Analysis of Temperature Dropping of Molten Steel in Ladle for Steelmaking

CHANG-SHENG LIN

Iron & Steel Research & Development Department
China Steel Corporation

The temperature control of molten steel is essential for improving both product quality and productivity in the steelmaking industry. By analyzing the cause of the temperature drop of the molten steel loaded in the ladle during the steelmaking process, it is known that the heat loss of the molten steel is mainly due to the heat convection and radiation from the outer ladle shell and slag formation on top of the molten steel, and heat absorption by the ladle body. The drop rate of molten steel temperature can be estimated by combining the degree of influence of these known ways and change the holding time. This is helpful for more accurately adjusting the parameters of the steelmaking process.

Keywords: Ladle, Molten steel temperature, Temperature drop rate

1. INTRODUCTION

After the blowing process in the converter, the molten steel is tapped into the ladle, and then sent to the secondary refining sites for further processing. After refining, the ladle is transported to the continuous casting equipment, and the molten steel is poured from the bottom of the ladle into a tundish. After the molten steel feeds into the mold, it is then cast into either a bloom, billet or slab. The molten steel temperature has a great influence on the quality of the bloom, billet or slab. If the temperature of molten steel is too high, the chances of breakout, segregation and defects during casting will increase. If the molten steel temperature is too low, problems such as clogging of the submerged nozzle and failure of the ladle slide gate may occur.

In general operations, the molten steel is heated to higher than the target temperature, and when the temperature is too high, the casting speed is reduced to deal with it. But this will increase the heating cost, the productivity and the slab quality are also decreased. The heating cost saved by reducing the superheat temperature is considerable, so it is necessary to keep the temperature of the molten steel within a reasonable range.

The control of molten steel temperature is always a problem. This is not only because appropriate temperature not only has a great impact on the quality of the steel billet, but also because each process station has its own temperature requirements. Usually, the continuous casting temperature requirement is used as the standard, and the overheat temperature is added to the previous station according to the operator's experience. This method heavily relies on the personal experience of the operator, so errors are easy to occur.

Fig.1. shows the temperature of molten steel varies with processes and time(1). The temperature of molten

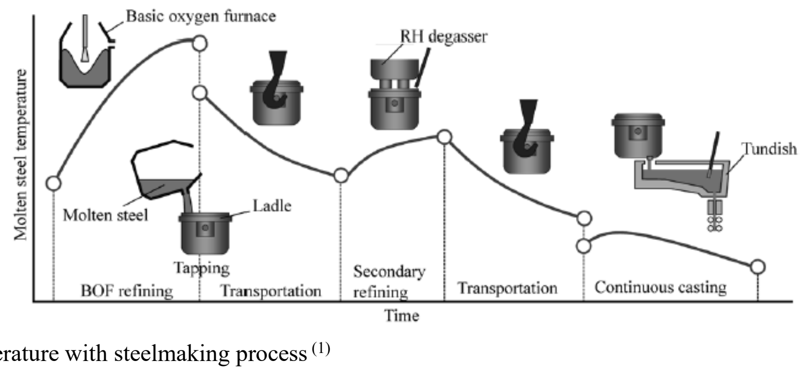

Fig.1. Molten steel temperature with steelmaking process (1)

iron rises greatly by oxygen blowing in the converter. When the steel is tapped to the ladle, the heat of the molten steel is absorbed by the ladle, so the temperature of molten steel drops significantly in a very short period. On the way to the secondary refining stations, the heat is continuously absorbed by the ladle and dissipated to the environment, and the temperature drops gradually. In the refining station, the temperature can be increased by electrical energy (LF) or chemical energy (RH). When the molten steel is sent to the continuous casting station, the heat is continuously dissipated during the transportation process. When the molten steel is poured into the tundish, the temperature of the molten steel will drop significantly in a very short period of time, similar to when it is tapped to the ladle.

In order to produce various types of steel in a steel plant, several kinds of refining and continuous casting equipment are intertwined. Since the operation schedule may change accidentally due to different conditions, it is difficult to manage the temperature of the molten steel in the ladle totally according to the operation schedule. There have been many studies for predicting the temperature of molten steel, but it is difficult to accurately predict the temperature of molten steel because the temperature of the refractory material of the ladle is difficult to measure.

The converter tapping and refining temperature adjustment together with the molten steel cooling behavior control the target temperature of continuous casting. In order to evaluate the molten steel cooling conditions, many heat loss point paths need to be considered. During tapping, the poured molten steel dissipates heat to the surrounding environment and the refractory material at the tap hole of the converter. Afterwards, during the process of transportation and casting, the temperature of the molten steel decreases due to the different ways of heat loss.

The main reasons for heat loss of molten steel in a ladle are due to the absorption of heat, by heat conduction, through the ladle refractory, by heat convection and radiation from the outer ladle shell and slag formation on top of the molten steel, and melting of the alloy additions to the ladle. Heat loss at the top of the molten steel depends on the thickness and condition of the slag and whether the ladle is covered or not. The temperature drop caused by heating and melting of the added alloy is affected by the amount of alloy added and the alloy material properties. The heat loss of the ladle refractory is greatly affected by the temperature distribution of the refractory, which in turn depends on the thermal state of the ladle. The thermal condition of the ladle usually depends on the transport conditions of the empty ladle when it is returned from the casting machine to be filled with the steel again. Important factors for heat loss are listed in Table 1. In addition, due to natural convection, the molten steel flows down the ladle wall, as shown in Figure 2[(2)].

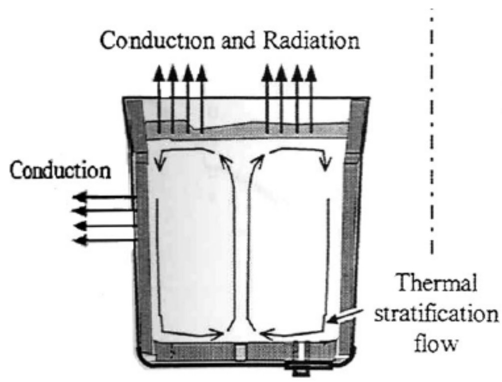

Fig.2. Steel flow phenomena in a ladle.[(2)]

The mathematical model, which describe the temperature change of molten steel in a ladle at LF refining, shows that the reduction in capacity of the ladle is proportional to the increase in specific power consumption, and this is related to the increase in the specific heat transfer surface of the steel.[(3)] Figure 3 shows the smaller the ladle, the more rapidly the steel in

Table 1 Heat loss paths and important factors

Heat Loss Paths	Key Factors
Heat conduction from ladle refractory	Ladle thermal condition and material properties
Heat absorption from ladle	Ladle thermal condition and material properties
Convection and radiation from the top of molten steel	Thickness and properties of slag, ladle cover
Melting of alloys	Alloy amount and material properties
Tapping heat loss	The condition of the refractory material at the tapping hole and the tapping time
Secondary refining heat loss	Bottom blowing stirring gas and RH vacuum vessel condition
Tundish heat loss	Tundish thermal condition

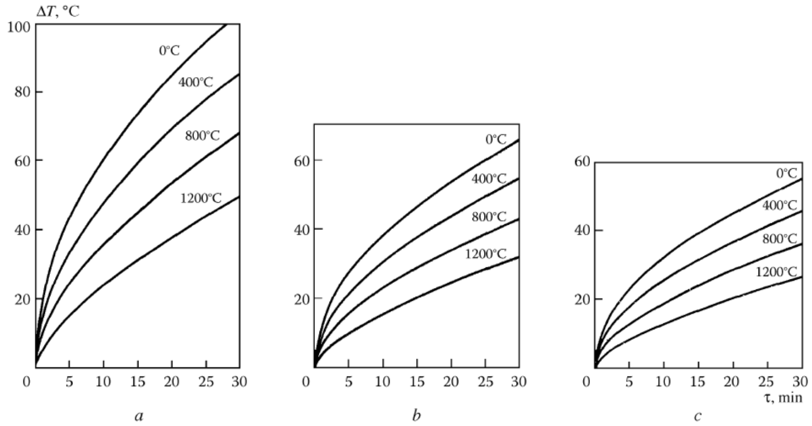

Fig.3. Cooling of steel in ladles with capacities of 10 tons (a), 40 tons (b), and 80 tons (c); the numbers next to the curves are the temperatures to which the lining was heated.(3)

it cools. The cooling rate is also significantly affected by the temperature of the lining, this is similar to what was observed at CSC operating site.

2. EXPERIMENTAL METHOD

The research is mainly carried out in two directions: one is the analysis of the actual measured temperature change and the other one is the characteristics of the ladle. The steps are as follows:

1. Collect information on the temperature of molten steel in each process, the temperature inside and outside the ladle before the steel is poured from the converter, the outside temperature of the ladle before and after the secondary refining treatment, the outside temperature of the ladle on the continuous casting machine, the preheating schedule time, etc. Then, analyze the possible factors for temperature changes.
2. Analyze the influence of the ladle refractory structure, heat transfer characteristics, molten steel loading times, etc. on the temperature change.
3. Integrate the measurement information in the process and then characterize of the ladle to build a reasonable model of the temperature change of the molten steel in the ladle.
4. Compare the molten steel temperature predicted by the model with the actual measured results to verify its accuracy and optimize the model.

3. RESULTS AND DISCUSSION

After the molten steel is loaded into the ladle, the heat dissipates to the outside environment, as shown in Figure 4. It mainly includes the heat absorbed by the ladle itself, and the heat radiation and convection of the ladle and slag surface. Taking the steel ladle used in CSC steelmaking plant as an example to discuss, its basic properties are: the outer iron shell is about 60 tons, the inner refractory material is about 55 tons, and the load of molten steel is 250 tons. The temperature in the ladle before tapping the molten steel is usually 600~1000°C, the temperature of the outer wall of the ladle in use is about 200~400°C, and the temperature of the slag surface is about 600~900°C. The liquid specific heat of AISI 1008 structural steel with molten steel temperature set to 1600°C is about 0.68kJ/kg·K.

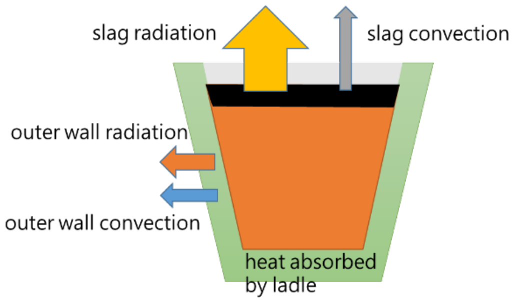

Fig.4. The way of heat dissipation of molten steel

3.1 Analysis of Heat Absorption of the Ladle

3.1.1 Calculation of Heat Absorption from a New Ladle to a Steady State

After the molten steel is poured into the ladle, the heat will be quickly absorbed by the refractory material, and the temperature of the refractory material will rise rapidly. For example, a new ladle that has been re-used after a long period of maintenance, the inner/outer temperature of the ladle before molten steel tapping is 800 /200°C, and when it reaches the continuous casting machine, the inner and outer temperature of the ladle is 1600 /250°C. The heat absorbed by the ladle itself is at most to reach a thermal steady state, and the total temperature of the molten steel will drop by about 190°C at most. But in fact, the loading time of one single heat cycle from converter to casting end is not enough for the ladle to reach a steady state. Generally speaking, one single heat processing time is about 2hrs, which will reduce the temperature of the molten steel by about 100°C. In addition, the temperature drop rate of heat absorbed by the ladle from the end of refining to continuous casting is about 0.15°C /min. There will be a difference of ±0.05°C /min with the actual time of molten steel in the ladle. The longer the time molten steel is in the ladle, the lower the temperature drop rate.

3.1.2 Ladle Using Times and the Heat Absorbed by the Ladle Itself

After the ladle is poured with molten steel, the working layer refractory is gradually eroded by the steel flow and becomes thinner, resulting in a decrease in thermal resistance and an increase in the temperature of the outer ladle wall. Generally speaking, the temperature of a new ladle outer wall is about 250°C when measured at the continuous casting machine, and after about 130~140 rounds of heat cycles, the temperature will rise to about 400°C. At this time, there is less than 10cm left on the working layer of the refractory, and it needs to be taken offline for complete maintenance. During the steelmaking process, as the quality of the refractory gradually decreases, the heat absorbed from the molten steel also decreases. On the other hand, since the loss of refractory material will reduce the thermal insulation ability, the outer wall temperature will increase, which is equivalent to an increase in the average center temperature of the refractory.

Figure 5 shows a trend diagram of the change of times the ladle is used and the heat absorption of the ladle itself. It can be found that with the increase of times of ladle used, the weight of the refractory gradually decreases. But due to the rising of the overall temperature, the heat absorption of the refractory only shows slight reduction. The weight of the iron shell does not decrease with use, so when the temperature of the outer shell rises, the heat absorbed by the outer iron shell continues to increase. For ladles with longer offline waiting time require additional compensation for the heat absorption of the ladle body is required when loading molten steel for the first few times. The temperature of the ladle itself increases very slowly after secondary refining, so the heat absorption only accounts for less than 5% of the ladle's total absorption. If it is a multi-refining process, the ladle thermal state is closer to the steady state. However, the accumulated heat absorption during this period cannot be ignored.

3.2 Analysis of External Heat Dissipation

3.2.1 Heat Dissipation of the Ladle Outer Wall and Slag Surface

A renewed ladle after a long period of maintenance is taken as an example too. When it reached the continuous casting machine, the temperature inside and outside the ladle rises from 1600 /200°C to 1600 /250°C. Considering that heat dissipation is reduced due to the lower temperature parts such as cover plates and ribs on the outer wall of the steel ladle, it can be obtained that the natural convection heat dissipation rate of the outer wall of the steel ladle is about 2000KJ /min, and the radiation heat dissipation rate is about 6200KJ /min, which is equivalent to about 0.05°C /min cooling rate. The temperature of the slag surface is about 700°C, the natural convection heat dissipation rate from the top slag

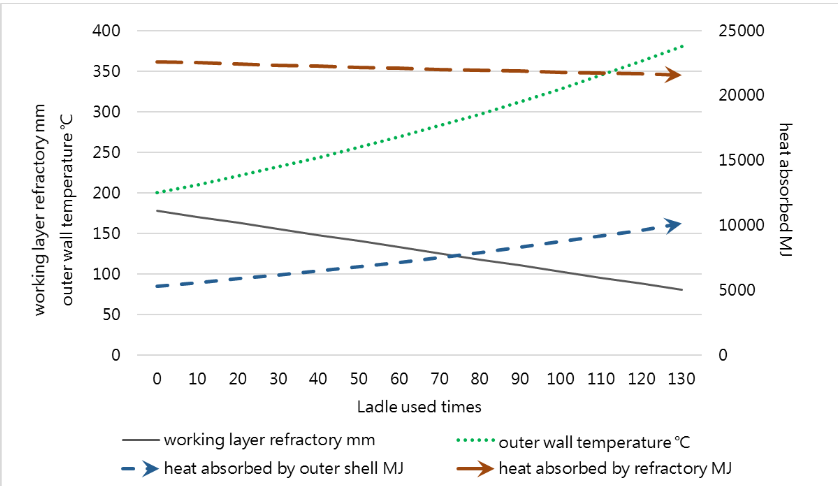

Fig.5. Effect of re-used times on heat absorption of the ladle

surface is about 4300KJ /min, and the radiation heat dissipation rate is about 31000KJ /min, which is equivalent to about 0.2°C /min cooling rate. The heat dissipation rate of the overall ladle outer wall and the slag surface to the environment is about 43300KJ /min, which is equivalent to a cooling rate of about 0.25°C /min.

The time for transporting molten steel in the ladle from converter to the continuous casting table is usually between 90~120min. Regardless of alloy addition and RH vacuum circulation, the heat dissipated to the environment will cause the molten steel temperature to drop around 23~30°C. It can be easily observed in Fig.6, where the slag surface radiation and convection occupy about 63% of the total heat dissipation, which is almost twice that of the 37% dissipated by the outer wall of the ladle. This means that if the ladle is covered with an insulation cover to avoid heat loss from the slag surface, it will greatly reduce the temperature drop of the molten steel. This is why many advanced steelmaking companies adopt a ladle cover.

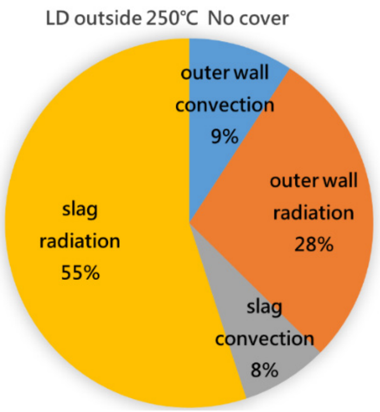

Fig.6. Heat dissipation of a ladle with molten steel

If a cover is placed on the ladle, the actual temperature of the cover top is about 300°C, the temperature drop rate of the slag surface is reduced from 0.2°C /min to about 0.03°C /min, and the heat dissipation ratio of top slag is greatly reduced to 20% in total.

Under normal situations, for a re-new ladle loaded with 250 tons of molten steel, the overall drop rate of molten steel temperature during continuous casting stage is about 0.05 (outer wall) + 0.2 (slag) + 0.15 (ladle) = 0.4 °C /min.

3.2.2 The Influence of the Number of Times in Use and the Degree of Heat Dissipation

After the ladle is used, the working layer is gradually thinned by the erosion of molten steel, and its thermal resistance decreases, which gradually increases the temperature of the outer wall. Therefore, the use of steel ladles with a large number of cycles will result in poor thermal insulation, higher outer wall temperature, and the rate of heat loss to increase more than that of the slag surface. It will result in the overall molten steel temperature drop rate to increase. Estimating the molten steel temperature drop rate of the a new ladle is 0.4°C /min, and it will increase to 0.51°C /min when the ladle working layer refractory is worn out. Besides, although the heat dissipation of the outer wall increases, if the ladle is covered, the total temperature drop rate can still be reduced about 0.17°C /min. It means that the ladle cover still has a very significant impact to help retain the molten steel temperature.

3.3 Predicted Molten Steel Temperature at Continues Casting Stage

To validate the model, the temperatures of molten steel in the tundish during continuous casting are predicted by using the aforementioned temperature drop rate of molten steel, and are compared with actual steelmaking plant data in Figure 7. The green circles in the figure indicate that the temperature error between the predicted temperatures and the actual measured temperatures is less than 10°C, while that of the yellow triangles are less than 20°C, and that of the red crosses are more than 20°C. It can be obtained that the predicted and actual temperature is highly correlated. If the data that temperature drop rate exceeds a reasonable range is removed, the correlation will be significantly improved. The predicted and actual temperature error less than 10°C will be more than 98% of the filtered data.

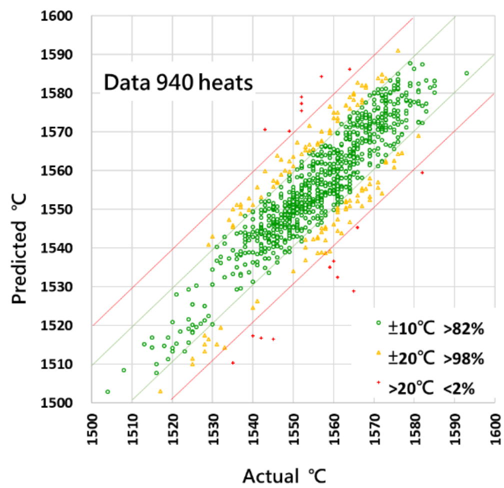

Fig.7. Predicted and actual temperature

4. CONCLUSION

Using the heat transfer theory with the characteristics of the ladle, and the measured temperature of the molten steel and slag surface to discuss the heat dissipation mechanism, this study found the following results:

1. The iron shell and refractory material of the ladle can absorb up to 60% of the total heat lost by the molten steel, which is quite considerable. Good ladle preheating and heat preservation, and continuous using with a high turnover rate, can save a lot of costs for reheating molten steel.
2. The heat energy dissipated by radiation and convection from the top slag surface depends on the temperature of the slag surface, which can be more than twice of that dissipated by the outer wall of the ladle, which shows the importance of the insulation cover of the ladle top.
3. As the using times of a ladle increasing, the thickness of the refractory material will gradually decrease, and the thermal insulation effect will become weak. (1) The temperature of the outer wall rises, and the heat loss from the outer wall increases, even exceeding the heat dissipation of the slag surface. (2) The total heat absorption of the ladle gradually increases; and the overall heat dissipation rate of the molten steel increases.

REFERENCES

1. N. Tomochika et al. Development of Prediction Technique for Temperature Distribution of Molten Steel in Steelmaking, Kobelco Technology Review (2019), NO. 37, pp. 57-62.
2. N. Gupta, S. Chandra, Temperature prediction model for controlling casting superheat temperature, ISIJ International 44 (2004) pp. 1517-1526.
3. A. G. Belkovskii, Y. L. Kats, Mathematical model of the cooling of steel in a small ladle, Metallurgist 53 (2009 pp. 261-273.