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Evaluation of efficacy of ceramic paper in controlling heat loss from steel ladles by mathematical modelling

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ABSTRACT

A ladle with high heat content is desirable for steel making in order to minimise heat loss from steel in the period between tapping and casting. Casting into cooler ladles also leads to high localised wear due to thermal spalling. A possibility of specific casting advantages, lowering in tap temperatures and associated cost savings accrued by minimising heat loss from the melt led to the concept of preheating and insulation in the steel ladles. It has been a practice in Tata Steel to use 5 mm thick ceramic paper as an insulation. This work studies the efficacy of the ceramic paper in controlling heat losses from steel ladles. Transient heat transfer analysis has been employed using finite element modelling.

INTRODUCTION

Casting temperature of a melt is of paramount importance to the solidification behaviour of the castings. A considerable loss in heat content of the melt occurs from the time it is tapped to the end of casting and is evident from the accompanying fall in temperature. Ladle heat content plays a significant role in this drop in temperature and hence efforts are always directed towards minimising the heat loss and maximising the heat content. Moreover, tapping into colder ladles leads to high localised refractory wear due to spalling and thermal shock, associated operational problems and escalation in overall manufacturing cost. It is for this reason that ladle preheating and insulation have been receiving increasing attention of late. With a shift towards the use of high alumina bricks and basic bricks for ladle construction, there has been an increase in heat loss as the conductivities of these materials are high. For the purpose of minimising this heat loss in a steel ladle, the use of a 5 mm ceramic paper insulation between safety lining and shell has been the established practice in Tata Steel. The work described in this report was taken to re-examine this arrangement by means of a finite element based mathematical simulation of a ladle cycle.

The thermal conditions in a ladle change continuously with variations in the surface condition and the amount of steel contained. For this reason, a transient state heat transfer analysis was carried out and is very different from the steady state heat transfer analysis that was carried out in the earlier work[1].

DESCRIPTION OF THE MODEL

Considering the structural symmetry of the ladle, a section of the ladle refractory lining was analysed by means of a finite element (FE) based 2D model using three noded triangular elements on MSC NASTRAN, FEM package and was considered to be an approximate representation of reality. For the purpose of the study, at any given moment, the temperature of the hot face of the ladle refractory was assumed to be uniform throughout the ladle. A schematic diagram of the geometry considered for analysis is given in Figure 1. The geometry was discretised into an optimum number of 130 nodes in direction 1 and 90 nodes in direction 2 and was subjected to analysis under appropriate boundary conditions. Transient one-dimensional conduction equation has been considered in this work for calculating the heat transfer from

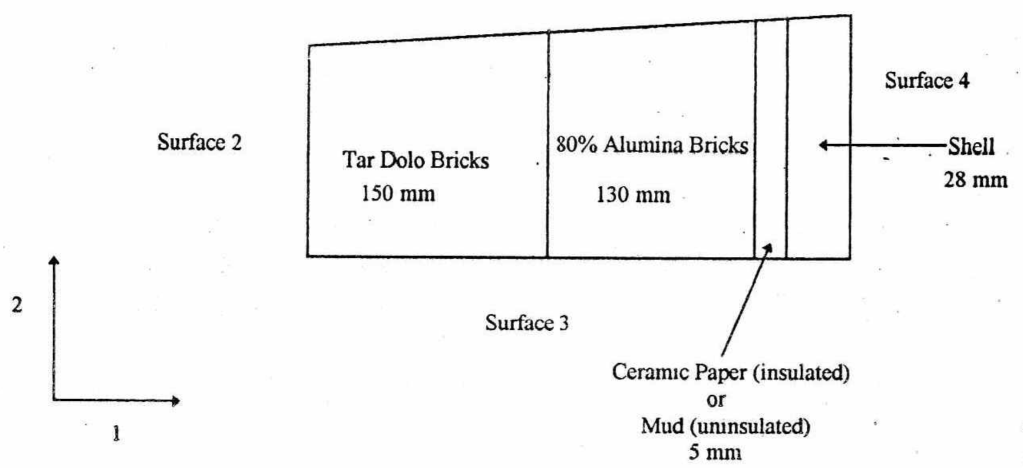

Fig. 1 : Schematic diagram of the geometry considered for Finite Element Analysis

the hot face of the working refractories lining to the rest of the ladle lining. The transient heat conduction equation is given by :

$$\delta^2T/\delta x^2 = [\delta T / \delta t]/\alpha \quad ... 1$$

Natural convection is one of the two modes of heat transfer from the shell to the atmosphere and the governing equation is :

$$q = h\ A\ (T_s - T_o) \quad ... 2$$

Throughout this work the heat transfer coefficient, h, has been considered to vary with shell temperature. The different values of h are given in Table 1.

The second mode of heat transfer from the shell to the atmosphere is radiation, which is governed by the following equation :

$$q = A\{\sigma\varepsilon\ (T_s^4 - T_o^4)\} \quad ... 3$$

where σ = Stefan-Boltzmann constant = 5.672×10^{-8} W/m²K⁴

ε = Emissivity of steel shell = 0.75

Table 1

$h (W/m^2K)$	$T_s (K)$
0	303
3.003	323
4.017	343
4.7	373
5.127	473
5.612	510

Table 2 : Lists the properties of the materials utilised for ladle construction

Material	Conductivity W/m-K	Density kg/m^3	Specific Heat J/kg-K
Tar Dolo	2.4	2850	1050
80% Alumina	1.84	2600	1200
Ceramic Paper	0.038	100	700
Steel Shell	52	7800	552
Liquid Steel	782	7100	782

Throughout this work, insulated ladle signifies ladle with ceramic paper lining.

ANALYSIS

Ladle Preheating

Preheating the ladles is an established procedure adopted to reduce the temperature loss from the melt. For the purpose of this study, a typical preheating programme for Dolomite ladles recommended by Wulfrath Refractories[2] was simulated both for an uninsulated and an insulated ladle in order to obtain the temperature distribution in the ladle lining before tapping. The program recommends a linear increase in temperature of the bottom from room temperature to 1000°C in ten hours. From the temperature measurements made in the plant, the shell temperature in this period rises from room temperature to upto about 200°C. Heat is transfer/red from the hot face of the lining to the rest of it by means of conduction and is governed by equation[1]. The above equations (1)-(3) need to be solved for the ladle geometry under the following boundary conditions :

Surface 1, $\delta T / \delta y = 0$ (Adiabatic condition)

Surface 2, T = 30°C at t = 0

T = 1000°C at t = 36000 seconds

Surface 3, $\delta T / \delta y = 0$ (Adiabatic condition)

Surface 4, h = 0 W/m²K at T = 30°C at t = 0

h = 5.127 W/m²K at T = 200°C at t = 36000 sec.

where t is the time elapsed.

Table 3 : The shell temperatures after a period of 10 hrs, for insulated and uninsulated ladles obtained from the solution of the above equations.

Ladle	Hot Face Temp.	Shell Temp.
Uninsulated	1000°C	140.26°C
Insulated	1000°C	128.587°C

Tapping

Tapping of the steel melt from the furnace into the ladle is accompanied by a very rapid drop in the melt superheat. The time for which the melt can be maintained in its superheated state depends on the tapping temperature, the extent of ladle preheat, the time taken to fill the ladle, ladle refractory material properties and the thickness of the slag cover. Tapping temperature loss can thus be attributed to the following reasons : heat lost by the pouring stream to the atmosphere by radiation, heat lost by convection to the slag layer and heat lost to the ladle walls as the ladle is filled. Henzel et al[3] have reported heat loss to the ladle refractory to be contributing up to 87% of the total tapping heat loss and this is the phenomenon that has been studied in this work.

With the temperature distribution at the end of preheating as the initial body load, the process of tapping of the melt was simulated under the following conditions :

1) Time taken from the start of tapping start to the end of tapping has been assumed to be 5 min.
2) The melt temperature at the end of the tapping has been assumed to be uniform at 1650°C.
3) The temperature of the refractory face in contact with the metal has been assumed to be same as the temperature of the melt.
4) The rise in temperature of the hot face of the ladle refractory from 1000°C to 1650°C in 5 min. has been assumed to be linear.

The governing equations for heat transfer at various surfaces are identical to the ones used for preheating and are solved for the following conditions :

Surface 1, $\delta T / \delta y = 0$ (Adiabatic condition)

Surface 2, $T = 1000°C$ at $t = 0$

$T = 1650°C$ at $t = 300$ seconds

Surface 3, $\delta T / \delta y = 0$ (Adiabatic condition)

Surface 4, $h = 4.7\ W/m^2 - °K$ at $T = 140°C$ at $t = 0$

$h = 5.127\ W/m^2 - °K$ at $T = 200°C$ at $t = 300$ sec.

Table 4 : The shell temperatures obtained after 5 minutes on solving the governing equations.

Ladle	Hot Face Temp. °C	Shell Temp. °C
Uninsulated	1650°C	141.78°C
Insulated	1650°C	129.46°C

Casting

Once the ladle is full, the melt is held in the ladle for some time before casting. In this intervening period, the melt continues to lose heat to the ladle walls and to the atmosphere. The process has been modeled assuming a linear drop in the hot face temperature from 1650°C to 1560°C (a typical casting temperature) in one hour. The solution was obtained for governing equation similar to the ones described for preheating and tapping under the following boundary conditions and the calculated shell temperature values have been presented in table 5 below.

Surface 1, $\delta T / \delta y = 0$; (Adiabatic Condition)

Surface 2, T = 1650°C at t = 0

T = 1560°C at t = 3600 seconds

Surface 3, $\delta T / \delta y = 0$; (Adiabatic Condition)

Surface 4, h = 4.7 W/m² - °K at T = 140°C at t = 0

h = 5.612 W/m² - °K at T = 237°C at t = 3600 sec.

Table 5

Ladle	Hot Face Temp. °C	Shell Temp. °C
Uninsulated	1560°C	167.47°C
Insulated	1560°C	145.2°C

EFFECT ON HEAT CONTENT OF MELT

In our analysis we have assumed that the heat loss through the slag layer is the same for both the insulated and uninsulated cases. Therefore, the heat loss from the melt will only be due to convective and radiative losses from the shell of the ladle. Thus the total heat loss given by the summation of equations (2) and (3). For the heat loss calculations, we have considered the shell temperatures after casting. The ceramic paper lining is taken to be 3.53m. high in the ladle.

q_u (uninsulated) = 73080.8 W

q_i (insulated) = 55717.4 W

Therefore, the reduction in heat loss of the melt due to the presence of ceramic paper is Δq = 17363.4 W.

Assuming the effective residence time of the melt in the ladle to be 105 minutes, the associated drop in temperature of the melt in the absence of ceramic paper has been found to be 1.5°C. The cost of total energy saved by the presence of ceramic paper amounts to Rs. 53000/- per month for both LD1 and LD2, whereas the total cost of ceramic paper alone amounts to Rs. 2,73000/- per month. It is therefore recommended that the practice of installing ceramic paper be discontinued.

CONCLUSIONS

From the transient heat transfer analysis of one cycle of a green ladle the following conclusions were drawn :

1. Due to the presence of a 5mm thick ceramic paper in the lining of a ladle, the reduction in heat loss (compared to the case where no ceramic paper is used) has been calculated to be 65316 kCal for one full cycle of use of a ladle. The full cycle consists of waiting period, preheating, tapping, holding and casting.
2. The drop in temperature of the melt due to the absence of ceramic paper was determined as 1.5°C.
3. It is therefore suggested that the use of ceramic paper in the refractories lining of LD ladles may be discontinued as the benefits are not commensurate with the expenditure involved.

NOMENCLATURE

T = hot face temperature
t = time
x = distance along the radial direction
α = diffusivity of the material
σ = Stefan-Boltzmann constant
ε = Emissivity of steel shell
h = heat transfer coefficient
A = surface area of the shell
T_s = shell temperature and
T_0 = ambient temperature
q = heat content
u = uninsulated
i = insulated

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