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Temperature Fluctuations and Heat Transfer in a Fluidized-Bed Combustor of Waste Oil

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Abstract−Temperature fluctuations and heat transfer characteristics were investigated in a fluidized-bed combustor of 0.102 m ID and 2.5 m in height, which was designed for waste oil combustion. Effects of excess air (A_E), injection height (H_I) and feeding rate of waste oil (Q_F) on the mean bed temperature (T_B), Kolmogorov entropy (K_2) of phase space portraits and heat transfer coefficient (U_0) in the fluidized-bed combustor were determined. T_B increased, but K_2 and U_0 decreased with increasing A_E. K_2 had a local minimum, but T_B and U_0 had a maximum at H_I of 0.4 m. T_B increased, but K_2 had a minimum and U_0 had a maximum with increasing Q_F in the combustor. T_B, K_2 and U_0 obtained at the optimum operating condition (A_E=40%, H_I=0.4 m, Q_F=30 g/min) were about 855 °C, 22 bits/s and 382 W/m^{2}K, respectively.

Key words: Fluidized-bed Combustor, Waste Oil, Heat Transfer Coefficient, Temperature Fluctuations, Chaos Theory

INTRODUCTION

Disposal of industrial hazardous wastes has become an important public concern in view of environmental protection. Combustion of waste oil is one of the appropriate methods instead of landfill, especially considering the heating value of waste oil (10,000 kcal/kg) [Saxena and Jotshi, 1996; Chu, 1999]. There are many advantages in applying fluidization technology to the combustion of industrial hazardous wastes such as waste oils, sludge, plastics and tires, since the wastes can be well dispersed and mixed with bed materials by means of fluidizing air [Lee and Chun, 1993; Anthony, 1995; Gu et al., 2002].

However, there has been relatively little attention given to the characteristics of waste oil combustion in a fluidized bed. Even the fundamental characteristics of hydrodynamics and heat transfer in the combustor have not been well understood, because the combustion system is much too complicated, irregular and random to measure and analyze easily. The hydrodynamics and transport phenomena in multiphase flow systems have been successfully analyzed and described by means of the chaotic parameters [Kikuchi et al., 1997; Zijerveld et al., 1998; Kang et al., 1996, 1999, 2000]. It can be understood that the combustion of waste oil is quite different from that of the other solid wastes.

In the present study, thus, the characteristics of temperature fluctuations and heat transfer in a fluidized-bed combustor have been investigated by adopting somewhat the noble chaos theory. More specifically, the time series of temperature fluctuations, which can visualize the gas-solid thermal flow behavior in the fluidized-bed combustor directly, were measured and analyzed by means of chaos analysis to visualize them as the phase space portraits and Kolmogorov entropy. In addition, effects of excess air (A_E), injection height (H_I) and feeding rate (Q_F) of waste oil on the mean bed temperature (T_B), Kolmogorov entropy (K_2) of phase space portraits as well as on the heat transfer coefficient (U_0) in the combustor were determined. The results of this study can be used to determine the optimum conditions for the combustion of waste oil in a fluidized-bed combustor.

ANALYSIS

1. Phase Space Portraits

Multidimensional phase space portraits can be constructed from the temperature difference fluctuation time series by means of the time delay method [Packard et al., 1980; Roux et al., 1983]. That is, the experimentally obtained time-series signal, X(t), is digitized with a time step of Δt; the resultant (m+1) values of the signal, X(i Δt), are stored for i=0, 1, 2, …, m.

Thus, the vector time series is defined as

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

where τ=k Δt, k=1, 2, 3, … and p is the dimension of the vector, Z(t). Therefore, moving along with time t, a series of *p*-dimensional vectors representing the *p*-dimensional portrait of the system can be obtained. Occasionally, *p* is referred to as the embedded phase-space dimension of the reconstructed trajectory or attractor.

2. Kolmogorov Entropy (K_2)

K_2 has been known to be used for a direct measure of the generation rate of information of a system, since it can be used more easily to scale the time dependent behavior of multiphase flow systems [Van der Stappen et al., 1992; Huilin et al., 1995]. K_2 can be estimated by considering the fraction of pairs (N) separated by a distance given smaller than a given r_0, in an embedding dimension p as follows:

$$N(r_0, p)\propto\exp(-K_2 p\tau) \tag{2}$$

where τ is time delay in the reconstruction. Actually, the rate of growth

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of the distance between two initially close points on the attractor can be measured by counting the number of steps, Δt, in time where the distance between the points can be followed along the attractor before it becomes larger than some prescribed distance (r_0). This discrete number of steps is exponentially distributed with a cumulative probability distribution $N(r_0, p)$ such as Eq. (2). For a dissipative ordered or periodic system, the Kolmogorov entropy is zero, indicating that no information is generated as the system evolves in time. The system is said to be predictable at any time. A random system has a $K_2=\infty$, making the system totally unpredictable even after the next time step.

EXPERIMENTAL

Experiments were carried out in a fluidized-bed combustor whose inside diameter is 0.102 m and 2.5 m in height. A schematic diagram of the experimental apparatus is shown in Fig. 1. The combustor consists of a wind box, distributor, spray nozzles, riser and cyclone. Specifically, the lower bed stage is 0.102 m ID and 1.5 m in height and the upper free board is 0.203 m-ID and 1 m in height. Perforated plate containing 36 evenly spaced holes of 2 mm diameter served as an air distributor, where 400-mesh stainless steel screen was attached to support the bed materials. The spray nozzle was used to spray the waste oil into the bed, and it had 5 holes of 1 mm in diameter.

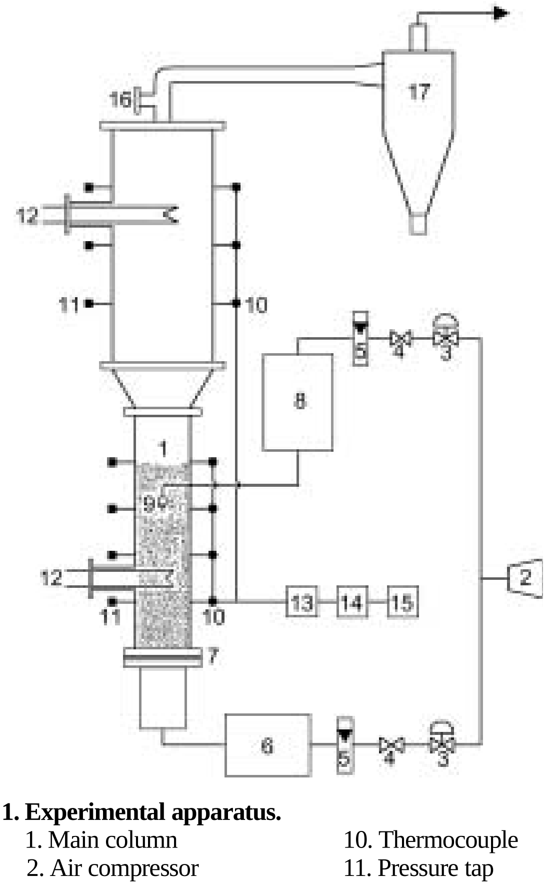

Fig. 1. Experimental apparatus.

1. Main column	10. Thermocouple
2. Air compressor	11. Pressure tap
3. Pressure regulator	12. Heat exchanger
4. Valve	13. TIC
5. Rotameter	14. A/D converter
6. Air preheater	15. Computer
7. Distributor	16. Sampling hole
8. Waste oil tank	17. Cyclone
9. Injection nozzle	

Table 1. Physical and chemical properties of waste oil

Viscosity at 40 °C [cP]	240
HHV [kcal/kg]	10640
Flash point [°C]	180
Ultimate analysis	C:84.62, H:11.41, N:0.08, S:0.05, O:0.67

Waste residual oil and compressed air were supplied in the ranges from 10 to 40 g/min and from 0.6 to 3.5 m/s, respectively. The bed material was silica sand whose diameter range was from 500 to 600 μm (d_{sv}=556 μm) and density was 2,500 kg/m^3, respectively. The static bed height of the bed material was 0.5 m. Physical and chemical properties of waste oil are shown in Table 1.

In starting up of the combustor, the bed temperature was controlled by means of a PID control system with a heater of 8 kW capacity. The temperature was measured by means of K-type thermocouples, which were mounted along the wall of the bed with a 0.2 m interval in the axial direction. To measure the pressure variation in the bed pressure, taps were also installed at the wall of the bed with a 0.2 m height interval in the opposite side from the temperature measuring system.

The output signals from the thermocouples were processed by means of a data acquisition system (Data Precision Model, DT3001) and a personal computer. The voltage-time signals, corresponding to the temperature-time fluctuations, were sampled at a rate of 0.002 sec and transferred to the data acquisition system. The total sampling time was 10 sec with 5,000 data points. This combination of sampling rate and time can detect the full spectrum of temperature signals (500 Hz) in a multiphase flow system [Karamavruc et al., 1995; Kang et al., 1996, 1999, 2000].

The immersed heat exchanger was installed 0.3 m from the air distributor. The heat transfer coefficients between the heat exchanger and the bed were determined by Eq. (3) from the total amount of heat transfer and logarithmic mean value of temperature difference between them.

$$\mathbf{M}_w\mathbf{C}_{pw}\Delta\mathbf{T}=\mathbf{U}_0\mathbf{A}_0\Delta\mathbf{T}_L=\mathbf{U}_0\mathbf{A}_0\frac{\Delta\mathbf{T}_i-\Delta\mathbf{T}_0}{\ln\Delta\mathbf{T}_i/\Delta\mathbf{T}_0} \quad (3)$$

RESULTS AND DISCUSSION

Effects of gas velocity (U_G) on the pressure drop (ΔP) and its fluctuations are shown in Fig. 2. In this figure, the minimum fluidization velocity (U_{mf}) can be detected easily from the variation of pressure fluctuation signals. That is, the ΔP-fluctuations were not significant in fixed bed conditions; however, the ΔP in the bed began to fluctuate dramatically at the beginning of fluidization. The U_{mf} of bed material has been determined from this information.

Since the temperature of the bed interior could vary as a result of combustion behavior, the combustion characteristics can be described more conveniently by analyzing the temperature fluctuations as well as pressure signals in the combustor [Waghmare et al., 1998; Kim et al., 2001]. A typical example of temperature fluctuations

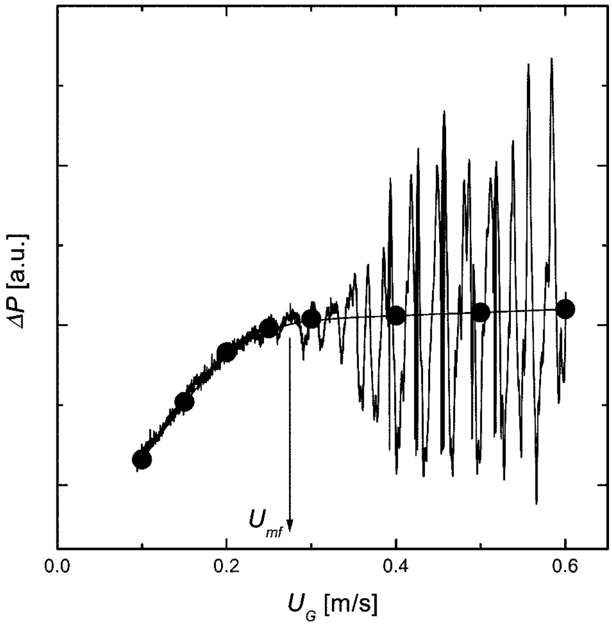

Fig. 2. Effects of U_G on the ΔP in fluidized-bed combustor.

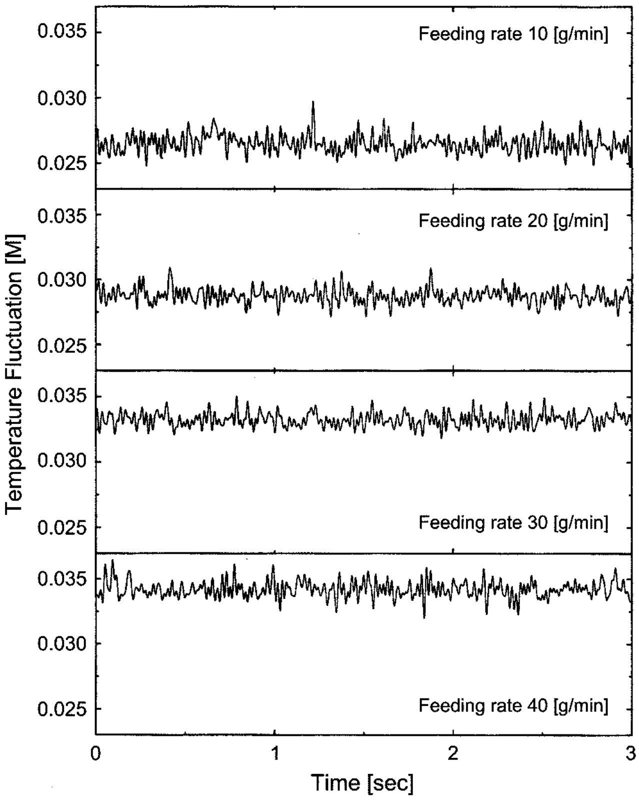

Fig. 3. Typical examples of temperature fluctuations in the combustor (A_E=20%, H_I=0.2 m).

with the variation of Q_F can be seen in Fig. 3. In this figure, the amplitude and frequency of temperature fluctuation in the combustor change with altering the operating conditions. Note that, in addition, the mean value of temperature in the combustor in a given condition was determined from these T-fluctuation data. To visualize

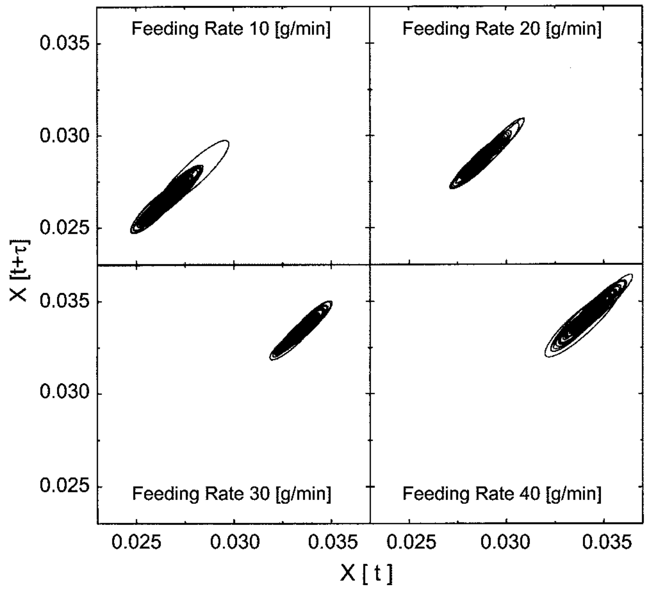

Fig. 4. Typical examples of phase space portraits of temperature fluctuations (A_E=20%, H_I=0.2 m).

the characteristics of temperature fluctuations in the phase space, these fluctuations of temperature were reorganized by means of phase space portraits in the reconstructed trajectory.

Fig. 4 shows a typical example of attractor of the temperature fluctuations in the fluidized-bed combustor. It can be noted in this figure that the increase of Q_F can increase the temperature due to the increase of calorific value generated during a given combustion time. And thus, the phase space portrait was moved to the upper region in the phase space with increasing the Q_F. In addition, the behavior of the temperature fluctuations becomes regular and stable when the feeding rate of waste oil increases from 10 g/min up to 30 g/min; however, it becomes irregular and unpredictable with further increase of feeding rate (Q_F=40 g/min). This is because the attractor becomes less scattered with increasing the feeding rate, whereas it tends to be scattered with a further increase of feeding rate. It has been understood that the shape and position of the attractor in the phase space help in identifying the underlying systems with their physical events [Packard et al., 1980; Kang et al., 2000; Kim et al., 2001]. The reason can be attributed to the unburned waste oil in the combustor. This enables us, thus, to state that the optimum Q_F of waste oil in this system would be around 30 g/min to maintain the relatively stable combustion condition.

The characteristics of temperature fluctuations in the combustor can be elucidated quantitatively by means of K_2. It was understood that K_2 is finite and positive for a chaotic system. The system can be predicted to some extent for small time step; however, for large time delays the state of the system is not effectively predictable. K_2 therefore can provide a direct measure for the dynamical temperature fluctuation behavior in fluidized-bed combustor.

Fig. 5 shows the effects of A_E (or U_G) on T_B and K_2 of phase space portraits in the combustor. The amount of A_E was obtained from the stoichiometric oxygen (or air) balance for the combustion of waste oil. In this figure, K_2 decreases, but T_B increases with increasing A_E in the combustor. It can be noted that T_B and K_2 do not change considerably when the excess air is 40-60%. This means that the

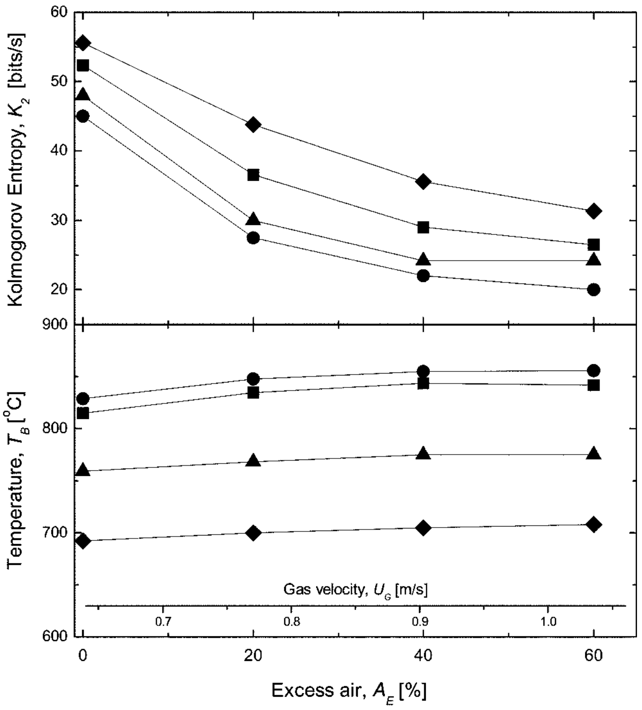

Fig. 5. Effects of A_E on T_B and K_2 in the combustor (Q_F=30 g/min).

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H_I [m] : 0.2 0.4 0.6 0.8

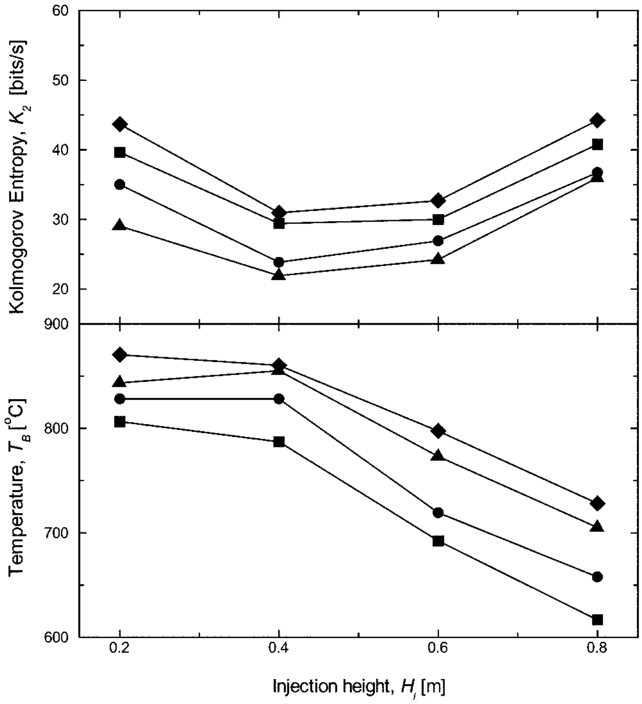

Fig. 6. Effects of H_I on T_B and K_2 in the combustor (A_E=40%).

■ ● ▲ ◆
Q_F [g/min] : 10 20 30 40

behavior of temperature fluctuations in the bed of combustor becomes more regular, stable and predictable. And, the excess air of 40-60% is sufficient for the complete combustion of waste oil in the bed. From these results, it is reasonable to state that the optimum amount of excess air would be 40-60% in this system.

It has been understood that the combustion characteristics of liquid fuels are dependent on the atomization or spray of fuels. The spray properties as well as the dynamics of air flow have been important aspects in determining the mixing pattern in diffusion flames [Ballester et al., 1994; Umemura et al., 1994; Takami et al., 1997]. However, in the fluidized bed combustor, the combustion characteristics can be dependent on the H_I of waste oil rather than the spray quality, since the waste oil should be well distributed at optimum H_I, contacted and mixed with bed materials by means of fluidizing air for an efficient combustion. Thus, the effects of H_I on the behavior of temperature fluctuations were examined.

Effects of H_I of waste oil on T_B and K_2 can be seen in Fig. 6. In this figure, K_2 exhibits a local minimum, but T_B decreases gradually, with the increase of H_I in the combustor. Note that K_2 has a local minimum when the H_I is around 0.4-0.6 m from the gas distributor. In addition, T_B does not decrease significantly when the oil injection height is 0.2-0.4 m. Thus, it can be anticipated that the optimum injection height of waste oil would be around 0.4 m from the distributor to maintain the relatively stable temperature fluctuations without considerable decrease of T_B. This could be, of course, related to the height of combustion region where the vigorous contacting and mixing between the waste oil and the bed material would occur by means of fluidizing air, because the desired combustion zone is located in the expanded bed region. It seems to be important to let the temperature fluctuations in the combustor become more regular and stable for the waste oil to be well mixed and contacted with bed material and thus for the stable combustion.

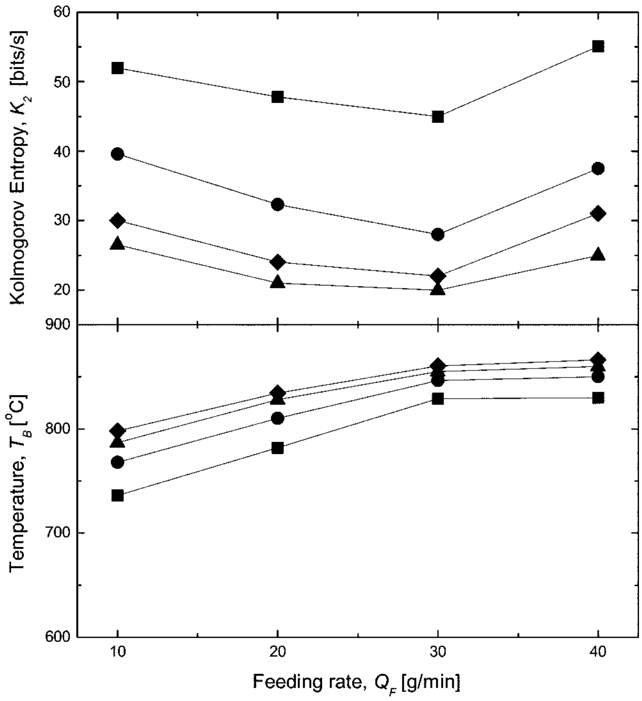

Fig. 7. Effects of Q_F on T_B and K_2 in the combustor (H_I=0.4 m).

■ ● ▲ ◆
A_E [%] : 10 20 40 60

Effects of Q_F on T_B and K_2 can be seen in Fig. 7. In this figure,

K_2 attains its local minimum at Q_F of 30 g/min, but T_B is increased, with increasing Q_F of waste oil in the fluidized-bed combustor. It can be noted from this figure that the optimum value of Q_F would be 30 g/min under the operating condition of this study to maintain a relatively stable as well as high bed temperature in the combustor. This has been anticipated from the visualization of phase space portrait of temperature fluctuations in the beds (Fig. 4).

Effects of A_E on U_0 in the combustor can be seen in Fig. 8. U_0 decreased with increasing A_E. It can be explained as the decrease

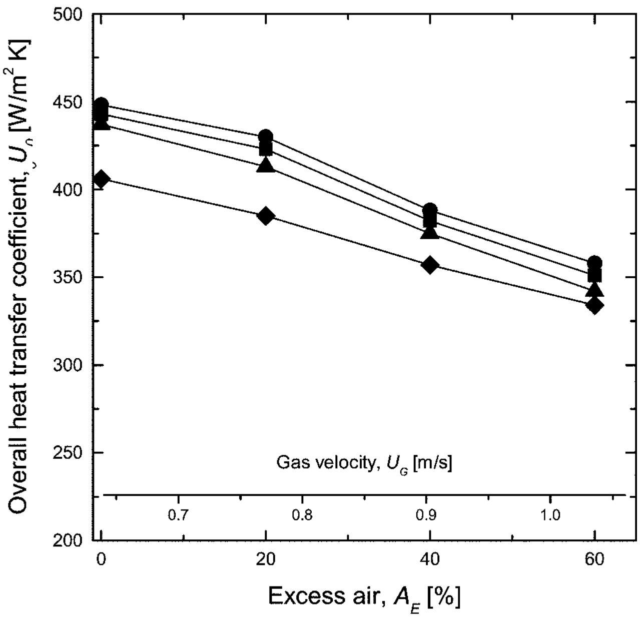

Fig. 8. Effects of A_E on U_0 in the combustor (Q_F=30 g/min).
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H_I [m] : 10 20 40 60

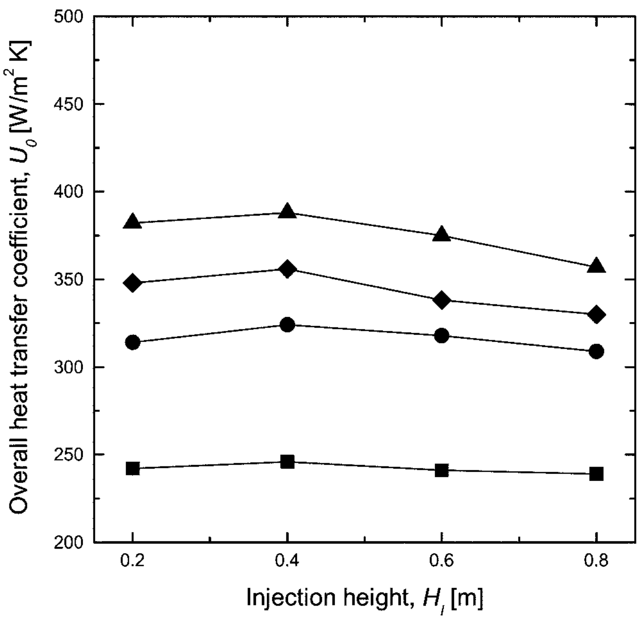

Fig. 9. Effects of H_I on U_0 in the combustor (A_E=40%).
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Q_F [g/min] : 10 20 30 40

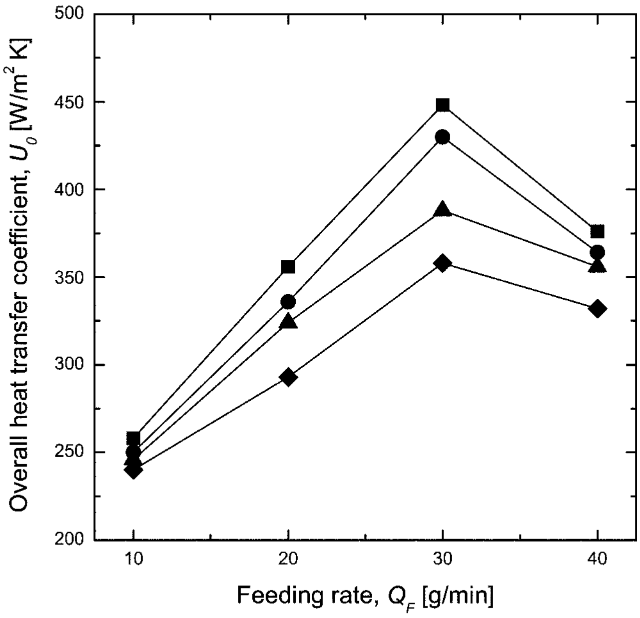

Fig. 10. Effects of Q_F on U_0 in the combustor (H_I=0.4 m).
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A_E [%] : 10 20 40 60

of contacting frequency between the heat exchanger surface and solid particle with increasing U_G (or A_E). U_G has an effect only on the heat transfer through changes in the solids concentration, since the solids concentration decreases with increasing U_G. It is generally accepted that the overall heat transfer coefficient between an immersed surface and a gas-fluidized can be expressed as the sum of the particle convective, gas convective and radiative transfer coefficients. Also, it has been shown by many researchers that the dominant heat transfer mechanism in the fluidized bed is the solid particle convection [Yates, 1996; Ma and Zhu, 2000].

Effects of H_I on U_0 in the combustor can be seen in Fig. 9. As expected, U_0 has a local maximum at H_I of 0.4 m. Therefore, the optimum H_I of waste oil would be around 0.4 m from the distributor to maintain the relatively high U_0 and stable K_2 (Fig. 6). Effects of Q_F on U_0, also, can be seen in Fig. 10. U_0 value attains its local maximum at Q_F of 30 g/min in the fluidized-bed combustor. It is interesting to note that the optimum value of Q_F would be 30 g/min to maintain the relatively high U_0 and stable K_2 under the operating condition of this study (Fig. 7).

CONCLUSION

The characteristics of the temperature fluctuations and heat transfer in a fluidized-bed combustor have been successfully described by means of T_B, K_2 and U_0. T_B increased, but K_2 and U_0 decreased with increasing A_E. K_2 had a local minimum, but T_B and U_0 had a maximum at H_I of 0.4 m. T_B increased, but K_2 had a minimum and U_0 had a maximum with increasing Q_F in the combustor. T_B, K_2 and U_0 obtained at the optimum operating condition (A_E=40%, H_I=0.4 m, Q_F=30 g/min) were about 855 °C, 22 bits/s and 382 W/m^{2}K, respectively. The results of this study can be used to determine the optimum condition of fluidized-bed combustor for the combustion of waste oil and design as well as scale-up of the combustor.

ACKNOWLEDGMENT

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NOMENCLATURE

A_E : excess air [%]
A_O : outside area of tube [m^2]
C_{pw} : specific heat of water [J/kg K]
d : distance on the attractor
H_I : injection height of waste oil [m]
K_2 : Kolmogorov entropy [bits/s]
m : number of data point
M_w : flow rate of cooling water[kg/s]
P : embedding dimension
Q_F : feeding ratio of waste oil [g/min]
r : distance on attractor [-]
t : time [s]
ΔT : temperature difference [°C]
ΔT_L : logarithmic mean temperature difference [°C]
ΔT_i : temperature difference through inside fluid [°C]
ΔT_o : temperature difference through outside fluid [°C]
U_0 : overall heat transfer coefficient [W/m^2 K]
X : reconstructed state vector

Greek Letter

τ : time delay

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