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Temperature Drop of Molten Metals in Open Channels

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Abstract

The temperature drop of molten metal flowing in open channels is numerically determined. Rectangular, trapezoidal and triangular geometries are considered. The overall heat transfer coefficients for the bottom, side walls and free surface of the channel have been taken from the literature. For each geometry, the volumetric flow rate, mean residence time and temperature drop as a function of the channel inclination angle were determined. The rectangular and trapezoidal geometries present the smallest temperature drops, while the triangular geometry presents the greatest temperature drop. The factors that most affect this drop are the value of the free surface area of the channel, and the average residence time of the molten metal in the channel.

Keywords

Free Surface, Heat Transfer, Molten Metal, Open Channel Geometry, Residence Time, Temperature Drop

1. Introduction

For a long time, the vast majority of studies on open channels have focused on the design and analysis of channels, whether natural such as streams and rivers, or constructed by humans, for the transportation of irrigation water, the evacuation of sewage and industrial waste [1]. In metallurgical industries, the transportation of molten metals and slags through open channels is an economical way to carry these materials from one place to another in the plant. For example, in the steel industry, pig iron is transported from the crucible of the blast furnace to the torpedo ladles through a kind of open channels commonly named as runners or troughs [2]. In the aluminum industry, molten aluminum is carried from the melting furnace to the degassing unit also through an open channel. Unfortunately, during transport of molten metals through open channels the metal is subject to reoxidation by atmospheric oxygen and sufffers heat losses from the free surface, side walls and bottom of the channel. Sometimes the channel is covered with a lid to minimize reoxidation and heat loss [3].

The literature on the isothermal flow of molten metals in open channels is very scarce [4]-[8]. Even more scarce is the literature on heat transfer in molten metals flowing in open channels [9]-[11]. In these last articles, the transient analysis of heat transfer in open channels for pig iron transport is carried out through Computational Fluid Dynamics simulations and finite element software. In this work the heat losses suffered by a molten metal flowing in an uniform way through an open channel are studied. Three open channel geometries are considered, namely rectangular, trapezoidal and triangular. These three geometries are the most used in the industry for water and molten metal transportation [12]. The intensity of heat losses by conduction, convection and radiation for each surface of the channel are taken from the literature [13], and computed in accordance to the residence time of the molten metal in the channel. The temperature drop is calculated for each geometry considering two cases: first, that the metal height in the channel remains constant, and second, that the volumetric flow rate of molten metal remains constant.

2. Open Channel Flow

The dimensions of a generic open channel are shown in **Figure 1**. L is the lengh of the channel, H is the height of the molten metal, b is the channel widht, α is the inclination angle of the channel, and β is the inclination angle of the side walls. For a rectangular channel $\beta = 90$ degrees, and for a triangular channel $b = 0$.

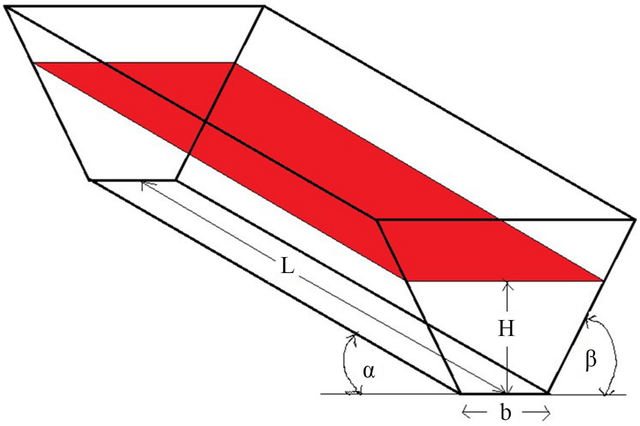

Figure 1. Open channel dimensions.

A balance of forces in the open channel yields the following expresión for the volumetric flow rate Q of molten metal under an uniform flow [4]:

$$Q = A_f D_h^{2/3} e_r^{-1/6} \left(g \sin \alpha \right)^{1/2} \quad (1)$$

where A_f is the transversal flow area, D_h is the hydraulic diameter, e_r is the roughness of the walls, g is the gravity acceleration, and α is the channel inclination angle. Flow area, wetted perimeter, hydraulic diameter and molten metal volume for each channel geometry can be determined from the expressions shown in **Table 1** [12].

Table 1. Open channel properties [12].

Shape	Flow Area, A_f	Wetted Perimeter, P_w	Hydraulic Diameter, D_h	Molten Metal Volume, V
Rectangular	bH	$b+2H$	$\frac{4bH}{b+2H}$	LbH
Trapezoidal	$H\left(b+\frac{H}{\tan\beta}\right)$	$b+\frac{2H}{\sin\beta}$	$\frac{4H\left(b+H/\tan\beta\right)}{b+2H/\sin\beta}$	$LH\left(b+\frac{H}{\tan\beta}\right)$
Triangular	$\frac{H^2}{\tan\beta}$	$\frac{2H}{\sin\beta}$	$2H\cos\beta$	$\frac{LH^2}{\tan\beta}$

To determine the parameters of the three geometries considered, the dimensions of the rectangular open channel reported in [4] were used, namely: L = 20 m, b = 0.2 m, H = 0.15 m, α = 5 degrees, e_r = 0.0005 m. Besides, it was assumed that β = 60 degrees for the trapezoidal and the triangular geometries. **Table 2** shows the calculated parameters of the open channels for the three geometries considered.

Table 2. Parameters of the considered open channels. For the triangular channel b = 0.0 m, and for the rectangular one β = 90 degrees.

Parameter	Rectangular	Trapezoidal	Triangular
Wall area (A_w), m^2	3.0	3.4641	3.4641
Bottom area (A_b), m^2	4.0	4.0	0.0
Surface area (A_s), m^2	4.0	7.4641	3.4641
Flow area (A_f), m^2	0.030	0.043	0.013
Wetted perimeter (P_w), m	0.50	0.5464	0.3464
Hydraulic diameter (D_h), m	0.240	0.3147	0.150
Metal volume (V), m^3	0.60	0.8598	0.2598

3. Heat Transfer

The molten metals that are transported in open channels experience heat losses through the bottom, side walls and free surface. On the free surface there are the greatest heat losses, which occur by convection and radiation, mainly. In the bottom and side walls, heat losses occur by conduction and convection. A theoretical analysis of heat transfer in the channel involves detailed knowledge of the thermal properties of the side walls and the bottom, as well as the physical and thermal properties of the molten metal transported. Good results can be obtained if average plant values for similar systems reported in the literature are used. In [13] heat losses are reported in W/m^2 for a continuous casting tundish in which molten steel flows from the discharge of the submerged entry nozzle to the nozzles that feed the steel to the molds. The thermal and flow conditions are analogous to those of the molten steel flow in an open channel. Numerical values for heat losses (W/m^2) reported in [13], and that are used in this work for an open channel that transports molten steel, are shown in **Figure 2**.

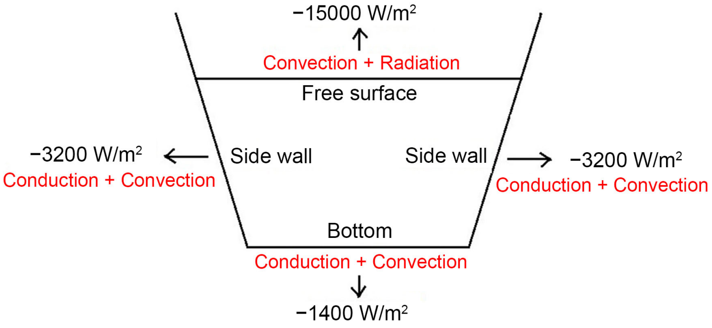

Figure 2. Heat losses in an open channel.

Total heat losses per unit of time is the sum of the losses through each surface:

$$\dot{q} = W_b A_b + 2W_w A_w + W_s A_s \tag{2}$$

and the total heat lost q suffered by the molten metal is given by

$$q = \dot{q}\theta_r \tag{3}$$

where

$$\theta_r = \frac{V}{Q} \tag{4}$$

is the mean residence time of the molten metal in the open channel. The average temperature drop can be determined using the expression

$$\Delta T = -\frac{q}{mC_p} \tag{5}$$

where the $m = V\rho$ is the mass of molten metal, ρ is the density and C_p is the specific heat.

Algebraic calculations of temperature drops were carried out considering that the molten metal height H in the channel remains constant at 0.15 m. A molten metal similar to iron was considered, with $\rho = 7100$ kg/m^3 and $C_p = 750$ J/(kg·K). Besides, $L = 20$ m and $\beta = 60$ degrees remains constant too. For the triangular channel $b = 0.0$ m, and for the rectangular one $\beta = 90$ degrees. During the calculations, the angle of inclination of the channel varied from 1 to 10 degrees from one degree to one degree, namely $\alpha = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10$. **Figure 3** shows the volumetric flow rate as a function of the channel inclination angle for each channel geometry. Two things are observed: that the volumetric flow increases by increasing the angle of inclination of the channel, and that for $H = 0.15$ the trapezoidal geometry has a greater volumetric flow than the other two. Besides, the triangular geometry presents the lower volumetric flow rate.

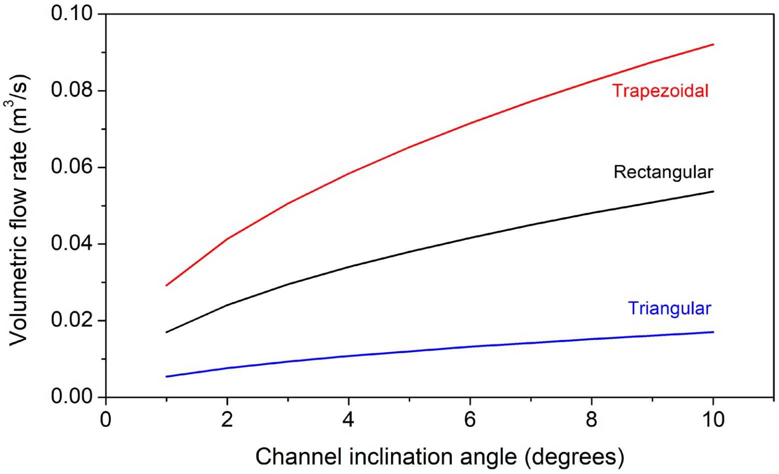

Figure 3. Volumetric flow rate of the molten metal as a function of the channel inclination angle.

Figure 4 depicts the evolution of the mean residence time of the molten metal in the channel as a function of the channel inclination angle. The mean residence time decreases non-linearly as the channel inclination angle increases. According to **Figure 4**, the triangular geometry is the one that presents the greatest residence times. The average residence time is an important factor that influences heat loss and temperature drop since it determines the time in which molten metal remanins in contact with the channel surfaces. It is expected that as the residence time of the molten metal is increased, the heat losses and the metal temperature drop will be increased. The above can be corroborated in **Figure 5**, where it is observed that the triangular geometry is the one with the highest temperature drops, while the rectangular and trapezoidal geometries have lower but similar temperature drops.

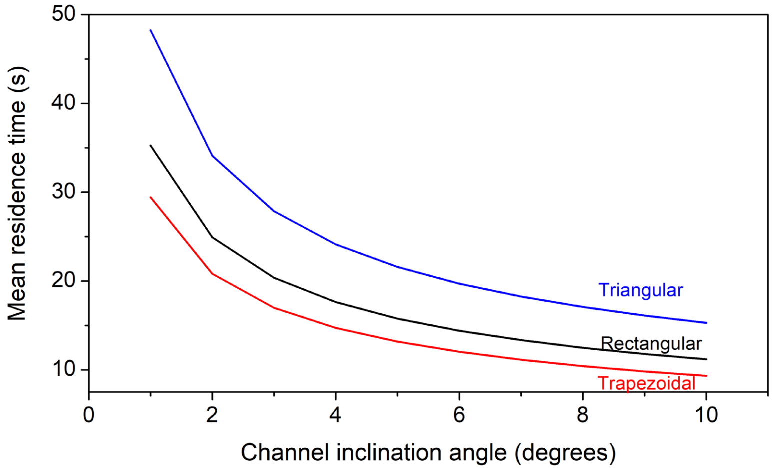

Figure 4. Mean residence time of the molten metal as a function of the channel inclination angle.

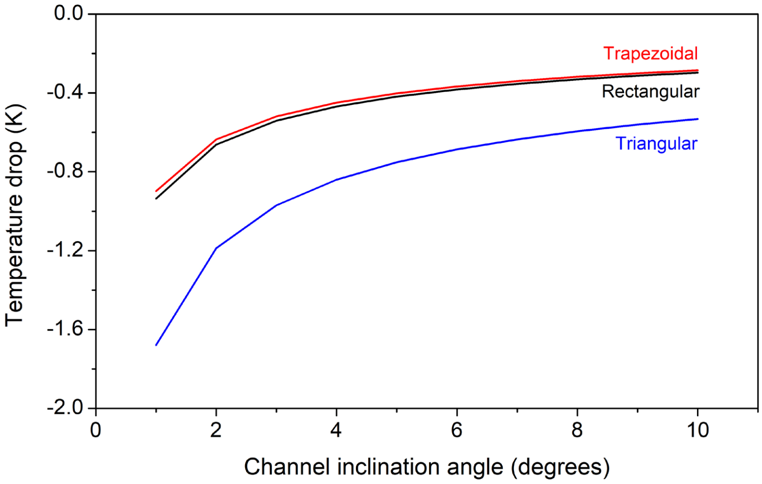

Figure 5. Temperatura drop of the molten metal as a function of the channel inclination angle.

Algebraic calculations were carried out maintaining constant the volumetric flow rate of the molten metal in the open channels. According to [4], for $L = 20$ m, $b = 0.2$ m, $H = 0.15$ m, $\alpha = 5$ degrees, and $\beta = 90$ degrees, the rectangular channel has a volumetric flow rate $Q = 0.038$ m^3/s. This value of Q was used for the three geometries, but in order to keep it constant, the metal heights were recalculated in the trapezoidal and triangular channels. If H is changed, all other parameters of the channels (flow area, wet perimeter, hydraulic diameter, areas of the free surface, the walls and the bottom, etc.) are changed too, as is shown in **Table 3**. Again, in this case in which Q remains constant, the triangular channel presented the highest temperature drop. However, unlike the case with constant H, for Q constant the rectangular channel presented the lowest temperature drop. This may be due to the fact that the rectangular channel presents the lowest free surface area, as indicated by **Table 3**, since the free surface is the one with the highest heat losses.

Table 3. Channel parameters when the volumetric flow rate is kept constant at 0.038 m^3/s.

Parameter	Rectangular	Trapezoidal	Triangular
Metal height (H), m	0.15	0.11	0.30
Wall area (A_w), m^2	3.0	2.5403	6.928
Bottom area (A_b), m^2	4.0	4.0	0.0
Surface area (A_s), m^2	4.0	6.54	6.928
Flow area (A_f), m^2	0.03	0.029	0.052
Wetted perimeter (P_w), m	0.50	0.454	0.6928
Hydraulic diameter (D_h), m	0.24	0.256	0.30
Metal volume (V), m^3	0.60	0.5797	1.0392
Metal mass (m), kg	4 260.0	4 116.0	7 378.5
Temperatura drop (ΔT), K	−0.4188	−0.5928	−0.7327

4. Conclusions

The temperature drop of molten metals flowing in open channels has been studied here. Heat transfer data previously published in the literature have been used for the bottom, side walls and free surface of the channel. Three geometries have been considered, namely rectangular, trapezoidal and triangular. Temperature drop is calculated for each geometry considering two cases: first, that the metal height in the channel remains constant, and second, that the volumetric flow rate of the molten metal remains constant. From the algebraic calculations, the following conclusions arise:

1) The channel geometry notably affects the volumetric flow of the molten metal and its mean residence time. The triangular geometry has the longest mean residence time whether the metal height or volumetric flow rate is kept constant.

2) The greatest temperature drop is related to the value of the free surface area and the mean residence time, which depends on the type of geometry of the channel considered.

3) When the molten metal height remains constant, the free surface area of the triangular channel is smaller than that of the rectangular channel and the trapezoidal channel, however, its temperature drop is greater due to its longer residence time.

4) The triangular geometry presents the greatest temperature drop for the two cases considered: when the height of the molten metal is constant, or when the volumetric flow rate of the molten metal is kept constant too.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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