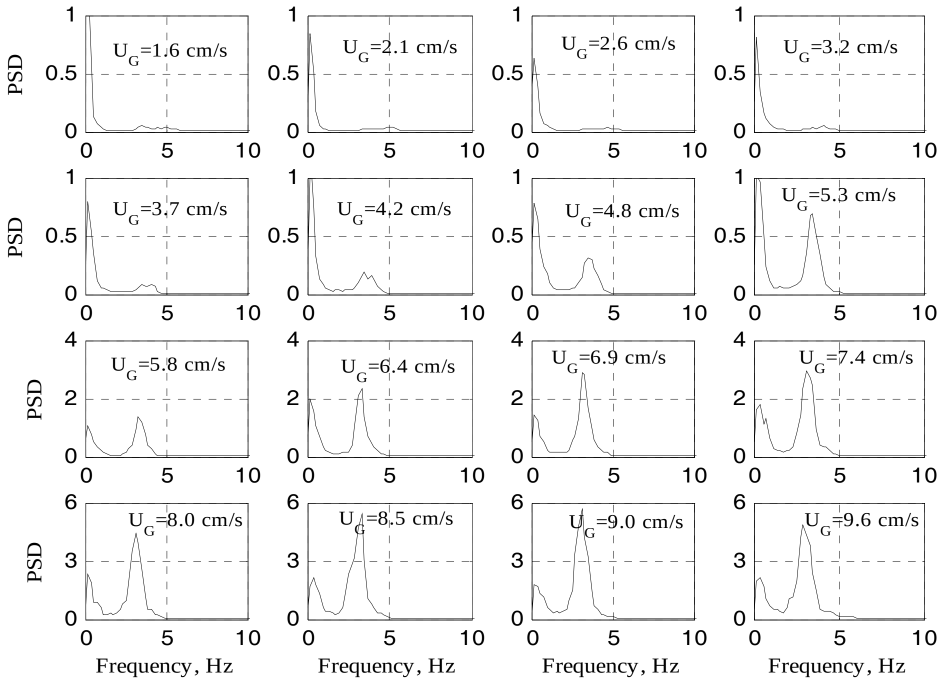

Fig. 7. Spectral density for 5% polyethylene using 100 Hz sampling frequency.

Applying the above rule produces the average frequency shown in Fig. 8. Clearly, both average spectral frequency starts from a small value around 0.9 Hz at low gas velocity and grows until it reaches a larger value around 2.6 Hz at high gas velocity. The low frequency band is due to the fact that at low gas velocities the spectra are dominated by the liquid level fluctuation. Conversely, at high gas velocities, the frequency of the liquid circulation prevails and hence larger frequency band is typical. Note that the average value for the liquid circulation frequency is 2.6 Hz, but the true value which is detected from the spectral density in Figs. 3 and 7 is 3 Hz. The latter is in a good agreement with the reported value in the literature. By inspecting the average frequency trend for air-water system, it is observed that the average frequency remain nearly constant up to 3.7 cm/s where it starts escalading rapidly. Similarly, for the polyethylene case, the evolution of average frequency increases gradually with gas velocity till the critical velocity of 3.7 cm/s. Afterward, the average frequency increases rapidly in the transition region. The critical point of 3.7 cm/s corresponds probably to the end of the homogeneous regime. Note that the averaged frequency for air-water system is slightly lower than that for polyethylene solution. It can not be assured that this is due to the coalescence behavior of the liquid phase because the difference is marginal and may fall within the acceptable numerical and experimental errors.

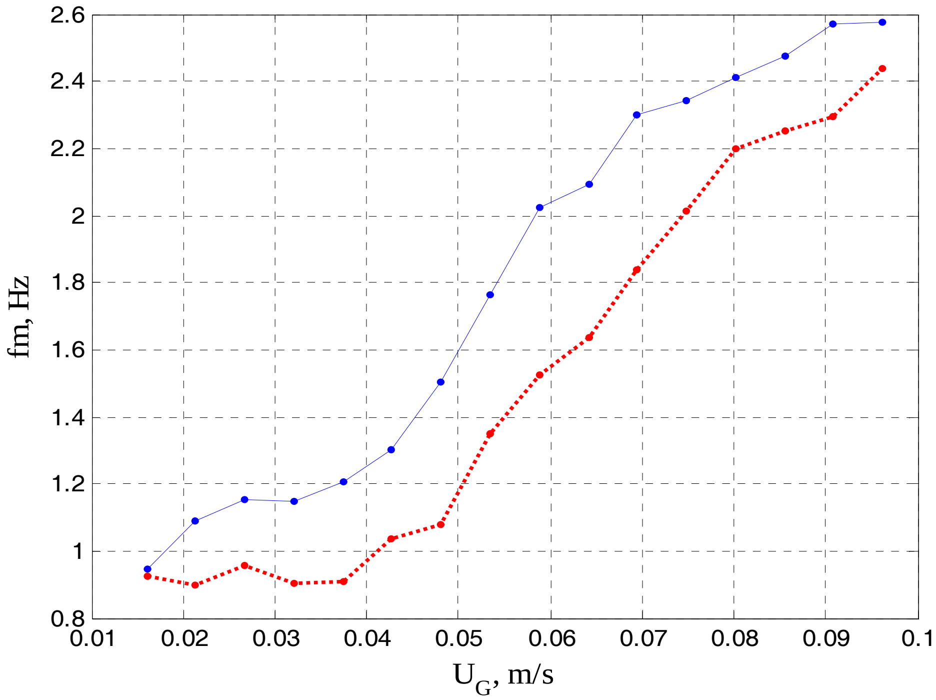

Fig. 8. Average spectral frequency; (dotted) water, (solid) 5% polyethylene.

Next, the attention is shifted to examine the Hurst exponent. Fig. 9 illustrates the variation of *H* with the superficial velocity for air-water and air-water-polyethylene solution. Evidently, for both cases Hurst exponent shows moderate correlation at low gas velocity (i.e. at homogeneous flow) and pronounced correlation at high gas velocity (i.e. at heterogeneous flow). More important is that the curves identify two regime transition points. For example, at gas velocity of 3.7 cm/s both curves start inclining rapidly through the transition region. When the Hurst drift reaches a value between 5-6 cm/s, which is believed to mark the beginning of the heterogeneous regime, the response slows down and alternates around a constant value. These critical values for the gas velocity matches those found earlier in this work and previous works. The inspection of Fig. 9 further demonstrates minor differences in the Hurst trend at low and high gas velocities. At low gas velocity, the non-coalescence behavior of polyethylene creates more uniform small bubble sizes than air-water system does. In this case, the pressure signals become highly persistent. At high gas velocity, the bubble collision induced by increasing fluid-circulation and holdup alleviates the non-coalescence effect. As a result, bubble heterogeneity prevails and the holdup in the polyethylene case drops reducing the persistent correlation. Our observation coincides with that reported by Gourich *et al.* [1]. Their results show that the pressure signal is only slightly persistent at low gas velocity and highly correlated at elevated gas velocity. They noted that for air-water system, Hurst exponent increase sharply at around 4 cm/s followed by gradual increase up to 7 cm/s where it almost settles down afterward. For 5% propanol solution, which is also a coalescence inhibitor, the sudden increase in *H* occurs at delayed gas velocity of 7 cm/s. It follows that Hurst analysis does not only identify the flow pattern in bubble columns, but also can distinguish the influence of surfactant solutions.

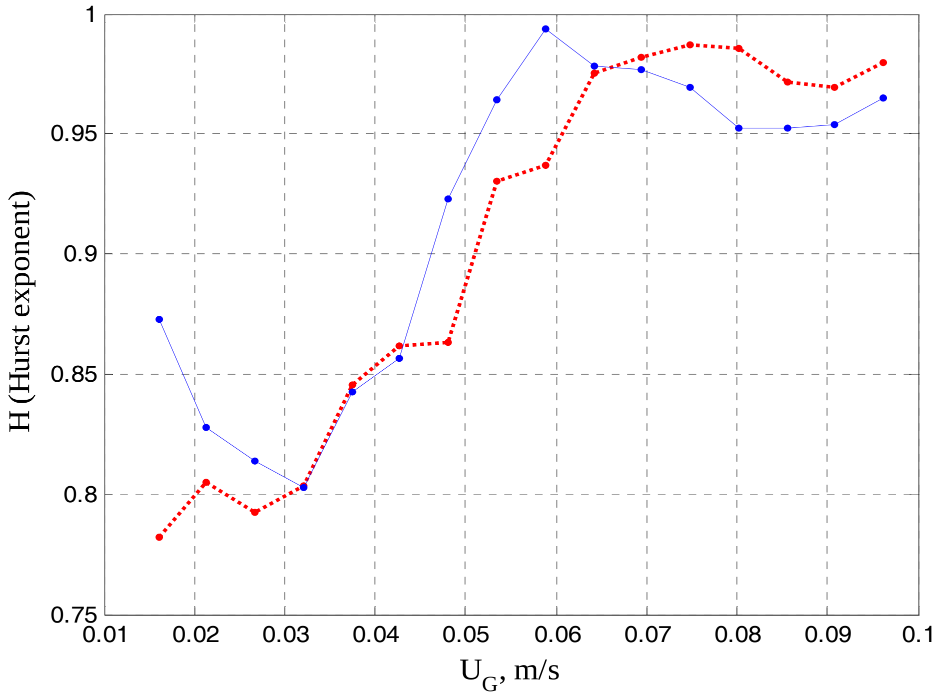

Fig. 9. Hurst exponent, (dotted) water, (solid) 5% polyethylene.

Conclusions

This paper investigates the hydrodynamic characteristics of bubble columns using differential pressure measurements. Specifically, statistical, spectral and fractal analyses were applied for this regard. Specifically, the effect of two sampling frequencies namely, 100 and 10000 Hz, on the flow regimes was examined. The statistical analysis demonstrated that the rapidly sampled data can provide useful information, whereas the slowly sampled data fails. The spectral analysis indicated that both signals can help in identifying the regimes transition points. The fractal analysis indicated that the slowly sampled signal is highly persistent, whereas the rapidly sampled signal is anti-persistent. However, no clear information about the flow pattern can be deduced from these trends.

Furthermore, the effect of the surfactant solution such as polyethylene is studied. It is found that both the statistical moments and power densities provided almost the same character for the coalescence and non-coalescence solutions and that no significant details about the flow regimes can be extracted. On the other hand, the averaged frequency of the power spectra and the Hurst exponent were able to detect the critical velocities at which the transition occurs. Moreover, these tools were able to show some discrimination between the coalescence and non-coalescence media.

Notation

f frequency, Hz
n number of bubble pulsation
N number of data points
x time series signal
U_G superficial gas velocity, cm/s
σ standard deviation

Appendix

Hurst analysis calculations are as follows (Vial *et al*. [8]):

1. Divide the time series in N intervals of length τ called subperiod.
2. For each sub-period k:
    a. Calculate the signal average:

    $$\overline{x_k} = \frac{1}{\tau}\int_{t_k}^{t_k+\tau} x(t)dt$$

    b. Calculate the standard deviation of the signal:

    $$S_k = \left[\frac{1}{\tau}\int_{t_k}^{t_k+\tau}\left(x(t)-\overline{x_k}\right)dt\right]^{0.5}$$

    c. Calculate the accumulated departure from the average:

    $$X_k = \int_{t_k}^{t_k+\tau}\left(x(u)-\overline{x_k}\right)du$$

    d. Calculate the range R_k

    $$R_k = \max_{0\le t\le\tau} X_k(t) - \min_{0\le t\le\tau} X_k(t)$$

    e. Calculate the rescaled range $(R/S)_k$

    $$\left(R/S\right)_k = \frac{R_k}{S_k}$$

3. Average the $(R/S)_k$ obtained for the N sub-periods

$$\left(R/S\right)_\tau = \frac{1}{N}\sum_{k=1}^{N}(R/S)_k$$

Repeat the procedure for different time lags.

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تأث تواتر أخذ العينات وا ؤثرات السطحية على تغ نظام السريان أعمدة الفقاعات باستخدام إشارات فرق الضغط

وحيد عطية ا صري و عماد مصطفى علي

قسم الهندسة الكيميائية ، كلية الهندسة ، جامعة الملك سعود

ص ب ٨٠٠ الرياض ١١٤٢١ ، المملكة العربية السعودية

(قدِّم للنشر في ٢٠/٠٩/٢٠٠٦م ؛ وقبل للنشر في ٢٧/٠١/٢٠٠٧م)

ملخص البحث. تم في هذه الورقة دراسة تأثير تواتر أخذ العينات في وجود المؤثرات السطحية الكيميائية على تغير نظام السريان في أعمدة الفقاعات. اعتمدت الدراسة على تطبيق طرق إحصائية وطيفية وجزئية على إشارات فرق الضغط المسجلة في نظام الماء والهواء. لقد وجد أن التواتر العالي لأخذ العينات يمكن أن يعطي معلومات مفيدة باستخدام الوسائل الطيفية والإحصائية، بينما وجد أن التواتر المنخفض يعطي معلومات مفيدة إذا استخدمت الطرق الطيفية فقط. إضافة إلى ذلك، لقد وجد أن إضافة ٥٪ بولي إيثيلين - والذي يعمل كمثبط لالتصاق الفقاعات لنظام الماء والهواء – يعطي نتائج إحصائية وطيفية مماثلة لنظام الماء والهواء فقط، لكن وجد أن استخدام متوسط التواتر لقوة الطيف واس الهيرست أمكنا من إيضاح الخصائص والتعارضات بين نظام السريان في كلا الوسطين السائلين المساعد للالتصاق (الماء والهواء) والمانع للالتصاق (٥٪ البولي إيثيلين إلى الماء والهواء).