Melt Stratification in Ladles*

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Synopsis

A mathematical formulation has been developed, and computed results are presented describing the evolution of the temperature and the velocity profiles in ladles holding molten steel. The calculations, which have been carried out using the PHOENICS computational package, have shown that, notwithstanding the strong turbulent recirculating flows, significant stratification may take place. However, this stratification may be greatly minimized by a relatively gentle agitation.

Key words: natural convection; heat transfer; stratification; ladles; induction stirring.

I. Introduction

When molten steel is held in ladles, heat losses will inevitably occur through both the side walls and the bottom of the ladles, due to transient conduction. As shown in now classical papers by Hlinka^{1,2)} and others,^{3,4)} an important consequence of this heat loss is a possible stratification, the existence of which was demonstrated experimentally. In continuous casting, a logical and undesirable consequence of this stratification is that the steel fed from the ladle from the tundish may have a more strongly time-dependent temperature than would be the case otherwise, as the ladle is being emptied. The progressively increasing stress on the quality of continuously cast products mandates much tighter tundish temperature control, which in turn would require a more precise definition of both the extent of melt stratification in ladles, and the means to prevent its occurrence.

Until recent times, the quantitative mathematical description of such systems would have been quite difficult, because one has to deal with transient, turbulent natural convection in a cylindrical cavity. For this reason, previous investigators have been employing physical modeling techniques, which at best can give only semi-quantitative answers because of the approximations involved.

In the following, we shall present a mathematical formulation of this problem, together with solutions obtained using a computational subroutine. The theoretical predictions will be compared with measurements.

II. Formulation

Let us consider a cylindrical ladle of radius *R* and containing molten steel with a depth *H*. Initially, the steel is stagnant and at a uniform temperature and from time=0, heat will be lost by (transient) conduction into the bounding solid surfaces, while

the top surface will be assumed to be completely insulated by a thick slag layer.

As a result, temperature gradients will be set up in the vicinity of the solid surfaces, which in turn will give rise to convective motion (downwards near the vertical walls, and upwards toward the center), and in time this convection will modify the temperature profiles.

The question is then to calculate the velocity fields and the associated temperature fields as a function of time, both as a result of thermal natural convection and also to examine how these results would be modified if a complementary induction stirring were employed.

The problem is readily stated by writing down the equation of continuity, the equation of motion and the differential thermal energy balance equation, which take the following form:

(Continuity)
$$\nabla \cdot \rho \underline{U} = 0 \dots\dots\dots(1)$$

(Motion)
$$\frac{D\rho U}{Dt} = -\nabla p - \mu \nabla^2 \underline{U} + \underline{F}_B + \underline{F}_E \dots\dots\dots(2)$$

where,
$$\frac{D}{Dt} (\quad) = \frac{\partial}{\partial t} (\quad) + \underline{U} \cdot \nabla (\quad) \dots\dots\dots(3)$$

(Thermal Energy Balance)
$$\frac{DT}{Dt} = \alpha \nabla^2 T \dots\dots\dots(4)$$

where α is the thermal diffusivity, and μ is the effective viscosity, which is the sum of the molecular and turbulent viscosities.

It should be noted that in the equation of motion, we have two possible driving forces. One, the buoyancy force, is defined as:

$$\underline{F}_B = \rho \underline{g} \dots\dots\dots(5)$$

The other, the electromagnetic force when induction stirring is being applied, is defined as:

$$\underline{F}_E = \underline{J} \times \underline{B} \dots\dots\dots(6)$$

where, $\underline{J}$ is the current density and $\underline{B}$ the magnetic flux density, which can be obtained by solving Maxwell's equations. The flow is expected to be turbulent, and the well-documented *k-ε* model will

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be used to represent the turbulent viscosity.

1. Boundary Conditions

The boundary conditions employed were the usual ones for problems of this type, no slip at all the bounding surfaces, symmetry about the centerline and transient conduction into the solid surfaces, which gave the following relationship for the heat flux:

$$\dot{q}_w = K \Delta T / \sqrt{\pi \alpha t}^{1/2} \dots\dots\dots(7)$$

where, α : thermal diffusivity of refractory material. The top surface is assumed to be insulated. From the work of Szekely and Chen,⁵⁾ this would be a suitable condition for at least 6 inch of slag cover.

The melt was assumed to be at the initial temperature given in Table 1, while the initial refractory temperature was deduced approximately from the data of Hlinka and Miller.²⁾

III. Technique of Solution and the Computed Results

The governing equations were solved using a computational package,⁶⁾ employing 22×18 and 32×28 grids for the small and the large ladle, respectively. The electromagnetic force field calculations were performed using a previously described computational procedure, which was embedded into the computer code in the present instance.

A typical run required about 5~10 h on an Apollo DN 330 digital computer.

The principal input parameters used are summarized in Table 1.

1. Results

A selection of the computed results is shown in the following Figs. 1 to 12.

Figures 1(a) to 1 (c) show the computed temperature profiles, velocity fields and turbulent kinetic energy, respectively, in an 80-t ladle after 5 min. The isotherms clearly illustrate the counteracting effects of melt circulation and the steep temperature gradients in the vicinity of the walls, where the cooling takes place. The cool portion near the bottom of the ladle is also readily apparent. The velocity fields seen in Fig. 1(b) represent the pattern that one would expect, namely downward flow near the side walls and upward flow near the middle. The characteristic velocity of about 5 cm/s is relatively low com-

Fig. 1(a). Temperature stratification in 80-t ladle after 5 min.

Fig. 1(b). Velocity vectors in 80-t ladle after 5 min.

Fig. 1(c). Turbulence kinetic energy in 80-t ladle after 5 min.

Table 1. Principal input parameters.

Property	80-t ladle	7.5-t ladle	200-t ladle
Melt	Steel	Steel	Steel
Melt tempera- ture	1 600°C	1 640°C	1 600°C
<i>Gr</i>	2×10 ¹¹	1.2×10 ¹¹	3.18×10 ¹
<i>K</i> (Refractory)	30.3 W/km	1.39 W/km	1.39 W/km
α (Refractory)	5.6×10 ⁻⁶ m ² /s	5.5×10 ⁻⁷ m ² /s	5.5×10 ⁻⁷ m ² /s
<i>I</i> (Cases with stirring)	300 A	—	—
<i>f</i>	50 Hz	—	—
<i>n</i>	30 turns	—	—

pared to the velocities one can expect in argon-stirred or inductively-stirred ladles (say 30~100 cm/s) which explains why stratification can take place.

Figures 2 and 3 show similar plots, but after the passage of 10 and 15 min, respectively. It is seen

that stratification is being maintained, while the maximum value of the velocity is being gradually decreased as the driving force for the circulation

Fig. 2(a). Temperature stratification in 80-t ladle after 10 min.

Fig. 3(a). Temperature stratification in 80-t ladle after 15 min.

Fig. 2(b). Velocity vectors in 80-t ladle after 10 min.

Fig. 3(b). Velocity vectors in 80-t ladle after 15 min.

Fig. 2(c). Turbulence kinetic energy in 80-t ladle after 10 min.

Fig. 3(c). Turbulence kinetic energy in 80-t ladle after 15 min.

diminishes.

One should note here that the flow is turbulent, with the ratio μ_{eff}/μ being of the order of 300.

In order to obtain a little more insight into the system behavior, Figs. 4 and 5 show the time dependence of temperatures close to the side wall and in the central position, with the vertical coordinate as a parameter.

Figure 4 shows the evolution of the dimensionless temperature profiles in the vicinity of the side wall, at various vertical positions. The initially very steep temperature gradients are due to largely conductive transfer; the role of convection is obvious in flattening out these gradients. Figure 5 shows a similar behavior, but here the flattening of the profiles is rather more pronounced.

Fig. 4. Temperature evolution near side wall of 80-t ladle at $y/R=0.99$; $T_0=1\ 600^\circ\text{C}$

Fig. 5. Temperature evolution near axis of 80-t ladle at $y/R=0.15$; $T_0=1\ 600^\circ\text{C}$

Since stratification is undesirable, it is of interest to examine the effect of agitation. Figures 6 to 8 show the evolution of the temperature profiles, the

Fig. 6(a). Temperature stratification in an inductively-stirred 80-t ladle after 5 min.

Fig. 6(b). Velocity vectors in an inductively-stirred 80-t ladle after 5 min.

Fig. 6(c). Turbulence kinetic energy in an inductively-stirred 80-t ladle after 5 min.

Fig. 7. Temperature stratification in an inductively-stirred 80-t ladle after 10 min.

Fig. 8. Temperature stratification in an inductively-stirred 80-t ladle after 15 min.

corresponding velocity profiles, and the turbulence-energy distribution when the heat transfer process described above is accompanied by a relatively mild induction stirring, using a single phase coil arrangement.

It is seen that, notwithstanding the relatively gentle stirring, it was possible to minimize the extent of stratification. The maximum velocity for the induction-stirred case was of the order of 15 cm/s, which being some 3 times larger than that due to the thermal natural convection, appears to be consistent with the general findings reported here.

It is of interest to examine how the physical size of the ladle would affect these considerations. Figure 9 shows the evolution of the velocity profiles calculated for a 200-t ladle, which are seen to be qualitatively similar to the previously given plots for the smaller systems, except for the larger melt velocities found for the 200-t ladle.

Figures 10 and 11 show the evolution of the dimensionless temperatures near the side wall and near the axis for a 200-t ladle; this behavior is again

Fig. 9(a). Velocity vectors in a 200-t ladle after 5 min.

Fig. 9(b). Velocity vectors in a 200-t ladle after 10 min.

Fig. 9(c). Velocity vectors in a 200-t ladle after 15 min.

Fig. 10. Temperature evolution near side wall of 200-t ladle at $y/R=0.99$; $T_o=1\ 600^\circ\text{C}$.

Fig. 11. Temperature evolution near the axis of 200-t ladle at $y/R=0.15$; $T_o=1\ 600^\circ\text{C}$.

quite analogous to that seen earlier for the smaller systems seen in Figs. 4 and 5.

Finally, while these calculations are based on well-established physical relationships, it is still important to compare the theoretical predictions against experimental measurements. This is done in Fig. 12, using previously reported measurements by Hlinka.¹⁾ The very good agreement between measurements and predictions is readily apparent.

IV. Discussion

A mathematical formulation has been developed, and computed results are presented, describing the evolution of the temperature and velocity profiles in ladles holding molten steel, the top surface of which is insulated.

The calculations have shown that, notwithstanding the development of a fairly strong turbulent recirculating flow due to natural thermal convection, significant stratification will take place. This stratification may, however, be minimized by relatively gentle agitation. The case considered for agitation was electromagnetic stirring, but it is thought that gas bubble stirring would provide acceptable results also.

Fig. 12. Stratification in a 7.5-t ladle compared with data of Hlinka and Miller.²⁾

Going somewhat beyond the actual computed results, the following physical picture emerges from these calculations:

When the molten steel is brought into contact with the cold walls, initially transient conduction will take place, but a thermal buoyancy driven recirculating pattern is rapidly established. The turbulent mixing brought about by this recirculating flow will diminish the temperature gradients, which drive the circulation, and hence the characteristic velocity will diminish with time.

While the turbulent recirculating flow will counteract the thermal stratification of the system to some extent, significant axial temperature gradients will be established.

It is of interest to note that the 7.5-, 80- and 200-t ladles behave in a fairly similar manner, which is consistent with experience that pilot scale work using, say, 4~6 t ladles does give a fairly good indication as to the behavior of the much larger production-scale units.

It should be remarked that the order of magnitude of the melt velocity may be estimated using the following relationship:

$$U = \frac{\nu Gr^{1/2}}{H} \dots\dots\dots(8)$$

which would give characteristic velocities of the order of 10 to 15 cm/s for the 80- and 200-t ladles, respectively, and which seems to be in fairly good agreement with the computed values.

The Peclet number for this system is quite high for all the units, of the order of ten thousand, indicating that the convection dominates in consensus with physical reasoning.

The principal practical conclusions that may be drawn from this work are the following:

- In the absence of agitation, thermal stratification has to be an inherent feature of any ladle operation holding molten steel.
- This stratification, which may seriously interfere with subsequent processing operations, may be readily and quantitatively predicted, as can the extent of agitation needed to eliminate it.

Nomenclature

B : magnetic field density
 $\tilde{F}_B$: buoyancy force
 $\tilde{F}_E$: electromagnetic force
 $\tilde{g}$: gravity acceleration
 Gr : Grashof number
 H : melt height
 I : current in induction coil
 J : current density
 k : thermal conductivity
 n : number of turns of coil
 p : static pressure
 $\dot{q}$: heat flux
 R : radius of ladle
 t : time
 T : temperature
 U : velocity
 y : radial distance from axis of ladle
 α : thermal diffusivity

ρ : density
 μ_{eff} : effective viscosity
 μ : molecular viscosity
 ν : kinematic viscosity

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