A Study of Fluidized Bed Control System

(Part 2 : Minimum Gas Velocity for Binary Mixtures Bed)

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Abstract

Control algorithms for minimum fluidization, which identify the bed regime from information on pressure drop fluctuations, were presented for binary size mixturses. Responses to rampwise and stepwise increment of the hold up were studied experimentally among the controls adopting a critical point prediction from the operation points and the controls maintaining the aggregative condition perceiving the state from amplitude of the fluctuations. Results showed that the system was adjusted to the final condition with higher accuracy by the former algorithm than by the latter, and variance methods provided more stability compared with the method employing the amplitude measurement.

1 Introduction

Minimum fluidization provides the ideal operation point for minimizing the energy consumed in the system in which the bed is controlled in particulate fluidization region. To estimate minimum fluidization velocity, several correlations have been proposed[1),2)]. For the bed comprised of multiple size mixture particles, the minimum condition can be predicted by the equation proposed by Wen and Yu[3)], Gossens et al.[4)], and Chiba[5)] in wellmixed condition. However, in general, the bed structure will change during fluidization especially in lower gas velocity regions due to the size segregation. In increasing the velocity at fixed bed condition, small sized particles go upward passing through the void formed between large sized particles. This characteristic is different from that of a well-mixed or uniform-sized condition. Kondukov and Sosna[6)], and Gelprin et al.[7)] characterized the fluidization for binary mixture by the beginning of the bed fluidization and total fluidization. And they also proposed the calculation method for the values from the characteristic curves experimentally obtained for pressure drop versus gas velocity. Chen and Keairns[8)] presented a phase diagram for particles of the same density, which correlates the fluidization mode with mixing ratio for binary particle size beds. These predictions, however, could not provide the bed with enough accuracy in order to maintain the minimum fluidization condition, since in real time processing of the calculation it is difficult to estimate the values of the variables at the critical point according to the alteration of the bed conditions such as particle size and density distribution, hold up, and gas velocity or pressure drop as subsequential variables. In this paper, four control algorithms have been studied, in which the bed mode of the fluidization was identified from the detection of the pressure alteration.

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Controlabilities were compared experimentally among these systems, and their applicabilities were discussed for a binary size mixtures bed.

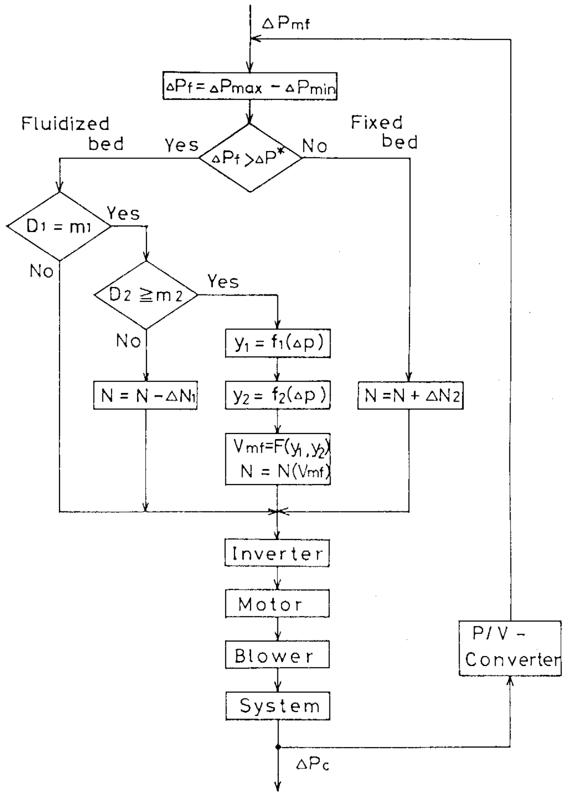


Fig. 1 Flow diagram of the control algorithm-1

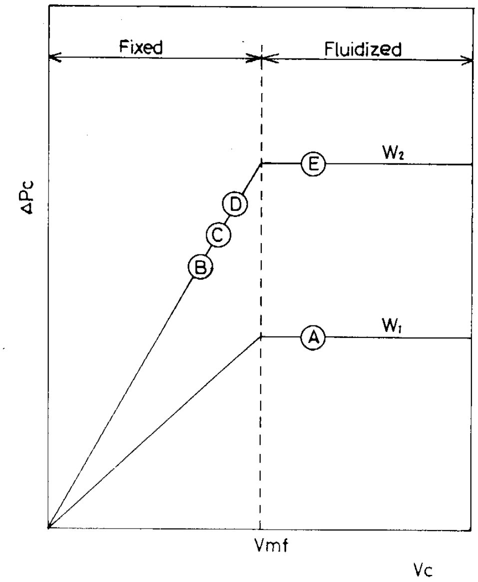


Fig. 2 Schematic of control procedure

2 Control Algorithm

2.1 Algorithm 1

The control algorithm adopted for system-1 is shown in Figure 1. The amplitude of the bed fluctuation is calculated from the extrema of the pressure drop through the bed. According to the value, the system identified the bed mode. In the case of a fixed mode bed, the system increases the blower speed by N_2. The average pressure with time is calculated and memorized at each operating point. In the case of a bed in the fluidizing condition, the number of trial point m_1 in fluidized bed mode is checked. If m_1 satisfies the condition, the number of trial point m_2 for fixed bed is also checked. If these points are enough for both regions, the characteristic curves f_1 and f_2 for each bed mode are predicted in order to estimate the minimum fluidization condition as their intersection point.

Behavior of the system controlled by this algorithm is depicted in Figure 2. For a change of the characteristic line of the bed from W_1 to W_2 owing to alteration of the bed hold up or size distribution of the particles, the operating point (A) which is minimum fluidization for W_1 shifts to (B) on the corresponding line for W_2 maintaining a constant blower speed. Since the system recognizes that the bed mode is in the fixed condition, the blower speed is increased and the operation point moves to (C) and (D) accordingly. Checking the number of trials, the system transfers to fluidization mode if the condition is satisfied. Intersection of the two curves determined from these points in each region provide the blower speed N_{mf} at minimum fluidization. The bed whose initial point is in aggregative condition can be controlled in the same procedure. Least mean square method was used in determining the characteristic curves.

2.2 Algorithm 2

Figure 3 shows the control for the system with algorithm-2. The variance σ calculated from the fluctuation of pressure drop through the bed is used as the identification index for the bed mode. Dependence of σ on the blower speed N is shown in Figure 4. σ increases as N_{mf} increases for each bed mode with different proportional ratio. The absolute values of σ show large differences.

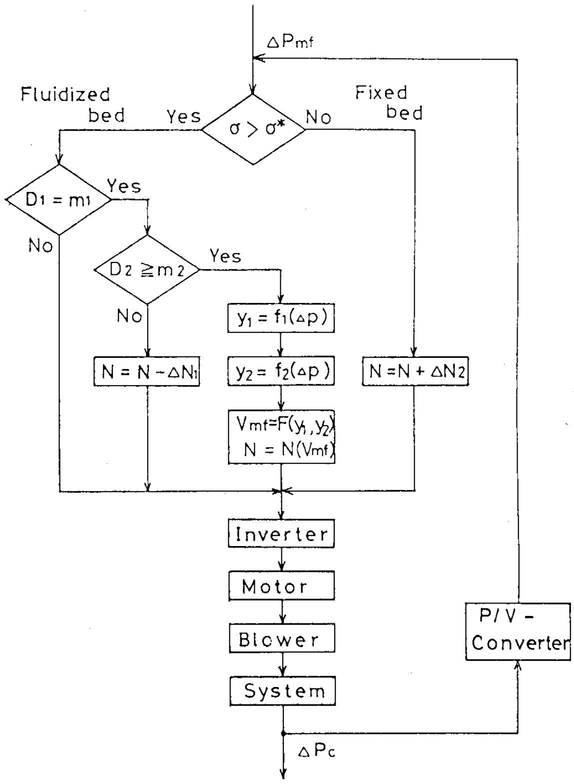


Fig. 3 Flow diagram of the control algorithm-2

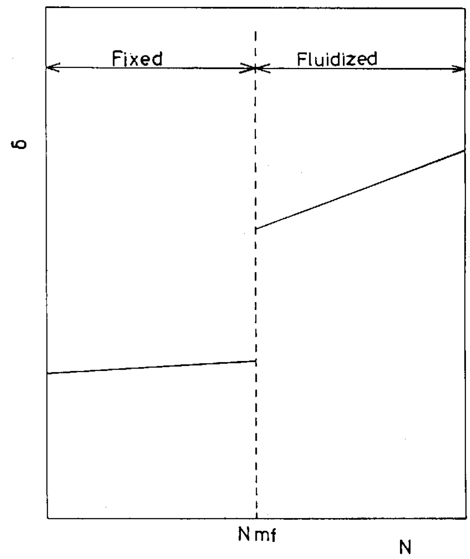


Fig. 4 Relationship between the variance of fluctuation and blower speed

2.3 Algorithm 3

System-3 applies the characteristics of a bed where both pressure drop through the bed, and the blower speed at minimum fluidization N_{mf} vary according to the total weight of the bed. The trend of alteration of the pressure drop is calculated from the detected data, as shown in Figure 5. According to the sign of this trend, the system recognizes the bed condition. In the case of bed weight increases, the bed mode will transfer to a fixed bed condition. To maintain fluidization, blower speed should be increased. In the case where the sign is negative, the system should decrease blower speed. Fluctuation is also monitored in order to know the intensity of fluidization. Since the pressure fluctuation increases with gas velocity, intensity of aggregation of the bed is known from the value. In practical control, the allowance will be required because at minimum fluidization point the fluctuation is very small, and it will be difficult to identify whether the bed is fluidized or not.

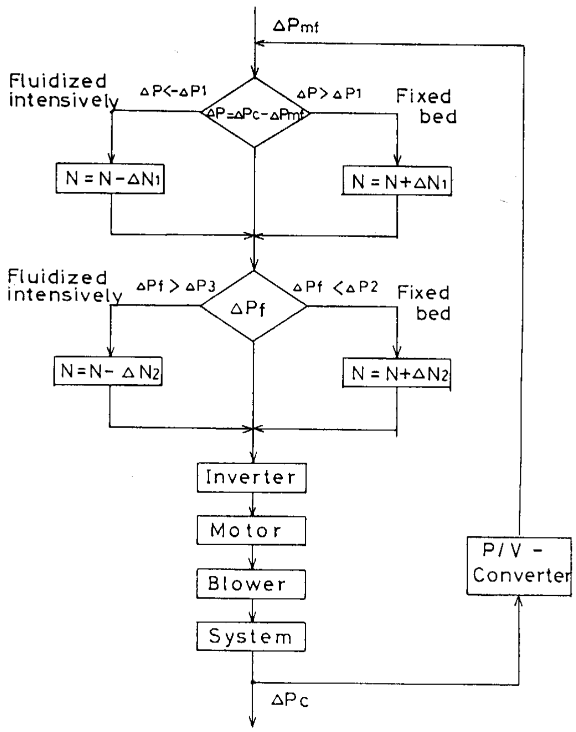


Fig. 5 Flow diagram of the control algorithm-3

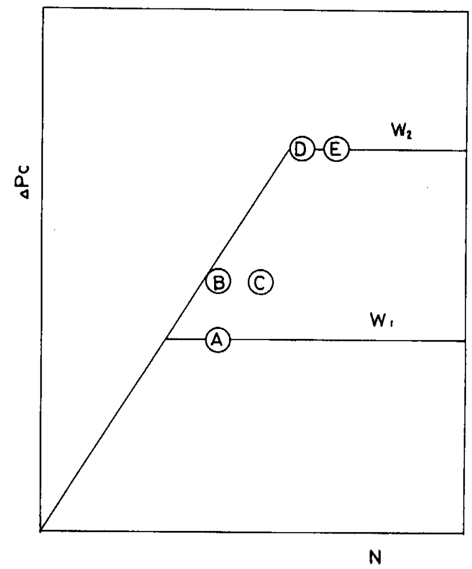


Fig. 6 Schematic of control procedure

A schematic drawing of the movement of operation point is shown in Figure 6. In the initial stage, the system drives the bed at (A) on the characteristic line for weight W_1. As the bed weight increases, the point transfers to (B), (C), (D), and (E) on the corresponding lines. In general, the blower revolution number is not consistent with the weight of the bed under the uniform-sized particle condition.

2.4 Algorithm 4

Since variance of the pressure fluctuation σ with time depends on the blower speed, as for system-4, σ is used in place of Δp in the algorithm-2, whose flow chart is depicted in Figure 7. Minimum fluidization point is identified from the value which gave the allowance of practical recognition for the system.

3 Experimental Apparatus

A column with 800 mm height, 300 mm width, and 100 mm breadth was used. Configuration of the experimental apparatus is the same as the employed in the previous report [9]. Relationship between pressure drop through the bed and superficial gas velocity was measured at the constant bed weight increasing the blower speed from

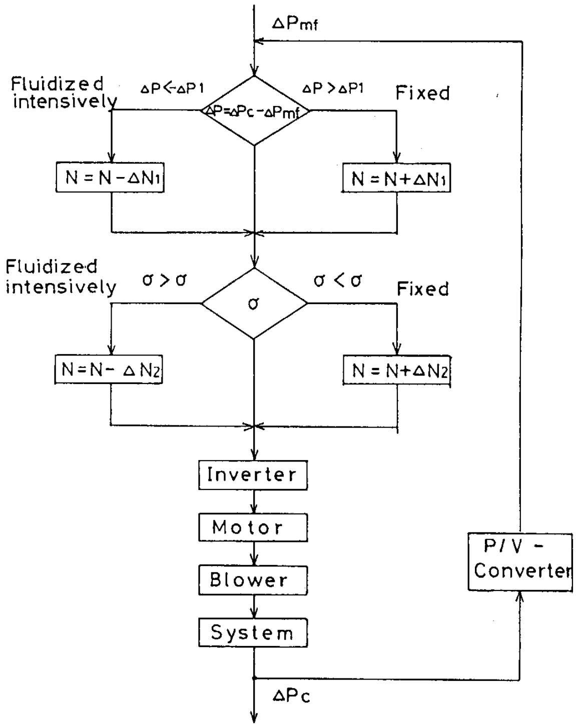


Fig. 7 Flow diagram of the control algorithm-4

fixed to fluidized condition. For the characteristic in increasing gas velocity, measurement was started at turbulent fluidization condition in which gas velocity was high enough so as to not segregate the bed. Materials were fed as an input for the system through the vend installed at the top part of the column. As for rampwise input, materials stored in the hopper, which was equipped outside the column, were fed through a rotary valve driven in a constant speed. For stepwise input, materials were stored once at the end part of the vend inserted into the column. At the precise moment, the bottom was opened quickly to increase the bed amount in stepwise. Limestone, whose physical properties are shown in Table 1, was used as the material. To simplify the size effect of the bed, binary size mixtures were used. Mixing ratio R_{mix} was defined as the weight fraction of large size particles to total bed [10),11)].

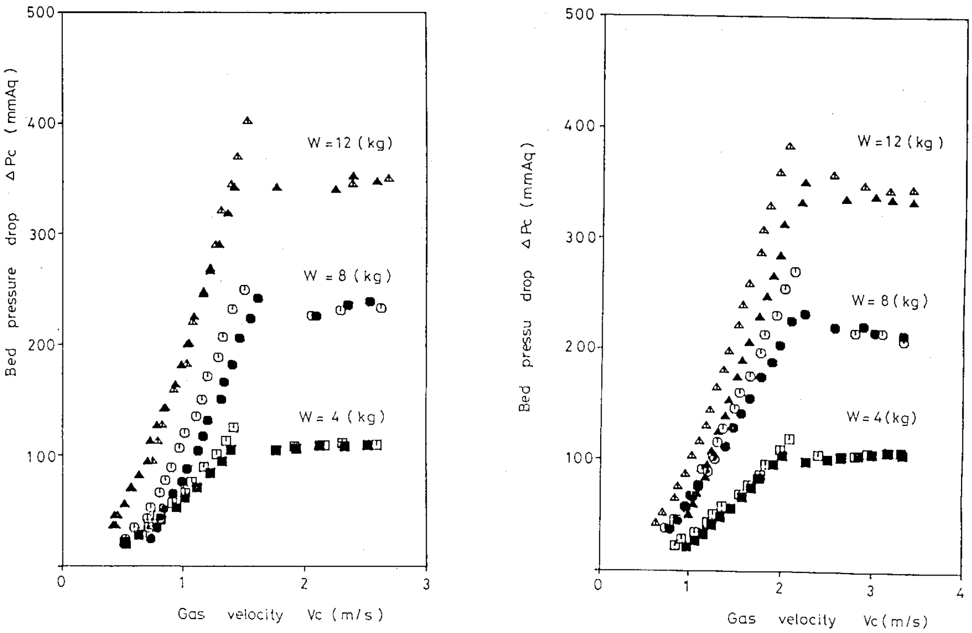
Table 1 Physical properties of the materials

Materials	D_p [mm]	ρ_s [mm]	ρ_b [gr/cm]
Limestone A	3.26	2.70	1.43
Limestone B	7.07	2.70	1.45

4 Results and Discussion

4.1 Properties of binary mixtures bed

Fundamental properties of fluidization for the bed composed of binary particle size



(a) $R_{mix}=25\%$ (b) $R_{mix}=75\%$

Fig. 8 Characteristics of fluidization

Table 2 Physical properties of the mixtures

R_{mix} [%]	d_p [mm]	U_{bf} [m/s]	U_{cf} [m/s]
25	3.77	1.26	2.13
32	3.94	1.29	2.17
33	3.97	1.29	2.18
36	4.04	1.31	2.20
50	4.46	1.37	2.31
55	4.63	1.40	2.36
56	4.67	1.40	2.37
57	4.71	1.41	2.38
64	4.98	1.45	2.44
67	5.10	1.47	2.47
68	5.15	1.47	2.49
75	5.47	1.52	2.56

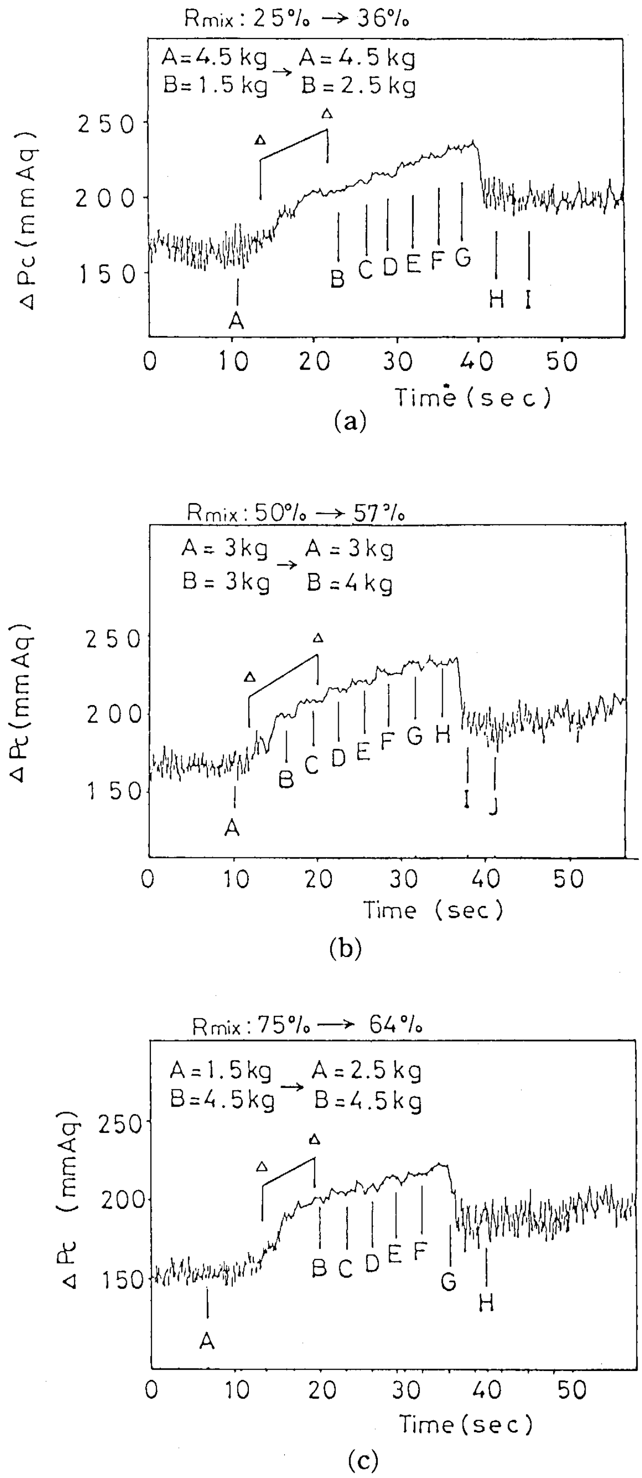


Fig. 9 Response of the system with algorithm-1 to rampwise increment of the bed hold up

mixtures were studied experimentally. Figure 8 shows variation of the pressure drop through the bed with superficial gas velocity V_c. In multiple size mixtures bed which consists of uniform density particles, it is well known that the size separation of the particles is observed especially at the low gas velocity region. In static regime, pressure drop is logarithmically proportional to superficial gas velocity. Starting from the fluidization region, as gas velocity decreases the characteristic line of pressure drop exhibits a lower value than the increasing velocity condition. Gas velocity V_{bf} at onset of fluidization and V_{vf} at complete fluidization were calculated by Vaid and Gupta's equation[12] as shown in Table 2.

4.2 Response to rampwise increment of the materials

In the initial stage, the bed was operated at minimum fluidization point. As a ramp input, the particles of one size component were added to the bed in proportion to time, altering the mixing ratio. Pressure drop through the bed, blower revolution number, and amplitude of the fluctuation of the pressure drop were observed during the period until the bed reached a new fluidization point.

For the system with algorithm-1, initial R_{min} were tested at 25%, 50%, and 75%. Figure 9-(a) shows an example of the response of the system in which the bed was in minimum fluidization condition for the initial bed weight of 6 kg. Materials were added to the system in proportion to time during the period indicated by triangles in the figures. While increasing the bed amount, the bed condition drifted to fixed bed mode and exhibited a small amplitude of fluctuation. During (B) to (G), the system was in fixed mode, in which the system increased the blower speed. At (H), the system was transferred to fluidization condition, then after checking the operation points, two characteristic lines were calculated between the points (H) and (I). At (I), the speed was fixed at N_{mf} which gave the minimum fluidization condition for altered bed weight. It took 32.3 seconds from the beginning of input till the system controlled to the new fluidization point. Calculation of two lines and determination of critical point were done in 4.0 seconds. The absolute values of these times obviously depend on the interval of the input duration, and the increment of operation point.

Control result for the initial mixing ratio R_{min} = 50% is shown in Figure 9-(b), in which the system required 29.5 seconds to transfer and settle at the minimum condition corresponding to the altered bed condition. In the case of initial value of 75%, shown in Figure 9-(c), mixing ratio was decreased by 9% since coarse materials were increased. Settling time was approximately equal to the response mentioned above on the basis of the ratio of response to input duration.

Control result for system-2 is shown in Figure 10-(a). The materials were added to the bed during the marks in the same way as in system-1. The system was in fixed bed mode from the beginning of the input until point (H), and the mode transferred to aggregative condition during (H) and (I) decreasing the blower speed. It took approximately 35.8 seconds from the onset of input until the bed mode shifted to the new fluidization regime. Calculation to determine the new minimum fluidization point took 5.8 seconds.

Response for the initial conditions of R_{min} = 50% and 75% are shown in Figure 10-(b) and 10-(c) respectively. Settling time in the response by algorithm-2 was longer than by algorithm-1, beause it took longer to calculate the variance from the pressure data than to calculate the amplitude from the pressure fluctuation. However the variance method was more reliable than the system detecting the amplitude because the fluctuation was random and sometimes the latter method could not obtain an appropriate value as a representative of the condition within the limited time interval of the measurement. To avoid this error it may be better to increase the number of detection. However, it will lead to a worse response from the system.

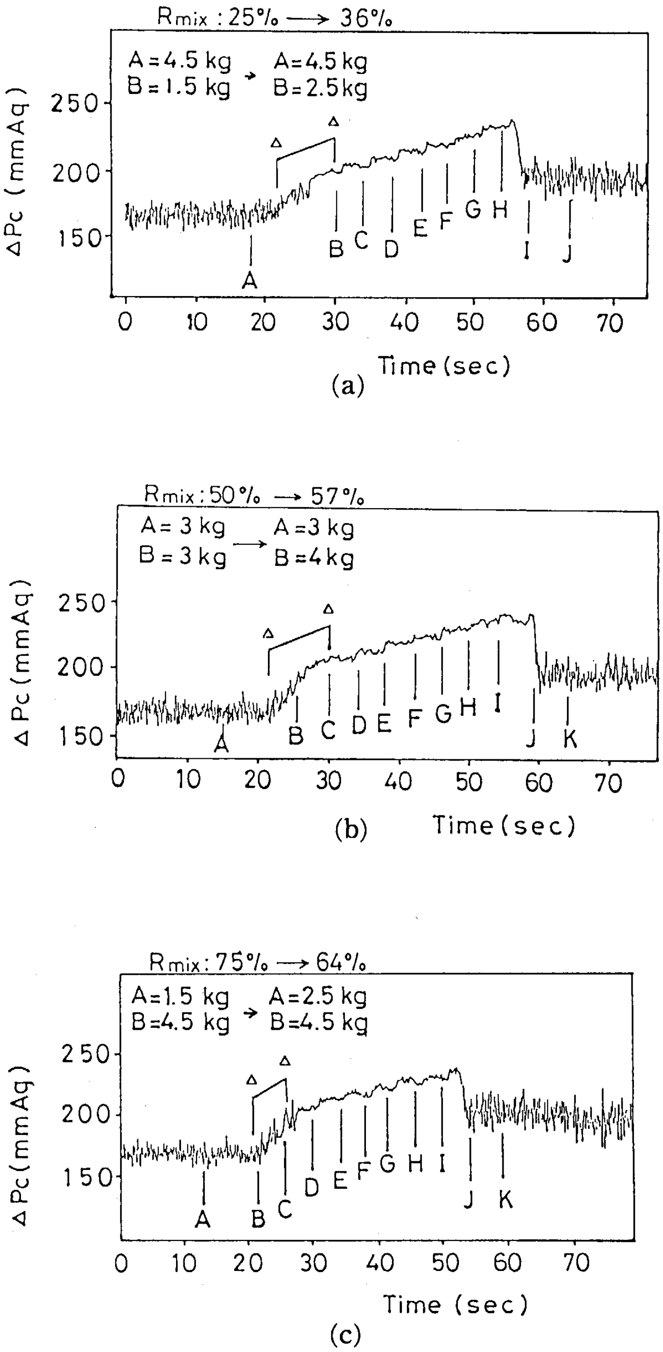
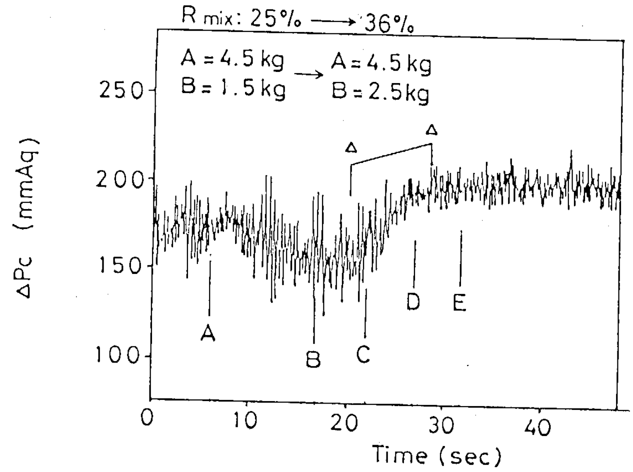
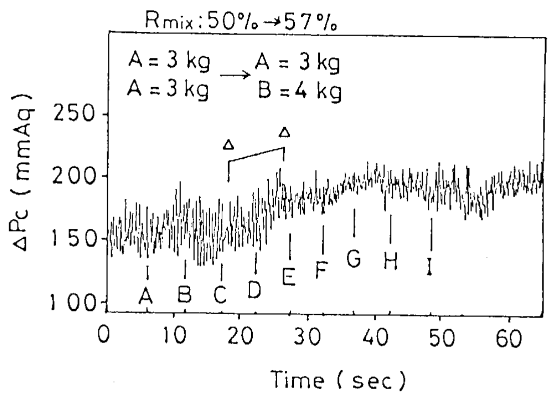


Fig. 10 Response of the system with algorithm-2 to rampwise increment of the bed hold up

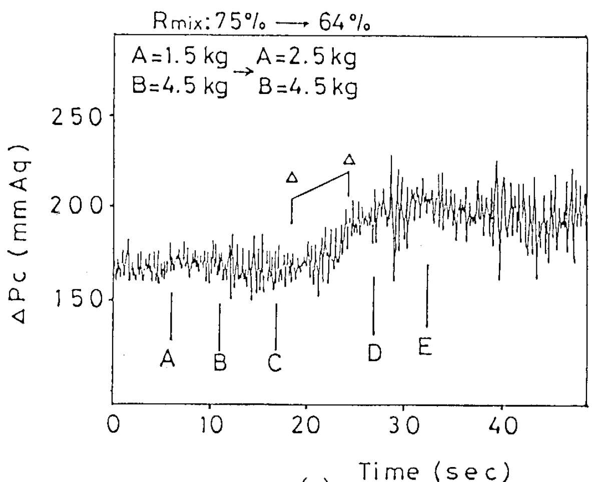
In the behavior of the system controlled by algorithm-3, the bed maintained aggregative condition during the response, as shown in Figure 11. According to the



(a)



(b)



(c)

Fig. 11 Response of the system with algorithm-3 to rampwise increment of the bed hold up

increase in the bed amount, the system followed rapidly without a drift to fixed bed condition. Observation of the system parameters indicated that the operating variables for minimum fluidization were calculated out immediately after the end of input duration. In the case where pressure fluctuation had swollen with long frequency period, the system presented unstable behavior as shown in Figure 11-(b). Though the system settled at point (E) once, subsequently blower speed began to increase again in order to follow the movement of the fluctuation. Such action was repeated until point

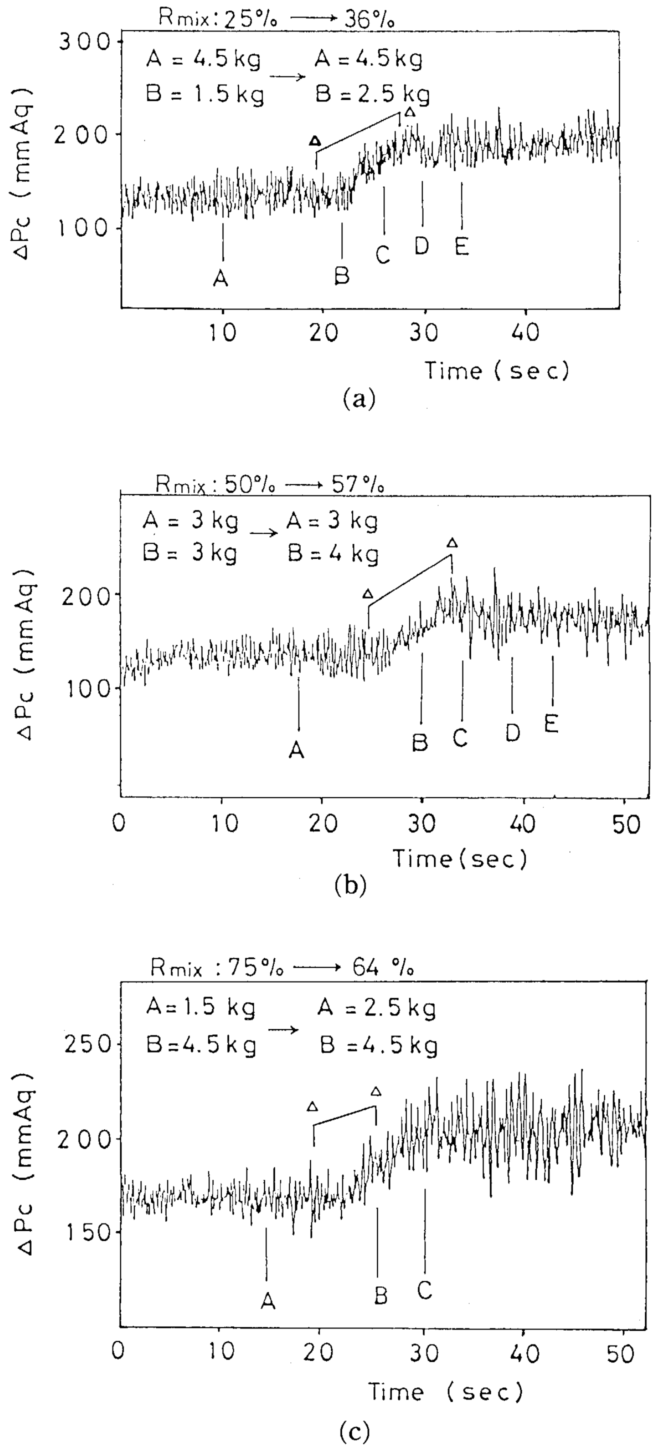


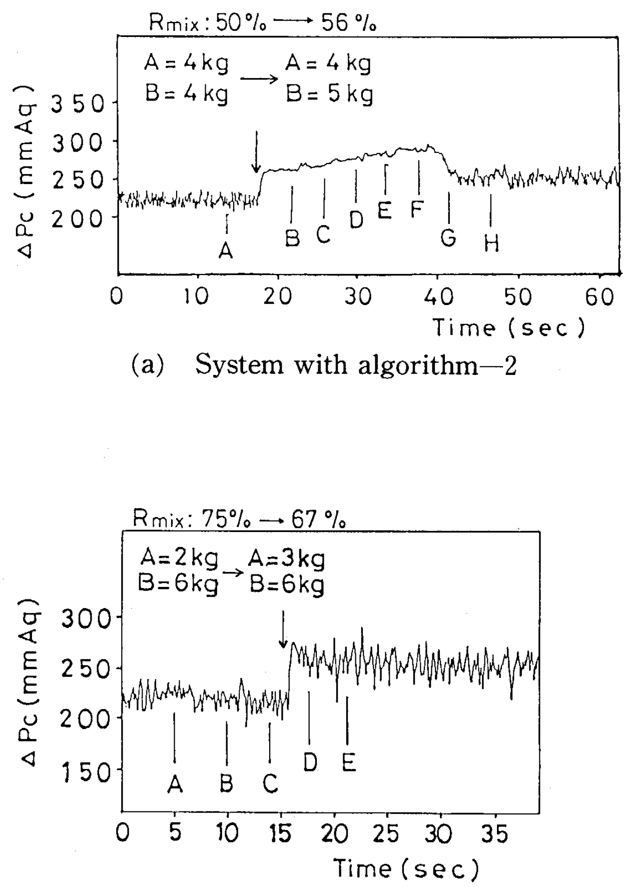
Fig. 12 Response of the system with algorithm-4 to rampwise increment of the bed hold up

(I) frequently altering the blower speed. For intensive fluctuation, the system required a settling within a short interval as shown in Figure 11-(c). Though fluctuation appered to have swollen, the system perceived the bed condition to be stable since the condition was identified with allowance from the average value of the altering data.

Figure 12 shows the response of the system controlled by algorithm-4. In these results, variance was accounted for each detecting point. Since these calculation times were longer, system drifted to fixed bed condition for every short moment or at critical condition between fixed and aggregative mode during the response. In Figure 12-(a), response showed this phenomena shortly after the end point of input duration. Response presented in Figure 12-(b) demonstrates this more clearly. In the interval, variance itself was less than half that in aggregative bed condition.

4.3 Response to stepwise increment of the materials

Behavior of the controlled system to a sudden increase of bed amount was studied for algorithm-2 and algorithm-4. Figure 13-(a) shows the response for algorithm-2, in which a certain amount of material was, as indicated by an arrow, thrown on to the bed which was operated initilly at minimum fluidization condition. In the case of initial ratio R_{min} = 50%, pressure data showed that the bed had transferred to fixed bed mode, The state continued approximately 25 seconds, and the blower speed was regulated 6



(a) System with algorithm—2

(b) System with algotithm—4

Fig. 13 Response of the system to stepwise increment of the bed hold up times during the interval.

On the contrary, for algorithm-4 settling was done very rapidly as shown in Figure 13-(b). Detecting the sudden change of the pressure drop, system controlled revolution of the blower in a very short time to increase up to the corresponding value which provided the critical condition for altered bed. From point (D) to (E), manipulated variables were still adjusted to search for the more accurate value. However, the system drove the blower in order to maintain the aggregative regime. The response time could be adjusted by setting the allowance to discriminate the bed modes in the algorithm.

4.4 Comparison of the algorithms

Response of the system controlled by algorithm-1 and 2 were slower than by algorithm-3 and 4, since several operations were required in fixed bed mode in determining the characteristic lines. Comparing the results obtained from the method detecting amplitude of pressure drop and the method calculating variance of pressure drop as criteria for perceiving the bed condition, the former presented identification error occasionally, where aggregative mode was recognized as fixed regime owing to the instability in the detection of the variables. Accuracy of the final point N_{mf} attained by the control procedure was higher by amplitude method than by variance method.

To operate the system at economical condition on the basis of energy consumed, minimum gas velocity provides the ideal point for fluidization[10]. The methods studied in this paper consisted of simple measurement and operation systems, and presented good control behaviors for minimum fluidization control for binary bed.

5 Conclusion

Four algorithms were proposed to control fluidized bed at minimum gas velocity condition. Their properties in control and applicabilities to the binary mixtures bed were studied experimentally. In the system with algorithm-1, bed was operated approximately on the critical point after reaching the final state to disturbance input. As for final point attained and settling time, the response by the system-2 was similar to that of system-1. In the controlled fluidization condition, system with algorithm-3 and 4, whose responses were similar to each other, presented more intensive fluctuations in comparison with the system-1 and 2. System showed higher reliability in the algorithm adopting variance of the pressure fluctuation than in the algorithm employing amplitude of pressure alteration.

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