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PHYSICAL AND MATHEMATICAL MODELLING OF THERMAL STRATIFICATION PHENOMENA IN STEEL LADLES

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Abstract:
The paper is meant to present a physical hot-water model of industrial steel ladles. With this physical model, thermal stratification phenomena due to natural convection in steel ladles during the holding period before casting were investigated. By controlling the cooling intensity of the water model to correspond to the loss rate of steel ladles temperature distributions in the water model can simulate those in the steel ladles. Consequently, the temperature profile in the hot-water bath in the model can be used to deduce the thermal stratification phenomena in steel bath in the ladles.

Key words: *Steel ladle, natural convection, physical modelling, mathematical modelling, thermal stratification.*

1. INTRODUCTION

Due to inevitable heat losses, natural convection is a common phenomenon occurring in steel ladles during the holding period prior to casting. A typical consequence of this phenomenon is thermal stratification of the liquid steel bath. The thermal stratification phenomenon in steel ladles and its potential influence on temperature control during continuous casting are important in steelmaking. This is because the temperature of liquid steel coming from a thermally stratified melt bath held in the ladles, will have a direct impact on the temperature of steel melt held in the tundish.

The measurement of thermal stratification were made mostly on pilot-scale 6-7.5 tonne steel ladles by using instrumented refractory rods on which thermocouples were mounted at different heights or by installing thermocouples (with some penetration into the steel bath) at different levels on the ladle wall.

Based on the computational fluid dynamics (CFD) theory, several mathematical models have already been developed for simulating natural convection phenomena in steel ladles. The CFD models numerically solve the turbulent Navier-Stokes type partial differential equations describing the flow and heat transfer phenomena of interest, thus enabling the researchers to obtain flow patterns and temperature distribution inside the steel ladles.

An alternative approach that has the potential to achieve the same goal is physical modelling. Unlike the direct measurement of thermal stratification in steel ladles, physical models, established on the basis of the similitude theory, are normally easy to set-up, economic and efficient in implementation. In addition, the physical modelling results can also be used for verification of the mathematical modelling results.

2. EXPERIMENTAL

For the purpose of simulating fluid flow and heat transfer in steel ladles by means of the water model, a systematic analysis on the similarity between natural convection phenomena in steel ladles and in hot-water models has been carried out [5]. This similarity study suggested that water models with size scales in the range between 1/5 and 1/3 and using hot water of 45 ^{0}C or higher could be appropriate for modelling steel ladles with a promising similarity both in fluid flow and in heat transfer. Accordingly, in the present work, a 1/4-scale hot-water model has been established in the laboratory. The model is based on the mid-aged 107-tonne steel ladles. Fig. 1 illustrates this physical model set-up with (a) and (b) showing the sketches of inside arrangement.

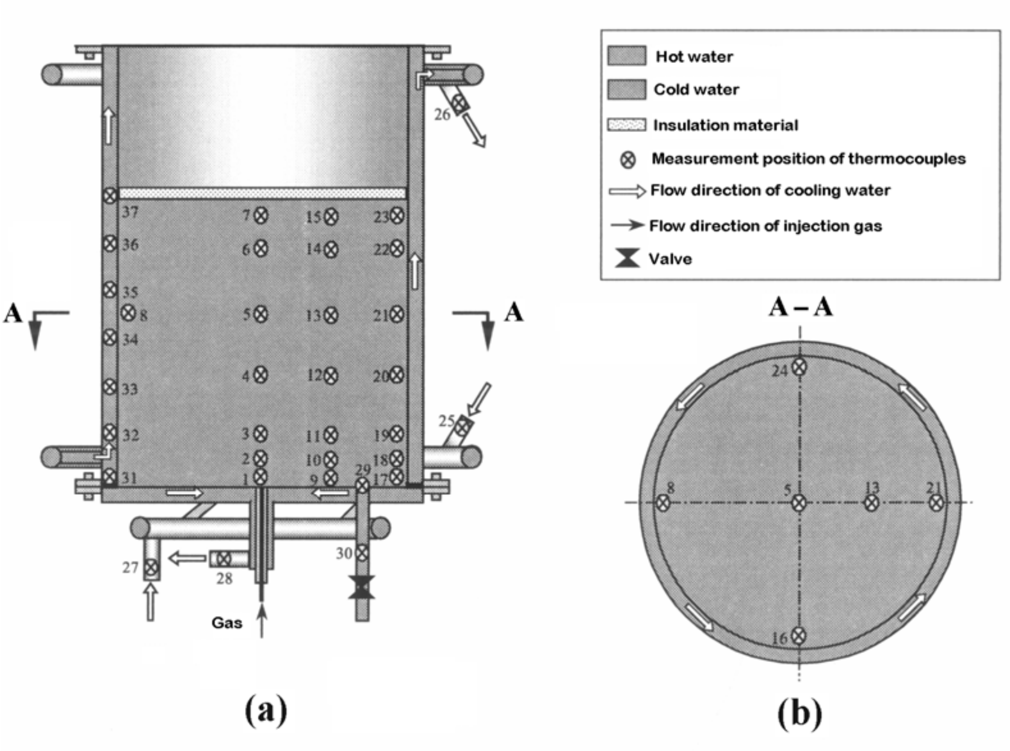


Fig.1. *Hot-water model set-up.*

The water model consist of two cooling chambers: the one is a cylindrical chamber for simulating ladle wall, and the other is a flat cooling chamber for simulating ladle bottom. The cooling chambers are made of 2 mm thick stainless steel sheet. Hot water is used as the liquid bath simulating liquid steel bath in ladles, while cold water with controllable temperatures is tangentially introduced into the cooling chambers in directions shows in Figs. 1a and 1b. T-type (cooper-constantan) thermocouples (TCs) were employed to get information from the water model. Figs. 1a and 1b also schematically illustrate the TC measurement position. 21 TCs were used for measuring the temperature profile in the water bath on a vertical plane bounded by sidewall and center axis. 7 TCs were used for measuring the temperature distribution in the side-cooling chamber under the level of the hot-water bath. 4 TCs were used for measuring temperatures of water inflows and outflows of the cooling chambers. In addition, for the purpose to check the symmetry of cooling intensity, 3 more TCs (No.8, No.16 and No.24) were used, together with TC No.21, to measure temperatures along the periphery of the hot-water bath, as shown in Fig. 1b. All the temperature signals were recorded into an data logger for post processing. To prevent heat loss from the top free surface of the water bath, the free surface was covered with a light porous plastic plate that can float on the surface. In order to homogenize the hot-water bath, if needed, pressurized air can be blown into the water bath via the tuyere located at the center of the bottom-cooling chamber.

3. RELATIONSHIP BETWEEN HEAT LOSS FLUXES OF WATER MODEL AND STEEL LADLE

One of the major aims of the present study is to explore the possibility of directly simulating thermal stratification phenomena in steel ladles by using the temperature information obtained from the hot-water model. This can be realized by scaling up, via certain similarity criteria, the water temperature distribution in the model into the steel temperature distribution in the prototype ladle. The criteria for such a scale-up can be derived from the similarity between natural convection phenomena in water models and in steel ladles [10], the key similarity criteria were found to be the following:

$$Fr_m = Fr_p \tag{1}$$

and

$$(\beta\Delta T)_m = (\beta\Delta T)_p \tag{2}$$

where: Fr – Froude number,[-];
β - thermal expansion coefficient, [1/K];
ΔT – difference of temperature from the initial temperature, [K];
m and p stand for the water model and the prototype steel ladle, respectively.

The above similarity criteria lead to a relationship between the heat loss flux of the water model and that of the prototype steel ladle as, [10]:

$$q_m = q_p \frac{\rho_m \cdot C_m \cdot \beta_p}{\rho_p \cdot C_p \cdot \beta_m} f_t \tag{3}$$

with

$$f_t = \frac{t_m}{t_p} = \sqrt{f_G} \tag{4}$$

where: q_m, q_p – heat flux to model and to prototype steel ladle, respectively, [W/m^2];
ρ_m, ρ_p – density of model and of prototype steel ladle, respectively, [kg/m^3];
C_m, C_p – thermal capacity of model and of prototype steel ladle, respectively, [J/kg K];
β_m, β_p – thermal expansion coefficient of model and of prototype steel ladle, respectively, [1/K];
t_m, t_p – time in model and in prototype steel ladle, respectively, [s];
f_t – time scale factor, f_t = 0,5;
f_G – geometry scale factor, for the present hot-water model f_G = 1/4 ;

Table 1. *Thermal-physical properties of steel, liquid steel and water*.

Property	Unit	Solid steel *	Liquid steel	Water
Temperature	^0C	< 400	1580	45
Density	kg/m^3	7900	6962,8	990,22
Thermal expansivity	$1/^0C$	-	0,00015	0,0004
Thermal conductivity	$W/m{\cdot}^0C$	15	27,9	0,637
Thermal capacity	$J/kg{\cdot}^0C$	500	787	4182
Viscosity	Pa·s	-	0,006	0,00089

* Model shell material: ASTM 304 stainless steel

Introducing the thermal-physical properties of liquid steel and water given by Table 1 into eq. (10), after rearrangement, results in:

$$q_p = 7{,}0574\ q_m \tag{5}$$

Eqs. (4) and (5) are used in this work for scaling up the transient heat loss flux for water model to that for the steel ladle.

4. PREDICTION OF STEEL TEMPERATURES IN LADLE WITH USE OF WATER TEMPERATURES IN MODEL

The present work focused on using the temperature distribution in water model to directly predict the temperature distribution in steel ladles. The relation between the temperatures in the water model and the temperatures in the ladle is governed by Eq. (2), which can be further expressed as:

$$T_p = T_{0,p} - \frac{\beta_m}{\beta_p}\left(T_{0,m} - T_m\right) \tag{6}$$

where $T_{0,p}$ and $T_{0,m}$ are the initial temperatures of liquid steel and hot water, respectively. Eq. (6) is actually adopted in the present study for scaling up the water temperatures in the model to the steel temperatures in ladles.

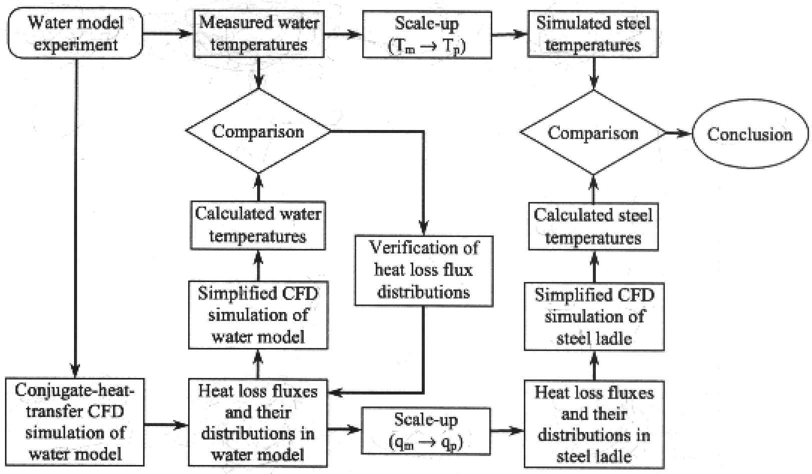
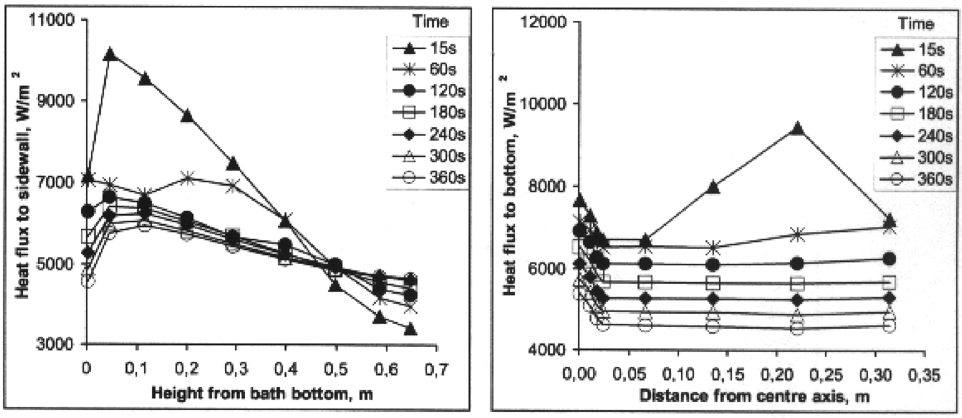


Fig. 2. *Flow chart showing a method for verification of using hot-water model to simulate thermal stratification in steel ladles.*

A method of verifying the feasibility of using the measured water temperatures in the model to directly predict the steel temperature in ladles has been developed in the present work, as shown in Fig. 2. This figure depicts how to establish consistent heat loss fluxes, obeying Eq. (5), for the water model and the steel ladle. Using the heat loss fluxes, scaled up, via Eq. (5), from those for the water model (predicted by the conjugate-heat-transfer CFD model) as thermal boundary conditions for the steel ladle, the steel temperatures can be predicted with the simplified CFD model and compared to the temperatures scaled up, via Eq. (6), from those measured in the water model experiment. This comparison will indicate the validity of using water model to deduce the extent of thermal stratification in steel ladles.

Following the flow chart given in Fig. 2, the same water model experimental case which was once simulated by the conjugate-heat-transfer CFD model, is further analyzed here. Fig. 3 illustrates the local heat fluxes from hot-water bath to cooling chambers at different times during cooling in this experimental case, predicted by the conjugate-heat-transfer CFD model. It is seen from Fig. 3a that the distribution of the heat flux along the height of the side-cooling chamber looks rather complicated. Apart from transient features, generally, larger heat loss fluxes exist in the lower section of the wall, while smaller loss fluxes occur in the upper section of the wall. Fig. 3b shows that during cooling (after the first 15 seconds) the heat flux from the hot-water bath to the bottom-cooling chamber appears to be nearly uniformly distributed along the radius of the chamber appears to be nearly uniformly distributed along the radius of the chamber, except for the center region.



(a) Side-cooling chamber (b) Bottom-cooling chamber

Fig. 3. *Predicted distributions of heat fluxes from hot-water bath to cooling chambers.*

In order that the heat fluxes predicted by the conjugate-heat-transfer CFD model, as shown in Fig. 3, can be applied as thermal boundary conditions to the simplified CFD model, it is expected that these heat fluxes can be represented (approximated) with *simple equations*.

For the heat loss flux to the sidewall, according to Fig. 3a, it is assumed that the heat flux has a quadratic distribution along the height of sidewall and follows an exponential decay with time. Thus, trough quadratic and exponential curve fitting analyses, the heat loss flux and its distributions on the sidewall can be approximately by the following *simple equation*:

$$q_{s,m} = \left[1{,}2 + 0{,}2\left(\frac{h_m}{H_m}\right) - 0{,}9\left(\frac{h_m}{H_m}\right)^2\right]\left(1668{,}0 \cdot e^{-1.0374 \cdot 10^{-2} t_m} + 5202{,}3\right) \qquad (7)$$

where: $q_{s,m}$ is the local heat flux to the sidewall of the water model;
H_m – the height of the hot-water bath;
h_m – the distance from the bottom of the hot-water bath ($0 \le h_m \le H_m$).

As for heat flux to the bottom of the water model, according to Fig. 3b, it is assumed that this heat flux is uniform at the model bottom and equal to the average heat flux that also follows an exponential decay with time,

$$q_{b,m} = 3987{,}1 \cdot e^{-3{,}3003 \cdot 10^{-3} t_m} + 3622{,}9 \quad (8)$$

where $q_{b.m}$ is the local heat flux to the bottom of the water model.

Now Eqs. (7) and (8) can be scaled up, via Eqs. (4) and (5), so that similar expression of heat loss fluxes to the sidewall and bottom of the prototype steel ladle can be derived as:

$$q_{s,p} = \left[1{,}2 + 0{,}2\left(\frac{h_p}{H_p}\right) - 0{,}9\left(\frac{h_p}{H_p}\right)^2\right]\left(11771{,}7 \cdot e^{-5{,}187 \cdot 10^{-2} t_p} + 36714{,}5\right) \quad (9)$$

and
$$q_{b,p} = 28138{,}4 \cdot e^{-1{,}6502 \cdot 10^{-3} t_p} + 25568{,}1 \quad (10)$$

where: $q_{s,p}$ and $q_{b,p}$ are, respectively, the local heat fluxes to the sidewall and bottom of the prototype steel ladle;
H_p – the height of the liquid steel bath;
h_p – the distance from the bottom of the liquid steel bath ($0 \le h_p \le H_p$).

Eqs. (7) through (10) are finally used as thermal boundary conditions for the simplified CFD model to simulate thermal stratification phenomena both in the water model and in the prototype steel ladle.

5. CONCLUSIONS

The present non-isothermal water model study has confirmed the validity of the dimensionless numbers Fr and $\beta\Delta T$ as key criteria governing the similarity between natural convection phenomena in hot-water models and in prototype steel ladles.

Establishing a non-isothermal water modelling system is useful for verification of CFD mathematical modelling results. In addition to mathematical methods, the hot-water model provides an alternative means of studying fluid flow and heat transfer phenomena in steel ladles.

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