Development of waste heat recovery technology from steel slag

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Abstract. The temperature of molten steel slag produced by the steelmaking process is 1500℃~1700℃, and the total amount of energy contained is considerable. Therefore, the efficient recovery and utilization of sensible heat of steel slag has always been the focus of attention of the metallurgical field all over the world. However, at present, the average recovery rate of waste heat resources per ton of steel in China's iron and steel industry is less than 26%, while the sensible heat recovery rate of various molten slag (including steel slag) is only 1.6%. There are huge room and a broad market for improvement.

1. Introduction

In the steelmaking process, the discharge of steel slag is about 10%~15% of the steel output. In recent years, China's steel industry has developed rapidly. In 2021, China's crude steel output is 1.03 billion tons, accounting for 53% of the global total. With the development of the iron and steel industry, the output of steel slag is also increasing year by year. In 2021, the output of steel slag is about 150 million tons. In terms of sensible heat recovery and utilization of steel slag, there are no application examples in the world. The main reason is that the technology is still immature. Therefore, accelerating the research and development of metallurgical slag sensible heat recovery and utilization technology will become an urgent imperative for metallurgical energy-saving researchers. It is also an important direction for the research of metallurgical energy-saving technology.

2. Steel Slag Waste Heat Recovery Technology

In terms of the waste heat recovery and utilization of steel slag, there are no applica-tion examples in the world. Important development direction of metallurgical energy-saving technology research and development.

2.1. Physical Method in Waste Heat Recovery

Heat Energy Recovery of Granulated Steel Slag with Double Inner Cooling Drum. The technology was developed by Nippon Steel Corporation (NKK). The basic principle is: let the molten slag be cooled by the heat medium circulating inside the drum on the surfaces of the two counter-rotating cylinders, and then recover the remaining heat from the heat medium to produce steam for power generation. Since the slag layer is very thin and heat transfer is fast, the obtained active slag can be used as cement raw material. The use of heat medium is the biggest feature of this method [1]. The heat medium is a high-boiling point cooling liquid mainly composed of diphenyl ether, with a boiling point of 257°C.

Air Quenching and Granulating Molten Steel Slag and Waste Heat Recovery Process. Mistubisih and NKK jointly developed the air-quenching and granulating slag-melting waste heat recovery system, and at the end of 1981, the world's first converter steel slag air-quenching and granulating heat recovery device was built at Fushan Iron Works [2]. When the temperature is decreased from 1500°C to about 300°C, the heat recovery rate can reach 40~45%.

Air Quenching and Granulation Vibrating Fluidized Bed Heat Recovery Process. The Ural Iron and Steel Research Institute of Russia has developed a slag treatment process for air quenching heat energy recovery. After the liquid steel slag is quenched and broken by high-pressure air, it enters the first waste heat recovery chamber to collect radiant heat, cools the slag into small crystal particles, and enters the second waste heat recovery chamber for further cooling to 160~200℃. The recovered waste heat is used to produce hot water, steam, etc., but this process is only suitable for processing liquid steel slag with good fluidity [3].

"Continuous Casting and Rolling" Method for Slag Waste Heat Recovery Pro-cess. In 1986, Dnepropetrovsk Institute of Metallurgy, based on the concept of con-tinuous casting and rolling, developed slag granulation sensible heat recovery tech-nology, which is slag continuous casting followed by slag crushing and recovery of slag heat energy by waste heat boilers. Experts have transformed it according to na-tional

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conditions in China, and developed a sensible heat recovery process for sedi-ment.

The working process is as follows: the slag transported by the slag tanker is poured into the slag pool, the slag flows continuously from the slag supply nozzle to the wa-ter-cooled flat roller and the water-cooled mesh roller, and then enters the chain con-veyor, and cold air is introduced into the lower part of the conveyor, and the slag is discharged. The heat is transferred to the cold air and the membrane-type water wall, the cooled slag is broken in the slag crusher, the softened water flows into the water tank through the roller, and is pressed into the economizer by the feed pump and then into the steam drum, and the saturated water is pressed into the membrane by the circulating pump. It is heated and gasified and returned to the steam drum to become superheated steam [4]. Heat balance calculations for the system showed a heat recovery rate of 66.5%.

Heat Energy Recovery Technology of Rotor Granulation Fluidized Bed Slag. British Kevanner Metals has developed a rotary cup granulation fluidized bed heat recovery technology. At present, this technology is still in the application research stage. Many iron and steel enterprises in the world pay more attention to this technol-ogy [5]. Japan has done a lot of research, and the results are almost practical.

2.2. Chemical Method in Waste Heat Recovery

Methane Steam Reforming Process. The high-temperature slag particles can provide sufficient heat for the catalytic reaction of water vapor and the carbonization and decomposition of hydrocarbons, and the sensible heat of the slag can be converted into chemical energy by using this endothermic chemical reaction. Japanese scholars have proposed two schemes for hydrogen production from mixed gas combined with centrifugal granulation process:

① Catalytic hydrogen production from methane-steam :

$CH_4(g)+H_2O(g)=3H_2(g)+CO(g)$;

②Hydrogen production from biogas:

$CH_4(g)+CO_2(g)=2H_2(g)+2CO(g)$

According to thermodynamic analysis, the loss of chemical method is only 15% of that of traditional physical method [6].

Slag Granulation and Coal Gasifier Process. Chinese scholars have also proposed a coal gasifier based on a centrifugal granulation device. Coal gasification is an endo-thermic process, and the sensible heat of blast furnace slag is used to ensure the reac-tion temperature. The pulverized coal gasification rate and the influence of pulverized coal residue on the utilization of blast furnace slag need to be studied.

While recovering the sensible heat of molten slag, it must also be premised that the treated tailings have excellent comprehensive utilization value and utilization perfor-mance.

The key technologies that need to be solved in the new process are:

(l) The adaptability of steel slag types, that is, the system must ensure that it can handle hot steel slag materials with different fluidities;

(2) The problem of controlling the flow rate of steel slag, that is, to ensure that the recovered heat is continuously stable and easy to use;

(3) The problem of continuous renewal of the hot steel slag surface is to ensure that the heat in the steel slag is released completely and uniformly, and at the same time, the granulation of the steel slag is achieved.

3. Materials and Methods

Test material: converter steel slag of a steel factory.

Test methods: chemical composition detection, temperature test in the process of steel slag cooling.

4. Analysis of Steel Slag Test

4.1. Analysis of chemical composition of steel slag

Steel slag is rich in calcium (Ca), silicon (Si) and other elements, and has a hard and dense texture with few pores. The composition of steel slag fluctuates greatly with different steel grades, raw materials and steelmaking processes. In most cases, its main chemical components are: calcium oxide (CaO), silicon dioxide (SiO_2), alumi-num oxide (Al_2O_3), ferrous oxide (FeO), iron oxide (Fe_2O_3), magnesium oxide (MgO), etc.; Some also contain vanadium pentoxide (V_2O_5), titanium dioxide (TiO_2), etc., and the composition is basically stable.

Due to the difference in chemical composition and cooling conditions, the appear-ance and color of steel slag are very different. The steel slag with lower basicity is dark gray, while the slag with higher basicity is brownish gray or grayish white. Alt-hough the chemical composition of different steel slag will fluctuate, but some of the main components are roughly the same, as shown in Table 1. The chemical composi-tion of steel slag samples was tested and the test results are shown in Table 2..

Table 1. Main chemical composition range of steel slag, wt%.

Element	CaO	SiO_2	Al_2O_3	FeO	Fe_2O_3	MgO	P_2O_5
Content	45~60	10~15	1~5	7~20	3~9	3~13	1~4

Table 2. Test results of main chemical components of steel slag samples, wt%.

Element	CaO	SiO_2	Al_2O_3	FeO	Fe_2O_3	MgO	P_2O_5
Content	41.27	11.67	6.7	22.4	26.32	13.25	8.55

4.2. On-site Temperature Drop Law Test of Steel Slag

In order to find out the temperature drop law of the steel slag during cooling, on-site measurements were made on the temperature of the steel slag at each node in normal production and the temperature of the steel slag temperature at different nodes with time. The experimental results are shown in Table 3.

After the steel slag is poured into the steel slag, the surface is rapidly crusted to form a "black slag layer". After 20 minutes, the surface temperature of the steel slag is about 500~600 °C; after stirring by the stirring claw, the surface temperature of the steel slag quickly rises to about 1000 °C. The biggest difficulty in sensible heat recovery of steel slag is that the surface of steel slag quickly "crusts" when it is cooled, and the heat in the core is difficult to be exported and utilized.

In order to comprehensively analyze the temperature change of steel slag in the whole hot soak process, the temperature change of steel slag under different process operations was detected. The experimental results are shown in Table 4.

It can be seen from the test data in Table 4 that the steel slag is cooled by natural cooling, water cooling, stirring cooling and other methods. The cooling rate and trend of steel slag are relatively consistent. The cooling rate in the high temperature section before 10 min is relatively large; After 10min, as the temperature of the steel slag itself decreases, a black slag layer is formed on the surface, which makes the heat inside the steel slag can not be released, resulting in a decrease in the cooling rate. The cooling rate of high temperature section (natural cooling) and low temperature section (water pumping section) is the same, which proves that the main reason for affecting the heat release of steel slag is the insulation effect of black slag formed in the low temperature section of steel slag, which affects the heat release of steel slag. The key of steel slag heat recovery process is how to destroy the black slag of steel slag and release the heat of steel slag quickly.

Table 3. Steel slag temperature drop test data (℃).

Test point		A	B	C
Steel slag temperature when the slag tank is dumped		1450	1350	1450
Inside the slag pit	Bright slag temperature	1175	1150	1175
	Dark slag temperature	775	725	800
Temperature during stirring		1250	1220	1250
After stirring	Bright slag temperature	1050	1025	1050
	Dark slag temperature	775	725	750
Slag temperature after water spray	Bright slag temperature	850	775	825
	Dark slag temperature	475	450	475

Table 4. Steel slag process temperature test data (℃).

Test point		0 min	5 min	10 min	15 min	20 min
Steel slag temperature when the slag tank is dumped				1350~1400		
Inside the slag pit	Bright slag temperature	1075	950	850	800	600
	Dark slag temperature	715	600	475	475	475
Temperature during stirring				1100~1200		
After stirring	Bright slag temperature	1025	875	825	825	825
	Dark slag temperature	750	675	575	575	575
Slag temperature after water spray	Bright slag temperature	875	450	450	375	375
	Dark slag temperature	450	275	275	375	375

5. Difficulties in Heat Recovery and Utilization in Steel Slag

At present, the treatment of steel slag is traditional cooling methods such as water spraying or air cooling, which require energy consumption. The large amount of heat contained in steel slag is not utilized, which is also due to the particularity of steel slag itself. Especially when considering the use of various heat exchange methods to recover and utilize the residual heat in steel slag, although it theoretically conforms to the principles of heat transfer and energy conversion, it is difficult to apply it in practice. However, the problems faced by the characteristics of steel slag are:

1) Although steel slag itself carries a large amount of heat, when it is first discharged, the temperature drops rapidly after contact with air. Once it is accumulated, the cooling rate is very slow. The surface of steel slag accumulation forms a slag film when it comes into contact with air, sealing a large amount of heat inside. The internal temperature is high and lasts for a long time, and the heat cannot be released.

2) The overall temperature of steel slag shows a gradual downward trend.

3) When the temperature drops below 700 ℃, slag blocks are formed, making it difficult to break the slag.

The waste heat boiler mainly utilizes industrial waste heat, which is generally the waste gas that is burned or heated at high temperature by the main equipment, to conduct continuous convective heat exchange with the heating surface of the boiler. Convection heat transfer is used to heat water into steam, and the amount and temperature of flue gas supplied with residual heat must be stable. However, for steel slag, it is completely different. Due to the above reasons, convection heat transfer cannot be used because the heat in the steel slag cannot be circulated by heating air to form hot smoke.

Therefore, how to control the discharged steel slag, how to obtain a stable temperature field, and how to release the heat of the steel slag are the difficulties that we need to overcome when using a waste heat boiler to recover the residual heat of the steel slag.

In order to make it possible, it is necessary to take some measures to release its heat, and when the temperature drop of steel slag is basically stable within a certain range, use its radiant heat to recover the sensible heat of steel slag. According to years of observation by steelmaking plants, the cooling rate of the discharged steel slag after accumulation is indeed very slow. The internal and high temperatures of the steel slag after accumulation can be maintained for a considerable period of time, so we can use the relatively stable temperature drop process during this period to recover the sensible heat of the steel slag.

6. Conclusion

For many years, the steel slag treatment process of iron and steel enterprises has been a big problem. The traditional method is to treat and utilize after cooling with water or air. First, it wastes a lot of water resources or electric energy. Second, the surrounding environment of high temperature steam and dust is bad during the cooling process. So far, there is no good treatment method. The method of recycling a large amount of heat in the steel slag will undoubtedly make a huge contribution to energy saving and environmental protection.

References

1. Yu, Z., Jian Z., Tianyou, Z: Analysis of steel slag treatment technology and waste heat recovery technology. vol. 24(8), 33–37. China Metallurgy(2014).
2. Huigang, W. Long, W. Ben, P.: Characteristics and research progress of steel slag primary treatment technology. vol. 20(13), 5025-5031. Science Technology and Engineering(2020).
3. Shaoyang, H. Xiaotian, D. Xianzhao, N.:Treatment process and comprehensive utilization of steel slag. vol. 40(2), 220-224. Foundry Technolog(2020).
4. Shengtao, L. Kai, W. Li, Z.: Pracice on comprehensice recycling of solid waste resource in shouqin company. vol. 28(11), 73-78. China Metallurgy(2018).
5. Gang, Z.: Overview of blast furnace slag treatment and resource utilization technology. vol. 39(3), 57-58. Shanxi Metallurgy (2016).
6. Wenyuan, Z.: The choice of treatment process for various sorts of steel slag. vol. 11(5), 107-108. China water Transport (2011).