

# Efficiency improvement of the hot blast generating system by waste heat recovery

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## Abstract

To meet the increasing demand for energy saving and sustainable CO<sub>2</sub> reduction, a heat-pipe heat exchanger has been applied in the hot blast generating system to recover the flue gas sensible heat for the purpose of fuel gas preheating. In this paper, the performance evaluation method for the hot blast generating system is proposed and used to investigate the fuel gas preheating effect on the system's thermal efficiency. Experimental observation revealed that 3.1% of the efficiency improvement was achieved by the application of waste heat recovery. Accordingly, the energy consumed to enhance the blast air temperature was diminished by 0.115 kJ/°C-Nm<sup>3</sup>. In addition to energy saving, the fuel gas preheating also led to the reduction of the enrichment gas depletion rate. Based upon the field test results, the records indicated that the implementation of the flue gas heat recovery scheme in the hot blast generating process resulted in a saving of fuel consumption by 822 l/h on an oil equivalent basis. The benefits of energy saving over 1.9 million US dollars and the CO<sub>2</sub> reduction 15,000 tons can be achieved annually.

*Keywords:* waste heat recovery, hot stove, energy saving, thermal efficiency.

## 1 Introduction

Hot stoves are thermal regenerators applied to produce hot blast air in blast furnace iron making process. In China Steel Corporation, the hot blast air generating system for the No.2 Blast Furnace consists of four hot stoves. Each stove is operated alternatively with on-gas and on-blast cycles to deliver stable hot blast air flow to blast furnace under specific conditions. During the on-gas



cycle, the fuel is burned in the combustion chamber to heat up the refractory bricks. The main fuel used for hot stove combustion is the Blast Furnace Gas (BFG), which is enriched with Coke Oven Gas (COG) in order to get the required brick temperature. With the completion of the on-gas cycle, the system proceeds to the stove change stage to purge the flue gas. Thereafter, it switches to the on-blast cycle. The on-blast cycle is the hot blast generating cycle, in which, the heated refractory bricks serve as the heat source to enhance the temperature of the cold blast air that is blown through the hot stove. The process flow diagram is illustrated in Fig. 1.

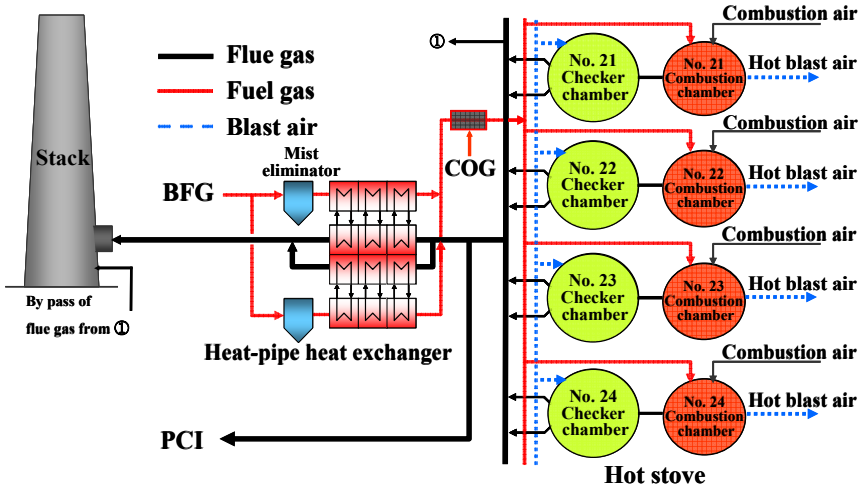


Figure 1: Process flow diagram of the hot blast air generating system.

The flue gas exhausted from the hot stoves is approximately 250,000 Nm<sup>3</sup>/h at a temperature of around 260°C. According to the original engineering design, around 20% of the flue gas was recycled to the Pulverized Coal Injector (PCI) for coal preheating, and the remaining part of the flue gas was discharged to the atmosphere via the stack. To increase the process energy efficiency, a waste heat recovery scheme has been implemented to recover the flue gas sensible heat by a heat-pipe heat exchanger.

Heat-pipe heat exchanger plays an important role in enhancing the performance of various industrial processes [1–3] for different kinds of purposes. In this heat recovery plan, the recovered energy is utilized to preheat the fuel gas used for hot stove combustion. The main purposes are to improve the thermal efficiency of the system as well as to reach the sustainable CO<sub>2</sub> emission reduction throughout the hot blast generating process. In this work, the performance of the heat-pipe heat exchanger is analyzed and the efficiency improvement of the hot blast air generating system by waste heat recovery is investigated. Moreover, the benefits of energy saving and CO<sub>2</sub> reduction by operation of the heat recovery system are explored.

## 2 Waste heat recovery system

Fig. 2 illustrates the schematic diagram of the heat-pipe heat exchanger, which is categorized as a counter-flow gas-to-gas heat exchanger consisting of two ducts with a common wall. The evaporation section of the heat pipes is arranged in the lower duct for the exhausted flue gas to flow through, and the condensation section of the heat pipes is arranged in the upper duct for the BFG to flow through. With the joint operation of the heat-pipe heat exchanger, the flue gas exhausted from the hot stoves is fed into the heat-pipe heat exchanger before discharging to the atmosphere via the stack. This system is composed of 5520 heat pipes arranged in 92 rows. The detailed physical parameters are presented in Table 1.

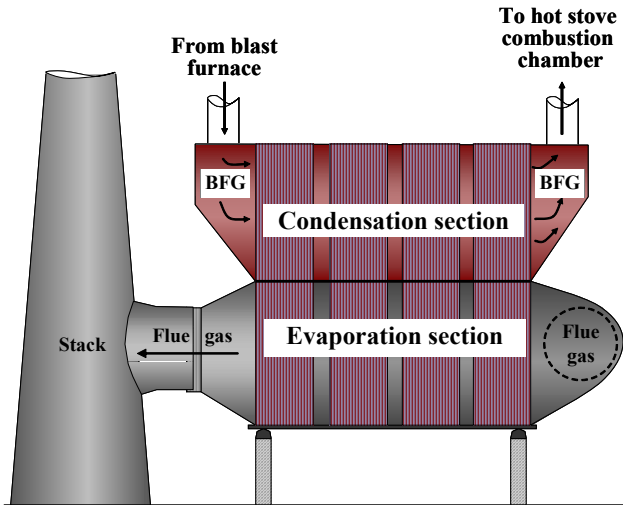


Figure 2: Schematic diagram of the heat-pipe heat exchanger.

Table 1: Physical parameters of the heat-pipe heat exchanger.

Physical dimension	10,525 mm×6,000 mm×8,540 mm
Physical dimension of single heat pipe	Ø54 mm × 9643 mm
Tube bundle arrangement	Inline
Total number of heat pipes	5,520
Pitch(Traverse / Longitudinal)	67.5 mm / 67.5 mm
Working fluid	Water

## 3 Results and discussion

Experiments were carried out in the hot stoves of the No.2 Blast Furnace in CSC to explore the waste heat recovery effect on the efficiency of the hot blast generating process. In order to get further insight into the energy recycling

process, the field performance of the heat-pipe heat exchanger is firstly investigated. Then, the performance evaluation method for the hot blast generating system is proposed and used to analyze its efficiency under various operation conditions. Finally, the annual benefits of energy saving and CO<sub>2</sub> reduction by operation of the heat recovery system are explored

**3.1 Performance of the heat recovery system**

The hot blast generating system is operated with four hot stoves. In general, they are operated with fixed cycle time. The cycle time for the on-gas and on-blast cycle is 50 and 60 minutes, respectively. The period for stove change is around 10 minutes. To keep stable hot blast air supply to blast furnace, the system is controlled in a way that two of the four hot stoves are in the on-blast operation mode all the time. Correspondingly, three typical operation conditions were selected and presented in Table 2 to investigate the relation between flue gas head load and heat recovery performance of the heat-pipe heat exchanger.

Table 2: Performance test results of the waste heat recovery system.

Operation condition		1	2	3
Flue gas	Volume flow rate(Nm <sup>3</sup> /h)	141,016	201,190	253,582
	Density (kg/m <sup>3</sup> )	1.43	1.43	1.43
	Specific heat (kJ/kg-K)	1.05	1.05	1.05
	Inlet temperature(°C)	261	263	264
	Outlet temperature (°C)	132	123	124
	Flue gas sensible heat(kW)	13,851	19,988	25,035
BFG	Volume flow rate(Nm <sup>3</sup> /h)	81,429	144,791	175,291
	Density (kg/m <sup>3</sup> )	1.36	1.35	1.36
	Specific heat (kJ/kg-K)	1.04	1.04	1.04
	Inlet temperature(°C)	24	21	22
	Outlet temperature (°C)	240	226	223
	Heat recovery rate(kW)	6,894	11,548	13,864
Heat recovery efficiency (%)		49.8	57.8	55.4

The definitions for heat recovery rate and heat recovery efficiency [4] calculated in Table 3 are defined in Equation (1) and Equation (2).

$$\text{Heat recovery rate (kW)} = \dot{m}_{\text{BFG}} \times c_{p,\text{BFG}} \times (T_{\text{BFG,out}} - T_{\text{BFG,in}}) \quad (1)$$

$$\text{Heat recovery efficiency (\%)} = \frac{\dot{m}_{\text{BFG}} \times c_{p,\text{BFG}} \times (T_{\text{BFG,out}} - T_{\text{BFG,in}}) \times 100}{\dot{m}_{\text{FLUE}} \times c_{p,\text{FLUE}} \times (T_{\text{FLUE,in}} - 273.15)} \quad (2)$$



Table 2 depicted the heat recovery rate increased with an increase of the flue gas sensible heat within the test conditions. However, the outlet temperatures of the BFG showed an opposite trend. In accordance with the energy conservation relation between the BFG and flue gas, the temperature enhancement of the BFG is proportional to the energy that is absorbed by per unit volume of BFG. For operation condition 1, 2 and 3, it was 305.5 kJ/Nm<sup>3</sup>, 287.1 kJ/Nm<sup>3</sup> and 284.7 kJ/Nm<sup>3</sup>, respectively. Therefore, the outlet temperatures of the BFG decreased with an increase in the heat load supplied from the flue gas. Regarding the heat recovery efficiency, Table 2 indicated that it first increased from 49.8% to 57.8% when flue gas sensible heat increased from 13,851 kW to 19,988 kW, then it decreased slightly to 55.4% when the flue gas sensible heat further increased to 25,035 kW. The phenomena implicated that the heat-pipe heat exchanger could be operated in a higher efficiency when the heat load is close to 20,000 kW.

### 3.2 Thermal efficiency of the hot blast air generating process

The thermal efficiency of the hot blast air generating system is defined as the ratio of net energy increase in the blast air and the energy fed into the hot stoves. The total energy fed into the hot stoves is the sum of the chemical energy of the fuel gas (BFG enriched with COG) and the sensible heat of the fuel gas and the combustion air. The calculation formulae [5, 6] can be expressed as follows.

$$\eta_{TH} = \frac{\dot{Q}_{BA}}{\dot{Q}_{BFG} + \dot{Q}_{COG} + \dot{Q}_{cair}} \quad (3)$$

$$\begin{aligned} \dot{Q}_{BA} = & \dot{m}_{HB} \cdot (C_{p,air} \cdot T_{HB} - C_{p,air} \cdot T_{CB}) \\ & + \dot{m}_{HB} \cdot \frac{AH}{\rho_{H_2O}} (C_{p,H_2O} \cdot T_{HB} - C_{p,H_2O} \cdot T_{CB}) \end{aligned} \quad (4)$$

$$\dot{Q}_{BFG} = \dot{m}_{BFG} \cdot H_{BFG} + \dot{m}_{BFG} \cdot C_{p,BFG} \cdot T_{BFG} \quad (5)$$

$$\dot{Q}_{COG} = \dot{m}_{COG} \cdot H_{COG} + \dot{m}_{COG} \cdot C_{p,COG} \cdot T_{COG} \quad (6)$$

$$\dot{Q}_{cair} = \dot{m}_{air} \cdot (C_{p,air} + \omega \cdot C_{p,H_2O}) \cdot T_{cair} \quad (7)$$

Table 3 presented the field test results of the hot blast generating system at two different operation conditions, CASE 1 and CASE 2. The duration for each test was 24 hours. The hot blast outlet temperature was set to be 1155°C for both cases. The main purpose of the tests was to explore the fuel gas preheating effect on the thermal efficiency of the hot blast generating system. As shown in



Table 3, the inlet temperature of the BFG was 30°C in CASE 1, in which the waste heat was not recycled in the hot blast generating process. With the operation of the heat-pipe heat recovery system, the BFG was preheated to 231°C in CASE 2. Under this operation condition, 12,542 kW of the hot stove waste heat was recovered through the heat recovery system.

Based on the formulae described above, the calculations depicted the process efficiency of the entire hot blast generating system for CASE 1 and CASE 2 was 75.6% and 78.7%, respectively. This result revealed that the energy consumed in the generating process to enhance the blast air temperature decreased from 2.008 kJ/Nm<sup>3</sup>-°C to 1.893 kJ/Nm<sup>3</sup>-°C, indicating that the energy saving achieved by fuel gas preheating was 0.115 kJ/Nm<sup>3</sup>-°C.

Table 3: Field performance of the hot blast generating system.

Item		CASE 1	CASE 2	
Operational conditions	Environment temperature(°C)	29	20	
	Blast air volume flow rate (Nm <sup>3</sup> /hr)	299,134	302,142	
	Inlet temperature(°C)	230	219	
	Outlet temperature(°C)	1,155	1,155	
	Combustion air volume flow rate (Nm <sup>3</sup> /hr)	129,780	112,802	
	COG temperature(°C)	40	30	
	COG volume flow rate (Nm <sup>3</sup> /hr)	8,827	2,671	
	COG low heating value (kJ/Nm <sup>3</sup> )	16,765	17,673	
	BFG temperature	30	231	
	BFG volume flow rate (Nm <sup>3</sup> /hr)	123,116	147,826	
	BFG low heating value (kJ/Nm <sup>3</sup> )	3,224	3,255	
	Relative humidity of the atmosphere (%)	83	72	
	Absolute humidity of the blast air (g/Nm <sup>3</sup> )	27	16	
Performance analysis	Energy input	Sensible heat (kW)	2,943.4	1,956.8
		Chemical energy (kW)	151,351.2	146,750.4
	Hot blast sensible heat (kW)	116,664.4	117,104.2	
	Efficiency (%)	75.6	78.7	

In addition to energy saving, the change in BFG and COG depletion rates indicated that the fuel gas preheating also led to the reduction of the enrichment gas consumption. In CASE 2, only 8.9% of the energy supplied to the hot stoves was contributed by the COG, whereas it was 27.2% in CASE 1.

A parametric study by varying the hot blast outlet temperatures was made to examine the operation characteristics of the system under various hot blast temperature levels. The temperature range of the tests was between 1130°C to 1155°C. As shown in Fig. 3, the calculation results depicted that the thermal efficiency of the hot blast generating system kept above 78% with the operation of the waste heat recovery system.



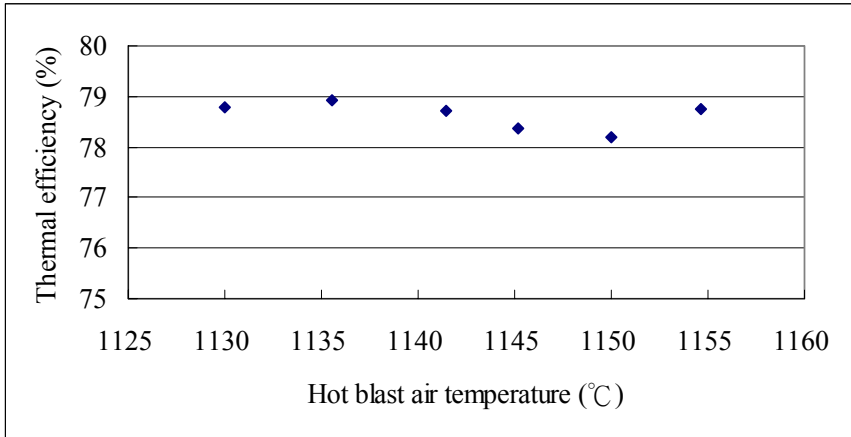


Figure 3: Thermal efficiency of the hot blast generating system at various hot blast air temperatures.

### 3.3 Energy saving and CO<sub>2</sub> reduction

In accordance with the operation records, the major difference observed in operation conditions was the fuel gas consumption rate of the hot stoves. Furthermore, to overcome the additional pressure loss and maintain the same BFG feeding pressure for hot stove combustion, the top pressure recovery turbine, the TRT, power generation rate was reduced. Table 4 summarized the breakdown of energy savings and CO<sub>2</sub> reduction per year. The economic evaluations were referred to US dollars. These calculations were performed based on the following assumptions:

1. Oil price: 0.34 USD/ l
2. Cost of electricity: 0.045 USD/kWh
3. CO<sub>2</sub> emission conversion factors: 0.66 kg/kWh
4. Operation hours: 7,884 h/year
5. Hot blast air outlet temperature: 1,155°C.

As presented in Table 4, the advantage of operating the heat recovery system is evident in the fuel consumption reduction by 822 l/h on an oil equivalent basis. However, the TRT power generation rate was reduced by 621 kW and some additional power needed to be consumed for fan operation. The total economic benefits for energy saving can exceed 1.9 million US dollars per year. In the mean time, the CO<sub>2</sub> emission can have a reduction of 15,254 ton/year.

Table 4: Annual energy saving and CO<sub>2</sub> reduction analyses.

Items	Operation conditions		Benefits	
	Before	After	Savings (USD /year)	CO <sub>2</sub> reduction (ton/year)
Fuel consumption in oil equivalent basis (l/h)	14,393	13,571	2,178,278	19,115
TRT power generation (kW)	10,688	10,067	-219,518	-3,230
Additional power consumption (kWh/year)	-	956,081	-42,879	-631
Total			1,915,881	15,254

## 4 Conclusion

Waste heat recovery is an efficient way to reach the aim of energy saving and CO<sub>2</sub> emission reduction through the energy recycling process. In this article, the effect of fuel gas preheating on the thermal efficiency of the hot blast generating system is investigated. Experimental results revealed that the efficiency of the hot blast generating process was increased from 75.6% to 78.7%. Accordingly, the energy spent for producing the hot blast air decreased by 0.115 kJ/Nm<sup>3</sup>-°C. In the meantime, the fuel gas preheating led to the reduction of the enrichment gas consumption. According to the test results, the advantage of operating the heat recovery system was evident in the reduction of fuel gas depletion rate by 822 l/h on an oil equivalent basis. The annual energy saving over 1.9 million US dollars and the CO<sub>2</sub> reduction 15,000 ton/year can be achieved.

## Nomenclature

AH: Absolute humidity of the blast air (g/Nm<sup>3</sup>)

$C_p$ : Specific heat, (kJ/ kg- K)

H: Low heating value of the fuel gas (kJ/kg)

$\dot{m}$ : Mass flow rate, (kg/h)

$\dot{Q}$ : Energy flow, (kJ/h)

T: Temperature (°C)

$\rho$ : Density (g/Nm<sup>3</sup>)

$\omega$ : Humidity ratio of the combustion air(kg/kg).





## Subscripts

Air: Combustion air  
BA : Blast air  
BFG: Blast furnace gas  
CB: Cold blast air  
COG: Coke oven gas  
FLUE: Flue gas  
HB: Hot blast air  
In: Inlet condition  
Out: Outlet condition.

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