Factors Affecting Solidification of Steel in the Mould during Continuous Casting of Steel Billets

H. T. Abuluwefa, M. A. Al-Ahresh, A. A. Bosen

Abstract— Casting of steel is an operation which is sensitive to a number of factors. It should be performed with great control and steadiness in such a way to produce safe casting operation and sound steel mechanical properties, and ensure a continuous process with limited delays. In this study, effects of factors encountered in the process of continuous casting of steel billets on the thickness of solidified steel layer in the mould area were mathematically modeled in order to identify the most predominant ones. Of these factors modeled are mould thickness, mould material thermal conductivity and molten steel superheat. Simplified calculation were performed in which heat transfer equations governing the process solidification were solved using an explicit method of finite difference technique. The results showed that the most effective factor on solidified steel thickness in the mould is the magnitude of molten steel superheat prior to entering the mould. Thermal conductivity of mould material showed little effect due to the small thickness of mould wall. Changing mould thickness showed some effect of solidification but were not significant.

Index Terms— solidification, heat transfer, finite difference, explicit method, superheat.

I. INTRODUCTION

CONTINUOUS casting of steel is now the method of choice by all steel producers replacing the old method of ingot casting. Distinguished by its many advantages, this process has gone through many improvements and was and still is the subject of wide range of studies both empirically and mathematically. Continuous casting of steel billets is one type of continuous casting adopted in steel industry, by which, steel billets are produced continuously and simultaneously [1]. This type of process requires great control of operating parameters in order to produce sound and continuous billets. The process can be divided into a number of steps starting by pouring the hot molten steel from the furnace into the ladle, where the steel chemistry is being adjusted, then pouring into the distributor, and from the distributor into the casting mould. Solidification of steel begins in the copper casting mould by indirect cooling, an area which was subjected to many studies [2], [3].

Direct water cooling of the steel begins immediately after exiting the copper mould, Fig. 1. In this operation, consistency must be met among molten steel pouring rate from the distributor, rate of cooling of steel and steel withdrawal from the mould. In the primary cooling within the mould, heat transfer from the solidifying steel along the mould walls, through the mould material and to the cooling water plays an important role in determining the rate of growth of the solid steel shell.

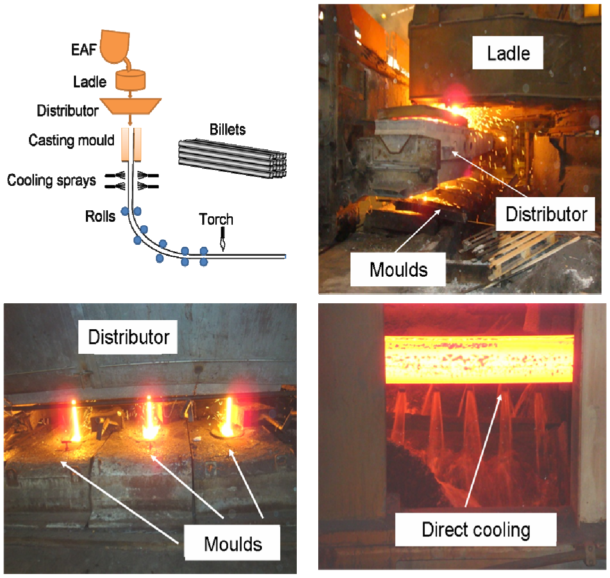

Fig. 1. Continuous casting of steel billets at the Libyan Iron and Steel Company.

The steel, when first exiting the mould, should exhibit a just thick enough outer shell to prevent it from splashing over the casting system components. It is only to serve this purpose where the rest of the cooling is done through the faster direct cooling of the steel strand by direct water sprays. The work of this paper is confined to studying the effects of some parameters involved in the casting operation during steel solidification within the mould. Simplified mathematical modeling of heat transfer from the steel to the cooling water through the mould wall was employed. A number of parameters involved in casting process were varied in this model and their effects on the rate of solid steel shell growth within the mould was examined.

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II. MATHEMATICAL TREATMENT OF STEEL SOLIDIFICATION IN THE MOULD

The steel billet casting system consists of the components: copper mould, pouring nozzle, cooling water. Due to the high temperatures involved in the process (up to 1600°C), it is not possible to do reliable direct measurements of system parameters. An alternative in studying the cooling and solidification of steel in the mould is through the use of mathematical modeling of heat transfer through the casting components. A schematic illustrating the temperature calculation grid is given in Fig. 2 in which the temperature at each node, in the steel as well as mould wall, is calculated at subsequent time steps during the solidification time period within the mould.

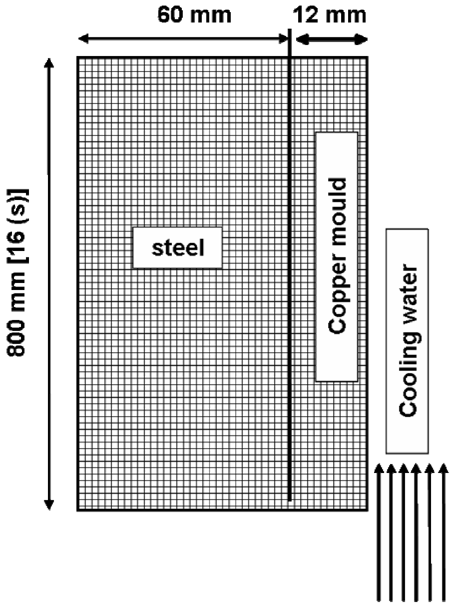

Fig. 2. Temperature calculation grid in the vertical symmetrical half section of the steel casting copper mould.

A. Assumptions

In calculating heat transfer through the mould during steel solidification the following main assumptions are made:

- The predominant heat transfer is along the horizontal direction vertical to the cooling water moving direction.
- Thermal properties of the steel and mould material are kept constant, i.e., independent of temperature.
- The are no effects of any precipitants at the interface between the mould surface and cooling water.
- The steel is in perfect and constant contact with the mould surface, i.e., no gap development between the solid steel and mould wall due to steel shrinkage as a result of cooling.

The general equation governing transient heat transfer by conduction in the three directions is:

$$\frac{d^2T}{dx^2}+\frac{d^2T}{dy^2}+\frac{d^2T}{dz^2}+\frac{Q'''}{k}=\frac{1}{\alpha}\frac{dT}{dt} \tag{1}$$

where the parameters T, Q''', k, α, t are temperature (°C), heat rate of heat generation/consumption (W/m^3), thermal conductivity (W/m-°K), time (s) and diffusivity (m/s^2), respectively. Based on the above assumptions, (1) can be simplified to:

$$\frac{d^2T}{dx^2}=\frac{1}{\alpha}\frac{dT}{dt} \tag{2}$$

This equation represents transient heat transfer by conduction in one direction, and coupled with appropriate boundary conditions evolved in the cooling process, it can be solved to give temperature distributions in the calculation domain. The method adopted in solving this equation is by the use of finite difference technique and solving the resulting equations explicitly. Referring to the nodal distribution both in the steel and mould wall areas shown in Fig. 1., (2) can be descritized as follows [4]:

$$\frac{d^2T}{dx^2}=\frac{T_{n+1}+T_{n-1}-2T_n}{\Delta x^2} \tag{3}$$

where Δx is space interval along the horizontal direction, n denotes a node and ($n+1$, $n-1$) represent the next and previous nodes in the same horizontal direction, respectively. Similarly, descritizing the right term in time gives:

$$\left.\frac{dT}{dt}\right|_n=\frac{T_n^{p+1}-T_n^p}{\Delta t} \tag{4}$$

where Δt is the time interval chosen in dividing the total time the steel remains in the mould into small time intervals, m, and p indicates the previous time step. In this case the total time of cooling is given as:

$$t=m\Delta t \tag{5}$$

Using (4) and (5), (3) becomes:

$$\frac{T_{n+1}^p+T_{n-1}^p-2T_n^p}{\Delta x^2}=\frac{1}{\alpha}\frac{T_n^{p+1}-T_n^p}{\Delta t} \tag{6}$$

rearranging

$$T_n^{P+1}=F_0\left(T_{n+1}^p+T_{n-1}^p\right)+\left(1-2F_0\right)T_n^p \tag{7}$$

Where the first term indicated the temperature at node n at the current time ($p+1$) which is calculated from temperatures of the previous time step (p). Fo in (7) is known as Fourier's number which is given as:

$$F_0 = \frac{\alpha \Delta t}{(\Delta x)^2} \qquad (8)$$

Equation (7) is used to calculate temperatures within the steel and mould wall, however, for calculation of the temperatures at the external nodes, i.e., at the shared interface between the mould surface and cooling water, the following equation is used:

$$T_N^{P+1} = 2\, F_0 \left[T_{N-1}^{P} + B_i\, T_w \right] + (1 - 2\, F_0 - 2\, B_i\, F_0)\, T_N^{P} \qquad (9)$$

where B_i is known as the dimensionless Biot's number expressed as [6]:

$$B_i = \frac{h\ \Delta x}{k} \qquad (10)$$

The coefficient h is known as the convective heat transfer coefficient and is given by:

$$h = N_u \frac{k}{D} \qquad (11)$$

Nu is the dimensionless Nusslt's number given as:

$$N_u = \frac{\left(f/8 \right) R_e\ P_r}{1.07 + 12.7 \sqrt{f/8} \left(P_r^{2/3} - 1 \right)} \qquad (12)$$

where R_e and P_r are the dimensionless Reynold's and Prandtl's numbers and f is the friction factor, respectively. The friction factor can be expressed as:

(13)

Equations (7) and (9) are solved with the appropriate parameters shown in Table I using MS Excel worksheet by which temperatures at each node in the steel and mould wall were solved at accumulative time intervals covering the whole residence time of the steel in the mould. The total residence time of steel in the mould was determined from knowledge of mould height and volumetric steel casting speed. This time period was divided into a number of calculation time intervals satisfying the stability requirements of (7) and (9).

III. RESULTS AND DISCUSSION OF RESULTS

Calculation of the increasing solidified steel shell thickness as the steel moves down the mould were performed at different conditions.

TABLE I
PARAMETERS USED IN THE CALCULATIONS AND THEIR VARIATION VALUES.

Parameter	Units	Varied values	Constant value	Remarks
Thermal conductivity of copper mould	*W/m-°K*	50, 150, 250, 350		
Thermal conductivity of steel	*W/m-°K*	25, 30, 35, 40		
Super heat	Degrees	5, 10, 15, 20		
Mould wall thickness	mm	12, 16, 20, 24		
Convective heat transfer coefficient (calculated)	*W/m²-°K*		250	Constant
Prandtl's number	P_r	7		Assumed

When pouring steel into the mould, the amount of superheat which it exhibits (the temperature above the solidifying temperatures) is of paramount importance on how fast the steel starts to solidify when it enters the mould. Solidified steel shell thicknesses were calculated using different superheats of 5, 10, 15 and 20 degrees where the results of these calculations are shown in Fig. 3.

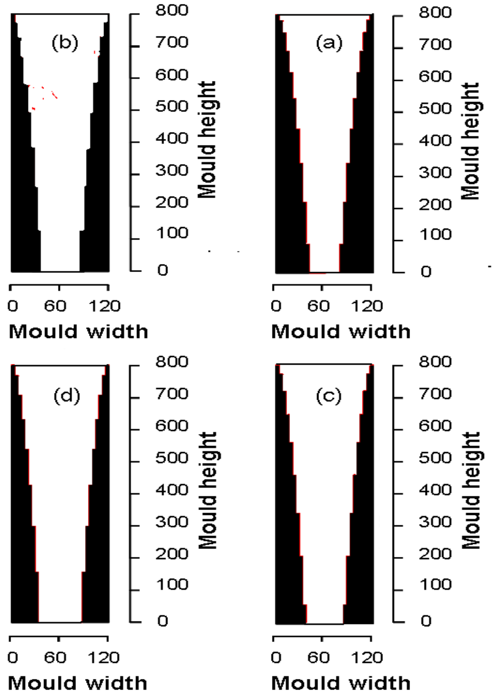

Fig. 3. Calculated solid steel thickness along the mould walls at molten steel superheats: (a) = 5, (b) = 10, (c) = 15, (d) = 20 degrees.

It can be seen from the figure that the degree of steel superheat has a big effect on the thickness of solidified steel. However, steel superheat is not too easy to control and is dependent on a number of factors which include steel pouring temperature out of the furnace, temperature of the tundish and distributor and number of heats being poured in sequence, and hence, requires a steady state casting operation to maintain a constant steel superheat.

Mould thermal properties such as its thermal conductivity controls the rate of heat transfer from the steel to the cooling water, i.e., the cooling and solidification processes. This factor has been varied in the calculations and the results of theses variations are shown in Fig. 4.

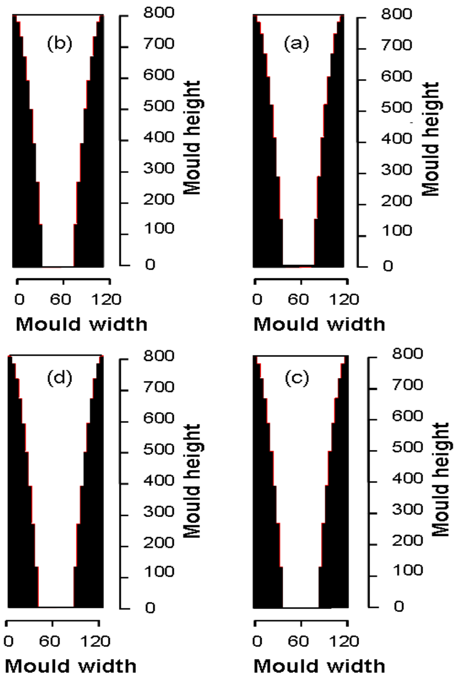

Fig. 4. Calculated solid steel thickness along the mould walls at mould thermal conductivities: (a) = 50, (b) = 150, (c) = 250, (d) =350 (W/m-^{o}K).

Very little change in the solidified steel thickness can be seen due to changing the thermal conductivity of the copper mould. This result indicates that it would be possible to replace the very highly conductive copper mould with a cheaper stainless steel mould which would withstand physical aspects more than the copper mould, and hence, performs more heats. It is to bring in mind at this point that, the small thickness of the copper mould makes its thermal conductivity less importance and will certainly have greater effect if this thickness is bigger.

The casting mould wall thickness should be thick enough to withstand liquid steel pressure and thin enough to give the desirable cooling rate. The effect of varying mould wall thickness was examined and the results are given in Fig. 5. As can be seen from the figure, changing the thickness of the mould has an affect on the solidifying steel shell thickness even thought the material is the very highly conductive copper metal. However, in reality, mould thickness should be specified as described above.

A factor in steel casting which is of great importance is changing steel chemical composition. Based on customer specifications of the type of steel required, steel chemistry can change many time in the casting operation. Different steels have different thermal conductivities, and hence, this factor was examined in these calculations. As can be seen from Fig. 6., changing steel thermal conductivity resulted in great variations in the calculated solidified steel shell thickness. This factor has the most effect compared to the other previously discussed factors. This shows that great care should be taken when changing heat chemistries, especially when the steels differ greatly in this property.

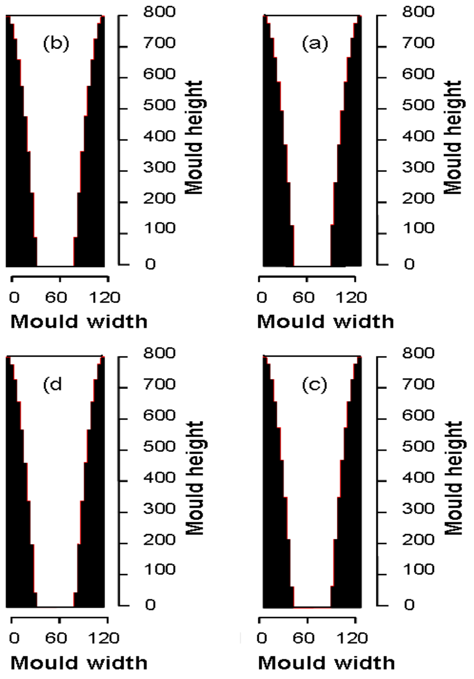

Fig. 5. Calculated solid steel thickness along the mould walls at mould thicknesses: (a) =12, (b) = 16, (c) = 20, (d) = 24 (mm).

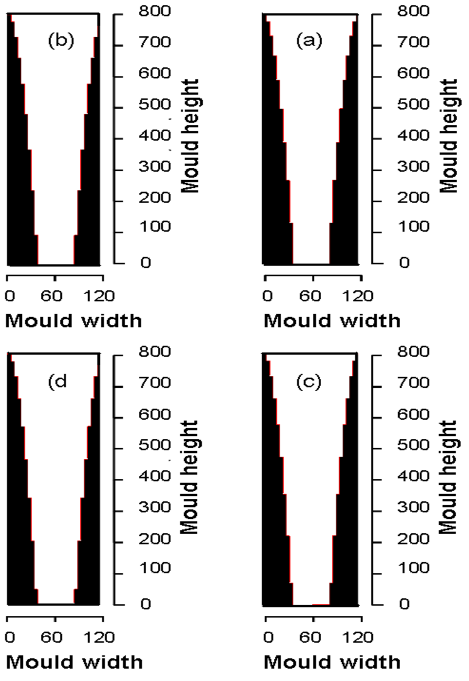

Fig. 6. Calculated solid steel thickness along the mould walls at steel thermal conductivities: (a) = 25, (b) = 30, (c) = 35, (d) = 40 (W/m-^{o}K).

IV. CONCLUSIONS

Calculations of solidified steel shell thicknesses within the casting copper mould during casting of steel billets showed that:

- The degree of steel superheat has a noticeable effect on solidified steel thickness, and hence, this factor should be well controlled in the casting operation.
- Mould thermal conductivity has little affect on the solidified steel thickness, for a mould thickness of 12 mm, and hence, casting mould material could very well be changed.
- Thermal conductivity of molten steel is of great importance in the casting operation, and hence, great care should be taken when changing steel grades of differing thermal conductivities.

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