UDC 669 . 162 . 263

Floating/Sinking of Deadman and Liquid Flow Behavior in Blast Furnace Hearth

Akihiko SHINOTAKE*1 Morimasa ICHIDA*1
Hajime OOTSUKA*2 Yasushi KURITA*3

Abstract

The warm water model experiment that assumed the blast furnace hearth has been performed, and the liquid flow and the heat transfer property have been examined. The experimental result was considered using the calculation based on the mathematical model, and the flow and the heat transfer of a real furnace were presumed. The flow was not uniform in the direction of coke free layer height when the deadman floating height was large, there existed fast flow region in the right under part of the deadman bottom and stagnation region in the furnace bottom part. Not the furnace bottom upheaval but the deadman low permeability did strengthen circulating flow near the sidewall. Measures for floating or sinking of the deadman in an actual blast furnace were evaluated from the balance between solid load and buoyancy. In some cases a negative correlation was found between the calculated sinking depth and the center temperature of furnace bottom with some time delay. It was considered that when a deadman behaves in a specific manner, it may affect the temperature of furnace bottom through the liquid flow in the hearth region. From the consideration of period and spatial distribution of temperature rise, it was estimated that flows of molten iron which move in the hearth toward tapholes are the cause of the sidewall temperature rise.

1. Introduction

The wear of the bottom of a blast furnace is ascribable chiefly to the disappearance of the solidified layer and embrittlement of the carbon brick. This mechanism of wear is significantly influenced by the molten iron flow in the hearth. The molten iron flow varies according to the furnace equipment conditions (e.g., furnace bottom shape, taphole positions and eroded wall profile), the furnace operating conditions (e.g., method of using tapholes) and the furnace packing condition, which itself depends on the continuation or fluctuation of specific furnace operating conditions (e.g., deadman shape and packing condition) over a certain period of time.

There have been several studies on molten iron flow in blast furnace hearths. For example, Tachimori et al.[1] studied the effect of a coke free zone in the hearth on the flow of molten iron using numerical calculations and model experiments, and reported that the mol-

*1 Environment & Process Technology Center
*2 Former Environment & Process Technology Center (now working for Taihei Kogyo Co., Ltd.)
*3 Yawata Works

ten iron flowed easily through coke free layer. Tomita et al.[2] also used numerical calculations and model experiments to study the flow of molten iron, and reported that the molten iron selectively flowed through the coarse coke layer, rather than the fine one, when the coke size distribution in the deadman was uneven. Standish et al.[3] experimentally studied the influence of coke size distribution on the flow of molten iron. Shibata et al.[4] found when using a two-dimensional model experiment that a free zone was formed in the hearth corners during storage and discharge of molten iron and reported that the results of numerical calculations on a three-dimensional liquid flow showed that the free zones in the corner promoted circulatory flow near the side wall. Inada et al.[5] reported on their model, which combined the flow of molten iron in the hearth and the progressive erosion of the hearth. Watakabe et al.[6] reported the results of their estimation of the hearth protection mechanism by injection of a tracer and examination of a dissected hearth.

As mentioned above, there are a good number of study reports on the flow of molten iron focused on the coke free zone. Nevertheless, there are only a few study reports on the subject with the emphasis placed on the influence of the deadman packing structure on the flow of molten iron, or the relationship between any floating/sinking of the deadman and the flow of molten iron in an actual blast furnace.

In the present study, initially a model experiment was conducted with the aim of clarifying the relationship between the packing structure and liquid flow paying attention to the packing structure in the blast furnace hearth. Next, using a mathematical model, calculations were made relating to the heat transfer of molten iron flow in the hearth to study the change in fluidity and temperature distribution in an actual furnace when the hearth packing structure changes. Then, from the dynamic balance in the hearth of an actual blast furnace, estimates were made relating to the floating/sinking behavior of the deadman while studies were made to its relationship with the hearth temperature. In addition, discussions focused on the hearth packing structure and fluidity when the hearth side-wall temperature changed.

2. Model Experiment on Fluidity in Hearth

2.1 Experimental apparatus and procedure

The experimental apparatus is presented schematically in **Fig. 1**. A packing material (polypropylene particles 4 mm in diameter) was put into a cylindrical vessel (ID: 0.57 m) simulating the hearth of a blast furnace (the packing material simulates the deadman) and the temperatures of the vessel bottom and side wall and the temperature distribution in the direction of the vessel height were measured while warm water of a prescribed temperature was circulated around the vessel. Heat flux was also measured at certain points of the vessel bottom and side wall. The packing material density was about 900 kg/m^3. With the temperature distribution inside the vessel in equilibrium, colored liquid was injected as a tracer into the vessel and the time required for the tracer to reach the taphole (tracer travel time) and the output waveform were measured using transmission photosensors. The points of tracer injection and the points of measurement of temperature and heat flux are shown in **Fig. 2**.

The standard experimental conditions were as follows. Either of two tapholes – one 15 cm above the vessel bottom and the other 25 cm above the vessel bottom – was used. With the level of water kept constant (10 cm above the taphole), 60℃ warm water was dripped evenly into the vessel at a rate of 66.7 cm^3/s and discharged at the same rate. The degree to which the deadman floated was varied between 0 and 5 cm (0 and 20 cm depending on circumstances).

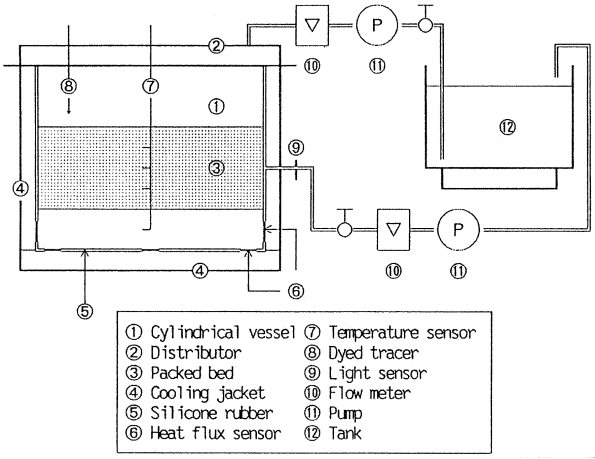

Fig. 1 Experimental apparatus

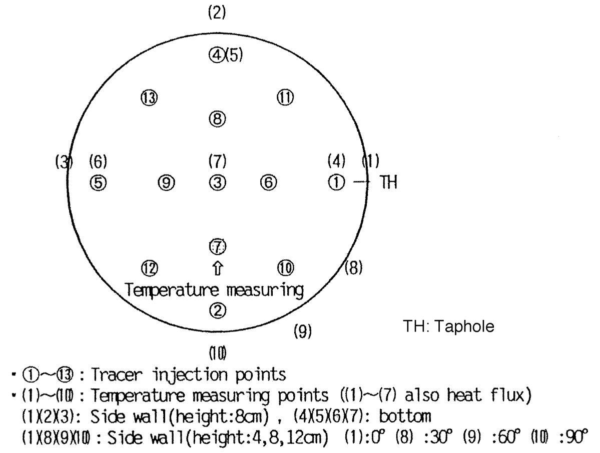

Fig. 2 Temperature measurement and tracer injection points

The bottom and side walls of the vessel were cooled by 20℃ water.

2.2 Experimental results

Concerning the deadman floating height, many of the studies carried out in the past focus on the difference in liquid flow between when the deadman sinks and when it floats slightly to form a narrow coke free layer. According to these, a rapid liquid flow region occurs in that coke free layer. In the present study, giving consideration to the fact that in recent years many blast furnaces are provided with a deeper hearth than before, there were even experiments with conditions under which the deadman floated sufficient to form a wide coke free layer. As an example of the experimental results, **Fig. 3** shows the change in tracer travel time (i.e., the time between the instant at which the tracer is injected and the instant at which it comes out of the taphole) while the deadman floating height was varied between 0 and 20 cm with the taphole height set at 25 cm above the vessel bottom. With the level of water kept constant at 35 cm above the vessel bottom, the deadman floating height was varied by adjusting the quantity of packing material. In Fig. 3, the horizontal axis represents the horizontal distance from the tracer injection point to the taphole. Concerning the tracer travel time, it was assumed that the time at which the tracer density peaked as being the time when the main stream of tracer arrives at the taphole. Namely, the vertical axis

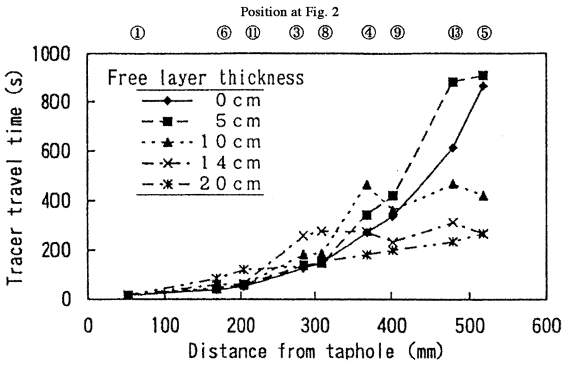

Fig. 3 Tracer travel time (taphole height: 25cm)

represents the time in which the attenuation of transmitted light intensity at the taphole reaches its maximum after the tracer injection, that is, the time in which the waveform reaches its peak.

Compared with when the deadman sinks (floating 0 cm), when the deadman floats 5 cm, the tracer travel time increases, indicating that the liquid flow velocity in the packing layer has decreased or that the liquid flow has taken a roundabout course. When the deadman floats 10 cm or more and the distance from the taphole exceeds a certain point, the tracer travel time decreases, indicating that the tracer has passed through a rapid liquid flow region (coke free layer) near the vessel bottom. In the region in which the tracer is supposed to pass through the rapid liquid flow region when the deadman floating height is 10 cm or more, the higher the deadman floats, the shorter the tracer travel time. This fits in with the fact that the thickness of the packing layer through which the tracer reaches the coke free layer decreases, suggesting that the liquid flow velocity in the coke free layer does not decrease much even when the coke free layer widens. Namely, when the coke free layer in the hearth is large, it is considered that the liquid flow velocity in the coke free layer varies according to what level of the coke free layer the liquid passes, that a rapid liquid flow occurs right under the deadman bottom, and that a flow stagnation region is formed in the neighborhood of the hearth as pointed out by Ohno et al.[7,8].

In an actual blast furnace, the change of molten iron flow into a circulatory flow is considered one of the reasons why the temperature of the hearth sidewall rises. The occurrence of such a circulatory flow can hardly be explained by the rise and fall of the deadman and the formation of a coke free zone alone. There is the possibility that a circulatory flow might be caused by a rise of the hearth due to the growth of a sticky (solidified) layer or by an expansion of the low-permeability region in the deadman. Therefore, we studied their effects experimentally.

In an experiment to measure the influence of a rise in the hearth, a cone-shaped block (D = 20 cm and h = 5 cm for a small one; D = 40 cm, h = 10 cm for a large one) was installed at the center of the vessel bottom. In the experiment to measure the influence of a low-permeability region in the deadman, a cylindrical block (D = 40 cm, h = 20 cm) was installed under the deadman. Thus, the most extreme condition – impermeable deadman – was simulated.

Examples of tracer travel times (from time of injection to arrival at taphole) measured under each of the above conditions are shown in **Figs. 4** and **5**. A circulatory flow did not always occur even when there was a conical block on the bottom of the vessel. On the other hand, when there was an impermeable region, the tracer travel time

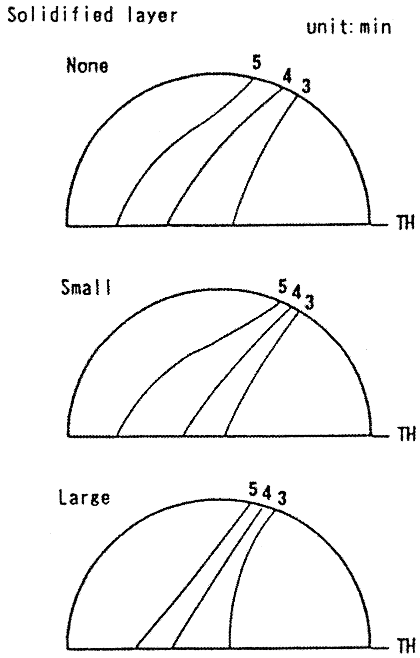

Fig. 4 Tracer travel time map (effect of solidified layer, free layer 5cm)

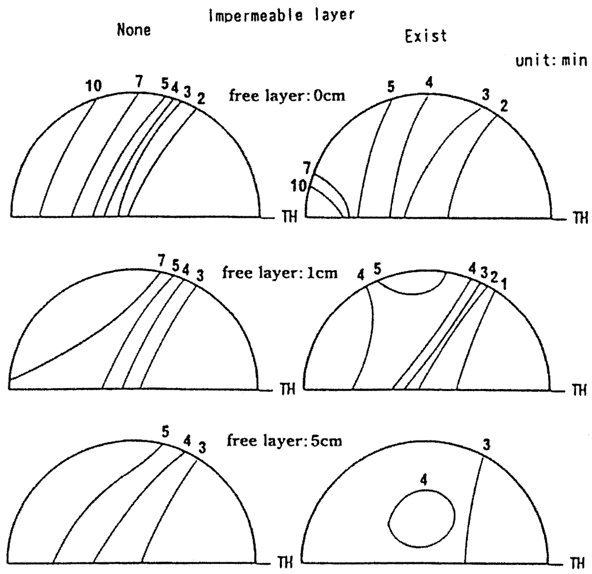

Fig. 5 Tracer travel time map (effect of impermeable region)

decreased regardless of how high the deadman rose. In particular, the tracer from the peripheral part at an angle of 90 degrees or more against the taphole traveled fast, suggesting the development of a circulatory flow. The heat flux in the neighborhood of the side wall increased as well.

3. Calculation of Heat Transfer Using Mathematical Model

The mathematical model used is a three-dimensional, cylindrical, coordinate-system steady model applicable to the pouring basin of the hearth of a blast furnace. In the calculation of heat transfer,

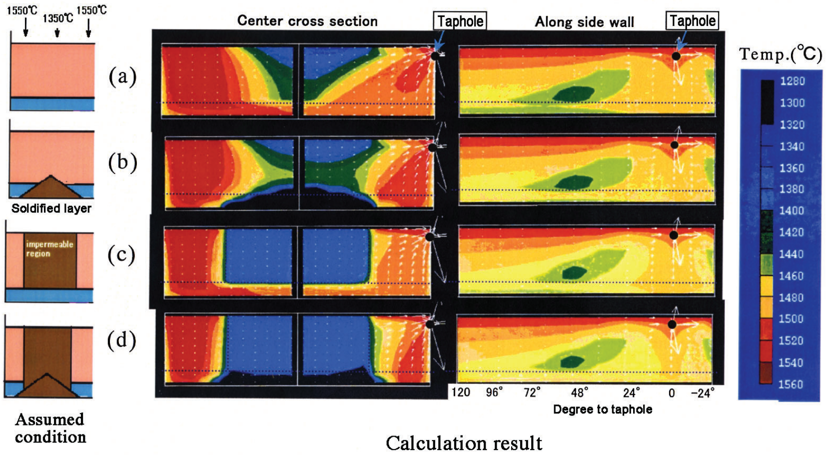

Fig. 6 Effect of solidified layer and impermeable region on liquid flow and temperature

only molten iron was considered as the liquid: slag was left out of consideration.

The basic equation is given in the form of (1). $\phi = 1$ is the equation of continuity; $\phi = \mu, \nu, w$ is the equation of conservation of momentum; and $\phi = h$ is the equation of conservation of energy. Since the generation terms for velocity variables μ, ν, and w constitute a three-dimensional, cylindrical coordinate system, they are given by equations (2) - (4).

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v\phi) + \frac{1}{r}\frac{\partial}{\partial \theta}(\rho u\phi) + \frac{\partial}{\partial z}(\rho w\phi) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_\phi\frac{\partial\phi}{\partial r}\right) + \frac{1}{r}\frac{\partial}{\partial\theta}\left(\Gamma_\phi\frac{\partial\phi}{r\partial\theta}\right) + \frac{\partial}{\partial z}\left(\Gamma_\phi\frac{\partial\phi}{\partial z}\right) + S_\phi \quad (1)$$

($\phi = 1, \mu, \nu, w, h$)
(μ, ν, w: *velocity of* θ, *r*, *z direction*; *h*: *enthalpy*)
(Γ_ϕ: *diffusion coefficient*; S_ϕ: *cource term*)

$$S_u = -\frac{\partial P}{\partial\theta} + \frac{2\mu}{r}\left(\frac{\partial v}{\partial\theta}\right) \quad (2)$$

$$S_v = -\frac{\partial P}{\partial r} + \frac{\rho(ur)^2}{r^3} - \left(\frac{\mu}{r^2}\right)\left[\left(\frac{2}{r}\right)\frac{\partial(ur)}{\partial\theta} + v\right] \quad (3)$$

$$S_w = -\frac{\partial P}{\partial z} \quad (4)$$

$$grad\,P = -\left\{f_1 + f_2\,|\vec{v}|\right\}\vec{v} \quad (5)$$

$$f_1 = 150\,\frac{(1-\varepsilon)^2\mu}{(\Phi d_P)^2\varepsilon^3\rho} \quad (6)$$

$$f_2 = 1.75\,\frac{1-\varepsilon}{(\Phi d_P)^2\varepsilon^3\rho} \quad (7)$$

$$q/A = \alpha(T - T_0) \quad (8)$$

As the liquid permeability resistance of the coke-packing layer, it was assumed that the external force determined by Ergan's equations (5) - (7) was applied. In those equations, ρ, μ and ε denote liquid density, viscosity and void ratio, respectively, and *d* and Φ denote particle diameter and shape factor, respectively. As a boundary condition for the liquid flow, the wall function was used at the side wall and bottom. As a boundary condition for the heat transfer, on the assumption that the temperature of the packing layer solid particles was the same as that of the liquid, the heat removal rate per unit area at the side wall and bottom was given as a function of temperature of the liquid nearest to the boundary plane (in equation (8)). The left-hand term of equation (8) represents the heat flux per unit area, and heat transfer coefficient α was calculated from experimental results while heat loss data was obtained from actual blast furnaces. PHOENICS – a general-purpose software program – was used for the calculation.

Fig. 6 shows examples of calculated liquid flows in the hearth when a rise of the hearth bottom and a low-permeability region were assumed to exist in a blast furnace (hearth diameter: 11 m, basin depth: 3 m, taphole height: 2.55 m). As shown in the figure, the molten iron drop distribution was divided into two regions – the central region and the peripheral region. The temperature of the peripheral region was 1,550℃ and that of the central region was 1,350℃. The molten iron dropping rate in the central region was assumed to be a fifth that of the peripheral region. The coke-free zone above the hearth was assumed to be 0.6 m. In Fig. 6, the left-hand center cross-sections are diametric cross-sections passing through the taphole, and the right-hand side wall projections show the liquid flows and temperature distributions in the outermost region along the side wall. Each of the side wall projections was obtained by projecting the curved surface of the side wall viewed at an angle of 48 degrees from the taphole onto a plane. Both the calculation results and experimental results showed that the rise of the hearth alone would not cause the liquid flow and temperature near the side wall to increase but that the liquid flow and temperature would increase when a low-permeability region existed as well.

4. Estimation of Rise/Fall of Deadman in Actual Blast Furnace

Since the rise and fall of the deadman in an actual blast furnace can hardly be measured directly, it has not been commonly recognized by all blast furnace operators. Therefore, using past blast furnace operation data, calculations were made for the load-buoyancy balance of the deadman while a study was apllied to its relationship with the center temperature of the hearth to estimate the presence or absence of any rise or fall of the deadman. The balance was calculated by using the "deadman settlement index" developed by Tanaka et al.[9]. Load was defined as the sum of the weight of ore and coke above the average height of the cohesive zone and the weight of coke below that height, and buoyancy was defined as the sum of the buoyancy of molten iron and slag and the pressure drop of the blast gas. To calculate the average cohesive zone height, the distance of Si movement calculated by using the equation of Tamura et al.[10] was assumed to be the vertical distance between the cohesive zone and the tuyere. The deadman settlement index calculated by this method has a dimension of length and physically corresponds to the depth of the deadman falling below the liquid level, that is, the vertical distance between the liquid level and bottom of the deadman. However, the index shows a larger value than the actual depth of fall because the stress caused by the burden and furnace wall is not considered. Therefore, the index was regard simply as an indicator of whether the deadman of a particular blast furnace shows a tendency to rise or fall.

Fig. 7 shows the changes in the calculated deadman settlement index and hearth center temperature of Tobata No. 1 BF at Nippon Steel Yawata Works for the period July 1995 to September 1996. Each of the calculated values is an average for a 10-day term. **Fig. 8** shows the relationship between deadman settlement depth and hearth temperature measured at the same time, and **Fig. 9** shows the relationship between deadman settlement depth and hearth center temperature measured with a time lag of three terms (one month). There was no correlation between deadman settlement depth and hearth center temperature measured at the same time. However, a negative correlation was observed between deadman settlement depth and hearth center temperature measured with a time lag of one month. Some data obtained in consecutive terms deviated from the line showing the negative correlation.

The above results can be interpreted as follows. The hearth center temperature has much to do with the flow of molten iron in the hearth. When a deadman that has been sinking begins to float and causes a coke-free zone to form in the hearth, the molten iron flow through this zone increases, causing the hearth center temperature to rise. Up until the floating deadman reaches a certain height, the hearth center temperature continues rising as the flow of molten iron through the coke-free zone increases. When the deadman floats above that limit, the molten iron flow in the hearth stagnates, causing the hearth center temperature to begin declining[1]. When the deadman sinks partially, the molten iron flow in the hearth continues to maintain a correlation with the size of the settling region for as long as the deadman remains partially floating. However, when the deadman settles completely and the coke-free zone disappears, the molten iron begins to flow through the packing layer and the molten iron flow does not change much. Thus, a correlation between deadman settlement depth and hearth center temperature tends to appear as long as the deadman settlement index is within a certain range.

It is when an increase or decrease in the calculated value of the settlement index lasts for a long time that the effect of the deadman settlement depth on the hearth center temperature appears after such a large time lag that cannot be explained simply by the delay in heat transfer calculated from blast furnace operation data obtained in the

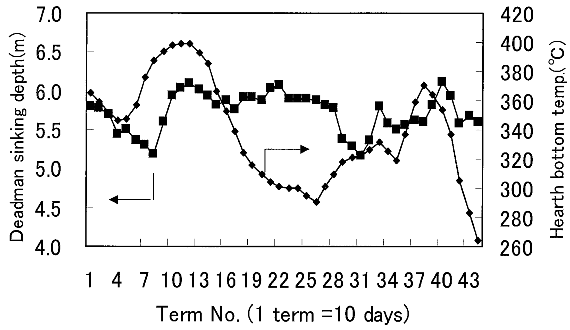

Fig. 7 Deadman sinking depth and hearth temperature (Tobata 1BF)

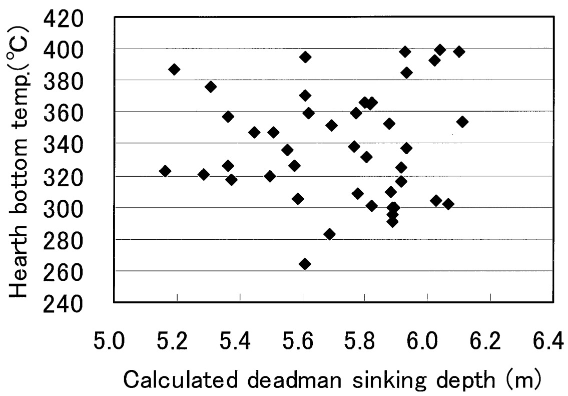

Fig. 8 Relation between deadman sinking depth and hearth temperature (Tobata 1BF)

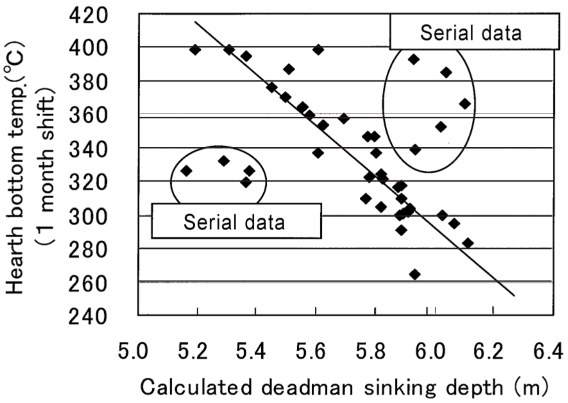

Fig. 9 Relation between deadman sinking depth and hearth temperature considering delaying time (Tobata 1BF)

past. One possible interpretation is that the large time lag is due to the fact that the deadman – an aggregate of solid particles – does not sink straight down as a single rigid body but that it shows a general tendency to sink (or float) as the individual particles move about discretely. Therefore, it is considered that a negative correlation tends to appear between the deadman settlement index and the hearth center temperature measured after a certain time lag when the calculated deadman settlement index is within a certain range and when it continues increasing or decreasing for a considerable period of time. Concerning this phenomenon, it is necessary to carry out a more detailed study, including a discrete analysis of the motion of particles making up the deadman.

5. Estimation of Molten Iron Flow when Hearth Sidewall Temperature Changes

Fig. 10 shows examples of rises in temperature of the sidewall of the Tobata No. 1 blast furnace measured during the period from the end of 1996 till the beginning of 1997. The change in temperature of each of sidewall stages 8, 9 and 11 is shown. While the temperatures of 9A-25, 8A-26 and 11A-26 rose and fell at the same time, the other circumferential parts did not show any significant temperature change. This suggests that there was a strong upward flow of molten iron toward the No. 3 taphole. In addition, at stage 8, 8A-21 shows a similar trend of temperature change, though it is not very conspicuous. Although in the lower part of the hearth there are upward flows in a relatively wide region as shown in **Fig. 11**(a), it is estimated that they converge into a narrow, strong flow as they approach the taphole. In the blast furnace under consideration, the phenomenon whereby the hearth center temperature drops while the sidewall temperature rises had been observed frequently. It is estimated that the phenomenon occurred as a low-permeability zone was formed down to the bottom of the deadman center while deadman coke floated to form a coke-free zone near the sidewall.

Fig. 12 shows the circumferential temperature distributions at

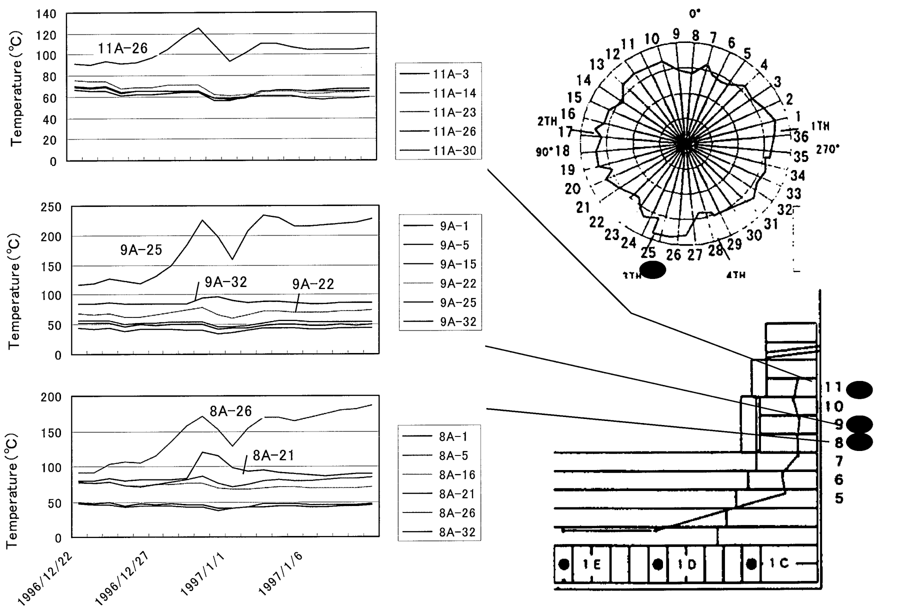

Fig. 10 Example of hearth sidewall temperature change

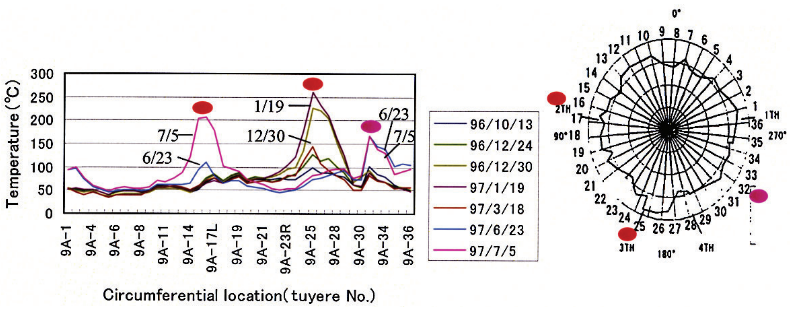

Fig. 11 Temperature distribution at various period

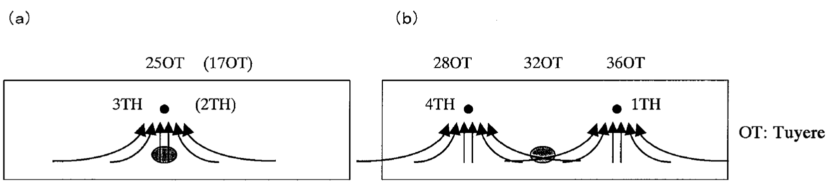

Fig. 12 Estimated liquid flow pattern

stage 9 measured at different times. In the period from the end of 1996 till the beginning of 1997, only the sidewall temperature under the No. 3 taphole (near 25OT) rose as mentioned above. However, since the sidewall below the No. 3 taphole had been badly eroded, the No. 3 taphole was decommissioned and only the three other tapholes (Nos. 1, 2 and 4) were used. In the summer of 1997, the temperature of the sidewall below the No. 4-1 taphole (31-34OT) and No. 2 taphole (near 17OT), respectively, rose. In this blast furnace, a sidewall temperature rise along the entire periphery at the same time had never occurred before. It is estimated that the above temperature rise was due to the unique mechanism of sidewall temperature rise below the No. 4-1 taphole (the mechanism of sidewall temperature rise below the No. 2 taphole is the same as that below the No. 3 taphole). Namely, as shown in Fig. 11(b), regardless of the taphole used, the temperature of the intermediate region through which the molten iron flows toward the taphole was assumed to have risen. This phenomenon, too, attests to the fact that the molten iron flow toward the taphole can wear the blast furnace sidewall.

6. Conclusion

Using a warm water model of 1/20 scale, the authors carried out a series of experiments to study the change of molten iron flow in the blast furnace hearth by varying the packing structure in the hearth. The authors also performed heat transfer calculations using a mathematical model to study the changes in molten iron flow and temperature distribution in an actual blast furnace. In addition, the floating/sinking behavior of the deadman was estimated in the blast furnace hearth to study its effect on the hearth temperature, while a study was conducted to the relationship between the hearth packing structure and molten iron flow during any changes in hearth sidewall temperature.

(1) When the deadman floats significantly, the flow of molten iron through the resulting coke free layer is uneven in the direction of the coke free layer height. In this case, a rapid flow region occurs right under the deadman bottom and a flow stagnation region occurs in the neighborhood of the hearth.

(2) As long as the deadman packing structure remains unchanged, the existence of a solidified layer in the hearth alone causes neither a circulatory flow of molten iron nor a temperature rise of the furnace sidewall. If there is a non-permeable region in the center of the deadman, however, a rapid circulatory flow of molten iron occurs near the sidewall.

(3) There are cases in which the deadman settlement index calculated from the load-buoyancy balance showed a negative correlation with the hearth center temperature measured after a certain time lag. A theory was applied that this was due to the influence of the floating/sinking behavior of the deadman exerted on the hearth temperature via the flow of molten iron.

(4) There are cases in which the temperatures at different stages of the blast furnace sidewall rose at the same time. Again, a theory was applied that this was due to the formation of a coke-free zone in the neighborhood of the hearth that caused molten iron to flow upward from the hearth toward the taphole.

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