Thermal rhythms in composite ladle walls

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1. Introduction

The ladle is essential to the operation of a modern integrated iron and steel plant. It is a refractory lined vessel, typically holding 300 tonnes of liquid metal, which is used to transport iron or steel in molten form with a minimum heat loss and also to pour steel into moulds prior to solidification and further processing.

This paper is concerned with the thermal response of a composite ladle wall during day-to-day operations in a steel making plant. Typically a ladle will be filled with molten metal at, for example, 1600 °C. The system will lose heat by conduction through the top slag surface and the ladle wall and then by convection and radiative transfer into the environment. Internally the molten metal will thermally stratify by a process of conduction and convective motion.

The ladle standing period normally lasts for one hour and during that time the molten metal/inner wall local temperature is observed to decrease slowly. For simplicity it is here taken to be 1600 °C. During the next hour the liquid metal is poured from the ladle either into the mould of a concast machine or into moulds for producing ingots. The convective motion and heat transfer within the liquid is now more complex than in the standing period, see for example the mathematical model proposed in Egerton et al. [2,3] where viscous flow effects, buoyancy force and heat capacitance of the walls were ignored. Here the heat loss at the inner ladle wall is approximated by an average constant heat flux which is found experimentally. Of course this local condition at the inner wall depends on whether it is in contact with molten metal or if it is radiating heat back into the empty portion of the vessel. This work is concerned with the former situation.

The total time from filling to re-filling the ladle is typically four hours and this process is repeated continuously in day-to-day operations. After a long time when initial thermal responses have died away, the conduction profile in the ladle wall becomes periodic in time. These transient responses (evolving to a state which is periodic in time) are herein called the thermal rhythms of the ladle wall during cycles of standing and pouring.

The ladle wall is constructed of high Al2O3 refractory material and in an attempt to control the heat loss from the ladle wall it is proposed to insert a
layer of insulating material into the wall, see Fig. 1. Assuming that the heat
conduction across the composite wall is locally at any point one-dimensional
then in a steady state situation the heat loss from the outer ladle surface is
independent of the location of the inserted insulated layer; it is dependent on
the relative thickness of the insulating layer and on the thermal properties of
the refractory lining and the insulating layer. However, as previously dis-
cussed, the day-to-day operations involving a ladle is a time dependent process
and in the case of thermal rhythms in the composite wall the heat loss at the
outer ladle surface will also depend on the thermal capacitance of the
composite wall and on the location of the insulating layer.

It is the objective of this paper to construct a one-dimensional mathemati-
cal model to simulate the thermal response of a composite ladle wall, to
various cycles of heating and cooling as would occur in day-to-day operations.
There are three main questions to be answered:

(a) If the composite ladle wall starts out as “cold” how many cycles (heating
followed by cooling) must take place so that the thermal rhythm becomes
periodic?
(b) What is the effect of preheating the composite ladle wall on the heat loss
from the outer ladle surface during the first few plant operations? and
(c) For specified thickness and properties of the insulating layer is there an
optimal location for it, so as to achieve minimum heat loss from the outer
ladle surface?

Another interesting aspect of this investigation would be to use the tran-
sient thermal profiles to compute the thermal stresses in the ladle wall. Such
results could be useful in ladle design technology.

In Section 2 the transient heat conduction problem is formulated for the
nonlinear boundary conditions simulating day-to-day operations. Section 3
deals with simplified linear models in which either the ladle wall temperature
or heat flux is periodic. In Section 4 a fully implicit Crank-Nicolson method is
used to solve the full nonlinear equations. Analytical and numerical results are
discussed in Section 5. Conclusions are given in Section 6.

2. Formulation

A typical composite ladle wall is shown in Fig. 1. Let $D$ denote the thickness
of the composite wall and $\lambda D$ ($\lambda < 1$) that of the insulating layer which is
located at distance $\gamma D$ from the inner ladle wall, so that $(\lambda + \gamma) \leq 1$; measure
$z$ along the normal to the inner ladle surface, $z \in [0, D]$.

The general case will consist of three heat conduction regions. The govern-
ing equations and boundary conditions for the related thermal fields $T_i$
($i = 1, 2, 3$) are as follows:

Region 1: For $z \in [0, \gamma D], \; t > 0$

$$k_1 \frac{\partial^2 T_1}{\partial z^2} = \frac{\partial T_1}{\partial t}, \quad (2.1)$$