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FRACTAL ANALYSIS OF PRESSURE FLUCTUATIONS IN A THREE PHASE BUBBLE COLUMN REACTOR OPERATING AT LOW PRESSURE

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Abstract – Pressure fluctuations in a three phase bubble column reactor operating at relatively low pressure (92 KPa) have been analyzed by adopting the spectral and fractal analyses to get the engineering informations for the on-line control and fault diagnosis of the reactors. The mean value, standard deviation, skewness and kurtosis of the pressure fluctuations have been obtained. The local fractal dimension has been determined from the Pox diagram obtained by means of the rescaled range analysis of the pressure fluctuations based on the fractional Brownian motion. The local fractal dimension of pressure fluctuations has increased and thus the pressure fluctuation signals have become less persistent and irregular, with increases in the gas flow rate reaction temperature, particle size and solid content in the slurry phase. The local fractal dimension has been well correlated in terms of the operating variables.

Key words: Fractal Analysis, Three Phase, Bubble Column, Low Pressure, Pressure Fluctuations

INTRODUCTION

Bubble columns have been widely adopted for reactors and contactors by taking advantage of their several unique features such as effective gas-liquid or gas-liquid-solid contact, high rates of heat and mass transfer, simple construction and easy continuous operations [Shah et al., 1982; Deckwer, 1992; Deckwer and Schumpe, 1993; Kim and Kang, 1995]. Since the bubble column generally comprises gas bubbles as a dispersed phase flowing upward in the continuous liquid medium, it can be utilized effectively as a reactor to remove the water vapor continuously generated during the dehydration of ortho-boric acid [Shim et al., 1994; Kang et al., 1995a]. Although the performance of bubble column reactor operating at atmospheric or higher pressures has been studied by several investigators[Shah et al., 1982; Idogawa et al., 1986; Kang et al., 1990; Suh et al., 1991; Deckwer and Schumpe, 1993], there has been little attempt focused its attention on the bubble column reactor or contactor operating at relatively low pressure as in the case of dehydration of ortho-boric acid [Kang et al., 1994, 1995].

In the bubble column reactor, bubble properties have been regarded as the fatal elements to determine the hydrodynamic characteristics of it. Thus, several investigators [Yu and Kim, 1991; Prince and Blanck, 1990] have examined the bubble properties and its flow behavior in bubble columns. However, the effects of bubble properties on the performance of bubble column reactors or contactors have not been well recognized until now because of highly complicated, nonlinear and stochastic behavior of bubbles in the column.

Recent works on the multiphase flow systems [Fan et al., 1990, 1993, 1995; Yashima et al., 1992; Kwon et al., 1994; Kang et al., 1994, 1995b; Drahos et al., 1992; Luewisuthichat et al., 1995] have indicated that the concept of fractional Brownian motion can be applicable to the analysis of the overall multiphase flow behavior in the three phase bubble column reactor.

In the present study, the pressure fluctuations in three phase bubble column reactor, which is operating at low pressure to perform the dehydration of ortho-boric acid, have been analyzed by resorting to the spectral and fractal analyses. The mean value, standard deviation, skewness and kurtosis of the pressure fluctuations have been obtained. The local fractal dimension has been determined from the Pox diagram obtained by means of the rescaled range analysis of the pressure fluctuations based on the concept of fractional Brownian motion. The local fractal dimension has been correlated in terms of the operating variables. The results can serve us with engineering informations on the on-line control and fault diagnosis of the three phase bubble column reactor.

ANALYSIS

1. Spectral Analysis

The pressure fluctuation signals, X(t), which can represent the historical random data can be effectively processed by means of spectral analysis [Bendart and Piersal, 1980; Yoon et al., 1995].

The mean value of the ensemble of the pressure fluctuations can be obtained as Eq. (1)

$$X_M = \int_{-\infty}^{\infty} X(t)P(X)\ dx \tag{1}$$

Where P(X : t) is the first probability density function.

If the P(X : t) is independent of time it can be written as P (X), and the system is ergodic and stationary state. Then, the mean value, variance, skewness and kurtosis of the X(t) can be calculated from the following equations, respectively

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$$X_M = \int_{-\infty}^{\infty} X(t)P(t)\ dx \tag{2}$$

$$\sigma^2 = \int_{-\infty}^{\infty} (X - X_M)^2 P(X)\ dx \tag{3}$$

$$S = \frac{1}{\sigma^3} \int_{-\infty}^{\infty} (X - X_M)^3 P(X)\ dx \tag{4}$$

$$K = \frac{1}{\sigma^4} \int_{-\infty}^{\infty} (X - X_M)^4 P(X)\ dx \tag{5}$$

2. Fractal Analysis

The sample of the subrecord and sample sequential range have been defined and constructed to obtain the fractal dimension of pressure fluctuations [Feder, 1988; Fan et al., 1990, 1993; Kang et al., 1994, 1995b]. For a given time series of the recorded pressure fluctuations, X(t), evenly spaced in time from t=1 to t=T, their mean values within the subrecord from time (t+1) to time (t+τ) have been obtained. And the cumulative departures of X(t+u) from the mean, $<X(t)>_\tau$, for the subrecord have been determined as Eq. (6).

$$C(t,u) = [X^*(t+u) - X^*(t)] - (u/\tau)[X^*(t+\tau) - X^*(t)] \tag{6}$$

where $X^*(t)$ is defined as

$$X^*(t) = \sum_{u=1}^{t} X(u) \tag{7}$$

The sample sequential range, R(t, τ), is defined as the difference between the maximum and the minimum values of the cumulative departure of X(t+u) from the mean for the subrecord.

Moreover, the sample sequential variance of the subrecord from time (t+1) to (t+τ) can be written as

$$S^2(t, \tau) = \frac{1}{\tau}\sum_{u=t+1}^{t+\tau} X^2(u) - \left[\frac{1}{\tau}\sum_{u=t+1}^{t+\tau} X(u)\right]^2 \tag{8}$$

Thus, the ratio, R(t, τ)/S(t, τ) can be obtained and is termed the rescaled range. This ratio has been found as a power function of τ [Feder, 1988] as,

$$\frac{R(t, \tau)}{S(t, \tau)} \propto \tau^{2-D_F} \tag{9}$$

where D_F is the local fractal dimension of the time series.

EXPERIMENT

Experiments were carried out in a Plexiglas column (0.05 m i.d.×1 m high) as can be seen in Fig. 1. A sintered plate which was made of 0.1 mm glass powder served as the gas distributor. The distributor was situated between the main column and a 0.1 m high stainless steel distributor box into which the air was fed from the compressor. The air was filtered and controlled by means of an air filter and regulator, and its flow rate was measured by a calibrated rotameter connected to the feed line.

A condenser was installed at the top of the column, and it was connected to a three-neck flask and a two-neck flask orderly to obtain the water evaporated. The air in the sealed column was withdrawn by means of a vacuum pump connected to the end of the two-neck flask to maintain the reaction pressure at a constant value.

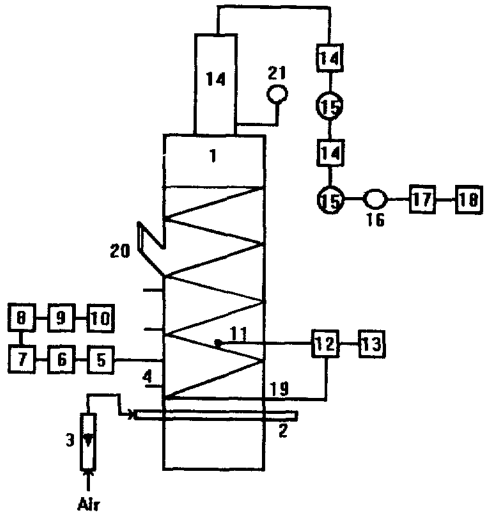

Fig. 1. Schematic diagram of experimental apparatus.

1. Reactor
2. Distributor
3. Rotameter
4. Pressure tap
5. Pressure transducer
6. Amplifier
7. Oscilloscope
8. Filter
9. A/D converter
10. Computer
11. Thermocouple
12. Digital relay
13. Temperature
14. Reflux condenser
15. 3-neck flask
16. Filter & regulator
17. Vacuum pump
18. Controller
19. Heating mantle
20. Feed inlet
21. Pressure gauge

To adjust the reaction temperature the column was fitted with a heating mantle which was controlled by a temperature control system. The particle size of the ortho boric acid was in the range of $0.09\text{-}0.6\times10^{-3}$ m, and n-paraffin liquid had a density of 820 kg/m^3 and a surface tension of 22.01×10^3 N/m. The flow rate of oil-free compressed air was in the range of 0.03-0.08 m/s, and the range of reaction temperature was 125-145°C. The reaction pressure was maintained at 92 KPa, which was known to be the optimum condition in the continuous stirred tank reactor [Kodo et al., 1975; Kang et al., 1995a]. The solid content in the slurry phase was varied from 8 to 38 wt% of the liquid phase.

The pressure fluctuations were measured by pressure sensor (Copel Electronics) through pressure taps located at 0.05 m and 0.1 m from the distributor, at the wall of the column. The pressure transducer produced an output voltage proportional to the pressure fluctuation signal. The signal was processed by a data acquisition system (PCLS-805) and a personal computer. The voltage-time signals, corresponding to the pressure-time signal, were sampled at a rate of 0.03 sec and stored in the data acquisition system. A typical sample comprized 3000 points. This combination of sampling rate and sample length ensured that the full spectrum of hydrodynamic signals, typically 30 Hz, was captured from the three-phase bubble column reactor.

RESULTS AND DISCUSSION

Typical pressure fluctuation signals in three phase bubble

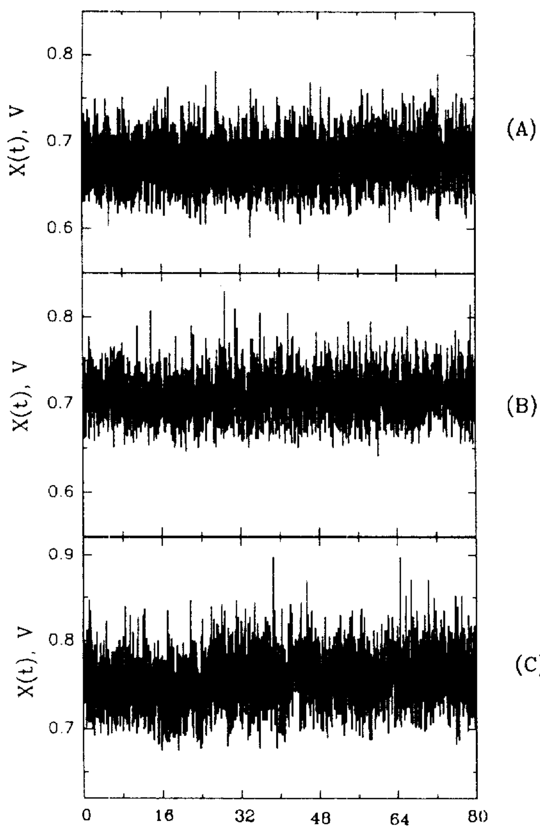

Fig. 2. Typical examples of pressure fluctuations from three phase bubble column reactors (U_G=0.06 m/s, t=40 min, P=92 KPa, S=28 wt%, d_p=2.15×10^{-4}m).
(A) T=125°C, (B) T=135°C, (C) T=145°C

column reactors operating at relatively low pressure (92 KPa) can be seen in Fig. 2. The operating pressure of this study has been maintained at 92 KPa, since this condition has been known to be optimum for the dehydration of ortho boric acid [Kodo et al., 1975; Kang et al., 1995a]. It can be seen in this figure that the variation of reaction temperature can affect the pressure fluctuations and thus hydrodynamics of multiphase flow in the bubble column reactor.

Effects of gas flow rate, U_G, on the characteristics of pressure fluctuations such as mean value, standard deviation, skewness and kurtosis can be seen in Fig. 3. It can be indicated from these figures that the mean value, standard deviation and skewness of the pressure fluctuations in the test section have increased, while the kurtosis of them has decreased, with an increase in the gas flow rate. The increase of mean value can be due to that the fraction of the boric acid particle can increase in the test section owing to the increase of bed expansion with increasing the gas flow rate in the column. The increases of standard deviation and skewness with gas flow can be explained that the increase of gas flow rate results in the increases in the volume and number of bubbles existing in the bubble column, which can lead to the more vigorous contact among multiphases, and thus the distribution of bubble size is less uniform and more fluctuating. The broad bubble size distribution results in the decrease in the kurtosis of pressure fluctuation signals as can be seen in the figure.

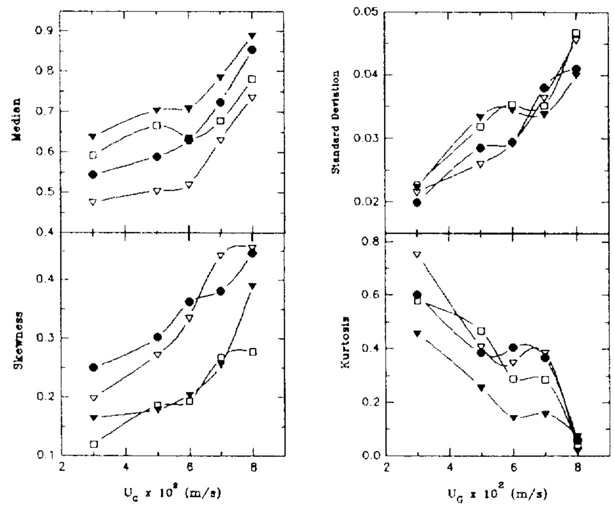

Fig. 3. Effects of U_G on median, standard deviation, skewness and kurtosis of pressure fluctuations from three phase bubble column reactors (t=40 min, P=92 KPa, S=28 wt%, T=140°C).

	●	▽	▼	□
d_p × 10^3 (m):	0.215	0.215	0.375	0.37
probe height (m):	0.05	0.10	0.05	0.10

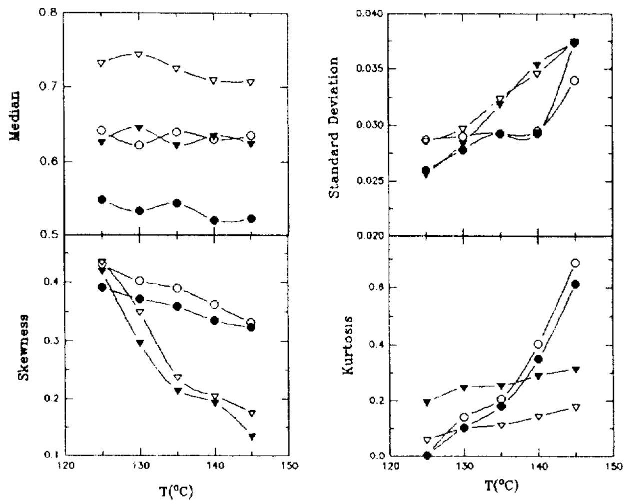

Fig. 4. Effects of T on median, standard deviation, skewness and kurtosis of pressure fluctuations from three phase bubble column reactors (U_G=0.06 m/s, t=40 min, P=92 KPa, S=28 wt%).

	○	●	▽	▼
d_p × 10^3 (m):	0.215	0.215	0.375	0.37
probe height (m):	0.05	0.10	0.05	0.10

Effects of reaction temperature on the characteristics of pressure fluctuations in the bubble column reactor can be seen in Fig. 4. Note in this figure that the mean value is not affected significantly, however, the standard deviation and kurtosis have increased but the skewness has decreased with an increase in the reaction temperature. It can be anticipated from these figures that the increase of reaction temperature can lead to more rapid reaction among multiphases, however, it can not affect the phase holdup in the test section. And the pressure fluctuations become symmetric and the distribution of it become

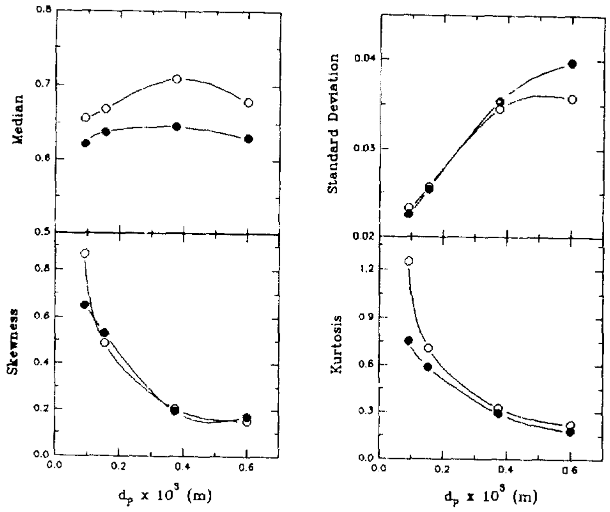

Fig. 5. Effects of d_p on median, standard deviation, skewness and kurtosis of pressure fluctuations from three phase bubble column reactors (U_G=0.06 m/s, t=40 min, P=92 KPa, S=28 wt%, T=140°C).

	○	●
probe height (m):	0.05	0.10

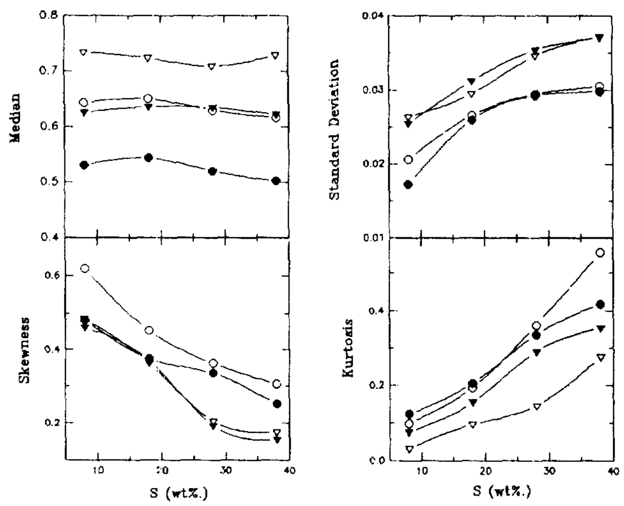

Fig. 6. Effects of S on median, standard deviation, skewness and kurtosis of pressure fluctuations from three phase bubble column reactors (U_G=0.06 m/s, t=40 min, P=92 KPa, T=140°C).

	○	●	▽	▼
$d_p \times 10^3$ (m):	0.215	0.215	0.375	0.37
probe height (m):	0.05	0.10	0.05	0.10

narrow, with an increase in the reaction temperature.

In a given gas flow rate, the increase of particle size can increase the mean value of pressure fluctuations only slightly and it has increased the standard deviation, while it has decreased the skewness and kurtosis of pressure fluctuations, as can be seen in Fig. 5. These implies that the increase of particle size of ortho boric acid makes the pressure fluctuations in the bubble column reactor less symmetric and more scattered from the mean position.

Effects of solid content in the slurry phase on the pressure fluctuations can be seen in Fig. 6. In these figures, the standard deviation and kurtosis of pressure fluctuations have increased,

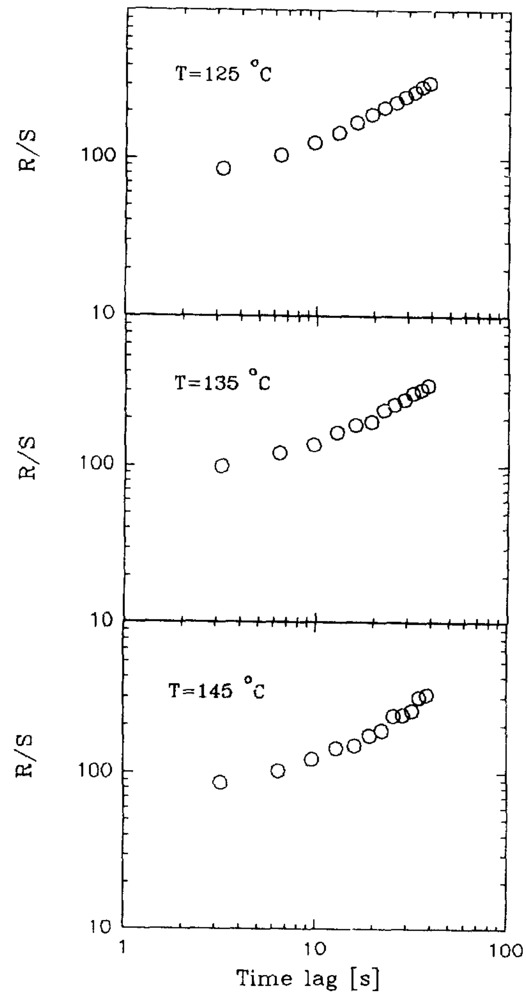

Fig. 7. Pox diagram of pressure fluctuations with the variation of reaction temperature from three phase bubble column reactors (U_G=0.06 m/s, P=92 KPa, t=40 min, S=28 wt%, d_p=2.15×10^{-4}m).

while the skewness of them has decreased, with an increase in the weight percent of ortho boric acid to the normal paraffin. It can be noted from these figures that the pressure fluctuations become symmetric and the narrow distributed but the bubble size would be larger, with increasing the solid content in the slurry phase.

The complex and irregular behavior of pressure fluctuations can be analyzed more conveniently and quantitatively by resorting to the fractal analysis; the pressure fluctuation signals have been analyzed by construction of the sample and rescaled ranges, to obtain the Pox diagram representing the non-linear behavior of the signals [Fan et al., 1990, 1991, 1993; Kwon et al., 1994]. As can be seen in Fig. 7, the resultant rescaled range, R/S, correlates almost linearly with the time lag, from which the individual value of the local fractal dimension has been recovered by adopting the regression method.

Fig. 8 shows the effects of gas flow rate on the local fractal dimension of pressure fluctuations in the bubble column reactor. In this figure, the local fractal dimension increased with increasing gas flow rate in all the cases studied. This trend of fractal dimension can also be anticipated from Fig. 3. This trend means that the inner structure of the hydrodynamic behav-

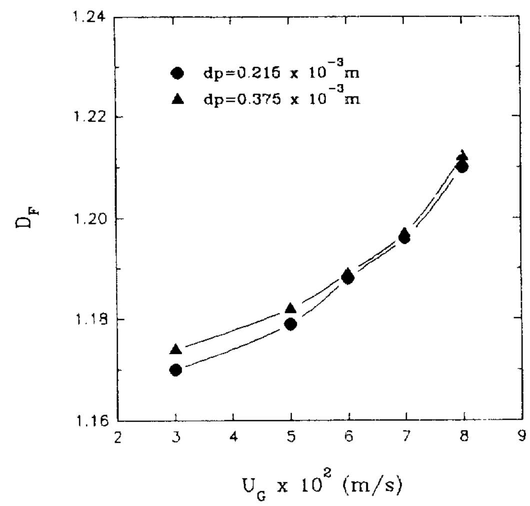

Fig. 8. Effects of U_G on Fractal Dimension of pressure fluctuations from three phase bubble column reactors (P=92 KPa, t=40 min, T=140°C, S=28 wt%).

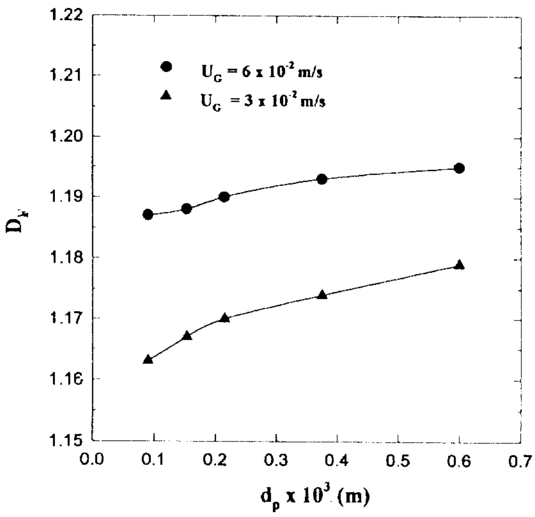

Fig. 10. Effects of d_p on Fractal Dimension of pressure fluctuations from three phase bubble column reactors (U_G= 0.06 m/s, P=92 KPa, t=40 min, T=140°C, S=28 wt%).

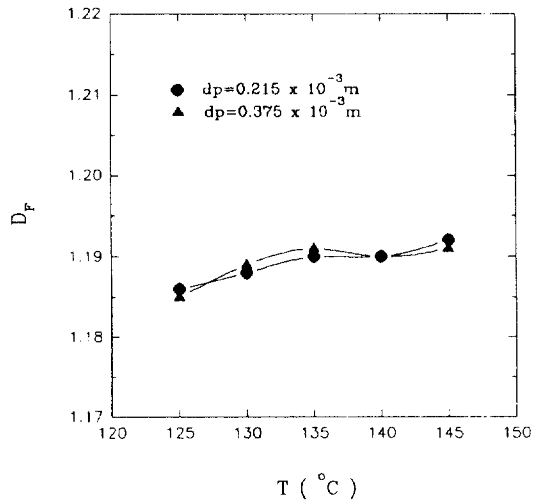

Fig. 9. Effects of T on Fractal Dimension of pressure fluctuations from three phase bubble column reactors (U_G= 0.06 m/s, P=92 KPa, t=40 min, S=28 wt%).

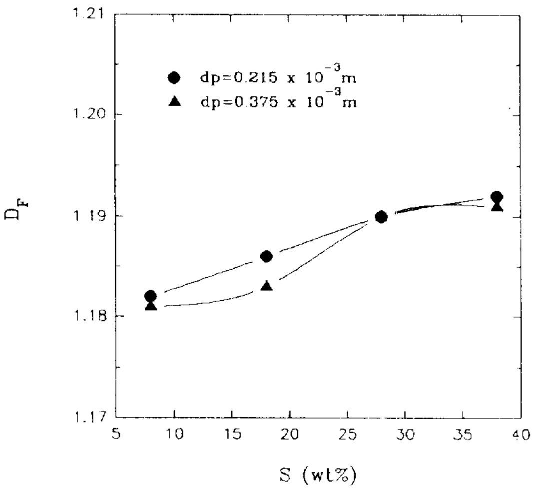

Fig. 11. Effects of S on Fractal Dimension of pressure fluctuations from three phase bubble column reactors (U_G= 0.06 m/s, P=92 KPa, t=40 min, T=140°C).

ior of the bubble column reactor becomes less persistent owing to the relative vigorous contact among gas, liquid and solid phases, with an increase in the gas flow rate [Kwon et al., 1994; Kang et al., 1994, 1995b]. In other words, the informations in the pressure fluctuations become more complex and irregular with increasing the gas flow rate. This can be due to that the frequency and size of rising bubbles in the column increase with increasing gas flow rate; the former increases the frequency and the latter increases the amplitude of the pressure fluctuation signals as in the cases of bubble column operating at atmospheric pressure [Kwon et al., 1994; Kang et al., 1994].

The resultant quantative effects of reaction temperature on the local fractal dimension of pressure fluctuations can be seen in Fig. 9. Although the effects of reaction temperature is relatively small, the similar increase trend of local fractal dimension with reaction temperature can be observed. This is also consistent with the results of spectral analysis (Fig. 4). This can be attributed to the fact that the higher temperature can let the water generated during the reaction evaporate more easily [Kang et al., 1995a].

Effects of particle size and solid content in the slurry phase on the local fractal dimension of pressure fluctuations can be seen in Fig. 10 and 11, respectively. In these figures, the D_F values have increased gradually with increasing particle size and solid content, respectively. As in the cases of spectral analysis, these trends can mainly be attributed to the bubbling phenomena in the bubble column reactor. In the slurry phase containing the relatively large solid particles, the energy required for the bubbling can be larger than that required for the relatively small solid particles in the slurry phase; the more energy dissipation and the more complex contact between phases would occur for the more larger particles in a given bubbling condition. Thus, the informations inhering in the pressure fluctuation signals become less persistent with increasing the particle size in the slurry phase. The effects of solid content in

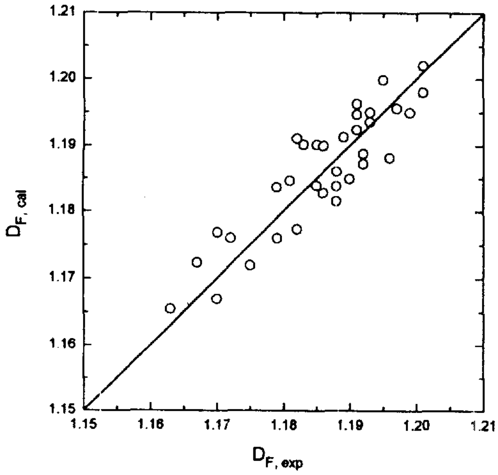

Fig. 12. Comparison between the experimental determined and calculated values of Fractal Dimension, D_F.

slurry phase on the local fractal dimension of pressure fluctuations can be similar to those of particle size, because the energy dissipation during the bubbling can be larger in the bubble column with higher solid content than that in the column with lower solid content [Lindner et al., 1988; Kawase and Moo-Young, 1989].

The resultant local fractal dimension has been correlated in terms of dimensionless groups as Eq. (10),

$$D_F = 1.132 \left(\frac{d_p U_G \rho_L}{\mu_L} \right)^{0.0112} \left(\frac{T}{T_o} \right)^{0.0132} S^{0.0050} \tag{10}$$

with the correlation coefficient of 0.906.

As can be seen in Fig. 12, Eq. (10) has been well fitted with the experimentally obtained values.

CONCLUSION

Pressure fluctuation in three phase bubble column reactor operating at low pressure have been effectively analysed by resorting to the stochastic method such as spectral and fractal analyses. The local fractal dimension of pressure fluctuations has increased with increases in the gas flow rate, reaction temperature, particle size and solid content in the slurry phase; the pressure fluctuations has become less persistent with increasing them. The effects of gas flow rate on the pressure fluctuations and thus hydrodynamics has been dominant over other three operating variables.

The local fractal dimension of pressure fluctuations has been well correlated with the operating variables.

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NOMENCLATURE

C(t, u) : cumulative departure of X(t+u) from the mean
D_F : local fractal dimension
d_p : particle diameter [m]
K : kurtosis of X(t)
P : reaction pressure [Pa]
P(X) : probability density function
P(X: t) : first probability density function
R(t, τ) : sample sequential range for lag τ
S : solid content in the slurry phase [wt%]
S : skewness of X(t)
S^2(t, τ) : sample sequential variance
t : time [sec]
T : reaction temperature [°C]
T_o : ambient temperature [°C]
U_G : gas flow rate [m/s]
X_M : mean value of X(t) [V]
X(t) : time series of pressure fluctuations [V]

Greek Letters

τ : time lag [sec]
σ^2 : variance

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