

# CHARACTERISTICS OF THE INTERNALLY CIRCULATING FLUIDIZED BED BOILER

T. HIROTA, T. OHSHITA, S. KOSUGI, S. NAGATO,  
T. HIGO, AND N. INUMARU

Plant Engineering Division, Ebara Corporation  
Tokyo, Japan

## ABSTRACT

### Areas: Fluidized Bed

The problems of heat exchange tube erosion in fluidized beds have been overcome with a new Internally Circulating Fluidized-bed Boiler (ICFB) by Ebara Corporation. The ICFB efficiently co-combusts industrial waste and coal, provides steam production control, and sets new standards in limiting  $\text{SO}_x$  and  $\text{NO}_x$  generation.

## INTRODUCTION

Fluidized bed combustion boilers (FBC) were developed because of their capacity to accept different fuels, and to perform desulfurization and denitration within the furnace. In fact, however, all FBC boilers are by requirements of combustion efficiency, and  $\text{NO}_x$  and  $\text{SO}_x$  removal, etc., restricted in the types of coal and fuel they can handle. The complexity of fuel feed systems and difficulty with load variations have also emerged as problem areas.

The circulating fluidized bed combustion boiler (CFBC) was developed in an attempt to solve such problems, but suffers from the fact that the circulation ratio is nearly 100 times the input, that the circulation is external to the main combustion chamber, and that

heat exchange surfaces are limited to the vertical walls to avoid problems of excessive abrasion.

The internally circulating fluidized bed combustion boiler (ICFB), solves the problems of the FBC and CFBC, and makes possible high-efficiency, low-pollution combustion, with a wide-range of load control.

This paper discusses the combustion characteristics of the ICFB.

## PROFILE OF CONVENTIONAL FLUIDIZED BED BOILERS

The most prominent characteristic of the FBC, and its most prominent fault is that the combustion cell and the heat recovery system are integrated. The fluid bed combustion cell is equipped with an immersed heating surface. This basically restricts the load changing capability on the furnace bed. This requires that techniques such as bed temperature control, velocity turn-down and bed slumping be used instead. However, each of these have their own problems. When bed temperature control is used,  $\text{SO}_x$  and  $\text{NO}_x$  must be dealt with; with velocity turn-down there is the problem of abrasion; and bed slumping makes operation more complex.

The CFBC attempted to solve these problems by applying a circulating fluidized bed to the boiler, and

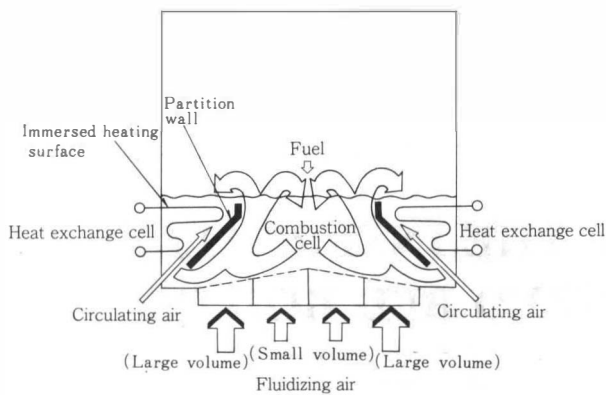


FIG. 1 SCHEMATIC VIEW OF INTERNALLY CIRCULATING FLUIDIZED BED BOILER

attracted attention not only for that, but for its capacity to handle a wider variety of fuels. CFBCs are available both with and without external heat exchangers, and turn down functions are quite enhanced for those equipped with them. Even with these improvements, there still remains the problem of how to handle the high level of assorted particles, especially the control of particles returned from the external heat exchanger to the combustor. CFBC boilers without external heat exchanges are therefore becoming more prominent [1].

However, the basic principles behind the CFBC involve the external circulation of solids at high gas flow rates and circulation ratios, resulting in a level of abrasion that restricts heat exchange elements to the surface walls, and has the same problems as high-temperature cyclones.

Research has led to the development of a mid-speed, mid-range temperature circulating fluidized bed boiler, which avoids the pitfalls of the FBC and CFBC while still taking advantages of their strong points.

### THE INTERNALLY CIRCULATING FLUIDIZED BED BOILER (ICFB)

#### Structure

Figure 1 illustrates the structure of the internally circulating fluidized bed boiler. The technology is fundamentally an extension of the bubbling fluidized bed boiler, except a slanted partition wall has been added between the main combustion cell and the heat exchange cells on either side, and silica sand is used as the bed material. A rotational flow is formed within the main combustion cell, and a secondary circulation

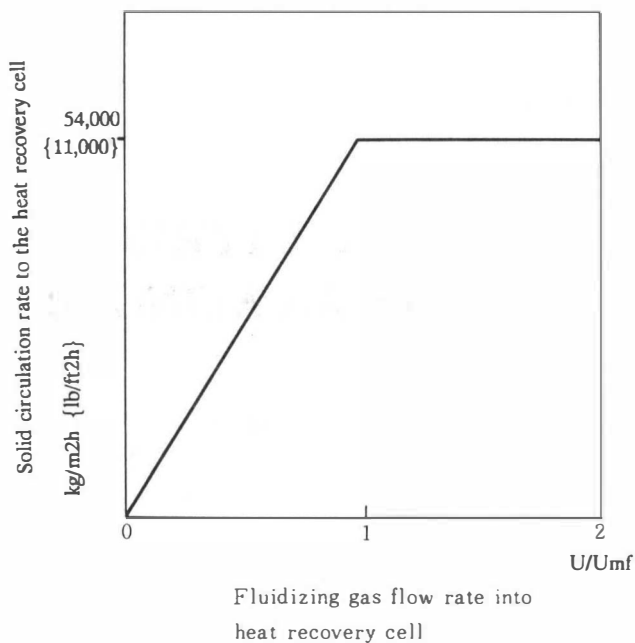


FIG. 1(a) SOLID CIRCULATION RATE TO THE HEAT RECOVERY CELL VS GAS FLOW RATE INTO THE HEAT RECOVERY CELL

is established between the main combustion cell and the heat exchange cells. This latter circulation occurs as a back flow of the bed material thrown up against the slanted partition walls.

The descent and circulation of material in the heat exchange cell is controlled by the volume of fluidizing air supplied to the lower part of the heat exchange cell. The relationship between the solid circulation rate to the heat recovery cell vs gas flow rate into heat recovery cell is shown in Fig. 1(a). When fluidizing air is increased from zero to the  $U_{mf}$  (minimum fluidization velocity), the descent rate of bed materials increases almost linearly. However, beyond the  $U_{mf}$ , the descent rate remains fairly constant. In the range 0–1  $U_{mf}$ , the level of circulation results essentially from the difference in the weight of bed material (difference in bed height) between the heat exchange cell (moving bed) and the combustion cell (fluid bed and moving bed). At velocities over 1  $U_{mf}$ , the heat exchange cell height is fractionally higher but essentially the same, and the strength of circulation results from the level of back flow of bed material from that thrown up against the partition wall.

Technically speaking, a bed with superficial gas velocity ( $U$ ) less than  $U_{mf}$  ( $U < U_{mf}$ ) is termed a fixed

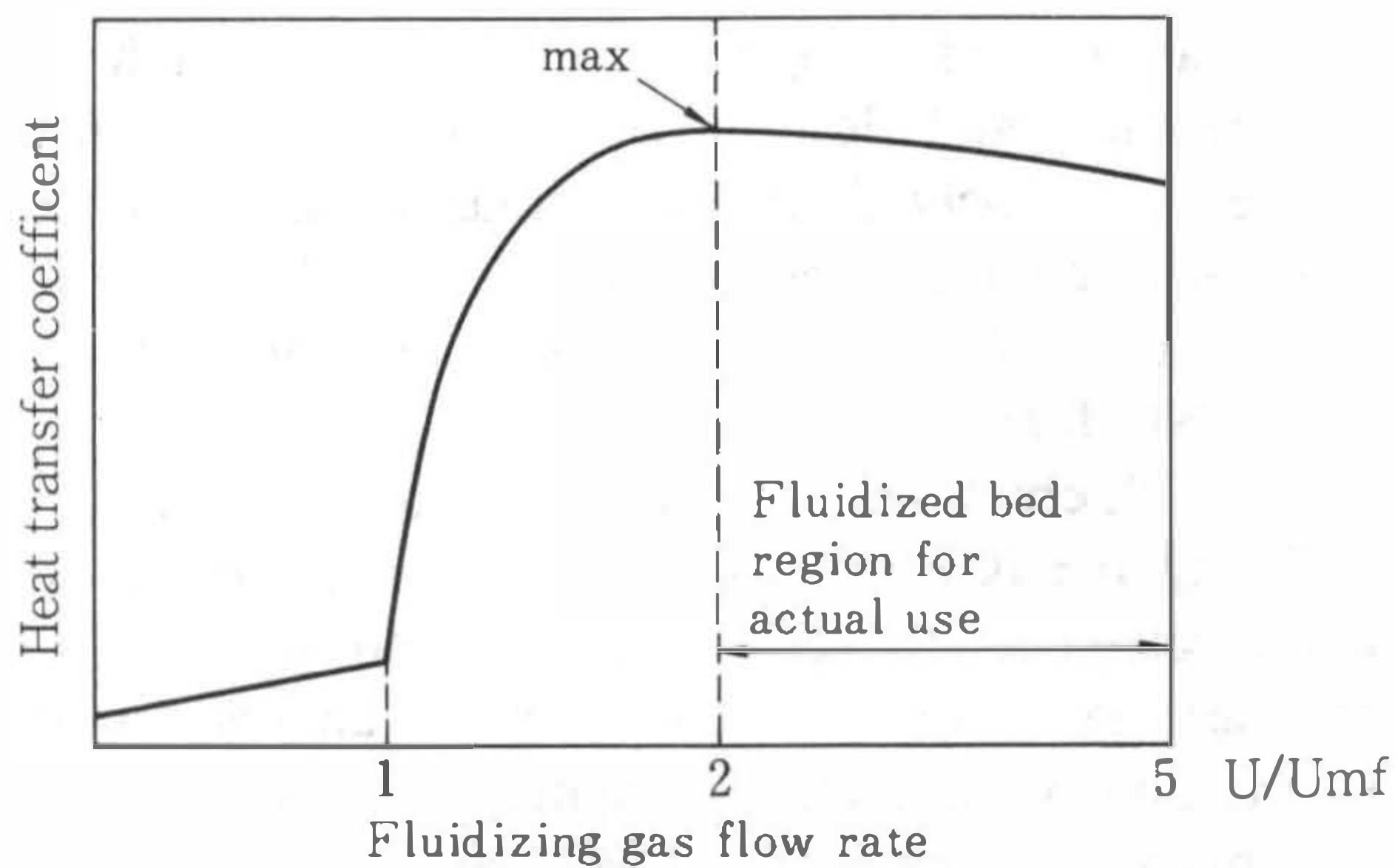


FIG. 2 OVERALL HEAT TRANSFER COEFFICIENT VS FLUIDIZING GAS FLOW RATE IN FBC

bed, and a bed with  $U > U_{mf}$  is a fluidized bed. It is generally agreed that a minimum of twice the  $U_{mf}$  is needed to form a stable fluidized bed. In this technology however, even up to  $1.5-2 U_{mf}$  there is virtually no wide bubbling disturbance to the moving bed. A steady descent is achieved because the particles have something of a vibrating, or fine trembling action which disperses circulating air into small smoothly rising bubbles.

### Principles

The general relationship between the overall heat transfer coefficient and the fluidizing gas flow rate in conventional bubbling beds is shown in Fig. 2. When the fluidizing gas flow rate is between zero and the  $U_{mf}$ , the overall heat transfer coefficient shows little increase, but it rises sharply once the  $U_{mf}$  is exceeded. Wing panel boilers try to take advantage of this phenomenon as a turn down technique, but changes in the heat transfer coefficient from changes in the fluidizing gas flow rate are either "insensitive" (fixed bed) or "too sensitive" (fluid bed) [2].

Several attempts to separate the combustion and heat recovery cells in ways similar to the ICFB can be found in patent specifications from countries other than Japan, though all of them use vertical partitions [3]. Most also treat the bed material in the heat recovery cell as changing in an off/on pattern between the fixed and fluid bed states: fixed for small heat recovery and fluidized upwardly with air from below for large heat recovery. This is because it is more difficult to generate the back flow with vertical partitions than with diagonal partitions. Also, in vertical partition units a dif-

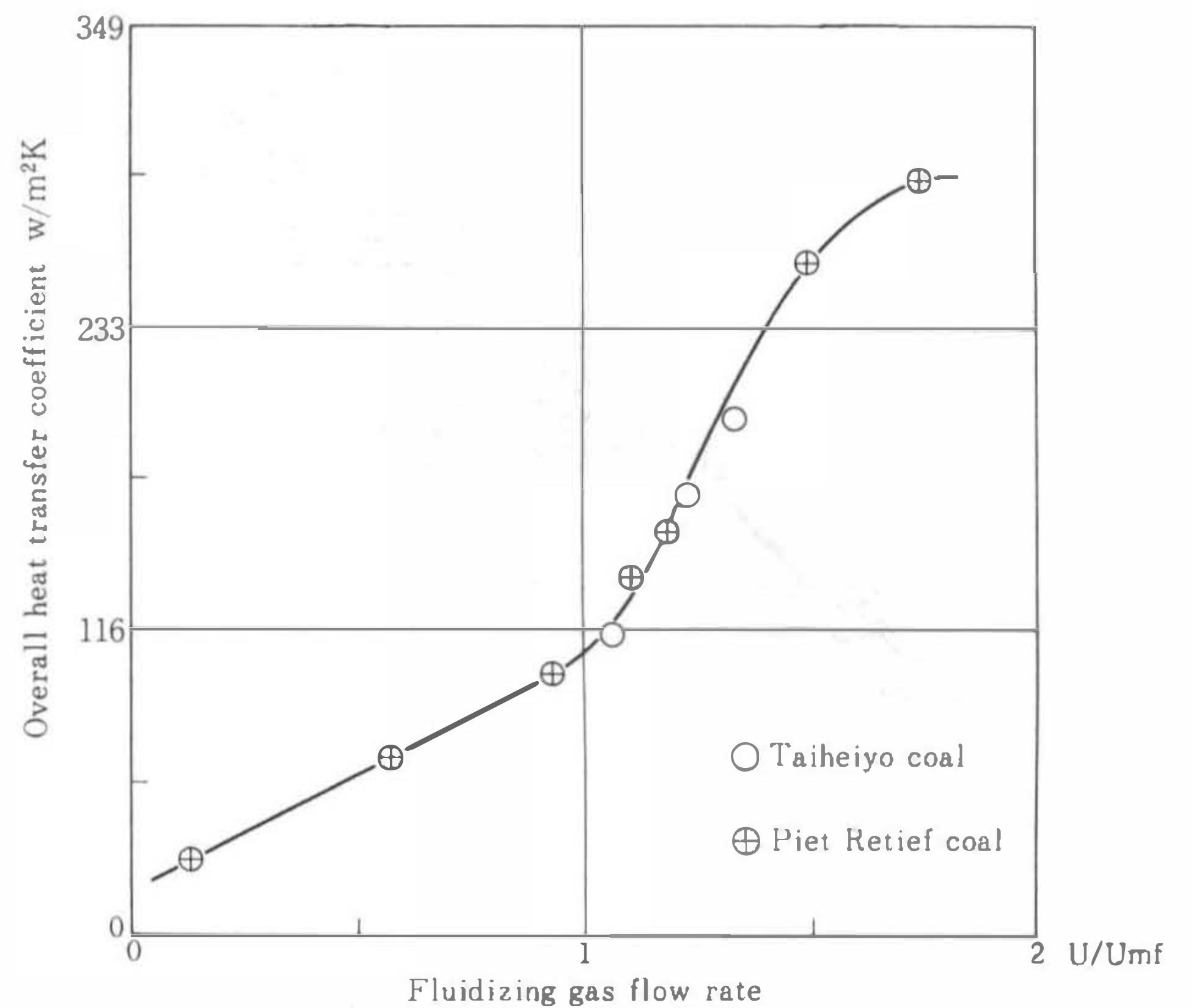


FIG. 3 OVERALL HEAT TRANSFER COEFFICIENT VS FLUIDIZING GAS FLOW RATE IN ICFB

ferential in bed material weight is not established between the combustion and heat recovery cells as both cells remain in a fluid state and cannot freely intermix. For these reasons, no examples of fluidized bed boilers with a heat exchange cell with a descending bed fluidized in the range  $0-2 U_{mf}$  can be found.

The relationship between the overall heat transfer coefficient and fluidizing gas flow rate in the moving bed of the heat recovery cell is shown in Fig. 3. As can be seen from the figure, the change is essentially linear, which makes it possible to control the fluidized bed temperature at will. Furthermore, this control can be accomplished merely by changing the amount of circulating air in the heat exchange cell.

In addition, abrasion of the immersed heat exchange tubes, which is said to be proportional to the cube of the fluidizing gas flow rate, is overcome by making the heat exchange cell a (lightly fluidized) moving bed.

### COMPARISON OF FBC AND ICFB TECHNOLOGY

The three circulation zones of the ICFB boiler are illustrated in Fig. 4. They are:

1. Internal circulation in the main combustion cell.
2. Circulation to the heat exchange cell.
3. Circulation of char back to the fluidized bed.

The main features of these circulation zones are discussed below.

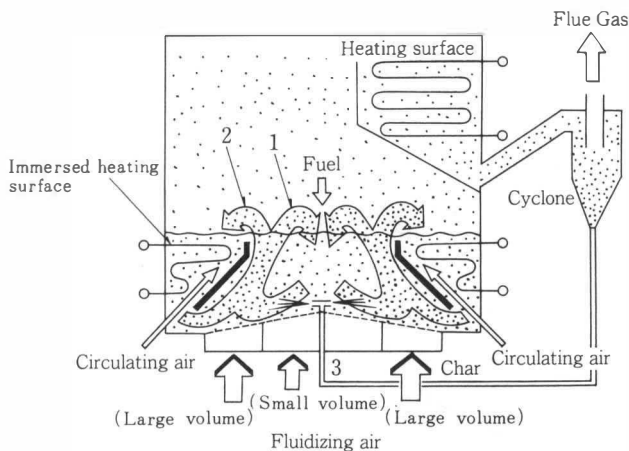


FIG. 4 THREE CIRCULATIONS OF THE ICFB

### Effects of Internal Circulation in the Main Combustion Cell (Circulation 1)

Unburned ash returned to the main combustion cell by the char circulation system is effectively dispersed and passed to the fluidized bed by the descending, spreading action of the moving bed. This results in efficient and thorough combustion even with high fixed carbon ratio fuels. CBCs (carbon burn up cells) are therefore unnecessary. At the same time, the dispersion of the recycled char within the bed creates a reducing atmosphere in the bed, which minimizes the formation of nitrogen oxides.

As the bed material itself circulates within the combustion cell, input fuel is effectively dispersed and fuel feeding is simplified.

### Separation of Combustion and Heat Exchange Functions and the Effects of Heat Recovery Circulation (Circulation 2)

The functions of combustion and heat recovery have in effect been separated, and the amount of heat recovered can be controlled at will by controlling the amount of air to the heat exchange cell. This means that stable operation is easily established even if the type of fuel and the amount of heat generated are changed after commissioning. It also allows for arbitrary variation of steam load. Since there is little temperature loss from bed material in the main combustion cell after shutdown, intermittent or batch operation is also possible.

As abrasion of the immersed heat exchange tubes is substantially avoided, silica sand can be used as the

bed material. The opposing problems of bed height maintenance and desulfurization have thus been simultaneously solved, and limestone consumption dramatically reduced. The use of silica sand also avoids the catalytic effect of high levels of CaO on  $\text{NH}_3$ , and limits NO formation [4].

Load fluctuations are controlled by a method peculiar to the ICFB. The bed material is used to give and receive heat between the main combustion cell and the heat exchange cell according to changes in the steam flow rate, taking advantage of the enormous thermal storage capacity of the bed.

Specifically, feed forward control has been introduced for the fuel feed in order to avoid combustion lags. The heat excess or shortfall resultant from load changes is anticipated before the steam pressure varies by adjusting the amount of heat stored through very slight bed temperature changes. As the heat exchange rate can be controlled independently of the air supply to the main combustion cell, controllability is further enhanced.

It is thus possible to vary the steam load with almost no change in bed temperature, and to avoid the non-combustible sulfur portion forming  $\text{SO}_x$ . An explanation is provided in control characteristics regarding the data for the turn down ratio at 30%.

Figure 5 is a cut-away view of the ICFB. When coal is used as fuel, this coal is supplied to the spreader from the sidewall. When solid waste is used as fuel, this waste is supplied by a double axis screw from the ceiling (not illustrated).

### COMPARISON OF CFBC AND ICFB TECHNOLOGY

Because it promised to solve the problems associated with FBC technology, organizations around the world worked to develop the CFBC boiler with unprecedented speed. While the technology has more or less achieved its purposes, it has been fraught with problems resulting from most of the combustion occurring in the entrained state, and high-temperature, high-speed circulation.

The mid-speed, mid-temperature range circulation fluidized bed boiler (FBC + CFBC) was devised as a way to break through the limitations of both FBC and CFBC technology, and promises to be a fruitful development concept.

The concept behind the ICFB is close to that of the FBC + CFBC technique. The multiple circulation zones described in Comparison of FBC and ICFB Technology is an approach to solving the outstanding



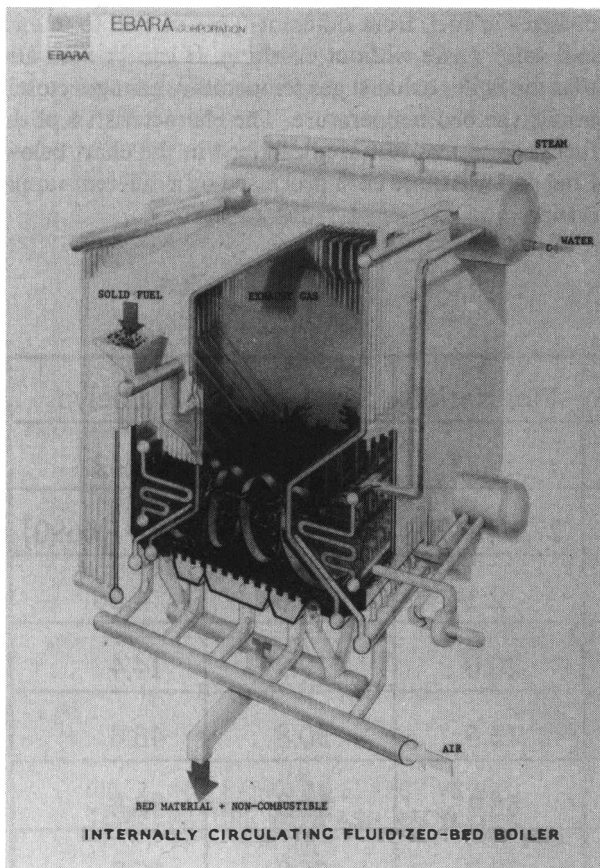


FIG. 5 CUT-AWAY VIEW OF THE ICFB

problems. The unique advantages of this approach are described below.

## ADVANTAGES UNIQUE TO THE ICFB

### Combustion/Pollution

Experimental results are discussed below. (More detailed data of the experiments can be found in the listed references [5-9].

Combustion efficiency of just under 99% was obtained with some types of coal, though most were over 99% combusted. When municipal solid waste is used as fuel, all is combusted with a combustion efficiency of over 99.8%. If the fuel feed rate is lowered, combustion efficiency decreases even more, though the actual amount is very small.

It is important to keep the fluidized bed temperature within the range  $825^{\circ}\text{C} \pm 25^{\circ}\text{C}$  in order to minimize  $\text{SO}_x$  levels. In this temperature range, free sulfur is virtually the only source of  $\text{SO}_2$ , but outside this range

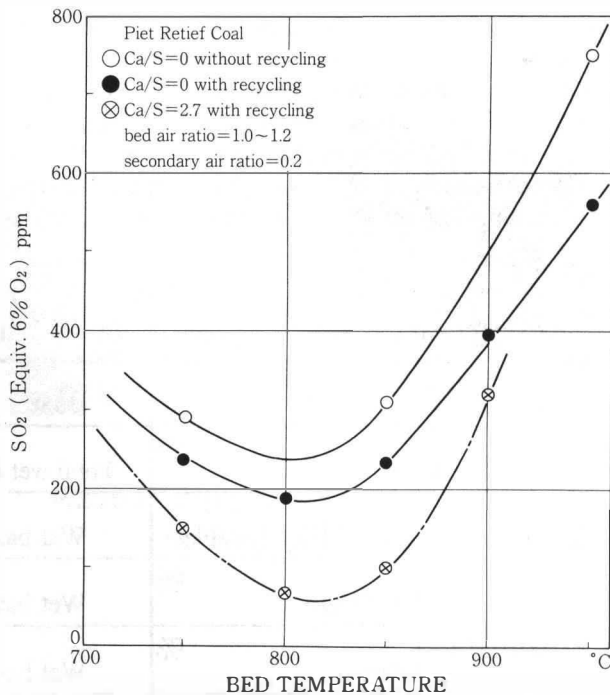


FIG. 6  $\text{SO}_2$  REMOVAL EFFECT VS BED TEMPERATURE

even the essentially noncombustible sulfur may become  $\text{SO}_2$ . The internal and char circulations enable a desulfurization rate of 90% with a Ca/S (total sulfur) ratio of 2.7 when the temperature of the fluidized bed is  $825^{\circ}\text{C}$ . (Refer to Fig. 6.)

The recirculation of porous char and the internal circulation in the main combustion cell combine to sharply reduce  $\text{NO}_x$  emissions. Experimental data shows that coal with a fixed carbon to volatiles ratio of over 1.5 will produce less than 80 ppm of  $\text{NO}_x$ , and high fixed carbon coal less than 50 ppm. (Refer to Fig. 7.)

### Bed Temperature Control Functions

One supposed advantage of the conventional FBC boiler was that it was suitable to a variety of fuels. All that meant, however, was that it could be designed for different fuels, but once the design had been set (ie. after the area of the bed heat exchange surfaces had been matched to the calorific content), the fuel variation tolerance was relatively small.

By contrast, if the area of immersed heat exchange surfaces in the heat exchange cells of the ICFB is designed for coal of, for example, 29.3 MJ/kg (7000

kcal/kg) of low calorific value (net heat value), the boiler will run with fuel anywhere in excess of 6.3 MJ/kg (1500 kcal/kg) (though beyond 29.3 MJ/kg, reductions of course may be necessary in the feed rate).

Figure 8 is the temperature record over a 100 hr period of continuous operation plus start up, showing the stability of bed temperature through various

changes in fuel, from different types of coal to municipal solid waste without crushing. It can be seen also that the boiler exhaust gas temperature changes closely mimic the bed temperature. The characteristics of the fuel used in this test are described in the chart below. Coal and waste are each processed by a different supply device.

**Coal Properties (particle sizes are under 1 in.)**

Item		Coal	Base	Piet Retief	Saxon Vale	Taiheiyo
Total Moisture		%	Total wet base	5.73	9.60	5.42
Calorific Value		MJ/kg {kcal/kg}	Wet base	27.1 {6470}	27.8 {6630}	28.0 {6690}
Proximate analysis	Moisture	%	Wet base	2.14	1.6	4.86
	Ash	%	Wet base	20.0	17.9	14.4
	Volatile Matter	%	Wet base	13.6	30.8	46.8
	Fixed carbon	%	Wet base	66.4	51.3	38.8
Ultimate analysis	Carbon	%	Dry ash free base	70.7	66.8	65.8
	Hydrogen	%	Dry ash free base	3.2	4.6	6.1
	Nitrogen	%	Dry ash free base	1.76	1.28	0.8
	Oxygen	%	Dry ash free base	4.08	9.1	12.9
	Total sulfur	%	Dry base	0.69	0.39	0.27
	Combustible sulfur	%	Dry ash free base	0.26	0.32	0.08
Fuel ratio (Fixed carbon / Volatile matter)				4.88	1.67	0.83

**Municipal waste properties (Particle sizes are under 20 in.)**

Net Heat Value MJ/kg	Moisture %	Density kg/m <sup>3</sup>	Constituent distribution %						
			Paper	Wood Bamboo	Plastic	Kitchen waste	Textiles	Metal Glass	Others
8.3	55.4	148	36.7	1.1	20.7	24.3	5.4	7.1	4.7

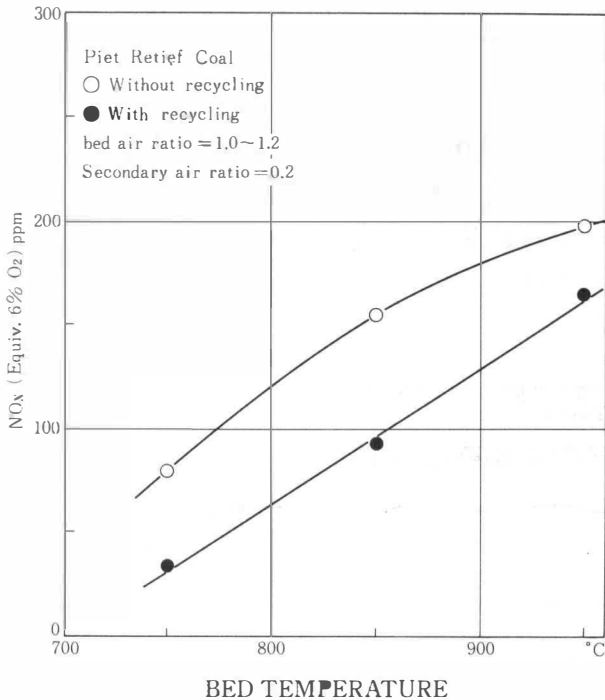


FIG. 7 NO<sub>x</sub> REMOVAL EFFECT VS BED TEMPERATURE WITH ASH RECYCLING

**Control Characteristics**

Figure 9 illustrates the control characteristics with step changes in the steam flow rate. As shown, even instantaneous changes in the steam flow rate are achieved with only minor fluctuations in bed temperature and steam pressure. Bed temperature variation is within the range of ±12°C, and steam pressure varies less than ±0.03 MPa (4.27 lb/in.<sup>2</sup>). This is because the in-bed heat transfer coefficient can be controlled directly by manipulating the amount of circulation air so that released variations in required steam (surplus or lack of load) are transiently absorbed by the fluidized bed. Control speed is therefore rapid, and not immediately dependent on the amount of bed material exchanged with the heat exchange cells, and not affected by scale of the equipment.

**Noncombustibles Discharge**

The conventional FBC boiler cannot handle fuels containing noncombustible materials, as various noncombustibles conglomerate on the immersed heat exchange surfaces and disturb fluidization.

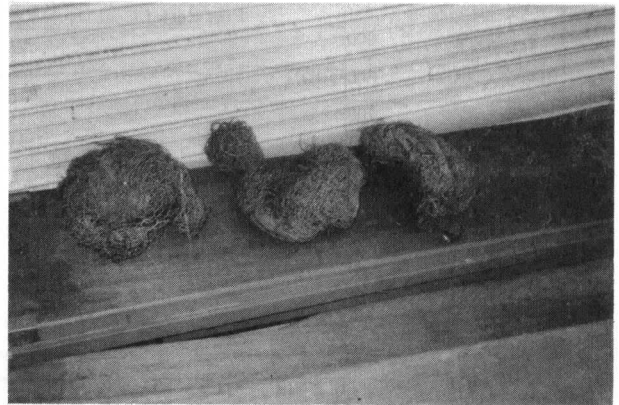


PHOTO 1 STEEL WIRE DERIVED FROM TIRES

In the ICFB, the separation of combustion and heat exchange functions, with most of the combustion taking place in the fluidized bed of the main combustion cell, enables noncombustibles to be passed to the outlets on either side of the main bed and discharged.

Since a small amount of the noncombustibles will ride on the back flow of fluidized bed materials and pass to the heat exchange cell, the immersed heating surfaces inside the cell are arrayed in parallel so that in all cases the noncombustibles still pass to those outlets and are discharged.

In order to verify the features discussed above, low calorific value of 21 MJ/kg (5000 kcal/kg) refuse rich in plastics was mixed together with various noncombustibles and incinerated. Stable operation was still maintained with no build up of noncombustibles in either the combustion or the heat exchange cells, even when the refuse had a noncombustible content of over 40%. Photograph 1 shows an example of discharged noncombustibles (tire reinforcing). The steel belts have been rolled into balls by the internal circulation before discharge.

**IMPLEMENTATION**

Construction of the first commercial plants commenced in the latter part of 1988, and the following projects are underway:

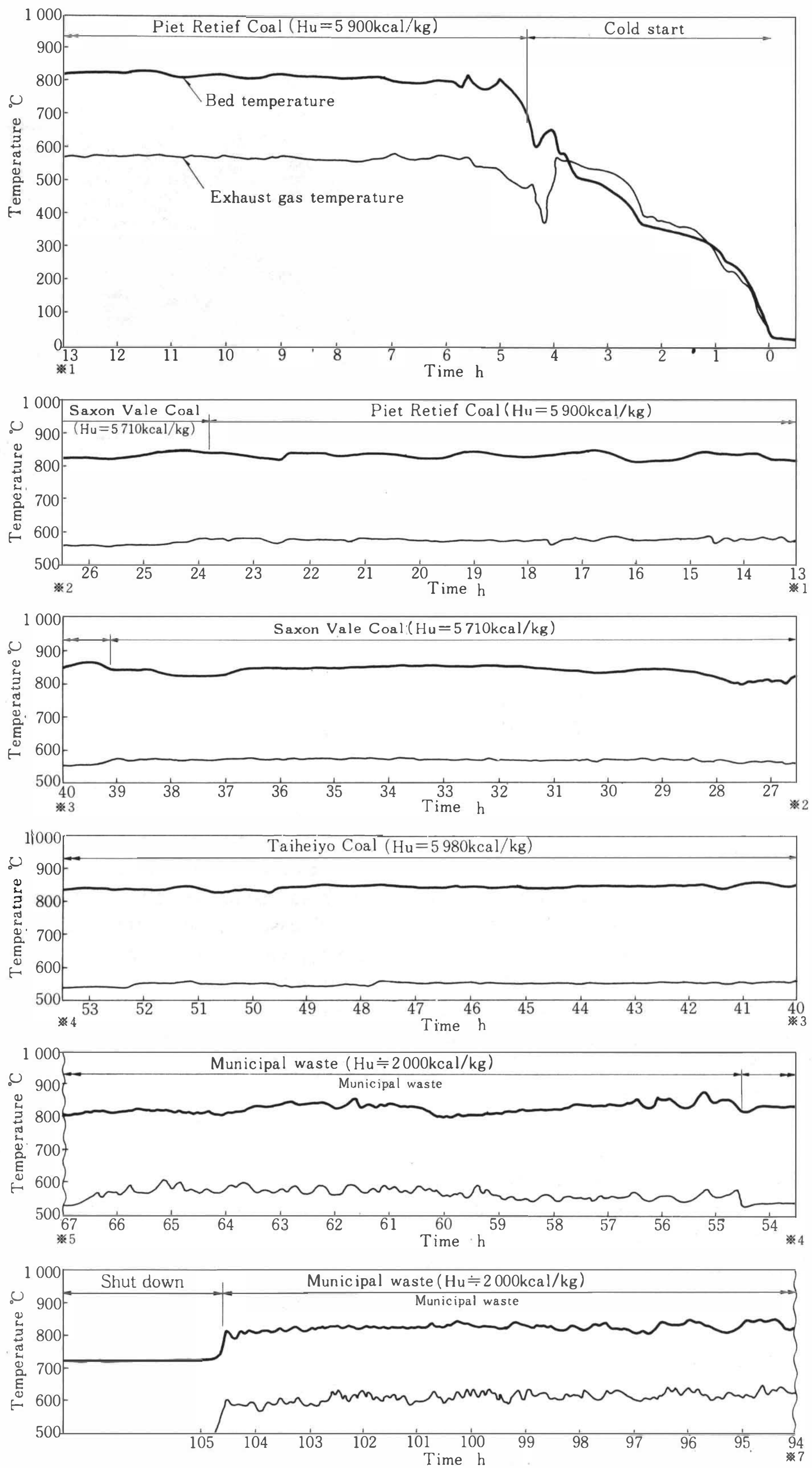


FIGURE 8



No.	Steam Rating (t/h)	Steam Pressure (MPa)	Steam Temp. (°C)	Steam Use	Fuel	Year of Completion
1	11.5	1.8	Saturated	Power generation	General refuse	1990
2	11	1.8	Saturated	Process	Industrial waste	1989
3	70	6.0	460	Power generation & Process	Coal and industrial waste	1990
4	10	1.8	Saturated	Combustion research	Various coals	1990
5	18	1.6	Saturated	Process	Industrial waste	1990

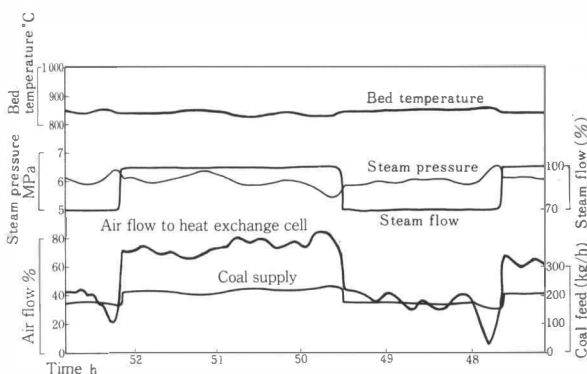


FIG. 9 CHARACTERISTICS OF STEAM FLOW CONTROL

## GENERAL OBSERVATIONS

The development of the CFBC tried to avoid immersed heating surfaces all together in order to solve the problems associated with their inclusion in the concentrated fluidized bed of the FBC. In the ICFB we have faced these problems head on, and by creating a moving bed in the heat recovery cell have solved the problem of abrasion on the immersed heating surfaces, and have provided U value control (control of Overall heat transfer coefficient by changing the fluidizing gas flow rate; see Fig. 3) as well.

In addition, the effects of the multiple circulations— internal (in-bed) circulation, heat exchange circulation and char circulation — have allowed us to both overcome long-standing technical barriers and to establish new merits.

In terms of its fuel flexibility, low pollution and ease of load control, the ICFB can be said to be a coal-fired boiler the equal of any oil-fired boiler.

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**Key Words:** Boiler; Combustion; Efficiency; Emissions; Fluidized Bed; Refuse; Steam