A Study of Fluidized Bed Control System

(Part 1 : Pressure Fluctuation Detection for Uniform Size Bed)

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Abstract

A fluidized bed control algorithm in which the bed mode was identified by the variance of the pressure fluctuation at the free board has been proposed. The control characteristics of the system regulated by the integral, and proportional plus integral corrective algorithms were studied experimentally and theoretically. The results showed that integral action provided the stable behavior for the system with an intensively fluctuating process. The relationships between the pressure fluctuations observed in the bed were examined by spectrum analysis under the condition of packed bed, minimum fluidization, bubbling, and slugging state. Frequency ranging between 1 and 2 Hz was found to be valid for the recognition of the fluidization regimes.

1 Introduction

Fluidization shows several modes such as particulate, aggregative, and slugging according to the gas and material conditions[1)-3)]. Gas velocity is the major factor in determining the state of the bed being fluidzed. The mode is also heavily dependent upon the properties of the materials as Geldart[4)] suggested. Size and its distribution, density, shape, mixing ratio, and other miscellaneous chemical and physical properties are the important factors in the fluidizing condition[5)6)]. For a bed in practical use, these properties may change during the operation of the equipment[7)], for example in the feeding of the raw materials, the quality and/or quantity may deviate to some extent from the original specification, consequently resulting in the alteration of fluidizing mode. To avoid these problems, the system should be controlled to maintain the reference point of the fluidizing operation. In detecting the mode of the bed, a simpler algorithm is recommended for the system in order to minimize the error expected to occur in the measurement and to shorten the processing period.

This paper proposes a method of identifying the bed condition by a simple procedure in which the variance of the pressure fluctuation will be used as the index of the bed mode. Its applicability has been studied experimentally for the fluidized bed system adopting the conventional algorithm in the field of process control for the regulating element.

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2 Control Algorithm

Pressure fluctuation with time is observed at the free board of the fluidized bed. At the gas flow rate less than minimum fluidizing velocity v_{mf}, the fluctuation is small since the system is in packed bed condition. The variation increases with increasing gas velocity. It was confirmed by visual observation that the low frequency in the fluctuation coincided with the eruption of the bubble at the surface of the bed[8). Variance of the pressure transition calculated and shown in Figure 1 suggests that the mode of the bed such as the packed bed, the slugging fluidization, and the bubbling fluidization might be identified by the measurement of the value.

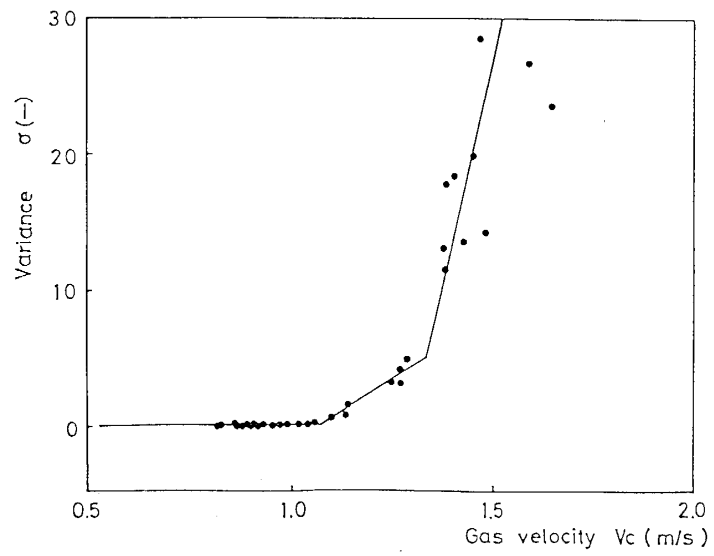


Fig. 1 Relation between the variance of the pressure fluctuation σ and the superficial gas velocity V_c

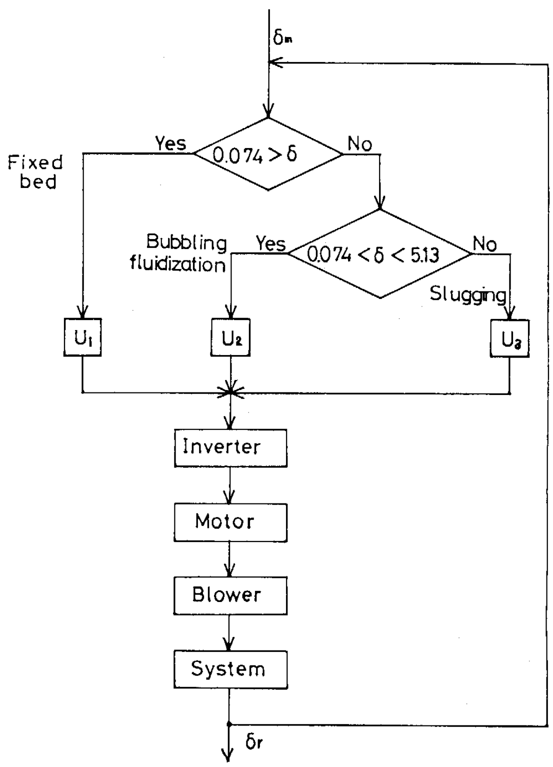


Fig. 2 Flow diagram of the control algorithm

The control procedure adopted in this paper is shown in Figure 2. The mode of the bed is recognized by the variance of the fluctuation. According to the perception of the state of the bed, the value of the manipulated variable is determined by the control element. The revolution number of the blower is regulated by the computer through the converter.

Integral action (I-action) and proportional plus integral action (PI-action) are used as the correction algorithms of the control element. The former is adopted to eliminate the offset of the system, and the latter is to quicken the response time in the first stage of the regulation.

3 Apparatus

The configuration of the experimental apparatus is shown in Figure 3. The column is made of acryl glass with rectangular cross section. Pressure drop through the bed is measured by semiconductor type sensors installed on the wall of the wind box and the upper part of the column above the granule surface. The pressure loss at the distributor, with holes in a staggered arragement and a triangular pitch, was subtracted in the calculation according to the characteristics obtained from preliminary experiment. Flow rate is detected by Pitot tubes at inlet and outlet conduits. All the data were processed in real time by micro computer. The revolution number of the blower is detected by tachogenerator directly connected to the axis of the blower. Flow rate is controlled by the inverter which is regulated by the computer.

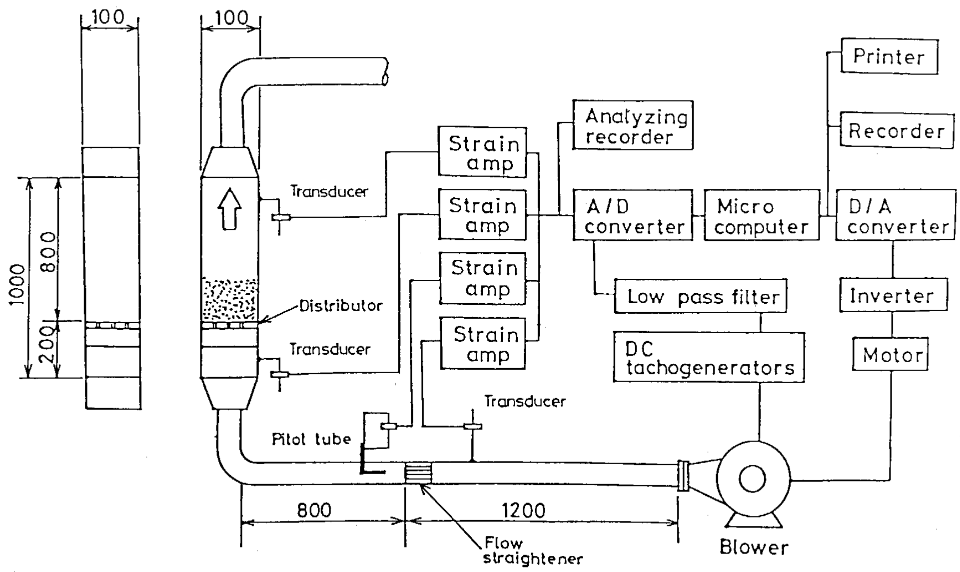


Fig. 3 Experimental apparatus

Glass beads whose properties are shown in Table 1 were used. A single particle size system can be assumed as size distribution is narrow. In packed bed condition, the pressure drop through the bed increases in proportion to the superficial gas velocity. In fluidized condition, the pressure drop remains constant despite the gas velocity. This indicates that the assumption can hold for these particles.

Table 1 Physical properties of the glass beads

Mean diameter	1.57 [mm]
True density	2.53 [gr/cm³]
Bulk density	1.53 [gr/cm³]

The relationship between the superficial gas velocity v_C and control variable U which is the voltage for control unit of the blower was obtained as shown in Figure 4. This relation provides the gain of the final control element K_B.

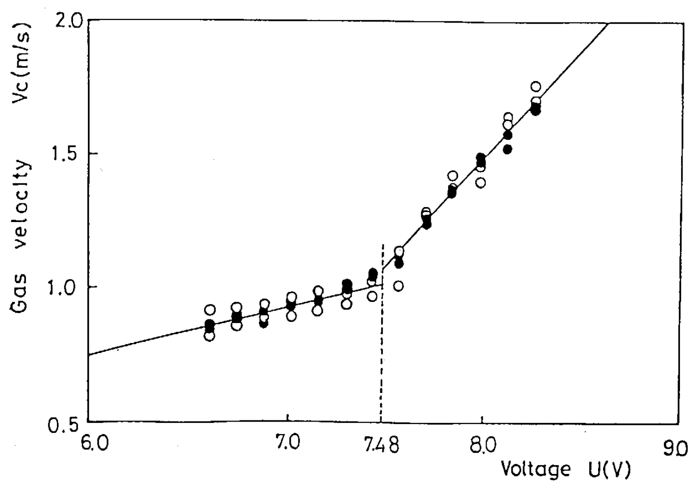


Fig. 4 Relationship between the superficial gas velocity v_c and the input voltage of the blower U

4 Results and Discussion

4.1 Transfer Function

The transfer function of the blower was determined by the step response test. The results showed that it was appropriate to describe the element as the one-order function with time constant T_B and the gain K_B as shown in Table 2-(a).

$$G_B(s)=\frac{v_C(s)}{u(s)}=\frac{K_B}{1+sT_B} \quad \cdots\cdots(1)$$

The relationship between the velocity of the bed and the variance of the pressure fluctuation at the free board of the bed was assumed to be the gain element as the first approximation for the system. The values of this element obtained experimentally are shown in table 2-(b) for each condition of the bed.

$$G_F(s)=\frac{\sigma(s)}{v_C(s)}=K_V \quad \cdots\cdots(2)$$

4.1.1 I-control System

The block diagram illustrated in Figure 5-(a) provides the total transfer function of the system adopting I-action as a controller,

Table 2 System gain

(a) Gain of the bed

Particulate	0.105
Bubbling	19.1
Slugging	133

(b) Gain of the blower

W	3 [kg]	4 [kg]
Particulate	0.197	0.181
Bubbling and Slugging	0.642	0.819

$$G(z)=\frac{K_I K_B K_F(1-P)z}{z^2+\{K_I K_B K_F(1-P)-(1+P)\}z+P} \qquad \cdots(3)$$

where $P=\exp(-T/T_B)$.

Substituting zero for P, G(z) is rewritten as

$$G(z)=\frac{K_I K_B K_F z}{z(z+K_I K_B K_F-1)} \qquad \cdots(4)$$

Therefore, the poles of this system are obtained at

$$z=0, \quad z=1-K_I K_B K_F$$

The stability conditions for these systems are

$0<K_I<104.7$ for packed bed

$0<K_I<0.128$ for fluidized bed with bubbling

$0<K_I<0.018$ for fluidized bed with slugging

4.1.2 PI-control System

Overall transfer function G(z) of the PI-control system was obtained from Figure 5-(b),

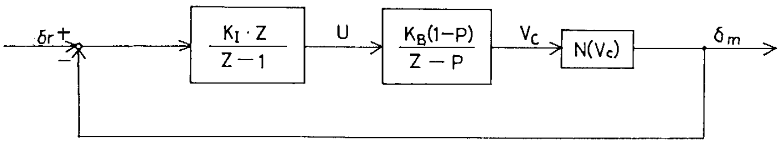
$$G(z)=\frac{(K_P+K_I)K_B(1-P)K_F z-K_P K_B(1-P)K_F}{z^2-\{(K_P+K_I)K_B(1-P)K_F-(1-P)\}z+P-K_P K_B(1-P)K_F} \quad \cdots\cdots(5)$$

Assuming P is approximately zero, then

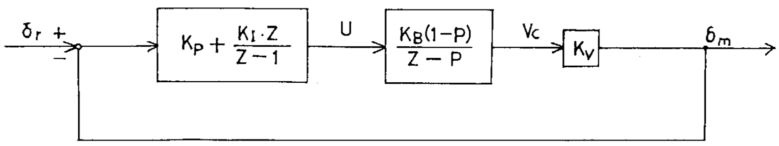
$$G(z)=\frac{(K_P+K_I)K_F z-K_P K_B K_F}{z^2-\{(K_P+K_I)K_B K_F-1\}z-K_P K_B K_F} \quad \cdots\cdots(6)$$

As for K_I and K_B, the following values were used so as to provide the same poles in the case of integral action,

$K_I=83.43$	, $K_P=4.44$	for packed bed(w=3kg)
$K_I=90.90$	, $K_P=4.83$	(w=4kg)
$K_I=0.0892$	, $K_P=0.00177$	for fluidized bed with bubblling (w=3kg)
$K_I=0.0549$	, $K_P=0.00138$	(w=4kg)
$K_I=0.01157$	, $K_P=0.0001168$	for fluidized bed with slugging (w=3kg)
$K_I=0.009066$	, $K_P=0.0000915$	(w=4kg)



(a) Integral control system



(b) Proportional plus integral control system

Fig. 5 Block diagram of the system

4.2 Results for I-control System

When the system is in the packed bed condition, it is desirable for the system to reach the fluidized bed condition rapidly. Therefore K_I should be large within the range of stability. For a large value of K_I, the response of the system will vary considerably since the real part of pole becomes negative.

In the case of bubbling fluidization, the bed should be transferred to the minimum fluidization condition while maintaining fluidization. Hence K_I must be small in order to have zero pole which gives fast response for the system.

The pole for the slugging condition should be zero for the same reason mentioned regarding bubbling fluidization.

The controlled responses from packed bed to the fluidized bed are shown in Figure 6. The bed pressure loss takes the peak value at the point where the bed changes from the packed mode to the fluidized condition. There the modes of the pressure fluctuation vary inconsistently. In the steady state, the variance of the pressure at the free board of the bed shows variation. This explains the randomness of the fluctuation and also the nonlinearity of the relationship between the blower revolution and the manipulated variable.

The response of the system from the slugging bed to the bubbling fluidization are shown in Figure 7. The simulations coincide well with the experimental results. In these cases, the bed condition changed gradually and continuously.

4.3 Results for PI-control System

Figure 8 shows the experimental results and their simulations, in which the bed is altered from the packed bed condition to the bubbling fluidization condition. Comparing the results, the trends of the responses are similar to that of an I-control system.

The controlled results from slugging to fluidized bed, shown in Figure 9, exhibit the same tendencies as an I-control system.

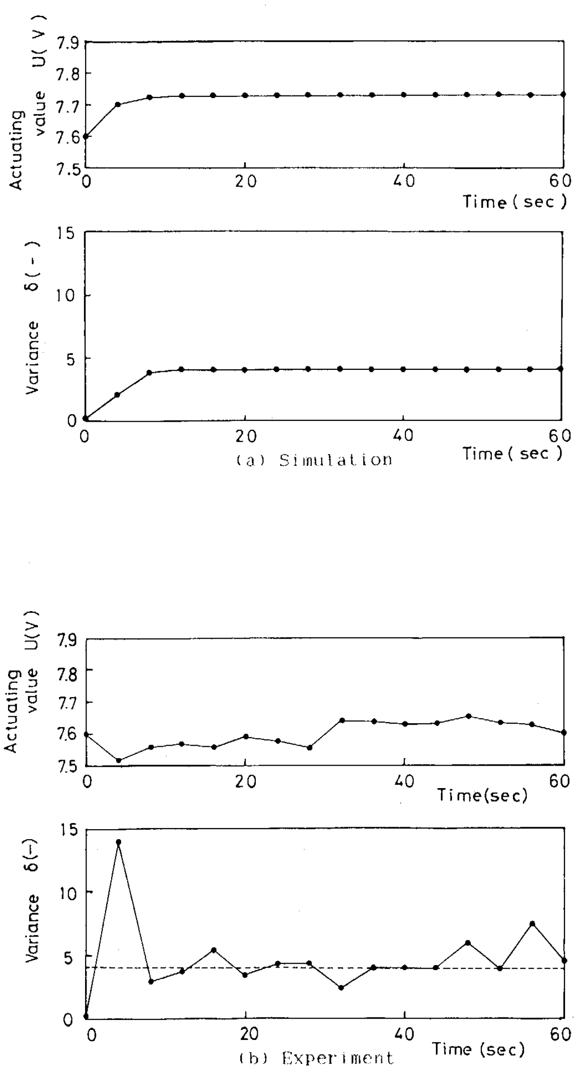


Fig. 6 Response to the step reference input for the system controlled by integral action, altering the bed from particulate mode to bubbling mode

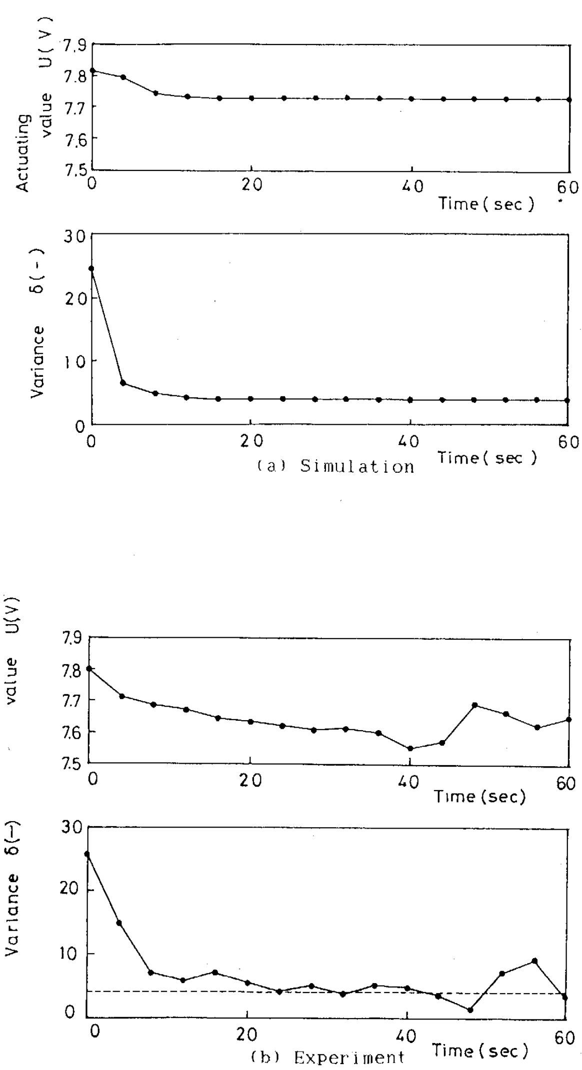


Fig. 7 Response to the step reference input for the system controlled by integral action, altering the bed from slugging mode to bubbling mode

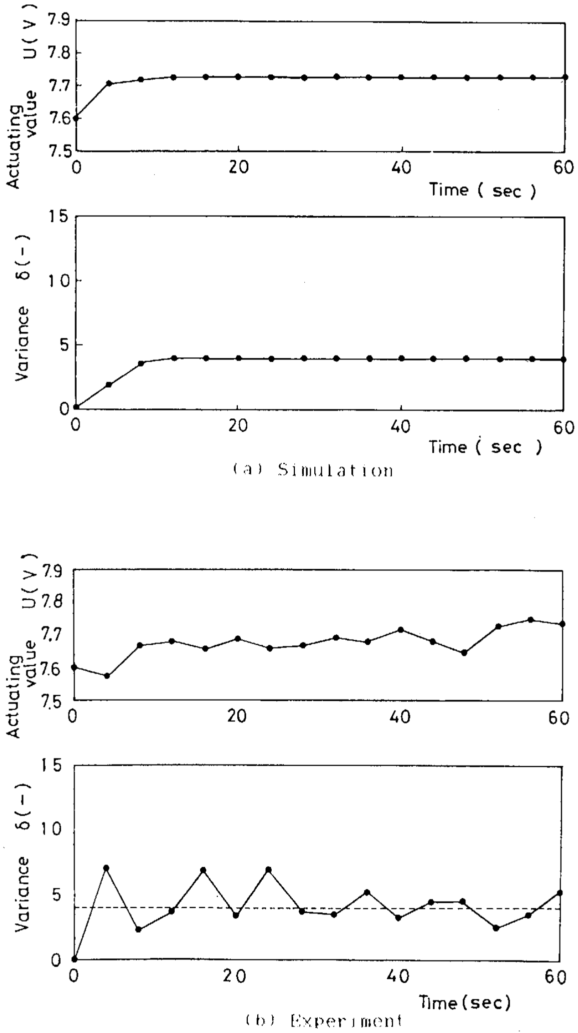


Fig. 8 Response to the step reference input for the system controlled by proportional plus integral action, altering the bed from particulate mode to bubbling mode

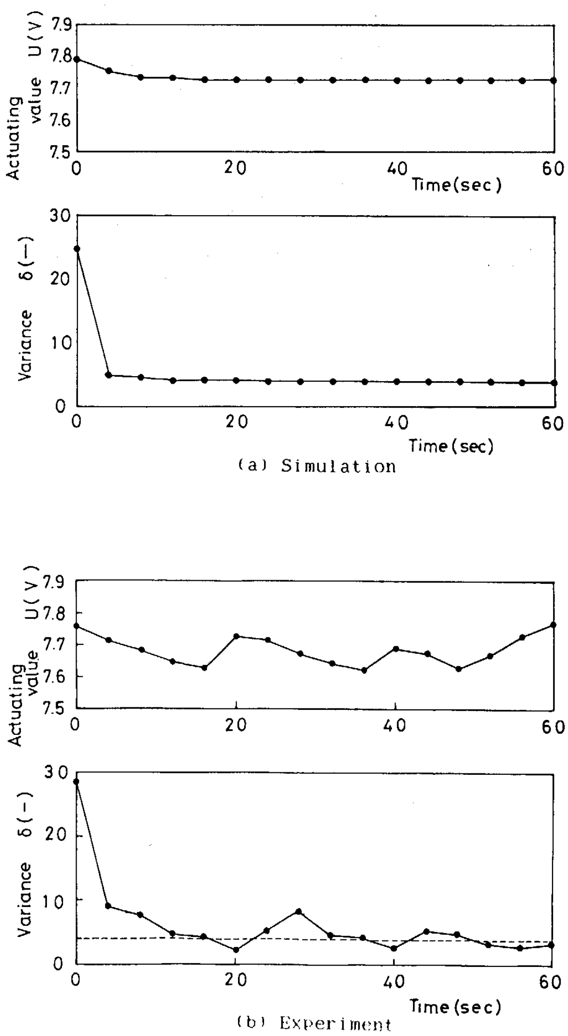


Fig. 9 Response to the step reference input for the system controlled by proportional plus integral action, altering the bed from slugging mode to bubbling mode

4.4 Comparison of I-control System and PI-control System

The variation of the manipulated variable and the variance are smaller in the system controlled by I-action than in the system controlled by PI-action. Even though under the same conditions, the variables are not consistent since the pressure fluctuation at the top of the bed is a completely random process. The system controlled by PI-action shows a wide change in the manipulated variables, and its fluctuation is large even in the steady state. I-action drives the manipulator except when the error is zero. However I-action connot eliminate the error as positively as P-action because the manipulated variable is not zero even if the error is zero. Therefore in the system controlled by I-action, the manipulated variable does not change widely and the fluctuation in the steady state is slmall. For these reasons, I-action provides a more stable control characteristic than PI-action.

4.5 Analysis of the Pressure Fluctuation of the Fluidized Bed

In previous works[9)–11)], the dynamic behavior of fluidization was analyzed.

However there seems to be no discussion on the basis of the applicability for control detection. Hence the relationship between the pressure fluctuation observed in the fluidized bed was studied by the spectrum analysis. Static pressure P_u at the bed, P_b in the wind box, and dynamic pressure P_d were detected under the condition of constant blower speed and constant powder weight charged in the column. Gas velocities adopted were the minimum fluidization v_{mf}, the velocity less than v_{mf}, and three different values which provided slugging conditions. Measurements were carried out for the three differennt weights. Power spectrum and cross spectrum were calculated by Fast Fourier Transform with the analyzer directly connected to the detecting elements.

The pressure fluctuation with time and its power spectrum of the pressure at the free board of the bed are shown in Figures 10 and 11. The fluctuation is induced by factors such as (1) the vibration of the bed caused by the slugging, (2) the eruption of the small bubble accompanied with the larger size bubble collapse, and (3) the subsequent flow in and flow out of the particles of the bed. These fluctuations are related to a certain width of the frequency range, that is ;

Region A (1 Hz - 2 Hz)···············Factor (1)
Region B (2 Hz - 6 Hz)···············Factor (2)
Region C (6 Hz - 10 Hz)···············Factor (3)

The power spectrums for each frequency region are illustrated in Figures 12, 13, and 14.

For the bed of W=2kg, the spectrum caused by the large bubble eruption shows less than -66 dB at the point close to the minimum fluidization. The bed vibrates at the ratio v_c/v_{mf} greater than 1.3. As the bed weight increases, the bed tends to start vibrating at the minimum fluidization condition. The power spectrum increases are subject to the increase of the superficial gas velocity. However the spectrum remains constant at velocities higher than the ratio of 1.5.

As for the frequency in the region B, the spectrum higher than -60 dB can be observed at velocity ratios larger than or equal to unity. The similar tendency is shown for the region C.

If the pressure fluctuation at the free board is assumed to be induced by the eruption of the bubble, two phase theory indicated that the power spectrum should be constant in spite of the amount of the granules contained in the column. However as shown in Figures 12 and 13, it is clear that the spectrum depends on the bed weight, although the mechanism of bubble formation in fluidized bed still needs to be discussed[12]. Currently, it could be proposed that the growth speed and size of the bubble formed just above the distributor depend on the plenum gas pressure and the weight of the bed.

The spectrum of the dynamic pressure and the pressure at the wind box were examined. These characteristics were intensively affected by the blower dynamics and the noise emerging from the conduit. Therefore it was difficult to eliminate these influences from the results. Further analysis was carried out concerning the cross spectrum of the free board pressure and plenum pressure, and also the dynamic pressure and plenum pressure. Results showed that strong correlation exsists especially in the regions B and C.

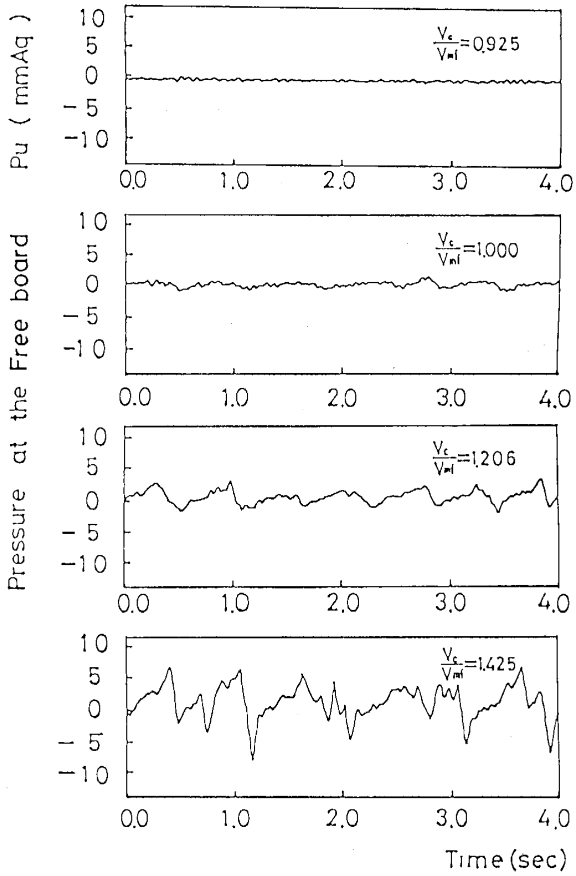


Fig. 10 Pressure fluctuation with time observed at the free board of the bed

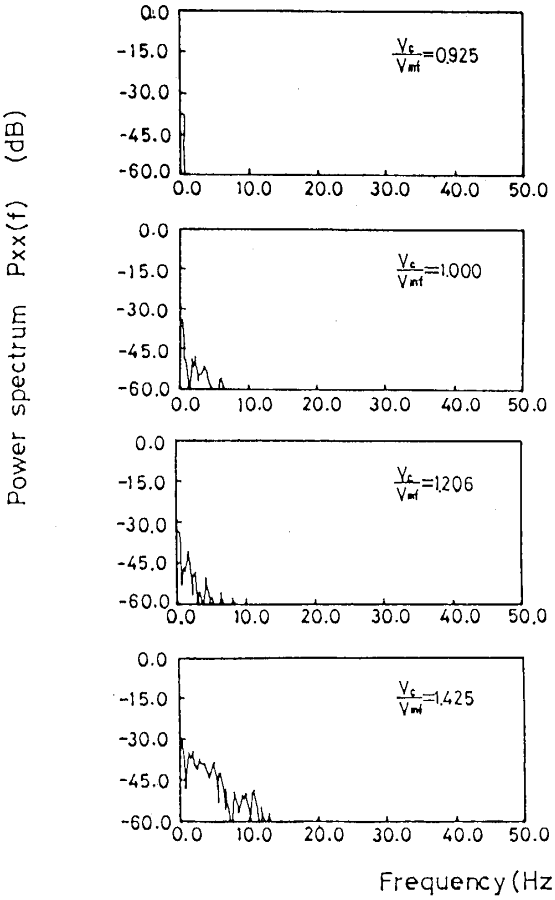


Fig. 11 Power spectrum of the pressure fluctuation at the free board of the bed

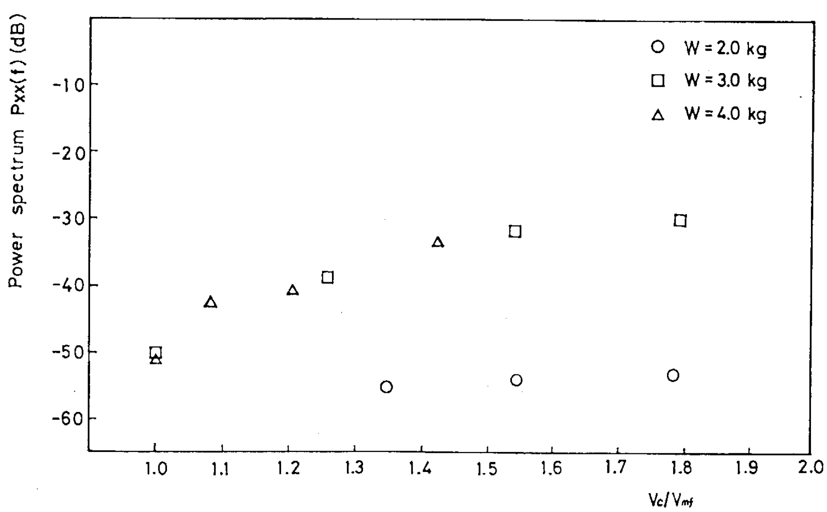


Fig. 12 Dependence of the power spectrum of the free board pressure fluctuation upon the gas velocity and the bed weight, for the frequency ranging between 1 and 2 Hz

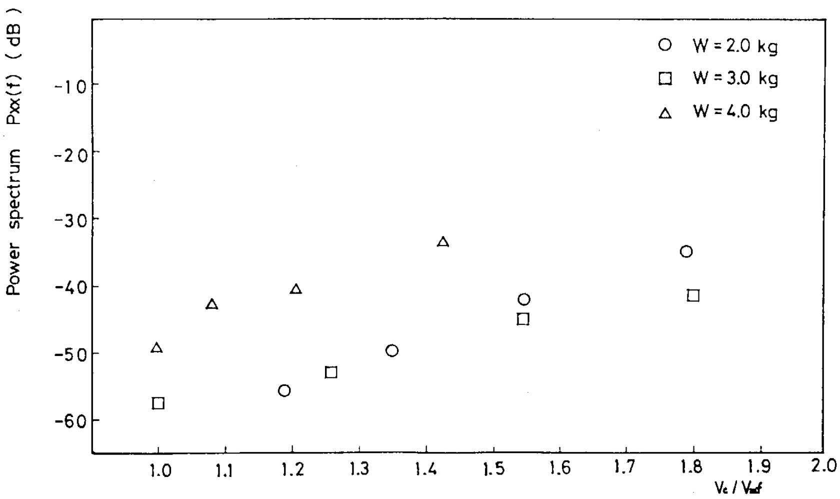


Fig. 13 Dependence of the power spectrum of the free board pressure fluctuation upon the gas velocity and the bed weight, for the frequency ranging between 2 and 6 Hz

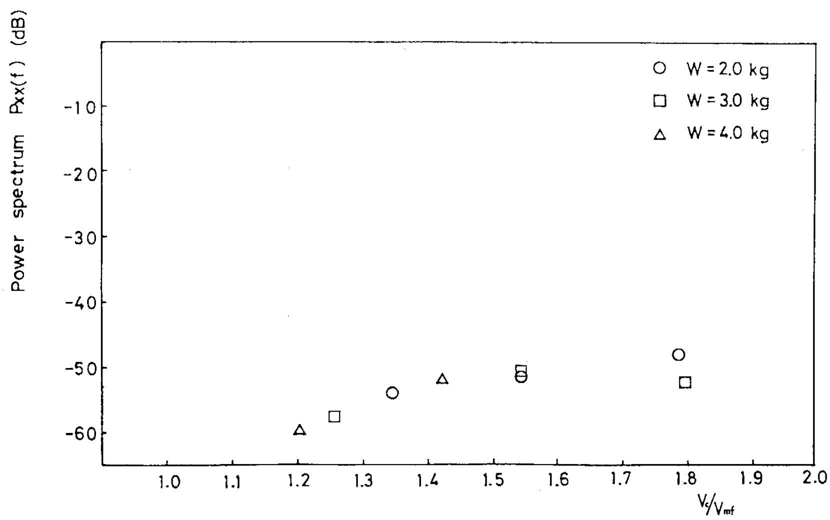


Fig. 14 Dependence of the power spectrum of the free board pressure fluctuation upon the gas velocity and the bed weight, for the frequency ranging between 6 and 10 Hz

5 Conclusion

The results are summarized as follows,

(1) The variance of the pressure fluctuation at the free board of the fluidized bed was sufficient to identify bed conditions such as minimum fluidization, bubbling, and slugging state including packed bed condition.

(2) The controlled behavior of the system adopting integral action and proportional plus integral action for the correcting algorithms were studied experimentally and theoretically. The comparison of the responses showed that the system equipped with integral action provided stable results for the fluidized bed.

(3) Spectrum analysis was carried out, in which power spectrum and cross spectrum were examined for the free board pressure, the plenum pressure, and the dynamic pressure. It indicated that the frequency range between 1 and 2 Hz was valid for the recognition of the regimes for the fluidized bed.

Nomenclature

G_B transfer function of the blower
G_F transfer function of the fluidized bed
K_B blower gain
K_I $\equiv K_P/T_I$
K_F fluidized bed gain
K_P proportional gain
T sampling period
T_B time constant of the blower
T_I integral time
u manipulated variables
v_c gas velocity
v_{mf} minimum gas velocity
W bed weight
σ variance of the pressure fluctuation

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