Heat Transfer Behavior of Molten Iron and Nickel during the First 0.2 Seconds of Solidification

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This study aims at developing a fundamental understanding of the factors controlling strip casting. Heat transfer behavior of molten iron and nickel during the first 0.2 s of solidification has been clarified experimentally. The transient phenomena during solidification were successfully observed using a photo-sensor to measure cast surface temperatures and one wire thermocouple technique to measure the copper plate temperatures. T-type thermocouples were employed as one wire thermocouple method. The following results were obtained by this study.

The molten metal ejected from a silica tube was kept as liquid state during the first 0.02 s along with undercooling after which recallescence took place. In addition, fluctuations in temperatures of the cast surface and inside the copper plate, that were co-related each other, were observed during recallescence. The copper plate temperature could catch up with the cast surface temperatures at the plate side thanks to one wire thermocouple technique where one constantan wire was set inside the copper plate. The peak values of heat fluxes were found to be higher with higher superheat of the molten metal. Almost constant values of 10 000 (kW/m²) were obtained over 55°C while 3 500 (kW/m²) at 40°C in superheat.

According to the results comparing the temperatures of the cast surface and the copper plate, the peak point of the heat flux physically implies how long molten metal state is kept as for solidification of metal.

KEY WORDS: heat transfer; heat flux; heat transfer coefficient; casting; solidification; mold; thermocouple.

1. Introduction

In casting process, surface quality is determined at very short times during initial stage of solidification. Manufacturing sound product without any defect is primarily necessary to avoid costly repairing processes such as grinding surface, welding cavities and holes and so on after casting. In particular, any surface defect cannot be allowed in case of near net shape casting, for example, strip casting process because product has almost final contour to be used. Therefore an exact knowledge of heat transfer behavior at very short times is primary required to control the initial solidification.

A series of studies have been performed to understand the heat transfer behavior1–7) to clarify the effects of superheat, metal compositions and ejection pressure on heat transfer behavior in casting. However, as shown in Fig. 1,6,7) at the first moment, a part can be seen where the heat transfer coefficient is increasing from zero up to the peak point. This is considered to be attributed to the delay in heating of thermocouples installed in the copper mold. The obtained time-dependent coefficients usually reached their peak points at 0.1 to 0.4 s by when nucleation had already begun because phenomena that undercooling ended and recallescence started within 0.2 s were seen by the measurements of surface temperature of cast metal.1–7) Accordingly, it was not yet succeeded to evaluate solidification phenomena during melt undercooling by thermocouples.

As mentioned above, most of studies to measure heat transfer rate in solidification of metals have been so far made focusing on relatively longer casting duration such as several minutes. An exception was a study carried out by Strezov8) who set very thin K-type thermocouple as close to the copper plate surface as possible. The plate was then dipped into molten steel to obtain fast response to monitor heat transfer rate within 50 ms of casting. For example, 20 MW/m² of peak heat flux was successfully obtained during the first 10 ms when using textured copper substrates. This value is even higher than the other studies.

Fig. 1. Time-dependent heat transfer coefficient showing a problem caused by response time of thermocouples.
Recently, Miyazaki\(^9\) studied the effect of surface roughness and mold texture on the heat transfer behavior. They successfully revealed these effects at the steady state of casting. However, it could be said that the response of the measurement was not fast enough to argue the behavior at the earliest moment of solidification. Further, Kim and Guthrie\(^10\) recently studied the interfacial heat resistance and characterization of strip microstructures of Al–Mg alloys. They cast the alloys by means of a single belt caster to measure the heat interfacial heat resistance using K-type thermocouples. The results showed that the response of the thermocouple appeared to be order of several seconds.

Summarizing the above literature survey, as far as one uses K-type thermocouples, they have to be installed as close to the mold surface as possible to achieve extremely fast response. However, the installed position of the thermocouple is very difficult to be defined for analysis because the diameter of the wires and their beaded size are of argument if it is extremely close.

To overcome the problem in response of thermocouple, T-type thermocouples were employed for the temperature measurement in the copper mold\(^11,12\) followed by the early works\(^1-7\) by our research group. The point was that only one constantan wire was installed in the copper mold through a drilled hole while copper wire was connected with the copper mold. This allows us to measure the temperatures at the point where constantan wire directly contacts the mold. Thereby, faster response can be accomplished. The principle of benefit in response by this method, installing a wire of the same material as the object of temperature measurement, has been already explained in detail by pioneering researches conducted by Cassagne\(^13\) and Loulou.\(^14\) Cassagne\(^13\) has proved theoretically that 90% of the temperature of the truth can be achieved within 0.01 s when the object of temperature measurement is comparatively conductive enough and the contact between the object and the wire is intimate enough.

The latest work by Nolli\(^11,12\) focused on the heat transfer behavior of initial solidification of molten steel droplets with the improved apparatus, in which T-type thermocouples was installed, revealing the effect of formed oxide or sulfide film on the copper chill surface. They, however, did not measure the surface temperature of the cast metal. Therefore, the relation of the temperature variation of cast metal and the mold has not been discussed.

Therefore, this study basically aims at revealing the relation of temperature variation of the cast metal and the mold to understand how they are related each other. To achieve this objective, the one wire thermocouple method was employed improving the earlier experimental set-up.\(^1-7\) Especially, the phenomena that occur during the first 0.2 s have been focused on because so many phenomena occur as stated above.

## 2. Preliminary Experiment

A preliminary experiment was first performed to confirm the faster response with one wire thermocouple technique proposed by Cassagne\(^13\) and Loulou.\(^14\) In the present study, because copper plate is used, T-type thermocouple, a combination of copper and constantan wires, is tried. As illustrated in Fig. 2, a copper block with both K- and T-type thermocouples installed inside at 1 mm above the bottom surface was immersed into hot water kept at 85°C. Difference in characteristics of both thermocouple techniques is explained in Figs. 3(a) and 3(b) as proposed by Cassagne.\(^13\) K-type thermocouple was sheath type with the bead exposed. The diameter of the two wires of K-type was \(\phi 0.051\) mm each while a constantan wire for T-type \(\phi 0.076\) mm. The measured temperatures were recorded in a computer through a data acquisition system with the sampling rate of every 20 ms.

Figure 4 shows the measured temperatures demonstrating that the T-type has faster response than K-type particularly during the first 0.2 s immediately after the immersion.

### 3. Response Time of Thermocouple

Followed by the above experiments, time delay of one
wire technique of T-type thermocouple was estimated referring to the report by Loulou.\textsuperscript{14} Time delay at 97% of the true temperature is given by the following equation:

\[ t_c = \frac{100 r^2}{\alpha} \] ..........................(1)

where \( t_c \) is time delay (s), \( r \) is the junction size (m) where it is shown as the point C in Fig. 3(b) that is equal to the radius of the constantan wire and \( \alpha \) is thermal diffusivity of the copper plate (m\(^2\)/s). Thermal diffusivity is expressed as follows:

\[ \alpha = \frac{k}{\rho C_p} \] ..........................(2)

where \( k \) is thermal conductivity (381 W/mK),\textsuperscript{15} \( \rho \) the density (8940 kg/m\(^3\))\textsuperscript{15} and \( C_p \) the specific heat (413 J/kg · K)\textsuperscript{15} of copper, respectively. The radius of the constantan wire \( r = 0.038 \times 10^{-3} \) m and \( \alpha \) value calculated by Eq. (2) are substituted to Eq. (1). The time delay is thereby led to be 0.0014 s. This value is short enough to discuss the first 0.2 s of initial solidification.

4. Experimental

4.1. Apparatus

Figures 5(a) and 5(b) show the apparatus and the thermocouple positions installed in the mold, respectively. The apparatus was basically the same as previous set-up\textsuperscript{1–7}} except for the thermocouples. The constantan wire was carefully insulated not to touch on the way in the drilled hole while copper wire connected with copper plate.

The experimental procedure was basically the same as documented in the previous studies.\textsuperscript{2–7}} 3.5 grams of the metal sample was contained in a silica tube having a 1 mm of hole at the bottom under an argon gas atmosphere. In the experiments, pure iron and nickel whose compositions were the same as used in the previous study\textsuperscript{6,7} were used. The metal was melted with an induction coil at an aimed temperature. The temperature was measured and adjusted by using a two-color pyrometer sited from above. Thereafter, the molten metal was ejected onto a copper plate (Ø15 mm) surface by pressurized argon gas stored in an 80 mL gas server. The plate was cooled by water with initial temperature of 5°C in average.

Experimental conditions are given in Table 1. Superheats were varied in some experiments while ejection pressure was adjusted as 2 atm. The mold surface was polished with diamond paste after every experiment to remove adhered oxide scale. The surface roughness \( R_a \) was 0.35 μm in average.

The surface temperature of the ejected molten metal was measured through a drilled hole with Ø0.5 mm by a photodiode sensor installed beneath the copper plate. The sensor was the same as developed by Mizukami\textsuperscript{16}} and the response time of the system was measured as being less than 20 μs. The measured data were documented by a high speed data acquisition system with sampling rate of 2 ms on a personal computer.

Temperatures within the copper plate were also measured according to the method explained above. As shown in Fig. 5(b), constantan wires (Ø0.076 mm) were installed at three different locations to determine the variations in heat transfer rate. At each position, two wires were horizontally installed at 1 and 4 mm below the surface. A copper wire with the same diameter was connected to the copper plate. The molten metal was intentionally dropped onto the No. 2 position in this study because the hole for the photo-sensor

| Run No. | Metal | Superheat (°C) | Peak heat flux (W/m\(^2\)) |
|---------|-------|---------------|-----------------------------|
| ArFe217a | Fe   | 80            | 9600                        |
| ArFe217c | Fe   | 40            | 3500                        |
| ArFe226c | Fe   | 55            | 9800                        |
| ArNi211b | Ni   | 80            | 10200                       |
| ArNi211c | Ni   | 80            | 10000                       |

Fig. 4. Result of preliminary experiment.

Fig. 5. Experimental apparatus (a) and the positions of thermocouples installed in the copper plate (b).
is closest to the No. 2 position, where it is 2 mm from the hole. The data were also collected by another high speed data acquisition system with sampling rate of 20 ms on another personal computer.

4.2. Calculation

Heat flux and heat transfer coefficient was calculated by the following manner assuming that all heat transfers from a cast metal to a chill plate at the cast/pllate interface. Heat transfer coefficient is expressed as the following equation:

$$h_j = \frac{q_j}{T_{s,j} - T_{0,j}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldOTS
thermocouple position, the temperature fluctuations almost are in accordance each other. At the moments, shell growth should rapidly proceed and contacting and detaching against the plate is possible caused by inhomogeneous shrinkage. After the fluctuation periods, it gets into relatively steady-state. Here, the shell should have strength resulting in little movement.

At the last moment at (9) for iron, apparently contact became more intimate due to the clear drop in the cast temperature and the clear increase in the plate temperature that contrary took place. In fact, these behaviors were almost simultaneously observed. This definitely proves that the present thermocouple technique can detect the actual event with the response fast enough. The corresponding behavior for nickel at (6) is not as clear as for iron but the shell may be detached from the plate since a more gradual decrease in the cast temperature starts.

Figures 10(a) and 10(b) show the results for the cast surface temperature of iron and the plate temperature measured by K-type thermocouples, respectively. The superheat was 83°C similar to the conditions of Figs. 8 and 9. Obviously Figs. 10(a) and 10(b) do not co-relate each other unlike the profiles in Figs. 8 and 9. Further the temperature at 1 mm from the surface in Fig. 10(b) increases to 135°C and takes almost constant until 1 s, while the cast surface temperature continuously decreases after 0.2 s. Another notice is that no fluctuation at the first moment is undesirably seen. This behavior may be attributed to the thermocouple inertia cautioned by Loulou. This implies that effort to have thermocouple inertia as small as possible is extremely important to observe transient phenomena. Thus the solidification behavior during the first 0.2 s can be cleared with this experiment of one wire thermocouple technique.
5.2. Interfacial Heat Flux and Heat Transfer Coefficient

Calculated interfacial heat fluxes and heat transfer coefficients of the cast iron are shown in Figs. 11 to 13(a) and 13(b) at different superheats, respectively. Same series of the cast nickel are shown in Figs. 14 to 15(a) and 15(b). Numbers 1, 2 and 3 written in these figures mean the positions of the thermocouple locations shown in Fig. 5(b).

It should be notified that, as can be seen in Figs. 11 through 15, the calculated values at the No. 2 positions are not fluctuated differing from the temperature variations inside the copper plate shown in Figs. 8 and 9. The reason is attributed to the fact that the calculations had a problem. The fitting of the temperatures of 1 mm from the plate surface as the equations of seventh order could not be perfectly done because of the significant fluctuated curves as seen in Figs. 8 and 9. This fact was quite different from the case using K-type thermocouples shown in Fig. 10 as an example since every temperature curve inside the copper plate was smooth owing to the less sensitive response than in this study.

We thus decided consequently that the approximation was firstly made to perfectly fit at the first peaks of the copper plate temperatures because we were to argue how fast and large the first peaks appeared in the present study. The points of (3) and (2) in Figs. 8 and 9, respectively, correspond to the first peaks. After fitting the first peaks, then, the time-dependent variations were approximated by relatively smooth lines so as to pass almost the center of the
threshold between the peaks and the valleys. Therefore, certainly, the heat flux and heat transfer coefficient values in Figs. 11 to 15 are accurate enough until the first peak points. After that, the curves express the smoothing lines which describe the averages of the fluctuated heat flux and heat transfer coefficients.

One can realize that the peak values of both heat fluxes and heat transfer coefficients at No. 2 positions are the highest and that these peaks are attained at 0.02 s. The peaks are attained at much shorter times than by K-type thermocouples (Run No. 610b).6,7 This comparison is shown in Fig. 16 where nickel is experimented with superheats ranging 80 to 87°C. In this figure, reasonable reproducibility of the experiments is also recognized by the com-

Fig. 11. Heat flux (a) and heat transfer coefficient (b) as a function of time.

Fig. 12. Heat flux (a) and heat transfer coefficient (b) as a function of time.

Fig. 13. Heat flux (a) and heat transfer coefficient (b) as a function of time.

Fig. 14. Heat flux (a) and heat transfer coefficient (b) as a function of time.
parison between two series of experiments with the same superheats of 80°C.

Furthermore, behaviors that seem to be strange are seen in Figs. 11 to 15; the values of heat fluxes and heat transfer coefficients sometimes become negative at No. 1 and 3 positions. This may be explained by accounting for the three-dimensional heat flow pattern in the plate as illustrated in Fig. 17. Namely, the situation where the point at 4 mm below the surface is hotter than at 1 mm is probable owing to the released heat flow from the surface to the atmosphere. Therefore, as far as one-dimensional heat flow is assumed, one has to keep it in mind that the accurate values can be obtained only at the impingement point.

5.3. Effect of Superheat on Heat Transfer Rate

Table 1 and Fig. 18 show the relationship between the peak values of heat fluxes and superheats of the molten metals. The peak heat flux increases with increasing superheat with no difference between iron and nickel. This tendency should be linear as shown in Fig. 8 same as previously reported.2–7) It is difficult in this study to determine whether or not the tendency is really linear because the data plots are not enough. However, molten metal with very high superheat is expected to keep molten for longer times even at the surface in contact with copper plate. This will lead to higher peak heat flux. Thus the relationship between superheat and the peak heat flux should linearly behave.

5.4. Comparison to the Other Results

Approximate values of 10 000 (kW/m²) were obtained as the peak values of heat fluxes with superheat of 55 to 90°C at 0.02 s as stated above. This result is discussed in comparison with the other studies.8,9) In the study by Strezov,8) they immersed a copper plate with smooth or ridged surface into SUS304 stainless steel melted in an induction furnace. They showed that the variation of heat fluxes with time depends on the superheat, surface condition of smooth or ridged, gas atmosphere and immersion velocity. The condition of the present study is close to their case using smooth surface with superheat of 75°C. The result of this condition showed the peak heat flux of 10 000 (kW/m²) that is very similar to our value with superheat of 55 to 90°C. They further showed that the peak heat fluxes were higher using the plates with ridged surface when comparing at the same superheat. This is because the ridges widen the contacting area with molten steel. This implies that the surface state of a substrate is of primary importance and that it significantly affects the heat transfer rate. Regarding their finding for the
effect of superheat, the opposite tendency was obtained in comparison to our results. The reason for this difference is not fully understood at this moment.

Miyazaki\(^9\) has studied the effect of ridge state of the copper plate surface on the heat flux during solidification of 3 g of SUS304 stainless steel melts. The apparatus similar to the present study was used except for the cast surface temperatures which were not measured by them. Apparent relationship eventually could not be revealed between the heat flux values and Ra value (10–16 µm) of the copper plate surface unlike the work by Strezov.\(^8\) Miyazaki\(^9\) focused mainly on the nucleation behavior from the edges of the ridges. Comparing our values of peak heat fluxes to theirs, however, the heat fluxes of 500 to 5 000 (kW/m\(^2\)) of the ridges. Comparing our values of peak heat fluxes to focused mainly on the nucleation behavior from the edges of the ridges. Comparing our values of peak heat fluxes to theirs, however, the heat fluxes of 500 to 5 000 (kW/m\(^2\)) were obtained by them. These are lower than the present results. This reason for this is considered as follows. Firstly, they installed K-type thermocouples, whose tips were exposed, at the positions of 1.5 and 2.5 mm below the copper mold surface. One reason might be attributed to the position of 1.5 mm that is deeper than the present set-up. In addition, the two thermocouples installed in the mold are too close each other. Furthermore, they calculated the heat flux assuming that temperature gradient in the copper plate is linear. This may cause lower temperature gradient at the very surface of the plate leading to the lower values of heat fluxes.

But they successfully revealed the tendency showing the effect of mold texture on the heat transfer rate. Therefore, the development of set-up strongly depends on what phenomena one would like to observe.

6. Conclusions

Heat transfer behavior of molten iron and nickel during the first 0.2 s of solidification has been clarified experimentally. The transient phenomena during solidification were successfully observed using the photo-sensor to measure the cast surface temperatures and one wire thermocouple technique to measure the copper plate temperatures. As one wire thermocouple, T-type thermocouples were employed. The following conclusions can be stated:

1) The molten metal ejected from the silica tube was kept as liquid state during the first 0.02 s along with undercooling after which recalcitence took place.

2) Fluctuations in temperatures of the cast surface and the copper plate, that were co-related each other were observed during recalcitence.

3) The copper plate temperature could catch up with the cast surface temperatures at the plate side thanks to one wire thermocouple technique where one constantan wire was set inside the copper plate.

4) The peak values of heat fluxes were found to be as a function of superheat of the molten metal. Almost constant values of 10 000 (kW/m\(^2\)) were obtained over 55°C while 3 500 (kW/m\(^2\)) at 40°C in superheat.

5) The peak point of the heat flux physically implies how long molten metal state is kept as for solidification of metal according to the results comparing the temperatures of the cast surface and the copper plate.

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REFERENCES

1) I. Jimbo, T. Suzuki, A. W. Cramb and H. Todoroki: Abstracts of the 117th Meeting of JIM, Sendai, (1995), 454.

2) H. Todoroki, R. Lertarom, A. W. Cramb, I. Jimbo and T. Suzuki: Proceedings of 54th Electric Arc Furnace Conference, ISS, Warrendale, PA, (1996), 585.

3) H. Todoroki, R. Lert-a-Rom, T. Suzuki and A. W. Cramb: Proceedings of 80th Steelmaking Conference Proceedings, ISS, Warrendale, PA, (1997), 667.

4) H. Todoroki, R. Lert-a-Rom, T. Suzuki, and A. W. Cramb: Thermec 97, TMS, Warrendale, 2 (1997), 2227.

5) H. Todoroki, R. Lert-a-Rom, T. Suzuki and A.W. Cramb: Solidification 1998, ed. by S. P. Marsh et al., TMS, Warrendale, PA, (1998), 327.

6) H. Todoroki, R. Lert-a-Rom, I. Jimbo, T. Suzuki and A. W. Cramb: Proceedings of the Alex McLean Symposium, ISS, Warrendale, PA, (1998), 155.

7) H. Todoroki, R. Lert-a-Rom, T. Suzuki and A. W. Cramb: ISS Trans. Iron Steelmaker, 26 (1999), April, 57.

8) L. Strezov and J. Herbertson: ISIJ Int., 38 (1998), 959.

9) M. Miyazaki, H. Yamamura, W. Ohashi and T. Matsumiya: Tetsu-to-Hagané, 93 (2007), 673.

10) J. S. Kim, M. Iacu, R. L. Guthrie and J. Byun: Can. Metall. Q., 41 (2002), 87.

11) P. Nolli and A. W. Cramb: ISIJ Int., 47 (2007), 1284.

12) P. Nolli and A. W. Cramb: Metall. Trans. B, 39B (2008), 57.

13) B. Cassagne, J. P. Bardon and J. V. Beck: Proc. of the 8th Conf. on Heat and Mass Transfer, Hemisphere Pub., Washington DC, (1986), 483.

14) T. Loulou, E. A. Artyukhin and J. P. Bardon: Int. J. Heat Mass Trans., 42 (1999), 2129.

15) C. A. Mustrcikwu, I. V. Samarasekera and J. K. Brimacombe: Metall. Trans. B, 26B (1995), 361.

16) H. Mizukami, T. Suzuki and T. Umeda: Tetsu-to-Hagané, 77 (1991), 1672.