International Journal of Minerals, Metallurgy and Materials
Volume 17, Number 1, February 2010, Page 17
DOI: 10.1007/s12613-010-0103-4

Periodic flow characteristics during RH vacuum circulation refining

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(Received: 26 February 2009; revised: 30 March 2009; accepted: 2 April 2009)

Abstract: The circulation period of RH vacuum refining was studied to promote the refining efficiency. The influences of the lift gas flow rate and submersion depth of snorkels on the circulation period, and the relationship between mixing time and circulation flow were discussed. The effects of the lift gas flow rate and submersion depth on the degassing rate in one circulation period were studied by water modeling. The results show that the circulation period is shortened by increasing the lift gas flow rate. The circulation period is the shortest when the submersion depth of snorkels is 560 mm. The whole ladle can be mixed thoroughly after three times of circulation. Increasing the lift gas flow rate can enhance the degassing rate of RH circulation.

Keywords: RH treatment; mixing; water model; flow characteristics

[*This work was financially supported by the National Key Technology R & D Program of China (No.2006BAE03A06).*]

1. Introduction

It is well known that during RH treatment, molten steel is periodically circulated between the vacuum vessel and the ladle, and the periodic circulation has an important influence on the RH refining efficiency. RH periodic circulation not only has the characteristic of macro flow, which is described by circulation rate [1-6], but also has the characteristic of periodic flow, which is described by circulation period. It is necessary to study the characteristics of periodic circulation.

In this article, the method for measuring circulation period was determined, and the characteristics of periodic circulation and its influence factor were studied by water model experiments. Some researchers claimed that mixing was influenced by the characteristics of periodic circulation [7], so the relation between mixing [8-10] and periodic flow was also investigated.

2. Experimental

2.1. Similarity

In order to make the prototype and the model identical in both geometric and dynamics, a water model of a 210-t RH vacuum degasser was fabricated with a scale factor of 1:4. The modified Froude number is equivalent, the parameters of the prototype and the model can be calculated as [11]:

$$Q_M = 0.0996 Q_S \quad (1)$$

where Q_M is the experimental injection gas flow rate, and Q_S the actual injection gas flow rate. Table 1 shows the operational and geometrical parameters of the prototype and physical model.

Table 1. Dimensions of the prototype and the model mm

Equipment	Dimension	Prototype	Model
Ladle	Height	4060	1015
	Upper internal diameter	3884	971
	Lower internal diameter	3222	806
	Liquid level	3300	825
Vacuum vessel	Internal diameter	2138	535
	Height	8225	2056
Snorkel	Length	1075	268
	Internal diameter	650	162

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2.2. Experimental apparatus

Fig. 1 shows a schematic drawing of the experimental apparatus. It mainly includes a vacuum pump, an electrical conductivity meter, a manometer, and a velocimeter. Oxygen was used as the lift gas.

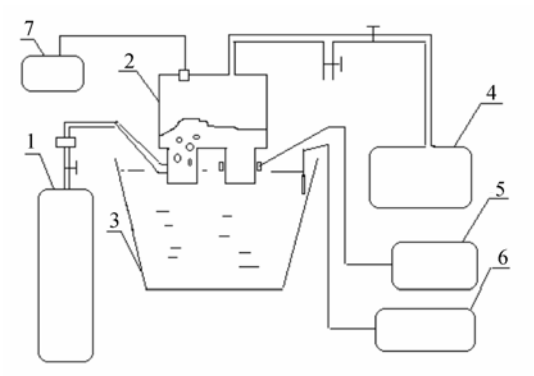

Fig. 1. Schematic drawing of the experiment apparatus. 1—gas cylinder; 2—vacuum vessel; 3—ladle; 4—vacuum pump; 5—velocimeter; 6—electrical conductivity meter; 7—manometer.

2.3. Measurements of circulation flow rate and mixing time

It is more precise to use an LGY-II intelligent velocity instrument and a new velocity sensor to measure the circulation flow rate which is similar to the method of pitot tubes [12].

An electrical conductivity meter [13] was used to measure the mixing time. The saturated NaCl aqueous solution was used as the tracer. Meanwhile the DJ800 system was employed to measure the conductivity until a stable value (C_∞) was reached. The time for reaching the stable value is called mixing time.

2.4. Definition of circulation period

When fluid circulated in the reactor, multiple peaks in the tracer concentration curve appeared. A typical experimental conductivity curve *vs.* time for RH modeling is shown in Fig. 2. There are two peaks in the curve that indicate RH is a typical circulation reactor. The water is sucked through the up-snorkel into the vacuum vessel, then through the down-snorkel flowing back to the ladle. The circulation period is the interval between the two peaks:

$$T=t_2-t_1 \tag{2}$$

where t_1 and t_2 stand for the time when the first peak and the second peak appear, respectively.

3. Results and discussion

3.1. Effect of the lift gas flow rate on circulation period

The time dependence of conductivity was measured and the circulation period was calculated at different lift gas flow rates (prototype) when the submersion depth of snorkels (prototype) was 400, 480, 560, 640, and 720 mm, respectively. The results are shown in Fig. 3.

As can be seen in Fig. 3, the circulation period is in the range from 15 to 32 s for different lift gas flow rates. For the submersion depth of 400, 480, 560, 640, and 720 mm, the circulation period is shortened by 10.45, 7.89, 7.75, 7.91, and 8.99 s by increasing the lift gas flow rate from 400 to 800 NL/min, and is shortened by 2.25, 1.25, 1.64, 2.01, and 2.32 s by increasing the lift gas flow rate from 800 to 1400 NL/min.

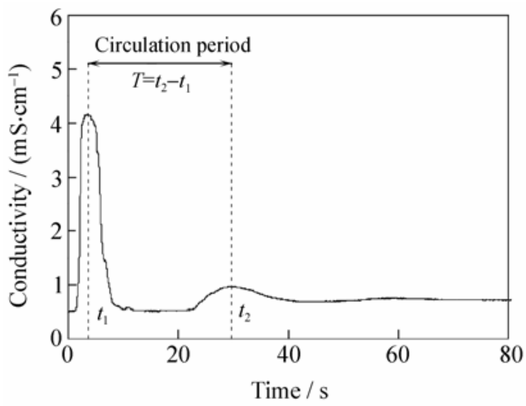

Fig. 2. Determination method of circulation period.

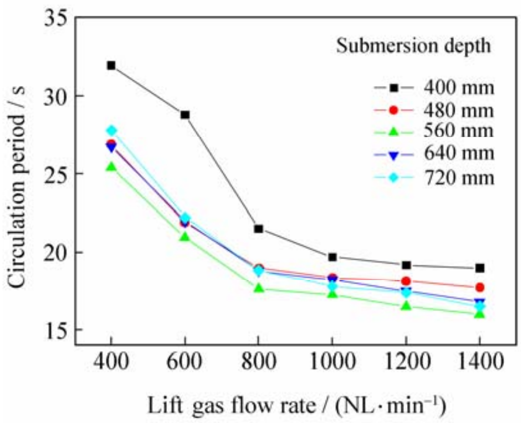

Fig. 3. Relationship between circulation period and lift gas flow rate.

The circulation velocity is increased by enhancing the gas flow rate. There are two effects on the circulation period caused by the increase in circulation velocity. On the one hand, the circulation period is shortened by increasing the circulation velocity. On the other hand, increasing the circulation velocity disturbs the molten steel flow which is obstructive to shorten the circulation period. The experimental results show that when the gas flow rate is less than 800 NL/min, the circulation period is reduced rapidly. When the gas flow rate is bigger than 800 NL/min, the circulation period is reduced smoothly.

In conclusion, the circulation period is shortened with the increase in gas flow rate. The short circulation period promotes the circulation of molten steel and the refining efficiency. In the experiment, the effect is obvious when the gas flow rate is less than 800 NL/min.

3.2. Effect of the submersion depth of snorkels on circulation period

The circulation period was measured under different submersion depths and lift gas flow rates. The results are shown in Fig. 4.

It can be seen from Fig. 4 that the effect of submersion depth on circulation period is almost the same at different lift gas flow rates. When the submersion depth is less than 560 mm, the circulation period is shortened with the increase in submersion depth; when the submersion depth is bigger than 560 mm, the circulation period is prolonged; and the circulation period is the shortest when the submersion depth is 560 mm. When the submersion depth is less than 480 mm, the effect of submersion depth on circulation period is obvious.

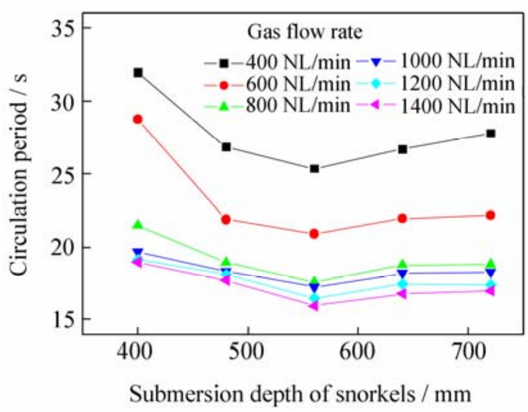

Fig. 4. Relationship between circulation period and submersion depth.

Under the same other conditions, there are two aspects of the effect on circulation period caused by the increase in submersion depth. On the one hand, the molten steel flow route is reduced with the increase in submersion depth, accordingly, the circulation period is shortened. On the other hand, many studies show that the velocity and resistance of molten steel at the ladle bottom increase with the increase in submersion depth [14], so the circulation period becomes longer. The experimental results show that the effect of the first aspect is greater than that of the second one when the submersion depth is less than 560 mm.

To sum up, the circulation period is the shortest when the submersion depth is 560 mm, and is the longest when the submersion depth is less than 480 mm.

3.3. Relationship between molten steel circulation and mixing in RH refining

The following equation expresses the relationship among the number of circulation period, mixing time, and circulation period.

$$n = t/T \tag{3}$$

where n is the number of circulation period, t the mixing time, and T the circulation period.

The mixing time at different lift gas flow rates and submersion depths was measured. The relationship between the number of circulation period and gas flow rate is shown in Fig. 5. Fig. 5 shows that n is between 2.19 and 2.97. When the gas flow rate is beyond 800 NL/min, n is about constant. If the gas flow rate is below 800 NL/min, n changes rigidly. In our experiment, n is below 3, which means 3 times circulation is enough to make the molten steel mix up in the ladle.

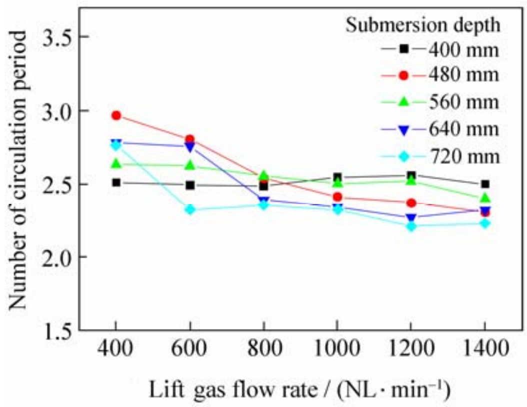

Fig. 5. Relationship between the number of circulation period (*n*) and lift gas flow rate.

Ref. [15] adopted flow circulation to analyze the mixing behavior in the ladle injection process, considered the mixing as a process of fluid getting uniform after several circulations. The number of circulation period (n) that is necessary for mixing is expressed as

$$n=t/T\approx\ln(100/i) \quad (4)$$

where i is the mass ratio of the unmixed fluid to total fluid. Therefore, three times circulations are enough to make molten steel uniform. This conclusion is consistent with the experiment results.

3.4. Relationship between the degassing rate in one circulation period and lift gas flow rate

The degassing rate can be defined as the mass ratio of vacuum treated molten steel to total molten steel in one RH circulation period. It is related to the RH refining efficiency. The greater the degassing rate, the higher the RH refining efficiency. The degassing rate (R) in one RH circulation period is expressed as

$$R=Q_0/W=Q/(W\cdot T) \quad (5)$$

where Q_0 is the mass of vacuum treated molten steel in one circulation period, W the mass of total molten steel in the ladle, and Q ($Q=Q_0\cdot T$) the circulation rate.

The relationship between R and lift gas flow rate for different submersion depths are shown in Fig. 6.

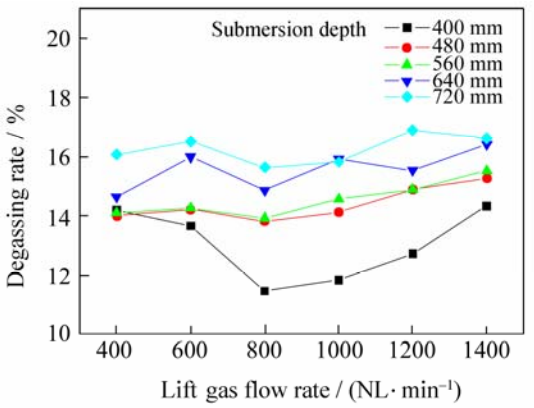

Fig. 6. Relationship between degassing rate (R) and lift gas flow rate.

When the lift gas flow rate is lower than 600 NL/min, the degassing rate (R) in one circulation period increases with the increase of lift gas flow rate (except the submersion depth of 400 mm). Especially, when the submersion depth is 640 mm, the increase range is relatively higher than others. When the lift gas flow rate is between 600 and 800 NL/min, the degassing rate in one circulation period decreases with the increase in lift gas flow rate. The decrease range is greater as the submersion depth is 400 mm. When the flow rate is greater than 800 NL/min, the degassing rate in one circulation period increases with the increase of lift gas flow rate (except the submersion depth of 640 mm). The degassing rate in one circulation period is the lowest when the lift gas flow rate is 800 NL/min at any submersion depth.

The experimental results show that the influence of lift gas flow rate on R is rather complex. When the lift gas flow rate is greater than 800 NL/min, the increase of lift gas flow rate is beneficial for improving the RH refining efficiency. However, when the flow rate is between 600 and 800 NL/min, decreasing lift gas flow rate is helpful to improve the RH refining efficiency.

3.5. Relationship between R and the submersion depth of snorkels

The relationship between R and the submersion depth of snorkels is shown in Fig. 7. In Fig. 7, it can be seen that increasing submersion depth can improve the degassing rate in one circulation period, except that the gas flow rate is lower than 600 NL/min and the submersion depth is smaller than 480 mm.

There are two aspects of the effect on degassing rate caused by the increase in submersion depth. On the one hand, the molten steel route is reduced which is caused by the increase in submersion depth. On the other hand, as analyzed above, the resistance of molten steel at the ladle bottom increases with the increase in submersion depth. The experimental results show that when the lift gas flow rate is lower than 600 NL/min and the submersion depth is smaller than 480 mm, the increase of submersion depth enhances the resistance of molten steel flowing through the ladle.

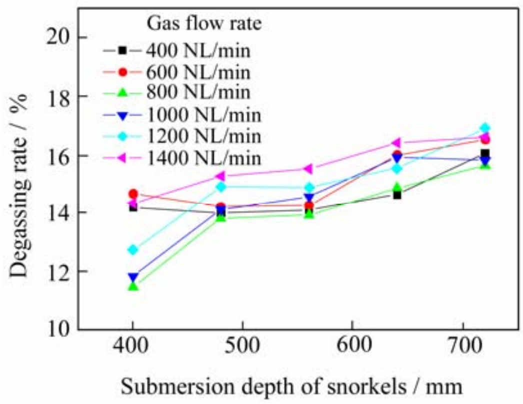

Fig. 7. Relationship between degassing rate (R) and submersion depth.

4. Conclusions

(1) The circulation period is in the range from 15 to 32 s. The circulation period is shortened with the increase in gas flow rate. The short circulation period promotes the circulation of molten steel and the refining efficiency. In the ex-

periment, the effect is obvious when the gas flow rate is less than 800 NL/min.

(2) The circulation period is the shortest when the submersion depth is 560 mm, and is the longest when the submersion depth is smaller than 480 mm.

(3) When the gas flow rate is more than 800 NL/min, the number of circulation period is about constant. Three times circulation is enough to make the molten steel mix up in the ladle.

(4) When the gas flow rate is 800 NL/min, the degassing rate is the least in RH circulation. When the gas flow rate is over 800 NL/min, increasing the gas flow rate can enhance the degassing rate in RH circulation.

(5) Increasing submersion depth can improve the degassing rate in the circulation period, except that the gas flow rate is lower than 600 NL/min and the submersion depth is smaller than 480 mm.

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