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APPLICATION OF HIGH-LOW BED CFB COMBUSTION TECHNOLOGY TO OIL SHALE COMBUSTION

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Abstract. *A 75 t/h pulverized coal-fired boiler has been successfully revamped to a 65 t/h oil shale-fired circulating fluidized bed (CFB) boiler employed by the high-low bed CFB combustion technology. The 65 t/h boiler was installed in Suixi cement factory, Guangdong province, China, and put into operation in 2006. The designed fuel is oil shale and comes from Maoming deposit, Guangdong province. The average low heating value is about 4.1 MJ/kg. Boiler performance tests showed that the main technical and economic parameters meet the designed requirements, which can provide a theoretical and technical basis for the design and operation of a large-scale oil shale-fired circulating fluidized bed boiler.*

Keywords: *oil shale, pulverized coal-fired boiler, CFB, design.*

1. Introduction

Oil shale is an organic-rich fine-grained sedimentary rock containing significant amounts of kerogen from which shale oil and combustible gas can be extracted. It can also be burnt directly in furnaces as a low-grade fuel for power generation and district heating [1, 2]. In burning oil shale for electricity and heat generation, Estonia, China and Israel have gained vast experience.

Estonia owns the largest, mostly oil shale-fuelled power plants in the world, which burn about 11–12 million tons of oil shale yearly. Almost 95% of electric power in Estonia is produced from oil shale [3]. So far, for oil shale combustion in industrial boilers in Estonia three technologies have been employed, i.e. grate firing, suspension combustion (pulverized coal combustion) and fluidized bed combustion.

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Early in 1924, Tallinn Power Plant started to burn oil shale, using a steam boiler equipped with a grate-firing furnace. That year can be considered the start of the oil shale-based power industry, and the 1920s as a whole mark an important milestone in the history of the industry [4].

The second stage in the development of the oil shale-based power industry started in 1949, when the suspension combustion technology, also called pulverized firing technology, was first introduced to burn oil shale at Kohtla-Järve Power Plant, with the designed electrical capacity of 48 MW. In 1951, another oil shale-pulverized firing boiler was put into operation at Ahtme Power Plant, and the available capacity is 30 MW of electricity and 370 MW of heat. In 1959, the first high-pressure pulverized firing boiler specially designed for firing oil shale was launched at Balti Power Plant, with the designed capacity of 1624 MW of electricity and 505 MW of heat. Eighteen TP-17 boilers and eight 100 MWel turbines were initially installed in the old part of the plant. In 1969, the construction of Eesti Power Plant, with a capacity of 1610 MW of electricity and 84 MW of heat, began. The plant was completed in 1973. It initially had sixteen TP-101 boilers, one 210 MW and seven 200 MW steam turbines, of which fourteen boilers and seven turbines were in service in 2002.

The third stage in the growth of the industry may be called an epoch of CFB. From the beginning of the 1990s in Estonia, considerable efforts have been made and numerous tests performed to burn oil shale in CFB [5, 6]. Until 2004, a power unit with an electrical capacity of 215 MW equipped with two CFB combustion boilers was put into operation at Eesti Power Plant. Some months later, a power unit of the same type was put into service at Balti Power Plant [4, 7, 8]. This indicates that the oil shale-fired CFB boiler can successfully be used for large-scale purposes. As a next step, Eesti Energia will start to build a new oil shale-run power plant near Eesti Power Plant with one or two 300 MW power units based on the CFB technology [9].

In Israel, oil shale has been found all over the country and most of the exploitable deposits are concentrated in the Northern Negev. One semi-commercial demonstration plant was built in 1987–1989. The fluidized bed boiler with a capacity of 50 t/h of steam was acquired from Ahlstrom Corporation, Finland [10].

In China, the first fluidized bed boiler with a capacity of 14.5 t/h of steam, which burns Maoming particulate oil shale, was designed in 1965 and put into operation in 1967 [11]. In 1985, a power unit with an electrical capacity of 6000 kW furnished with two 35 t/h oil shale-fired fluidized bed boilers was put into operation in Maoming Petroleum Industrial Corporation. Until 1996, the first oil shale-fuelled power plant with a CFB boiler was completed in Huadian city, Jilin province, China. Three 65 t/h low-circulation-ratio oil shale-fired CFB boilers and one 12 MW and one 6000 kW turbine were installed in the oil shale-run demonstration power plant. The 65 t/h boiler was the country's biggest oil shale-fired CFB boiler before in

Estonia, a CFB boiler was put into service at Eesti Power Plant where by now three similar boilers have been operating without failure for sixteen years [12–15].

In 2005, a 75 t/h pulverized coal-fired boiler was successfully revamped to a 65 t/h oil shale-fired CFB boiler employed by the high-low bed CFB combustion technology. It was installed in Suixi cement factory, Guangdong province, China, and put into operation in 2006. The retrofit project was provided by Northeast Dianli University, China, and the high-low bed CFB boiler technology introduced from Germany by Jiangxi Jianglian Energy & Environment Co., Ltd., China, was used.

This paper concentrates on the design of the 65 t/h oil shale-fired high-low bed CFB boiler based on the high-low bed CFB combustion technology. The principle and method of the retrofit will be provided and operating results presented.

2. High-low bed technology

The high-low bed means that there are two regions in the dense phase zone (fluidizing zone) of CFB. A typical structure of the fluidizing zone is given in Figure 1. Compared to the conventional CFB boiler, the dense phase zone in the high-low bed CFB is cross-sectionally divided into two parts which have different operating velocities and heights. One part is called main bed, also high-speed bed. The other part is called side bed, also low-speed bed. The height of the main bed is lower and the fluidizing velocity and pressure higher than those of the side bed. This means that two kinds of air distribu-

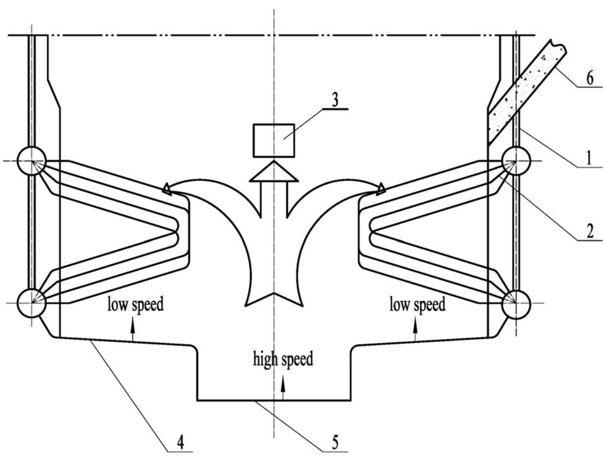

Fig. 1. Structure of the fluidizing zone.

1 – water wall; 2 – embedded tubes (in-bed tubes); 3 – coal feed port; 4 – air distribution grate for the side bed; 5 – air distribution grate for the main bed; 6 – recycled solids entry.

tion grates need to be used. The embedded tubes, i.e. in-bed tubes, are placed in the side bed with relatively low operating velocity. In addition, the structure and arrangement of the heating surface in the other parts of the high-low bed CFB boiler, such as dilute phase zone, superheater, economizer, air perheater, are the same as those of the conventional CFB boiler [16].
During the boiler operation, fresh fuel is sent to the main bed from the fuel feed ports and mixed with the hot-bed materials to ensure the combustion of fuel. In the process of fluidization, the solids having moved upward in the main bed can be thrown sideways of the boiler, which then also fall into the side bed. The solid particles in the side bed can return to the main bed through the orifices of the partition wall between the main and side beds. So, the up-and-down movements of solids in the core and annulus, as well as their transversal movement between the main and side beds generate an internal circulation in the bed. However, coarse solid particles cannot be carried to the side bed from the main bed due to the height difference between the beds. The life of embedded tubes can be prolonged since the operating velocity in the side bed is lower than in the main bed, so, the wear of embedded tubes is also lower.

3. 75 t/h pulverized coal-fired boiler

The 75 t/h pulverized coal-fired boiler named DG75/3.82-4 was installed in Suixi cement factory. The device was put into operation in 1996. The designed fuel was category II bituminous coal with a heating value of 18.9 MJ/kg. However, the boiler was forced to close in 2005. The main design parameters of the 75 t/h coal-fired boiler are given in Table 1.

The schematic structure of the 75 t/h pulverized coal-fired boiler is shown in Figure 2. It is a single-drum, natural-circulation, Π-type boiler. The cross section of the furnace is 6240 mm × 11700 mm. The elevation of the drum center is 26500 mm from the floor. The high- and low-temperature superheaters are installed in the horizontal flue gas pass, the economizer and tubular air preheater are located in the back vertical pass of the boiler.

Table. 1. Main design parameters of the 75 t/h coal-fired boiler

Main steam flow rate, t/h	75
Steam pressure, MPa	3.82
Steam temperature, °C	450
Feed water temperature, °C	150
Cold air temperature, °C	20
Hot air temperature, °C	150

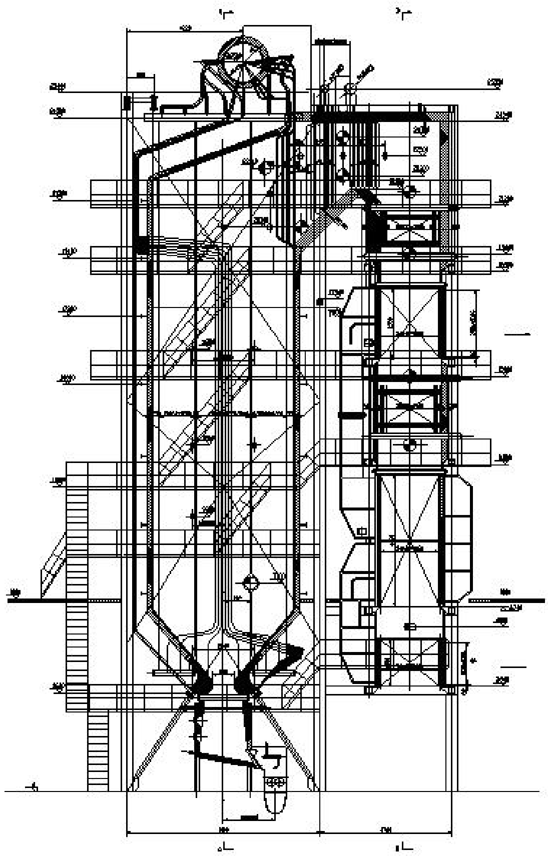

Fig. 2. Schematic structure of the 75 t/h pulverized coal-fired boiler.

4. 65 t/h oil shale-fired high-low bed CFB boiler

4.1. Total design consideration

A revamped CFB boiler with a capacity of 65 t/h of steam was designed according to calculations, taking into account also drawbacks of the structure of the 75 t/h pulverized coal-fired boiler. In the process of the retrofit, the steel frame, basement, and drum of the original boiler could be utilized, but heat surfaces such as water walls, superheater, economizer and air preheater, need to be redesigned. The height of the CFB boiler should remain the same as that of the 75 t/h pulverized coal-fired boiler due to the height limitations of the boiler room. As to parts of the original auxiliary equipment, the coal pulverizing system with a ball mill is not available and needs to be dismantled. For rewamping purposes, another system should be considered, taking into account requirements for the CFB boiler.

4.2. Design fuel

The design fuel is Maoming oil shale. The characteristics of design and check fuels are presented in Table 2.

Table 2. Proximate and ultimate analysis of Maoming oil shale for design

Content	Proximate analysis, wt%				Ultimate analysis, wt%				
	M_{ar}	V_{daf}	A_{ar}	$Q_{ar,net}$, MJ/Kg	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}
Design fuel	16.39	78.93	61.83	5.4	13.38	2.23	5.10	0.46	0.61
Check fuel	18.00	83.07	61.51	4.5	11.86	1.87	5.73	0.38	0.65

4.3. Main design data

Boiler type is named JG-65/3.82-M. In order to meet the requirements for cement production and enviromental protection, the carbon content of the slag discharged from the bottom of the boiler should be lower than 1% and the carbon content of fly ash lower than 2%. It should be ensured that the emissions of SO_2 and NO_x would be lower than 800 mg/m^3 and 200 mg/m^3, respectively.

The main design data of the 65 t/h boiler are shown in Table 3.

Table 3. Main design parameters of the 65 t/h oil shale-fired boiler

Main steam flow rate, t/h	65
Steam pressure, MPa	3.82
Steam temperature, °C	450
Feed water temperature, °C	104
Cold air temperature, °C	20
Hot air temperature, °C	150
Bed temperature, °C	850
Boiler blow-down rate, %	2
Boiler thermal efficiency, %	83.7

4.4. Structural considerations

The schematic structure of the 65 t/h oil shale-fired high-low bed CFB boiler is shown in Figure 3.

1) The furnace is divided into two regions, one is the dense phase zone below the secondary air port and the other is the dilute phase zone above the secondary air port. The high-low bed is situated in the dense phase zone. The embedded tubes are placed in the side bed. Primary air is divided into two parts, one part is fed through the bottom of the air distributor in the main bed and the other in the side bed. The feed of air parts is separately controlled by the respective blower fans. The fluidizing velocity in the main bed is 3–4 m/s and in the side bed, 1.5–2 m/s. The height difference between the two beds is 500 mm.

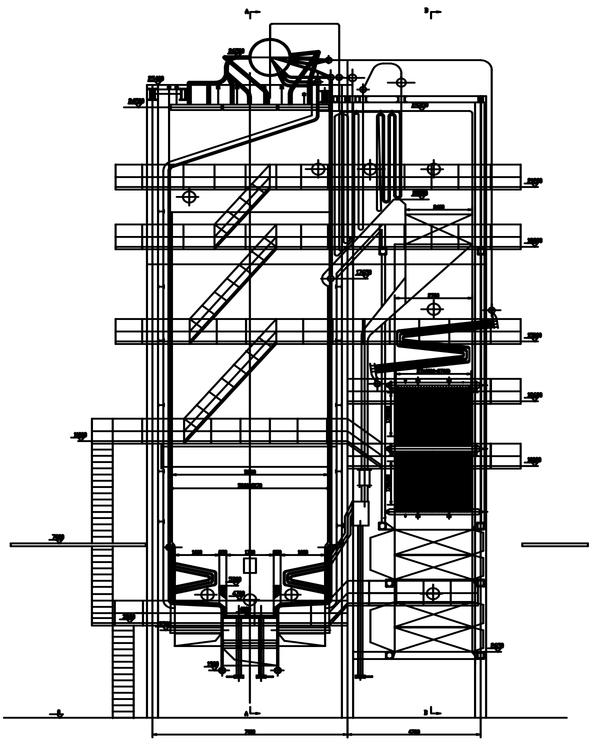

Fig. 3. Schematic structure of the 65 t/h oil shale-fired high-low bed CFB boiler.

2) Instead of smooth tubular water walls of the original 75 t/h coal-fired boiler, the membrane water walls are used around the furnace wall in the dilute zone. The furnace cross-sectional area is 5170 mm × 5800 mm.

3) The high- and low-temperature superheaters are located in the horizontal flue gas pass at the furnace exit. The superheaters are made from seamless steel pipes with a pipe diameter of 42 mm for the high-temperature superheater and 38 mm for the low-temperature superheater. The surface type desuperheater, which ensures steam temperature as high as 450 °C and also prevents superheater pipes from sintering due to deterioration of heat transfer, is located between the two superheaters.

4) A medium-temperature multitubular cyclone is newly designed and is located in the upper part of the back-pass. The U-valve is used to enable the circulation ash separated by the cyclone to return to the furnace. The recirculation ratio of the recycle ash is 5.

5) The back-pass heating surface consists of a steel tube type economizer and air preheater. The economizer is installed in two stages. The tubular air preheater is also mounted in two stages.

4.5. Auxiliary system retrofit

1) New fuel supply systems including fuel drying, crusher, fuel storage bunker and fuel belt conveyor are designed to meet the requirements of the oil shale-fuelled power plant.

2) The limestone supply system is added and limestone is sent to the furnace to realize desulfurization in the bed. The design molar ratio of Ca/S is 2 to reduce the emission of SO_2. In addition, three-layer secondary air ports are located in the front and rear walls to promote combustion in the furnace and to act as a partial combustor to decrease the emission of NO_x. The primary/secondary air proportion is 65/35.

3) A new slag cooler is used to handle oil shale ash drained from the bottom of the boiler. The ash with a temperature of 800–850 °C may be cooled below 150 °C in the cooler.

4) The electrostatic precipitator and bag filter are used together to guarantee an at least 99.95% dust collection efficiency.

5) The original forced and induced draft fans are demolished. New primary/secondary forced draft fans, induced draft fans and recycle fans are installed according to power plant requirements.

5. Evaluation of 65 t/h oil shale-fired high-low bed CFB boiler

Thermal performance tests were carried out in 2006. Four kinds of Maoming oil shale with a heating value 4.1, 4.2, 4.6 and 4.7 MJ/kg, respectively, were used to test and verify the thermal performance of the boiler. The test fuel characteristics are given in Table 4. Compared with the design fuel, the heating values of oil shale used in the tests are lower than that of oil shale in the design. The results of tests on the 65 t/h oil shale-fired CFB boiler based on Chinese National Standard (GB10184-88) are presented in Table 5.

As can be seen from Table 5, the combustion and thermal efficiencies of the boiler satisfy the design requirements. It is feasible to burn oil shale with low heating value, using the high-low bed CFB technology.

Table 4. Proximate and ultimate analysis of Maoming oil shale for testing

Content	Proximate analysis, wt%				Ultimate analysis, wt%				
	M_{ar}	V_{daf}	A_{ar}	$Q_{ar,net}$, MJ/kg	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}
Test fuel 1	18.10	87.33	62.99	4.1	9.70	1.65	6.12	1.08	0.36
Test fuel 2	17.90	85.86	62.73	4.2	10.14	1.67	6.32	1.02	0.22
Test fuel 3	18.62	84.65	61.48	4.6	10.56	1.70	6.45	0.84	0.35
Test fuel 4	18.40	83.52	61.31	4.7	10.86	1.72	6.57	0.76	0.37

Table 5. Main parameters of the 65 t/h boiler under design and test conditions

Item	Design value (Design fuel)	Test value 1 (Test fuel 1)	Test value 2 (Test fuel 2)	Test value 3 (Test fuel 3)	Test value 4 (Test fuel 4)
Main steam capacity, t/h	65	63.3	63.5	74.1	64.55
Steam pressure, MPa	3.82	3.68	3.66	3.70	3.70
Steam temperature, °C	450	440.8	438.7	443.5	441.5
Feed water temperature, °C	104	111.0	111.0	111.0	107.0
Cold air temperature, °C	20	17	17	17	17
Stack gas temperature, °C	150	199.5	197.5	216.7	180.1
Waste heat loss, %	9.18	10.80	10.86	10.87	10.10
Unburned gas loss, %	0.50	0.74	0.84	0.99	0.93
Unburned carbon loss, %	4.04	1.06	0.95	2.19	1.36
Heat leakage, %	0.80	0.80	0.80	0.70	0.90
Thermal loss of bottom ash, %	1.78	2.52	2.42	2.34	1.92
Combustion efficiency, %	95.46	98.20	98.21	96.82	97.71
Thermal efficiency, %	83.70	84.07	84.13	82.90	84.80

6. Conclusions

The high-low bed CFB combustion technology was first applied to burning oil shale. The 75 t/h pulverized coal-fired boiler was successfully revamped to the 65 t/h high-low bed CFB oil shale-fired boiler. The rewamped boiler was put into operation in 2006 and has been functioning without failure since then. The operation results indicate that the boiler can meet the needs of electric power generation and requirements for ash utilization. The design and operation experience with the 65 t/h oil shale-fired high-low bed CFB boiler may provide a technical foundation for developing a large-scale oil shale-fired CFB boiler.

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