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STABILIZATION AND DESTABILIZATION OF SLUGGING BEHAVIOR IN A LABORATORY FLUIDIZED BED

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ABSTRACT

In this paper, we present a method for feedback control of slugging in fluidized beds. Several recent studies have concluded that some modes of fluidization can be classified as low-dimensional and chaotic, implying a sensitivity to small perturbations that may be useful for control. We demonstrate here that selective application of small perturbations to a slugging bed of Geldart group D particles can greatly change the overall dynamics, permitting stabilization or destabilization of the slugging.

We make control perturbations by injecting small pulses of fluidization gas through a nozzle located on the bed wall just above the distributor. Pulse timing and duration are adjusted based on feedback from the bed as indicated by pressure drop. The pressure drop is measured much faster than the slugging frequency, while control perturbations are made at time scales on the order of the dominant bed frequency. The time-averaged gas flow through the injector is typically less than four percent of the total gas flow through the bed.

From our experimental results we conclude that it may be possible to employ similar feedback control strategies in commercial fluidized beds of group D particles to enhance or reduce slugging.

INTRODUCTION

Many industrial fluidized beds operate in a fluidization regime characterized by vigorous bubbling. Bubbles promote solid circulation and bed-mass homogeneity, but when they grow excessively large, bubbles also serve as conduits for gas by-pass, reducing gas-solid contacting. Many fluid-bed devices like combustors use particles of Geldart's (1973) group B-D transition or D classification. For these coarse particles, the inherent tendency to slug is high.

Various schemes, such as different distributor designs or introduction of baffles or packing in the bed, have been tried to improve gas-solid contacting by reducing the size or inducing breakup of bubbles. The results have been mixed and are not always practical for a wide variety of applications.

Concepts such as pulsing the fluidized beds with sonic energy (Morse, 1955) or intermittent gas flows have been investigated for many years. Zabrodski and Bokun (1966,1968), Massimilla et al. (1966), Kobayashi et al. (1970), and Moussa et al. (1987) have worked with intermittent gas flow pulsing and have observed improved gas-solid contacting.

Previous gas-pulsing schemes have relied on modulating the entire fluidizing gas flow. By cycling the gas flow at an optimum frequency, the bed behavior is modified. The pulsing frequency and duration are fixed for a particular bed and operating condition, with no provision for feedback from the bed.

Recent studies by Skrzycke et al. (1993), Daw et al. (1990), Daw and Hallow (1991,1993), Schouten and Van den Bleek (1991) and Van der Stappen et al. (1993,1994,1995) have shown that fluidized beds exhibit many features associated with deterministic chaos. Here we attempt to exploit the well-known sensitivity of chaotic systems to small perturbations in a closed feedback loop to modify slugging behavior. Tests are performed in a laboratory-scale fluidized bed operating in the slugging regime with Geldart's group D particles. Differential pressure signals, known to correlate well with the fluidization dynamics, are used to assess bed behavior and to take control action.

The control action involves introduction of a small fraction (less than 4 percent on a time-average basis) of the total fluidizing gas flow through a nozzle pointing upward and located near the wall just above the distributor. The optimum timing and duration of the pressure pulses are determined based on the desired mode of bed behavior for each operating condition. The system response to the control action is reflected in the differential pressure signal, which then is used to determine the next control action. Through this feedback control scheme, both stabilization and destabilization of slugging behavior can be achieved.

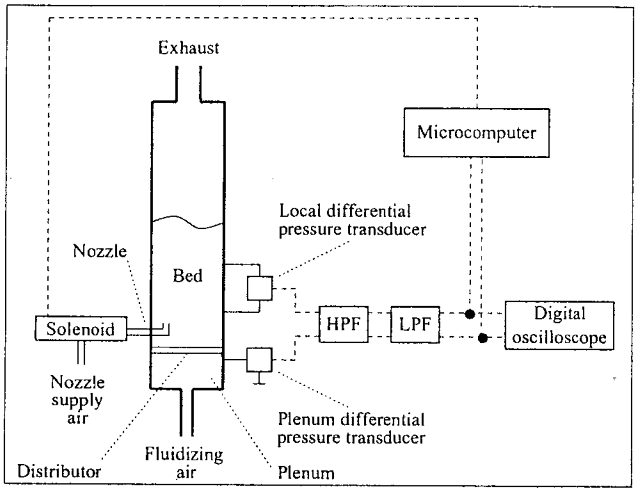


FIG. 1. SCHEMATIC OF EXPERIMENTAL APPARATUS.

EXPERIMENTAL APPARATUS

A schematic of the experimental apparatus is shown in Fig. 1. A detailed description of the apparatus can be found in Skrzycke et al. (1993). The laboratory-scale fluidized bed is constructed from a 10.2 cm inside diameter plexiglass pipe and is 140 cm tall. A bubble-cap distributor is used. The pulse nozzle is a 0.635 cm outer diameter stainless steel tube bent as shown in Fig. 1. The nozzle is located at 4.8 cm above the distributor and projects 1 cm into the bed. The nozzle is connected to a fast-acting solenoid valve rated for 1500 cycle/min duty.

Building air supply is throttled to 207 kPa gage pressure and supplied to the bed through a rotameter and a regulating valve as fluidizing air. In the nozzle air supply line, a surge chamber of 7.5 cm diameter and 52 cm long is used to damp the transient pressure fluctuations during solenoid firing. Two configurations are possible for nozzle air supply: one from a separate pressure regulator and another from upstream of the regulating valve in the fluidizing air line. The second configuration is used in the experiments presented in this paper.

Two rapid-response differential pressure transducers (Baratron model 223BD) were used to measure pressure-drop variations. The measured pressure drops are the differential pressure between the plenum and atmosphere (designated as "plenum" signal) and the differential pressure between two locations in the bed at elevations of 10.3 and 23.0 cm above the distributor (designated as "local" signal). The signals are analog bandpass filtered between 0.1 and 40 Hz and sampled with 12-bit precision at 200 Hz by a digital oscilloscope (Nicolet model 440). For data analysis, data sets of 60000 points are stored by the oscilloscope. The analog control signal (either local or plenum) is taken after filtering and input to the data-acquisition board (Data Translations DT2821) mounted on an Intel 80486-based microcomputer.

The control routine samples the data at approximately 2 kHz and executes the control action according to a predetermined (but modifiable) rule. The control algorithm generates a 10 mA pulse for the set pulse duration which is converted to 115 V signal by a solid-state relay to open the solenoid valve.

DATA ANALYSIS

Pressure signals were analyzed with Fourier transforms, time-delay phase-space reconstruction, mutual information and time return maps. A detailed discussion on these techniques can be found in Skrzycke et al. (1993), Daw and Hallow (1991,1993), and Martien et al. (1985). Maximum-likelihood dimension and entropy estimates were based on the methods of Schouten et al. (1994a,1994b).

Cycle period and magnitude comparisons were also used for analysis. Figure 2 illustrates the determination of cycle period and magnitude from the differential pressure signal. A *cycle* is defined as trough-to-trough oscillation of the signal; physically, it corresponds to the rising of a bubble or slug. Time return maps are constructed with time taken for the phase-space trajectories to complete one orbit. The orbital times are used to construct a three-dimensional map with successive orbit times (Martien et al., 1985).

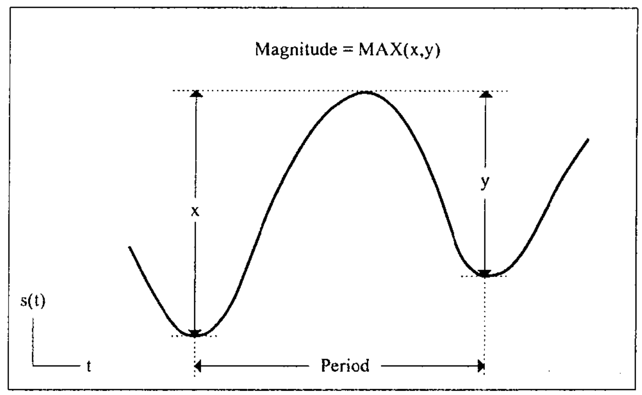


FIG. 2. DEFINITIONS OF CYCLE PERIOD AND MAGNITUDE.

BEHAVIOR OF SLUGGING BEDS

Slugging behavior of two Geldart's group D particles, spherical steel particles and glass, were investigated over a wide range of fluidization conditions from the onset of slugging to the transition to turbulence. Table 1 list the physical properties of the particles, and Table 2 lists the operating conditions for both steel and glass runs. Bed behavior was characterized using the "local" signal, as defined above.

Both solids exhibit similar behavior over the range of fluidization conditions investigated. Just above the minimum fluidization velocity, the bubbles or voids do not fill the cross section of the bed, and the behavior of global bed motion is irregular. We classify this regime as the *developing-slug* regime. It should also be noted that the magnitude of the pressure-drop fluctuations is very small compared with the regimes described below. As the gas velocity further increases, the bubbles become larger. Near a particular gas velocity, the bubbles or slugs are fully developed, and individual members of the slug train are very similar, evidenced by regularity and periodicity of the bed-level

TAB. 1. PHYSICAL PROPERTIES OF PARTICLES.

	Material	
Property	Steel	Glass
Particle density [gm/cm^3]	7.5	2.6
Mean diameter [mm]	4.5	2.9
Minimum fluidization velocity [m/s]	3.24	1.45

TAB. 2. OPERATING CONDITIONS.

	U/U_{mf}	
Run	Steel	Glass
1	1.19	1.05
2	1.23	1.11
3	1.28	1.16
4	1.33	1.19
5	1.42	1.31
6	1.56	1.40
7	1.72	1.51
8	1.86	1.61
9	1.99	1.81
10	2.16	1.91
11	2.30	2.01

and pressure-drop fluctuations. We designate this condition as *maximum stable slugging* and the corresponding velocity as U_{mss}. These fluctuations become increasingly erratic with increasing velocity, corresponding with progressively more irregular slugs. At high gas flow, large fluctuations and large unstable voidage pockets are observed. We classify this regime as the *breaking-slug* regime.

Figure 3 shows typical time series segments measured at four flow conditions. The segments have been resized on the plot to illustrate the dependence of pressure-signal complexity on flow. Segment (A) shows the small-amplitude, highly irregular fluctuations at minimum fluidization, segment (B) illustrates the developing-slug regime, segment (C) represents maximum stable slugging, and segment (D) depicts the breaking-slug regime.

Figures 4 and 5 show the evolution of bed behavior with flow as determined with cycle magnitudes and periods. These figures suggest that the most regular behavior occurs in Run 5 for steel and Run 4 for glass. Away from U_{mss}, bed behavior is more complex, characterized by a wide distribution in cycle periods and magnitudes.

We estimate the maximum-likelihood dimension and entropy to observe trends with flow. Note that we have used a resolution scale (i.e., cutoff length) of one average absolute deviation about the mean for estimating the dimension and entropy of each signal.

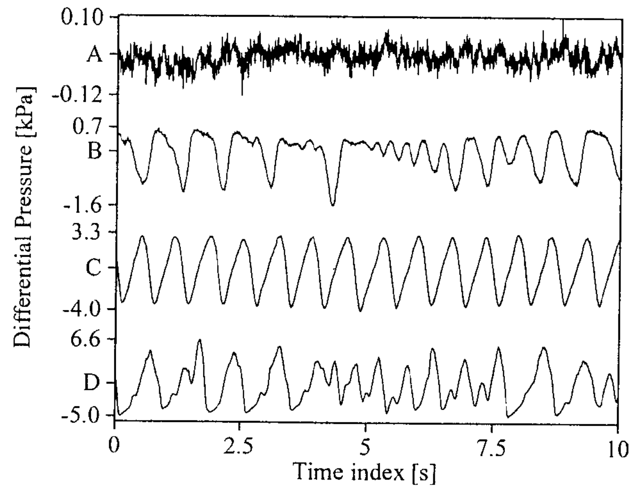


FIG. 3. TIME SERIES SEGMENTS FOR U/U_{mf} VALUES OF ≈1.0 (A), 1.19 (B), 1.42 (C) AND 1.99 (D). EACH SEGMENT IS ON A SEPARATE SCALE.

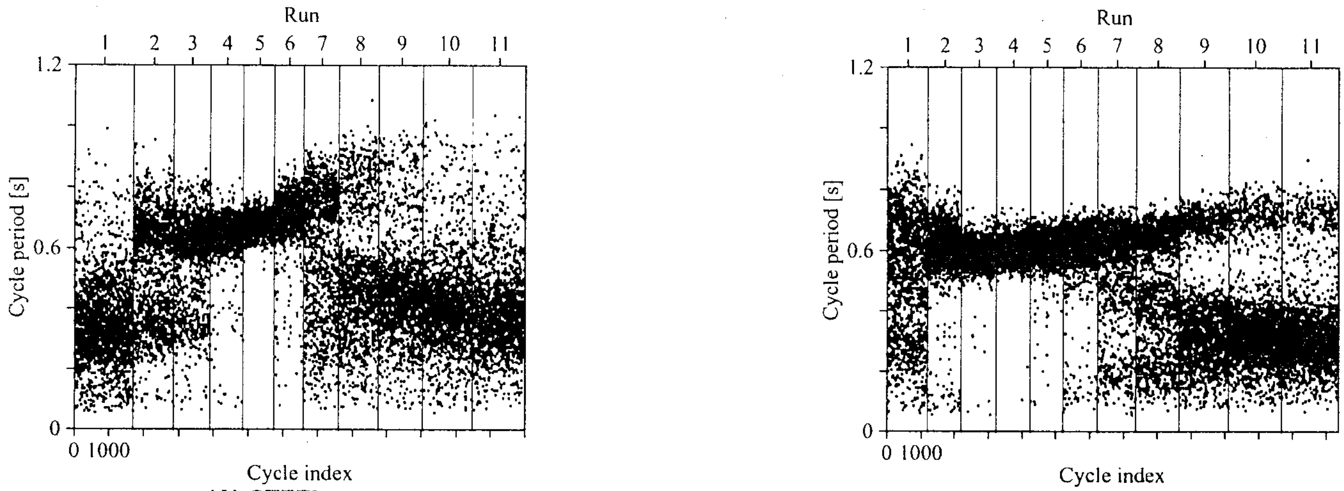
This scale is consistent with the recommendation of Schouten et al. (1994a,1994b) but tends to amplify small-scale particulate effects at low air flow (because of the small signal amplitude). We are currently investigating the replacement of this criterion with one based on a fixed resolution scale for all signals (e.g., the average absolute deviation at U_{mss}). We expect that the revised criterion will be better able to separate large-scale bulk motion associated with slugging from smaller particulate-scale motion.

Near the minimum slugging velocity, the system is characterized by high dimension and entropy. With increase in flow, the system becomes more ordered and has the lowest dimension and entropy values at U_{mss}. Beyond U_{mss}, the system becomes more disordered, characterized by higher dimension and entropy values. These effects can be observed in Fig. 6.

Time return maps constructed using the orbital periods of the phase-space trajectories provide another perspective on this dynamic transition. Selected maps for the steel runs at flows below, above and at U_{mss} are shown in figs. 7 to 11. At minimum slugging velocity, the very small-amplitude fluctuations are aperiodic except for a weak clustering around 0.3 s, as seen in Fig. 7.

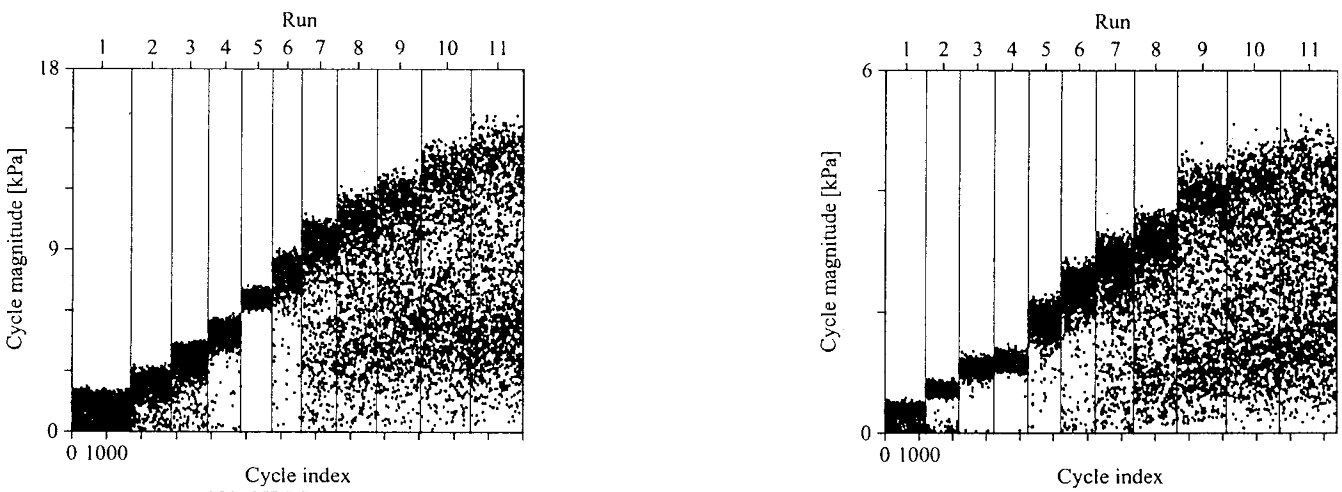
As flow increases, the global bed behavior is dominated (progressively) by the slug, and at U_{mss}, the bed motion is completely driven by and synchronized with the slugging motion. At U_{mss}, the orbital times reflect the dominant slug period of approximately 0.7 s, as manifested by the dense cluster of points in the time return map (Fig. 9).

As flow increases beyond U_{mss}, the bed behavior is more irregular, and the return maps become more diffuse. The average cycle period, seen as a diffuse cluster on the time return maps, tends to increase with flow, up to a limit. Beyond this limit, a new timescale at a lower period appears, and this period becomes more significant with increasing flow. The lower period appears to be a consequence of the disintegration of slugs. At still higher



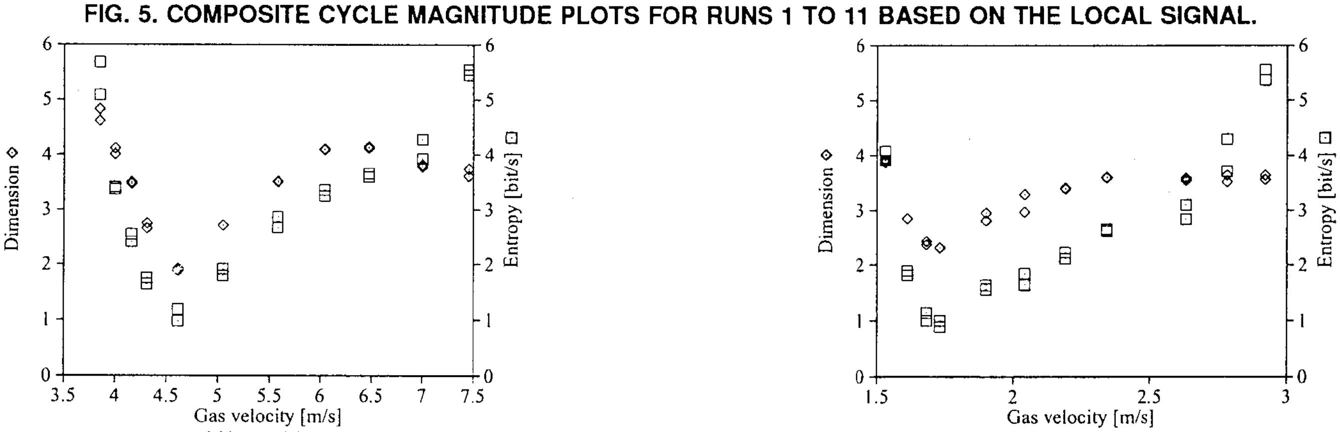
(A) STEEL **(B) GLASS**

FIG. 4. COMPOSITE CYCLE PERIOD PLOTS FOR RUNS 1 TO 11 BASED ON THE LOCAL SIGNAL.



(A) STEEL **(B) GLASS**

FIG. 5. COMPOSITE CYCLE MAGNITUDE PLOTS FOR RUNS 1 TO 11 BASED ON THE LOCAL SIGNAL.



(A) STEEL **(B) GLASS**

FIG. 6. VARIATION OF DIMENSION AND ENTROPY WITH GAS VELOCITY BASED ON THE LOCAL SIGNAL.

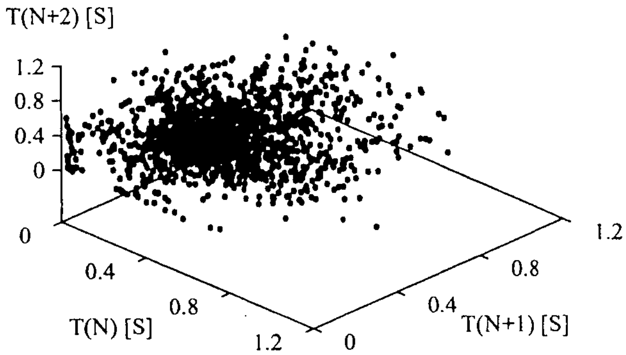


FIG. 7. TIME RETURN MAP FOR STEEL RUN 1.

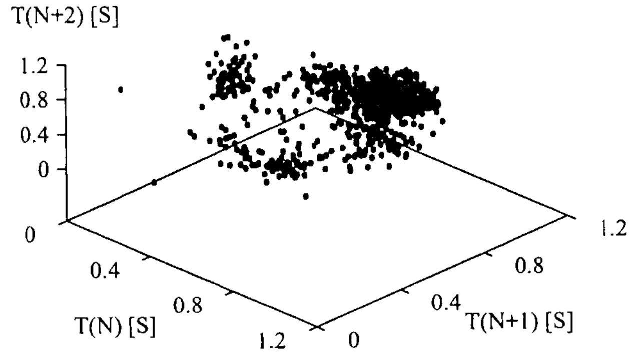


FIG. 10. TIME RETURN MAP FOR STEEL RUN 7.

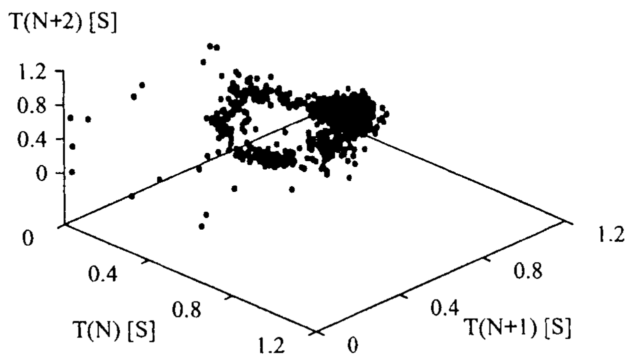


FIG. 8. TIME RETURN MAP FOR STEEL RUN 3.

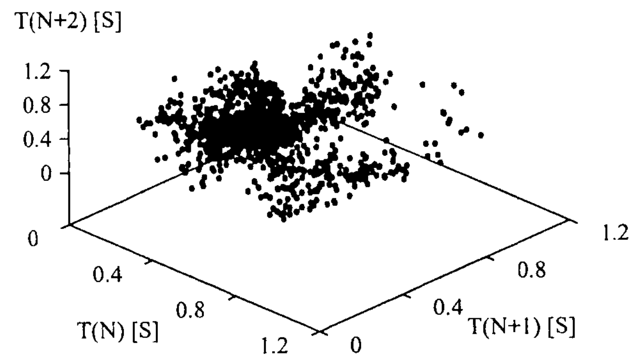


FIG. 11. TIME RETURN MAP FOR STEEL RUN 10.

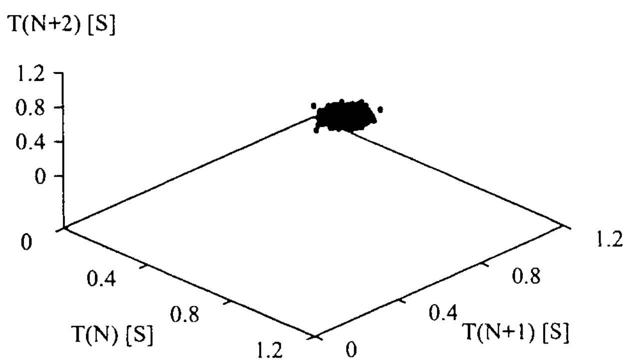


FIG. 9. TIME RETURN MAP FOR STEEL RUN 5.

velocities the lower cluster becomes dominant, and the upper cluster is no longer distinct. This new cluster (Fig. 11) develops around a period of 0.4 s, closer to the initial weak cluster seen just above the minimum fluidization velocity (Fig. 7).

Time return maps of the glass time series were qualitatively similar with the steel return maps.

In the terminology of non-linear dynamics, the dense clusters seen in the maps are manifestations of a large number of similar orbits and are fixed points associated with unstable limit cycles. We speculate that the dispersed points outside the dense clusters (when $U > U_{mss}$) delineate stable and unstable manifolds.

Slugging beds seem to have two unstable fixed points, except within a small range of flows in the vicinity of U_{mss}. Depending on the gas flow, one point is relatively more stable than the other. The low dimensionality of the system over a wide range of gas velocities gives rise to the hope that control of system behavior could be achieved through stabilizing or destabilizing the unstable fixed point by manipulating its location and utilizing the patterns shown by the return maps.

CONTROL PROCEDURE

The computer samples the band-pass filtered control signal at approximately 2 kHz. Based on this signal, the routine determines the dynamical state of the system and takes appropriate control action. Two parameters of critical importance in this scheme are *pulse timing* and *pulse width*. In the present control scheme, the pulse timing is when the signal value crosses a specified threshold known as the ''trigger level'' either in an ''upward'' or ''downward'' direction, and the pulse width is the duration in which the solenoid valve is open (see Fig. 12). This control strategy produces dynamical feedback, as each control action depends on the dynamical response of the system to the previous control action. For different gas velocities, the pulse

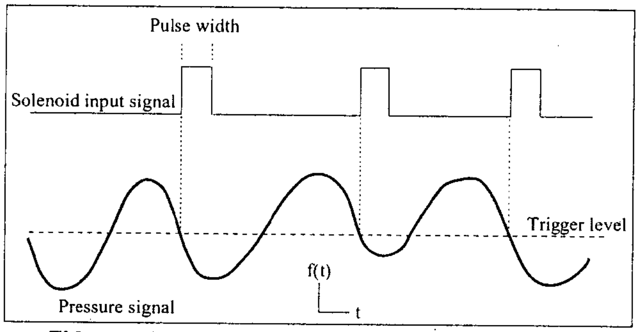


FIG. 12. CONTROL SCHEME FOR THRESHOLD DOWNCROSSINGS.

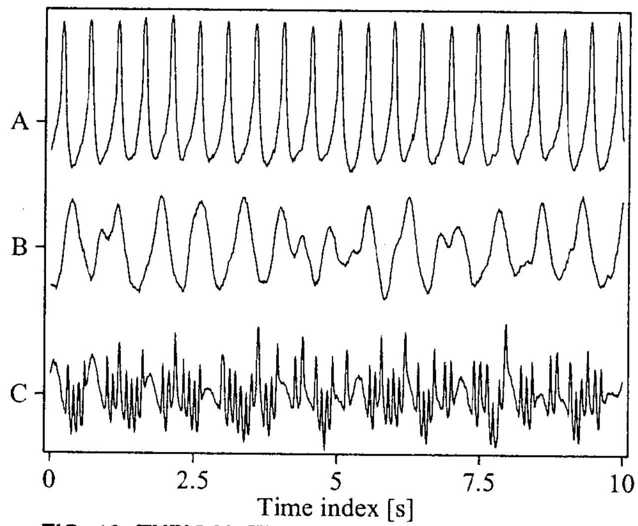


FIG. 13. TYPICAL TIME SERIES SEGMENTS FOR STABILIZATION (A), NO CONTROL (B) AND DESTABILIZATION (C) PLOTTED ON SAME SCALE.

timing and pulse width must be empirically determined based on a set of control experiments, which are explained in detail in the next section.

PRELIMINARY RESULTS

We observed that the bed of spherical steel particles behaved most regularly at U_{mss} (i.e., slugging was most pronounced), and we chose this condition to investigate our control methodology. The system behavior was monitored using both the pressure signals. Although either the plenum or local signal may be used for control and yield qualitatively similar results, we restrict the present discussion to control based on the plenum signal.

Figure 13 shows typical plenum-signal time-series segments at three different control conditions. Note that although the stabilization control signal is higher in magnitude than that for no control, the former case demonstrates very regular cycles, whereas the latter is fairly irregular from cycle to cycle.

TAB. 3. OPERATING CONDITIONS FOR PULSE TIMING EXPERIMENTS.

	Trigger	
Run	Level [kPa]	Crossing Direction
A1	-0.93	Upward
A2	-0.47	Upward
A3	0.00	Upward
A4	+0.47	Upward
A5	+0.93	Upward
A6	+0.93	Downward
A7	+0.47	Downward
A8	0.00	Downward
A9	-0.47	Downward
A10	-0.93	Downward

Effect of Pulse Timing

The pulse timing, fixed by trigger level and direction, is the most critical parameter in the control scheme, and by varying it, a wide variety of bed behavior from slug stabilization to destabilization can be achieved. A set of experiments (Table 3) varying the pulse timing with constant pulse width was performed for a systematic evaluation of bed response. Gas velocity was maintained at U_{mss}, and pulse width was maintained at 50 ms. Qualitative information about the effect of pulse timing can be inferred from Fourier analysis, cycle period and magnitude distribution, and time return maps. Pulsing during control experiments introduces a direct disturbance in the "local" pressure signals, and the results from some of these qualitative techniques must be carefully interpreted.

Dimension and entropy are measures of the complexity of system behavior and can be used to quantify the effect of varying the control parameters, and the results are shown in Fig. 14. The highest or lowest dimension and entropy values indicate that slugging is at its most irregular or regular behavior, respectively. Because the resolution scale for the estimates is set according to the average absolute deviation about the mean for each data set, the estimates should be carefully interpreted. For runs A1 to A5, as the trigger threshold increases with the upward direction, the dimension and entropy values steadily decrease for both plenum and local signal. However, at Run A6, when the crossing direction is changed to downward, the dimension values increase, but entropy values remain nearly the same and increase in the subsequent runs.

When the trigger level is decreased further with downward crossing direction (runs A6 to A10), the dimension and entropy values increase steadily up to Run A9. After that, except the plenum signal dimension, the dimension and entropy of local signal and entropy of plenum signal all decrease. These trends in signal complexity with changes in pulse timing depend on when

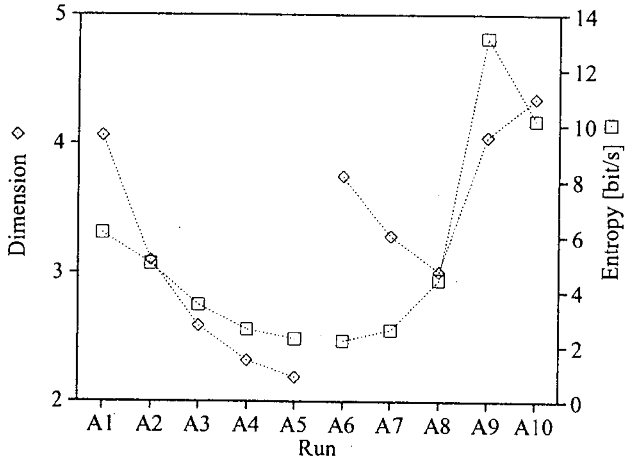


FIG. 14(A). VARIATION OF DIMENSION AND ENTROPY WITH PULSE TIMING (PLENUM SIGNAL).

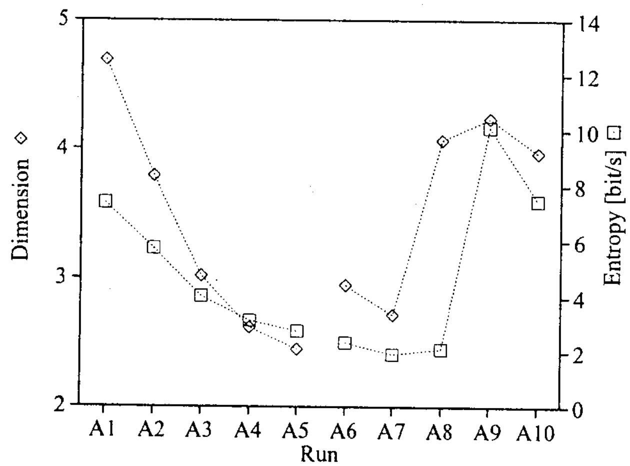


FIG. 14(B). VARIATION OF DIMENSION AND ENTROPY WITH PULSE TIMING (LOCAL SIGNAL).

in the slugging cycle the pulse is applied, and as the slugging behavior changes with flow, the pulse timing (trigger level and direction) might change accordingly. The transient effects of pulsing increases the dimension and entropy estimates compared with the no control case, but from the observed trend, it can be inferred that the system is most ordered at Run A5 and most disordered at Run A9.

Effect of Pulse Width

The pulse timing was set at the optimum stabilizing and destabilizing conditions as determined from the preceding experiments, and the pulse width was varied between 25 and 150 ms to study the effect of pulse width. Table 4 lists the operating conditions for these experiments. Pulse width as a control parameter does not affect the system behavior in a drastic way as the trigger level does.

As shown in Fig. 15, increasing the pulse width in stabilization mode generally results in a decrease in dimension and entropy. However, there appears to be a minimum in dimension at 100 ms pulse width.

TAB. 4. OPERATING CONDITIONS FOR PULSE WIDTH EXPERIMENTS.

Run	Trigger Level [kPa]	Trigger Crossing Direction	Pulse Width [ms]
Stabilization Control			
B1	+0.93	Upward	25
B2	+0.93	Upward	50
B3	+0.93	Upward	75
B4	+0.93	Upward	100
B5	+0.93	Upward	150
Destabilization Control			
B6	-0.48	Downward	25
B7	-0.48	Downward	50
B8	-0.48	Downward	75
B9	-0.48	Downward	100
B10	-0.48	Downward	150

Dimension and entropy estimates for the destabilization runs are presented in Fig. 16. Up to 75 ms pulse width, the system has higher entropy and dimension. Increasing the pulse width beyond 75 ms tends to stabilize the system, as indicated by the decrease in dimension and entropy.

Physical Explanation of Control Action

Based on visual and video observations, the opening of the solenoid valve was seen to cause a sequence of two distinct events: a pressure pulse followed by a bubble or voidage pocket. The pressure pulse disrupts the solids circulation pattern and tends to increase the voidage in the bed above the nozzle, influencing the formation and rise of slugs. The voidage pocket influences the slug-formation cycle and coalescence pattern in the bed.

In the stabilization mode, the solenoid valve is opened when the slug is just above the nozzle. The pressure pulse tends to accelerate the slug, thus increasing the slugging frequency, and the voidage pocket introduced by the pulse coalesces with the existing slug.

In the destabilization mode, the air pulse enters when the slug is still developing just above the distributor. The pulse increases the voidage in the bed above the slug, inducing part of the air to flow into the voidage pocket introduced by the nozzle, causing a reduction in slug size.

By manipulating the pulse timing, which is closely linked to the pressure pulse, and the pulse width, which influences the voidage-pocket size, the control scheme can achieve stabilization or destabilization objectives at various operating conditions.

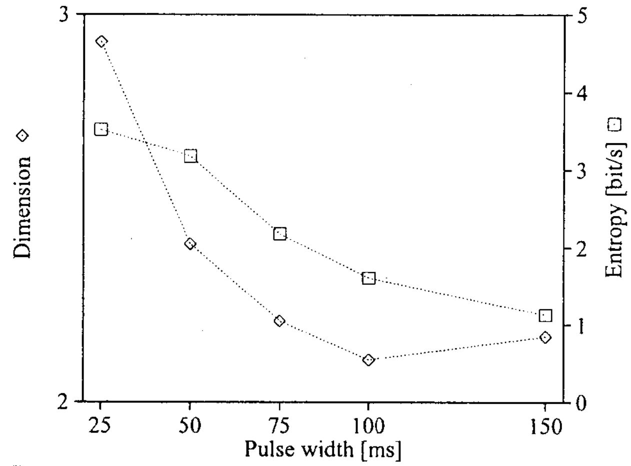


FIG. 15(A). VARIATION OF DIMENSION AND ENTROPY WITH PULSE WIDTH FOR STABILIZATION CONTROL (PLENUM SIGNAL).

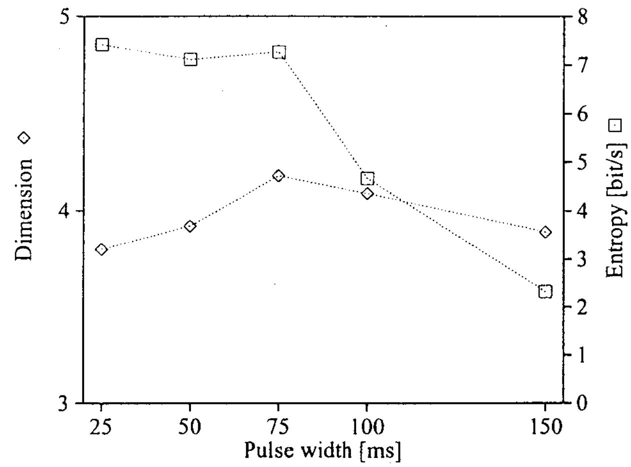


FIG. 16(A). VARIATION OF DIMENSION AND ENTROPY WITH PULSE WIDTH FOR DESTABILIZATION CONTROL (PLENUM SIGNAL).

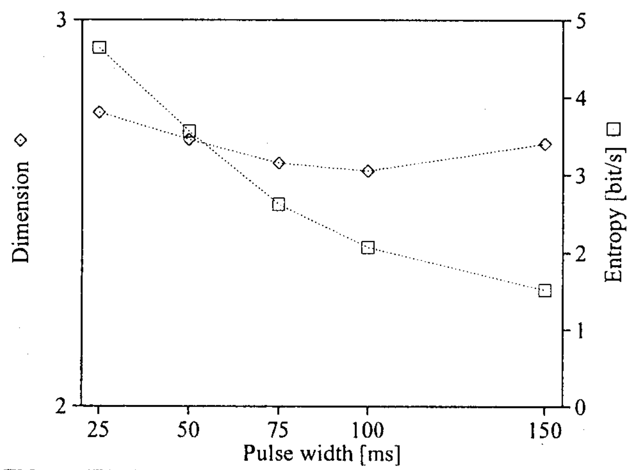


FIG. 15(B). VARIATION OF DIMENSION AND ENTROPY WITH PULSE WIDTH FOR STABILIZATION CONTROL (LOCAL SIGNAL).

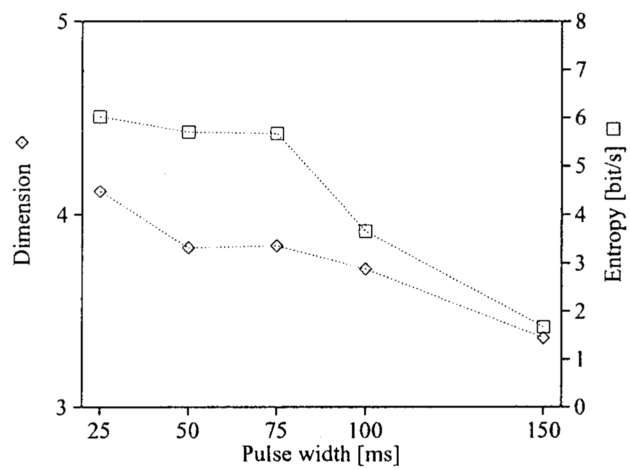


FIG. 16(B). VARIATION OF DIMENSION AND ENTROPY WITH PULSE WIDTH FOR DESTABILIZATION CONTROL (LOCAL SIGNAL).

Control of Bed Behavior

At various operating conditions, the pulse timing and width were manipulated to control the bed behavior. This section presents the evaluation techniques and the results for three operating conditions, which are in Table 5. The system behavior with no control is compared with both stabilization and destabilization control runs.

Figures 17, 18 and 19 show the Fourier power spectra for runs C1 to C6. Compared with the no control case, stabilization results in a more distinct, narrow-band spectrum, whereas destabilization results in a more broad-band spectrum.

The shift in peak frequencies is also useful for understanding the system behavior. The earlier section ''Behavior of slugging beds'' discusses the shift of the unstable fixed point with gas velocity. For stabilization control, such a shift to a lower unstable fixed point around a period of 0.5 s was seen in runs C1 and C2. Time return maps show this shift more clearly. For Run C3, no such frequency shift occurs, and the control seems to stabilize the existing unstable fixed point, as evidenced by a tighter cluster in the time return map for the plenum signal. Destabilization usually results in a lower-period cluster in the time return maps.

Time return maps for the above runs are shown in figs. 20, 21 and 22. As the local signal observes only a small vertical section and the plenum signal observes the entire bed fluctuation, return maps of the two signals frequently differ. In the control experiments described above, the plenum signal was used for control, and hence the effects of control mode are more visible in the plenum signal. For instance, the overall bed pressure behavior as measured from the plenum is effectively stabilized even though the local-signal return map exhibits discretization.

TAB. 5. OPERATING CONDITIONS FOR CONTROL OF BED BEHAVIOR RUNS

Run	U/U_{mf}	Trigger Level [kPa]	Trigger Crossing Direction	Pulse Width [ms]	Pulse Air [pct]
Stabilization control					
C1	1.28	+0.09	Upward	60	1.9
C2	1.42	+0.93	Upward	150	3.8
C3	1.72	+0.60	Downward	100	1.4
Destabilization control					
C4	1.28	-0.21	Downward	20	1.2
C5	1.42	-0.48	Downward	75	2.1
C6	1.72	-0.60	Upward	100	2.5

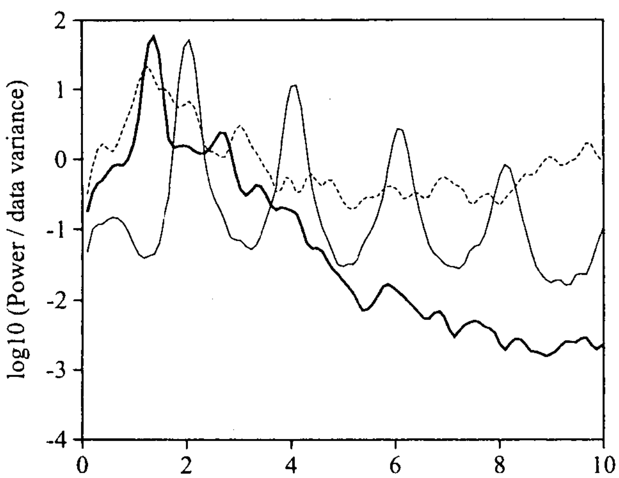


FIG. 17. POWER SPECTRA FOR STABILIZATION (THIN), NO CONTROL (THICK) AND DESTABILIZATION (DASHED) AT U/U_{mf} = 1.28 (PLENUM SIGNAL).

The effect of control mode on maximum cycle magnitudes from the plenum signal are shown in figs. 23, 24 and 25. Cycle magnitudes are closely linked to slug size. For runs C1 and C2, the control very effectively stabilizes the slugging, and the cycle magnitudes are narrowly distributed. For Run C3, although there are fewer low-magnitude cycles than with the no control case, slugging is not as effectively stabilized as in runs C1 and C2.

In destabilization control, the cycle magnitudes generally are lower because slug sizes are reduced by the control action. For runs C4 and C5, control is effective, resulting in the dense bands seen in figs. 23 and 24. In Run C6, the slug-size distribution is very dispersed, and the reduction in cycle magnitudes is not as dramatic as in runs C4 and C5.

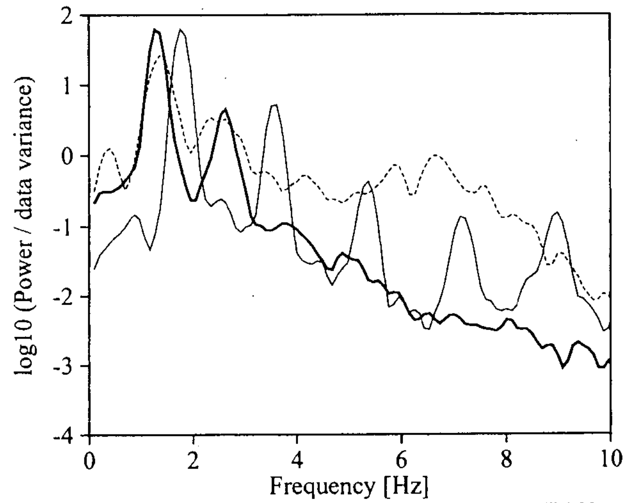


FIG. 18. POWER SPECTRA FOR STABILIZATION (THIN), NO CONTROL (THICK) AND DESTABILIZATION (DASHED) AT U/U_{mf} = 1.42 (PLENUM SIGNAL).

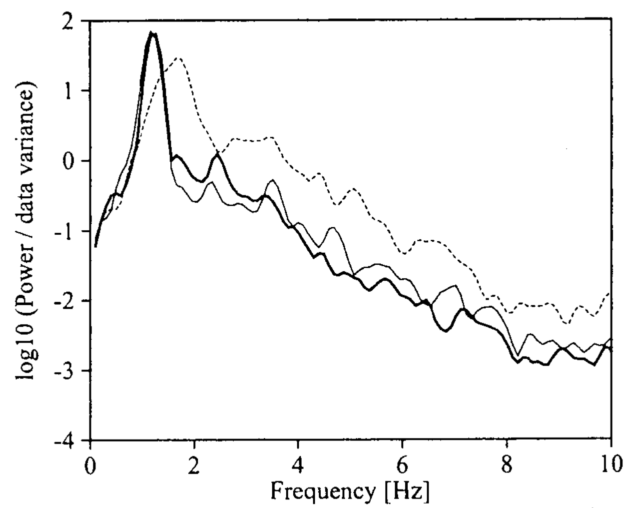


FIG. 19. POWER SPECTRA FOR STABILIZATION (THIN), NO CONTROL (THICK) AND DESTABILIZATION (DASHED) AT U/U_{mf} = 1.72 (PLENUM SIGNAL).

Dimension and entropy estimates for the plenum signal (figs. 26 and 27) clearly show the change in system behavior with different control modes, and a qualitatively similar trend is also seen in the results from the local pressure signal. In destabilization control, entropy and dimension significantly increase, reflecting a more complex bed behavior. In stabilization control, entropy and dimension do not significantly change, but in a few cases, the added signal complexity resulting from the air pulse yields slightly larger values. As discussed previously, the degree of resolution used to define dimension and entropy (i.e. the cutoff length) affects the detailed estimates. However, it is clear

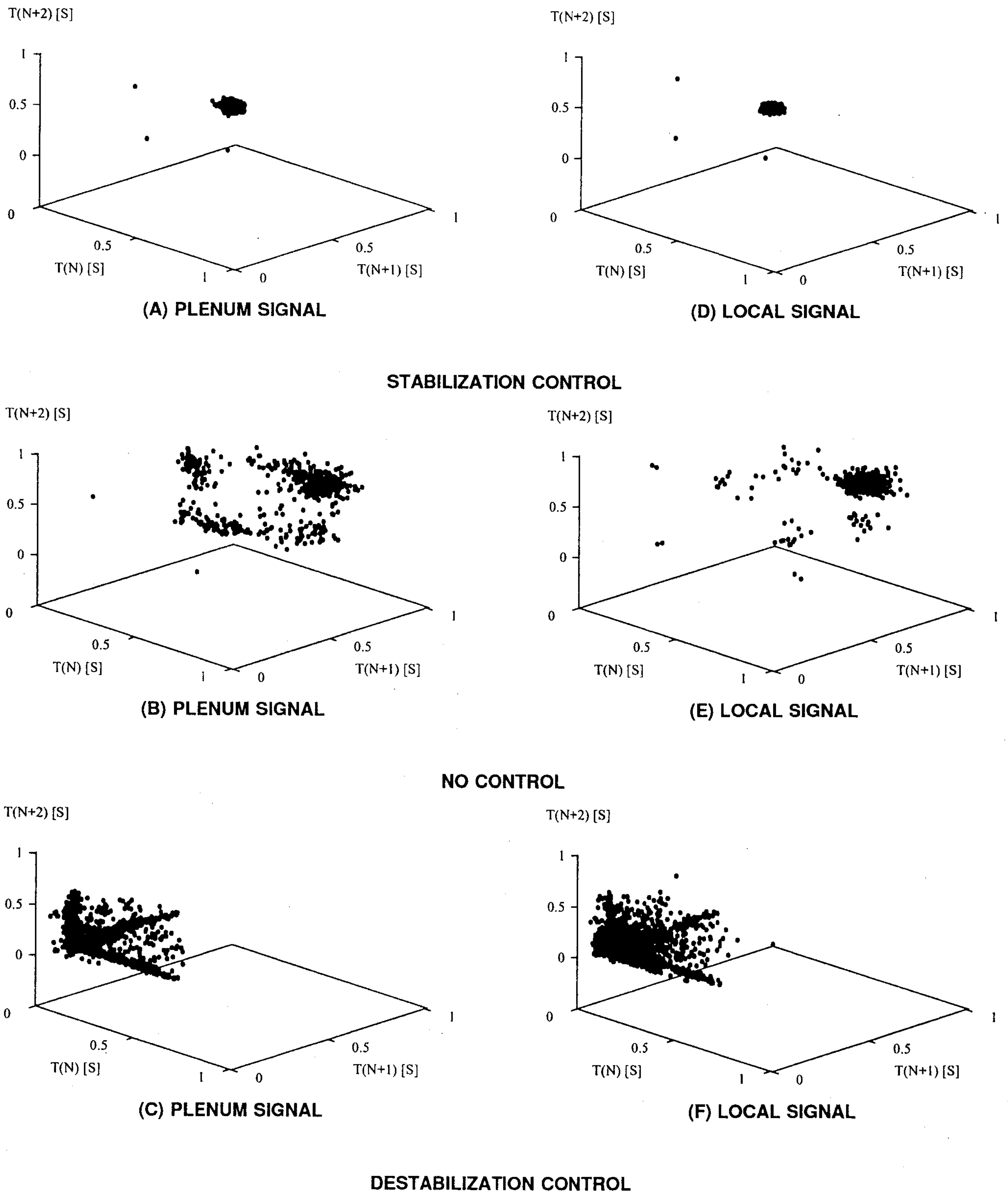
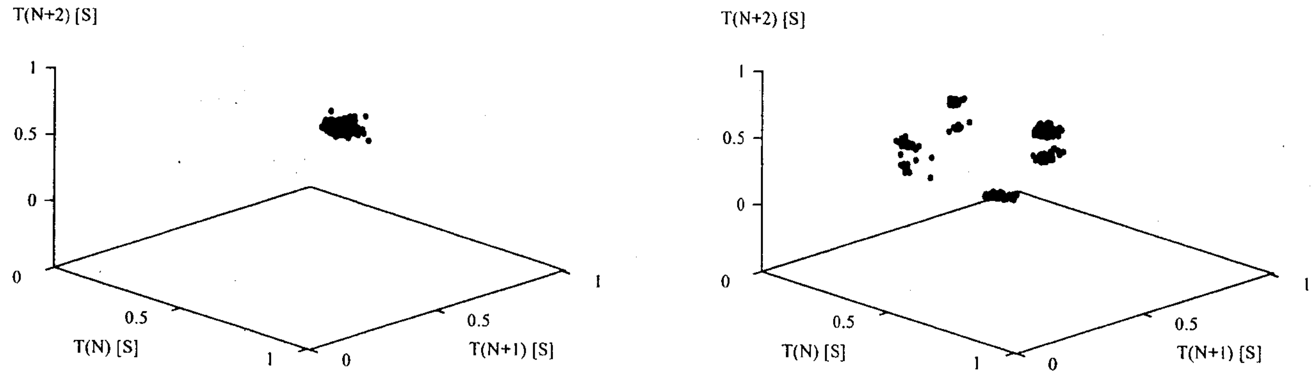


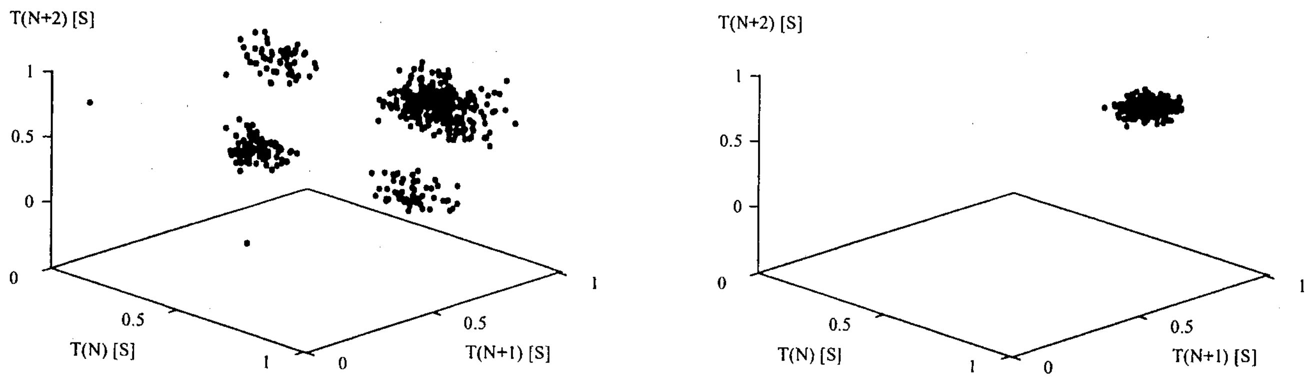
FIG. 20. TIME RETURN MAPS FOR DIFFERENT CONTROL MODES AT U/U_{mf} = 1.28.



(A) PLENUM SIGNAL

(D) LOCAL SIGNAL

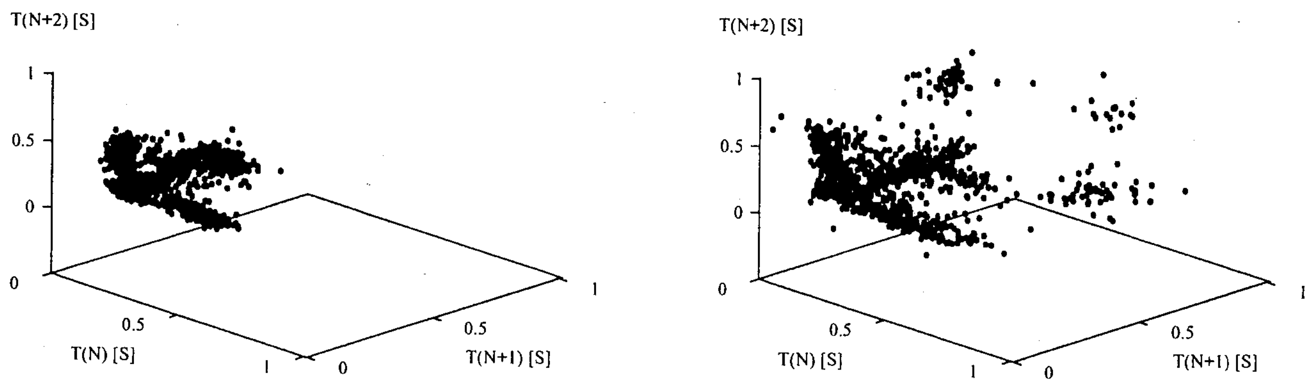
STABILIZATION CONTROL



(B) PLENUM SIGNAL

(E) LOCAL SIGNAL

NO CONTROL



(C) PLENUM SIGNAL

(F) LOCAL SIGNAL

DESTABILIZATION CONTROL

FIG. 21. TIME RETURN MAPS FOR DIFFERENT CONTROL MODES AT U/U_{mf} = 1.42.

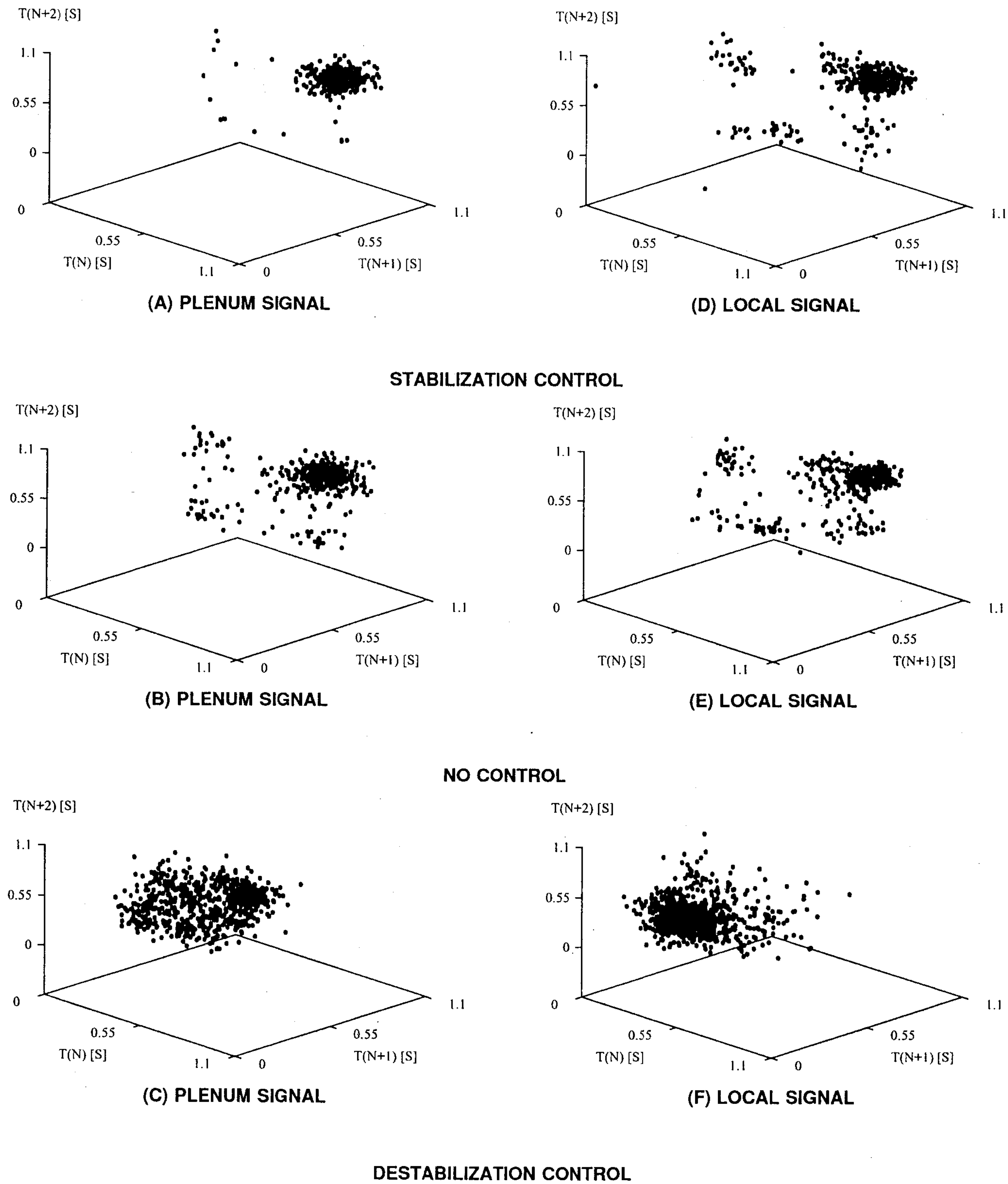


FIG. 22. TIME RETURN MAPS FOR DIFFERENT CONTROL MODES AT $U/U_{mf} = 1.72$.

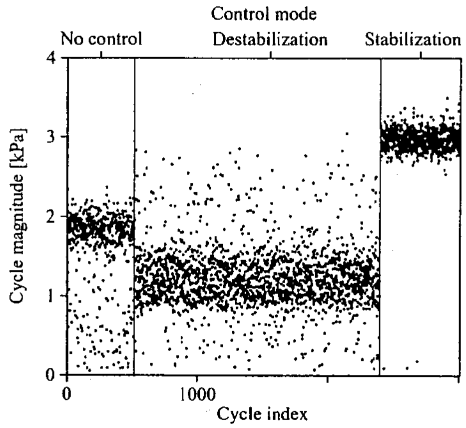


FIG. 23. VARIATION IN CYCLE MAGNITUDES WITH CONTROL MODE AT U/U_{mf} = 1.28 (PLENUM SIGNAL).

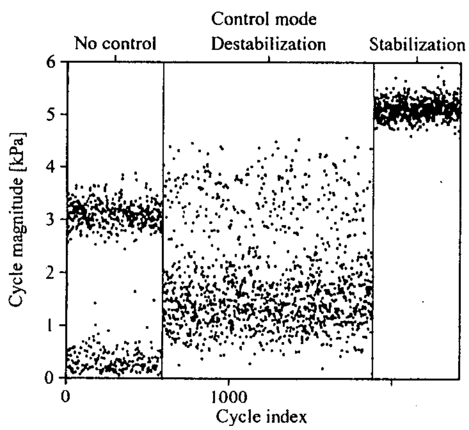


FIG. 24. VARIATION IN CYCLE MAGNITUDES WITH CONTROL MODE AT U/U_{mf} = 1.42 (PLENUM SIGNAL).

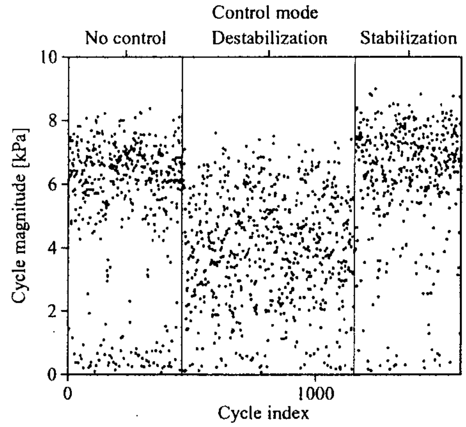


FIG. 25. VARIATION IN CYCLE MAGNITUDES WITH CONTROL MODE AT U/U_{mf} = 1.72 (PLENUM SIGNAL).

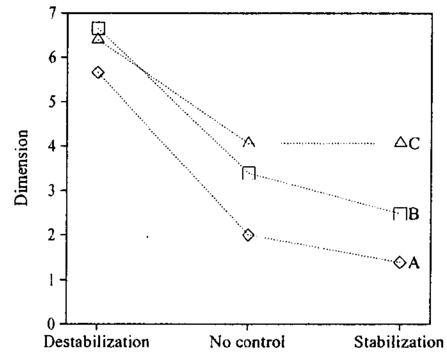


FIG. 26. VARIATION IN DIMENSION WITH CONTROL MODE AT U/U_{mf} OF 1.28 (A), 1.42 (B) AND 1.72 (C) (PLENUM SIGNAL).

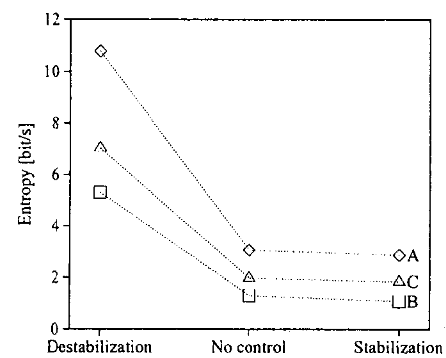


FIG. 27. VARIATION IN ENTROPY WITH CONTROL MODE AT U/U_{mf} OF 1.28 (A), 1.42 (B) AND 1.72 (C) (PLENUM SIGNAL).

that the basic trends in these quantities are consistent with the observed dynamic complexity of the bed.

CONCLUSIONS AND FUTURE ACTIVITIES

This study indicates that introducing a high-pressure, short-duration gas pulse into a slugging fluidized bed can modify slugging intensity effectively. The pressure-drop feedback control strategy implemented in this study both stabilized and destabilized slugging based on simple choices of pulse timing and intensity.

More sophisticated control strategies, based on recent advances in adaptive or chaotic control, could be devised to achieve a wide range of target behaviors. The control scheme can be revised to utilize the stable and unstable manifolds delineated by the dispersed points in time return maps to improve control effectiveness.

We suggest that the perturbation system should be modified for larger and deeper beds to include pulse nozzles located in the distributor. This will allow perturbation of the interior portions of beds with greater horizontal extent.

ACKNOWLEDGEMENT

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