Numerical simulation of the temperature field in the electromagnetic semi-continuous casting of slab

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Abstract

Electromagnetic casting of aluminum is a semi-continuous casting process and the corresponding mathematical model is a non-steady non-homogeneous heat-transfer equation. This paper indicates and testifies that the dynamic temperature field can be calculated with a three-dimensional non-steady homogeneous heat-transfer equation. The software program has universal use. Further, a casting process of $1860 \times 510$ mm aluminum slab is simulated, the results agreeing well with those reported in the literature. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Slabs of aluminum alloys are now usually produced in such semi-continuous casting processes as electromagnetic casting (EMC) or hot top direct chill casting (DCC). With the downward movement of the bottom block, liquid metal is poured from the top continuously until the desired length of ingot is obtained (shown in Fig. 1; the left refers to EMC and the right to DCC). In EMC, the liquid aluminum column is mainly supported by the electromagnetic forces acting at its periphery, while in DCC, it is the water-cooled molds that support the liquid metal. However, as far as the temperature field is concerned, the two casting methods have common characteristics because in both casting processes the ingots are mainly cooled by the spraying of water. Although the influences of the electromagnetically induced heat in EMC and the hot top in DCC on the liquid column temperature are different, they can be neglected considering the latent heat of fusion.

The numerical simulation and control of the dynamic temperature field is the fundamental work for the calculation of viscoplastic–elastic stress, cracking, deformation, and the fluidity of the liquid and mushy zones, to control the quality of the ingot. For the steady state of the continuous casting of steel, the calculated temperature field can be regarded as steady-state [1,2]. Different from the continuous casting of steel, the electromagnetic casting of aluminum is in fact a semi-continuous casting process. The process can be divided into three phases, i.e. start phase, stationary phase (casting with a certain velocity), ending phase. Its character is that ingot expands its space with a certain casting speed, and the temperature field is non-steady. However, heretofore, the corresponding heat transfer models presented are the following two: one fixes the coordinate system at the moving slab, considering the process to adapt to the heat conductivity equation [3], whilst the other considers the process to be a quasi-steady heat transport process [4]. Clearly, both models have not established the ideal energy equations describing the heat transfer and their discrete models.

This paper first testifies an equation which indicates that the temperature of a point calculated at one time is just the temperature at the next location to which it moves at the next time step. Then a temperature field model for a slab casting with a velocity $v$ is implemented and tested by comparing it with the measured results; good agreement is found.

2. Heat transfer equation of semi-continuous casting

The assumptions of the model are as follows: (1) Neglect the convective heat transport in the liquid pool; (2) Latent heat of fusion is treated by enhancing the specific heat.

Considering the slab cast at time $t$ as the domain of analysis,
the heat-transfer equation is:

\[ cp \frac{\partial \theta}{\partial t} = \nabla \cdot (k \nabla \theta) - c_p \rho \frac{\partial \theta}{\partial z} \]  

(1)

The coordinate system is a spatially-fixed system and the origin is at the top of the slab, which is shown in Fig. 2. \( v \) is the casting speed, \( ox \) means the direction along the broad face of the slab, \( oy \) means the direction of the short face, \( oz \) means the casting direction. Fig. 2 (a) and (d) refers to the slab at time \( t \) and time \((t + \Delta t)\), respectively. Points A and B are positions that are at a distance \( z \) below the top, C is the location of A after the slab expands its space and at a distance \( z + \Delta z(\Delta z = v\Delta t) \) below the top. The shaded section in the figure refers to the liquid metal poured over time \( \Delta t \).

According to Eq. (1), the temperature of point B at time \((t + \Delta t)\) is:

\[ \theta_B^{t+\Delta t} = \theta_A^t + \frac{\Delta t}{c_p} \nabla \cdot (k \nabla \theta) - v \Delta t \frac{\partial \theta}{\partial z} \]  

(2)

At time \((t + \Delta t)\) the temperature relationship of points B and C can be seen:

\[ \theta_C^{t+\Delta t} = \theta_B^{t+\Delta t} + \frac{\partial \theta}{\partial z} dz \]  

(3)

As \( \Delta z = v\Delta t \), substitution of Eq. (2) into Eq. (3) gives

\[ \theta_C^{t+\Delta t} = \theta_A^t + \frac{\Delta t}{c_p} \nabla \cdot (k \nabla \theta) \]  

(4)

For a spatially-fixed slab, at time \( t \), the governing equation describing the flow of heat is:

\[ cp \frac{\partial \theta}{\partial t} = \nabla \cdot (k \nabla \theta) \]  

(5)

Thus, after time interval \( \Delta t \), the temperature of point A is:

\[ \theta_A^{t+\Delta t} = \theta_A^t + \frac{\Delta t}{c_p} \nabla \cdot (k \nabla \theta) \]  

(6)

Based on Eqs. (4) and (6), the following result can be obtained:

\[ \theta_C^{t+\Delta t} = \theta_A^{t+\Delta t} \]  

(7)

Eq. (7) clearly indicates that for a temperature field that has both heat transfer and mass transfer, the calculated temperature field at one time is just the temperature field at its new position at the next time step. The top space with a height of \( v\Delta t \) can be looked upon as the newly filled liquid metal. This continues until the whole ingot is cast. Then the spatially-fixed temperature field should be calculated using Eq. (5).

Obviously, while the well-known Eq. (5) can ensure convergent solutions, it is rather difficult to solve Eq. (1) directly. However, Eq. (7) now ensures an easy solution to the calculation of a dynamic temperature field.

3. Boundary conditions

At the top: Liquid metal is poured from the top of the aluminum pool whether in EMC or in DCC. Because of the effect of magnetically induced heat or hot top, the heat flux here is very small and can be considered as heat insulating. After casting, it can be considered as air-cooling.

At the bottom: At the beginning of casting, hot metal contacts the cold bottom block, the slab bends and an air gap forms, which has an influence on the heat extraction. However, after entering the steady-state regime, this effect is tiny and can be ignored.

At four outside vertical surfaces: The four outside vertical surfaces are cooled by sprayed cooling water, as shown in Fig. 1. The cooling intensity is largest at the spraying position. Away from the spraying position, water flows and evaporates along the slab surface. A solid shell forms and extends from outside to inside until the whole cross-section solidifies and cools down. The heat transfer coefficient depends on many factors including the water flow rate, the water temperature, the nozzle type, the surface temperature of the slab, and so on. Generally, it can be calculated with a practical equation and then adjusted according to the actual conditions. The practical equation is:

\[ h = 2.25 \times 10^4 \omega^{0.55} (1 - 7.5 \times 10^{-3} \frac{\theta_n}{\theta_w}) \]  

(8)
4. Calculation and results

According to the discrete model of Eq. (5), a general software system CONTEM has been programmed to be used in three-dimensional non-steady heat-transfer processes.

Adopt the 1860 x 510 mm aluminum slab mentioned in Ref. [5] to calculate its temperature field. The height of the liquid column is managed to maintain 40 mm. The casting parameters are as follows: casting speed 80 mm/min; water flow rate 8001 min⁻¹; initial cooling water temperature 20°C; the water nozzles are distributed equally at four sides; the incoming aluminum alloy AAlxxx temperature is 670°C; the latent heat of fusion is 358.5 J/g; and the density is 2650 Kg/m³. The comparison of the calculated results and the experimental data provided by Ref. [5] is shown in Fig. 4. It can be seen that they match well. If more accurate technology parameters were available, a smaller discrepancy would occur.

5. Conclusions

1. For the non-steady non-homogeneous heat-transfer Eq. (1) that a semi-continuous casting moving ingot conforms to, the dynamic temperature field at any next time step can be calculated using the three-dimensional non-steady homogeneous Eq. (5). Then, the temperature field should be moved down by a distance vΔt, and at the same time the vΔt length at the top should be filled with liquid metal.

2. When the casting process is finished, the temperature field of the spatially-fixed slab can be calculated using Eq. (5).

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