Development of Prediction Technique for Temperature Distribution of Molten Steel in Steelmaking

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To promote the transfer to younger workers through operation support, a technique has been developed to present, in a probability distribution, the deviation risk for molten steel temperature in the converter furnace, molten steel treatment, and continuous casting steps involved in processing. This technique constructs a probability distribution by converting and transferring massive amounts of recorded data concerning past performance into information corresponding to the current operational state. It is based on a physical model, weighing the information in accordance with the degree of similarity. Its advantages are that calculable factors are separated from uncertain factors in a deterministic manner, the time change of the uncertain factors is taken into account on the basis of thermal influence, and Just-In-Time modeling is applied, which enables the systematic calculation of the probability distribution even for different conditions of such factors as steel types and facilities. This technique has been applied to an actual steelmaking process, which has reduced the deviation of casting temperature from the target value to less than half of the conventional one.

Introduction

The number of skilled operators is decreasing at production work sites such as steelworks, and it is urgent to transfer their skills to younger operators. There is an increasing need for an operation support system effective not only in maintaining work standards and documenting explicit knowledge, but also in making tacit knowledge into explicit knowledge to be inherited.

Meanwhile, the prevalence and progress of ICT have enabled the collection and utilization of large amounts of data, a task that is conventionally inconceivable; and various systems have been developed on the basis of large-scale operational data in the past, such as Just-In-Time (JIT) modeling.[1),2)]

It is against this backdrop that Kobe Steel has been focusing on the development of operational support systems applying JIT modeling technology.[3),4)] These systems are not limited to the mere listing of actual data and visualization of trends, but have the following features; (A) selecting and emphasizing cases with high similarity from past data, (B) converting the data into virtual experience information corresponding to the on-going operational state on the basis of physical models, (C) presenting the images in the heads of experts as visual information to complement the experience of younger operators, and (D) supporting their appropriate decisions and actions.

This paper focuses on the complex logistics of transferring molten steel in ladles among converter furnaces and continuous casting machines in the Kakogawa Works of Kobe Steel and describes a method for predicting the probability distribution of molten steel temperature and a system for presenting such information to operators to support accurate temperature management.

1. Background and purpose of this technical development

After being blown at a converter furnace, molten steel is transferred to a ladle and transported to molten steel processing equipment (e.g., RH furnace). After the completion of molten steel treatment, the ladle is transported to continuous casting equipment, and molten steel is poured from the bottom of the ladle into a tundish (**Fig. 1**). At this time, too high a molten steel temperature increases the risks of, among others, breakout, cracking and segregation during casting. On the other hand, too low a molten steel temperature may result in the clogging of immersion nozzles and/or a failed ladle opening. For the purpose of avoiding those risks, the temperature of molten steel is kept higher than the target value and, when it is too high, the casting speed is lowered to cope with this. Such measures, however, can adversely affect heating cost and productivity. Therefore, keeping the temperature of molten steel in a tundish within a more appropriate range is indispensable for realizing stable operation.

In the Kakogawa Works, multiple apparatuses for molten steel treatment and continuous casting are arranged in a plurality of steel plants in order to produce various types of steel materials, intertwining the logistics of molten steel in a

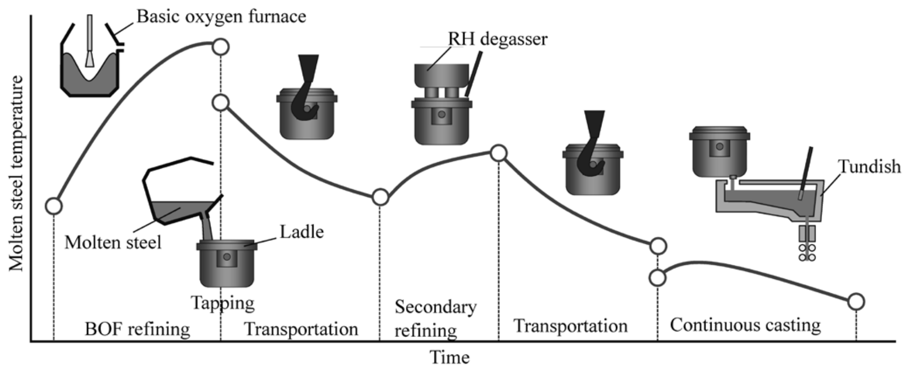

Fig. 1 Outline of steelmaking process and change of molten steel temperature

complicated manner. Hence, it is very difficult to manage, without interruption, the molten steel in a tundish within the specified temperature range in accordance with the operation schedule, which changes from time to time.

In such circumstances, the continuous casting operators, for example, input the correction values for the target temperature of the next molten steel to be transferred from the molten steel processing step even before it is subjected to the molten steel treatment. At this time, adjustments are made so that the molten steel temperature (and eventually the casting temperature) after the transfer falls within a predetermined range, taking into account the casting temperature management range and operation schedule information.

Hence, efforts have been made to predict the molten steel temperature during ladle transportation and in tundish on the basis of theories using various data.[5), 6)] It is not possible, however, to measure the refractory temperatures of the ladle and tundish, making it difficult to accurately predict the molten steel temperature. With the temperature being unpredictable, it would be beneficial for the operators to be provided with information as to whether there is a high risk that the actual temperature will deviate to the higher side of its predicted value, or whether there is a high risk that it will deviate to the lower side. In fact, interviews with skilled operators have revealed that they imagine in their heads something like probability distributions of molten steel temperature to recognize the risk of deviation from the predicted temperature.

Therefore, an attempt has been made to support accurate decision making by the operators by presenting the variation of molten steel temperature as a probability distribution in accordance with the operating conditions, rather than predicting the molten steel temperature at only one point. Although there are other studies on temperature distribution,[7)] the present technological development is characterized by JIT modeling that allows flexibility in handling different steel types and processes and by the consideration of the difference in the thermal influence factor.

2. Skilled operator's view

When predicting the deviation risk of molten steel temperature, skilled operators do not necessarily recall all the past cases equally. They retrieve examples close (highly similar) to the on-going operating conditions from their memories, make corrections for the difference between the past conditions and the on-going operating conditions, and replace (transfer) them with on-going conditions before their recognition. In other words, they recognize each past case by converting it into virtual experience information corresponding to the on-going operating condition. At that time, the skilled operators separate factors with clear cause-and-effect relationships (behaviors regarded as criteria for modeling in a deterministic way) from uncertain factors (variability that can be considered statistically) to interpret the temperature change.

As an example, in a past case where the operating conditions were similar to those of the on-going charge, it is assumed that the molten steel temperature was 10°C below the target value when the transport time after molten steel treatment was 20 minutes. If the transport time for the on-going charge is 30 minutes, there will be two ways of interpretation; one is that the molten steel temperature will drop as much as the 10-minute increase of the transport time, and the other is that, since the temperature was 10°C lower than the target value for the transport time of 20 minutes, the transport time of 30 minutes will cause a more significant deviation. The former corresponds to factors with physically clear causal relationships; the latter, to uncertain factors.

Skilled operators predict the change in time series (reference line) of molten steel temperature from the former point of view and replace the variation of similar past cases (deviation from the reference line) with the on-going conditions from the latter viewpoint. Then, they stochastically grasp the temperature deviation risk by weighting the past cases on the basis of their similarity with the on-going operational state.

3. Outline of procedure for predicting probability distribution of variation in molten steel temperature

3.1 Basic concept

In accordance with the skilled operators' view described in the previous section, the probability distribution of variation in molten steel temperature is calculated by the following steps (A) to (E). For simplicity of explanation, this and the following sections describe the example of molten-steel temperature distribution calculation during ladle transportation from the converter furnace to the molten steel treatment.

(A) Calculating the variation of molten steel temperature (the deviation from the reference line) in past charges. Here, the deviation from the upper limit line of the temperature based on the theoretical model is defined as a variation.
(B) Mapping the temperature variation of each past charge for the predicted time of the on-going charge in consideration of the thermal influence factor.
(C) Transcribing the variation after mapping on the basis of the upper limit line of the on-going charge.
(D) Weighing the value of each temperature variation after transcription in accordance with the degree of similarity between each past charge and the on-going charge.
(E) Constructing a weighted histogram and a probability distribution therefrom by normalizing the area to be 1 so as to grasp the temperature variation risk.

Of the above, (A) to (C) are views based on the theory of physical phenomena, while (D) and (E) are stochastic and statistical views. The deterministic part consists of a view based on physical phenomenology, and the probabilistic part is constructed with a statistical model.

3.2 Specific calculation procedure

The specific procedure to calculate the probability distribution of variation in molten steel temperature will be explained with reference to **Fig. 2**.

[Step (A)] First, in the i^{th} past charge (i = 1 to N), the molten steel temperature $T_i(t)$ at time t is expressed by the sum of the reference line (upper limit line of temperature drop calculated from physical model[5]), $f_i(t)$, and error factor $\Delta_i(t)$ (Equation (1)):

$$T_i(t)=f_i(t)+\Delta_i(t) \quad\cdots\cdots (1)$$

Then, the error $\Delta_i(t_i)$ at the time, t_i, of temperature measurement is expressed by Equation (2):

$$\Delta_i(t_i)=T_i(t_i)-f_i(t_i) \quad\cdots\cdots (2)$$

[Step (B)] The error $\Delta_i(t_i)$ is time-mapped and converted into a value $\Delta_i(t_0)$ corresponding to the predicted time t_0 of the on-going charge.

[Step (C)] The error $\Delta_i(t_0)$ is added to the molten steel temperature reference line $f_0(t)$ of the on-going charge calculated by the physical model, thereby obtaining a point, $T_{0i}(t_0)$, constituting the temperature variation of the on-going charge at the predicted time t_0.

$$T_{0i}(t_0)=f_0(t_0)+\Delta_i(t_0) \quad\cdots\cdots (3)$$

[Step (D)] For each past charge, $T_{0i}(t_0)$ is calculated. Following the rule of thumb that the deviation from the reference line is similar if the operating conditions are similar, the similarity between the on-going charge and each past charge is made to

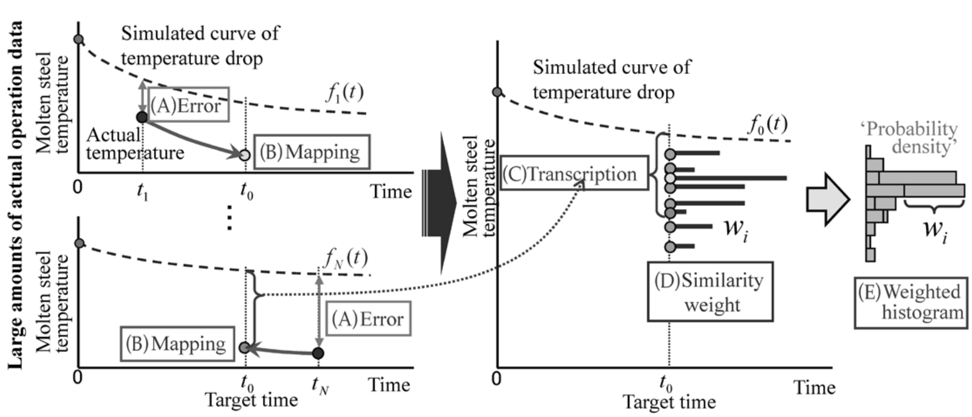

Fig. 2 Outline of calculation method for probability distribution of molten steel temperature

correspond to each temperature, $T_{0i}(t_0)$.

[Step (E)] A histogram weighted by similarity is constructed, and the one whose area is normalized to be 1 is presented to the operators.

4. Construction method of probability distribution considering factors of molten steel temperature variation

The main subject in the series of procedures described in the previous section is how to map the value of the error $\Delta_i(t_i)$ to calculate the value of $\Delta_i(t_0)$ in Step (B). In other words, the subject is how to determine the change in the value of the error $\Delta_i(t_i)$ in the time axis direction. The following describes an example of calculating the temperature variation during ladle transportation.

4.1 Variation factor during ladle transportation

In the ladle transportation from the converter furnace to the molten steel processing equipment, the three factors affecting the temperature variation are summarized as follows (**Fig. 3**).

(a) Variation of initial molten steel temperature
(b) Variation of initial refractory temperature
(c) Variation of heat transfer coefficient

Factor (a) is attributable to an error of temperature measurement at the time (t=0) when the steel is discharged from the converter. This is a view stating, "The initial value of molten steel temperature in the i^{th} past charge was measured as $T_{Mi}(0)$, while the true value deviates by $T_{Mi}(0)+\Delta_{Mi}$, due to the influence of measurement error. As a result, deviation by $\Delta_i(t_i)$ from the reference line occurred at time t_i."

Factor (b) is caused by an error in refractory temperature (accumulated heat of ladle refractory) at the time of converter furnace tapping. This is a view stating, "The initial value of the ladle refractory temperature in the i^{th} past charge was recognized to be $T_{Ri}(0)$. However, in reality, there was an error, Δ_{Ri}, and, as a result, a deviation by $\Delta_i(t_i)$ from the reference line occurred at time t_i"

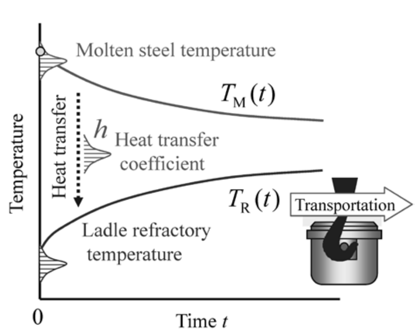

Fig. 3 Factors of temperature variability in ladle transportation

Factor (c) is due to an error in heat transfer from molten steel to ladle refractory during the ladle transport. This is a view stating, "For the heat transfer coefficient h_i in the i^{th} past charge, there actually was an error Δ_{Hi}, which caused the deviation from the reference line by $\Delta_i(t_i)$ at time t_i."

4.2 Time variation of error due to each variation factor

In order to grasp the influence of the error caused by each variation factor, (a), (b), and (c), mentioned in the previous section, a simulation was performed with a highly accurate calculation model[5] based on a theory. As shown in **Fig. 4**, if caused by the initial molten steel temperature variation ((a)), the value of $\Delta_i(t_i)$ is almost constant irrespective of time. On the other hand, if caused by the initial refractory temperature variation ((b)), the value of $\Delta_i(t_i)$ increases with time. Moreover, if caused by the heat transfer coefficient variation ((c)), $\Delta_i(t_i)$) increases with time and then converges to 0.

As described above, although $\Delta_i(t_i)$ can be mapped for an arbitrary time by simulation, there are two problems.

One problem is the calculation cost. Although the ICT has advanced remarkably, it is difficult to execute high accuracy calculation on tens of thousands or more of past data in real time. Without a measured value for the refractory temperature, how to calculate is also an issue.

Another problem is that it is unknown which variation factor is predominant. The mapping direction depends on the variation factor, and it is not known what causes the actual error. Consequently, it cannot be determined which direction to map.

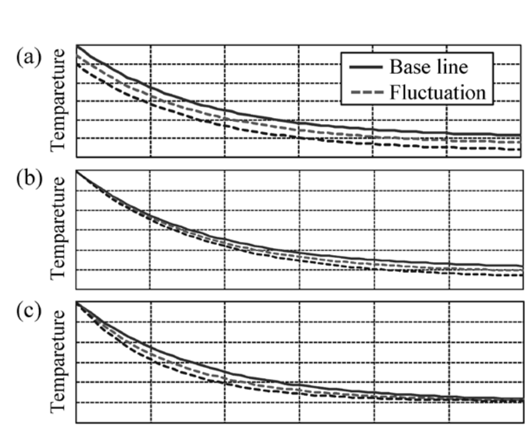

Fig. 4 Variation with time of temperature in each variability factor

4.3 Formulation based on simplified physical model

The dominant equation of two-body heat transfer is used for the calculation of a state without variation. The dominant equations of molten steel temperature $T_M(t)$, heat transfer $Q(t)$, refractory temperature $T_R(t)$ are as follows, respectively:

$$\rho_M c_M v_M \frac{dT_M(t)}{dt} = -Q(t) \quad \cdots\cdots (4)$$

$$Q(t) = A \cdot h \cdot (T_M(t) - T_R(t)) \quad \cdots\cdots (5)$$

$$\rho_R c_R v_R \frac{dT_R(t)}{dt} = Q(t) \quad \cdots\cdots (6)$$

wherein ρ_M, c_M, and v_M are the density, specific heat, and volume, respectively, of molten steel,

ρ_R, c_R, and v_R are the density, specific heat and volume, respectively, of ladle refractory,

A: contact area between molten steel and refractory, and

h: heat transfer coefficient.

Further, the replacements,

$$\alpha = \rho_R c_R v_R / (\rho_R c_R v_R + \rho_M c_M v_M),$$
$$\beta = (\rho_R c_R v_R + \rho_M c_M v_M) / (\rho_R c_R v_R \cdot \rho_M c_M v_M)$$

result in the well-known basic equation,

$$T_M(t) = -\alpha \cdot (T_M(0) - T_R(0)) \cdot (1 - e^{-\beta h t}) + T_M(0) \quad \cdots\cdots (7)$$

Equation (7) is an expression without a variation factor and corresponds to the temperature reference line. The equations expressing the changes in molten steel temperature due to initial molten steel temperature variation, Δ_M, initial refractory temperature variation, Δ_R, and heat transfer coefficient variation, Δ_H, are as follows, respectively.

$$T_M(t,\Delta_M) = -\alpha \cdot (T_M(0) + \Delta_M - T_R(0)) \cdot (1 - e^{-\beta h t}) + T_M(0) + \Delta_M \quad \cdots\cdots (8)$$

$$T_M(t,\Delta_R) = -\alpha \cdot (T_M(0) - T_R(0) - \Delta_R) \cdot (1 - e^{-\beta h t}) + T_M(0) \quad \cdots\cdots (9)$$

$$T_M(t,\Delta_H) = -\alpha \cdot (T_M(0) - T_R(0)) \cdot (1 - e^{-\beta (h+\Delta_H) t}) + T_M(0) \quad \cdots\cdots (10)$$

4.3.1 Influence of variation in initial molten steel temperature

By taking the difference between the reference lines expressed by Equation (7) and Equation (8), the time variation $\Delta(t, \Delta_M)$ of the variation of the initial molten steel temperature is formulated.

$$\Delta(t,\Delta_M) = T_M(t,\Delta_M) - T_M(t) = \Delta_M \cdot \{-\alpha(1 - e^{-\beta h t}) + 1\} \quad \cdots\cdots (11)$$

From Equation (7),

$$\alpha \cdot (1 - e^{-\beta h t}) = (T_M(0) - T_M(t)) / (T_M(0) - T_R(0)) \quad \cdots\cdots (12)$$

So, substituting Equation (12) for Equation (11) and rearranging lead to:

$$\Delta(t,\Delta_M) = \Delta_M \cdot (T_M(t) - T_R(0)) / (T_M(0) - T_R(0)) \quad \cdots\cdots (13)$$

Since the initial temperature of the refractory is much lower than the molten steel temperature, it can be approximated as follows:

$$(T_M(t) - T_R(0)) / (T_M(0) - T_R(0)) \approx 1$$

Therefore, the influence of initial molten steel temperature variation can be approximated as constant.

$$\Delta(t,\Delta_M) \approx \Delta_M = const. \quad \cdots\cdots (14)$$

4.3.2 Influence of initial refractory temperature variation

Similarly, taking the difference between Equation (7) and Equation (9) and rearranging it by substituting Equation (12), the time change $\Delta(t, \Delta_R)$ of the variation in the initial refractory temperature is given by Equation (15).

$$\Delta(t,\Delta_R) = T_M(t,\Delta_R) - T_M(t) = \Delta_R \cdot (T_M(0) - T_M(t)) / (T_M(0) - T_R(0)) \quad \cdots (15)$$

The ratio of the variation $\Delta(t_i, \Delta_R)$ with respect to the reference line at the temperature measurement time t_i in the i^{th} past charge to the variation $\Delta(t, \Delta_R)$ at a given time t is;

$$\Delta(t,\Delta_R) / \Delta(t_i,\Delta_R) = (T_M(0) - T_M(t)) / (T_M(0) - T_M(t_i)) \quad \cdots (16)$$

Therefore,

$$\Delta(t,\Delta_R) = \Delta(t_i,\Delta_R) \cdot (T_M(0) - T_M(t)) / (T_M(0) - T_M(t_i)) \quad \cdots (17)$$

Consequently, the influence of the variation of initial refractory temperature on the variation of molten steel temperature becomes analogous in the temperature axis direction.

4.3.3 Influence of variation in heat transfer coefficient

Equation (10) is same as Equation (7) whose t is replaced with $((h+\Delta_H)/h \cdot t$. In other words, assuming that τ_i is the time when the measured temperature value $T_M(t,\Delta_H)$ at time t_i and the temperature reference line $T_M(t)$ of Equation (7) have the same value, then $((h+\Delta_H)/h) \cdot t_i = \tau_i$, and consequently $(h+\Delta_H)/h = \tau_i / t_i$. Therefore, the variation of temperature with respect to the reference line at a given time t is given by:

$$\Delta(t,\Delta_H) = T_M(t_i,\Delta_H) - T_M(t) = T_M((\tau_i/t_i) \cdot t) - T_M(t) \quad \cdots (18)$$

As can be seen from Equation (18), the influence of the heat transfer coefficient variation on the molten steel temperature becomes analogous to the time axis direction.

As described above, the mapping can be done at any time with a relatively simple calculation formula for any of the variation factors, if $f_i(t)$ calculated with the temperature reference line physical model[5] of the past charge and measured temperature values are given.

4.4 View on variation factor ratio

When actual data is mapped at the transport time t_0, the distribution shape of temperature varies depending on the ratio of the variation factor, that is, the mapping method using the ratio of Equation (14), or (17), or (18) (**Fig. 5**). From the relationship between the transport time and the degree of temperature drop, the transport time and the variation factors are considered to have no relationship. Therefore, in the past recorded data, the mapping at the time t_0 of the data group with short transport time and the mapping at time t_0 of data group with long transport time are considered to have consistent distribution shapes if the mapping method is appropriate. Hence, among the factor ratios η_M, η_R and η_H when

$$\Delta_i(t_0)=\eta_M\cdot\Delta_i(t_0,\Delta_M)+\eta_R\cdot\Delta_i(t_0,\Delta_R)+\eta_H\cdot\Delta_i(t_0,\Delta_H) \quad\cdots\quad (19)$$

in Equation (3), the value of η_M was varied in the range of 0.0 to 1.0 to obtain the optimum point where the distribution shape after mapping of the two data groups most closely matched. In the range of actual operation time, the distribution shapes were similar, and hence $\eta_R=\eta_H=(1-\eta_M)/2$.

The evaluation of different data groups showed that η_M became optimum within the range of 0.30 to 0.36 and hence $\eta_M=\eta_R=\eta_H=1/3$.

4.5 Weighting based on similarity

Data items of the i^{th} past charge and the on-going charge are assumed to be

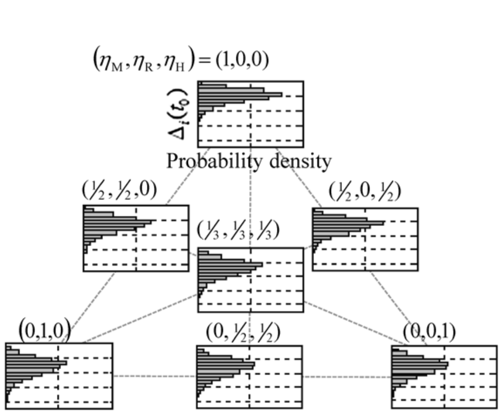

Fig. 5 Difference in temperature distributions after mapping by ratio of variability factors

$X_i=[x_{i1}\ x_{i2} \cdots x_{iL}]$ and $X_0=[x_{01}\ x_{o2} \cdots x_{0L}]$, respectively, to determine the weighted Euclidean distance d_i for evaluating their proximity.

$$d_i=\sqrt{\sum_{j=1}^{L} q_j (x_{ij}-x_{oj})^2} \quad\cdots\cdots\cdots\quad (20)$$

wherein $q_i>0$: weighting factor.

The similarity, $w_i=\exp(-\lambda d_i)$, calculated from the distance d_i is taken as a weight and corresponded to the temperature $T_{0i}(t_0)$ of Equation (3) to construct a weighted histogram (λ is the adjustment parameter), of which area is normalized to be 1 as a probability distribution to be presented to the operators.

5. Results of actual application

This technique was put into practical use in June 2011 in the steel-making process of the Kakogawa Works. **Fig. 6** shows the calculation results for molten steel temperature distribution and the temperature measured in a tundish. Here, the examples were chosen where the temperature distribution shape and its time change were characteristic. As shown in (a)-(d), it is confirmed that differences in temperature variation corresponding to each operating condition can be appropriately predicted.

Moreover, by evaluating the difference between the target value of molten steel temperature and the actual temperature in the tundish, the present system has been confirmed to reduce the deviation from the target value to less than half (about 41%) of the conventional value.

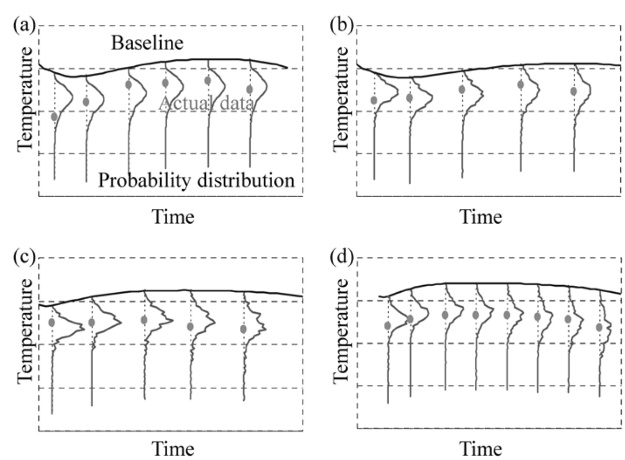

Fig. 6 Comparison between shapes of predicted distribution of molten steel temperature and measurement data in tundish

Conclusions

A method capable of uniformly predicting the multi-step probability distribution was developed by mapping the variation from the temperature reference line based on the physical model considering the thermal influence factor and constructing a weighted histogram in accordance with the similarity between the two.

By weighting in accordance with the similarity with the on-going charge during actual operation against the massive amount of past data accumulated by utilizing ICT, and by converting this to virtual experience information to be presented to the operators, it has become possible to supplement their experience and support them in making appropriate decisions and taking actions.

References

1) H. Shigemori. *JFE TECHNICAL REPORT*. 2015, No.35, pp.8-13.
2) Y. Kadoya et al. *Transactions of the Society of Instrument and Control Engineer*. 2014, Vol.50, No.7, pp.528-535.
3) Kobe Steel, Ltd. *Output value prediction method, the apparatus and method of the program*. JP5363238, 2013-9-13.
4) N. Tomochika et al. *Current Advances in Materials and Processes* 2017, Vol.30, No.2, p.782.
5) T. Nakaoka et al. *Current Advances in Materials and Processes* 2009, Vol.22, No.1, p.83.
6) T. Okura et al. *Current Advances in Materials and Processes* 2011, Vol.24, No.1, p.29.
7) S. Sonoda et al. *Current Advances in Materials and Processes 2011*, Vol.24, No.1, p.33.