Design and Operational Performance of RPF Fired Circulating Fluidized Bed Boiler

YOSHIHISA ARAKAWA*1
TATSUO YOKOSHIKI*1
TOSHIYUKI SAKAI*1
HITOJI YAMADA*2
SHIGEHARU KOKURYO*2
ISAO TORII*3

In boilers for industrial steam power generation, recycled fuel such as RPF known as clean new energy has come into widespread use as a means of promoting effective use of limited resources and saving fuel cost. Mitsubishi Heavy Industries, Ltd. (MHI) constructed an RPF fired circulating fluidized bed boiler with steam flow rate of 200 t/h for the Oita Mill of Oji Paperboard Co., Ltd. in 2004. This boiler is designed by optimizing the combustor pressure drop in order to prevent metal aluminum contained in the RPF from depositing to the inner wall of cyclone. In actual boiler operation, depositing of ash to cyclone does not occur, and favorable results are obtained in flue gas pollution levels (CO, NOx, SOx, dioxins, etc.).

1. Introduction

In Japan, the Basic Environment Law and regulations were instituted in the 1990s with the aim of realizing a recycle-oriented society, and attempts have been made to lower the environmental impact on the basis principle of 3Rs (reduce, reuse, and recycle). The conventional fuels for industrial steam power boilers have been mainly heavy oil and coal, and recently these are being replaced by recycled fuels such as RPF (refuse paper and plastic fuel). RPF is less expensive than coal, and cost merits are expected after shift of fuels in boiler operations. MHI has already constructed many circulating fluidized bed (CFB) boilers(1)(2). This time, a combustion method has been newly developed for CFB boiler firing RPF, and a CFB boiler with steam flow rate of 200 t/h has been in operation at the Oita Mill of Oji Paperboard Co., Ltd. An outline of development and boiler operating records is given in this paper.

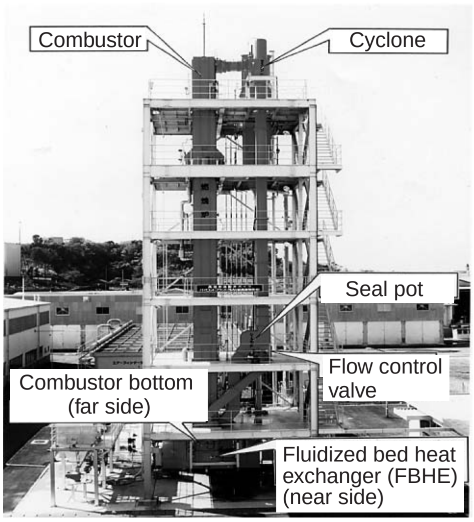


Fig. 1 Combustion test apparatus
The furnace is 0.4 m X 0.4 m in sectional area and 21 m in height. Heat input is 0.6 MWth.

2. Combustion test

2.1 Purpose of test

When using RPF in a CFB boiler, there is a risk of depositing of metal aluminum in the fuel on the inner surface of the cyclone. In order to ascertain the adhesion properties of metal aluminum and RPF combustion characteristics, combustion tests were executed by varying the combustor pressure drop and metal aluminum concentration in RPF so as to optimize the combustor operating conditions.

2.2 Test apparatus and fuel

The appearance of the test apparatus is shown in **Fig.1**. The combustor is 0.4 m x 0.4 m in sectional area, and 21 m in height. The heat input is 0.6 MWth. RPF is fed from the hopper by screw feeder, and supplied to the combustor by gravity. As bed material, quartz sand with average particle size of 190 μ m is used. The appearance of RPF is shown in **Fig. 2**. The shape is cylindrical, about 8 mm in diameter and 10 to 15 mm in length.

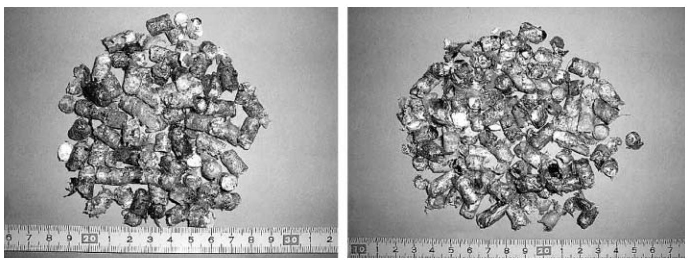


Fig. 2 Appearance of RPF (metal Al: 0.9% at left, 3.0% at right)
Cylindrical, approximately 8 mm in diameter and 10 to 15 mm in length.

*1 Power Systems Headquarters
*2 Nagasaki Shipyard & Machinery Works
*3 Nagasaki Research & Development Center, Technical Headquarters

Analysis result of the RPF composition is shown in **Table1**. The metal aluminum concentration is defined by the difference of acid-soluble aluminum and water-soluble aluminum.

2.3 Test method

The test conditions are shown in **Table 2**. In condition 1, the base condition is combustor pressure drop (⊿P-combustor) of 14 kPa, and combustor temperature (T-combustor) of 850°C. In condition 2, the influence of metal aluminum concentration in RPF was evaluated. In condition 3, the ⊿P-combustor was lowered to 7 kPa from condition 2, and in condition 4, with the ⊿ P-combustor kept in a lowered state, the metal aluminum concentration in RPF was reduced to 0.9%, and the test was performed.

Limestone was not supplied to the combustor for desulfurization in any of the conditions. The test time period was 20 hours in each condition. Conditions 1 and 2 were tested continuously.

In terms of the evaluation of combustion characteristics in each condition, flue gas pollution levels were analyzed respectively, and after the test the combustor, cyclone and back pass were inspected for ash deposits.

2.4 Test results and application to actual boiler

Table 3 shows flue gas properties at the cyclone outlet in each condition. **Table 4** shows the cyclone inspection results in each test.

In condition 1 and condition 2, in the operating condition of ⊿P-combustor of 14 kPa, and T-combustor of 850°C, the test was executed at metal aluminum concentration in RPF of 1.9% and 3.0%. In both conditions, ⊿ P-combustor distribution and T-combustor distribution are in suitable state, and the operation is stabilized. In the boiler inspection after the test, no ash deposits were found in the cyclone or water cooled tubes in back pass, and no clinker was observed in the lower part of the combustor.

In condition 3, in order to understand the effects of the ⊿P-combustor, 14 kPa in conditions 1 and 2 was lowered to 7 kPa. When the ⊿P-combustor was lower, particle concentration became lower in the lower part of the combustor, and the temperature of the combustor bottom tends to fluctuate. In the boiler inspection, as shown in Table 4, ash deposits was observed to collide against the cyclone vortex finder. In the water cooled tubes in back pass, however, no ash deposits were found, and cleaning by air blowing was sufficient for removing ash.

Table 1 RPF analysis results

			Condition 1	Condition 2	Condition 3	Condition 4
Proximate analysis	Moisture	(%)	3.3	2.5	2.3	7.0
	Ash	(%)	10.4	9.7	7.2	7.1
	Volatile matter	(%)	79.0	81.6	85.2	78.6
	Fixed carbon	(%)	7.3	6.3	5.2	7.3
Ultimate analysis (dry base)	C	(%)	51.4	56.6	64.3	57.9
	H	(%)	7.3	7.9	9.2	8.0
	O	(%)	30.2	25.2	18.4	25.7
	N	(%)	0.24	0.37	0.6	0.39
	T-S	(%)	0.02	0.05	0.0	0.07
	V-S	(%)	$<$0.01	$<$0.01	$<$0.01	0.03
	T-Cl	(mg/kg)	1 200	1 300	1 381	3 540
	V-Cl	(mg/kg)	1 100	1 200	1 319	3 410
	T-Ca	(%)	1.8	1.3	0.5	1.1
	T-Na	(mg/kg)	390	322	232	470
	T-K	(mg/kg)	162	122	91	760
	Metal Al	(%)	1.9	3.0	3.0	0.9
Higher heating value		(Kcal/kg)	5 520	6 240	7 271	5 620
Lower heating value		(Kcal/kg)	4 920	5 710	6 772	5 180
Ignition temperature		(°C)	232	228	232	235

Table 2 Test conditions

Test condition		Condition 1	Condition 2	Condition 3	Condition 4
Test parameter		Base condition	Metal Al concentration	Combustor pressure drop	Combustor pressure drop, metal Al concentration
Combustor pressure drop	(kPa)	14.0	14.0	7.0	7.0
Combustor temperature	(°C)	850	850	850	850
Metal Al in RPF	(%)	1.9	3.0	3.0	0.9
Test duration	(h)	20	20	20	20

Table 3 Cyclone outlet flue gas pollution levels

Test condition		Condition 1	Condition 2	Condition 3	Condition 4
CO (12% O_2)	(ppm)	56	83	23	56
NOx (6% O_2)	(ppm)	67	75	82	77
SOx (6% O_2)	(ppm)	13	12	21	30

Table 4 Cyclone vortex finder

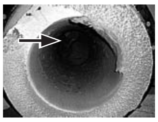
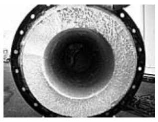
Test condition	Conditions 1 and 2 (continuous test)	Condition 3	Condition 4
Combustor pressure drop	14 kPa	7 kPa	7 kPa
Metal Al concentration in RPF	1.9%, 3.0%	3.0%	0.9%
Photograph (inside of vortex finder)	 No deposit	 Collision and deposit indicated by arrow	 No deposit

Table 5 Composition analysis of deposit ash in cyclone vortex finder

Test condition			Condition 3
Combustor pressure drop			7 kPa
Combustor temperature			850°C
Metal Al concentration in RPF			3.0%
Composition analysis	SiO_2	(%)	9.7
	Fe_2O_2	(%)	1.3
	T-Al	(%)	64.9
	Metal Al	(%)	39.4
	T-Ca	(%)	0.4
	T-Na	(%)	0.04
	T-K	(%)	< 0.03
	T-S	(%)	0.1
	T-Cl	(mg/kg)	146

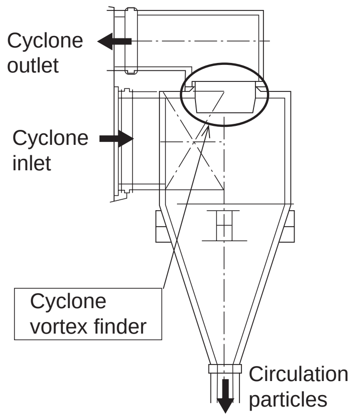


Table 6 Analysis of Al element in circulation particles

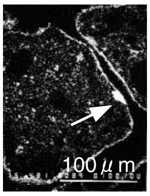
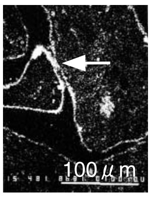
Identified element	Condition 2	Condition 3
Aluminum element (white area indicates aluminum) Element detected position is shown.		

Table 5 shows the analysis results of ash deposits in the cyclone vortex finder. Since the main component was 39.4% of metal aluminum, it is considered that metal aluminum in RPF is melted in the combustor, and collides against the cyclone vortex finder. In a comparison of this test result with condition 1 and condition 2, when the ⊿P-combustor is set slightly higher at 14 kPa, the combustor particle concentration is higher, mixing is further promoted, attrition of metal aluminum in RPF progresses in the combustor, and it is considered that the particle size becomes small enough to prevent collision and depositing to the cyclone vortex finder.

In condition 4, by reducing the ⊿P-combustor to 7 kPa, in order to evaluate the effect of metal aluminum concentration in RPF, the test was executed with the metal aluminum concentration lowered to 0.9%. In this test, as in condition 3, since the particle concentration was low, the temperature tends to fluctuate in the lower part of the combustor. In the boiler inspection after the test, no ash deposit were found in the cyclone inside or water cooled tubes in back pass, and no clinker is found in the combustor bottom.

For the purpose of investigating the chemical form of metal aluminum in circulating particles, EPMA (electron probe micro analysis) were executed. **Table 6** shows the analysis results of aluminum element in conditions 2 and 3. In the aluminum identification position indicated by the arrow, O (Oxygen) element was not identified, and it is considered that metal aluminum is present in single form, not in the form of oxide such as Al_2O_3.

When the ⊿P-combustor is as low as 7 kPa, in the state of collision of metal aluminum in RPF against bed material and insufficient attrition, the concentration of circulating particles is high and they are therefore considered to deposit to the cyclone. Accordingly, as application condition in actual boiler, the boiler is set at a ⊿P-combustor of 14 kPa at which suitability was confirmed in the test.

3. Outline of boiler for Oji Paperboard Co., Ltd.

The following is an outline of 200 t/h CFB boiler for Oita Mill of Oji Paperboard Co., Ltd. This is the RPF and coal fired CFB boiler newly constructed in order to replace the existing heavy oil and coal fired boilers. The generated steam is supplied into the existing back-pressure extraction turbines and paper manufacturing machine plants through the newly constructed extraction turbine, and all mill plant loads are provided by this boiler.

Table 7 Boiler main specifications

Type	Mitsubishi circulating fluidized bed boiler
Steam flow rate	200 t/h
Steam pressure	11.9 MPag
Steam temperature	541°C
Combustion system	Circulating fluidized bed combustion
Draft system	Balanced draft system
Fuel	RPF, coal

Table 8 Design fuel properties (RPF)

Type of fuel		RPF
Higher heating value	(MJ/kg)	25.1
Ultimate analysis (dry basis)		
Carbon	(%)	58.3
Hydrogen	(%)	8.0
Oxygen	(%)	27.2
Nitrogen	(%)	0.3
Sulfur	(%)	<1.0
Chlorine	(%)	<0.2
Ash	(%)	5.0
Metal aluminum	(%)	<1.0

Table 9 Design fuel properties (coal)

Type of fuel		Coal
Higher heating value (air dried basis)	(MJ/kg)	26.9
Proximate analysis (air dried basis)		
Moisture	(%)	7.9
Fixed carbon	(%)	46.1
Volatile matter	(%)	37.5
Ash	(%)	8.5
Total sulfur	(%)	0.53
Ultimate analysis (dry basis)		
Carbon	(%)	69.6
Hydrogen	(%)	4.8
Oxygen	(%)	14.7
Nitrogen	(%)	1.35
Sulfur	(%)	0.36

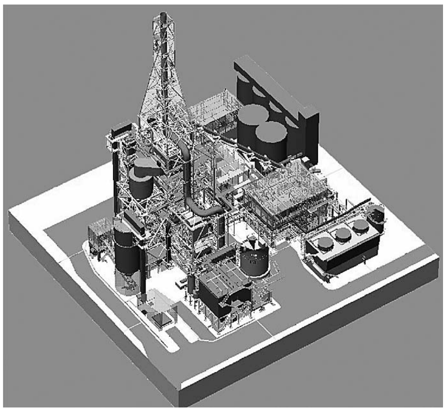


Fig. 3 Bird's-eye view of boiler
New boiler (center), turbine, cooling tower (right side), etc.

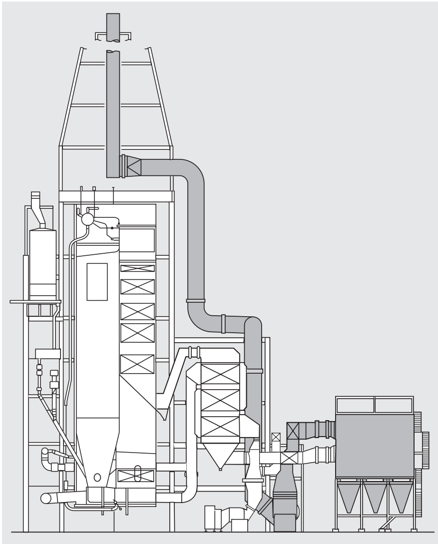


Fig. 4 Boiler plan
Exhaust duct in upper part of boiler; air preheater, fan and bag filter at right side.

The overall bird's-eye view of the boiler is shown in **Fig. 3**.

3.1 Boiler design specifications

Table 7 shows the boiler's main specifications. The design fuels are RPF and coal with each heat input varied from mono-fired to co-fired. **Tables 8** and **9** show the chemical properties of the design fuels.

Fig. 4 shows a schematic diagram of the boiler plan.

The boiler is of single drum natural circulation type. It consists of a water cooled membrane wall in the wind box, combustor bottom, peripheral wall and roof, and is formed in a compact integrated structure assembling the combustor, convection heat transfer part and FBHE (fluidized bed heat exchanger).

Multiple air nozzles are positioned uniformly in the lower part of the combustor and FBHE. In the FBHE, the evaporator and tertiary superheater is installed. Located in the back pass are the primary superheater, quaternary superheater, secondary superheater and economizer.

3.2 Steam and water system

Water is supplied into the steam drum after being preheated in the economizer located in the back pass in the convection heat transfer part. Boiler water is evaporated in the combustor peripheral wall, the evaporator in the FBHE and its peripheral wall, and peripheral wall of back pass, and is separated into water and steam in the steam drum.

Steam passes through the primary superheater and secondary superheater installed in the back pass, passes through the tertiary superheater installed in the FBHE, is further heated to the specified temperature in the quaternary superheater in the back pass, and sent into the main steam pipe.

Between the secondary superheater and tertiary superheater, the de-superheater device is installed for steam temperature control.

3.3 Circulating particle system

Particles circulate in two systems. In one system, particles discharged from the combustor are captured by the cyclone and returned to the combustor by way of the seal pot under the cyclone. In the other system, by the function of the flow control valve installed at the side of the seal pot, the amount of particles flowing into FBHE is controlled, and particles are cooled by FBHE and returned to the combustor.

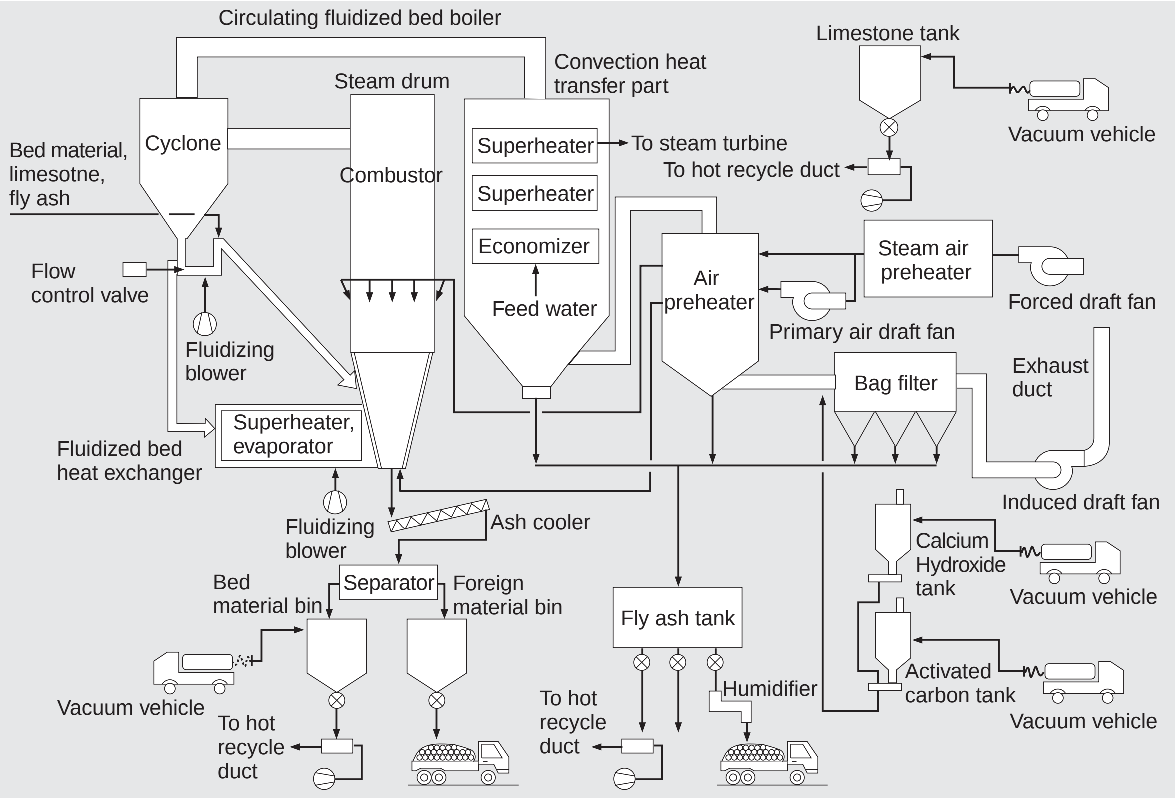


Fig. 5 Boiler plant block diagram
Boiler components, air and flue gas systems are shown.

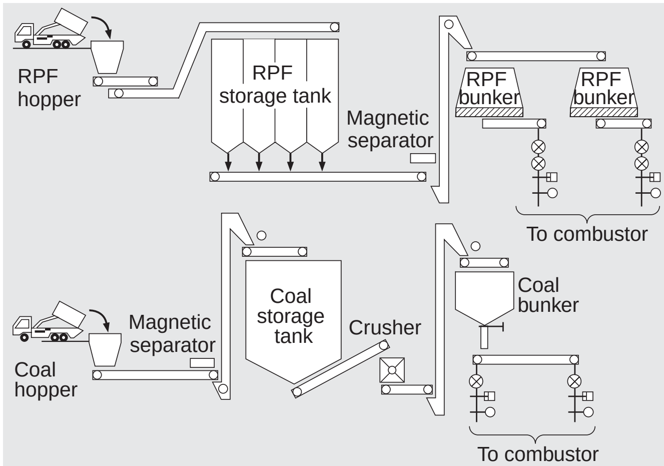


Fig. 6 Fuel supply system diagram
Two supply systems are prepared, respectively, for RPF and coal, and each fuel can be used in mono-firing.

3.4 Air and flue gas system

Fig. 5 is a block diagram of boiler plant. The draft system is a balanced draft system.

Primary air is boosted by a forced draft fan and primary air draft fan, preheated by an air preheater, and sent into the wind box at the bottom of the combustor. Secondary air is preheated by the air preheater, and injected into the combustor from the secondary air nozzle installed in the lower part of the combustor.

Combustion gas leaving the combustor is separated from the bed material in the cyclone, reaches the back pass to undergo heat exchange in the superheater and economizer, undergoes further heat exchange by the air preheater, and leaves the boiler. After leaving the boiler, the combustion gas is cleaned of dust by a bag filter, and is guided into a exhaust duct installed in the upper part of the boiler by an induction draft fan.

3.5 Fuel supply system

Fig. 6 is a diagram of the fuel supply system. The fuel supply system allows mono-fuel firing of RPF and coal. RPF is conveyed into the RPF bunker from the existing storage tank by a conveyor. The equipment after the RPF bunker is the same in both systems. From the RPF bunker, RPF is dropped into the RPF chute by gravity, in the same way as coal, via a weighing scale device, but in order to assure sealing property, two rotary feeders are assembled in series.

Coal is stored in the coal storage tank from the receiving hopper by a conveyor, crushed by a crusher to the proper grain size, and sent into the coal bunker. From the coal bunker, coal is dispensed into two coal chutes by way of a weighing scale device and divider. It is then dropped into the combustor by gravity through a rotary feeder.

3.6 Limestone and ash handling system

Limestone of specified grain size is carried in by vacuum vehicle, and stored in a limestone tank. Limestone is continuously supplied into the combustor for desulfurization.

In the combustor bottom, a bed ash discharge device is installed. Bed ash is cooled by bed ash coolers, sorted by a separator to remove impurities and stored in the bed ash bin. The bed ash is injected into the combustor by compressed air when the amount of bed materials decreased, and is reused. Removed foreign material is collected in the exclusive bin and discharged by truck.

Table 10 Boiler predicted performance of Oji Paperboard Co., Ltd.

		Predicted performance
Steam flow rate	(t/h)	200
Steam temperature	(°C)	541
Boiler efficiency	(%)	91.4/92.3*
NOx (O_2 6 %)	(ppm)	150
SOx (O_2 6%)	(ppm)	50
Dust concentration (O_2 6 %)	(mg/m^3_N)	30
HCl (O_2 12%)	(mg/m^3_N)	250
CO (O_2 12%)	(ppm)	100
Dioxins		
in flue gas (O_2 12 %)	(ng TEQ/m^3_N)	0.1
in fly ash	(ng TEQ/g)	3.0

* RPF mono-firing/RPF and coal co-firing

Fly ash collected by the bag filter, and the fly ash falling into the hopper under the economizer or hopper under the air preheater are conveyed into the fly ash tank by compressed air, and partly recirculated into the combustor. Collected fly ash is humidified by a humidifier and discharged by truck.

4. Boiler operation results at Oji Paperboard Co., Ltd.

4.1 Performance test results

Table 10 shows the specification of the boiler design. **Fig. 7** shows time trends during the plant performance test. Boiler performance was evaluated in two tests, the RPF mono-firing test and co-firing of 50% each heat input respectively. All the test results satisfy the design values and, in particular, environmental pollution levels were satisfactory with regard to NOx, SOx, CO, and HCl.

Boiler master was tested by using RPF in RPF mono-firing, and by using coal in RPF and coal co-firing. In both cases, stable operation were confirmed in terms of main steam pressure, main steam temperature, and main steam flow rate. It has been confirmed that operation using RPF as the master fuel is possible.

Combustor temperature is controlled by regulating the flow rate of circulation particles into the FBHE by flow control valve, and in both RPF mono-firing and RPF and coal co-firing, the combustor temperature is stably controlled around 820°C (the preset temperature in consideration of load changes), and combustor temperature control by means of a flow control valve is proved to be effective. As for dioxins, with stable combustor temperature of over 800°C and sufficient residence time, dioxins in flue gas and in fly ash are sufficiently lower than the design values.

4.2 Boiler inspection results

The boiler was inspected every three month for the first half a year operation in order to confirm ash deposits of cyclone and heat transfer tubes in back pass.

In the boiler inspection results, no metal aluminum deposits were found in the cyclone or heat transfer tubes in back pass. In RPF, the concentration of metal aluminum varies between about 0.3 to 1.3%.

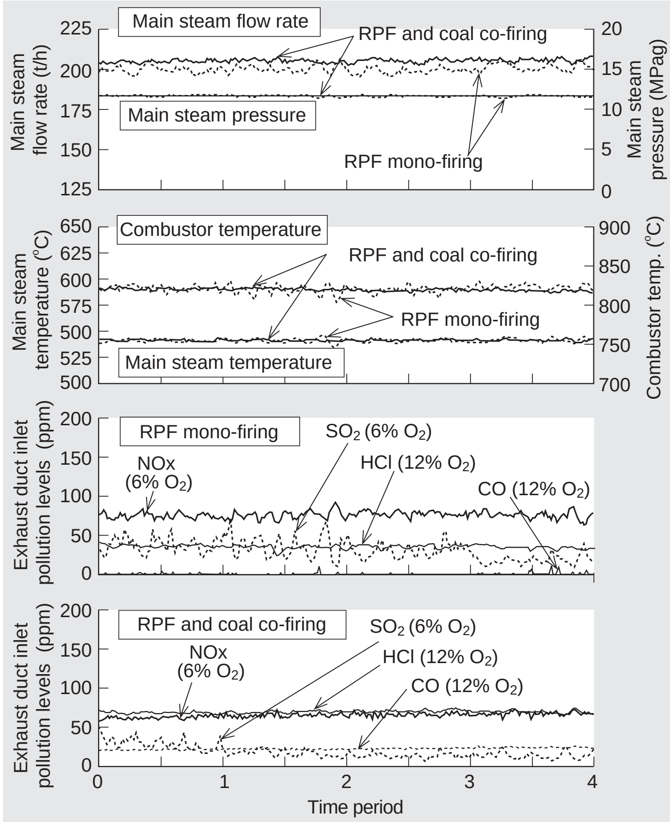


Fig. 7 Time trends of performance test
Main steam flow rate, pressure and pollution levels are all stable.

5. Conclusions

RPF (refuse paper and plastic fuel), a palletized fuel made from refuse paper and plastics, is used in circulating fluidized bed (CFB) boiler. The high reliability in boiler operation and conformity with environmental regulations of flue gas (CO, NOx, SOx, dioxins, etc.) and dioxins in ash have been successfully demonstrated. The demand for RPF as boiler fuel is likely to increase in the future, and MHI's fluidized bed technology will be fully utilized in order to contribute for the satisfaction of users.

References

(1) Hasegawa et al., Design and Field Operation Results of Mitsubishi-Lurgi Circulating Fluid Bed Boiler, Mitsubishi Juko Giho Vol. 27 No. 4 (1990)

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Yoshihisa Arakawa


Tatsuo Yokoshiki


Toshiyuki Sakai


Hitoji Yamada


Shigeharu Kokuryo


Isao Torii