Transient Flow and Heat Transfer in a Steelmaking Ladle during the Holding Period

J.L. XIA and T. AHOKAINEN

Transient, turbulent flow and heat transfer in a ladle during the holding period are numerically investigated. The ladle refractories including the working lining, safety lining, insulation layer, and steel shell have been simultaneously taken into account. No assumptions are made for the heat transfer between the liquid steel and the inside ladle walls. Both the initial ladle heating and the heat loss from the slag surface are changed to examine their effect on thermal stratification in molten steel. A simplified model for the heat loss from the molten steel to the refractory is proposed. Correlations for the history of mean steel temperature, thermal stratification, and heat loss rate are obtained, which can be easily applied for industrial operations. Predictions are compared with experimental data in an industrial ladle and a pilot plant ladle, and those from previous studies.

I. INTRODUCTION

IN metallurgical industry, the temperature of liquid steel supplied to a continuous caster *via* a tundish has to be controlled to a tight limit in order to obtain good quality steel. The temperature of steel emerging from the ladle has significant effect on the bulk tundish temperature during casting. Natural circulation within the molten steel appears due to heat loss from steel into the refractory, and thermal stratification in the melt will be formed during the ladle holding period. The mean steel temperature in the ladle can be predicted with reasonable accuracy by taking the sources and mechanisms of heat loss into consideration.[1,2] However, the temperature stratification in the ladle may strongly influence the ladle stream temperature. It is desirable that the change of the ladle stream temperature with time should not be great in order to obtain a small variation of the tundish temperature during the ladle casting. A good understanding of the flow and heat transfer occurring in this process is therefore essential for industrial operations.

A few studies on this issue have been conducted. Hlinka and Miller[3] showed that the ladle pouring temperature varies due to heat losses from molten steel into the surrounding refractory layers. The process is transient and leads to turbulent natural convection flow in the molten steel. This phenomenon was numerically simulated by Ilegbusi and Szekeley,[4] who focused on reducing the effect of stratification by using magnetic stirring to promote bulk mixing. They showed that gentle stirring could be enough to minimize stratification.

Austin *et al.*[5] carried out a transient analysis of the temperature and velocity distributions of steel during ladle standing and draining, using the PHOENICS code. Effects of ladle cooling rate, stand time, draining rate, and ladle geometry on the ladle stream temperature were calculated. Based on their numerical prediction, they suggested a simple empirical correlation to represent the dependence of the rate of increase in temperature difference between the central top and central bottom of steel, τ, and the average cooling rate of the steel into the refractory, c:

$$\tau = 2.0c$$

This relation can be used to estimate the extent of thermal stratification (defined as the temperature difference between the central top and bottom of liquid steel), but, because the average cooling rate is still unknown, the previous relation is not practical to use. It was shown that the stratification increases with time, and the outflow rate has a great effect on both the flow pattern and the temperature profile of the outlet stream. Rapid tundish filling can reduce the influence of ladle stratification. It should be noted that a uniform and constant heat flux over the ladle walls and base was used in their calculations, which is not realistic.

The effect of slag cover on heat loss and liquid steel flow in ladles before and during teeming to a continuous casting tundish was numerically simulated by Chakraborty and Sahai.[6] This was simulated by assuming that the heat loss from the top free surface of the melt in the ladle is zero for idealized thick slag or 100 kW/m^2 for very thin slag. The heat loss from steel to the lade wall was assumed to be a constant conduction heat loss rate q_w = 12.5 kW/m^2. The simulation considered both the holding period (between the end of the inert gas stirring and the beginning of pouring of the melts into the tundish) and the teeming period. They showed that significant temperature stratification occurs in the melts being held in the ladle with insulating slag layer, and the degree of stratification increases with the holding time. For a thin slag layer with appreciable heat loss from the top, the bulk of the melt in the ladle is well mixed due to strong buoyancy driven convection flows. This, in turn, results in temperature homogenization of the melt. However, the average temperature of the melt decreases continuously in this situation, and the trend continues during pouring of the melt from the ladle. The amount of heat loss through the top surface of the melts in the ladle primarily determines the variation of the melt stream temperature during the teeming. It may be noted that the two heat transfer boundary conditions assumed for the top (free surface) are extreme cases compared to those occurring in industry, and that the heat loss from the ladle wall has been assumed constant in their study.

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Grip[7] measured the surface temperature inside ladles using radiation pyrometers on their return from the plant and during preheating. Simple models for prediction of the decrease of the steel temperature in those ladles were developed and calibrated using data from numerical simulations of transient heat conduction. However, the effect of the thermal stratification in liquid steel and flows in steel has been neglected and the inside surface temperature of the ladle has been assumed to be equal to that of steel. He also studied the flows caused by thermal stratification and drainage flow in a cylindrical production ladle with asymmetrically-placed nozzle. The heat loss from steel to the refractory was set to be 9.6 kW/m^2 for both side wall and bottom wall. The concentration profiles of tracer elements added to the liquid steel was also modeled and compared with the experimental data.

Olika *et al.*[8] carried out a numerical simulation for the melt stratification in ladles holding molten steel, using the PHOENICS code. The heat loss from the slag surface was set at 8923 W/m^2, and the transient boundary heat loss from steel to the ladle wall was obtained separately from a temperature simulation code that calculates the temperature profiles in the ladle wall using the heat balance method, and the heat loss rate was assumed to have the form

$$q = a \exp(-bt) + c$$

Here, q is the heat loss to the wall; a, b, and c are constants; and t is the time. Because the previous relation for the heat loss into the ladle wall was obtained by only taking into account heat conduction of the ladle wall, it should be different from that when the influence of steel flows and thermal stratification is taken into consideration.

As discussed earlier, though, a few numerical studies of thermal stratification in ladles have been conducted; past investigations have used simplified assumptions for the heat loss from steel to the refractory such as assumed constant heat flux to the ladle walls (W/m^2), assumed constant steel temperature drop rate (°C/min), or heat loss obtained from calculations without melt in the ladle. There have at present been no studies in the open literature that consider the transient molten flows coupled with the heat transfer in the ladle walls.

The present study aims to accumulate the aforementioned information and simulates the conjugate, transient fluid flow and heat transfer of melt in ladles during the holding period. The physical model is taken from an industrial ladle. The heat losses caused by both convection and radiation from the outside ladle walls to the ambient have been taken into account. No assumptions are made of the heat transfer between steel and the inside ladle walls. Both the initial ladle thermal conditions and the heat loss through slag have been changed to examine their influence on thermal stratification in the ladle.

II. MODEL FORMULATION

A. *Problem Description*

The ladle considered is an industrial scale one, schematically illustrated in Figure 1. The ladle is of conical shape with a height of 3.58 m, with an outside diameter of 3.364 m at the top and 3.023 m at the bottom. The ladle bath is filled with molten steel up to a height of 2.799 m from the inside bottom wall, equivalent to a 105 ton ladle. The side wall of the ladle with a thickness of 0.294 m consists of four layers of different materials: working lining, safety lining, insulation layer, and steel shell; the thicknesses of the layers are 0.15, 0.064, 0.04, and 0.04 m, respectively. The bottom wall with a thickness of 0.344 m consists of three layers: working lining, safety lining, and steel shell, the thicknesses of which are 0.24, 0.064, and 0.04 m, respectively. The working lining of the side wall is high allumina brick with 80 pct Al_2O_3, and that of the bottom wall is cast spinel. The safety lining is chamotte. The insulation layer is ceramic fiber. This ladle geometry is quite the same as that of an realistic industrial design used in a company.[7] The schematic of the mathematical model is shown in Figure 2. The physical properties of liquid steel used in simulations are density $\rho = 7000$ kg/m^3, dynamic viscosity $\mu = 5 \times 10^{-3}$ kg/m s, specific heat $C_p = 787$ J/kg K, and thermal expansion coefficient $\beta = 2 \times 10^{-4}$ 1/K. The thermal properties of ladle walls used in the calculations are listed in Table I.

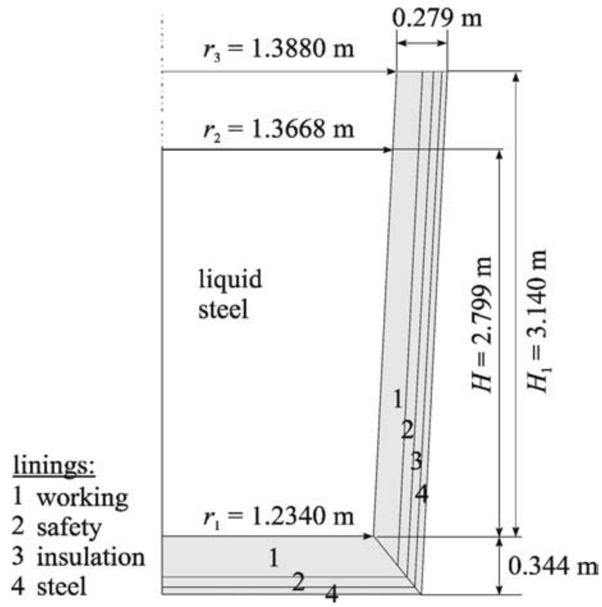

Fig. 1—Schematic of physical ladle.

B. *Governing Equations*

As heat is lost from the steel to the ladle refractory layers and from the slag surface to the ambient, there appears a transient, turbulent, and natural convection and heat transfer in the melt, conjugated with heat conduction in the ladle walls. In the case without gas injection into the melt, it is a single-phase flow and heat transfer process. In brief, the conservative governing equations for mass, momentum, and energy can be written in Cartesian tensor notation as follows.

In the melt region,

$$\frac{\partial(\rho U_j)}{\partial x_j} = 0 \qquad [1]$$

$$\frac{\partial(\rho U_i)}{\partial t} + \frac{\partial(\rho U_i U_j)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\mu + \mu_t)\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\right] + \rho g_i[1 - \beta(T - T_{\text{ref}})] \qquad [2]$$

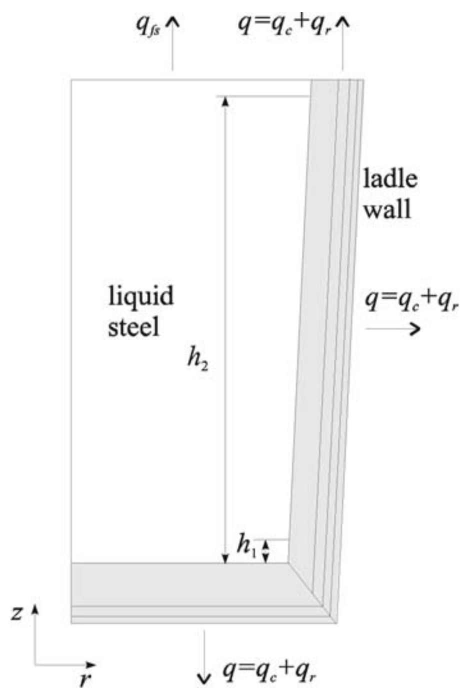

Fig. 2—Schematic of numerical model.

Table I. Thermal Properties of Ladle Walls Used in Calculations

	k (W/m K)	C_P (J/kg K)	ρ (kg/m^3)
Steel shell	52.0	787.0	7800.0
Insulation layer	0.04	1200.0	80.0
Safety lining	1.87	1200.0	2100.0
Working lining (side wall)	1.65	1200.0	2900.0
Working lining (bottom wall)	7.4	1200.0	3000.0

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho h U_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\frac{k}{C_p} + \frac{\mu_t}{\sigma_h}\right)\frac{\partial h}{\partial x_j}\right) \quad [3]$$

In the ladle walls, the heat conduction equation governs

$$\frac{\partial T}{\partial t} = \alpha_s \frac{\partial}{\partial x_j}\left(\frac{\partial T}{\partial x_j}\right) \quad [4]$$

Here, α_s ($=k/C_p\rho$) is the thermal diffusivity, which varies with different layers of the ladle refractory.

Turbulence in the melt is modelled using the high Reynolds number k-ε model,[9] with the buoyancy effect on the dissipation rate included in the ε transport equations with the coefficient C_3 being set to 1.0.

C. *Initial and Boundary Conditions*

The molten steel is initially assumed at a uniform temperature T_{si} = 1948 K, and the initial velocities of the steel are set to zero. This may correspond to the moment of the end of the gas stirring because agitation of the melt by gas injection results in thermal homogenization of the molten steel. It should be noted that the inert gas agitation should induce flow of the melt even after the gas injection into the melt has stopped for some time. However, it is assumed here that the influence of this kind of flow induced by gas injection is negligible compared with natural convection arising due to the heat loss of the melt through the ladle walls. Thus, the present simulation of thermal stratification within the molten steel considers the ladle holding period between the end of gas injection and the beginning of pouring the melts into the tundish.

The initial temperatures of the ladle side walls and the ladle bottom walls are assumed to be uniform. Two different initial wall temperatures (T_{wi} = 1073 K and T_{wi} = 1423) have been used to examine the effect of the initial heating level of the ladle wall on the flow and thermal stratification within the ladle. Actually, there is a temperature distribution in the ladle walls due to heat conduction. We assume that the effect of this initial distribution of the temperature within the ladle walls (the effect of the shape of the initial temperature profiles within the walls) on the flow and heat transfer in the melt is not significant. In fact, numerical predictions show that drastic temperature changes in the ladle wall during the transient are limited within a thin layer of the working lining; therefore, this assumption is reasonable.

At the top free surface, two different heat loss conditions ($q = 10^4$ W/m^2 and q = 3000 W/m^2) are imposed in order to model the effect of slag thickness on flow and temperature distributions in the melt. The free surface is assumed to be flat and frictionless. Along the inside ladle surfaces, no-slip boundary conditions are imposed and the standard logarithmic wall treatment is used. In contrast to previous studies, for the inside wall surfaces contacting with liquid steel, no assumptions are imposed for the steel-wall interface heat transfer because continuity of temperature and heat flux at the interface is used to compute the heat flux through the interface.

For the outside of the ladle walls, the heat loss to the ambient by both natural convection and radiation is taken into account. That is,

$$\begin{aligned} q(z,t) &= q_c(z,t) + q_r(z,t) \\ &= h(z,t)(T_w(z,t) - T_f) + \varepsilon\sigma(T_w^4(z,t) - T_f^4) \end{aligned} \quad [5]$$

where σ is the Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^{-4}). The term ε is the emissivity of the shell surface and is set to be 0.5; z is the space position; and h is the heat transfer coefficient, which is a function of Rayleigh number. For constant physical properties, it is a function of the temperature difference between the wall surface and the ambient and thus varies with the location and time. The Rayleigh number estimated at the initial stage is 2.1×10^7 for the top wall surface, 2.1×10^9 for the side wall, and 2.0×10^9 for the bottom wall. Thus, the natural convection of air along the outside ladle walls is in the turbulent region. The heat transfer coefficient are therefore calculated as follows:[10] the top wall surface is considered as a hot horizontal plate facing upward:

$$\mathrm{Nu} = 0.15\mathrm{Ra}^{1/3} \quad [6]$$

For the side wall of the ladle;

$$\mathrm{Nu} = 0.1\mathrm{Ra}^{1/3} \quad [7]$$

The ladle bottom wall is looked up a hot horizontal plate facing downwards:

$$\mathrm{Nu} = 0.27\mathrm{Ra}^{1/4} \quad [8]$$

Here, Nu is the Nusselt number (hL/k), L is the characteristic length, k is the thermal conductivity, Ra is the Rayleigh number ($g\beta L^3(T_w - T_f)/\nu\alpha$), ν is the kinematic viscosity, and α is the thermal diffusivity.

It should be noted here that, in contrast to the previous studies, the present model does not make any assumption of the heat transfer between the steel and the inside ladle walls. Heat loss from steel to the ladle walls is calculated according to the conservative energy equations. Thus, from this point of view, the present approach should give accurate solution to the realistic flow and heat transfer processes in the ladle during the holding period.

D. *Solution Procedures*

The CFX4.2 code[11] was used to solve the set of conservation equations, along with initial and boundary conditions. The QUICK scheme[12] is used for all the space derivatives and the pressure-velocity coupling is solved using the SIMPLEC algorithm.[13] In order to avoid the well-known problems due to cheque-board oscillations in pressure and velocity traditionally associated with the naive use of nonstaggered grids, the Rhie–Chow algorithm[14] is used. A refined 58 $\times$ 51 nonuniform mesh (axial and radial directions) was utilized, with 15 and 13 cells arranged in the side and bottom walls, respectively. Further refined mesh was tried (110 $\times$ 90), which gave minor changes of solutions. An adaptive time-stepping, which provides automatic control of the time-step (the maximum time step allowed is $\Delta t < 5 \times 10^{-3}$ s), was used, and at least 55 iterations were needed within each time-step to satisfy a strict convergence limit (all the scaled variable residuals are smaller than 5×10^{-4}).

III. RESULTS AND DISCUSSION

The flow patterns (fewer vectors are drawn to be readable) and temperature contours as a function of transient times are shown in Figure 3 for the case of the initial ladle wall temperature $T_{wi} = 1423$ K and the slag surface heat loss rate $q_{fs} = 10^4$ W/m^2. Note that the value for the iso-temperature line represents the steel temperature drop from the initial state, *i.e.*, $T_s(t) - T_{si}$. It is seen that, at the early stage of the transient ($t < 40$ s), a single recirculation is formed within the ladle: the liquid steel flows upward within the central region and downward along the ladle wall, where the downward flow is in a narrow band near the inside wall surface and the flow is the strongest, as shown in Figure 3(a). Then, slightly later on, at $t > 40$ s (*e.g.*, at $t = 60$ s, as shown in Figure 3(b), another vortex is formed in the central bottom region, and the flow becomes the two-vortex type. Thereafter, at large times of the transient, multiple vortices appear within the bottom region of the ladle, and the flow thereby becomes gradually unstable and chaotic, as shown in Figures 3(c) and (d). The velocity vector plots display similar flow patterns for all other cases. However, the transition times from one to two and then to multiple recirculation flow patterns become slightly smaller at lower initial ladle wall temperature or for initially colder ladle. For instance, the flow undergoes a change from one to two recirculation flow patterns at $t \approx 35$ s for the case of $T_{wi} = 1073$ K and $q_{fs} = 10^4$ W/m^2.

It was doubted, at first, that the phenomenon of the velocity vector irregularity in the bottom region of the ladle at large holding times was caused by unconverged numerical solutions; but, the same flow and heat transfer behavior had been obtained when we used smaller time-steps ($\Delta t < 10^{-4}$ s) and stricter convergence criterion. And, when a refined mesh (110 $\times$ 90) was used, a nearly identical solution was also obtained. These convinced us that this is an actual solution of the conservation equations. It should be mentioned that a similar phenomenon of velocity vector irregularity within the bottom region of the ladle was also observed by Austin *et al.*,[5] who assumed a constant cooling rate into the refractories. This velocity vector irregularity disappears when the liquid steel is stirred by gas injection from the central bottom of the ladle.[15] The possible reason for this phenomenon may be the jet effect from the stronger downward flow near the side wall and large axial upward flow in the initial stage, which may initialize oscillations. Second, relatively strong temperature fluctuation in the bottom region (Figure 4), as also observed in experiments,[16] may cause Rayleigh–Benard instability in that region. Further study is planned to clarify the mechanisms.

The decrease of the local steel temperature is mainly in the side and bottom wall regions at the initial stage, as shown in Figures 3(a) and 3(b). There exists a thermal boundary layer at the free surface (slag layer) because of heat loss from the top surface. The steel temperature difference between the top and the bottom enlarges with time. The isothermal contours become gradually flat after several minutes from the start, and the steel is thermally stratified in the ladle, except for the boundary layer near the side wall (Figure 3). Predictions also reveal that most of the steel temperature drop along the axial direction falls into the lower part of the ladle.

Figure 4 shows the steel temperature change with time at two axial heights $h_1 = 0.3$ m (near the bottom wall) and $h_2 = 2.3$ m (near the top free surface) for the case $T_w = 1423$ K and $q_{fs} = 10^4$ W/m^2. It is seen that the steel temperature decreases with time because of heat loss to the ladle walls and to the ambient from the free surface. Numerical predictions reveal the fluctuation behavior of the steel temperature, especially in the lower region of the ladle, a phenomenon which is consistent with the experimental observation.[16] It is noted that the local steel temperature is not a linear function with time. At $h_2 = 2.3$ m, the steel temperature remains unchanged within about 2 minutes, while, at $h_1 = 0.3$ m, it undergoes a sharp decrease within seconds from the start.

The effect of the initial ladle wall temperature (initial heating of the ladle) on thermal stratification (defined as the temperature difference of the molten steel between the axial positions $h_1 = 0.3$ m and $h_2 = 2.3$ m) is shown in Figure 5. The thermal stratification increases as the initial ladle wall temperature decreases, and is drastically influenced by the initial thermal state of ladle. This means that, practically, the ladle should be initially heated as much as possible to reduce the temperature difference between the top and bottom of the ladle. Thermal stratification increases with time. It is also seen that its increase with time is not a linear function and the nonlinear change with time becomes larger at a lower initial ladle thermal state. It is found that the history of the thermal stratification at a certain initial thermal ladle state can be very well represented by a fourth-order polynomial as follows:

$$T_s(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 \qquad [9]$$

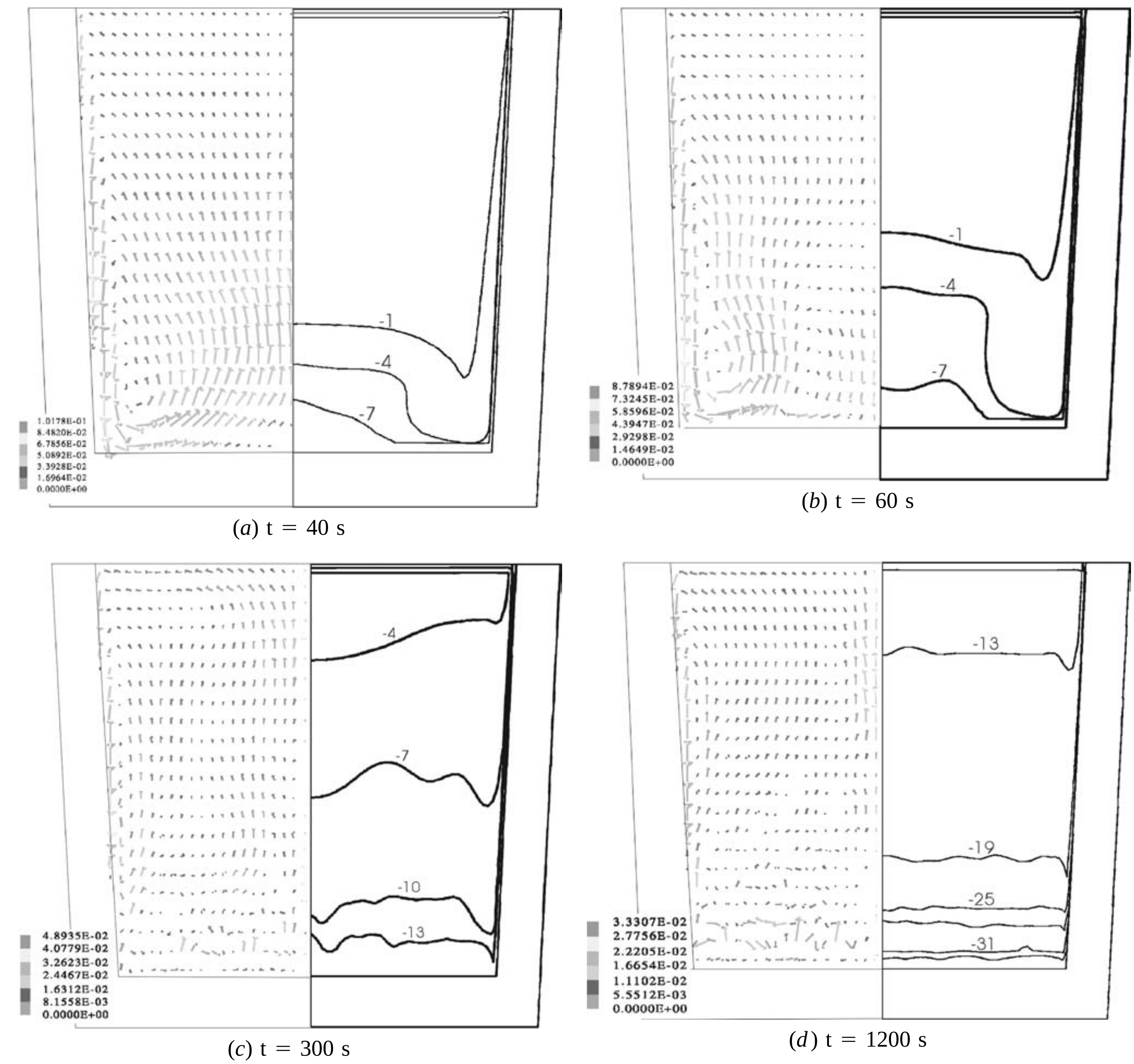

Fig. 3—(*a*) through (*d*) Velocity vector and temperature contours. The value of the contours is the temperature difference from the start, $T_s - T_{si}$.

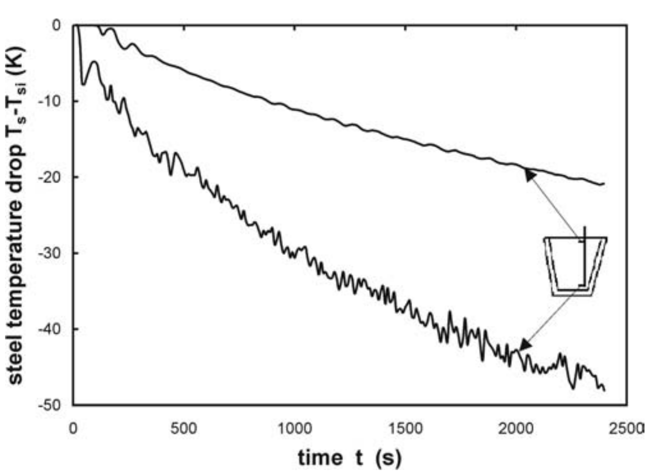

Fig. 4—Steel temperature as a function of time.

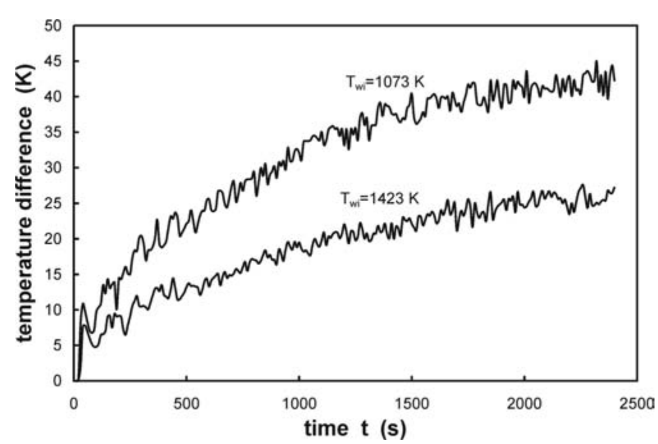

Fig. 5—Effect of initial thermal state on thermal stratification.

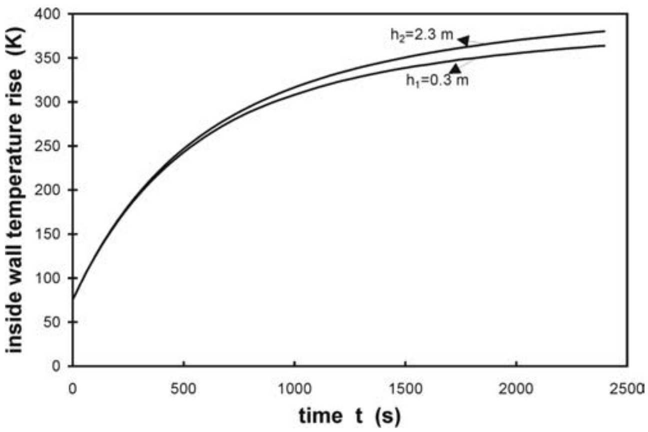

Fig. 6—History of the inside wall temperature.

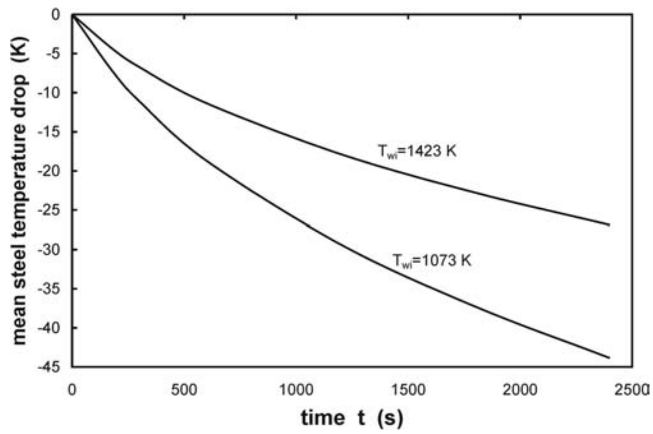

Fig. 8—Effect of initial thermal state on $T_{s,\mathrm{ave}}(t) - T_{si}$.

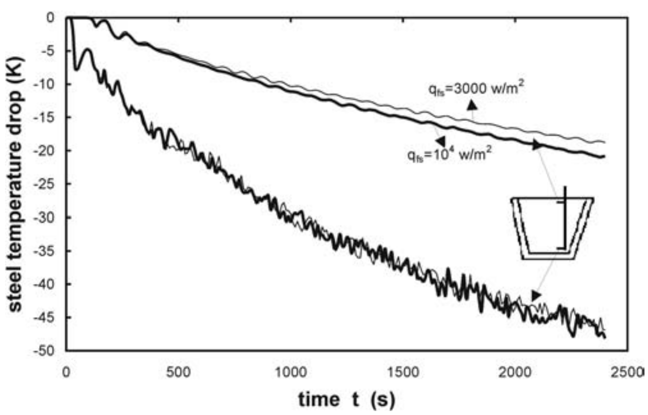

Fig. 7—Effect of slag surface heat loss on steel temperature.

where the coefficients a_0 to a_4 depend on the initial thermal states of the ladle. These are constants for a certain initial ladle thermal state. At $T_{wi} = 1073$ K,

$$\Delta T_s(t) = 4.5 + 4.94 \times 10^{-2}t - 3.217 \times 10^{-5}t^2 + 1.209 \times 10^{-8}t^3 - 1.90 \times 10^{-12}t^4 \qquad [10]$$

and, at $T_{wi} = 1423$ K,

$$\Delta T_s(t) = 2.9 + 3.03 \times 10^{-2}t - 2.298 \times 10^{-5}t^2 + 1.036 \times 10^{-8}t^3 - 1.82 \times 10^{-13}t^4 \qquad [11]$$

Such forms of polynomials can be conveniently used in industry and easily implemented in the expert system.

Figure 6 shows the inside ladle wall temperature rise, $T_w(t) - T_{wi}$, as a function of time at two positions (one near the bottom and the other near the top) for the case $T_{wi} = 1423$ K and $q_{fs} = 10^4$ W/m^2. The inside wall surface temperature is nonuniform and this nonuniformity increases with the ladle holding time. This is because thermal stratification in liquid steel becomes larger with time. The ladle wall is heated rapidly at the early stage of the transient, and later on, the increase rate of the inside wall temperature becomes smaller.

The history of steel temperature drop from the start, $T_s(t) - T_{si}$, is shown in Figure 7 for two different top free surface heat loss rates at $T_{wi} = 1423$ K. The difference between the upper and lower lines represents thermal stratification. It is seen that the heat loss rate from the free surface (or slag surface) affects the steel temperature near the free-surface region; however, its effect on the steel temperature in the lower part of the ladle is very small. On one hand, the greater the heat loss from the free surface (thinner slag), the larger the steel temperature drop mainly near the free surface, and thus the greater the decrease of the bulk mean temperature of steel. On the other hand, greater heat loss from the free surface will result in smaller thermal stratification due to enhanced natural convection within the molten steel.

The variation of the mean steel temperature drop, $T_{s,\mathrm{ave}}(t) - T_{si}$, with time is depicted in Figure 8 for two initial thermal ladle states at $q_{fs} = 10^4$ W/m^2. The mean steel temperature decreases with time because of heat loss into the refractories and to the ambient from the slag surface. Similar to thermal stratification, the mean steel temperature with time is found to be well represented by a fourth-order polynomial. At $0 \leq t \leq 2400$ s, it is obtained for the case $T_{wi} = 1073$ K,

$$T_{s,\mathrm{ave}}(t) = T_{si} - 4.36 \times 10^{-2}t + 2.607 \times 10^{-5}t^2 - 1.03 \times 10^{-8}t^3 + 1.598 \times 10^{-11}t^4 \qquad [12]$$

and, for the case $T_{wi} = 1423$ K,

$$T_{s,\mathrm{ave}}(t) = T_{si} - 2.64 \times 10^{-2}t + 1.586 \times 10^{-5}t^2 - 6.34 \times 10^{-9}t^3 + 9.93 \times 10^{-13}t^4 \qquad [13]$$

Using the lumped parameter assumption, we can deduce the average heat loss rate from steel into the refractories. Let us assume that nonuniformity of heat loss along the inside ladle walls (side and bottom walls) is negligible. In fact, it can be seen from Figure 6 that the change of the local inside wall temperature with height along the side wall is relatively small so that the local heat loss is a weak function of the position, taking into account thermal stratification of steel. Then, according to the total energy conservation law, the following is obtained:

$$-V\rho_s C_{p,s}\frac{dT_{s,\mathrm{ave}}}{dt} = A_2 q_{fs} + \int_0^A q_w\, dA \qquad [14]$$

If we assume that q_w is constant along the ladle walls, then the second term on the right hand of Eq. [14] can be integrated, *i.e.*, $\int_0^A q_w\, dA = q_w A$. Here, V is the volume of

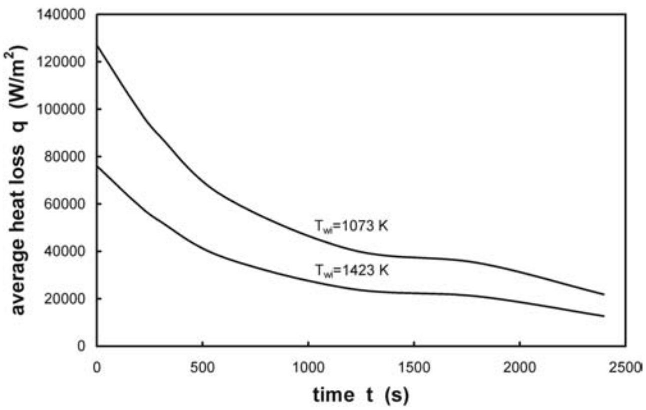

Fig. 9—History of predicted average heat loss.

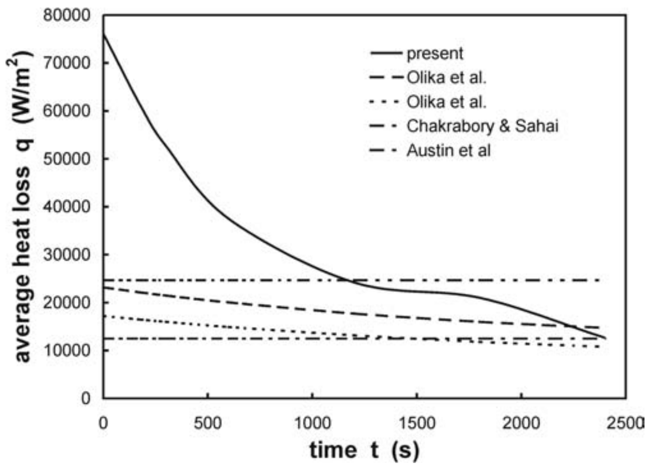

Fig. 10—Comparison of predicted heat loss with those from previous studies.

the ladle, ρ_s the density of steel, $C_{p,s}$ the specific heat of steel, A_2 the top slag surface area, A the area sum of the side and bottom walls of ladle, q_{fs} the heat loss rate from the top slag surface to the ambient, and q_w the heat loss rate from steel to the refractories. Then,

$$q_w = -\frac{\rho V C_{p,s}}{A}\frac{dT_{s,\text{ave}}}{dt} - \frac{A_2}{A} q_{fs} \qquad [15]$$

Substituting Eq. [12] or [13] into Eq. [15], we can obtain the dependence of the average heat loss rate from steel into the refractories with time for a certain initial thermal state of ladle. For the case $T_{wi} = 1073$ K,

$$q_w = \frac{\rho V C_{p,s}}{A}(4.36 \times 10^{-2} - 5.214 \times 10^{-5}t + 3.09 \times 10^{-8}t^2 - 6.393 \times 10^{-12}t^3) - \frac{A_2}{A} q_{fs} \qquad [16]$$

For the case $T_{wi} = 1423$ K,

$$q_w = \frac{\rho V C_{p,s}}{A}(2.64 \times 10^{-2} - 3.171 \times 10^{-5}t + 1.9304 \times 10^{-8}t^2 - 3.973 \times 10^{-12}t^3) - \frac{A_2}{A} q_{fs} \qquad [17]$$

The history of the average heat loss from steel into the refractories can be predicted from the preceding equations. The formulas of average heat loss rate obtained thereby for a certain initial thermal state of a ladle such as Eqs. [16] and [17] can be easily used for guidance in industrial operations and implemented in the expert system. Figure 9 shows the change of the heat flux with time for two initial thermal states of the ladle. It is seen that, at the early stage during the transient, the heat loss is quite large and decreases rapidly with time. This is because the temperature difference between the steel and the ladle walls is large at the initial stage. When the holding time increases, the inside ladle wall temperature rises rapidly (Figure 6) and the temperature difference becomes smaller so that the heat loss rate reduces. At later times during the transient ($t > 900$ s), the heat transfer between steel and the inside ladle surfaces is dominated by the heat conduction within the refractory walls and the heat flux decreases slightly with time. Numerical predictions also reveal that the wall temperature rise or the internal energy increase of the refractories concentrates within a thin layer of the working lining adjacent to the inside surface.

IV. COMPARISON WITH EXPERIMENTAL DATA AND PREVIOUS STUDIES

Comparison of the predicted average heat fluxes from Eq. [17] with those from previous studies is shown in Figure 10. It is seen that all the previous studies have given a much lower heat loss rate at the early stages ($t < 900$). This is because previous calculations did not simultaneously take transient heat conduction in the refractories into account, and the heat loss was assumed either a constant heat flux on the wall boundary or a constant heat loss rate or a heat loss deduced from heat conduction of the walls without the melt taken into consideration. At the initial stage, the temperature difference between the steel and refractory surface is large, resulting in a large heat flux ($q_w = h_w\{T_s(t) - T_w(t)\}/A$). The heat flux decreases with time because of the decreasing temperature difference due to increased wall temperature and decreased steel temperature. Only after about 900 seconds of the holding period of the ladle, the heat loss rate is then dominated by heat conduction within the walls, and the decreasing rate of the heat loss becomes lower. Because there exists a heat loss from the outside surface of the ladle to the ambient and a heat loss from the free surface, and the temperature difference between the liquid steel and the inside surface of the ladle becomes smaller with time, the heat loss rate from the steel to the refractory should always decrease with time, a fact revealed in our predictions. Eventually, after a very long time, it approaches zero when thermal equilibrium is reached (at that time, the liquid steel is already solidified). However, practically, the ladle holding period will not last that long at all. The reason why there exists a difference from previous studies after the heat conduction dominates the heat transfer may be that different initial ladle thermal states were used in other studies to obtain their (assumed) constant heat loss rate. Since the heat loss rate into the ladle walls is the main driving force of the transient natural convection in steel, it is crucial to have an accurate heat loss rate in order to obtain an accurate prediction of the transient flow and heat transfer or thermal stratification in a ladle. Therefore, the transient,

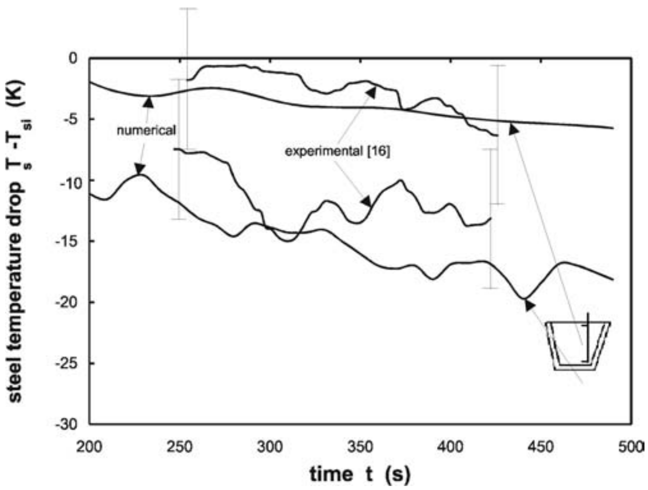

Fig. 11—Comparison of predicted and measured steel temperatures. The measured data are from Grip.[16] The experimental uncertainty is $\pm$(0.25 pct of T_{abs} + 1.0), which corresponds to approximately $\pm$5.9 °C, and the experimental repeatability was $\pm$0.15 pct of T_{abs}, which corresponds to about 2.9 °C.

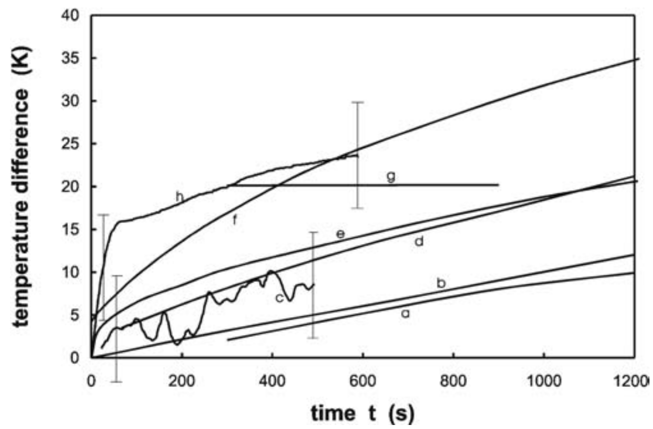

Fig. 12—Comparison of thermal stratification history among different sources: (*a*) Chakraborty and Sahai,[6] (*b*) Austin *et al.* Formula,[5] (*c*) measured data from an industrial ladle,[16] (*d*) Olika *et al.*,[8] (*e*) present prediction for T_{wi} = 1423 K, (*f*) present prediction for T_{wi} = 1073 K, (*g*) Ilegusi and Szekely,[4] and (*h*) measured data from a pilot plant.[17]

conjugate natural convection-heat conduction should be solved, as considered in the present study.

It is very difficult to conduct measurement of the steel temperature because of the hostile conditions in steelmaking ladles (the temperature is as high as about 1900 K). Therefore, very little experimental data are available to make intensive validation. The only experimental measurements appear to be reported by Grip[16] for an industrial ladle and by Lehner *et al.*[17] for a pilot plant ladle. Figure 11 shows comparison of the steel temperature drop $T_s(t) - T_{si}$ between the numerical predictions and the experimental data. Data were obtained from an industrial ladle by Grip.[16] The liquid steel temperature was measured by a pyrometer, which had a good accuracy. The experimental uncertainty was $\pm$(0.25 pct of T_{abs} + 1.0). This corresponds to approximately $\pm$5.9 °C for the present cases. The experimental repeatability was $\pm$0.15% of T_{abs}. This corresponds to about 2.9 °C for the present conditions. Taking into account these experimental uncertainties, we can see that agreement between predictions and measurements is quite reasonable and the predicted steel temperatures fall well into a range of the experimental accuracy.

Thermal stratification as a function of time is shown in Figure 12, in which comparison is made for numerical predictions from different researchers and experimental data from industrial[16] and pilot plant ladles.[17] It is seen that differences exist between different sources. The present numerical predictions fall into the region between the experimental data from the industrial and pilot plant ladles. The predicted (averaged) stratification for T_{wi} = 1073 K (curve f) is closer to the measurements from the pilot plant ladle (curve h), while the one for T_{wi} = 1423 K (curve e) is closer to the experimental data from industrial ladle (curve c). The reason for the difference between predictions and experimental data may be that there exist uncertainties in measurements (as stated previously, predictions are quite reasonable when the experimental uncertainties are taken into account); in addition, different initial thermal states of the ladle may be used in simulation from the experiments.

Austin *et al.*[5] pointed out that the rising rate of thermal stratification is proportional to the heat loss rate; a similar conclusion was also obtained by Olika *et al.*[8] The present predictions reveal that the rising rate is not a linear function of the heat loss rate, which is especially true during the initial stage of the ladle holding period. The reason for this difference is that, in previous studies, the ladle walls were not taken into account simultaneously for the transient prediction of the stratification in a steelmaking ladle, and the heat loss rate was either assumed a constant[5,6] or was obtained separately from heat conduction of ladle walls.[8]

V. CONCLUSIONS

Transient, turbulent fluid flow and heat transfer of melt in a ladle during the holding period have been numerically investigated. In contrast to the previous studies, the present simulation model makes no assumptions of the heat transfer between steel and the inside ladle walls, and simultaneously takes the ladle walls into account. The initial ladle thermal state and the heat loss through slag have been systematically changed to examine their influence on thermal stratification in the ladle. A simplified model for the heat loss rate from the steel to the refractory is proposed. Based on numerical predictions, the histories of thermal stratification, steel temperature, and heat loss rate are obtained. The main conclusions can be drawn as follows.

1. Flow in a ladle undergoes a flow pattern transition from one to two and to multiple vortex type during the holding period. At the initial stage of the transient, a single recirculation is formed in the ladle; when the ladle holding time is large than about 40 seconds, another vortex is formed in the region of the central bottom; thereafter, complex flow patterns gradually develop in the bottom region, and the flow thereby becomes gradually unstable.
2. The liquid steel is thermally stratified after several minutes from the start. The initial heating of the ladle (initial ladle wall temperature) has a significant effect on the thermal stratification. The lower the initial wall temperature, the larger the thermal stratification. Thermal stratification becomes larger with time.
3. The slag thickness or the heat loss rate from the top free

surface reduces the liquid steel temperature mainly near the free surface, but its effect on the steel temperature near the ladle bottom region, where the liquid steel is extracted during casting, is quite small. Though the thermal stratification is reduced at greater heat loss of the top free surface (thinner slag layer), the decrease in the mean steel temperature becomes larger.

4. The temperature at the inside wall surface is nonuniform along the height and the difference becomes larger with time. The inside wall surface temperature increases sharply at the early stage and then increases gradually.
5. Heat flux from steel to the refractory decreases rapidly with time at the early holding period of the ladle and is then dominated by the heat conduction of the ladle walls at $t > 900$ seconds.
6. A simplified model for the heat loss rate from the steel into the refractory of ladle is proposed. Correlations for the histories of thermal stratification, mean steel temperature, and heat loss rate have been obtained, based on the present numerical prediction. These correlations (Eqs. [11] through [14] and Eqs. [16] and [17]) can be easily used in industrial operations and as a reference for engineering design.
7. The predicted heat loss rate, steel temperature, and thermal stratification are compared with available experimental data and those from previous studies. The present study shows that the ladle walls should be simultaneously taken into account to obtain a reasonable prediction of flow and thermal stratification during the ladle holding period

NOMENCLATURE

A	wall area
A_2	top free surface area
C	model constant
D	ladle diameter
F	source term
g	gravitational acceleration
H	ladle height
h	heat transfer coefficient
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Q	heat transfer rate per unit volume
q	heat loss rate
r	radius
Ra	Rayleigh number
Re	Reynolds number
T	temperature
U_j	mean velocity in j direction
v	mean radial velocity
x_j	coordinate in j direction

Greek symbols

α	volume fraction
μ	dynamic viscosity
μ_t	turbulent viscosity
ρ	density
σ	model constant

Subscripts

i, j	spatial coordinates
l	liquid
s	steel
w	wall

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