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On cooling rate of metal melt in steel-teeming ladle and tundish during continuous steel casting

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Abstract. The thermal state of liquid metal at the continuous steel casting stage was studied by methods of correlation analysis under the assumption that measurable objects are random variables. The thermal state of metal melt is characterized by the values of metal temperature T_n at a given stage and duration of stages τ_n, and is described by the integrated index – cooling rate W_n. The cooling rate is the differential quotient of the liquid metal temperatures at the beginning and end of the stage to the duration of this stage. The metal cooling rate at various stages of continuous steel casting phase was calculated. The first stage includes the period from the end of metal processing at the integrated steel processing unit to the beginning of vacuum degassing. The second stage includes the period from the beginning of vacuum degassing to its completion. The third stage includes the period from the end of vacuum degassing to the first temperature measurement in the tundish. Then there are periods of consecutive temperature measurements in the tundish. The study established that metal cooling rates vary significantly depending on process stages. The absolute values of the cooling rate differ by more than an order of magnitude. The minimum rate of metal cooling was recorded in the tundish. Its value was 0.09 °C/min. The maximum metal cooling rate was detected during tapping from the steel-teeming ladle into the tundish. In this case, the cooling rate was 1.43 °C/min. The main factors affecting the metal cooling rate were determined. These factors include: the initial temperature of liquid metal after the end of processing at the integrated steel processing unit; the temperature of liquid metal after vacuum degassing; the presence on the liquid metal surface of the oxide solution formed by slag-forming mixtures; availability and effectiveness of heat insulating mixtures; as well as the heat insulating properties of refractory linings. During vacuum degassing, the metal cooling rate was essentially determined by convective energy losses and energy losses for inert gas heating. After the vacuum degassing stage, the cooling rate significantly decreases due to the use of heat insulating mixtures. The highest rate of metal cooling is achieved when it passes through the steel outlet channel and the metal protection tube during tundish filling. The lowest metal cooling rate was found in the tundish due to the presence of a porous shotcrete layer with low thermal conductivity.

Keywords: random value, correlation, selection, liquid metal, steel-teeming ladle, tundish, cooling rate of metal, time, temperature, steel continuous casting

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Оригинальная статья

К вопросу о скорости охлаждения металлического расплава в сталеразливочном и промежуточном ковшах на этапе непрерывной разливки стали

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Аннотация. Методами корреляционного анализа проведено исследование теплового состояния жидкого металла на этапе непрерывной разливки стали в предположении, что измеримые объекты являются случайными величинами. Тепловое состояние металлического расплава характеризуется значениями температуры металла T_n на данной стадии и длительностью протекания стадий τ_n и описывается интегральным показателем – скоростью охлаждения W_n. Скорость охлаждения представляет собой отношение разности температур жидкого металла в начале и конце стадии к длительности данной стадии. Вычислены скорости охлаждения металла на различных стадиях этапа непрерывной разливки стали. Первая стадия включает период времени от завершения обработки металла на агрегате комплексной обработки стали до начала вакуумирования. Вторая стадия включает период от начала вакуумирования до его завершения. Третья стадия включает период от момента завершения вакуумирования до первого измерения температуры в промежуточном ковше. И далее идут периоды последовательных измерений температуры в промежуточном ковше. Установлено, что скорости охлаждения металла варьируются в значительных пределах в зависимости от технологических стадий. Абсолютные значения скорости охлаждения отличаются более, чем на порядок. Минимальная скорость охлаждения металла зафиксирована в промежуточном ковше. Ее значение составляет 0,09 °С/мин. Максимальная скорость охлаждения металла выявлена при выпуске металла из сталеразливочного ковша в промежуточный ковш, при этом скорость охлаждения составляет 1,43 °С/мин. Определены основные факторы, влияющие на скорость охлаждения металла. К этим факторам относятся начальная температура жидкого металла после завершения обработки на агрегате комплексной обработки стали, температура жидкого металла после завершения вакуумирования, наличие на поверхности жидкого металла оксидного раствора, образованного шлакообразующими смесями, наличие и эффективность теплоизолирующих смесей, а также теплоизолирующие характеристики огнеупорных футеровок. При вакуумировании скорость охлаждения металла существенным образом определяется конвективными потерями энергии и потерями энергии с на нагрев инертного газа. После стадии вакуумирования скорость охлаждения значительно снижается за счет применения теплоизолирующих смесей. Наибольшая скорость охлаждения металла установлена при его прохождении через сталевыпускной канал и трубу защиты металла при наполнении промежуточного ковша. Наименьшая скорость охлаждения металла характерна при его нахождении в промежуточном ковше, за счет наличия пористого торкрет-слоя, обладающего низкой теплопроводностью.

Ключевые слова: случайная величина, корреляция, выборка, жидкий металл, сталеразливочный ковш, промежуточный ковш, скорость охлаждения металла, время, температура, непрерывная разливка стали

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Introduction

The continuous casting of steel is a special phase in metallurgical processing. It is at this stage that the metal alters its state of aggregation, passing from the liquid phase to solid. In the liquid phase in the steel-teeming ladle, the metal enters the continuous steel casting section. Here the metal is dosed through an intermediate melting tank (tundish) into one or more crystallizers forming an ingot of a given geometric shape. At this stage, both the liquid metal in the steel-teeming ladle and tundish and melting tanks themselves constitute a single interconnected energotechnological unit. The energy source for continuous casting is the energy of the liquid metal. The most important feature (in the energy sense) which distinguishes continuous casting from the previous phases of steel melting in the steelmaking unit (final finishing of the metal in the section of integrated processing of steel and vacuum degassing) is that at this phase it is impossible to increase the temperature of the liquid metal. The impossibility of heating the metal in the steel-teeming ladle at the casting stage is due to the technology itself. Several options have been proposed for heating the metal in the tundish. However, these are only theoretical developments [1 – 4]. Thus, the metal in these tanks is in a state of continuous natural cooling. The temperature of the metal during casting is strictly regulated, and is a determining factor in obtaining a high-quality final ingot. In this regard, several models have been proposed to predict the temperature of liquid steel in the steel-teeming ladle and tundish [5, 6], as well as a statistical model that takes into account a large array of data [7]. In this case, the preservation of the physical heat of the metal in the steel-teeming ladle and tundish during casting is an important process task. Slag-forming fluxes (mixtures) supplied to the melt surface, for example, in a tundish [8], as well as slag-forming fluxes with optimal viscosity in the liquid phase, also contribute to reducing the cooling rate of the metal melt [9 – 12]. The conditions of metal cooling in the steel-teeming ladle and tundish are different, and the factors affecting them are very diverse. Therefore, the study and analysis of the factors which affect metal cooling in the steel-teeming ladle and tundish are important in terms of both heat insulation of the exposed surface of the melt by specific mixtures [13 – 15], as well as in terms of modeling the metal temperature distribution under heat-insulating mixtures [16 – 19].

Research Objects and Methods

The objects of the study are: the values of the liquid metal temperature in the steel-teeming ladle and tundish; the moments of time at which temperature measurements were made; and the time periods of the beginning and end of the corresponding stages. The melt temperature was measured using standard immersion thermocouples. The time was recorded with stationary timers used commercially in the technological process. Studies were carried out using a selective method and correlation tools. The selection scope was limited to 14 melts. This scope was minimum. Further reduction of the selection scope can lead to incorrect conclusions. Two-dimensional selections were analyzed under the assumption that the measurable objects are random values in relation to the interrelation between parameters X and Y. In this case we made an assumption that their mathematical expectations EX and EY are related by linear (regression) dependence $EY = aEX + b$. Parameters a and b were estimated by means of the least-squares method [20, 21]. The degree of linear interdependence of the observed parameters was estimated using selective correlation coefficient R.

Experimental data

We studied the experimental data of the values of the liquid metal temperature in the steel-teeming ladle after out-of-furnace processing in the integrated steel processing unit (ISPU), vacuum degassing, and immediately before the beginning of casting. We also studied the experimental data of the values of the liquid metal temperature, obtained by several consecutive measurements in the tundish. We also recorded the time at which the corresponding temperatures were measured, the time period from the end of processing at the ISPU and to the beginning of vacuum degassing, as well as the time period from the temperature measurement after vacuum degassing to the beginning of casting. The experimental data obtained for the analysis is summarized in Table 1.

Table 1 shows the time data in "hours : minutes" format. The first column shows time τ_0 to complete metal processing at the ISPU. The second column shows the values of the liquid metal temperature in the steel-teeming ladle after the completion of process operations at the integrated steel processing section T_0. The third column shows the time of the beginning of vacuum degassing τ_1. The fourth column contains the values of the metal temperature at the beginning of vacuum degassing T_1. The fifth column shows the time of vacuum degassing completion τ_2. The sixth column contains the values of the metal temperature after vacuum degassing completion T_2. The seventh to sixteenth columns contain measurement times and values of metal temperature in the tundish, at the first measurement and then consecutively up to the fifth measurement.

The data in Table 1 shows that temperature measurements at the casting phase are carried out every 10 – 20 minutes on average. Further analysis will require certain calculated values to be obtained from experimental data. These parameters and their values are given in Table 2.

The data in Table 2 shows that the calculated values represent periods of time, temperature differences and metal cooling rates. Temperature differences were derived from the temperature values at the boundary points of the corresponding time period during which the measurement was made. The metal cooling rates were calculated as the temperature difference to the corresponding time period ratio. These values characterize the thermal state of the metal in the steel-teeming ladle and tundish at the consecutive stages of out-of-furnace processing and metal casting. These stages include metal processing in the steel-teeming ladle at the ISPU section, vacuum degassing, casting and the thermal state of the metal in the tundish, as well as its transportation stage.

Further analysis may feasibly be carried out by means of operating an integral parameter: metal cooling rate W [14, 22] and its relationship with the temperature at the stages under study.

Figure 1 shows a scatter diagram built in the "metal temperature in the steel-teeming ladle after processing at the ISPU section T_0 – cooling rate $\frac{T_0 - T_1}{\tau_1 - \tau_0}$ coordinates".

Table 1

Experimental data

Таблица 1. **Экспериментальные данные**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
τ_0	T_0	τ_1	T_1	τ_2	T_2	τ_3	T_3	τ_4	T_4	τ_5	T_5	τ_6	T_6	τ_7	T_7
18:41	1601	18:55	1592	19:46	1552	20:11	1514	20:27	1516	20:43	1519	20:59	1515	21:09	1515
20:27	1590	20:36	1586	21:07	1551	21:31	1516	21:47	1516	22:03	1519	22:18	1518	22:32	1512
21:51	1596	21:58	1589	22:34	1550	22:53	1513	21:09	1516	23:25	1514	23:40	1511	23:52	1508
23:02	1595	23:25	1584	23:52	1553	0:10	1519	0:26	1520	0:42	1517	0:58	1513	1:14	1513
0:25	1595	0:33	1586	1:08	1550	1:36	1516	1:52	1518	2:08	1515	2:24	1507	2:36	1508
1:51	1590	1:58	1586	2:31	1552	2:58	1513	3:14	1515	3:30	1514	3:46	1513	4:00	1512
3:10	1590	3:18	1587	4:04	1551	4:24	1518	4:40	1513	4:56	1517	5:12	1512	5:28	1510
4:33	1592	4:53	1583	5:28	1552	5:53	1509	6:04	1512	6:19	1513	6:35	1512	6:52	1507
6:06	1588	6:21	1577	7:07	1551	7:18	1516	7:33	1516	7:49	1513	8:03	1508	8:15	1505
0:45	1594	0:52	1586	1:06	1551	2:14	1522	2:31	1516	2:48	1514	2:59	1514	–	–
1:46	1583	2:04	1582	2:45	1544	3:19	1511	3:31	1516	3:46	1515	3:59	1514	–	–
2:52	1582	3:07	1580	3:49	1545	4:24	1516	4:41	1515	5:00	1512	5:16	1506	–	–
4:25	1582	4:32	1576	4:58	1541	5:33	1515	5:48	1515	6:02	1510	6:10	1512	–	–
6:24	1587	6:36	1580	7:13	1544	7:39	1516	7:56	1512	8:13	1512	8:28	1506	–	–

Table 2

Calculated values of time periods, temperature difference and metal cooling rate

Таблица 2. **Расчетные значения периодов времени, разности температур и скорости охлаждения металла**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
$\tau_1-\tau_0$	T_0-T_1	$\frac{T_0-T_1}{\tau_1-\tau_0}$	$\tau_2-\tau_1$	T_1-T_2	$\frac{T_1-T_2}{\tau_2-\tau_1}$	$\tau_3-\tau_2$	T_2-T_3	$\frac{T_2-T_3}{\tau_3-\tau_2}$	$\tau_4-\tau_3$	T_3-T_4	$\frac{T_3-T_4}{\tau_4-\tau_3}$	$\tau_5-\tau_3$	T_3-T_5	$\frac{T_3-T_5}{\tau_5-\tau_3}$	$\tau_6-\tau_3$	T_3-T_6	$\frac{T_3-T_6}{\tau_6-\tau_3}$	$\tau_7-\tau_3$	T_3-T_7	$\frac{T_3-T_7}{\tau_7-\tau_3}$
14	9	0.64	51	40	0.78	25	38	1.52	41	36	0.88	57	33	0.58	73	37	0.51	83	37	0.45
9	4	0.44	31	35	1.13	24	35	1.46	40	35	0.88	56	32	0.57	71	33	0.46	85	39	0.46
7	7	1.00	36	39	1.08	19	37	1.95	35	34	0.97	51	36	0.71	66	39	0.59	78	42	0.54
23	11	0.48	27	31	1.15	18	34	1.89	34	33	0.97	50	36	0.72	66	40	0.61	82	40	0.49
8	9	1.13	35	3	0.09	28	34	1.21	44	32	0.73	60	35	0.58	76	43	0.57	88	42	0.48
7	4	0.57	33	34	1.03	27	39	1.44	43	37	0.86	59	38	0.64	75	39	0.52	89	40	0.45
8	3	0.38	46	36	0.78	20	33	1.65	36	38	1.06	52	34	0.65	68	39	0.57	84	41	0.49
20	9	0.45	35	31	0.89	25	43	1.72	36	40	1.11	51	39	0.76	67	40	0.60	84	45	0.54
15	11	0.73	46	26	0.57	11	35	3.18	26	35	1.35	42	38	0.90	56	43	0.77	68	46	0.68
7	8	1.14	14	12	0.86	68	29	0.43	85	43	0.51	102	37	0.36	113	37	0.33	–	–	–
18	1	0.06	41	40	0.98	34	33	0.97	46	28	0.61	61	29	0.48	74	30	0.41	–	–	–
15	2	0.13	42	35	0.83	35	29	0.83	52	30	0.58	71	33	0.46	69	39	0.57	–	–	–
7	6	0.86	26	35	1.35	35	26	0.74	50	26	0.52	64	31	0.48	72	29	0.40	–	–	–
13	7	0.54	37	1	0.03	26	28	1.08	43	32	0.74	60	32	0.53	70	38	0.54	–	–	–

The cooling rate was calculated for the period from the completion of processing at the ISPU section τ_0 to the moment of the beginning of vacuum degassing τ_1. These parameters characterize the thermal state of liquid metal in the steel-teeming ladle at this stage to the fullest extent.

Figure 1 shows a certain trend in the joint change of experimental data, according to which this data is grouped around a straight line calculated on the basis of minimizing the sum of squares of deviations of random variables Y_j from $aX_j + b$, $j = 1, \ldots, 14$. The regression equation relating the expected values of the observed quantities, the estimates of regression parameters a and b, and the degree of interdependence of the observed values (selective correlation coefficient R) is given below

$$W_1 = 0.03T_0 - 45.78;\ R = 0.49. \quad (1)$$

Figure 2 is a scatter diagram of experimental data obtained at the next stage of metal processing: the stage of vacuum degassing in the steel-teeming ladle. The thermal state of the liquid metal at this stage can be fully characterized as follows: the temperature of liquid metal, measured at the beginning of vacuum degassing T_1; the melt cooling rate W calculated as ratio $\frac{T_1 - T_2}{\tau_2 - \tau_1}$; and temperature measured in the end of vacuum degassing T_2.

As Figure 2 shows, the experimental data reveal a pronounced linear regression dependence. Regression parameters:

$$W_2 = 0.02T_1 - 34.41;\ R = 0.76. \quad (2)$$

The next stage of the metal transportation and casting phase begins at the end of vacuum degassing, i.e. at the moment of temperature measurement T_2. It ends at the moment of the first temperature measurement in the tundish T_3. Note that defining the stage in this way does not seem to be strictly correct. This discrepancy is due to the fact that the moment of temperature measurement T_3 already refers to another metallurgical unit, the tundish. This forced discrepancy is due to the technical impossibility of measuring the temperature in the steel-teeming ladle before opening the slide gate and the beginning of casting. As will be shown below, this is the main stage in terms of the thermal state of the metal, determining the thermal stability of casting. The cooling rate of the metal in this case is calculated theoretically.

Figure 3 shows a scatter diagram of experimental data of the metal temperature values after the completion of vacuum degassing T_2. It also shows the metal cooling rate calculated from the data of the first temperature measurement in the tundish T_3 over a corresponding period of time.

As Figure 3 shows, in this case we can also observe a positive linear regression relationship between the experimental values. Regression parameters:

$$W_3 = 0.09T_2 - 138.73;\ R = 0.51. \quad (3)$$

In order to evaluate the thermal state of liquid metal in the tundish, we proceed as follows. We assume that the input initial parameters are the values of the temperature of liquid metal, obtained after the completion of vacuum degassing. The final parameters are the values of the temperature of liquid metal in the tundish at first and subsequent measurements. Consecutive temperature measurements are made every 14 – 20 minutes. Further, using the corresponding scatter diagrams, we can trace how the regression and its parameters change.

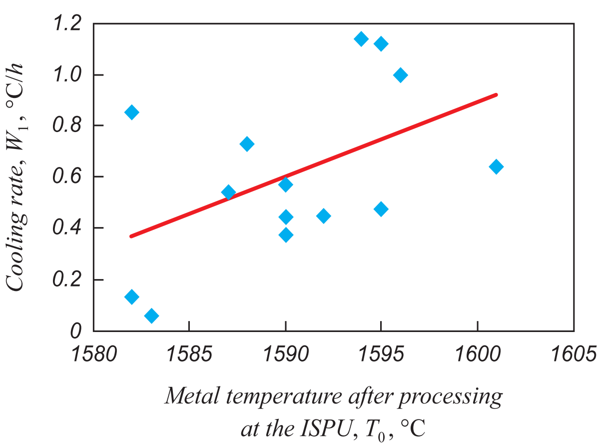

Fig. 1. Scatter diagram of the metal cooling rate and temperature values after processing at the ISPU

Рис. 1. Диаграмма рассеяния значений скорости охлаждения металла и его температуры после обработки на АКОС

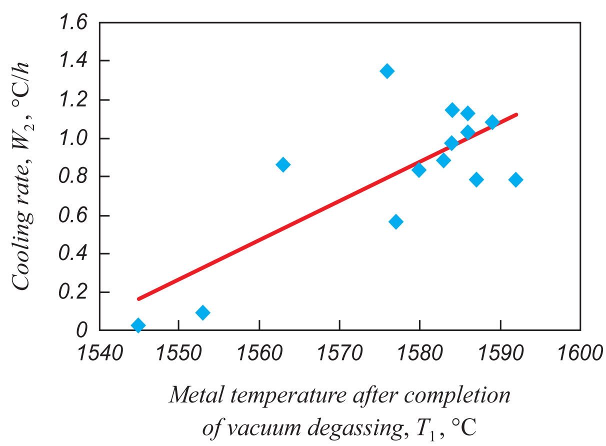

Fig. 2. Scatter diagram of the metal cooling rate and temperature at the vacuum degassing stage

Рис. 2. Диаграмма рассеяния скорости охлаждения металла и его температуры на стадии вакуумирования

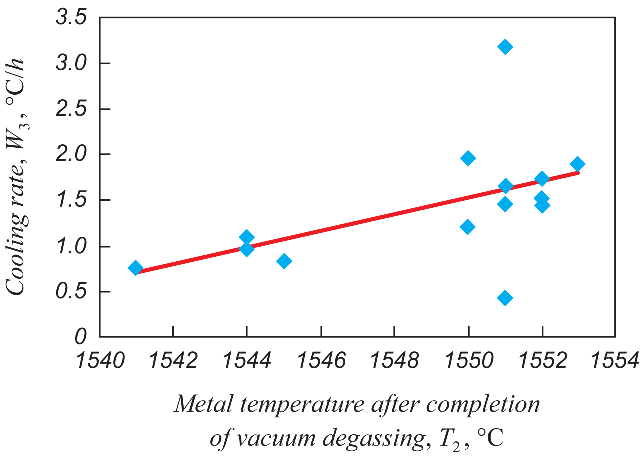

Fig. 3. Scatter diagram of the metal cooling rate and temperature at the casting stage

Рис. 3. Диаграмма рассеяния скорости охлаждения металла и его температуры на стадии разливки

Figures 4 – 8 show the scatter diagrams of liquid metal temperatures after vacuum degassing at the first and subsequent measurements in the tundish.

As Figure 4 shows, the experimental data represent an area with very minor linear regression dependence. Regression parameters:

$$T_3 = 0.12T_2 + 1331;\ R = 0.14. \tag{4}$$

As Figure 5 shows, the experimental data represents an area with a more pronounced linear regression dependence compared to the previous case. Regression parameters:

$$T_4 = 0.07T_2 + 1400.00;\ R = 0.28. \tag{5}$$

Figure 6 is a scatter diagram of experimental data of the liquid metal temperature values after vacuum degassing and the melt temperature in the tundish at the third measurement.

As Figure 6 shows, the experimental data represents an area with even more pronounced linear regression dependence compared to the previous two measurements. Regression parameters:

$$T_5 = 0.44T_2 + 837.70;\ R = 0.63. \tag{6}$$

The next group of experimental data obtained with the fourth temperature measurement in the tundish is shown in the scatter diagram in Figure 7.

As Figure 7 shows, at this temperature measurement, the experimental data is related by a clearly expressed linear regression dependence. The equation and regression parameters are given below:

$$T_6 = 0.33T_2 + 1004.00;\ R = 0.35. \tag{7}$$

The illustration of the experimental data obtained by successive temperature measurements in the tundish is completed with a scatter diagram (Figure 8).

Figure 8 also shows a clear correlation between the experimental data. The regression equation and its parameters are given below:

$$T_7 = 1.75T_2 - 1204.00;\ R = 0.54. \tag{8}$$

Discussion of results

The thermal state of liquid metal at the stage of metal transportation and casting was analyzed. At this phase,

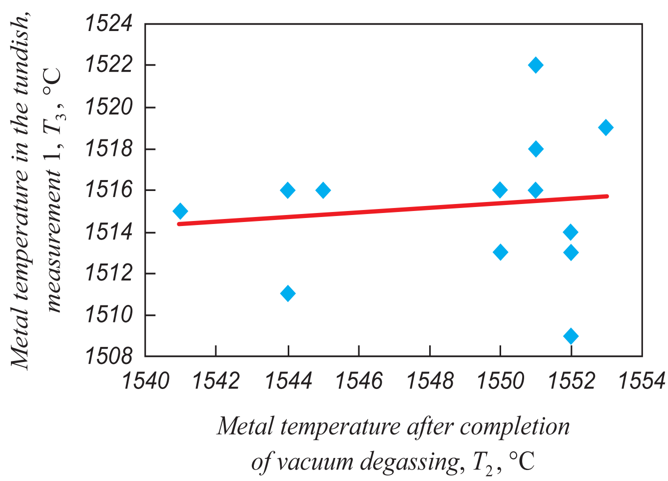

Fig. 4. Scatter diagram of metal temperatures after vacuum degassing and in the tundish during the first measurement

Рис. 4. Диаграмма рассеяния температуры металла после вакуумирования и температуры металла в промежуточном ковше при первом замере

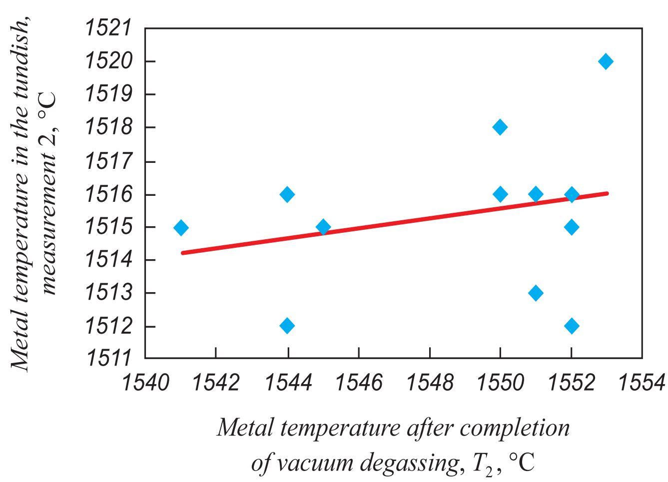

Fig. 5. Scatter diagram of metal temperatures after vacuum degassing and in the tundish at the second measurement

Рис. 5. Диаграмма рассеяния температуры металла после вакуумирования и температуры металла в промежуточном ковше при втором замере

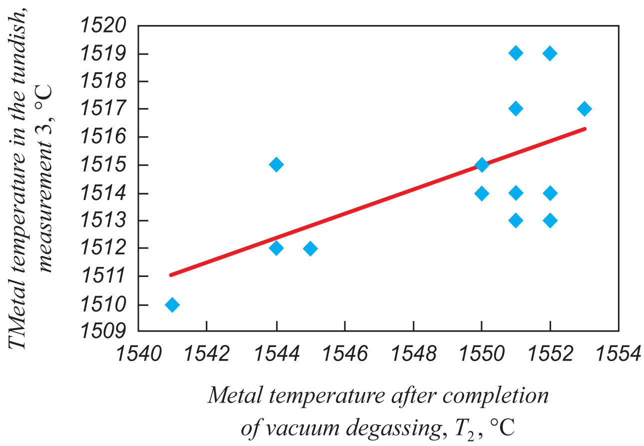

Fig. 6. Scatter diagram of metal temperatures after vacuum degassing and in the tundish at the third measurement

Рис. 6. Диаграмма рассеяния температуры металла после вакуумирования и температуры металла в промежуточном ковше при третьем замере

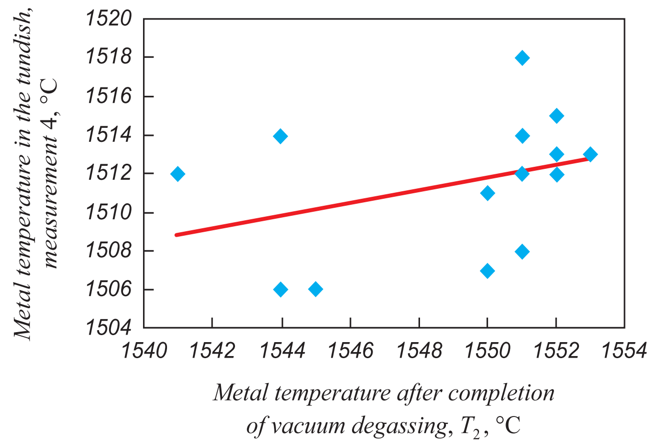

Fig. 7. Scatter diagram of metal temperatures after vacuum degassing and in the tundish at the forth measurement

Рис. 7. Диаграмма рассеяния температуры металла после вакуумирования и температуры металла в промежуточном ковше при четвертом замере

the stages at which metal cooling conditions differ significantly were identified. These differences are due to the following factors: the initial temperatures of liquid metal at the end of processing at the ISPU; the metal temperatures after the end of vacuum degassing; time periods between the stages; as well as the presence of a slag layer and a layer of heat-insulating mixture on the surface of the metal melt. The influence of these factors can be characterized by an integral parameter: metal cooling rate W.

At the first stage (see Figure 1), we observe positive regression, i.e., an increase in metal temperature after processing at the ISPU which causes an increase in cooling rate W_1. This result is in complete agreement with the physical cooling pattern of metal in the steel-teeming ladle at this stage. Most of the energy of liquid metal is lost due to heat transfer by radiation from the open surface of the melt. Heat loss associated with radiation is proportional to the fourth power of temperature. This the reason why the dependence of the cooling rate on the metal temperature after processing at the ISPU is so pronounced. The metal cooling rate at this stage would be even higher, if it was not for the presence on the surface of a metal melt layer induced by feeding lime, deoxidizers and other slag-forming materials. Highly basic slag prevents accelerated cooling of the metal melt.

A similar situation was identified at the next stage of out-of-furnace processing: vacuum degassing (see Figure 2). The cooling rate of liquid metal increases with increasing metal temperature at the beginning of vacuum degassing. Compared with the previous stage, the slope of the regression line is steeper and the cooling rate of the metal is higher. The higher cooling rate is due to significant non-stationarity of the vacuum degassing process.

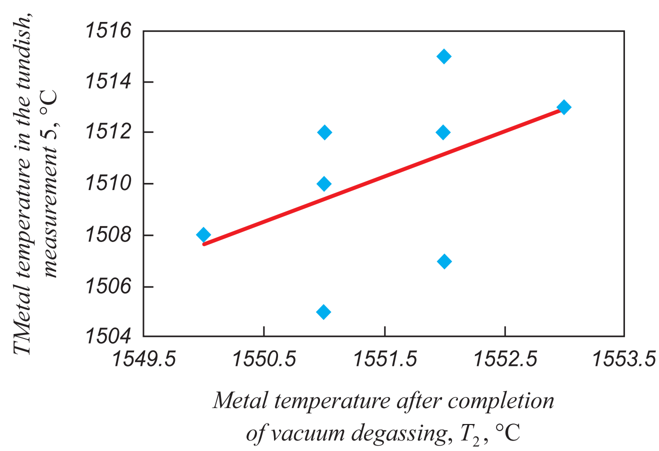

Fig. 8. Scatter diagram of metal temperatures after vacuum degassing and in the tundish at the fifth measurement

Рис. 8. Диаграмма рассеяния температуры металла после вакуумирования и температуры металла в промежуточном ковше при пятом замере

If at the previous stage liquid metal in the steel-teeming ladle was in a state of natural cooling, during vacuum degassing, additional heat losses occur other than heat losses due to radiation. They are associated with increasing convective heat transfer and loss of energy of liquid metal when it is blown by inert gas.

After the completion of vacuum degassing it is technically impossible to measure the temperature of liquid metal in the steel-teeming ladle immediately before the start of casting. This is due to the fact that, firstly, the ladle with metal is covered with a lid, and, secondly, it is raised to a height on a casting turntable. Nevertheless, this stage is very informative when it comes to analyzing the thermal state of the liquid metal. Intuitively, the cooling rate of the metal at this stage should be significantly lower than at the previous stages. This is due to the fact that after vacuum degassing, the heat insulating mixture is fed to the melt surface in the ladle and the ladle is covered with a lid. This causes a radical reduction of heat loss from the exposed surface of the melt by radiation and convection. In order to estimate the metal cooling rate, the results obtained in [15, 23] were used, and the calculation was performed using equation

$$W = \left(\ln T_0'\right)^{0.75} - \left(\ln M\right)^{0.64} - \left(\ln T_2'\right)^{0.10} + \left(\ln N\right)^{0.53}, \quad (9)$$

where T_0' is the temperature of metal at the outlet from the steelmaking unit; M is the weight of metal in the steel-teeming ladle; T_2' is the temperature of the refractory lining of the steel-teeming ladle during heating; N is the number of metal pours into the steel-teeming ladle.

The first summand in relation (9) was obtained for the conditions when the surface of liquid metal in the steel-teeming ladle is completely open, i.e., there is no heat-insulating or slag-forming mixture on the surface of the melt. In the presence of heat-insulating mixture and a lid, the logarithm of the first summand decreases and equals 0.35. The remaining summands are constants and can be used in calculations without any restrictions. The results obtained demonstratively refute the conclusions given in [5] that the thickness of the liquid slag layer in the steel-teeming ladle, the temperature of the liquid steel release from the steelmaking unit into the ladle, and the life of the ladle, i.e. the wear of the steel-teeming ladle lining, have no significant effect on the metal cooling in the ladle. For calculation purposes, we can make the following assumptions: the temperature at the steelmaking unit outlet is 1640 °C; the weight of metal in the ladle is 138 tons; the temperature of the refractory lining of the steel-teeming ladle during heating is 870 °C; and the number of pours is 80. As a result of calculation we obtain:

$$W = (\ln 1640)^{0.35} – (\ln 138)^{0.64} – (\ln 870)^{0.10} +$$
$$+ (\ln 80)^{0.53} = 2.02 – 2.78 – 1.21 + 2.19 = 0.22 \text{ °C/min}.$$

Thus, the metal cooling rate in the steel-teeming ladle at this stage is the lowest.

Figure 3 shows that the metal cooling rate calculated from the first temperature measurement in the tundish also increases as the metal temperature increases after vacuum degassing is completed. The absolute values of the cooling rate at this stage are the highest. This result, at first glance, does not seem obvious, if we take into account the data obtained by analyzing the dependence of the metal temperature in the tundish during sequential measurements (see Figures 4 – 8). The initial temperatures were taken to be the values measured after the completion of vacuum degassing.

The analysis of the data shown in Figures 4 – 8 shows that the degree of interdependence of parameters during successive temperature measurements in the tundish increases systematically. This regularity is due to the fact that the heat loss in the tundish is extremely low. The difference between the metal temperatures during the first and second measurements is comparable with the accuracy of measurements by a submersible thermocouple (see Figures 4, 5). A noticeable difference in the values of temperatures appears only at the third, fourth and fifth measurements. This is reflected in a significant increase in the selective correlation coefficient (see Figures 6 – 8). As these figures show, the metal cooling rate in the tundish is the lowest. It is of interest to estimate the metal cooling rate in the tundish. In order to achieve this, we calculate the average values of the cooling rate from ratio $\left(\dfrac{T_3 - T_7}{\tau_7 - \tau_3}\right)_{av}$. The average rate equals 0.09 °C/min. Such a low cooling rate of the metal in the tundish is due to the fact that the surface of the metal melt in the tundish is protected by layers of the slag-forming heat-insulating mixture and the lined lid. Therefore, heat losses due to radiation and convection are minimized. However, the main difference from the thermal state of liquid metal in the steel-teeming ladle is that the working lining of the tundish is made of porous magnesia shotcrete. This has much lower thermal conductivity relative to the thermal conductivity of the working periclase-carbon layer of the steel-teeming ladle. It is this circumstance that causes the lowest metal cooling rate in the tundish.

The average cooling rates of liquid metal at the studied stages of metal transportation and casting are shown below:

Stage	Metal cooling rate, °C/min
Completion of processing at the ISPU – beginning of vacuum degassing	0.60
Vacuum degassing	0.82
Completion of vacuum degassing – beginning of casting (theoretical calculation)	0.22
Completion of vacuum degassing – first measurement in the tundish	1.43
Metal in the tundish	0.09

At this stage, the nature of the cooling rate jump at the stage of vacuum degassing completion (the first measurement in the tundish – Figure 3) becomes clear. The liquid metal is exposed to intensive cooling here as it passes through the steel outlet channel of the steel-teeming ladle, the channel of the slide gate and the metal protection tube during casting. It is this circumstance that causes a jump in the cooling rate.

It should be noted that the results obtained are typical for enterprises where the process cycle includes a steel vacuum degassing stage. The input data may vary. The regularities thus established are also retained in the case when the vacuum degassing stage is absent, and are generally applicable to various methods of continuous casting.Obviously, the specific values of liquid metal temperatures and periods of stages may change. However, the metal cooling rates at the selected stages will be approximately the same, if the described conditions are met. This paper does not indicate specific brands of cast steels or names of enterprises. The above data was obtained and summarized using the "Isotherm1600" material as a heat-insulating and slag-forming mixture [23, 24] at different enterprises.

Conclusion

The study analyzed the features of liquid metal cooling in the steel-teeming ladle and tundish at the stage limited by the moment of completion of metal processing at the ISPU section and its continuous casting. At this phase the most important stages characterized by the integral indicator of metal cooling rate were identified. The study also showed that the metal cooling rate at these stages varies within a wide range and differs by more than an order of magnitude. The most significant factors affecting the metal cooling rate were identified. These factors include: the initial temperature of liquid metal after processing at the ISPU section; the temperature of liquid metal after vacuum degassing; presence on the surface of liquid metal of the oxide solution formed by slag-forming mixtures; presence and efficiency of heat-insulating mixtures; as well as heat-insulating properties of refractory linings.

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S. K. Vil'danov – formation of the main concept of the study, calculations, analysis of the results, preparation of the text, formation of conclusions.
D. Yu. Bondarev – obtaining experimental data, their classification, graphical representation.

Вклад авторов

С. К. Вильданов – формирование основной концепции исследования, проведение расчетов, анализ результатов, подготовка текста, формирование выводов.
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