FOULING REDUCTION CHARACTERISTICS OF A CIRCULATING FLUIDIZED BED HEAT EXCHANGER

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ABSTRACT

Fouling and cleaning tests are performed for a uniquely designed fluidized bed type heat exchanger for exhaust gas heat recovery The tested heat exchanger model (1 m high, 54 mm internal diameter) is gas-to-water and is composed of a main vertical tube and additional four auxiliary tubes through which particle circulate and transfer heat. Through the present study, fouling of heat exchanger surface could successfully be simulated by controlling air-to-fuel ratios (A/F) rather than introducing particles through external feeder, resulting in soft deposit layer about 1~1.5 mm thick on the inside pipe wall. Exhaust gas temperature at the heat exchanger inlet is maintained typically 450deg.C at the gas volume rate of 0.738-0.768 CMM (0.0123-0.0128 m^3/sec). According to the tested results, soft deposits are easily removed by introducing glass bead particles and also double folded heat transfer performance (in terms of overall heat transfer coefficient) could be achieved.

INTRODUCTION

Fouling reduction or maintaining 'no fouling' conditions in heat exchanger design and operation has double folded significance. In pursuing heat recovery from waste gases single most challenging issue is a fouling related problem. Due to the fouling and scaling of conventional shell-tube heat exchangers those systems suffer from significant degradation in heat transfer performance, which results in the over-sizing of the heat exchangers and the increased maintenance and downtime costs. In most industrialized countries the capital loss due to the heat exchanger fouling is estimated to amount to 0.25 to 0.30 percent of the gross national product (GNP) (ESDU Data Item No. 00016, 2000).

More importantly in an environmental point of view, maintaining initial design performance of the economizer such as in an municipal solid waste (MSW) incinerator applications is critical to the successful operation of the post treatment equipments of flue gas, in which the key role of the economizer is to temper down the gas temperature to a certain value to avoid Dioxin generation rather than to recover waste heat itself.

In the conventional industry sector, the issues are mostly studied in an aspect of fouling prediction and modeling, which are driven by the needs from the existing system operation and maintenance (Kaiser et al., 2002, Schreier and Fryer, 1995). However, the efforts to reduce or even to eliminate the fouling by introducing a new type of heat exchanger system was relatively limited (Cho et al., 1997). As one of the candidate technologies, fluidizing of particles with the carrier gas flow showed promising results with increased heat transfer performance along with the self-cleaning characteristics even under a corrosive condition. However, to achieve the expected feature in a real design, studies on the heat transfer mechanism in gas-solid two phase flow, mechanics of fluidization and particles motion, ash deposition and reduction mechanisms, and finally possible erosion behavior should be conducted.

In the present study fouling and cleaning tests are conducted for a lab scale non-baffle type circulating fluidized bed (CFB) heat exchanger with a single riser, which is originally devised by the present authors (Lee et al. 1998 & 2001). According to the experimental results, fouling could successfully simulated by using fuel-rich combustion and virtually completely cleaned by the introduction of glass beads particles. Performance deterioration due to fouling and the recovered heat transfer performance are also discussed.

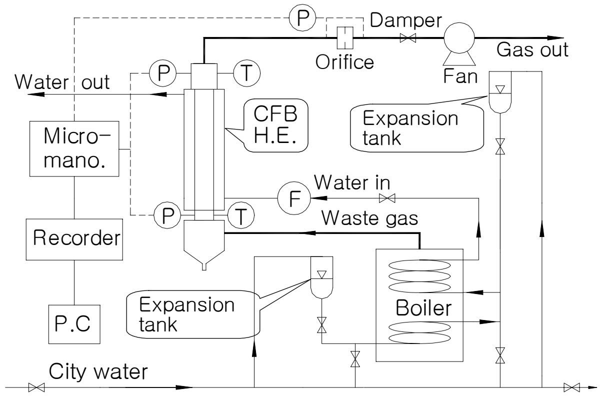

Fig.1. Schematic diagram of the test set up.

Table 1 Temperature and pressure measurement locations

Pressure tap		T/C	
P1	Orifice upstream	T1	H.E. inlet
P2	Orifice downstream	T2	Riser inlet
P3	H.E. exit	T3	Down comer exit
P4	Riser exit	T4	Riser exit
P5	Down comer exit	T5	H.E. exit
P6	Riser inlet	T6	Water inlet
P7	H.E. inlet	T7	Water exit

EXPERIMENTAL APPARATUS AND FOULING PROBE

Figure 1 show the schematic diagram of a fluidized bed heat exchanger test apparatus, which is composed of a combustor section and a heat exchanger section. The combustor section provides constant flow rate of hot gas to the inlet of the vertically oriented heat exchanger. A household boiler (30,000 kcal/hr) fueled by kerosene is modified for use as the combustor section of the test apparatus, by eliminating the heat transfer enhancement device and by prohibiting the circulation of feed water. About 450 ^{o}C of hot gas could be supplied to the heat exchanger inlet in this arrangement. The hot gas supplied from the combustor (boiler) enters the lower part of the heat exchanger to transfer heat energy to cooler part through the vertical tube surface and the surface of four particles down comer tubes wound around the main vertical tube. The gas flow rate is measured by the orifice installed at the downstream of the heat exchanger and is controlled by a damper. Measured pressure drop through the orifice is converted to the equivalent gas flow rate with temperature correction. The gas flow is driven by a radial fan located downstream of the damper. The feed water for the heat exchanger is supplied from the makeup water line of the boiler. The city water is pre-heated passing through the combustor (boiler) along the wound tube then enters the inlet of the CFB heat exchanger. The water flow rate is measured using a digital flow meter (OVAL) right upstream of the heat exchanger inlet. The temperature of the feed water is measured at five locations (from T1 to T5) including the inlet and the outlet of the heat exchanger by using K-type thermocouples (See Fig. 2 and Table 1).

For the measurement of temperature and pressure a digital recorder DA-100 (Yokogawa, 30Ch.) is used with micro manometers. Particles for circulation are dried and weighed ahead of feeding and are fed through the ball valve on the upper part of the heat exchanger. These particles first fall in the upper region of the heat exchanger unit where hot gas come out from the main vertical pipe(riser of I.D. 54 mm) and then fall again through the four wound tubes(down comer with I.D. of 11 mm), in which direct heat transfer between particles and tube surface may occur.

Particles are then collected in a small region under the down comer tubes to be introduced to the hot gas flow at the lower part of the riser through an annular slit.

Fouling probe as shown in Fig. 2 is prepared and installed in the middle part of the riser. The probe is carefully designed not to disturb the internal flow field and to measure the extent of the fouling after de-assemble of the heat exchanger system. The length of the probe is 34 mm with 7 mm threads on both ends to secure the seal. For better evaluation the weight of the probe before the test, after the fouling and after the cleaning test were measured (A&D, HF-400, Max. =400g, Resolution = 1mg) respectively, as well as the visual inspection. A view of the test apparatus has shown in Fig.3.

FOULING AND CLEANING TESTS

In the present study, two candidate methods to simulate the fouled conditions have been tested, that is,

(i) using a particle feeder
(ii) using fuel-rich combustion condition to simulate the fouled condition.

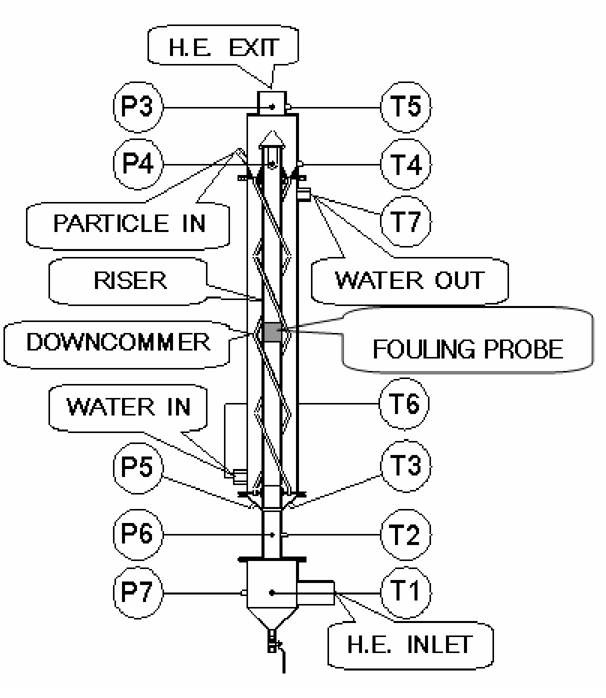

Fig. 2. Heat exchanger test apparatus

Fig. 3. A view of the test apparatus

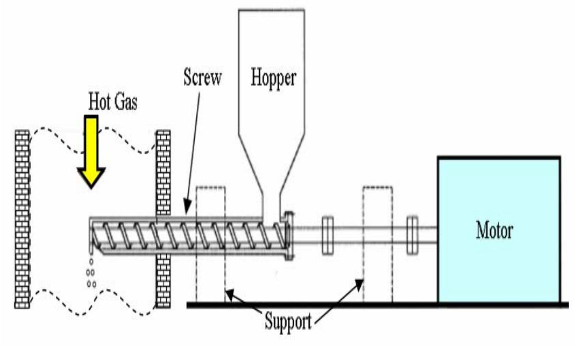

Fig. 4. Screw type particle feeder

Fouling Test - I (using a particle feeder)

To simulate experimentally the fouling due to the soot ashes a screw type particle feeder is designed and manufactured to be installed in the downstream of the combustor section. The particles are obtained from a light oil boiler from a local apartment complex. Fig. 4 and Fig. 5 show the designed screw feeder and the enlarged view of soot particles from light oil, respectively.

Although about 1 Jar of fly ash is being ingested, it was observed that no significant deposition could be identified after the test. The reason why deposition did not occur is not clear, however higher gas velocity that pass through the vertical tube under a normal combustion may be considered as one of several possible factors. Also particles physical and thermal condition which should be different from the state at the time of soot formation may be considered as another reason.

Fouling Test-II (soot generation by fuel rich combustion)

Because of the difficulties related with the heterogeneous ingestion of soot ashes using an external particle feeder, another approach to change the combustion condition is tried to achieve the fouling condition. By reducing the air flow rate that enters the combustion chamber, a fuel-rich combustion condition along with the lower gas velocity through the vertical heat transfer surface could be achieved. In out test case, the equivalence ratio of about 1.17 was maintained for about an hour to generate the soot to be deposited on the heat transfer surface, in which the gas temperature at the heat exchanger inlet was maintained around 340 °C. After the fouling test the tested heat exchanger unit is disassembled for visual inspection. Heat transfer surface and the fouling probe are visually inspected and the fouling probe is weighed for the estimation of the soot deposition.

Cleaning Test by Particle Ingestion

After the fouling test and inspection, the system is reassembled for the cleaning test, which is conducted under a normal combustion (equivalence ratio close to 1). The heat transfer performance under a fouled condition is monitored and thereafter glass bead particles are ingested step by step into the system to monitor the cleaning effect due to particles. Spherical glass beads of the diameter range from 425 to 850 μm are used for the present test.

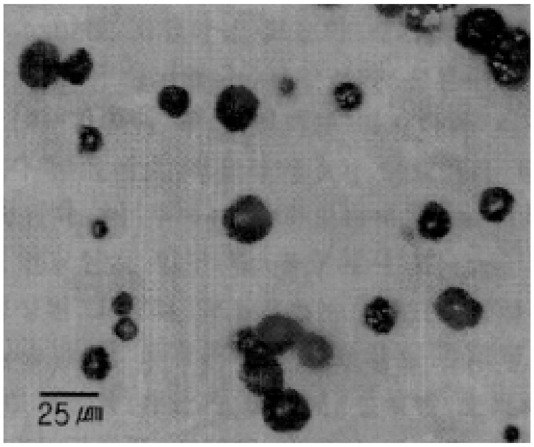

Fig. 5. Enlarged view of the ash particles from light oil boilers (800x)

(a) before fouling (b) after fouling

(c) after cleaning

Fig. 6. Fouling probe

Table 2 and 3 show the important mechanical properties and Chemical composition of these particles, respectively, which are supplied by the vendor.

Table 2 Important mechanical properties of particles (Sodalime glass beads)

Description	Unit	Values
Hardness	Kg/mm^2	425
Specific Gravity @ 20 ^{o}C	-	2.52
Compressive Strength	N/mm^2	16.64
Specific Heat	Cal/gr- ^{o}C	0.81
Softening Point	^{o}C	720
Thermal Conductivity	Kcal/(m-hr- ^{o}C)	0.65

Table 3 Chemical composition of the particles

Constituents	SiO_2	Al_2O_3	CaO	MgO	R_2O
% fraction	70-73	0.8-1.0	7-12	1.0-4.5	13-15

Table 4 Measured weight of the fouling probe

	Before fouling	After fouling	After cleaning
Weight, gram	110.810	111.147	110.777

Condition after Cleaning

Fig. 6 shows the fouling probe which is inserted in the middle of the vertical riser. Fig.6 (a) shows the probe before the fouling test, while Fig. 6(b) and 6(c) show the probe after the fouling test and after the cleaning test, respectively. According to the tested results (Fig. 6(b) and 6(c)), it could be seen clearly that after the fouling test by using fuel-rich combustion about 1~1.5 mm thick soot layer was deposited on the internal heat transfer surface of the vertical riser (Fig. 6(b)) and was cleaned almost perfect after the cleaning test using particles.

The effect of particles cleaning could be identified by the comparison of the measured weight of the probe before and after the test procedures along with the measured performance data. Table 4 shows the measured probe weight at each stage.

PERFORMANCE ANALYSIS

Total heat transferred can be expressed as

$$q_g = \rho_g Q_g c_{pg} \Delta T_g \text{ (Gas side)} \tag{1}$$

$$q_w = \rho_w Q_w c_{pw} \Delta T_w \text{ (Water side)} \tag{2}$$

where ρ ,Q , C_p and ΔT are density, volume flow rate, specific heat and temperature difference, respectively. The flow rate of the flue gas is measured by using D and D/2 taps orifice downstream of the heat exchanger unit. In the present study, a pipe of 70 mm inner diameter (D) and an orifice plate with diameter ratio (β=d/D) of 0.57 are used. The gas flow rate is expressed as

$$Q = C_d A_t \left[\frac{2(P_1 - P_2)/\rho}{1-\beta^4}\right]^{1/2} \tag{3}$$

where the dimensionless discharge coefficient C_d for D and D/2 taps orifice is as follows;

$$C_d = f(\beta) + 91.71\beta^{2.5}\,\mathrm{Re}_D^{-0.75} + \frac{0.09\beta^4}{1-\beta^4}F_1 - 0.0337\beta^3 F_2 \tag{4}$$

with

$$f(\beta) = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8 \tag{5}$$

and the values for F_1 and F_2 are 0.4333 and 0.47, respectively.

The overall heat transfer coefficient U (Holman, 1976) of the heat exchanger is related as

$$q = UA\Delta T_m \tag{6}$$

where ΔT_m is the log mean temperature difference defined as

$$\Delta T_m = \frac{(T_{g,e} - T_{w,e}) - (T_{g,i} - T_{w,i})}{\ln\left[(T_{g,e} - T_{w,e})/(T_{g,i} - T_{w,i})\right]} \tag{7}$$

For the present case, $T_{g,e} = T_5$, $T_{g,i} = T_1$, $T_{w,e} = T_7$, $T_{w,i} = T_6$.

The fouling factor R_f due to the fouling of the heat transfer surfaces is obtained from the overall heat transfer coefficients under a clean condition and that under a fouled condition as

$$R_f = \frac{1}{U_2} - \frac{1}{U_1} \tag{8}$$

where the subscripts 2 represents a fouled condition and the script 1 refers to a clean condition.

TEST RESULTS AND DISCUSSION

To observe the heat transfer performance of the present heat exchanger, tests have been conducted and compared for a clean condition, fouled condition and cleaned condition, respectively.

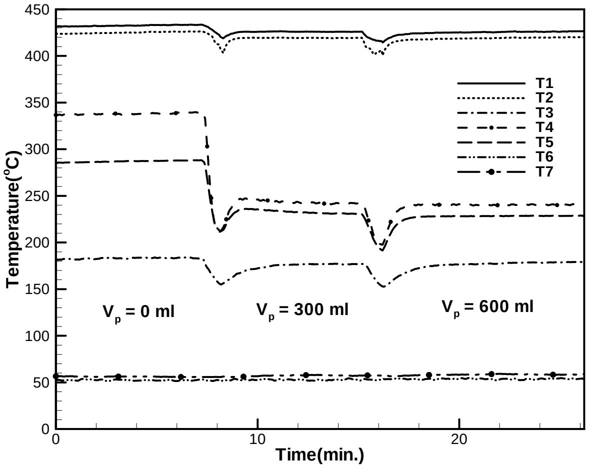

Fig. 7. Temperature in a clean condition (Q_g=0.74 m^3/min, Q_w = 7.8 L/min)

Performance before Fouling

The performance tests before fouling are performed at no-particle conditions followed by the case of particle ingestion. Particles are ingested carefully by 300 ml for two times. For the measurement of the temperature and pressure, DA-100 (Yokogawa, 30 Ch.) has been used.

Figure 7 shows the heat transfer test results with the gas flow rate Q_g=0.74 m^3/min and water flow rate Q_w = 7.8 L/min. Once the steady state condition is reached after the ignition of the burner, particles are fed into the heat exchanger by 300 milliliter through the hole on the top of the heat exchanger unit. Another dose of 300 milliliter particles are added into the system after the steady condition is obtained again. In the figure legend, measured temperature of the gas is represented by T_1 to T_5, while T_6 and T_7 represent inlet and outlet water temperature, respectively. According to the test results, the gas temperature at the heat exchanger inlet (T_1) and vertical pipe inlet (T_2) steadily approach the equilibrium temperature of approximately 430 °C. T_2 shows slightly lower values than T_1 by approximately 5°C, which seems due to the aerodynamic effect. When first 300milliliter of particles are fed, significant temperature difference at the exit is observed, however no significant change was monitored with the second dose.

For quantitative analyses, the test conditions and the temperature measurement results are summarized before and after the particle feeding and is shown in Table 5. According to this table the temperature drop through the vertical pipe (riser) [$\Delta T_{2\text{-}4}$] increases from 87.3 °C with no particles to 179.1 °C with 600 milliliter particles resulting in 105% increase. The temperature drop through the entire heat exchanger [$\Delta T_{1\text{-}5}$] changes from 145.5 °C with no particles to 197.4 °C resulting in 36% increase. The increase in the total heat transferred in gas side appeared to be 86% and the resulting increase in the overall heat transfer coefficient appeared to be 102%.

Table 5 Comparison of heat transfer performance with and without particle loading (before fouling)

Description	(1) No Particle (Vp=0ml)	(2) Particle (Vp=600ml)	ratio=(1)/(2)
$\Delta T_{1\text{-}5}$(°C)	145.5	197.4	1.36
$\Delta T_{2\text{-}4}$(°C)	87.3	179.1	2.05
ΔT_m(°C)	299.5	258.0	0.86
A(m^2)	0.39	0.39	-
Q_{air}(Kcal/hr)	1,836	3,424	1.86
U(W/㎡ K)	16.83	34.03	2.02

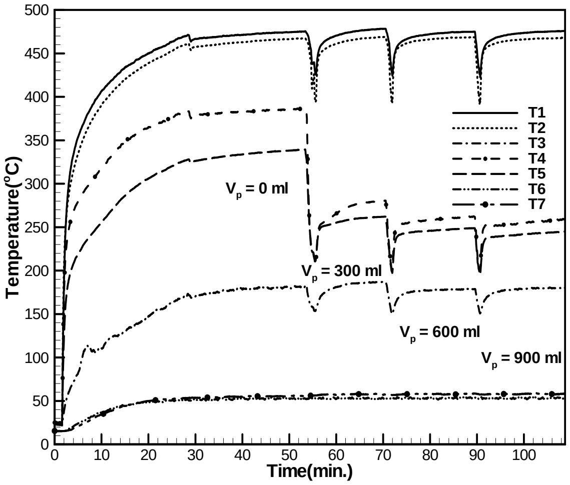

Fig. 8. Measured temperature during the cleaning process (Q_g=0.75 m^3/min, Q_w = 8.7 L/min)

Performance after Fouling & Cleaning

The cleaning test is performed maintaining a similar flow condition (gas flow rate Q_g=0.75 m^3/min and water flow rate Q_w = 8.7 L/min) before fouling. Fig. 8 and Table 6 show the temperature variation and the summarized heat transfer data, respectively. In this experiment, particles are ingested three times with 300 milliliter per dose. When the system is fouled (case (3) in Table 6), the temperature drop through the entire heat exchanger [ΔT_{1-5}] decreases by 6.4% compared to the clean state (case (1) in Table 5), while the overall heat transfer coefficient decreases by 21%. In this case, the resulting fouling factor, R_f, becomes 0.015. Table 6 compares the heat transfer performance in a fouled condition (3) and a cleaned condition (4).

According to the data shown in the table, the temperature drop through the vertical pipe (riser) [ΔT_{2-4}] increases by 159% with particles ingestion, while the temperature drop through the entire heat exchanger [ΔT_{1-5}] increases by 70%. The resulting overall heat transfer coefficient increases by 109%.

Table 6 Comparison of heat transfer performance in a fouled and cleaned condition

Description	(3) No Particle (Vp=0ml)	(4) Particle (Vp=900ml)	ratio=(4)/(3)
ΔT_{1-5}(°C)	136.2	231.3	1.70
ΔT_{2-4}(°C)	81.05	209.6	2.59
ΔT_m(°C)	347.5	288.2	0.83
A(m^2)	0.39	0.39	-
Q_{air}(Kcal/hr)	1,819	3,148	1.73
U(W/㎡ K)	13.42	28.01	2.09

CONCLUSIONS

In the present study heat exchanger fouling and cleaning tests are performed experimentally for a uniquely designed lab scale CFB heat exchanger to demonstrate cleaning (fouling reduction) and heat transfer enhancement feature of the system. Major findings from the present study are as follows:

1. Artificial fouling by external feeding was not successful in the present study mainly due to the heterogeneous property and high gas velocity. Fuel rich combustion, on the other hand, provided a satisfactory fouling condition which successfully deposited appreciable amount of deposition layer on the heat transfer surface.
2. Fouling reduction could be successfully demonstrated for the present CFB type heat exchanger model, showing that virtually complete cleaning is possible using this kind of cleaning operation.
3. Enhanced heat transfer performance could be successfully demonstrated by the introduction of selected glass bead particles for internal circulation. Under the tested condition in the present study, double folded increase in the overall heat transfer coefficient could be obtained with moderate pressure drop.

ACKNOWLEDGEMENT

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NOMENCLATURE

A	heat transfer area	(m^2)
C_d	discharge coefficient	
C_p	specific heat at constant pressure	(J/Kg K)
d	orifice inner diameter	(m)
D	orifice outer diameter	(m)
g	gravitational acceleration	(m/s^2)
m	mass flow rate	(kg/s)
P	pressure	(Pa)
q	rate of heat transfer	(W)
Q	flow rate	(m^3/s, m^3/min, m^3/hr)
R_f	fouling factor	
T	temperature	(K or ^{0}C)
U	overall heat transfer coefficient	(W/m^2 K)

β	diameter ratio(=d/D)	
ΔP	pressure drop along heat exchanger (Pa)	
ΔT_m	log mean temperature difference	(K)
ρ	density	(kg/m^3)

Subscripts

e	exit
g	gas side
i	inlet
p	particle
w	water side
1	clean condition
2	fouled condition

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