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Continuous casting heat transfer model – The spray cooling control problem

Modelo de transferência de calor no lingotamento contínuo – O problema do controle dos sprays de resfriamento

Modelo de transferencia de calor en colada continua - El problema de controlar los aerosoles de enfriamiento

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Abstract
In the steel industry, the continuous casting process is regarded as the second significant technical innovation after the advent of the oxygen steelmaking process. Prevailing thermal conditions are a dominant factor in the quality of the product. The common practice of spray control in which water flow in the sprays is proportional to the casting speed is inadequate to unsteady state conditions during speed changes. The objectives of the present study were twofold. The first was to study the basic principles of spray control. As a required tool, a mathematical model for the thermal field was developed. This model was to be used to simulate the temperature distribution in the strand. The second objective was to use these principles to develop a model for controlling the sprays. The thermal model has been used to analyze the effects of both practices on the surface temperature of the strand. The results have shown that a significant temperature fluctuation can be generated by proportional control and that the new control model realistically predicts the thermal requirements of the strand during changes in casting speed.
Keywords: Continuous casting; Mathematical models; Spray cooling; Automation; Casting defects.

Resumo
Na indústria siderúrgica, o processo de lingotamento contínuo é considerado a segunda inovação técnica significativa após o advento do processo de produção de aço a oxigênio. As condições térmicas predominantes são um fator dominante na qualidade do produto. A prática comum de controle de sprays, na qual o fluxo de água nos sprays é proporcional à velocidade de lingotamento, é inadequada para condições de estado transiente durante mudanças de velocidade. Os objetivos do presente estudo foram duplos. A primeira foi estudar os princípios básicos do controle de sprays. Como ferramenta necessária, foi desenvolvido um modelo matemático para o campo térmico. Este modelo deveria ser usado para simular a distribuição de temperatura no veio. O segundo objetivo foi utilizar esses princípios para desenvolver um modelo de controle dos sprays. O modelo térmico foi utilizado para analisar os efeitos de ambas as práticas na temperatura superficial do veio. Os resultados mostraram que uma flutuação significativa de temperatura pode ser gerada pelo controle proporcional e que o novo modelo de controle prevê realisticamente os requisitos térmicos do veio durante mudanças na velocidade de lingotamento.
Palavras-chave: Lingotamento contínuo; Modelos matemáticos; Resfriamento por spray; Automação; Defeitos de fundição.

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Resumen
En la industria del acero, el proceso de fundición continua se considera la segunda innovación técnica importante después de la aparición del proceso de fabricación de acero con oxígeno. Las condiciones térmicas predominantes son un factor dominante en la calidad del producto. La práctica común de control de pulverización en la que el flujo de agua en las pulverizaciones es proporcional a la velocidad de fundición es inadecuada para condiciones de estado inestable durante los cambios de velocidad. Los objetivos del presente estudio fueron dobles. El primero fue estudiar los principios básicos del control de aspersiones. Como herramienta necesaria se desarrolló un modelo matemático para el campo térmico. Este modelo se iba a utilizar para simular la distribución de temperatura en el cordón. El segundo objetivo era utilizar estos principios para desarrollar un modelo para controlar las pulverizaciones. El modelo térmico se ha utilizado para analizar los efectos de ambas prácticas sobre la temperatura superficial del cordón. Los resultados han demostrado que se puede generar una fluctuación de temperatura significativa mediante el control proporcional y que el nuevo modelo de control predice de manera realista los requisitos térmicos de la hebra durante los cambios en la velocidad de fundición.
Palabras clave: Colada continua; Modelos matemáticos; Enfriamiento por aspersión; Automatización; Defectos de fundición.

1. Introduction

The marked increase in steel production in the world may be attributed to the construction of larger plants and mill equipment, the application of the continuous casting process, and automation. Continuous casting is considered the “sine qua non” process in any steelmaking plant. Billets, blooms, and slabs with larger cross-sectional dimensions and a broad range of steel grades have been cast worldwide. At the same time, the quality standards for continuous casting products have also been upgraded, requiring more precise methods of controlling the operating conditions.

In developing suitable methods for producing high-quality castings, it is necessary to understand the effects of casting parameters on steel casting quality. Owing to several theoretical and empirical works in the continuous casting area, the major factors are now reasonably understood. However, many factors, such as spray cooling, require attention. It has been shown that improper spray cooling is related to many casting defects as described in a following section. As pointed out by Brimacombe[1], once optimum thermal conditions have been defined, it is relatively easy to design a spray system that will realistically achieve these conditions.

Although several works have been presented dealing with the development of spray practices[2-5] most of them assume that the continuous casting operation is performed at steady state conditions and little attention is given to the problem of controlling the sprays during transient events such as casting speed changes. However, as is emphasized in the present work, the unsteady-state operation may play a very important role in the continuous casting cycle. In modern casters, casting often continues uninterrupted for many hours or even days, and sometimes large changes in casting speed are required because of a late-arriving ladle, ladle or tundish-pouring problems, temporary malfunctions of some part of the casting machine, or various similar reasons. In other words, the casting machine must be able to keep the required thermal conditions during these or other unavoidable disturbances. The lack of knowledge in this area has provided an incentive for the present work.

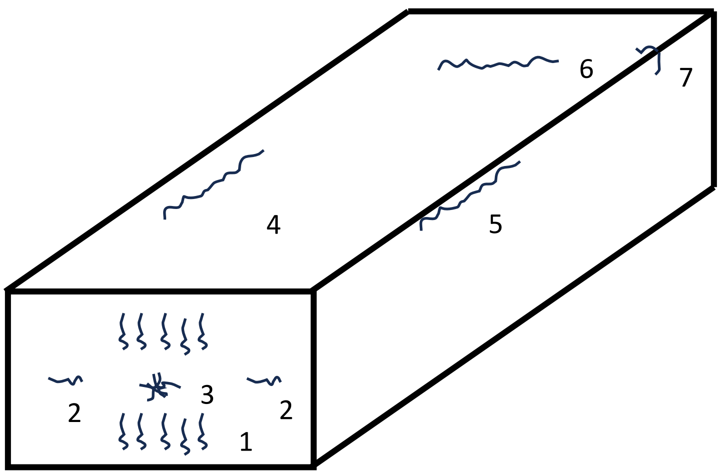
The objectives of the present study were twofold. The first was to study the basic principles of spray control. As a required tool, a mathematical model for the thermal field in the continuous casting process was to be developed. This model was to be used to simulate the temperature distribution in the strand. The second objective was to use these principles to develop a mathematical model for controlling the sprays. The model was to predict the thermal requirements of a strand during any casting speed change.

2. Methodology

The methodology applied to study the effect of cooling practices on the surface temperature of continuously cast steel products was the quali-quanti which is characterized by the combination of numerical simulations with the interpretation by the researchers about the phenomenon under study (Pereira et. al. 2018).

The formation of surface and internal cracks in a continuously cast steel strand is associated with thermal and mechanical stresses generated during the process. Irregular spraying has long been recognized as a prime source of these stresses. Furthermore, the mechanical properties of steel are strongly dependent on temperature. Lankford (1972) was one of the first authors to describe the brittle behavior of steel at high temperatures. Other authors like Weinberg (1979), Suzuki et al. (1982) also present key contributions on this subject. Van Drunen et al. (1975) and Brimacombe e Sorimachi (1977) connected the high-temperature properties with the crack formation mechanism. The temperature profile dictated by a particular spray practice affects the ability of the steel to withstand stresses. The major defects associated with spray cooling are shown in Fig. 1. Regarding internal cracks, they represent a significant challenge in producing high-quality products. Internal cracks result from steel's brittle characteristics close to the melting point. Material deformation under those conditions may result in a crack formation filled with sulfur-segregated inter-dendritic liquid resulting in a defect that cannot be eliminated by further rolling process.

Figure 1 - Defects in Continuously Cast Steel.



Internal Cracks

1- Halfway

2- Triple-Point

3 – Centerline

Surface Cracks

4- Longitudinal - mid-face

5- Longitudinal - corner

6- Transverse - mid-face

7- Transverse - corner

Source: Authors.

Van Drunen et al. (1975) have shown that surface reheating of the strand is a major cause of halfway cracks as seen in Fig. 1. The reheating expands the surface and, in so doing, imposes a tensile strain on the interior of the solid shell where it is more susceptible to cracking. This surface reheating occurs whenever the cooling rate at the surface decreases abruptly such as below the mold, between successive spray zones, or after the secondary cooling zone. Although under industrial conditions it is impossible to eliminate reheating altogether, it can be kept within an acceptable range by proper equipment project and cooling practices. However, even for the best approach, casting speed changes can result in an unsteady state situation that can generate significant surface reheating.

2.1 Mathematical models of the heat flow in the continuous casting of steel

In the operation of continuous-casting machines, it is important to understand the effects of operating conditions on the solidification profile and the surface temperature of the strand. As was seen in the previous section, prevailing thermal conditions are a dominant factor in the quality of the product. Thus, several mathematical models based on heat flow, have been developed to relate the thermal field to operating conditions.

All models are based on the unsteady-state conduction of heat from the interior of the strand to the surface. Because steel has a low thermal conductivity, and the casting rate in a continuous casting machine is high, heat conduction in the withdrawal direction can be considered negligible when compared with the heat flow in the other directions and, therefore, a two-dimensional approach can be used.

The real problem in modeling the continuous casting process does not lie in solving the differential equations but in realistically representing the surface cooling boundary conditions, the heat conduction in the liquid, and the release of the latent heat of solidification. The major solutions used in the present work are presented in a further section.

The solution of the differential equations for heat conduction can be achieved by three major methods:

a) Analytical (and empirical) methods,

b) Integral profile method, and

c) Numerical (finite difference or finite element) method.

Numerical methods offer the required versatility since they permit the use of any boundary condition, any dimensional approach, the release of latent heat over a broad freezing range, and temperature-dependent thermophysical properties. Nowadays, with the available computer power, it is the best solution to be chosen.

2.2 Control of secondary cooling

As pointed out in Section 2, secondary cooling practice is one of the most important factors affecting product quality in strand casting. In most continuous-casting installations, the water-spray parameters necessary to ensure good product quality are established experimentally for steady-state conditions, and “control” of the secondary cooling is accomplished by varying the total amount of water directly as a function of the casting speed. Although this procedure is reasonable for steady-state operation at the new casting speed, it has been shown that large surface temperature fluctuations, amounting to several hundred degrees centigrade can persist immediately after a change in casting speed. Because the thermal characteristics of the strand at a given point are a function of its thermal history, transient-cooling requirements vary widely as the distance from the meniscus increases and cannot be accounted for by a simple spray water/speed ratio control.

Production constraints make changes in casting speed unavoidable. They result either from normal operating procedures such as start-up; ladle, tundish, or shroud change; and end of casting or from unplanned incidents such as nozzle blockage. The unsteady state which follows any casting-speed change may occupy an important part of the working cycle of a caster.

Surface-temperature control in continuous casting poses a difficult problem because the normal feedback control approach, i.e., control of the cooling variables as a function of the difference between the desirable and the actual temperature, requires an accurate surface temperature measurement. Optical pyrometers have been used to indicate actual surface temperature but the hostile environment, presence of steam in the sighting path, and scale on the strand surface make the readings unreliable for automatic cooling control. Yamasaki et. al. (1981) have developed a control model using a surface temperature reading but it is used only to adjust a feed forward model

To solve this problem, the control strategy must be based on a process characteristic that allows the anticipation of temperature fluctuations and, therefore control the cooling variables directly from casting-speed measurements. The control model presented in this work assumes that, for steel, axial heat flow is negligible and, therefore, for a transverse slice of steel being cast the important variables are residence time in the machine and the cooling rate during this time. Thus, the cooling variables at any point are set only as a function of the residence time or age of a metal slice passing through this point, i.e., the time since the metal slice was formed in the mold. This ensures that each transverse slice is always subject to the correct heat extraction rate, which is entirely independent of the instantaneous casting speed.

2.3 Development of the mathematical model of heat flow.

The model is based on unsteady-state heat transfer conduction from the interior to the strand surface. Conduction in the withdrawal direction is assumed to be negligible. Mathematically, the two-dimensional heat flow is described by:

$$\rho c_p \frac{\partial T}{\delta t} = \frac{\delta}{\delta x}\left(K\frac{\delta T}{\delta x}\right) + \frac{\delta}{\delta y}\left(K\frac{\delta T}{\delta y}\right) \qquad ...(1)$$

where **ρ** is the density, $\mathbf{c_p}$ is the specific heat, and **K** the heat conductivity of the material.

To solve this equation, initial and boundary conditions, which are characteristic of each machine, must be considered.

The following assumptions have been adopted in the model:

a) Owing to two-fold symmetry across the center plane of the broad face, the calculation can be confined to half of the cross section. Symmetry across the narrow face center plane has not been considered to allow different cooling rates on the two broad faces as could occur in curved machines. Therefore, at the center plane of the broad face, a null heat flux boundary condition has been assumed.

b) In the liquid-pool region, heat flow is described by an effective thermal conductivity, K_{eff}, which includes the effect of convective mixing.

c) Owing to a general lack of qualitative information to the contrary, the latent heat of solidification has been assumed to be released linearly within the liquid/solid region by an artificial increase of the c_p value in this temperature range.

d) The surface boundary conditions are expressed as a heat transfer coefficient and a temperature of the surrounding medium.

$$-K\frac{\partial T}{\partial x} = h(T_s - T_a) \qquad ...(2)$$

where **h** is the heat transfer coefficient, and T_s and T_a are the surface and ambient temperatures respectively.

There are three major approaches for the formulation of the finite difference equations:

a) Normal explicit method,

b) Normal implicit method, and

c) Implicit alternating direction method of Peaceman & Rachford (1955) used for two-dimensional equations.

The methods are described by Carnahan, Luther, & Wilkes (1969). Although the explicit is much easier to use, it can be unstable depending on the mesh size and time interval. To avoid this restriction an implicit approach has been chosen,

However, this approach gives rise to two new problems:

a) The values of the thermophysical properties are now a function of unknown future temperatures, and

b) In the equation there are now five unknown temperatures that must be determined. Applying this equation to all nodes in the section leads to a system of simultaneous equations with five unknowns.

The most elegant solution for the former problem is to adopt an iterative technique, i.e., approximate K and c_p using the previous temperatures and employ the newly calculated temperatures to evaluate a more accurate value of K and c_p and then reevaluate the temperature field. However, the temperature dependence of K and c_p are not very strong so only the first step has been used, i.e., K and c_p are approximated by their values at the previous time-step. This procedure would limit time-step size since the accuracy of the values of thermophysical properties is a function of Δt, but this restriction is less severe than in the explicit case.

The latter problem can be overcome using the alternating-direction implicit method developed by Peaceman and Rachford (1955). This method involves the subdivision of the time step into halves. Over the first half time-step, the equations are made implicit only in the x direction while over the second half, they are made implicit in the y direction. Therefore, the problem of solving a system of simultaneous equations with five unknowns is reduced to solving two systems of simultaneous equations with three unknowns which can be solved by a Gaussian elimination method. Hence this method was chosen as the basis for this model.

To solve the heat conduction problem, the partial derivatives of the original differential equation are approximated by suitable finite-difference expressions. Since the thermal conductivity is a function of the temperature, Eq. (1) is nonlinear, but it must be approximated by a linear algebraic equation in its unknowns. The following approximations, suggested by Myers (1971) have been used in the present work:

$$\rho C_p \frac{T'(i,j) - T(i,j)}{\Delta t} = \frac{K_1 \frac{T'(i+1,j) - T'(i,j)}{\Delta x}}{\Delta x} - \frac{K_2 \frac{T'(i,j) - T'(i-1,j)}{\Delta x}}{\Delta x} + \frac{K_3 \frac{T'(i,j+1) - T'(i,j)}{\Delta y}}{\Delta y} - \frac{K_4 \frac{T'(i,j) - T'(i,j-1)}{\Delta y}}{\Delta y} \quad (3)$$

where the thermal conductivities K1, K2, K3, and K4 are calculated by averaging the values in the adjacent nodes in question and cp is evaluated at T(i , j)

Furthermore, to introduce the boundary conditions, the appropriate term describing heat flow by conduction must be replaced by a term describing heat exchange with the surroundings. For a node on the surface, Eq. (3) becomes:

$$\rho C_p \frac{T'(1,j) - T(1,j)}{\Delta t} = \frac{K_1 \frac{T'(2,j) - T'(1,j)}{\Delta x}}{\Delta x} - \frac{h(T_a - T'(1,j)}{\Delta x} + \frac{K_3 \frac{T'(1,j+1) - T'(1,j)}{\Delta y}}{\Delta y} - \frac{K_4 \frac{T'(1,j) - T'(1,j-1)}{\Delta y}}{\Delta y} \quad (4)$$

However, this direct substitution of the boundary condition to produce Eq. (4) is not satisfactory, as the approximations for the derivatives do not match, being a function of Δx (or Δy) for a surface node and of Δx2 (or Δy2) for an interior node. This difference can be corrected by imagining the existence of a fictitious external node at a distance Δx (or Δy) from the surface. The heat transfers between the strand and the surroundings is then considered equivalent to the heat transferred by conduction between the interior node immediately adjacent to the surface node and the imaginary node. This leads to the following equations:

$$\rho C_p \frac{T'(1,j) - T(1,j)}{\Delta t} = \frac{K_1 \frac{T'(2,j) - T'(1,j)}{\Delta x}}{\Delta x} - \frac{K_2 \frac{T'(1,j) - T^*(j)}{\Delta x}}{\Delta x} + \frac{K_3 \frac{T'(1,j+1) - T'(1,j)}{\Delta y}}{\Delta y} - \frac{K_4 \frac{T'(1,j) - T'(1,j-1)}{\Delta y}}{\Delta y} \quad (5)$$

where T*(j) can be found from the expression for the boundary condition:

$$K \frac{T(2,j) - T^*(j)}{2\Delta x} = h(T(1,j) - T_a) \quad ...(6)$$

2.3.1 Surface boundary conditions and thermophysical properties

Reliable values for boundary conditions and thermophysical properties are, by far, the challenge in modeling the continuous casting process. Data for the high temperature thermophysical properties of commercial steels are difficult to obtain, and variables such as effective thermal conductivity in the liquid pool and latent heat release during solidification present significant difficulties in experimental determination.

Fortunately, Lait et. al. (1974) have shown that the exact form of the latent heat release and Brimacombe (1976) that the value of the effective thermal conductivity employed1 do not significantly affect the calculated temperature field. Therefore, the effective thermal conductivity in the liquid pool has been estimated from the literature to be equal to seven times the actual conductivity of the liquid metal at that temperature.

In the mold region, owing to the complexities introduced by gap formation, the boundary conditions are best described by a heat transfer coefficient that decreases with time below the meniscus. Grill et al. (1976), Brimacombe et al. (1982), and

Samarasekera (1980) performed extensive mold heat flux experiments, and it was found that the heat transfer coefficient can be expressed by:

$$h = C_1 . e^{-0.02t} \qquad \ldots (7)$$

where C1 is a function of the mold powder characteristics and varies from 1.0 kW/m2.K for a mold powder with a high melting point to 1.8 kW/m2.K for a powder with a low melting point or oil.

In the spray cooling zone, the spray parameters have been related to heat transfer coefficients by a technique like that suggested by Nozaki et al. (1978). The equation describing the spray behavior developed by Mitsutsuka (1968), and adjusted by an accommodation factor α,

$$h = 1.33 \frac{W^{0.55}}{\alpha} \qquad \ldots (8)$$

has been used where W in l/m2.s is the water flux, and the cooling efficiency in each spray zone, expressed by α, is evaluated from surface temperature measurements made in the plant.

In the radiation cooling zone, the boundary condition is described by a heat transfer coefficient calculated from the Stefan-Boltzmann equation and the surface temperature at the previous time-step.

$$h_r = \frac{\varepsilon\sigma({T_s}^4 - {T_a}^4)}{(T_s - T_a)} \qquad \ldots (9)$$

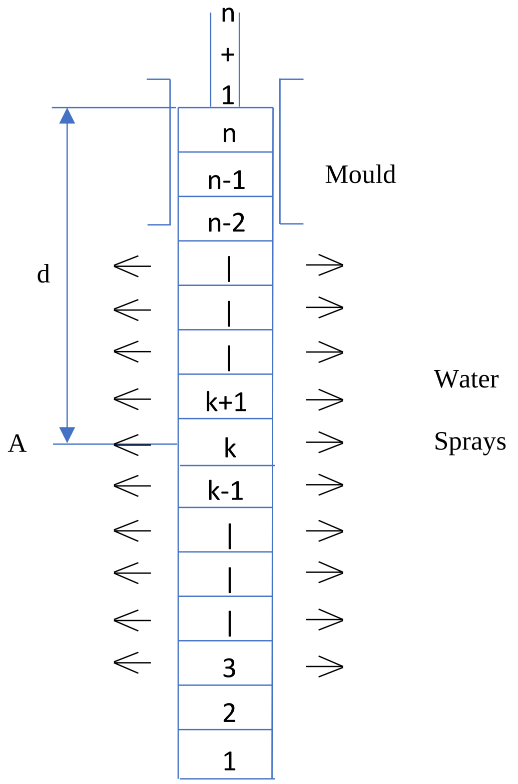
The emissivity ε is assumed to be equal to 0.8 for the oxidized steel surface over the temperature range in question.

2.4 Mathematical model for controlling the secondary cooling zone

The main objective of the control system proposed in this work is to adjust the water flow rates of the secondary cooling zone with respect to casting speed to maintain a given thermal history constant during the casting.

As pointed out in Section 2.2, since the axial heat flow is negligible, the events taking place in a transverse slice of steel going through the caster will be only a function for its cooling history. Therefore, the desired constant thermal history can be obtained by controlling the water flux at any point in the spray zone as a function of the residence time of the metal passing by this point. This is schematically shown in Fig, 2 where the spray parameters at a point A should be set up as a function of the age of the metal slice k.

Figure 2 - Schematic diagram of strand divided into slices. **d** is the distance of the kth slice from the meniscus.



Source: Authors.

The basic control equations are included in the model. The first is a relationship between the required heat transfer coefficient and the residence time, and the second equation relates the spray heat transfer coefficient to its water flux. The equations are used in the following way:

a) The strand is divided into several slices starting at the meniscus level.
b) Each slice residence time or "age" is evaluated, and the required heat transfer coefficients are obtained from the first control equation. In industrial machines, it is not practical to continuously control secondary cooling. Although the ideal would be a continuous decrease in the cooling rate in line with the increase in the solidified shell thickness along the machine, the secondary cooling is subdivided into individually controlled zones, replacing the continuous drop with a stepwise one.
c) An average heat transfer coefficient is calculated for each spray zone based on the slices going through the zone.
d) The average spray zone heat transfer coefficient is then related to water flux using the second control equation.
e) Furthermore, to take into accountant the start-up and end-of-casting situations, it is also necessary to keep track of either the head or tail of the strand. This is necessary because the averaging of heat transfer coefficients must be performed only over the occupied part of the spray zone by the strand.

2.4.1 Residence-time calculations

At constant casting speed, the residence time associated with a given point in the strand (Fig. 2) is easily calculated by dividing the distance from this point to the meniscus, d, by the casting speed V0,

$$t = \frac{d}{V_0} \qquad \ldots (10)$$

However, in the general case, it can only be evaluated by integrating the casting speed function.

$$d = \int_{\tau-t}^{\tau} V(\theta)d\theta \quad ...(11)$$

The value of the integral is the distance from the meniscus to the point in question. The upper limit is the present time τ, and the lower limit is the time when the element passing by the point was formed at the meniscus, i.e., the present time minus the residence time, τ – t. For any point below the meniscus, the integral value is fixed. The independent variables are τ and the casting speed function and the dependent variable is the lower limit or rather the value of t.

Unfortunately, there is no general analytical solution for this equation and a solution must be found for each casting speed function. A computer model based on a numerical technique has been developed to solve this problem.

2.4.2 Computer program formulation

The model is based on a simple trapezoidal rule integration, i.e., the integral of the casting speed function is approximated by:

$$\int_{\tau-y}^{\tau} V(\theta)d\theta = \Delta\theta\left(\frac{V(\tau)}{2} + V(\tau-\Delta\theta) + V(\tau-2\Delta\theta) + \ldots + \frac{V(\tau-n\Delta\theta)}{2}\right) \quad . (12)$$

Each segment of the cooling zone is then divided into several control points. The residence time for each control point is calculated by integrating the casting speed (or rather performing this summation), backwards until the value is greater than the distance from the meniscus to the point under consideration. An approximation of the residence time is therefore obtained by:

$$t = n\Delta\theta \quad ...(13)$$

The required cooling practice is obtained by using the heat transfer model to generate an equation relating the heat transfer coefficient to the residence time. For each spray zone, the required mean heat transfer coefficient is obtained by averaging the values at the points within the zone. The second control equation, the relationship between heat transfer coefficients and the spray water flux, is them used to calculate the recommended water flow for each zone.

3. Results and Discussion

3.1 Simulation of casting speed changes

A specific case study is presented to compare the effect of cooling practices on surface temperature. The case of a shroud change has been chosen for the present work because it is a unique fig change which is performed in a reasonably repetitive way. For this, the speed must be reduced to a very low level during around 1 minute. The metal flow is interrupted, the ceramic shroud is changed, the metal flow is started again, and the casting operations is resumed at an intermediated casting speed which is maintained for around 2 minutes after which the normal operation is resumed. This casting speed change produces a cooling transient that can generate large fluctuations in the slab surface temperature.

3.1.1 Casting machine parameters

For this purpose, data from a continuous casting machine used in an author’s previous work, Baptista (1979), will be employed. The machine is a Demag slab caster, two strands, curved mold with a 12.2 m radius. The caster is equipped with turret ladle arms supporting the 232 t ladles during the casting. A single tundish car rotates about the same axis as the turret arms, providing a vertical lift for the 21 t capacity tundish. Metal flow from the tundish is controlled by a slide-gate nozzle. The submerged ceramic shroud is also part of the system and can be changed during the cast. The machine can cast slabs from 813 to 1702 mm in width and 235 mm in thickness. The standard casting speed is 2.12 m/min. The secondary cooling system is divided into five separately controlled sections. Table 1 shows the dimensions of the sections.

Table 1 – Secondary Cooling Zone – Demag Caster.

ZONE	LENGTH (cm)
1 – Narrow Faces 1 – Broad Faces	34. 34.
2 – Narrow Faces 2 - Broad Faces A B C	81. 41. 41. 82.
3 – Top 3 – Bottom	589. 589.
4 – Top 4 – Bottom	488. 488.
5 – Top A B 5 - Bottom	405. 459. 864.

Source: Baptista (1979).

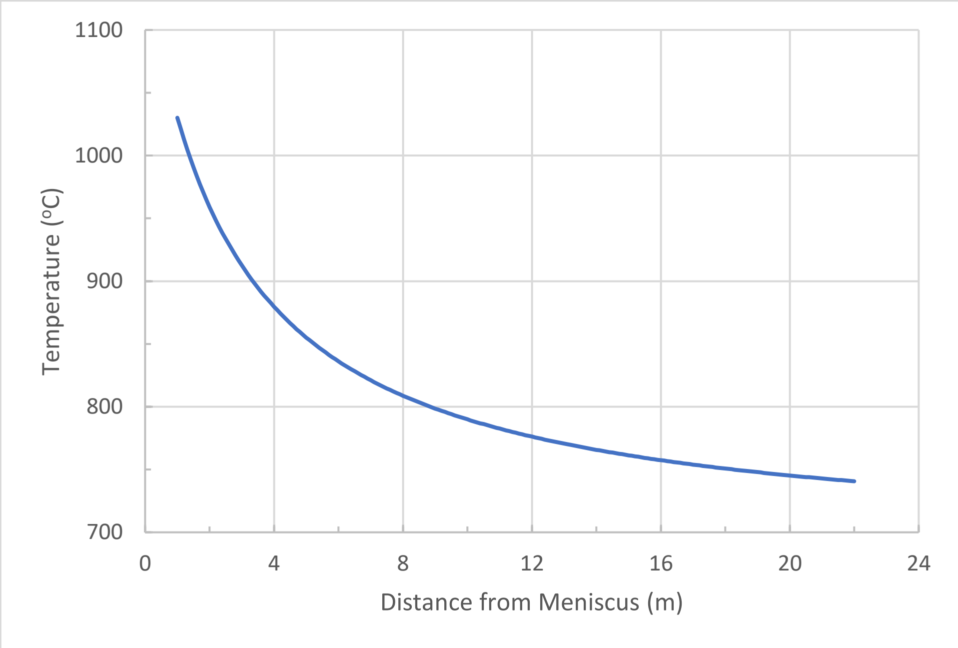
Owing to the excellent quality of the slabs cast during regular operation, it is assumed that the thermal history of the material cast under steady-state conditions can be used as "ideal" for the strand. Temperature measurements taken in the machine during the operation were used to estimate an "optimal" thermal profile (Fig. 3) and, using the heat transfer model, the required heat transfer coefficient function to obtain this profile. From the cooling practice, the heat transfer model can also estimate the accommodation factor, α, in Eq. (8) for each spray zone. Table 2 shows the calculated α factor for each spray zone.

Table 2 - Cooling Efficiencies – Demag Caster.

Zone	α
1	5.66
2 – Average 2A 2B 2C	4.37 3.75 4.19 3.57
3	3.41
4	3.72
5	3.78

Source: Baptista (1979).

Figure 3 - Assumed Surface Temperature Profile.



Source: Authors.

Using this procedure, it is possible to obtain the two required control equations, i.e., the relationship between heat transfer coefficient versus residence time and heat transfer coefficient versus spray water flow for each spray zone.

It should be emphasized that the spray nozzles are designed to work in a specific range of water pressures. This results in a limited range of water flow rates, in other words, you cannot use a water flow rate below a minimum value since the spry will not work or above a maximum value due to saturation. That means that even if the control equation requests a smaller value, the spray water flow must be kept above the minimum value. This is valid for any control strategy.

For this specific caster, the minimum and normal set point (for a 2.12 m/min casting speed) are shown in Table 3 as a percentage of the maximum flow rates available for each zone. The following equation is used to calculate the flow rates, W_n, for other speeds:

$$W_n = SP_n(0.709V_c - 0.5) \qquad \ldots (14)$$

where V_c is the casting speed and SP_n is the normal set point for the zone.

Table 3 - Spray Zones Water Flow – Demag Caster.

Zone	Min. (%)	Set (%)
1 -	57.1	71.4
2 - Narrow Face	46.9	62.5
2 – Broad Face	59.5	83.3
3 – Top & Bottom	38.5	96.1
4 – Top & Bottom	36.9	98.5
5 – Top & bottom	45.8	88.0

Source: Baptista (1979).

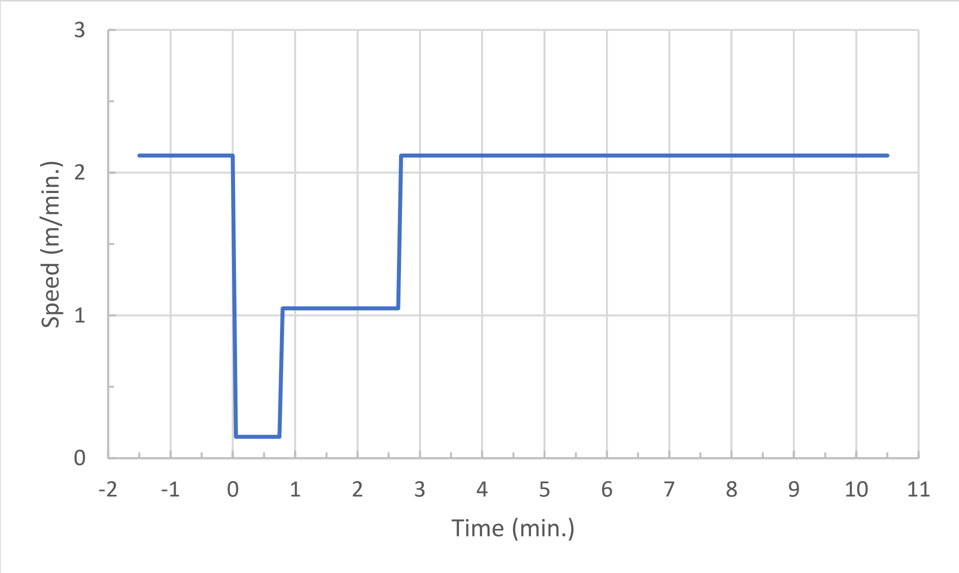
Eq. (14) is also used as the control equation for the conventional practice of controlling the spray water flow rate proportional to the casting speed.

3.1.2 Predictions of surface temperature fluctuations during shroud change

The mathematical model of heat flow has been used to predict a mid-face surface temperature fluctuation when using the conventional control practice (Eq. 14). The duration of the generated temperature fluctuation is a function of the distance from the meniscus. As the casting speed changes, the time required to reach a new steady-state condition increases with the distance from the meniscus; For example, assuming a step speed change from 1 to 2 m/min, for a point 2 m from the meniscus, after 1 minute the material passing through this point has been cast already all the time at the same speed of 2 m/min, however, for a position 18 m from the meniscus this steady state status will be achieved only after 9 minutes.

Figure 4 shows the assumed casting speed change during a shroud replacement. A position between zones 3 and 4 has been chosen as a significant situation considering that it is either not too close to the meniscus and, therefore, the transient will be too short or not close to the end of the machine where the strand is almost completely solid, and the effect will not be significant on the quality.

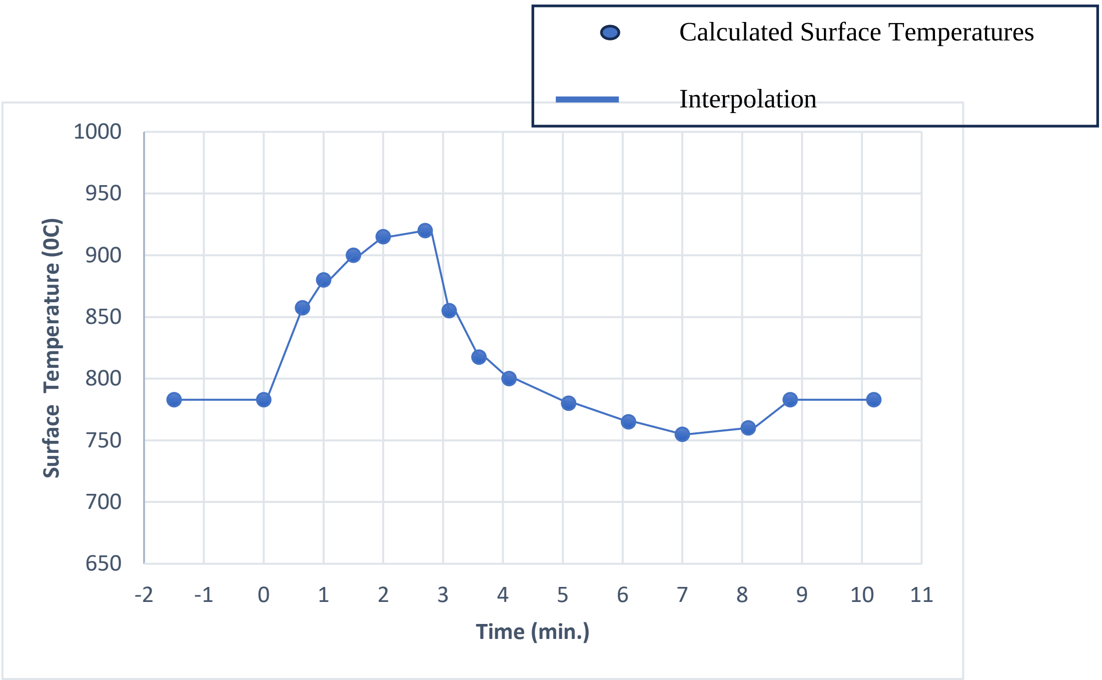
Figure 4 - Assumed Casting Speed Change during the Shroud Replacement.



Source: Authors.

Figure 5 shows the prediction of surface temperature change in this position for the assumed cast speed variation during shroud change using the conventional control practice (Eq. 14). A surface reheating of above 140 ºC is predicted as well as a sharp temperature decrease as the normal casting speed is resumed. It can also be observed that the total temperature transient can last more than 9 minutes, much longer than the casting speed change of only 2 minutes and 45 seconds.

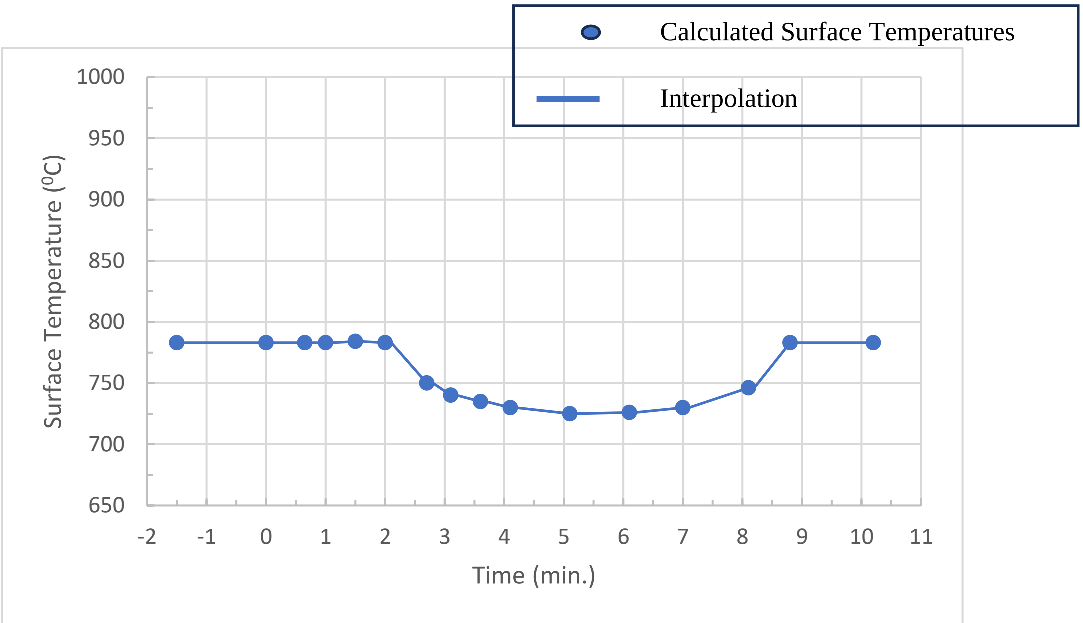
Figure 5 - Predicted Surface Temperature Fluctuation during Casting Speed Change using Conventional Control Practice.



Source: Authors.

Assuming a control practice based on residence time, the thermal history will be preserved during the casting speed change. Therefore, no surface temperature fluctuations would occur. However, in industrial casters, as noted in section 6, spray cooling cannot be continuously controlled. The spray zone is divided into individually controlled regions. Surface temperature fluctuations will always be observed as the strand moves from one spray zone to another. Surface reheat is kept within acceptable limits through correct spray design and cooling practices. This fact also prevents constant thermal history from being perfectly maintained during a speed change in the residence time control strategy. The control of the spray zone is carried out based on an average heat transfer coefficient calculated based on the residence time of the control points within the region. Fig. 6 shows the predicted surface temperature fluctuation using the proposed control model.

Figure 6 - Predicted Surface Temperature Fluctuation during Casting Speed Change using the Proposed Residence Time Control Model.



Source: Authors.

Although a temperature oscillation is still observed, it is much smaller and slower than those observed during velocity changes using spray cooling control based directly on pouring velocity (Eq. 14). Even more importantly, there is no sharp surface reheating that causes surface expansion, resulting in stress at the solidification front.

4. Conclusion

The basic principles of spray control in the continuous casting of steel were analyzed. A mathematical model was developed to study the thermal requirements of the strand during a casting speed change. Model simulations showed that the conventional practice of spray control based on casting speed generates strong surface temperature fluctuations already shown to be associated with operational problems and internal defects observed in continuously cast steel products.

A spray control practice based on residence time was developed. The model is based on maintaining the thermal history of the strand throughout the casting process regardless of any change in casting speed. Although industrial constraints prevent this objective from being fully achieved, as it would require a continuously controlled spray cooling zone, the simulations have shown that the reheating problem can be eliminated, and only acceptable temperature fluctuations are observed.

The model developed in this work appears to be adequate for the automation of the spray cooling control in continuous casting machines, and the required equipment is readily available.

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