Applied Thermal Engineering 84 (2015) 286–291

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Theoretical estimation of solidification length of continuously cast metals

Pavan Kumar Penumakala [a], Ashok Kumar Nallathambi [a, *], Eckehard Specht [a], Ulrich Urlau [b], Paulina Unifantowicz [b]

[a] Otto von Guericke University Magdeburg, Germany
[b] SWISS STEEL, Switzerland

HIGHLIGHTS

- Guidelines are presented for designing a new continuous casting process.
- Model is developed with a constant surface temperature assumption.
- 2-D conduction equation is solved including the solidification effect.
- Solidification length increases with mass flow and surface temperature.
- Solidification length decreases with increase in width to thickness ratio.

ARTICLE INFO

Article history:
Received 25 November 2014
Accepted 26 March 2015
Available online 4 April 2015

Keywords:
Solidification
Phase change
Heat transfer
Continuous casting
Secondary cooling
Stefan number

ABSTRACT

A semi-analytical model is presented to find the solidification length of continuously cast metals. An existing theoretical solution for solidification in an infinite slab, which is maintained at constant surface temperature is extended to a finite slab. For the case of a finite slab, the governing 2-D heat conduction equation is solved in the non dimensional form using a constant surface temperature as a boundary condition. The solution also delivers the guidelines for the kind of cooling profile which has to be applied in reality. It is found that the total solidification length (metallurgical length) in a continuous casting process is proportional to the mass flow rate and specific heat capacity and inversely proportional to the conductivity and width to thickness ratio of the slab. The novelty of this study is that it provides design guidelines for the process engineers to find the solidification length beforehand for a given cast alloy and ingot geometry.

1. Introduction

Continuous casting is a well established technique for casting metals such as steel, copper, aluminum *etc*. During the continuous casting, the total heat from the molten metal is extracted in a controlled manner in primary mold cooling and in the secondary water cooling. It is necessary to predict the heat transfer in these zones to find the location where the complete solidification occurs. Stefan was the first person who studied the freezing of ice and introduced the concept of moving interface [1]. A lot of research has been published in the literature to analyze the mold and secondary cooling heat transfer in a continuous casting. The quantitative analysis of the mold heat transfer was pioneered by J. K. Brimacombe [2,3]. Grill et al. presented a mathematical model to analyze the heat transfer and gap formation in the mold and investigated the conditions which can lead to breakouts [4]. Alizadeh et al. presented an analytical expression for the heat flux in the mold that includes practically controllable parameters such as mold height, cooling water flow rate and the cooling water temperature rise [5]. Straffelini et al. used the water flow dependent relation in the secondary cooling zone to calculate the local heat transfer coefficient [6]. Meng et al. takes into account the influence of rollers on heat transfer [7]. Ha et al. presented a 1-D numerical model to find the temperature and solidification length of slab casting [8]. Many 2-D slice models are presented to simulate the temperature evolution and the final solidification point of continuous casting [9].

---

* Corresponding author. Otto von Guericke University Magdeburg, Universitätsplatz 2, 39106 Magdeburg, Germany. Tel.: +49 3916752737; fax: +49 3916752762.

E-mail address: ashok.nallathambi@ovgu.de (A.K. Nallathambi).

http://dx.doi.org/10.1016/j.applthermaleng.2015.03.060
1359-4311/

Nomenclature

T_f	liquidus temperature (°C)
T_s	solidus temperature (°C)
T_w	surface temperature (°C)
λ	thermal conductivity (W/mK)
c	specific heat (J/kgK)
ρ	density (kg/m^3)
Δh	latent heat (J/kg)
a	thermal diffusivity (m^2/s)
V_c	casting speed (m/min)
$\theta = \frac{T-T_w}{T_f-T_w}$	dimensionless temperature
$X = \frac{x}{s/2}$	dimensionless space coordinate
$\Delta = \frac{\delta}{s/2}$	dimensionless solidification thickness
$Fo = \frac{at}{(s/2)^2}$	Fourier number
$Ste = \frac{c(T_f-T_w)}{\Delta h}$	Stefan number
B	width of the ingot
s	thickness of the ingot
δ	solidified layer thickness
$\dot{M}$	mass flow rate

Wang et al. investigated the effect of casting speed, slab size and superheat on temperature and the final solidification length using a 2-D slice approach [10].

The twin-belt caster received major attention for its excellent performance in the continuous casting of nonferrous metals [11]. Farouk et al. investigated the effect of process parameters on the heat transfer and solidification in a twin-belt caster [12]. Gerber et al. demonstrated that belt heat transfer and casting speed are most influential on solidification [13].

Even though many studies are presented in analyzing the existing continuous casting process, theoretical guidelines to design the plant based on the final solidification length are not yet well established. Therefore, a generalized theoretical model which incorporates all kind of metals is developed and the key design parameters are identified. The cooling strategies in different zones are normally obtained from the costly industrial trails. From the solution of the model developed, it is easier to design the secondary cooling spray arrangements which eliminates the heuristic approach.

2. Methodology

2.1. Assumptions

Fig. 1 shows the typical temperature profiles during the continuous casting process of steel. It is observed that the surface temperature drops to a certain value at the mold exit and fluctuates up and down over the range of temperature in the secondary cooling zone. The local oscillations in the temperature are due to the cooling by sprays with varying impingement density. The arrangement of nozzles causes the strand to heat and cool intermittently. Beyond the secondary cooling zone, the surface temperature increases suddenly and then slowly decreases due to the radiation mode of heat transfer. For the purpose of developing a theoretical solution, the surface temperature is approximated as constant from the beginning till the end of solidification. The temperature drop in the mold region is neglected because the mold length is typically less than 1 m, which is only 5–10 % of the total solidification length. It is observed that the core temperature does not change till the complete solidification. The effect of constant surafce temperature will not be felt at the core till the solidification front reaches.

Even though the constant surface temperature assumption is not correct, it is a worthful, valid and convincing one for the production personnel. The work in this manuscript is undertaken with the objective of providing guidelines for designing a new casting process. When there is no information about the convective heat transfer coefficient, it is better to assume infinite heat transfer coefficient i.e. constant surface temperature. After finding the required heat flux from the solution, it is better to achieve the finite heat transfer coefficient using the sprays. Due to this reason the work is carried out with constant surface temperature assumption. Due to this assumption, it is possible to set the benchmark model parameters for the design of new casting process for metals. In the later stage, one can search for sophisticated commercial packages for simulating the exact situation. The detailed numerical simulation of the designed casting process is only useful for optimizing the process, but not for providing the initial design guidelines.

2.2. Semi infinite slab

Consider a half-domain of length $(s/2)$ which contains fully molten metal at the liquidus temperature T_f as shown in Fig. 1. If the surface is maintained at a constant temperature T_w, which is well below T_f, solidification starts from the surface. The solid phase grows with time and the solidification front moves along the positive x-direction. The domain is considered as a semi infinite body for transient heat conduction and the heat transfer is purely one dimensional. Fig. 1 shows the typical temperature profiles at different times t_1, t_2 and t_f. The heat conduction in the solidified layer is governed by the Fourier differential equation of the form [14].

$$\rho c \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}. \tag{1}$$

The initial and boundary conditions are

$$T(x, t=0) = T_f, \quad T(x=\delta, t) = T_f, \quad T(x=0, t) = T_w. \tag{2}$$

The solid growth rate is controlled by the energy balance at the solidification front, which can be written as

$$\lambda \cdot \frac{\partial T}{\partial x}(x=\delta) = \Delta h \cdot \rho \cdot \frac{d\delta}{dt}. \tag{3}$$

The above system of equations can be written in the dimensionless form as,

$$\frac{\partial \theta}{\partial Fo} = \frac{\partial^2 \theta}{\partial X^2}. \tag{4}$$

$$\theta(Fo=0) = 1, \quad \theta(X=0) = 0, \quad \theta(X=1) = 1 \tag{5}$$

$$\frac{\partial \theta}{\partial X}(X=\Delta) = \frac{1}{Ste}\frac{d\delta}{dFo}. \tag{6}$$

Imposing the energy balance at the phase boundary, the analytical solution of Eq. (4) yields the relation

$$\frac{\Delta\sqrt{\pi}}{2\sqrt{Fo}} \cdot exp^{\left(\frac{\Delta^2}{4Fo}\right)} \cdot erf\left(\frac{\Delta}{2\sqrt{Fo}}\right) = Ste. \tag{7}$$

More details of the analytical solution are given in Refs. [15–17]. The dimensionless solidification thickness (Δ) is thus a function of