A Simple Estimation Method for Shell Thickness at the Mold Exit in the Continuous Casting of Steel

Carlos CICUTTI and Roberto BOERI

Centro de Investigación Industrial, FUDETEC. J. Simini 250 (2804) Campana, Argentina.
1) INTEMA, Facultad de Ingeniería, Universidad Nacional de Mar del Plata-CONICET, Argentina.

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1. Introduction

The heat extracted by the continuous casting mold has to produce a solid layer strong enough to withstand the ferrostatic pressure when the steel leaves the mold. An improper design of the system can cause strand breakouts or defects in the continuous casting product.

Mathematical models are useful tools not only to predict the solidified thickness at mold exit but also to understand the influence of the different variables involved in the process. In the last years, numerical models have been widely employed for this purpose due to their capability of dealing with complex boundary conditions and geometries. However, for certain applications, like daily plant operation, the use of analytical solutions which can quickly give the explicit dependence of the involved variables is still desirable. The objective of the present article is to apply an analytical solution to estimate the solidified thickness at the mold exit and to compare its results with measured data previously reported in the literature.

2. Mathematical Model

A small number of solutions are available to solve the problem of heat transfer with phase change. The solution developed by Neumann is probably the most suited to approach the continuous casting process. The main assumptions in this solution are:

i) The domain is semi-infinite.
ii) The metal or alloy has a specific solidification temperature.
iii) The thermophysical properties are constant.
iv) The temperature at the free surface is constant.

As the solidified layer in the continuous casting mold is small compared with the product thickness, the first assumption is acceptable. Similarly, the second assumption is valid for low alloyed steels where the freezing temperature range is small. Considering that the steel cools down in the mold from about 1530 to 1200°C, the use of constant thermophysical properties is also acceptable. From all of the assumptions, the one that imposes a constant surface temper-
Equation Eq. (5) can be used to calculate the surface temperature. Replacing (5) into Eq. (2) gives:

\[ \frac{\xi}{H_k} = \frac{C \cdot \sqrt{a_q \cdot a_k \cdot \exp(-\xi^2)} \cdot \exp(-\xi^2)}{H_k \cdot \xi} - \frac{\exp[-(a_q/a_k) \cdot \xi^2]}{\sqrt{(a_q/a_k) \cdot \exp(\xi \cdot (a_q/a_k))}} \cdot \frac{c_0 \cdot (T_c - T_f)}{\sqrt{\pi} \cdot H_k} \] ...(6)

Knowing \(C\), the steel superheat and the values of the thermophysical constants involved, this equation can be solved and the value of \(\xi\) calculated.

In an actual caster the heat flux distribution in the mold can be measured using pairs of thermocouples inserted at different distances from the meniscus. In such case, the value of \(C\) can be obtained by fitting Eq. (4) to the experimental data. However, only a small number of machines have such instrumentation. Alternatively Eq. (4) can be integrated to calculate the average heat extracted:

\[ Q_t = \frac{1}{t_m} \int_0^{t_m} \frac{C}{\sqrt{t}} dt = \frac{2}{\gamma} \int_0^{t_m} C \cdot \frac{dt}{\sqrt{t}} \] ............(7)

In most of the continuous casting machines, both the water flowrate and the increase of water temperature in the mold are registered. From these data it is possible to estimate the integral heat flux extracted by the mold. Therefore, if \(Q_t\) is known for a given residence time, \(C\) can be estimated from Eq. (7). Moreover, if \(Q_t\) is registered for different residence times, the value of \(C\) can be estimated by fitting data with an equation similar to Eq. (7).

Collecting data from many casters, Wolf obtained the following expression for the integral heat extraction:

\[ Q_t = \frac{8104}{\gamma} \cdot 2 \cdot 4052 \] ............(8)

which means, for the nomenclature employed in this paper, \(C=4.052 \text{ kW.m}^{-2} \cdot \text{s}^{-0.5}\). Inserting this value into Eq. (6) and assuming a steel superheat of 20°C and the values of the thermophysical constants listed in Table 1, \(\xi=0.5471\) is obtained. Replacing now this value into Eq. (1), the following expression results:

\[ c(\text{mm}) = 21 \cdot \frac{t_m}{\gamma} \text{(min)} \] ............(9)

which is in good agreement with the \(K^\text{sol}\) usually reported in the literature for continuous casting molds, which ranges between 16 and 27 mm.min^{-0.5}.

Considering that heat flux in the continuous casting mold depends not only on the residence time but also on many other factors, like steel composition and type of lubricant used, the value of \(C\) can be estimated for each plant from the values of such variables.

As the solution of Eq. (6) is not straightforward, calculations were performed for typical values of \(C\) and steel superheat, and a simpler equation was fitted as follows:

\[ K^\text{sol} = 13.624(\ln C) - 0.0572\Delta T - 90.89 \] ............(10)

Within the range analysed, this expression fits the results of Eq. (6) with an error smaller than 1%, as shown in Fig. 1.

3. Comparison of Calculations with Measured Data

In order to check the validity of the method developed in the previous section, calculations were compared with measured values published in the literature. Only those cases which included complete information about the mold cooling were selected. Table 2 lists the main characteristics of the cases analysed. In all cases, the solidified thickness was measured employing radioactive tracers. It is generally agreed that this technique reveals the solidified thickness corresponding to a solid fraction of about 0.5. Consequently, for calculations it was assumed that the melting temperature is \(T_f = 0.5 (T_m + T_c)\).

For all the cases analysed, \(C\) was calculated by using the mold cooling data and the thermophysical properties listed
in Table 1. Results are summarised in Table 2. The calculated and measured values are shown in Fig. 2. Considering the scatter of experimental data, a reasonable agreement is obtained with calculated values.

4. Conclusions

A simple model based on the analytical solution of Neumann was developed to estimate the solidified thickness at the mold exit in the continuous casting process. Mold cooling data usually recorded in industrial machines can be used to fit the model to each particular installation. Despite some crude assumptions made in the development of the model, the results are in good agreement with measured values of solidified thickness reported in the literature.

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REFERENCES