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Temperature Fluctuations and Heat Transfer in a Circulating Fluidized Bed

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Abstract−Characteristics of temperature fluctuations and heat transfer coefficient have been investigated in the riser of a circulating fluidized bed (0.102 m ID and 4.0 m in height). Effects of gas velocity and solid circulation rate on the temperature fluctuations, suspension density and heat transfer coefficient between the immersed heater and the bed have been considered in the riser. To analyze the characteristics of temperature fluctuations at the wall of the riser, the phase space portrait and Kolmogorov entropy of the fluctuations have been obtained, and the relation between the temperature fluctuations and the heat transfer coefficient has been examined. It has been found that the heat transfer system becomes more complicated and irregular with decreasing gas velocity and increasing solid circulation rate or suspension density in the riser. The heat transfer coefficient and Kolmogorov entropy of the temperature fluctuations have decreased with increasing the superficial gas velocity, while they have increased with increasing the solid circulation rate or suspension density in the bed. The heat transfer coefficient has been well correlated in terms of the Kolmogorov entropy, suspension density as well as operating variables in the riser.

Key words: Circulating Fluidized Bed, Heat Transfer Coefficient, Temperature Fluctuation, Kolmogorov Entropy

INTRODUCTION

Heat transfer in circulating fluidized beds has been widely investigated because of the increasing demands of industrial applications [Grace, 1986; Basu, 1990; Glicksman, 1988, Kim et al., 1999; Namkung et al., 1999; Kim and Han, 1999; Kage et al., 1999]. It has been known that the average local heat transfer coefficient decreases along with the height of the riser but shows the higher value near the wall of the riser. It has been also recognized that the increase of solid concentration or suspension density can lead to the increase of heat transfer coefficient, and the convection by means of particles is one of important factors to determine the heat transfer coefficient [Basu and Nag, 1987; Wu et al., 1989; Bi et al., 1991; Weimer et al., 1991; Cho et al., 1996].

However, effects of gas velocity on the heat transfer coefficient have not been consistent; some investigators reported that the heat transfer coefficient decreases with increasing the gas velocity due to the decrease in the suspension density [Fraley et al., 1983; Wu et al., 1989, 1990; Han et al., 1991], while the others found that the heat transfer coefficient increases with increasing gas velocity [Shen et al., 1991]. From the experimental results of Nag and Moral [1991] and Molerus [1993], the effects of gas velocity on the heat transfer coefficient become marginal at the operating conditions under similar suspension density.

For a reliable understanding of heat transfer phenomena in circulating fluidized beds, information on the characteristics of a heat transfer system such as temperature fluctuations or distribution have been necessary [Leckner and Andersson, 1992; Wang et al., 1996]. Analysis and characterization of the heat transfer phenomena in a circulating fluidized bed in terms of temperature fluctuations of its state variable could yield useful information relevant to the fault diagnosis and control of the system. The stochastic and random fluctuations of state variables in multiphase flow systems have been successfully treated and analyzed by means of stochastic and chaos analyses [Kang et al., 1997, 2000; Cho et al., 1994, 2001; Kim et al., 2001, 2002].

In the present study, temperature fluctuations in the riser have been measured and analyzed by adopting chaos analysis; the phase space portrait and Kolmogorov entropy have been obtained from the temperature fluctuations, and the relations between the chaotic parameters and the heat transfer coefficient have been considered. Effects of operating variables such as gas velocity and solid circulation rate on the phase space portraits and Kolmogorov entropy as well as heat transfer coefficient have been examined. Efforts are also made to correlate the heat transfer coefficient with the Kolmogorov entropy, suspension density as well as operating variables.

ANALYSIS

1. Phase Space Portraits

To construct the multi-dimensional phase space portraits, the time series of temperature fluctuation signals, T(t), have been digitalized with a time step of Δt. The resultant (m+1) values of the signal, $T(i\cdot\Delta t)$ have been stored for i=0, 1, 2, …, m; thus, the vector time series has been defined as [Roux et al., 1983]

$$Z_i(t)=[T(i\cdot\Delta t),\ T(i\cdot\Delta t+\tau),\ \ldots\ T(i\cdot\Delta t+(p-1)\cdot\tau)]\quad i=0, 1, 2, \ldots, [m-(p-1)\cdot k] \tag{1}$$

where $\tau=k\cdot\Delta t$, k=0, 1, 2, ….

In Eq. (1) p is the dimension of the vector, Z(t). Thus, a series of p-dimensional vectors representing the p-dimensional portrait of

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‡This paper is dedicated to Professor Dong Sup Doh on the occasion of his retirement from Korea University.

the system can be obtained moving along with time t.

2. Kolmogorov Entropy

It has been known that the Kolmogorov entropy can be used as a unique measure for the rate of generation of information of a system, since it is directly related to the average predictability of the system [Van der Stappen et al., 1992; Grassberger, 1986; Huilin et al., 1995].

The amount of information required to specify the evolution in time of the system during the time interval Δt can be given by

$$I=I_0+K_2(\Delta t) \quad (2)$$

where I_0 is the initial information. In this equation, the invariant parameter K_2 is the Kolmogorov entropy expressed in bits per unit time. The value of Kolmogorov entropy can be estimated by considering the fraction of pairs separated by a distance smaller than a given τ_0, in an embedded phase space of dimension m.

This fraction can be expressed as

$$T(\tau_0, m) \propto \exp(-K_2 m\tau) \quad (3)$$

In this equation τ is the time delay in the reconstruction.

EXPERIMENT

Experiments were performed in the riser of a circulating fluidized bed which is composed of three main sections such as the riser column, gas-solid separator and solid recycle device, as can be seen in Fig. 1 [Kang et al., 2000]. The riser and solid recycle device were constructed of several pieces of acrylic column. The diameter and height of the riser were 0.102 m I.D. and 4.0 m, respectively. The dried, filtered and compressed air was injected into the riser through the perforated type distributor installed between the main column section and an air box. The distributor contained 347 holes with triangular pitches and was covered with 400 mesh stainless steel screen for preventing from particle weeping. The diameter of each hole was 3 mm. Fluid cracking catalyst (FCC) whose density is 1,840 kg/m^3 and mean diameter is 74 μm was used as a solid phase.

The solid particles were returned to the bottom of the riser through the solid recycle device. The solid circulation rate was determined by measuring the amount of solids piled up above the butterfly valve in the solid recycle device [Cho et al., 1994; Kang et al., 1997, 2000]. Eleven pressure taps were mounted flush with the column wall at 0.3 m height intervals from the distributor. The gas velocity and solid circulation rate were in the range from 1.65 to 2.95 m/s and from 10 to 30 kg/m^2s, respectively.

As a heating source, a cone shape heater was placed vertically on the distributor at the center of the riser. The heater was constructed from a copper rod (4 m height×2.54 cm-I.D.) axially drilled to accommodate a cartridge heater. Six 1.0 mm diameter iron-constant thermocouples were mounted in 2.0 mm walls and soldered in place flush with the heater surface. Six thermocouples were also positioned 90° apart at the wall of the riser at the elevation of 0.2 m interval from the bottom of the riser. A teflon cone was attached to the bottom of the heater to provide the fully developed thermal boundary layer around the bottom of the heater.

The average heat transfer coefficient was determined from the measurement of temperature difference between the heater surface and the wall of the riser. The temperature fluctuations and their histograms at the wall of the column as well as heater surface were measured and recorded by temperature sensing systems after the gas-solid flow would attain a steady state condition in the riser. The signals were captured by a personal computer after A/D conversion, filtering and amplifying. The temperature sensing system was fast enough to follow the dynamic temperature fluctuations in the riser. The voltage-time signals, corresponding to the temperature-time signals, from the temperature transducer were fed to the recording system at selected sampling rate of 500 Hz. A typical sample comprised 5,000 points. This combination of the sampling rate and length ensured capturing of the full spectrum of hydrodynamic signals from the circulating fluidized bed at steady state operating conditions.

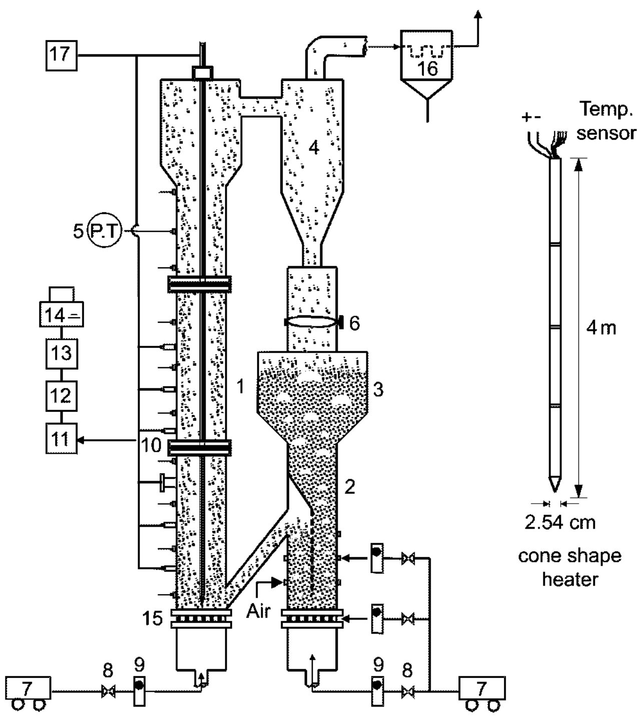

Fig. 1. Schematic diagram of circulating fluidized beds.

1. Riser
2. Down comer
3. Hopper
4. Cyclone
5. Pressure tap
6. Butterfly valve
7. Compressor
8. Control valve
9. Flowmeter
10. Temp. sensor
11. Amplifier
12. Low-pass filter
13. A/D converter
14. Computer
15. Gas distributor
16. Bag filter
17. DC Power supplier

RESULTS AND DISCUSSION

1. Temperature Fluctuations

A typical example of temperature fluctuations at the wall of the riser can be seen in Fig. 2 with the variation of gas velocity. In this figure, the amplitude and frequency of temperature fluctuations decrease with increasing gas velocity. But the fluctuations become more complicated and random with an increase in the particle circulation rate as can be seen in Fig. 3. From these figures, it can be anticipated that the heat transfer system becomes less stable with increasing particle circulation rate or decreasing gas velocity.

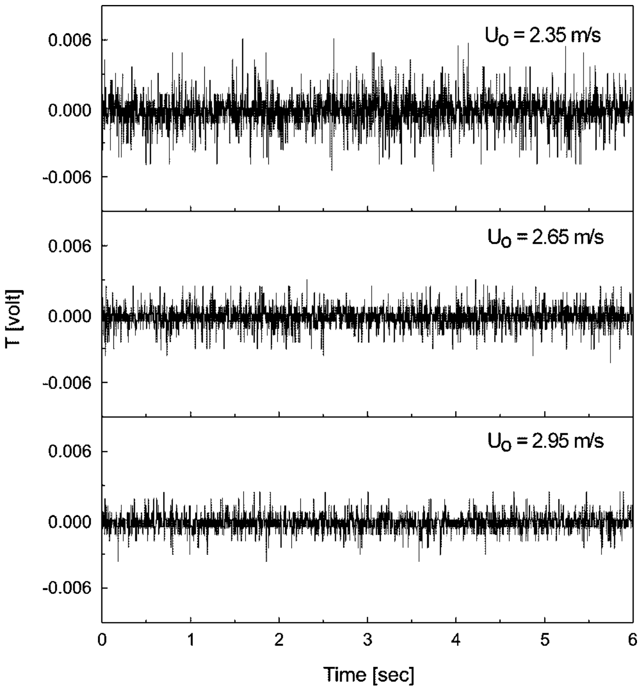

Fig. 2. Typical temperature fluctuation signals at the wall of the riser of a circulating fluidized bed (G_s=30 kg/m^{2}s).

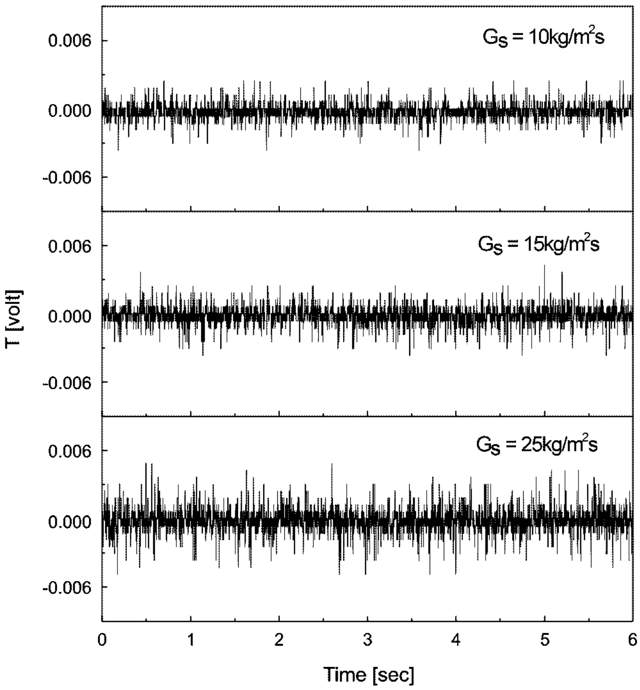

Fig. 3. Typical temperature fluctuation signals at the wall of the riser of a circulating fluidized bed (U_o=2.35 m/s).

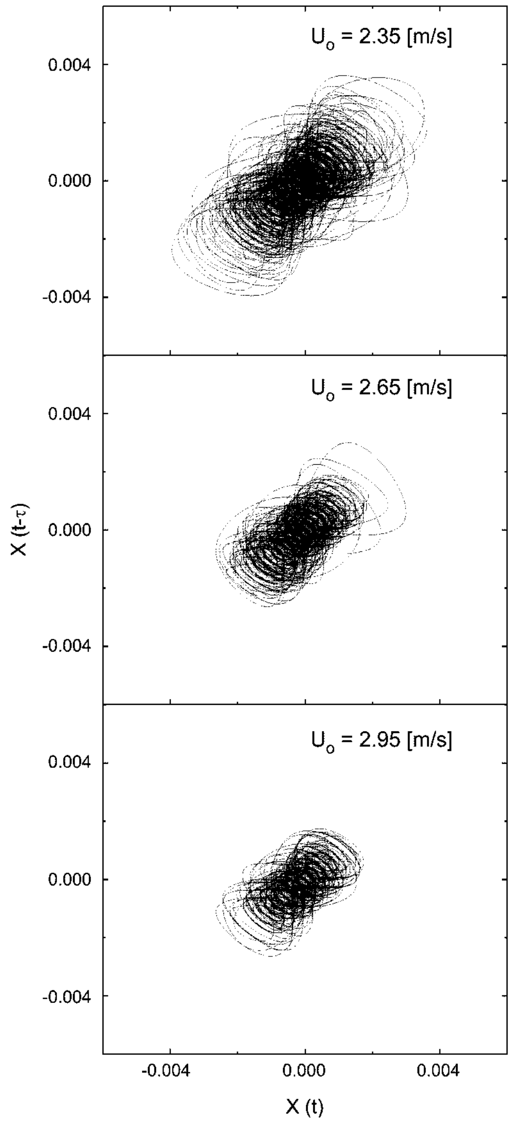

Fig. 4. Typical example of phase space portraits of temperature fluctuations (G_s=30 kg/m^{2}s).

The characteristics of temperature fluctuations can be represented more easily by means of constructing the multi-dimensional phase space portraits, as can be seen in Figs. 4 and 5. In these figures, the strange attractor tends to more scattering with decreasing the gas velocity or increasing the solid circulation rate. This implies that the information and unique features in the temperature fluctuations or heat transfer system cannot be maintained easily owing to the increase of rate of generation of other information, with increasing the solid circulation rate or decreasing the gas velocity. It has been generally understood that the flow of gas-solid particle suspension in the riser of a circulating fluidized bed exhibits a core-annulus structure involving downflowing of solids near to the wall of the riser [Rhodes et al., 1992; Tung et al., 1989]. Thus, the temperature fluctuations at the wall of the column tend to be more complicated with increasing the amount of solid at the region near the wall. It can be easily observed that the amount of solid particles in the annulus region of the riser increase with increasing the solid circulation rate or decreasing the gas velocity.

The unique features of chaotic behavior of temperature fluctuations can be expressed quantitatively by means of Kolmogorov entropy which is somewhat of a robust measure of the resultant behavior of the system. The variation of Kolmogorov entropy of temperature fluctuations with the variation of gas velocity can be seen in Fig. 6. Also, effects of solid circulation rate on the Kolmogorov en-

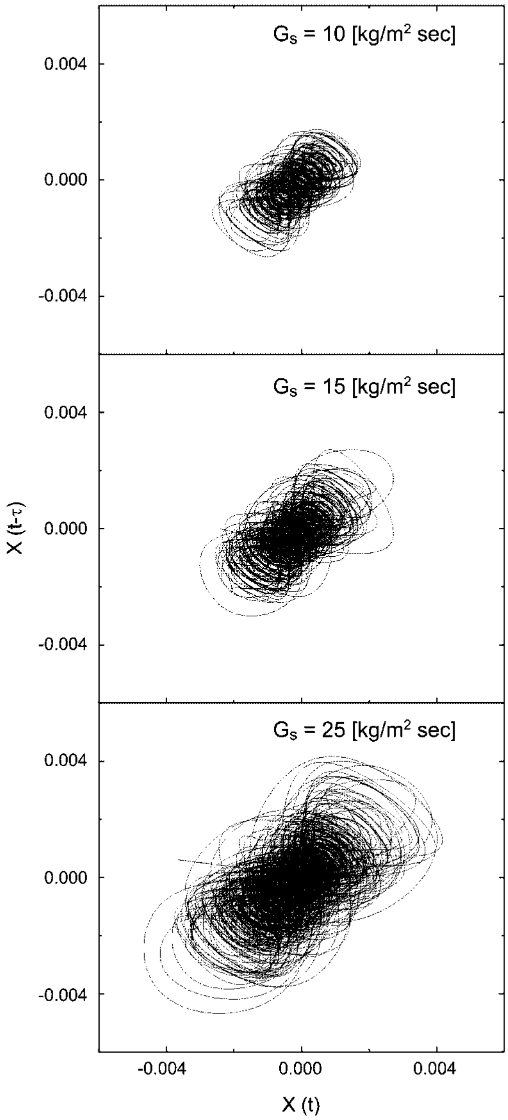

Fig. 5. Typical example of phase space portraits of temperature fluctuations (U_o=2.35 m/s).

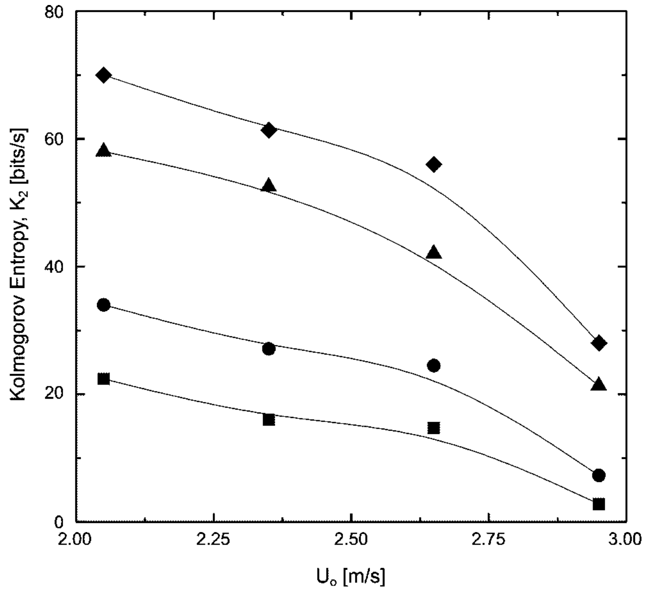

Fig. 6. Effects of gas velocity on Kolmogorov entropy of temperature fluctuations in the riser.
G_s [kg/m^{2}s] ■ 15 ● 20 ▲ 25 ◆ 30

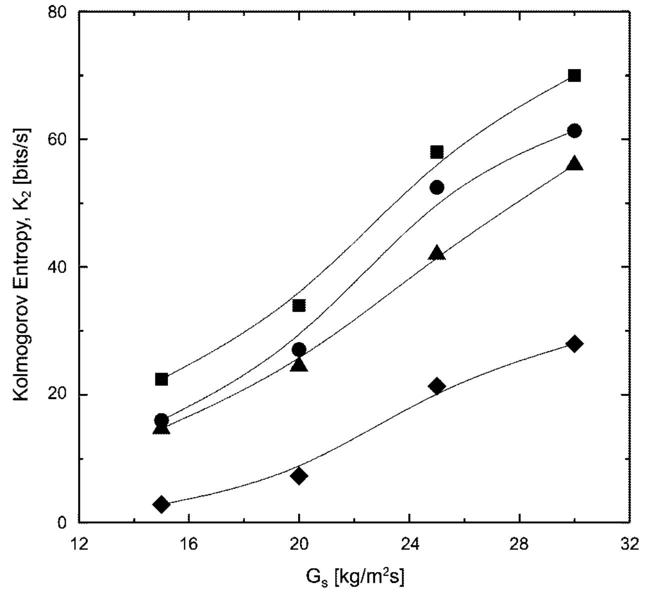

Fig. 7. Effects of solid circulation rate on Kolmogorov entropy of temperature fluctuations in the riser.
U_o [m/s] ■ 1.85 ● 2.05 ▲ 2.35 ▼ 2.65 ◆ 2.95

tropy of temperature fluctuations can be seen in Fig. 7. Note in these figures that the Kolmogorov entropy decreases gradually with increasing gas velocity, but it increases with increasing solid circulation rate. These trends of Kolmogorov entropy coincide with those of phase space portraits of temperature fluctuations; furthermore the Kolmogorov entropy can represent the states of system quantitatively (Figs. 6 and 7).

2. Heat Transfer Coefficient

The heat transfer coefficient between the immersed vertical heater and the wall of the riser has been determined from the knowledge of heat input, surface area of the heater and the mean value of temperature difference between the heater surface and the wall. The variation of h can be seen in Fig. 8 with the variation of gas velocity. In this figure, the heat transfer coefficient decreases with increasing the gas velocity. This can be due to the fact that the amount of solid particles at the annulus region near the wall of the riser decreases with increasing the gas velocity. It has been understood that the role of solid as a heat carrier medium for heat transfer can be one of the important factors in determining the h value in circulating fluidized beds [Basu and Nag, 1987; Weimer et al., 1991]. By a similar reason, the heat transfer coefficient increases gradually with increasing the solid circulation rate as can be seen in Fig. 9. Actually, the suspension density in the riser decreases with increasing gas velocity (Fig. 10), but it increases with increasing solid circulation rate (Fig. 11). Fig. 12 illustrates that the heat transfer coefficient increases with increasing suspension density in the riser. The reason why the heat transfer coefficient increases with increasing the suspension density in the riser can be explained: the increase of suspension density of particles can give rise to the increases in thermal capacity as well

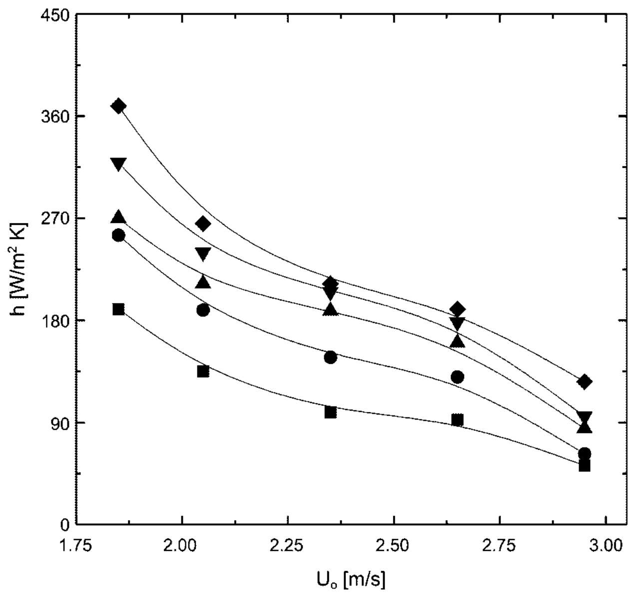

Fig. 8. Effects of gas velocity on the immersed heater-to-bed heat transfer coefficient in the riser.
G_s [kg/m^{2}s] ■ 10 ● 15 ▲ 20 ▼ 25 ◆ 30

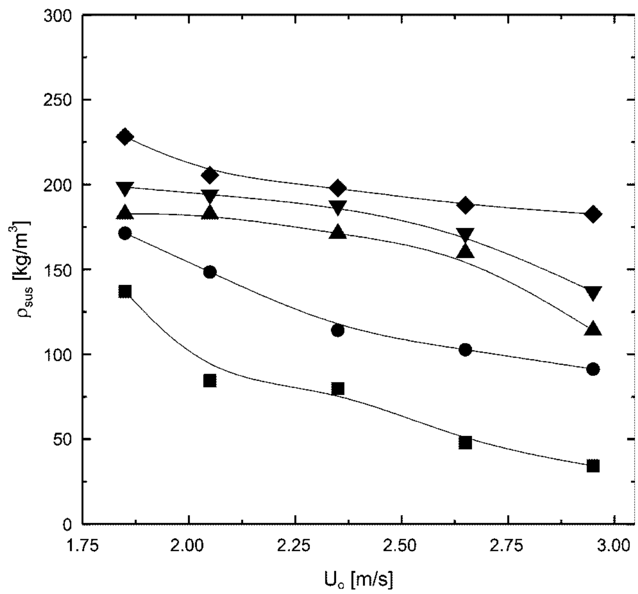

Fig. 10. Effects of gas velocity on the suspension density in the riser.
G_s [kg/m^{2}s] ■ 10 ● 15 ▲ 20 ▼ 25 ◆ 30

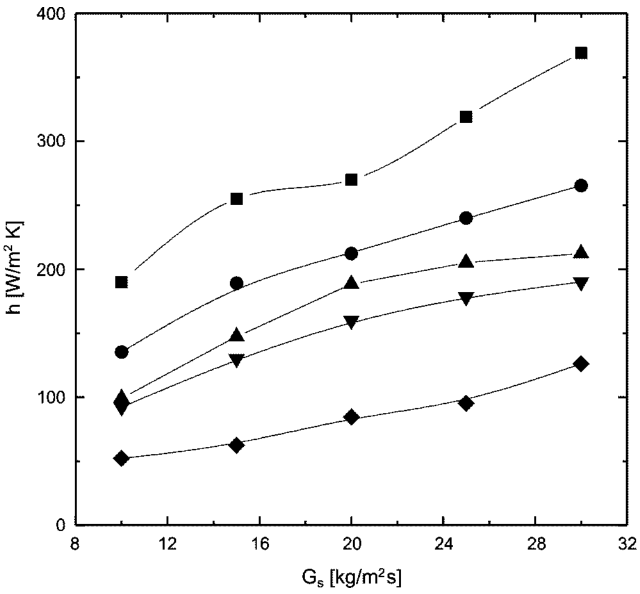

Fig. 9. Effects of solid circulation rate on the immersed heater-to-bed heat transfer coefficient in the riser.
U_o [m/s] ■ 1.85 ● 2.05 ▲ 2.35 ▼ 2.65 ◆ 2.95

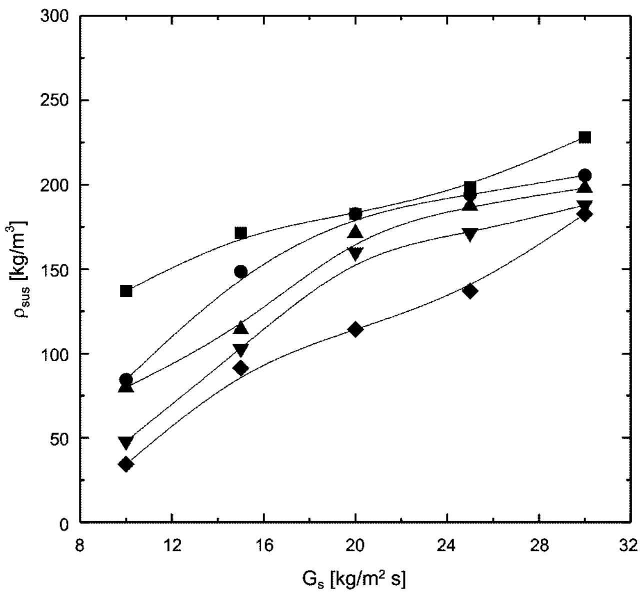

Fig. 11. Effects of solid circulation rate on the suspension density in the riser.
U_o [m/s] ■ 1.85 ● 2.05 ▲ 2.35 ▼ 2.65 ◆ 2.95

as turbulence in the heat transfer medium which, in turn, enables the heat to be transported more effectively. It can be noted that the thermal output from the circulating fluidized bed-boiler has been generally adjusted by means of the control of suspension density. It has been reported that the heat transfer coefficient is directly related to the behavior of particle packets [Wu et al., 1991; Wang et al., 1996].

As can be expected, the value of h increases gradually with increasing the value of Kolmogorov entropy as can be seen in Fig. 13, since the heat transfer coefficient exhibits the higher value at which the particles are fluidized and circulated more vigorously in the riser. The relation between the heat transfer and the suspension density or Kologorov entropy enables us to correlate the h value in terms of the suspension density or Kolmogorov entropy as Eqs. (4) and (5), respectively.

$$h=2.904\rho_{sus}^{0.826} \tag{4}$$

$$h=39.205K_2^{0.418} \tag{5}$$

The correlation coefficients of Eqs. (4) and (5) are 0.935 and 0.926, respectively. For practical information in the field, the heat transfer coefficient has been also correlated in terms of operating variables

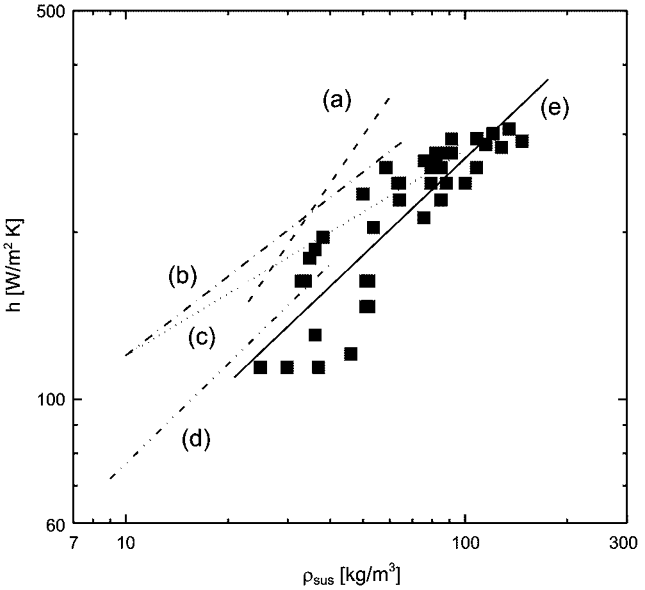

Fig. 12. Effects of suspension density on the immersed heater-to-bed heat transfer coefficient in the riser.
(a) Basu (1987) (b) Wu (1989) (c) Subbarao (1986)
(d) Dou (1992) (e) this study

within these operating conditions as

$$h=158.778U_o^{-2.358}G_s^{0.689} \quad (6)$$

with a correlation coefficient of 0.925.

CONCLUSION

The complicated temperature fluctuations in a riser of a circulating fluidized bed have been successfully analyzed by means of phase portraits and Kolmogorov entropy. It has been revealed that the heat transfer behavior in the riser becomes more complicated, random and irregular with decreasing gas velocity and increasing solid circulation rate or suspension density. The effects of gas velocity and solid circulation rate on the Kolmogorov entropy are very similar to those on the values of heat transfer coefficient as well as suspension density in the riser: The heat transfer coefficient and suspension density decrease with increasing gas velocity, but they increase gradually with increasing solid circulation rate. The characteristics of immersed heater-to-bed heat transfer phenomena in the riser of circulating fluidized bed can be analyzed and controlled in terms of temperature fluctuations of its state variable.

NOMENCLATURE

G_S : solid circulation rate [$kgm^{-2}s^{-1}$]
H_{riser} : Height of riser [m]
h : heat transfer coefficient [$Wm^{-2}K^{-1}$]
I : information [bits]
I_0 : initial information [bits]
K_2 : Kolmogorov entropy [bits s^{-1}]
t : time [s]
Δt : time interval [s]
U_0 : total air velocity [ms^{-1}]
U_1 : primary air velocity [ms^{-1}]
U_2 : secondary air velocity [ms^{-1}]
X(t) : time series [V]

Greek Letters

ε_S : solid holdup with secondary air injection [-]
ε_{S0} : solid holdup without secondary air injection [-]
τ : time lag [s]
ρ_{SUS} : suspension density [kgm^{-3}]

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