RESEARCHES ON THE MASS AND HEAT TRANSFER IN THE CONTINUOUSLY CASTED SEMI-PRODUCTS

Vasile Bratu

University Valahia of Targoviste, Bd. Carol I, Nr. 2, 130024, Targoviste, Romania

Email: v_bratu22@yahoo.com

Abstract. *Mass and heat transfer in the continuous cast are the key concepts of the processes in progress at the cooling of the partially solidified yarn. Thus, here are reported issues related to mass and heat transfer at the solidification of the continuously casted product..*

1. INTRODUCTION

Controlling the solidification process requires a good knowledge of the thermal state of the continuously casted semi-product.

Thermal phenomenon which causes the solidification process relies on the laws of heat transfer on the liquid metal - metal solidified - crystallizer wall - water cooling direction. [2].

The crust of the solidified metal is initially in contact with the wall of the crystallizer, and then it comes off, leaving a thin air separator, as stated in figure 1.

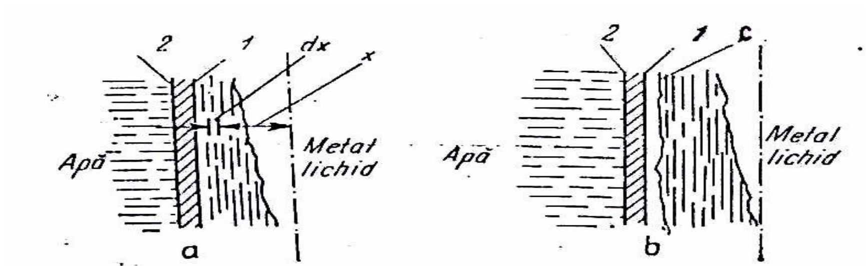

Fig. 1. The solidifying process in the crystallizer: a – contact area; b – separation area

The oscillation of the crystallizer by its stroke and frequency ensures the separation of the crust from the crystallizer wall [3] and the lubricant ensures the continuous formation of the crust. Crystallizer lubrication ensures crust detachment in the rhythm of its oscillations.

2. THE THERMAL TRANSFER IN CONTINUOUS CASTING OF THE ALLOYS

The heat transmission takes place through the crystallizer wall conductibility and through the forced convection between the crystallizer and the cooling water. In the separation area the heat transmission is added simultaneously by radiation, conductibility and convection in the air interstice.

The inner thermal state of the continuously cast semi-product while solidifying s characterized by the heat transfer through convection [4], between the solidified line and the liquid metal associated with the solidification latent heat release and the heat transfer by conduction in the solidified. The equation of the heat conduction in the contact area will be:

$$\lambda\frac{\partial T}{\partial x} = \frac{\lambda_c}{\delta_c}(T_1 - T_2) = h_{ca}(T_2 - T_a) \quad (1.1)$$

where: λ is the thermal conductibility of the solidified metal;

T – the temperature of the solidified metal;

T_a- the temperature of the cooling water;

λ_c - the thermal conductibility of the crystallizer wall;

δ_c – the thickness of the crystallizer wall;

h_{ca} –crystallizer-water convection coefficient.

For the separation area, the equation is supplemented by:

$$\lambda \frac{\partial T}{\partial x} = \varepsilon\sigma(T_c^{\ 4} - T_1^{\ 4}) + h(T_c - T_1) \quad (1.2)$$

where: ε is the emissivity ratio in the gap;

σ - Stephan- Boltzmann constant;

T_c – the temperature at the surface of the metallic crust;

h – global ratio of conductibility and convection in the interstice;

The equation of heat exchange by conduction in the solidified metal is:

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T_x}{\partial x^2} + \frac{\partial^2 T_y}{\partial y^2}\right) + q \quad (1.3)$$

where: $a = \frac{\lambda_s}{\rho_s C_s}$ is the thermal diffusivity of the solidified metal;

C_s – specific heat of the solidified metal;

λ_s – thermal conductivity;

ρ_s – metal density;

x, y – point coordinates;

q – source of inner heat.

The equation of heat exchange by convection and radiation in the secondary cooling area is:

$$-\lambda\left(\frac{\partial T}{\partial x}\right) = h\left(T_{yarn} - T_{aa}\right) + \varepsilon\sigma\left(T_{yarn}^4 - T_{aa}^4\right) \quad (1.4)$$

where: T_{yarn} is the temperature at the surface of the semi-product;

T_{aa} –the water temperature or the temperature of the air and water mix;

h – convection heat exchange ratio;

σ - Boltzmann constant.

ε - emissivity ratio.

λ - thermal conductivity.

The source of inner heat [4] may be defined as:

$$q = \begin{cases} 0 \text{ For } T > T_{lichidus} \\ \rho \cdot \Delta H \cdot \frac{df_s}{dT} \cdot \frac{\partial T}{\partial \tau} \text{ For } T_{solidus} \le T \le T_{lichidus} \\ 0 \text{ For } T < T_{solidus} \end{cases} \quad (1.5)$$

where:

ΔH is the solidification latent heat;

f_s – solid fraction;

$T_{solidus}$ - solidus temperature of the steel;

$T_{lichidus}$- liquidus temperature of the steel.

Solid fraction may be found through the relation:

$$f_s = \frac{T_{lichidus} - T + \frac{2}{\pi}\cdot\left(T_{solidus} - T_{lichidus}\right)\cdot\left[1 - \cos\left(\frac{\pi}{2}\cdot\frac{T - T_{lichidus}}{T_{solidus} - T_{lichidus}}\right)\right]}{\left(T_{lichidus} - T_{solidus}\right)\cdot\left(1 - \frac{2}{\pi}\right)} \quad (1.6)$$

The heat exchange between the crystallizer and the steel could be simulated by analogy with a set of series connected heat. Thus, the heat resistors may be marked from interior to exterior:

- r_{OL} for the liquid steel;
- r_{OS} for the solid steel;
- r_L for the lubricant (oil or slag mix);
- r_{Cu} for the copper wall;
- r_{apa} for water;

The total heat resistor will have the following expression:

$$r_{crist} = r_{OL} + r_{OS} + r_L + r_{Cu} + r_{apa} \quad (1.7)$$

and the ratio of heat exchange in the crystallizer will be:

$$h_{crist} = \frac{1}{r_{crist}} = \frac{1}{\frac{1}{h_{OL}} + \frac{1}{h_{OS}} + \frac{1}{h_L} + \frac{1}{h_{apa}}} \quad (1.8)$$

where h_i stands for the heat exchange ratio in *i* area.

The heat exchange ratio due to forced convection because of the crystallizer water flowing is:

$$h_a = \left(\frac{\lambda_a^3}{D_a}\right)^{0,2} \left(\frac{V_a^2 \cdot C_{pa}}{\eta_a}\right)^{0,4} \qquad (1.9)$$

where:

D_a is the equivalent diameter of the flowing channel,

V_a – the water specific mass flow,

η_a –the water dynamic viscosity,

C_{pa}= the water specific heat ;

λ_a – water thermal conductivity;

The equivalent diameter of the flowing channel can be calculated through the relation:

$$D_a = \frac{4S}{P} \qquad (1.10)$$

where:

S is the cross section of the flowing channel;

P – watered area perimeter.

The convection heat exchange ratio at the liquid – solid interface is:

$$h = \frac{2}{3}\sqrt[6]{\frac{\upsilon_{OL}^2 C_{OL}^2 \rho_{OL}^3}{\eta_{OL} \lambda_{OL}^4 l^3}} \qquad (1.11)$$

where:

ρ_{OL} is the density of the liquid steel,

C_{OL} – the specific heat of the liquid steel,

v_{OL} – the liquid steel flow speed,

η_{OL} – the dynamic viscosity of the liquid steel,

λ_{OL} – thermal conductibility of the liquid steel,

l – the crystallizer length.

The thickness of the slag film between the crystallizer and semi-product can be approximated by the relation:

$$\delta_{zg} = \sqrt{\frac{\eta_{zg} \cdot v_t}{g \cdot (\rho_{OL} - \rho_{zg})}} \qquad (1.12)$$

where:

η_{zg} is the dynamic viscosity of the slag;

v_t – the casting speed;

g – the gravitation acceleration,

ρ_{zg} = the slag density.

The heat exchange ratio in the secondary cooling area for watering is calculated with the relation:

$$h_{strop.apa} = 7{,}1 \cdot 10^5 \cdot \nu_{strop}^{0,75} \cdot T_{Leid}^{-1,2} + 116 \qquad (1.13)$$

where:

ν_{strop} is the specific average flow of water splashing;

$T_{Leid} = f(\nu_{strop})$ - Leidenfrost temperature point.

For air-water mix watering, the convective component of the air flow will be taken into consideration.

Since the thermo-dynamic and thermo-physical quantities as: densities, viscosities, thermal conductivity and specific heats depend on the temperature, their calculation will be made using the relations:

$$\rho_{(T)} = 7840 \frac{1}{1 + \alpha(T) \cdot (T - T_0)} \qquad (1.14)$$

where:

$$\alpha_{(T)} 10^6 = 10{,}7 + 0{,}6\left(\frac{T - 273{,}16}{100}\right) - \frac{2{,}9}{ch\left[0{,}76\left(\frac{T - T_0}{100}\right)^2\right]} \qquad (1.15)$$

$T_0 = 1178{,}16K$

For $T < 1041K$, $C_p(T)$ will be calculated by the relation:

$$C_p(T) = 1000\left[0{,}4814 + 0{,}1997\left(\frac{T - 273{,}16}{100}\right) + 0{,}812 \cdot e^{-0,0099(1041 - T)}\right] \qquad (1.16)$$

For $T > 1041K$, $C_p(T)$ will be calculated by the relation:

$$C_p(T) = 1000\left[0{,}4814 + 0{,}1997\left(\frac{T - 273{,}16}{100}\right) + 0{,}812 \qquad (1.17)$$

For $T \le 1173K$, $\lambda(T)$ will be calculated by the relation:

$$\lambda(T) = 26{,}74 + \frac{(\lambda_0 - 26{,}74)(1173{,}16 - T)}{1173} \quad (1.18)$$

where:

$$\lambda_0 = 74{,}42 - 16{,}28[\%C] - 34{,}88[\%Si] - 23{,}36[\%Mn], \quad (1.19)$$

For $T > 1173K$, $\lambda(T)$ will be calculated by the relation:

$$\lambda(T) = 0{,}01164 \cdot T + 13{,}08628 \quad (1.20)$$

3. MASS TRANSFER IN CONTNUOUS CASTING OF THE ALLOYS

In continuous casting, the mass transfer depends on the convection and the steel diffusion in the yarn. The movement in the crystallizer is strongly turbulent, the diffusion is significantly accelerated by swirl.

The transitory tridimensional equation will be:

$$\frac{\partial(\rho C)}{\partial t} + u\frac{\partial(\rho C)}{\partial x} + v\frac{\partial(\rho C)}{\partial y} + w\frac{\partial(\rho C)}{\partial z} = \frac{\partial}{\partial x}\left(D_c \frac{\partial C}{\partial x}\right) + \left(D_c \frac{\partial C}{\partial y}\right) + \left(D_c \frac{\partial C}{\partial z}\right) \quad (1.21)$$

where C is the composition or the relative concentration defined by:

$$C = \frac{C(x,y,z,t) - C_{old}}{C_{new} - C_{old}} \quad (1.22)$$

where $C(x,y,z,t)$ is a fraction of a given element in the specified position in the yarn or slab;

F_{old}, F_{new} – are the concentrations from the respective element.

Effective diffusivity is given by two components, molecular and turbulent:

$$D_c = \frac{\mu_L}{Pr} + \frac{\mu_t}{Sc} \quad (1.23)$$

where: Pr is Prandtl criterion ;

Sc –Schmidt criterion for ;

μ_L, μ_t - viscosities during rolling and turbulence, respectively.

The change of the chemical composition at the liquid-solid interface leads to the change of the solidification conditions, thus we can have the following two situations: [5]: For a slow cooling (with a local solidification time of more than 900 s) we have the equation:

$$\frac{C_L}{C_0} = p^{\frac{k-1}{1-\gamma k}} - \frac{k^2 \cdot (k-1) \cdot \gamma^3}{4\alpha \cdot (1-\gamma \cdot k)^3} \cdot p^{\frac{k-1}{1-\gamma \cdot k}} \cdot Q \quad (1.24)$$

And for a fast cooling we have the equation:

$$\frac{C_L}{C_0} = (1 - \Gamma \cdot f_s)^{\frac{k-1}{\Gamma}} \quad (1.25)$$

where:

$$p = 1-(1-\gamma k) f_s \quad (1.26)$$

$$\gamma = \frac{2\alpha}{1+2\alpha} \quad (1.27)$$

$$Q = \left[1 - \frac{k \cdot (1+\gamma)}{2}\right] \cdot \left(\frac{1}{p^2} - 1\right) - 5\left[1 - \frac{k \cdot (2+3\gamma)}{5}\right] \cdot \left(\frac{1}{p} - 1\right) - 3\left[1 - \frac{k \cdot (1+3\gamma)}{3}\right] \cdot \ln(p) \quad (1.28)$$

$$\Gamma = 1 - \frac{\beta \cdot k}{1+\beta} \quad (1.29)$$

$\beta = 4\alpha$ s the modified solid diffusion ratio;

$\alpha = \frac{4 \cdot D_s \cdot t_f}{\lambda_1^2}$ is the solid diffusion ratio, Brody – Fleming;

$\chi_1 = 2L$ is the distance between the main arms of the dendrites;

$L = \frac{\delta}{\sqrt{f_s}}$ is the semi-space, at the dendrite columnar model;

$t_f = \sqrt{\dfrac{\sqrt{\dfrac{k_{OS}}{\rho_{OS} \cdot c_{pOS}}}}{d}}$ is the local solidification time ;

(1.30)

d – the distance from the cooled surface;

$\delta = \left(\dfrac{D_l}{\nu_{OL}}\right)^{1/3} \cdot \delta_{termic}$ s the thickness of the chemical limit layer, defined as a function of the thermal limit layer thickness, δ_{termic}, which depends on the molten steel flowing conditions;

$D_{s,l}$ – chemical diffusivity ration n the solid and the liquid;

ν_{OL} - kinematic viscosity ratio of the liquid steel,

k – distribution ratio in equilibrium at solid – liquid interface.

4. CONCLUSIONS

Both heat and mass transfer have serious implications on the quality of the continuously casted semi-products, being in the same time the key of the processes in progress during the cooling of the partially solidified yarn.

The control of the solidification processes needs a strict control of the thermal regime of the continuously casted semi-product. In this way, most mathematical models aim to obtain solutions for the temperature distribution in the solidifying semi-product and not only to obtain values of technological parameters.

REFERENCES

1. BRATU, V. Metode experimentale si procedee privind îmbunătăţirea calităţii semifabricatelor trurnate continuu, Ed. Ştiinţifică F.R.M.Bucureşti, 2003

2. GAUTIER, J. ş.a. Mathematical Study of the Continuous Casting of Steel. Journal of the Iron and Steel Institute, nr. 12, 1970;

3. KIEFER, B. V. Cerinţe metalurgice şi de procesare pentru turnarea continuă a ţaglelor din oţel special în bare şi sârmă. Metallurgy and New Materials researches, nr. 1-2, 1994;

4. BRATU V., DRAGOMIR, I. Fenomenul convectiv şi implicaţiile acestuia asupra solidificării aliajelor turnate continuu, Metalurgia, nr. 11, 2001;

5. ILIE, S. Cercetări privind procesele fizico-chimice de la turnarea continuă a oţelurilor, Teză de doctorat, Universitatea "Politehnica" Bucureşti, 2000;

6.IVANESCU, A., ALBU, I. Model matematic al distribuţiei temperaturilor la produsele calde obţinute prin turnare continuă, Metalurgia, nr. 9, 1983;

7. CANANAU, N., IVANESCU, A.BRATU, V. Causes and methods of superficial cracks forestall to continuous casted slabs from superior building steels, Metalurgia Internaţional, no. 2, 2003;