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RESEARCH ON APPLICATION OF HEAT OF BLAST FURNACE SLAG WATER IN MULTI-EFFECT DESALINATION

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ABSTRACT

The iron and steel industry produces a large number of low-grade waste heat resources, which are not fully utilized. In addition, the iron and steel industry consumes a lot of water. This paper presents a method of utilizing waste heat of blast furnace slag flushing water for seawater desalination. After the flash process, heat exchange process and heat repair process, the blast furnace slag water was converted into steam which is 70 °C, which provided a heat source for MED (Multi-effect Desalination). This utilization method of waste heat was verified by thermodynamics and production data.

Keywords: *Slag flushing water, Water flashed, Heat exchange*

1. INTRODUCTION

The blast furnace produces iron melt and blast furnace slag at about 1500 °C. At present, the main method to deal with the slag is the water quenching method. This process produces a large amount of blast furnace slag flushing water with low-grade heat energy. The temperature of slag flushing water is about 70-90 °C. Waste heat is generally used to heat the houses in winter in China, but the utilization way is also limited by geographical conditions and seasonal factor (Gao *et al.*, 2011). In addition, other utilization ways of slag flushing water had been explored. Meng et al. (2014) investigated the thermoelectric power generation technology to recover the heat of blast furnace slag flushing water. Xiong et al. (2014) established a physical and numerical model of two-stage thermoelectric energy harvesting driven by waste heat of blast furnace slag flushing water. Wang et al. (2012) proposed a dual-loop organic Rankine cycle for recovering waste heat of blast furnace slag flashing water.

Iron and steel enterprises consume a lot of water. According to China Steel Yearbook, the water consumption per ton of iron and steel was 3.75 m3 in 2012. In order to deal with this problem, some coastal iron and steel enterprises want to explore seawater desalination. At present, the large-scale desalination methods applied in the production are multi-effect distillation (MED) based on thermal technologies and reverse osmosis (RO) (Elmekawy, 2014), those methods need a large number of heat sources. Mathioulakis et al. (2007) and Garcia-Rodriguez (2003) summarized the utilization of heat sources in desalination technologies. Among them, MED can utilize various forms of low-grade waste heat. At present, the heat source mainly comes from steam pumped out of the steam turbine, cooling water of a diesel engine (Zhang *et al.*, 2017), geothermal energy (Wang *et al.*, 2018), thermal solar energy (Zeaiter *et al.*, 2018; Sharaf *et al.*, 2011), other low-grade heat (Wang *et al.*, 2011), and the heat from heat pumps (Alarcón-Padilla, and García-Rodríguez, 2007).

This paper presents a utilization method of waste heat of blast furnace slag flushing water for MED. According to this method, iron and steel enterprises in coastal areas can not only make full use of low-grade waste heat, but also solve their water source problem.

The rest of the paper is organized as follows. Section 2 presents the main process of the whole system and thermodynamic analysis. Section 3 presents production data analysis of the flash process and heat exchange process.

2. PROCESS DESCRIPTIONS

2.1. Main-process Introduction

Fig. 1 shows the method that MED is powered by waste heat of blast furnace slag flushing water. High-temperature slag passed through the slag groove into the slag nozzle and was then turned into tiny particles after water quenching. This process produces a lot of steam. The water mixture passed through the spiral cage machine and drum filter. After separating slag and water, the water entered the bottom filter. Subsequently, slag flushing water was pumped into the flash chamber at all levels in flash tank. Due to the low-pressure environment in the flash chamber, slag flushing water was converted into low-pressure steam. These steam entered the corresponding steam water exchanger to heat clean water. Clean water absorbed the heat of the steam and the temperature of the clean water increased above 70 °C. It could also absorb the heat of the steam and low-temperature flue gas in the heat exchanger. After then, clean water entered another flash tank which has more than three levels.The steam above 70 °C in the first stage was directly fed into the gas collecting tank. Steam below 70 °C at other levels was sent into the gas collecting tank after heating. Steam in the gas collecting tank served as the heat source of multi-effect distillation. A clean water source was provided for the whole system by mixing the low temperature clean water discharged from the flash tank with complementary water. It could be preheated by utilizing the waste heat of slag flushing steam condensate. Slag flush steam condensate water,

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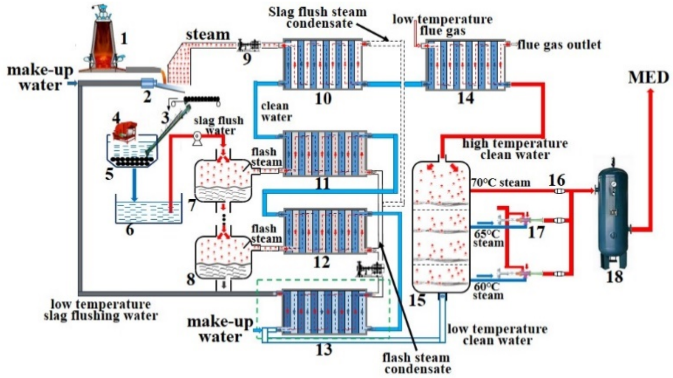
slag flushing water and complementary water was mixed together and then returned to the slag flushing nozzle for cyclic utilization. The main process is as shown in Fig. 1.



1-blast furnace 2-slag flushing nozzle 3-spiral cage machine 4-drum filter 5-cage pool 6-bottom filter 7,8-flash chamber 9-booster pump 10,11,12-steam water heat exchanger 13-water and water heat exchanger 14-gas water heat exchanger 15-flash tank 16-supercharger 17-ejector 18-gas collecting tank

Fig. 1 Schematic diagram of desalination equipment powered by waste heat of blast furnace slag flushing water

The whole process could be divided into four parts: slag flushing process, flash process, heat exchange process, and heat supply process. The slag flushing process, flash process and heat exchange process are described below in detail.

2.2. Slag Flushing Process

Blast furnace is one of the most important equipment in iron and steel production. When the iron was produced in blast furnace, slag (about 1400~1500 °C) was produced at the same time. The treatment of slag mainly involved dry granulation, chemical treatment process and water quenching. Among them, water quenching is the main process for slag treatment in China. Water quenching methods mainly include INBA, TYNA, OCP, and RASA. The study was mainly based on the existing equipment of Shougang Jingtang Company.

The slag of blast furnace entered the slag flushing nozzle through the slag groove, and high-speed water flow from the slag nozzle quenched the molten slag to form granulated slag. Slag water passed through the slag groove through the condensing tower and was then transported to the stirring cage pool. Slag and water were separated by the spiral cage machine in the stirring cage pool. The slag fell on the slag belt conveyor through the chute and was then transported to the slag heap. Slag flushing water was filtered in the stirring cage pool and then overflowed into the bottom pool for further use.

Table 1 The water quality report.

Component	*Unit*	*Value*	*Component*	*Unit*	*Value*
pH	-	8.72	Na^+	mg/L	84.30
Saltness	mg/L	2260	NO_3^-	mg/L	22.66
Carbonate hardness	mg/L	62.99	SO_4^{2-}	mg/L	1078.02
Alkalinity	mg/L	441.69	Al^{3+}	mg/L	0
CODcr	mg/L	5.81	SiO_2	mg/L	14.4
Suspended matter	mg/L	147.5	Mg^{2+}	mg/L	61.83
Hardness	mg/L	446	Cl^-	mg/L	500.75
Calcium stiffness	mg/L	75.35	PO_4^{3-}	mg/L	0.74
Phenolphthalein alkalinity	mg/L	26.27	Cu^{2+}	mg/L	0.044
Total iron	mg/L	0.076			

The water quality of blast furnace slag flushing water is complex. It can be seen from the naked eye that blast furnace slag flushing water was pale yellow and contained many suspended particles. The water quality is provided in Table 1.

The slag flushing process is generally a periodic process. The variation of slag water temperature could be divided into four stages. In the first stage, the temperature of slag water reduced from 80 °C to 70 °C because of mixing with low-temperature make-up water. In the second stage, the water impact the slag, and the temperature of slag water increased from 80 °C to 90 °C and the temperature was stable at 90 °C for a period. In the third stage, the temperature of slag water dropped from 90 °C to 80 °C when the water and slag were separated. In the last stage, the temperature stayed at 80 °C when the water is in bottom filter.

The slag flushing process of blast furnace was a periodic process, so we could study the energy flow in one cycle. Energy inflows included the physical heat brought by slag (Q_s), the physical heat of supplementary water (Q_{sw}), and the physical heat brought by circulating water (Q_{cw}). Energy outflows included the physical heat of slag ($Q_{s'}$), the heat of slag flushing steam ($Q_{fs'}$), the physical heat of circulating water ($Q_{cw'}$), heat dissipation capacity of slag pool wall ($Q_{w'}$), and evaporation heat of slag pool surface ($Q_{e'}$). Due to the energy balance, we can get the relationship as the equation (1).

$$Q_s + Q_{sw} + Q_{cw} = Q_s' + Q_{fs}' + Q_{cw}' + Q_w' + Q_e' \tag{1}$$

The parameters in equation (1) can be solved by equation (2)-(8).

$$Q_s = c_s m_s T_s \tag{2}$$

$$Q_{sw} = c_{sw} m_{sw} T_{sw} \tag{3}$$

$$Q_{cw} = c_{cw} m_{cw} T_{cw} \tag{4}$$

$$Q_w' = h_w' A_w' \left(T_w' - T_0' \right) \tag{5}$$

$$Q_{cw}' = c_{cw}' m_{cw}' T_{cw}' \tag{6}$$

$$Q_{cw}' = c_{cw}' m_{cw}' T_{cw}' \tag{7}$$

$$Q_e = \left(4.05 + 9V_{wind} \right) p_a A_{sur} \tag{8}$$

Where P_a refers to the water vaporization pressure corresponding to the temperature of the pool water in equation (8).

The temperature and flow of slag steam were not easily measured, so the heat of slag steam could be calculated based on the energy balance.

$$Q_{fs}' = Q_s + Q_{sw} + Q_{cw} - \left(Q_s' + Q_{cw}' + Q_w' + Q_e' \right) \tag{9}$$

We can also calculate heat efficiency of slag flushing by equation (10).

$$\eta_{sf} = \frac{Q_{cw}' - Q_{cw} - Q_{sw}}{Q_s} \times 100\% \tag{10}$$

2.3. Flash Process

In this paper, blast furnace slag water should be flashed into steam because the slag water has impurities and corrosiveness. High-pressure saturated liquid entered a relative low pressure container. Due to the sudden pressure drop, saturated liquid was changed into saturated vapor and saturated liquid under the vessel pressure. This process is called the flash process.

Slag water at 70 °C entered the flash chamber. Due to vacuum conditions, the boiling point of slag water was reduced. Slag water in the flash chamber was flashed into steam. The series in flash tank was selected based on the production demands. The flash chamber was nearly vacuum. Compared with slag water, steam had the less corrosiveness, so it could be exchanged with clean water in a steam water heat exchanger.

Through the heat exchange, obtained clean water was about 75 °C. In order to provide the heat source for desalination, we used the flash tank

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to change clean water into steam. By setting different pressure of each flash chamber, we can get the steam from the three flash chambers at 70°C, 65°C, and 60°C, respectively.

In this section, we mainly discussed the flash chamber where slag flushing water was flashed into steam. Since slag water was corrosive, it was necessary to flash it into steam and the steam was exchanged with clean water for heat exchange. According to the inlet temperature and outlet temperature of clean water, the pressure of the flash chamber at all levels could be determined. For each flash chamber, the energy inflows mainly include the heat of slag water flowing into the flash chamber (Q_{sw}). The energy outflows mainly include the heat of slag water flowing out of the flash chamber ($Q_{sw'}$), the heat of steam ($Q_{fls'}$) and the heat loss ($Q_{l'}$). The energy balance equation is formulated as equation (11).

$$Q_{sw} = Q_{sw}' + Q_{fls}' + Q_l' \tag{11}$$

The parameters in equation (11) can be solved by equation (12-14). The heat loss ($Q_{l'}$) can be calculated by equation (11).

$$Q_{sw} = c_{sw} m_{sw} T_{sw} \tag{12}$$

$$Q_{sw}' = c_{sw}' m_{sw}' T_{sw}' \tag{13}$$

$$Q_{fls}' = m_{fls}' \left(h_{g,fls} - h_{liq,fls} \right) \tag{14}$$

The thermal efficiency of each flash chamber is formulated as equation (15).

$$\eta_{fc} = \frac{Q_{fs}'}{Q_{sw}} \times 100\% \tag{15}$$

2.4 Heat Exchange Process

As shown in Fig. 1, each flash chamber corresponds to a steam water heat exchanger, where the latent heat of steam is used to preheat the clean water. The plate heat exchanger was used in this study. Compared with other types of heat exchangers, the plate heat exchanger had the high heat transfer efficiency, compact structure, small heat loss, and good heat exchange effect in liquid-liquid and gas-liquid exchange.

In this section, we mainly discussed the thermodynamic problems in the steam and water heat exchanger for heat exchange between steam and clean water. The energy inflows mainly include the heat of steam (Q_{fls}) and the heat of clean water inlet temperature (Q_{clw}). The energy outflows mainly include the heat of steam condensate (Q_{fsc}'), the heat of clean water outlet temperature (Q_{clw}') and the heat loss (Q_l'). The energy balance equation is formulated as equation (16).

$$Q_{fls} + Q_{clw} = +Q_{fsc}' + Q_{clw}' + Q_l' \tag{16}$$

The parameters in equation (16) can be solved by equation (17)-(20). The heat loss (Q_l') can be calculated by equation (16).

$$Q_{fls} = m_{fls} h_{g,fls} \tag{17}$$

$$Q_{clw} = c_{clw} m_{clw} T_{clw} \tag{18}$$

$$Q_{fsc} = c_{fsc}' m_{fsc}' T_{fsc}' \tag{19}$$

$$Q_{clw}' = c_{clw}' m_{clw}' T_{clw}' \tag{20}$$

The heat exchanger also satisfies equation (21). In this equation, we can calculate the thermal efficiency of each flash chamber.

$$\eta_{he} c_{fls} m_{fls} \left(T_{fls} - T_{fls}' \right) = c_{clw} m_{clw} \left(T_{clw}' - T_{clw} \right) = k_{he} A_{he} \frac{\left(T_{fls} - T_{clw}' \right) - \left(T_{fls}' - T_{clw} \right)}{\ln \left(T_{fls} - T_{clw}' \right) / \left(T_{fls}' - T_{clw} \right)} \tag{21}$$

3. PRODUCTION DATA ANALYSIS

We observed the production of the flash process and heat exchange process according to the non-dotted frame in Fig. 1. The thermodynamic parameters of each material are shown in Table 2.

Table 2 Thermodynamic parameters for flash and heat exchange process.

Symbol	*Parameter*	*Unit*	*Value*
T_s	Temperature of blast furnace	℃	1400.00
m_s	Flow of blast slag	t/h	128
T_{sw}	Temperature of slag flushing water	℃	83.40
m_{sw}	Flow of slag flushing water	t/h	153.60
p_1	Pressure of the first flash chamber	Mpa	0.04
p_2	Pressure of the second flash chamber	Mpa	0.03
p_3	Pressure of the third flash chamber	Mpa	0.02
T_{sw}'	Temperature of slag flushing water at outlet of flash tank	℃	57.70
m_{sw}'	Flow of slag flushing water at outlet of flash tank	t/h	148.02
$T_{cl,i}$	Temperature of clean water at inlet	℃	27.10
T_{cl3}	Temperature of clean water at outlet of third heat exchanger	℃	52.70
T_{cl2}	Temperature of clean water at outlet of second heat exchanger	℃	68.00
T_{cl1}	Temperature of clean water at outlet of first heat exchanger	℃	74.30
m_{cl}	Flow of clean water	t/h	66.3

In this model, the two assumptions are made as follows:

(1) The steam generated by each flash chamber is saturated steam under the pressure of the flash chamber.

(2) The latent heat of the steam is used to heat clean water.

Then, the temperature and flow rate of steam in each flash chamber can be obtained. The value of thermodynamic parameters of steam is shown in Table 3.

Table 3 Thermodynamic parameters of steam which produced by water flashed

Symbol	*Parameter*	*Unit*	*Value*
T_1	Temperature of steam in first flash chamber	℃	75.87
T_2	Temperature of steam in second flash chamber	℃	69.10
T_3	Temperature of steam in third flash chamber	℃	60.07
m_1	Flow rate of steam in first flash chamber	t/h	0.75
m_2	Flow rate of steam in second flash chamber	t/h	1.82
m_3	Flow rate of steam in third flash chamber	t/h	3.01

From the production data and thermodynamic parameters of steam, we can make a thermodynamic analysis of the flash process (Table 4). The gas production rate is the ratio of steam mass to total water mass.

Table 4 Thermodynamic analysis of flash process

Symbol	*Parameter*	*Unit*	*Value*
η_{fc}	The thermal efficiency of the flash process	-	24.43 %
m_{fls}	Gas production	t/h	5.58
λ	Gas production rate	-	3.63%

In the production process, after flash process and heat exchange process, slag water transferred the heat to clean water, which was heated to 74 °C. Clean water could be flashed and heated to form steam at 70 °C, thus providing a heat source for desalination.

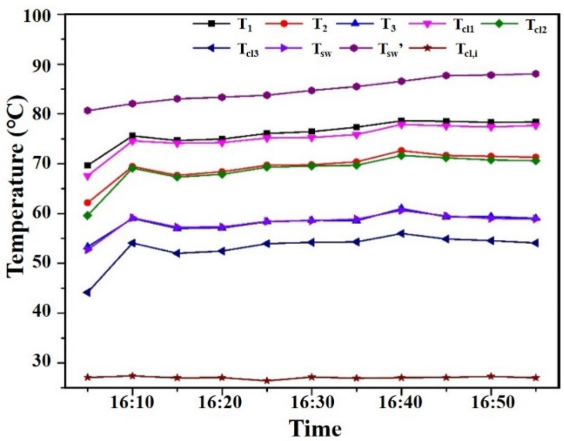

Fig. 2 temperature diagram for each point in the flash and heat exchange process

Fig. 2 shows a temperature change diagram for each point in the flash process and heat exchange process for a period of time. The implications of the illustrations (T_1 to $T_{cl,i}$) are shown in Table 2 and Table 3.

According to Fig. 2, the temperature of steam is approximately equal to the temperature of slag flushing water in the same flash chamber. Due to the heat exchange, the temperature of steam was approximately equal to the temperature of clean water in the first and second chambers. The temperature of steam was not equal to the temperature of clean water in the third chamber. The clean water at 27 °C could be heated to 70 °C with steam.

4. CONCLUSION

This paper presents a utilization method of waste heat of blast furnace slag flushing water for MED. Based on the above discussion, the conclusions can be drawn as follows:

(1) The whole system could be implemented based on the results of theoretical analysis and production verification.

(2) According to the production results, when the temperature of clean water at inlet was 27.1 °C and the temperature of slag flushing water was 83.4 °C, the temperature of clean water at outlet reached 74.3 °C. The gas production rate reached 3.63% and the thermal efficiency of the flash process was 24.43%.

NOMENCLATURE

Abbreviations

A	heat transfer area (m^2)
c	heat capacity (kJ/kg·°C)
h	enthalpy (kJ/kg)
k	heat transfer coefficient (W/m^2·°C)
m	flow rate (t/h)
MED	multi-effect distillation
MSF	multi-stage flash distillation
p	pressure (p_a)
Q	heat load (kW)
RO	reverse osmosis
T	temperature (°C)
V	velocity (m/s)

Greek letters

η	thermal efficiency
λ	gas production rate

Subscripts

cw	circulating water
clw	clean water
e	evaporation heat of slag pool surface
fc	flash process
fls	steam which produced by water flashed
fs	flushing steam
fsc	steam condensate
he	heat exchange process
i	inlet
l	heat loss
s	slag
sf	slag flushing process
sur	slag pool surface
sw	supplementary water
w	slag pool wall

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