Waste Heat Recovery from High-Temperature Blast Furnace Slag Particles

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Received 26 December 2015; revised 07 August 2016; accepted 27 December 2016

Heat transfer models for packed bed, moving bed and fluidized bed to recover thermal energy from high temperature slag particles were established. The sticking point, which blocked the application and development of recovering thermal energy from high temperature slag particles by air, was addressed. The results showed that the packed bed, moving bed and fluidized bed were not suitable for recycling thermal energy from slag particles with small diameter, high temperature and flowrate. Based on the problem mentioned above, a technique of thermal energy recovery from high temperature slag particles using gravity bed waste heat boiler was exploited. The waste heat boiler can produce steam obtained in the upper part of the gravity bed boiler and the heat recovery rate can reach as much as 91%. As a consequence, it is possible to recycle thermal energy from high-temperature slag particles using a gravity bed waste heat boiler to produce steam.

Keywords: Waste Heat Recovery, Slag, Granulation, Particles, Gravity Bed Boiler

Introduction

Blast furnace slag is one kind of solid waste, which is discharged from blast furnace. And the temperature of molten slag ranges from 1450 to 1650 °C. In 2014, the output of blast furnace iron was more than 0.71 billion tons, and there were about 0.21 billion tons molten slag discharged from iron making process. The thermal energy contained in the slag is equivalent to the energy in 12.3 million tons of coal equivalent. But a great deal of high quality thermal energy is usually not recovered¹. At present, the molten slag is tapped and cooled rapidly by water to make glassy granules which are used as feedstock for cement manufacturing. In the process of wet granulation, a large amount of water is consumed and harmful waste gas is discharged into the environment. Due to considerations of energy conversation and environmental protection, the iron making industry pays close attention to dry granulation, which is an attractive alternative to wet granulation²³⁴. In the late 1970s, the Sumitomo Metal Industries, Ltd. and the Ishikawajima-Harima Heavy Industries, Ltd. jointly undertook the research of rotary drum granulation. This method had several disadvantages: the processing capacity and efficiency were low, and it cannot be adapted to operate continuously in production⁵. From 1980, Nippon Steel, NKK, Kawasaki Steel, Kobe Steel, Sumitomo Metal Industries and Nisshin Steel were engaged in air granulation, and the experiments were operated for 6 years on the blast furnace in Nippon Steel. In the process of air granulation, there was a lot of power consumption for air blast. The complexity of structure and the great floor space of the air granulation device caused high cost of investment. It may take about 10 years to earn the cost of investment. In 1986, Ukraine exploited a new heat recovery method which was similar to continuous casting and rolling method⁶. But there was a serious drawback that the low heat conductivity and weak air permeability were inutile for heat exchange between flat slag and air. Pickering exploited a process of rotary cup atomization-fluidized bed⁷. A rotating cup atomized molten slag, and the liquid slag particles were cooled rapidly to produce a glassy product. The particles were cooled further as they travelled through air and were transported to two successive fluidized beds for heat recovery. Because of high productivity and controllable slag particle diameter, the rotary cup atomization had been extensively studied⁸¹¹. However, air was used as medium to recover thermal energy of molten slag, and hot air would be used for preheating combustion air or be utilized to produce electrical power. The specific heat of air was low and there must be a great amount of air to cool the high temperature molten slag with

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high energy consumption. In the process of producing electrical power using the thermal energy of molten slag, the recovery efficiency of thermal energy is low, which was caused by energy loss in every step. Based on the problem mentioned above, a technique of thermal energy recovery from molten slag was exploited. The molten slag was granulated by a rotary cup and the thermal energy of slag particles with high temperature were recovered by a gravity bed waste heat boiler which produced high pressure steam for generating electricity.

In this paper, the heat transfer models which described the process of waste heat recovery for packed bed, moving bed and fluidized bed were established respectively. The effects of air velocity, particle diameter and particle feeding rate on waste heat recovery were investigated. The sticking point, which blocked the application and development of recovering thermal energy from high temperature slag particles by air, was investigated. And a new method of thermal energy recovery from high temperature slag particles was exploited.

**Modeling and simulation**

This section introduces the heat transfer models for packed bed and moving bed, basing on energy balance. A typical moving bed consisted of a cylindrical tank containing slag particles and gas flows through the voids among the slag particles. And detailed modeling of the gas flow and heat transfer in such a complex configuration were difficult. Therefore, the following assumptions were applied:

- Due to the axial symmetrical configuration, we supposed that \(dT_s/dR=0\).
- The heat transfer between spheres was negligible because the heat was only transported through the point-to-point contact between spheres.

Based on the above assumptions, the mathematical model, describing the heat transfer between air and slag particles, was a quasi 2-D model. And the energy equations for the solid phase in fluidized bed can be expressed as Eq. (1). And the energy equations for the fluid phase in fluidized bed can be expressed as Eq. (3).

**Heat recovery in packed bed**

Fig. 1 showed temperature of slag particle at the entry and temperature of air at the entry in packed bed with different air velocity. It can be seen that temperature of slag particles at the exit of packed bed decreased gradually as the cooling time increased. At the beginning, air temperature at the entry of packed bed kept at a high level, about 1000°C. The flow rate of air was too low to cool down a large amount of slag particles filled in packed bed. With an increase in cooling time, temperature of air decreased after a long time, because the thermal energy of slag particles was recovered by a gravity bed waste heat boiler which produced high pressure steam for generating electricity.

<table>
<thead>
<tr>
<th>Diameter(mm)</th>
<th>0.800</th>
<th>1.215</th>
<th>1.715</th>
<th>2.250</th>
<th>2.850</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical fluidization velocity(m s(^{-1}))</td>
<td>0.44</td>
<td>0.74</td>
<td>1.02</td>
<td>1.26</td>
<td>1.49</td>
</tr>
<tr>
<td>Entrainment velocity(m s(^{-1}))</td>
<td>6.90</td>
<td>9.44</td>
<td>11.21</td>
<td>12.84</td>
<td>14.45</td>
</tr>
</tbody>
</table>
was taken away gradually by air. In the final stage, the value of air temperature at the entry of packed bed decreased to the initial value at the exit of packed bed. It was a long time for high temperature slag particles to be cooled down completely, especially at a low air flow rate. For a high air flow rate, the heat transfer between air and high temperature slag particles was intense, so the high temperature slag particles can be cooled down completely for a short time. Before the cooling time reached 770s, temperature of air at the entry (0.8m) kept at a constant high temperature level. After 770s, temperature of air at the entry decreased obviously, and dropped to the initial temperature (25ºC). Hence, the hot air, obtained before 770s, can be used as combustion air to reduce combustion gas, or be used to produce high pressure steam to generate electricity. Table 2 showed recovery efficiency of packed bed at different cooling time. The heat recovery efficiency was very low, especially before 1000s. Although temperature of air at the entry kept at a high temperature level, the packed bed was not suitable for recycling thermal energy of slag particles with high temperature and flowrate.

**Heat recovery in moving bed**

Fig. 2 showed temperature of slag particle at the exit and temperature of air at the entry in moving bed with different feeding rate. For a constant feeding rate, \( m=1000\text{kg/h} \), temperature of air decreased after 1570s and temperature of slag particles at the exit of moving bed kept constant. The temperature of air at the entry of moving bed became smooth-out and almost kept at a constant value at 5000s. At this moment, the heat recovery efficiency could reach 76%. But it was a long time for moving bed to produce constant high temperature air. When the feeding rate of slag particles was 2000kg/h, temperature of air at the entry of moving bed kept at 997ºC and temperature of slag particles at the exit of moving bed kept at 207 ºC all the time. Because of low air velocity, the high temperature slag particles could not be cooled down completely, and the heat recovery efficiency of moving bed was only 56%. It was effective to increase the air velocity in order to decrease temperature of slag particles at the exit of moving bed further. The critical fluidization velocity of a given slag particle, \( d=1.715\text{mm} \), was 1.02m/s. The slag particles will be in fluidized state in moving bed if the air velocity exceeded the critical fluidization velocity. In iron making process, the output of molten slag, discharged from blast furnace, was dozens or hundreds of tons per hour. Hence, temperature of slag particles at the exit will be high if the thermal energy of slag particles was recovered by moving bed, and then the recovery efficiency will be

![Figure 1](image1.png)

**Table 2**—Heat recovery efficiency of packed bed at different cooling time with \( U=1.0\text{m/s} \).

<table>
<thead>
<tr>
<th>Cooling time/s</th>
<th>100</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3000</th>
<th>4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat recovery efficiency (%)</td>
<td>4.55</td>
<td>22.59</td>
<td>44.71</td>
<td>53.41</td>
<td>53.41</td>
<td>53.41</td>
</tr>
</tbody>
</table>

![Figure 2](image2.png)
very low. From the above, it was not suitable to recycle thermal energy of slag particles with small diameter and high flowrate using moving bed.

**Heat recovery in fluidized bed**

Fig. 3 showed temperature of slag particle and air at the exit of continuous feeding fluidized bed. In fluidized bed, slag particles and air were discharged from the same exit, caused by the internal circulation of slag particles. And temperature of slag particles was same as that of air at the exit. As shown in Fig. 4(a), temperature of slag particles and air decreased with an increase in air velocity, and they kept at a constant value after 3000s. In order to improve the value of air temperature at the exit, one way was to decrease the air velocity and the other one was to increase the feeding rate of slag particles, as shown in Fig. 4(b). With an increase in feeding rate, temperature of air increased. And temperature of slag particles discharged from fluidized bed increased accordingly, which will cause low recovery efficiency. In order to solve the problem mentioned above, the technique of two-stage fluidized bed was proposed. The high temperature slag particles fell directly into the primary fluidized bed. And they were cooled to lower temperature by the air from secondary fluidized bed. The slag particles were discharged from the primary fluidized bed and then fell directly into the secondary fluidized bed. The slag particles were cooled by cold air, and the cold slag particles were discharged from the secondary fluidized bed. Then, the hot air, from secondary fluidized bed, was supplied into the primary fluidized bed. In the two-stage fluidized bed, temperature of air, discharged from the primary fluidized, was higher than that of ordinary fluidized bed. And temperature of slag particles, discharged from two-stage fluidized bed, was low, which resulted in high recovery efficiency. However, the process of two-stage fluidized bed was very complicated, and the problem of connection between primary and secondary fluidized bed should be solved. Besides that, the slag particles, obtained from dry granulation, were consist of several kinds of slag particles with different diameters. In fluidized bed, the air velocity should be lower than the entrainment velocity of slag particles with the smallest diameter. Otherwise, the small slag particles will be carried away, along with the hot air. If the air velocity was designed following the entrainment velocity of slag particles with the smallest diameter, there will be no fluidization occurring in big slag particles, and the recovery efficiency was low. Hence, it was not suitable to recycle thermal energy of slag particles with mixed diameter and high flowrate using fluidized bed.

**Waste heat recovery by gravity bed waste heat boiler**

Based on the problems mentioned above, the technique of thermal energy recovery from molten blast furnace slag was exploited\(^\text{12,13}\). The molten blast furnace slag was injected into the rotary cup. Because of centrifugal force, the molten slag droplets formed when the molten slag was released from the lip of the rotary cup. The slag droplets were cooled and then freezeed in the flight. When slag particles reached the cooled wall, they were cooled further to avoid recalscence. The high temperature slag particles were transmitted directly into the gravity bed waste heat boiler via the transport vibrating bed. Under the action of gravity, slag particles flowed around the boiler tubes. The thermal energy of slag particles transferred to sensible heat of water in the boiler tubes. The cooled slag particles discharged from the exit, which was at the bottom of gravity bed waste
heat boiler. The high temperature and pressure steam, coming from waste heat boiler, can enter the steam pipe network system or be used to generate electrical power by steam turbine. In this waste heat recovery system, thermal energy of slag particles was recovered directly by the gravity bed waste heat boiler. There was less energy loss and the recovery efficiency improves obviously. Meanwhile, slag particles moved downward under the action of gravity, without power consumption for air blast. The heat transfer coefficient between the slag particles and boiler tube and the recovery efficiency decreased with an increase in slag particle diameter. Based on packet theory, the gas blanket occurred between the slag particles and boiler tube caused by the void between the slag particles and boiler tube \(^{14,15,16}\). Delvosalle and Vanderschuren observed that the thickness of the gas blanket around a particle can be expressed by \(\delta = 0.1d\) \(^{17,18}\). For large slag particle diameters, there were a high percentage of voids, resulting in a small contact area between the slag particles and boiler tubes and a thick gas blanket between them, which resulted in high thermal resistance. Hence, less thermal energy of the slag particles was transformed into sensible heat of the water in the boiler tube because of the high thermal resistance between the slag particles and boiler tube. When descending velocity of slag granule \((d_s = 0.8 \text{ mm})\) equaled 1.9 mm/s, the waste heat boiler can produce steam obtained in the first row and second row tubes, and the heat recovery rate can reach as much as 91%. When the volumetric flow rate of water decreased further, there will be a mass of steam produced in gravity bed waste heat boiler. Hence, it was possible to recycle thermal energy from high-temperature slag particles using a gravity bed waste heat boiler to produce steam.

**Conclusions**

From the above, the packed bed, moving bed and fluidized bed were not suitable for recycling thermal energy from slag particles with high temperature and flowrate. It was possible to recycle thermal energy from high-temperature slag particles using a gravity bed waste heat boiler to produce steam, and the heat recovery rate can reach as much as 91%. It can produce 3 million tons of molten slag with regard to an iron making plant, which can produce 10 million tons of blast furnace iron annually. In contrast to water quenching, whose water consumption was 2.4 million tons every year, the gravity bed waste heat boiler system had no water consumption. It can save 1.8 million dollars for water charges annually. Besides that, there was no sulfide released into air and it can reduce the formation of acid rain and acid mist. Supposing that the waste heat recovery rate can reach up to 90%, the amount of energy conservation will be equivalent to 0.16 million tons of coal equivalent, i.e. 51.6 million dollars every year. So it will provide great benefits for industry and society if the gravity bed waste heat boiler system was used in iron making process.

**Acknowledgement**

This research was supposed by The National Natural Science Foundation of China (51274066, 51304048), The National Science Foundation for Post-doctoral Scientists of China (2013MS541240), The National Key Technologies R&D Program of China (2013BAA03B03), State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Kunming University of Science and Technology.

**Nomenclature**

- \(\rho\): density, kg m\(^{-3}\)
- \(c\): specific heat, J·kg\(^{-1}\)·ºC\(^{-1}\)
- \(U\): velocity of gas, m·s\(^{-1}\)
- \(T\): temperature, ºC
- \(\varepsilon\): voidage, m\(^3\)·m\(^{-3}\)
- \(\tau\): time, s
- \(h\): heat transfer coefficient, w m\(^{-2}\)·ºC\(^{-1}\)
- \(A\): heat exchanging area, m\(^2\)
- \(u_s\): velocity, m·s\(^{-1}\)
- \(\lambda\): thermal conductivity, w m\(^{-1}\)·ºC\(^{-1}\)
- \(H\): height of bed, m
- \(R\): radius of heat transfer bed, m
- \(d\): diameter of particle, m
- \(M\): mass stored in the bed, kg
- \(m\): feeding rate, kg·h\(^{-1}\)

**Subscripts**

- \(g\): gas
- \(s\): slag
- \(in\): in inlet
- \(out\): outlet

**References**