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INVESTIGATION OF HEAT TRANSFER AND COMBUSTION IN THE ADVANCED FLUIDIZED BED COMBUSTOR (FBC)

TO

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ABSTRACT

This technical report summarizes the research conducted and progress achieved during the period from January 1, 1997 to March 30, 1997.

The systematic tests were conducted to investigate the thermal performance and heat transfer effect on the exploratory hot model.

Test results were analyzed to understand thermal performance, heat balance, and heat transfer effect on exploratory hot model. Temperature was measured at different locations of the combustor chamber. The temperature was decreased along the increase the distance from the bottom of the combustor chamber.

The heat loss from the combustor wall to the environment is a great portion of the total heat transfer. The flame enthalpy and heat loss at the reactor center changed along the reactor height. The heat loss into the cooling water for case A is about two times lager than that of case B. The heat transfer coefficient from gas to the environment increased as the flame temperature increased.

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EXECUTIVE SUMMARY

Fluidized bed combustion (FBC) has grown with the prospect that it can burn coal and low grade fuels in an environmentally acceptable manner. However, several undesirable features [1,2] were found to be inherent with a first generation FBC boiler system. The bubbling fluidized bed combustor and circulating FBC are known for high elutriation of unburned coal chars, in-bed and convective wall erosion [3], and a relatively low combustion intensity/calcium utilization. In order to improve these problems, the advanced swirling fluidized bed combustor (SFBC) was proposed. In this study, combustion air is tangentially injected into the annular chamber through the nozzles at various levels to form a strong swirling flow.

The exploratory hot model [4] was designed and fabricated based upon the test results of cold flow model and computer simulation work. Based upon the preliminary test results, the auxiliary subsystem [5] were modified for the systematic test. A computer-assisted data acquisition system was developed to accelerate data recording and process.

The systematic combustion tests were conducted to investigate the thermal performance, heat balance, and heat transfer effect on exploratory hot model. The heat balance and heat transfer coefficients for the test results were calculated and predicted.

The computer simulation work will be conducted to better understand thermal performance and heat transfer effect on the advanced swirling fluidized bed combustor.

SECTION 1

RESULTS AND DISCUSSIONS

THERMAL PERFORMANCE OF EXPLORATORY HOT MODEL TEST

Two different tests were analyzed to understand the thermal performance on exploratory hot model under the exact same condition with the exception of the amount of fuel.

For the Test A, fuel (natural gas) flow rate was 19.5 cubic feet per hour (cfh), which is almost two times higher than that of Test B. The detailed test conditions are shown in Table 1 The average cooling water flow rate was 1.6 gallon per minute (gpm)-Temperature was measured at different locations of the combustor chamber. As shown in Table 1, the change of temperature was decreased along the increase of the distance from the bottom of combustor chamber.

For the Test B, fuel flow rate was reduced to 10 cfh, which was almost half of Test A. The average combustion gas temperature decreased from 1394 F to 1015 F while the fuel flow rate decreased as shown in Tables 1 and 2. When examining the data there is only 6% difference of temperature at the 8″ thermocouple location from the bottom of combustor chamber. However, the 16″ thermocouple location exhibits a temperature on the magnitude of 62.48%. The 24″ thermocouple location exhibits a temperature difference on the

Table 1 Summary of Hot Model Test (Case A)

Primary Air Pressure (inH2O)		0				
Primary Air Flow (CFM)		0.00				
FUEL: Natural Gas flow (CFH)		19.5	Maximum			
Fuel Nozzle (description)		5 hole nozzle 5" from chamber floor				
Sec. Nozzle Yaw Angle	TOP	90	BOTTOM	90		
Sec. Nozzle Roll Angle	TOP	45	BOTTOM	0		
Secondary Air Flow (CFM)	TOP	2	BOTTOM	2		
Total Air Flow (%)	TOP	50	BOTTOM	50	PRIMARY	0
Cooling Water Temp (F)	IN	52.7	OUT	66.9		
Cooling water flow(GPM)	1.6					
Water valve opening (%)	TOP	10	MIDDLE	10	BOTTOM	10
LENGTH OF BURN-IN	50 min					

Thermocouple No.	Distance (in) From Bottom	Temp (F) Center	Temp (F) 1" from center	Temp (F) 2" from cente	Temp (F) 2.5" from cen	AVG TEMP (F)	Temp (F) Surface	FLUE TEMP
K1	8	1560	1857	1777	1712	1726.50	442	1012.0
K2	16	1475	1374	1551	1179	1394.75	437	1001.0
K3	24.5	1200	1196	1124	723	1060.75	440	1008.0
AVG	TEMP (F)	1411.67	1475.67	1484.00	1204.67	1394.00	439.67	1007

Enerac 2000 Gas Analysis

Position	Stk temp (F)	Amb temp (F)	Efficiency (%)	O2(%)	CO2 (%)	CO(ppm)
Flue gas analysis	723	79	48.8	15.2	3.3	33

Table 2 Summary of Hot Model Test (Case B)

Primary Air Pressure (inH2O)		0				
Primary Air Flow (CFM)		0.00				
FUEL: Natural Gas flow (CFH)		10	Maximum			
Fuel Nozzle (description)		5 hole nozzle 5" from chamber floor				
Sec. Nozzle Yaw Angle	TOP	90	BOTTOM	90		
Sec. Nozzle Roll Angle	TOP	45	BOTTOM	0		
Secondary Air Flow (CFM)	TOP	2	BOTTOM	2		
Total Air Flow (%)	TOP	50	BOTTOM	50	PRIMARY	0
Cooling Water Temp (F)	IN	73.3	OUT	75.5		
Cooling water flow(GPM)	1.6					
Water valve opening (%)	TOP	100	MIDDLE	100	BOTTOM	100
LENGTH OF BURN-IN	55 min					

Thermocouple No.	Distance (in) From Bottom	Temp (F) Center	Temp (F) 1" from center	Temp (F) 2" from cente	Temp (F) 2.5" from cen	AVG TEMP (F)	Temp (F) Surface	FLUE TEMP
K1	8	1475	1123	1721	1406	1431.25	273.7	724.8
K2	16	928	905	880	774	871.75	264.3	733.5
K3	24.5	806.5	848	762	557	743.38	259	732.4
AVG TEMP (F)		1069.83	958.67	1121.00	912.33	1015.46	265.67	730.23

Enerac 2000 Gas Analysis

Position	Stk temp (F)	Amb temp (F)	Efficiency (%)	O2(%)	CO2 (%)	CO(ppm)
Flue gas analysis	723	79	48.8	15.2	3.3	33

magnitude of 45.76%. The flue gas temperature has a 65.5% decrease as shown in Test A vs Test B. When decreasing the fuel flow rate, the overall temperature decreases. The detailed heat balance calculations and heat transfer effect will be discussed in Section 2.

SECTION 2

RESULTS-AND DISCUSSIONS

HEAT TRANSFER EFFECT AND HEAT BALANCE WITH COOLING WATER

The heat balance calculations are summarized as follows;

1) The first law of thermodynamics (Energy Balance)
   The flow enthalpy increasing is equal to the sum of total heat exchange and mechanical works which done by the system.

$$H_i + Qi - (H_o + Q_o) = W \qquad (1)$$

$$H_o - H_i = Q_r - Q_w - Q_L + W \qquad (2)$$

2) For the combustion system the mechanical work is zero

$$W = 0 \qquad (3)$$

3) The flow enthalpy is defined as:

   For single flow component

$$H_i = Cp_j * \rho_i * q_j * \Delta T_j \qquad (4)$$

   For mixture of flow components

$$H = \sum_{j=1}^{k} m_j H_j \qquad (5)$$

4) Flow density, ρ

For water:

$$\rho_w = 1000 \text{ kg/m}^3 \qquad (6)$$

For gases:

The gas density is a function of gas temperature and pressure

$$\rho_{gas} = \frac{M_{gas}}{22.4}\left(\frac{T^o}{T_{gas}}\frac{P_{gas}}{P^o}\right) \qquad (7)$$

5) Heat capacity, Cp

For Water:

$$Cp_w = 4.18 \text{ kJ/kg.}^oC \qquad (8)$$

For Gases:

The gas heat capacity is a function of gas temperature.

$$Cp/R=a+bT+cT2+dT3+eT4 \qquad (9)$$

There a, b, c, d, e is constant values for each gas components and shown in the flowing table (6).

	a	b	c	d	e
C02	2.401	8.735e-3	-6.607e-6	2.002e-9	0
H20	4.07	-1.108e-3	4.152e-6	-2.964E-9	8.07E-13
N2	3.675	-1.208e-3	2.324e-6	-6.32e-10	-2.26e-13
CH4	3.826	-3.979e-3	2.456e-5	-2.273e-8	6.963e-12
air	3.653	-1.337e-3	3.294e-6	-1.913e-9	2.76e-13

(6) The average heat transfer coefficient from hot gas to the cooling water can be estimated by using the flowing equation:

$$h_{g-w}=(Q_w)/[A(T_g-((\Delta T_w)/2)] \qquad (10A)$$

(7) The average heat transfer coefficient from hot gas to the environment at room temperature can be estimated by using the flowing equation (7]:

$$h_{g-l}=Q_L/[A(T_g-((\Delta T_w)/2)] \qquad (10B)$$

(A) Heat Balance Calculation Results for Case A:

Based on 1 minute of time period. The fuel is natural gas (95%of CH 4)

Fuel combustion heat, Q_r:	468	kJ
Fuel input enthalpy, H_f:	0.355	kJ
Air input enthalpy, H_a:	3.573	kJ
The input flow enthalpy, H_i:	3.928	kJ

Flu. gas enthalpy, H_o: 92.71 KJ
Heat loss from cooling water, Q_w: 201.63 kJ

Heat loss from the reactor wall, Q_L can be calculated using the equation (2):

$$Q_L=Q_r-Q_w-(H_o-H_i) =177.58 \text{ (KJ)} \qquad (11)$$

The overall average heat transfer coefficient from hot gas to

the cooling water, h_{g-w}: 7.28 w/m^{2o}C

The overall average heat transfer coefficient from hot gas to

the cooling water, h_{g-l} 6.497 w/m^{2o}C

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The flame enthalpy and flame heat loss changing along the reactor height.

Distance from the bottom (inch)	Flame enthalpy (KJ)	Flame heat loss *(KJ)*
8	173.34	37.51
16	135.83	37.3
24	98.53	5.82

The dimensionless height based on the reactor height, H, for the three distance from the bottom are 0.28, 0.55, and 0.83. The Flame enthalpy and flame heat loss as a function of the dimensionless height is shown in Figure I for case A.

(B) Heat Balance Calculation Results for Case B:

Based on 1 minute of time period. The fuel is natural gas (95%of CH 4)

Fuel combustion heat, Q_r:	240.08	kJ
Fuel input enthalpy, H_f:	0.1823	kJ
Air input enthalpy, H_a:	3.573	kJ
The input flow enthalpy, H_i:	3.755	kJ
Flu. gas enthalpy, H_o:	59.55	kJ
Heat loss from cooling water, Q_w:	31.24	kJ

Heat loss from the reactor wall, QL, can be calculated using the equation (2):

$Q_L=Q_r-Q_w-(H_o-H_i)$ =153.02 (KJ)

The overall average heat transfer coefficient from hot gas to

the cooling water, h_{g-w}: 0.634 $w/m^{2o}C$

The overall average heat transfer coefficient from hot gas to

the cooling water, hg-w 7.854 $w/m^{2o}C$

The flame enthalpy and flame heat loss changing along the reactor height.

Distance from the bottom (inch)	Flame enthalpy (KJ)	Flame heat loss *(KJ)*
8	129.82	65.8
16	73.03	13.48
24	60.8	1.25

The dimensionless height based on the reactor height, H, for the three distance from the bottom are 0.28, 0.55, and 0.83. The Flame enthalpy and flame heat loss as a function of the dimensionless height is shown in Figure 2 for case B.

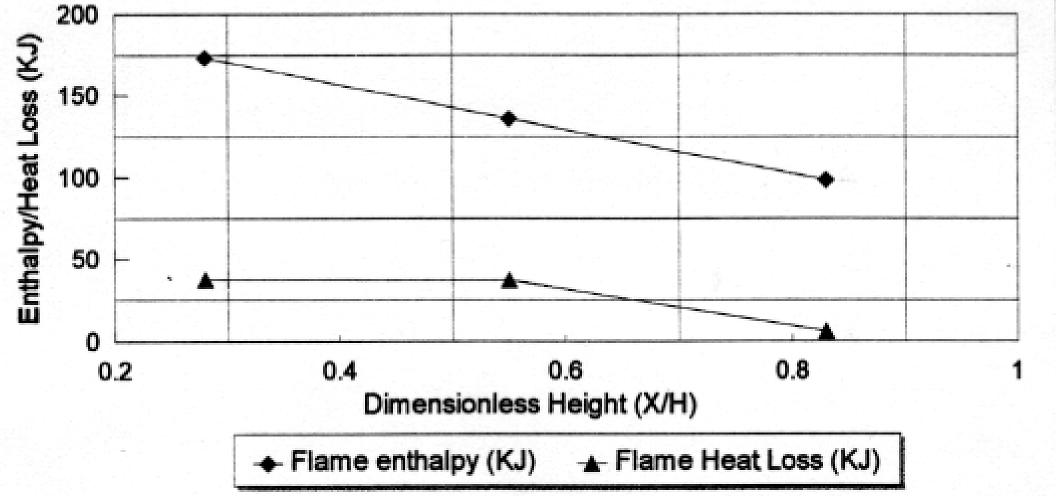

Figure 1. The Changes of the Flame Enthalpy/Heat Loss along the Combustor Height

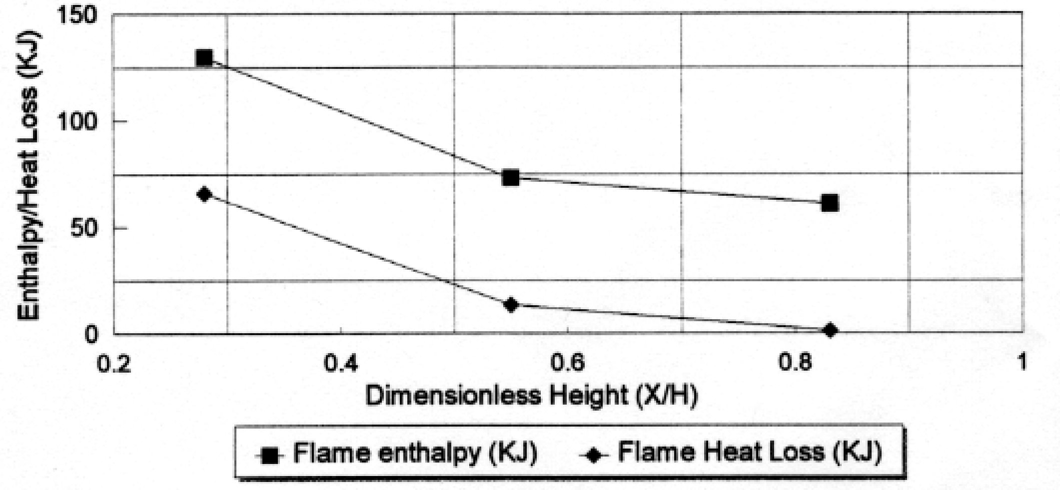

Figure 2. The Changes of Flame Enthalpy/Heat Loss along the Combustor Height

(C) DiscusSion:

Based on the heat balance calculation results for both case A and case B, the heat loss from the reactor wall to the environment is a great portion of the total heat transfer. For the case A, it is about 47 percent of the total heat loss; for the case B, it is about 83 percent of the total heat loss. In order to reduce the heat loss from reactor wall to the environment, it is necessary to increase the water cooling coil surface area to cover more the reactor wall. The heat loss into the cooling water for case A is about two times larger than that of case B, since the fuel input for case B is about half of the fuel injected for case A. The enthalpy of flame at the reactor center is changing along the reactor height that was measured at the three height levels from the reactor bottom, 8 inch, 16 inch, and 24 inch. The flame enthalpy can be used to estimate the flame heat losses in combustion chamber that may caused by the gas mixing process. They are 37.5 KJ, 37.3 KJ, and 5.82 KJ for case A; and 65.8 Ki, 13.48 KJ, and 1.25 KJ for case B as shown in Figures 1 and 2. It is believed that the better gas mixture was achieved for the case A.

For case A, the overall average heat transfer coefficients are 7.28 w/m2.OC from hot gas to the cooling water, and 6.497 w/m2.OC from hot gas to the environmental. For case B, the overall average heat transfer coefficients are 0.634 w/m2.OC from hot gas to the cooling water, and 7.854 w/m2.*C from hot gas to the environmental. Comparing the case A and case B, the overall heat transfer coefficient from hot gas to the cooling water decreased. The heat transfer coefficient from hot gas to the environmental increased as the flame average temperature increased. (D) Symbols:

H	Enthalpy (KJ)
Q	Heat (KJ)
Cp	Heat capacity (KJ/Kg.OC)
p	Density (kg/m3)
T	Temperature (OC)
p	Pressure (cm Hg)
q	f low rate (m3/min)
w	Mechanical work (KJ)
m	mass fraction of mixing gas
R	Universal gas constant (8.314 KJ/Kmol.OK)

Subscripts:

i	input data
o	output date
r	Reaction
w	water cooling
L	reactor wall

gas components in the mixture of gases such as CO **2J'** N 21 CH4, Air.

gas gas phase data

Superscripts:

0 standard condition

SECTION 3

CONCLUSIONS

The systematic tests were continued to analyze the thermal performance, heat balance, and heat transfer effect on exploratory hot model. The heat balance and heat transfer coefficient for two different test cases were calculated and predicted. it is found that the heat loss from the reactor (combustor) wall to the environment is a great portion of the total heat transfer.

The flame enthalpy and heat loss at the reactor center were changed along the reactor height. The overall average heat transfer coefficient is calculated for each test. The heat transfer coefficient from gas to the environment increased as the flame temperature increased.

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