International Journal of Heat and Mass Transfer 93 (2016) 250–256

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A particle swarm approach for optimization of secondary cooling process in slab continuous casting

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ARTICLE INFO

Article history:
Received 7 April 2015
Received in revised form 11 October 2015
Accepted 12 October 2015

Keywords:
Secondary cooling
Heat transfer
Particle swarm optimization
Continuous casting

ABSTRACT

Secondary cooling control is the key factor for stabilizing and enhancing slab quality in continuous casting. In view of practical importance of critical boundary conditions in offline or online simulation and control during continuous casting process, accurate estimation for heat transfer coefficient of secondary cooling zone is of utmost significance. To optimize the cooling process and temperature behavior of continuous casting slab, a novel method was presented to predict the heat transfer behavior in secondary cooling process. This approach applies the particle swarm optimization (PSO) algorithm in conjunction with the mathematical heat transfer model and the experimental temperature to determine the heat transfer coefficient. Through verifying the validity and efficiency of the integrated method proposed, the temperature variation of slab surface is more coincident with measured temperatures along the casting direction. The calculation results confirm that the heat transfer coefficient could be estimated precisely with measurement temperatures using PSO algorithm. The combined approach offers an applicable technology for optimization of cooling strategy and solidifying process in continuous casting.
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1. Introduction

Continuous casting is currently the primary method of producing steel slabs, billets and blooms. Heat transfer plays an important role in productivity and quality of steel prior to rolling. Various kinds of surface and internal quality defects originate from improper cooling practices [1,2]. Accurate description of heat transfer and reasonable control of secondary cooling process are the basic requirements for high efficient continuous casting. For the sake of competitiveness in manufacturing, there is a permanent requirement of proper cooling strategies in the secondary cooling areas to obtain excellent product quality.

Zone different casting speed are listed in Table 4. Many heat transfer models have been developed and successfully used to simulate steady state casting operations in online or offline mode. In terms of process control, this means a necessity to maintain operational parameters in a specific optimum range. Owing to the complicated and economic reasons, it is not feasible to undertake extensive experimental trials during the continuous casting process to evaluate the influence of several operational parameters. In this sense, the rapid development of better process control and optimization is increasingly dependent on simulations performed with heat transfer mathematical models and artificial intelligence techniques [3–5].

Aiming to enhancing internal quality of casting slab, the accurate prediction of surface temperature and solidifying state of strands are obviously essential and strongly dependent on the boundary conditions of heat flux, especially for the heat transfer coefficient in each secondary cooling zone. In the present work, this paper presents a mathematical heat transfer model combined with the particle swarm optimization (PSO) to optimize the secondary cooling process. The heat transfer model is built and uses a two-dimensional finite difference method to calculate the thermal field and the solid shell profile. The PSO algorithm is applied to find the optimal heat transfer coefficient in each secondary cooling zone for the production of slabs with a better temperature dropping trend. Improved calculation conditions of the new configuration are compared to the original one. The accuracy and efficiency of the integrated approach is investigated further.

2. Description of the mathematical model

The numerical modeling of the strand has been developed to track a transverse slice of a steel slab as it moves down along the casting direction. Model is based on the finite difference method.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.10.025
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In view of the geometric features of the slab, the temperature profile only needed to be calculated for one quarter of slab cross-section as shown in Fig. 1.

2.1. Assumptions

The following assumptions were made in the formulating of the model:

(a) Heat transfer along the direction of slab width and thickness is recognized as axial symmetry and that along the slab withdrawal direction is neglected. Therefore, the mathematical model is translated into a two-dimensional unsteady heat conduction equation.
(b) The latent heat of steel solidification is converted into an equivalent specific heat capacity in the mushy zone (semisolid zone).
(c) The density of steel is constant, but the specific heat capacity and the heat conductivity of steel are the temperature-dependent properties.
(d) The fluid flow is expected to affect thermal field via enhanced heat transfer and then an effective thermal conductivity is employed in the liquid core and mushy zone of slab.

2.2. Governing equations

According to above assumptions, a two-dimensional heat transfer equation is available as follows:

$$\rho c\frac{\partial T(x,y,t)}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T(x,y,t)}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T(x,y,t)}{\partial y}\right)+S \quad (1)$$

where ρ is steel density, kg m^{-3}; c is specific heat of steel, J kg^{-1} K^{-1}; T represents the instaneous slab temperature, K; t is time, s; λ is thermal conductivity, W m^{-1} K^{-1}; x and y are coordinates, m, and represent the direction of slab width and slab thickness; S is energy source term, W m^{-3}.

The equivalent specific heat method is adopted to calculate the latent heat of steel, which transforms the influence of latent heat to specific heat. The formula is expressed as follows proposed by Thomas [2]:

$$C_{eff}=C_p+\frac{L_H}{T_l-T_s}(T_s\leqslant T\leqslant T_l) \quad (2)$$

where C_{eff} represents equivalent specific heat, J kg^{-1} K^{-1}; C_p represents the specific heat of steel; L_H is the latent heat of solidification, J kg; T_l represents the liquidus temperature of steel, K; T_s represents the solidus temperature of steel, K.

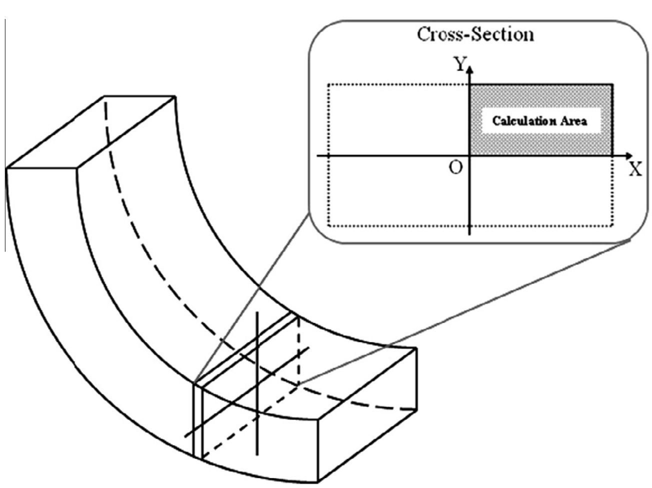

Fig. 1. Schematic diagram of the calculation domain.

Table 1
Overview of each secondary cooling zone for the caster.

Secondary cooling zone	1#	2#	3#	4#	5#	6#	7#	8#
Distance from meniscus (m)	0.8	1.04	1.97	3.34	5.26	9.10	12.94	19.65
Length (m)	0.24	0.93	1.37	1.92	3.84	3.84	6.71	9.69

In the temperature between T_l and T_s, the convection effect of the mushy zone kinetics on heat transfer is not known. The thermal conductivity is given as [3]:

$$\lambda_{eff}=\lambda_{sol}(1+6f_l) \quad (3)$$

where λ_{sol} is thermal conductivity of solid steel, f_l is the liquid fraction.

2.3. Initial and boundary conditions

At the beginning of the continuous casting ($t = 0$), the slice temperature profile at the meniscus is equal to the pouring temperature:

$$T(x,y,t)|_{t=0}=T_{cast} \quad (4)$$

where T_{cast} is the casting temperature, K, which is measured in tundish.

The boundary conditions are as follows:

In the mold, an average heat flux as a function of the casting time is utilized and the boundary heat flux is described by Savage and Pritchard [1]:

$$Q=A-B\sqrt{\frac{z}{V_{cast}}} \quad (5)$$

where Q represents the mold heat flux, W m^2; A and B are the coefficients relative to heat flux in the mold; z is the distance from meniscus, m; V_{cast} is casting speed, m min.

The heat transfer coefficient in the spray zones is usually related to spray water flow rates, and can be calculated through the formula (6) [4]:

$$h_{spray}=\frac{1570.0w^{0.55}[1.0-0.0075(T_{spray}-273.15)]}{\alpha} \quad (6)$$

where w is the spray cooling flux, L m^{-2} s^{-1}; T_{spray} represents the temperature of the spray cooling water, K; α is a machine dependent calibration factor; h_{spray} represents the spray cooling heat transfer coefficient, W m^{-2} K^{-1}.

A Newtonian heat-transfer coefficient is then used to compute radiation heat transfer between the slab and surrounding environment as described by Hardin et al. [5]:

Table 2
Casting conditions and thermo-physical properties.

Item	Symbol	Value	Unit
Slab section	$W \times N$	2450 × 320	mm × mm
Effective mold length	L_{mold}	800	mm
Carbon content	$C\%$	0.12	%
Pouring temperature	T_{cast}	1544.0	°C
Steel liquidus temperature	T_l	1514.4	°C
Steel solidus temperature	T_s	1453.3	°C
Casting speed	V_{cast}	0.65	m/min
Steel density	ρ	7200	kg/m^3
Latent heat	L_h	2.7−E5	J/kg
Spray water temperature	T_{spray}	30.0	°C
Ambient temperature	$T_{ambient}$	35.0	°C

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