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EVALUATION OF HEAT TRANSFER COEFFICIENTS ALONG THE SECONDARY COOLING ZONES IN THE CONTINUOUS CASTING OF STEEL BILLETS

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ABSTRACT

In the present work, heat transfer coefficients (h) along different cooling zones of a continuous caster billet machine were determined during casting of low and medium carbon steels. The effects of casting parameters, such as machine characteristics, the ingot dimension, mold, sprays zones, radiant cooling, melt composition and casting temperature were investigated and correlated with heat transfer coefficients. By using industrial measured billet surface temperatures, linked with a numerical solution of the solidification problem, ingot/cooling zones heat transfer coefficients were quantified based on the solution of the inverse heat conduction problem (IHCP). The experimental temperatures were compared with simulations furnished by an explicit finite difference numerical model, and an automatic search has selected the best theoretical-experimental fit from a range of values of h. The computer software algorithm has been developed to simulate temperature profiles, solid shell growth, phase transformations and the point of complete solidification in continuous casting of steel billets and blooms. Industrial experiments were monitored with an optical infrared pyrometer to analyze the evolution of surface temperatures during solidification along the machine. The results permitted the establishment of expressions of h as a function of position along the caster, for different steel compositions, casting parameters and melt superheats.

INTRODUCTION

The continuous casting process is responsible by most of the steel production in the world, and has largely replaced conventional ingot casting/rolling for the production of semi-finished steel shaped products. The process is essentially a process of heat transfer between the metal and different cooling zones. Fig. 1 shows a schematic representation of a continuous caster and the different cooling zones along the machine. The casters have been implemented with modern equipments for billets, slabs or blooms, multiple casting and process control.

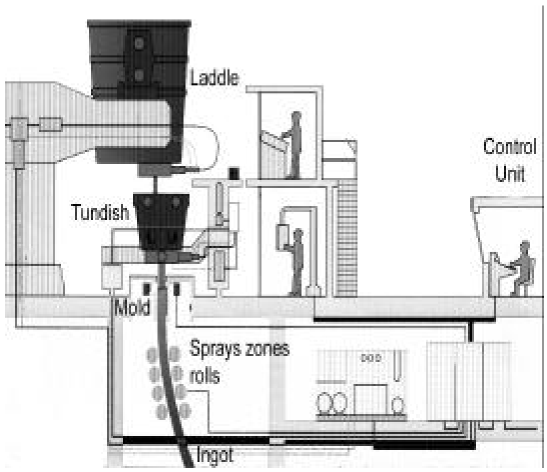

Figure 1. Representation of the continuous casting process of steel.

For the purpose of accurate mathematical modeling of solidification in the continuous casting of steel, it is essential that correct boundary conditions be established along the caster machine during casting operations. Heat transfer at the metal/cooling interface is one of these boundary conditions, which is of central importance when considering the magnitude of heat transfer during the stages of solidification in the mold, spray zones or natural cooling.

The present study describes a method for obtaining transient interfacial heat transfer coefficients as a function of position along the caster, from temperature experimental data concerning the solidification of steel during continuous casting. Ingot surface experimental temperatures obtained by optical pyrometers are compared with simulations furnished by a numerical model, and an automatic search selects the best fit from a range of values of interfacial heat transfer coefficients by IHCP procedure (*Inverse Heat Conduction Problem*). The effects of alloy composition, casting and dimensions of the ingot are also investigated.

HEAT TRANSFER COEFFICIENT

Several studies have attempted to quantify the metal/cooling transient interfacial heat transfer during solidification in continuous casting processes during operation in terms of a heat transfer coefficient [1-5]. These studies have highlighted the different factors affecting heat flow across metal/cooling interface during solidification. These factors include the thermophysical properties of the contacting materials, the casting and mold geometry, melt superheat, and mainly the specific configurations of each machine, as well as the operational casting parameters and solidification conditions. The heat transfer coefficients vary for each region along the machine [6-12]. Most of the methods of calculation of h existing in the literature are based on temperature histories at points of the casting or mold together with mathematical models of heat transfer during solidification. Among these methods, those based on the solution of the inverse conduction problem have been widely used in the quantification of the transient interfacial heat transfer [12-21].

This method makes a complete mathematical description of the physics of the process and is supported by temperatures measurements at known locations inside the heat conducting body. The temperature files containing the experimentally monitored temperatures are used in a finite difference heat flow model to determine h, as described in a previous article[17]. The process at each time step included the following: a suitable initial value of h is assumed and with this value, the temperature of each reference location in casting at the end of each time interval Δt is simulated by using an explicit finite difference technique. The correction in h at each interaction step is made by a value Δh, and new temperatures are estimated [$T_{est}(h+\Delta h)$] or [$T_{est}(h-\Delta h)$]. With these values, sensitivity coefficients (ϕ) are calculated for each interaction, given by:

$$\phi = \frac{T_{est}(h+\Delta h) - T_{est}(h)}{\Delta h} \qquad (1)$$

In the present work, a similar procedure determines the values of h, which minimizes an objective function defined by:

$$F(h) = \sum_{i=1}^{n} (T_{est} - T_{exp})^2 , \qquad (2)$$

where T_{est} and T_{exp} are, respectively the estimated and experimentally measured temperatures at various positions and times along the machine during casting operation, and n is the iteration stage. The procedure has been detailed by the present authors in a previous publication [17].

MATHEMATICAL SOLIDIFICATION HEAT TRANSFER MODEL

The mathematical formulation of heat transfer to predict the temperature distribution during solidification is based on the general equation of heat conduction in unsteady state, which is given for two-dimensional heat flux by eqn (3):

$$\rho . c . \frac{\partial T}{\partial t} = k . \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \overset{o}{q} , \qquad (3)$$

where ρ is density [kg/m^3]; c is specific heat [J/kg K]; k is thermal conductivity [W/m K]; $\partial T / \partial t$ is cooling rate [K/s], T is temperature [K], t is time [s], x and y are space coordinates [m] and $\overset{o}{q}$ represents the term associated to the internal heat generation due to the phase change. It was assumed that the thermal conductivity, density and specific heat vary only with temperature.

Approximating eqn (3) by finite-difference terms, we obtain eqn (4):

$$\rho . c . \frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} = k . \left[\frac{T_{i+1,j}^{n} - 2T_{i,j}^{n} + T_{i-1,j}^{n}}{\Delta x^2} + \frac{T_{i,j+1}^{n} - 2T_{i,j}^{n} + T_{i,j-1}^{n}}{\Delta y^2} \right] + \overset{o}{q} \qquad (4)$$

where i, j are the positions of element, n and n+ 1 refer to temperatures before and after the incremental time interval, respectively, and the stability criteria is given by $\Delta t < \frac{\Delta x^2}{2.\alpha}$ or $\frac{\Delta y^2}{2.\alpha}$ where $\alpha = \frac{k}{\rho . c}$ is the thermal diffusivity [m^2/s].

Phase change

In this study, a fixed grid methodology is used with a heat source term due to the phase transformation, which is given by an explicit solid fraction-temperature relationship. The solid fraction depends on a number of parameters, however, is quite reasonable to assume f_s varying only with temperature, where f_s is the solid fraction and L is the latent heat of fusion [J/kg]. So, we can write $c' = c - L.\frac{\partial f_s}{\partial T}$ and the term $\left(L.\frac{\partial f_s}{\partial T}\right)$ is called pseudo-specific heat. At the range of temperatures where solidification occurs for metallic alloys, the physical properties will be evaluated taking into account the amount of liquid and solid that coexists in equilibrium at each temperature. The sub-indices *S* and *L*, respectively, indicate solid and liquid states. For carbon steels, f_s is appropriately described by the lever rule.

Analogy between thermal systems and electrical circuits

Multiplying eqn (4) by $\Delta x.\Delta y.\Delta z$, where $A_t = \Delta y.\Delta z$, we obtain:

$$A_t.\Delta x.\rho.c'.\frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} = A_t.k\left[\frac{(T_{i+1,j}^{n} - 2T_{i,j}^{n} + T_{i-1,j}^{n})}{\Delta x} + \frac{(T_{i,j-1}^{n} - 2T_{i,j}^{n} + T_{i,j+1}^{n})}{\Delta y}\right] \quad (5)$$

where A_t is the area of element i,j [m^2]. By using an analogy between a thermal system and the passive elements of an electrical circuit, the thermal capacitance (C_T) represents the energy accumulated in a volume element i,j from the grid, and is given by [22]:

$$C_{Ti,j} = \Delta x.\ \Delta y.\Delta z.\rho.c', \quad (6)$$

where $\Delta x.\Delta y.\Delta z$ is the volume of the element i,j.

The thermal flux between central points has a thermal resistance at the heat flux line (R_T) from point i+1,j or i-1,j to point i,j or i,j+1 or i,j-1 to i,j given by:

$$R_T = \frac{\Delta x}{k.A_t} \text{ or } \frac{\Delta y}{k.A_t}, \quad (7)$$

where Δx and Δy correspond to the distance between central points of elements.

Then, eqn (5) becomes:

$$C_{Ti,j}.\frac{T_{i,j}^{n+1} - T_{i,j}^{n}}{\Delta t} = \frac{T_{i+1,j}^{n} - T_{i,j}^{n}}{R_{T(i+i,j)(i,j)}} + \frac{T_{i-1,j}^{n} - T_{i,j}^{n}}{R_{T(i-1,j)(i,j)}} + \frac{T_{i,j+1}^{n} - T_{i,j}^{n}}{R_{T(i,j+1)(i,j)}} + \frac{T_{i,j-1}^{n} - T_{i,j}^{n}}{R_{T(i,j-1)(i,j)}} \quad (8)$$

or:

$$T_{i,j}^{n+1} = \Delta t.\left[\frac{T_{i+1,j}^{n}}{\tau_{(i+1,j)(i,j)}} + \frac{T_{i-1,j}^{n}}{\tau_{(i-1,j),(i,j)}} + \frac{T_{i,j+1}^{n}}{\tau_{(i,j+1)(i,j)}} + \frac{T_{i,j-1}^{n}}{\tau_{(i,j-1)(i,j)}}\right] + \left(1 - \frac{\Delta t}{\tau_{(i,j),(i,j)}}\right).T_{i,j}^{n} \quad (9)$$

where: $\tau_{(i+1,j),(i,j)} = c_{T_{i,j}}(R_{T_{i+1,j}} + R_{T_{i,j}})$,(10)

$$\tau_{(i-1,j),(i,j)} = c_{T_{i,j}}(R_{T_{i-1,j}} + R_{T_{i,j}}) \text{ ,(11)}$$

$$\tau_{(i,j+1),(i,j)} = c_{T_{i,j}}(R_{T_{i,j+1}} + R_{T_{i,j}}) \text{ ,(12)}$$

$$\tau_{(i,j-1),(i,j)} = c_{T_{i,j}}(R_{T_{i,j-1}} + R_{T_{i,j}}) \text{ ,(13)}$$

$$\frac{1}{\tau_{(i,j),(i,j)}} = \frac{1}{\tau_{(i+1,j),(i,j)}} + \frac{1}{\tau_{(i-1,j),(i,j)}} + \frac{1}{\tau_{(i,j+1),(i,j)}} + \frac{1}{\tau_{(i,j-1),(i,j)}} \quad (14)$$

Eqn (9) is generic and can be applied to any geometry, by varying only area and volume to be considered. The stability criterion is $\Delta t \le \tau_{(i,j),(i,j)}$.

Boundary conditions

The application of the solidification model to the continuous casting of billets was based on the following key assumptions:

(a) two dimensional heat transfer was considered: z direction $\Rightarrow \frac{\partial T}{\partial z} = 0$;

(b) a control volume element was placed in a transverse section and was analyzed from the meniscus up to the cut-off region: $Z = V_{casting}.\Delta t$, where Z [m] is position along the caster and $V_{casting}$ [m/s] is casting velocity;

(c) the billet symmetry permits that only one-quarter of the cross section be modeled for a full thermal evolution characterization;

(d) the meniscus surface was assumed to be flat;

(e) the mold is considered uniform and with an initial temperature equal to the water-cooling temperature;

(f) the surface temperature of the molten metal is considered equal to the pouring temperature and given by $T_{pouring} = T_{tundish} - 20^{o}C$;

(g) at the range of temperatures where solidification occurs for metallic alloys, the physical properties will be evaluated taking into account the amount of liquid and solid that coexists in equilibrium at each temperature:

$k = (k_S - k_L) . f_s + k_L$, (15)

$c' = (c_S - c_L) . f_s + c_L - (L * df_s)$, (16)

$\rho = (\rho_S - \rho_L) . f_s + \rho_L$, (17)

where sub-indices *S* and *L*, respectively, indicate solid and liquid states. If $f_s = 0$, the element is still

liquid and only thermophysical properties of the liquid are considered, and if f_s=1, the element is completely solid.
(h) the initial transient metal/mold heat transfer coefficients (h_m) used in this work, are those proposed in the literature [23,24] and the metal/sprays and metal/environment heat transfer coefficients (h_s and h_R) are determined by the IHCP method (Inverse Heat Conduction Problem) by using experimental ingot surface temperatures obtained by optical pyrometers.
(i) effect of mold oscillation, mold curvature, segregation, and melt level fluctuation in the mold were considered in the knowledge base.

EXPERIMENTAL PROCEDURE

The experimental data were obtained in an industrial caster by using optical infrared mobile pyrometers located along the secondary cooling zones and radiation zones. The machine was divided in eleven (11) different "regions": mold, spray zone I, sprays zone II, sprays zone III, free (metal/environment heat flow) I, free II, free III, free IV, unbending point, free V, free VI and free VII. Surface temperatures were measured in the middle or end of each region called "positions". A schematic representation of the caster machine and the locations where surface temperatures were monitored until position 4 are shown in Figure 2.

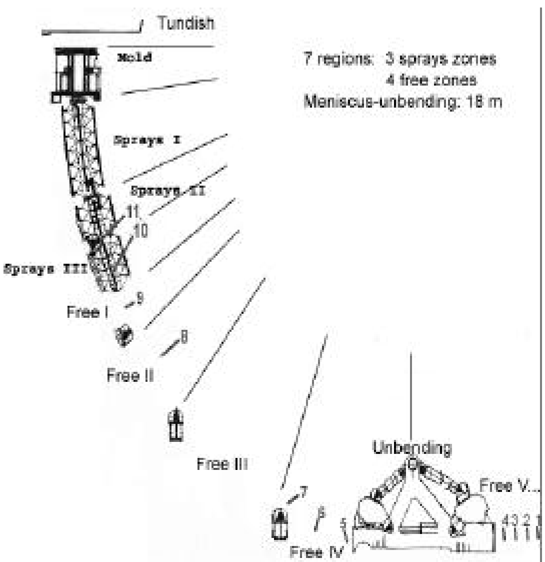

Figure 2: Location of experimental measured surface temperatures along the continuous casting process.

The input parameters used in casting operations and simulations are presented in Table 1. The temperature files containing the experimentally monitored temperatures during the continuous casting process were used in a finite difference heat flow program in order to determine nominal metal/sprays heat transfer coefficients (h). In this study the continuous casting of different dimensions and carbon contents were analyzed: SAE 1007 (150x150 mm) and SAE 1025 (240x240 mm).

Table 1. Input parameters for SAE 1007 and SAE 1025 billet conditions.

Dimension (mm)	150 x 150	
Mold length (mm)	685	
Metal	1007 Steel	
Specific heat (J/kg.K)	c_S: 600	c_S : 575
Density (kg/m^3)	ρ_S: 7800	ρ_S : 7000
Thermal conductivity (W/m.K0	k_S: 46.0	k_S : 30.0
Latent heat of fusion (J/kg)	260000	
Solidus temperature (°C)	1449	
Liquidus temperature (°C)	1514	
Sprays 1 (length mm / water flow)	1926	1.50
Sprays 2 (length / water flow-l/s)	855	0.80
Sprays 3 (length / water flow)	1045	0.60
Casting rate (m/min)	2.04	
Tundish temperature (°C)	1558	
Machine length (m)	20.0	

Dimension	240 x 240	
Mold length	680	
Metal	1025 Steel	
Specific heat	c_L: 640	c_L: 600
Density	ρ_L: 7850	ρ_L: 7000
Thermal conductivity	k_L: 30.7	k_L: 31.0
Latent heat of fusion	277000	
Solidus temperature	1468	
Liquidus temperature	1504	
Sprays 1 (length / water flow)	1926	0.59
Sprays 2 (length / water flow)	855	0.25
Sprays 3 (length / water flow)	1045	0.20
Casting rate	0.71	
Tundish temperature	1545	
Machine length	20.0	

RESULTS AND DISCUSSIONS

To determine the metal/sprays heat transfer coefficients for each spray cooling zone as a function of water flow rates, ingot surface measured temperatures shown in Tables 2 and 4 were used. The positions appearing in these tables are the same presented in Figure 2 corresponding to different distances from the top of the mold.

Figure 3 shows examples of experimental data measured by optical pyrometers in different positions along the machine during casting. The values used in the determination of the metal/cooling heat transfer coefficients are

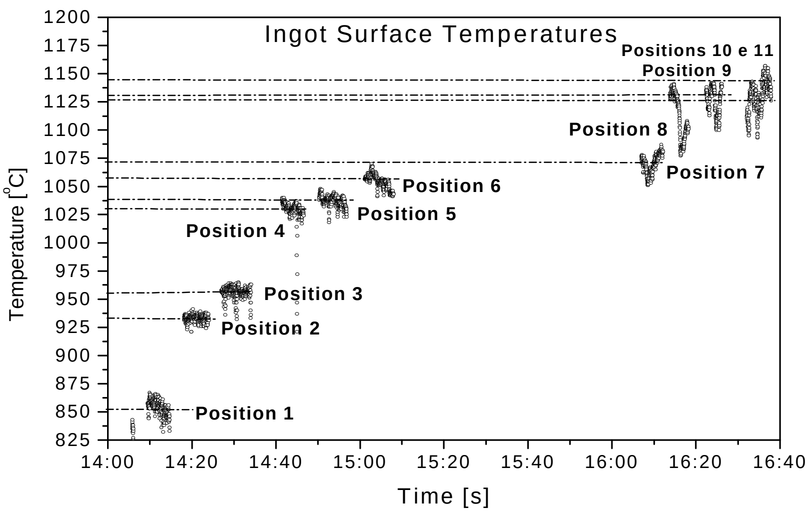

Figure 3. Example of the experimental ingot surface temperatures obtained during the continuous casting process.

SAE 1007

Table 2: Experimental surface temperature measured during casting (1007 steel).

Positions		Measured temperatures (average °C)		
11		1272		
10		1231		
9		1290		
8		1251		
7		1181		
5		1134		
4		1060		
$T_{tundish}$ (°C)	$T_{pouring}$ (°C)	$T_{Liquidus}$ (°C)	$T_{Solidus}$ (°C)	V_{Lingot} (m/min)
1558	1538	1514	1449	2.04

Figure 4 shows a comparison between experimental and simulated data for the 1007 steel billet.

average values of the measured values taken during 5 minutes.

The simulation was based on metal/mold heat transfer coefficients proposed by Toledo [16] and the metal/sprays heat transfer coefficients were determined by the present approach. A good agreement can be observed with differences between experimental and simulated values being lower than 40°C. Table 3 shows the experimental surface temperatures and those calculated by the mathematical solidification heat transfer model utilizing the heat transfer coefficients for each zone, respectively.

The main metallurgical parameters calculated by the mathematical model were (SAE 1007 billet): solid shell thickness at the mold exit: 13 mm; ingot surface temperature: 1181 °C; ingot surface temperature at flame cut-off point: 1070

°C; point of complete solidification: 17.13 m from the meniscus.

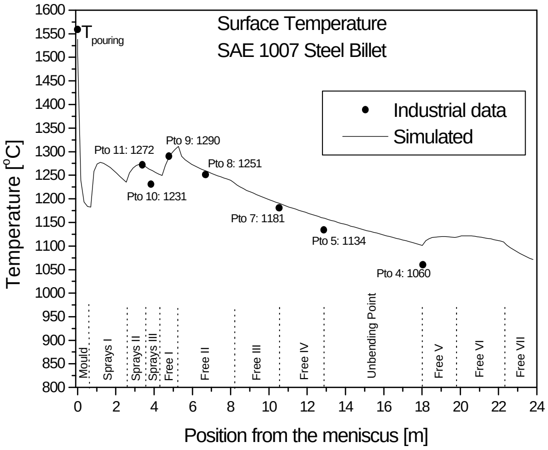

Figure 4. Comparison between calculated and experimental surface temperatures during casting of 1007 steel.

Table 3. Correlation between water flow rates and metal/sprays heat transfer coefficients and measured and calculated surface temperatures (1007 steel).

Regions	Heat transfer coefficients (W/m^2.K)	Experimental temperatures [°C]	Calculated temperatures [°C]
Sprays I	450	-	-
Sprays IIa	270	End 1272	1275
Sprays IIb	315	Middle 1231	1258
Free I	125	Middle 1290	1296
Free II	185	Middle 1251	1259
Free III	285	End 1181	1190
Free IV	285	End 1134	1159
Unbending	285	End 1060	1085
Free V	200	-	-
Free VI	175	-	-
Free VII	215	-	-

SAE 1025

Table 4: Experimental surface temperature measured during casting (1025 steel).

Positions	Measured temperatures (average °C)
4	1039
5	1039
7	1061
8	1152
9	1167
10	1181
11	1212

$T_{tundish}$	$T_{pouring}$	$T_{Liquidus}$	$T_{Solidus}$	V_{Lingot}
(°C)	(°C)	(°C)	(°C)	(m/min)
1545	1525	1504	1468	0.71

The main metallurgical parameters calculated by the mathematical model were (SAE 1025 billet): solid shell thickness at the mold exit: 25 mm; ingot surface temperature: 1038 °C; ingot surface temperature at flame cut-off point: 845 °C; point of complete solidification: 17.34 m from the meniscus. Table 4 shows the experimental surface temperatures and Figure 5 shows the comparison between experimental and calculated values.

The correlation between water flow rate and metal/sprays heat transfer coefficients, as well as calculated and measured temperatures during continuous casting of the 1025 steel billet can be seen in Table 5.

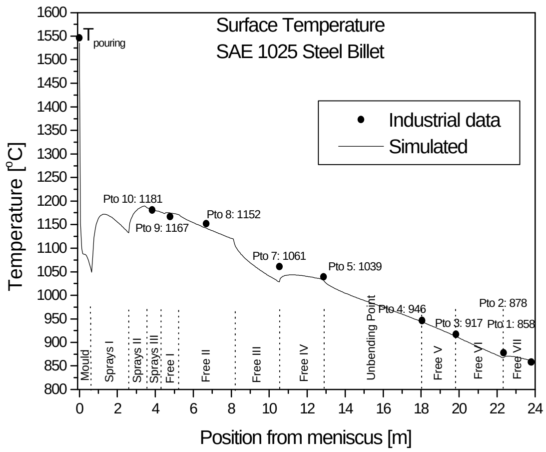

Figure 5. Comparison between calculated and experimental surface temperatures during casting of 1025 steel.

Table 5. Correlation between water flow rates and metal/sprays heat transfer coefficients and measured and calculated surface temperatures (1025 steel).

Locations	Heat transfer coefficients (W/m^2.K)	Experimental temperatures [°C]	Calculated temperatures [°C]
Sprays I	270	-	-
Sprays IIa	150	-	1185
Sprays IIb	166	Middle 1181	1175
Free I	155	Middle 1167	1169
Free II	166	Middle 1152	1138
Free III	200	End 1061	1041
Free IV	185	End 1039	1033
Unbending	190	End 946	943
Free V	190	End 917	915
Free VI	195	End 878	870

Free VII	166	End	858	849

In both cases, a gradient method has been used to find the heat transfer coefficients corresponding to an increment of about 5 $W/m^2.K$ and the criteria for convergence equal to a maximum difference between experimental and calculated ingot surface temperature values about 25°C. It can be observed in Figure 5, that the ingot thermal profile for the SAE 1025 billet presents surface temperatures lower than those observed for the SAE 1007 billet.

CONCLUSIONS

From the experimental and theoretical results on continuous casting of different steel grades, the following conclusions can be drawn:

- for both the SAE 1007 and the SAE 1025 billets, a rapid drop in interfacial heat transfer coefficient occurs along the continuous casting machine;
- the metal/cooling (h) or the overall heat transfer coefficient (h_g) can be expressed as a function of position, and depend on alloy composition, casting parameters and superheat. It is important to evidence that these results are valid only to specific casting conditions;
- the heat transfer coefficient in the sprays zones increases with decreasing casting dimensions;
- the use of an optical infrared mobile pyrometer has demonstrated to be efficient to measure ingot surface temperatures along the caster This method can be applied to various casting operations permitting to develop correlations between metal/cooling heat transfer coefficients and operational parameters.

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