The Cooling of a Granular Material in a Rotating Horizontal Cylinder

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Abstract In this chapter we investigate the cooling of the lateritic ore moving inside a rotating horizontal cylinder. The mineral, which has been previously milled, forms a granular bed. Due to rotation, the granular material undergoes discrete avalanching, whose characteristics depends either upon the angular velocity and the filling degree. The ore enters into the cooler at a temperature of approximately 750 °C and after moving along the cylinder its temperature decreases. The goal is to reduce the ore temperature to a value around 170 °C, so its metallic properties are preserved. To model this process a system of two differential equations and an algebraic equation depending only on the axial coordinate is solved. Otherwise we present data of the cooling in a cylinder 30 m long, a diameter $d = 3$ m and rotating with an angular velocity of 6.24 rpm. We show that numerical solution exhibits a partial agreement with experimental data.

1 Introduction

During the production of nickel, the ore is extracted from open-pit mines. After extraction the ore is milled to convert it in a granular media (the mean diameter of grains is 0.074 mm). In the next step the lateritic ore enters in a reduction oven where its temperature rises. After, the ore passes through the cooler before its metallurgical treatment. The cooler is a system consisting of a hollow steel cylinder and a basin

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filled with water (hereafter referred as the pool). The cylinder is 30 m long, has a diameter of 3 m and the shell thickness is 16 mm. In standard operating conditions the cylinder rotates at an angular velocity of 6.24 rpm, whereas the filling degree lies in the range 15–25 %. The ore enters into the horizontal cylinder through a conical cover, and then it is continually stirred and shifted from the entrance toward the exit, with the aid of internal scrapers. The mean speed of the granular media is in the range 0.01–0.017 m/s, so the residence time lies between 30 and 50 min. An additional feature of the scrapers is to avoid the ore to adhere to the solid walls, a fact that hinders the heat transfer to the wall. Concerning the pool, the water is continuously renewed with a flow rate varying from 15 to 100 m^3/h. The liquid moves in the opposite direction to the displacement of the granular material. It enters at ambient temperature at the end of the cooler and at the far side the water has attained a temperature lying in the range 60–85 °C. Besides from enhancing heat transfer, the water has also the role to make floating the cylinder, reducing the amount of energy to maintain it in rotation (Góngora-Leyva et al. 2012).

A frequent problem in the coolers is the inability to lower the ore temperature from 750 °C to a value around 170 °C, which is the design temperature (Valle-Matos et al. 2000a,b). The final temperature of the granular media depends on variables like the water flow rate, the ore mass flow and the angular velocity of the cylinder. The latter factor is closely related to avalanching because this phenomenon produces a mixing of material inside the cylinder.

Góngora-Leyva et al. (2007, 2009) deduced a model based on the energy balance for a volume element, from which a system of partial differential equations is derived. The system is supplemented with other equations that relate the heat transfer coefficients with some physical parameters. Following the way of some previous works, we assume that only the axial coordinate is relevant, then the system is transformed into one of ordinary differential equations. This is the case of the works by Wang et al. (2010) and Xiaodong et al. (2012) where the cooling process of ash is investigated. Their simplified model predicts and explains some important features of the system they studied.

The chapter is organized as follow: in Sect. 2 some details of the system under study are given, in particular, the features of granular and liquid flows. In Sect. 3 the system of equation for heat transfer is outlined. In Sect. 4 some data obtained for a cooler 30 m long are present and a comparison with numerical solution is made. Finally, the conclusions are drawn in Sect. 5.

2 Description of the Cooling System

The Fig. 1 shows the cross section of the system under study, formed by the reduced lateritic ore (1), the rotating horizontal cylinder (2), the pool (3) and the surrounding air (4). The ore is discharged into the cooler at a temperature of 750 °C. For this temperature the modes of heat transfer involved in the ore cooling are conduction, convection and radiation.

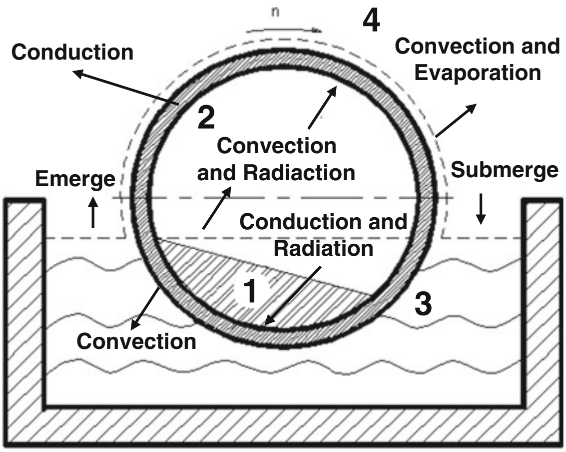

Fig. 1 Cross section of the cooler. The reduced ore (*1*) partially fills the rotating cylinder (*2*). Under standard operating conditions the filling degree is the range from 15 to 25 % and the angular velocity is 6.24 rpm. Otherwise, the cylinder is partially submerged in a pool (*3*) and it is contact with the surrounding air

In the system under study two flows exist. The first one is the motion of the granular bed, which is a mixing of a translation in the axial direction and a succession of avalanches induced by the rotation. The avalanching is characterized by a critical angle (θ_c) and a stop angle (θ_s), which determines the position of the granular bed inside the cylinder. According to a work Liu et al. (2010) in a system with low rotation and with irregular grains (they used rice grains), the value of θ_s is dependent on the filling degree, while the critical angle is nearly constant. Due to the difficulties to make measurement in the plant, the evolution of the granular bed has been investigated in a small rotating cylinder, its diameter being 30 cm and in which the front and back ends are covered by Plexiglas plates. Two different amounts of reduced ore were put inside the channel, which correspond to filling degrees of 10 and 20 %. Evolution of surface of the bed has been recorded with a video camera. The images have been digitized and the angle of the surface of the granular bed is measured. The results show that $\theta_c \approx 45°$ for a filling degree of 10 %, while $\theta_c \approx 35°$ for a filling degree of 20 %. For both cases the stop angle θ_s is less than 10°.

The second flow is the motion of the water from B to A (see Fig. 2). The liquid is injected into the pool at ambient temperature in the region where the ore leaves the cooler. As the water moves the temperature increases attaining a value between 60 and 85 °C at point A. Finally the water leaves the basin. The water motion is a forced convection used to flush thermal energy outside the system.

3 A Model for the Cooling Process

In order to construct a model for describing the ore cooling we start from the heat equation:

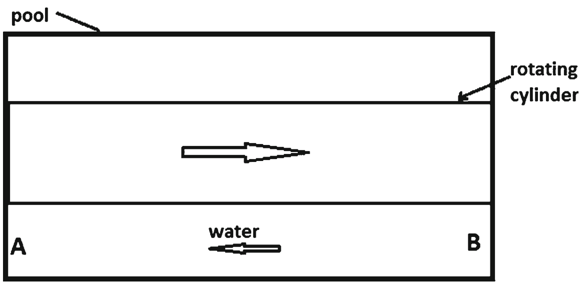

Fig. 2 *Upper view* of the cooling system. The lateritic ore moves from *left* to the *right*, whereas the water in the basin flows in the opposite direction. For this cooling system the water flow rate lies in the range 15–100 m^3/h

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \chi \nabla^2 T + \dot{q} \tag{1}$$

where $\vec{u}$ is the velocity of the fluid (or granular media), T is the temperature and $\dot{q}$ stands for heat sources and sinks.

To derive the model some assumptions must be made. First, we assume that the process is stationary, so the time derivative vanishes. This assumption is well verified because most of time the operating conditions of the cooler remain unchanged. Second, we assume (Wang et al. 2010) that temperatures of the granular bed, the cylinder and the water have a weak dependence on the radial and angular coordinates. This implies that solution depends only on the axial coordinate. Measurement in plant show that this assumption is reasonably fulfilled in certain cases. Third, we assume that heat transfer between two adjacent control volumes along the axial direction is negligible and consequently the laplacian in Eq. 1 also vanishes. These assumptions lead to a system of two differential equations and an algebraic equation:

$$\dot{m}_o C_o \frac{dT}{dx} = \alpha_{wco} A_{wco} (T - T_w) + \alpha_{wnco} A_{wnco} (T - T_w) \tag{2}$$

$$\alpha_{wco} A_{wco} (T - T_w) + \alpha_{wnco} A_{wnco} (T - T_w) = \alpha_l A_c \left(T_w - T_l\right) \tag{3}$$

$$\dot{m}_l C_l \frac{dT_l}{dx} = \alpha_{air} A_l (T_l - T_{air}) + \alpha_l A_c (T_w - T_l) + Q_{evp} \tag{4}$$

In Eqs. 2–4 subscripts *w, o, l* and *air* refer respectively to the solid wall (cylinder), the granular bed (ore), the liquid (water) and the air, T is the temperature, $\dot{m}$ is the mass flow (of the ore and the water), A_{wco} is the arc length where the ore and the cylinder cross section are in contact, A_{wnco} is the arc length of the cylinder cross section not in contact with the ore, A_c is arc length where water is in contact with cylinder cross section, α represents the coefficient of the heat transfer and Q_{evp} is the heat transferred by evaporation. The variable without subscript T is the ore temperature.

Table 1 Temperature of the ore at x = 30 m (exit of the cooler)

	$\dot{m}_o = 20$ experiment	$\dot{m}_o = 20$ model	$\dot{m}_o = 34$ experiment	$\dot{m}_o = 34$ model
$\dot{m}_l = 50$	144 °C	149 °C	214 °C	250 °C
$\dot{m}_l = 100$	132 °C	148 °C	188 °C	248 °C

The temperature is a decreasing function of the water flow rate and an increasing function of the ore mass flow. The agreement between numerical solution and measurements in plant is good only for the case $\dot{m}_o = 20$ and $\dot{m}_l = 50$

The coefficients of heat transfer were taken from a work of Góngora-Leyva (2013). As already stated in the introduction, convection, radiation and conduction are taken into account. The conduction is the dominant mode for heat transfer of the ore in contact with the cylinder, convection occurs in the gases that are in contact with the ore and radiation is present because the high temperature of the ore. The heat absorbed by the cylinder is transferred to the outer wall by conduction. For the heat transfer between the cylinder and the water we consider that the dominant mode is convection and that boiling doesn't exist. We assume that the cylinder is always covered with a thin layer of water in the region that is not inside the pool and that the liquid layer rotates at the same angular velocity as the cylinder. Then, the convection in water is the same as in a Couette flow (Incropera and Dewitt 1999). Finally, the heat transfer from the water to environment involves convection and evaporation of the water.

In order to obtain a solution of Eqs. 2–4 we need to impose two boundary conditions. The first one is the ore temperature at the entrance of the cooler (x = 0), which has been set to 750 °C. The second condition is the temperature of the water at x = 30, which is set to 30 °C.

The solution of the mathematical model (Eq. 2–4) was calculated with a fourth order Runge-Kutta method. The domain we use is 30 m long and the step is $\Delta x = 0.01$, then the solution is calculated in 3,000 points. The numerical code was implemented in the free software Scilab. The numerical data were calculated for values of ore mass flow and water flow rate respectively in the ranges 15–44 tons/h and 40–100 m^3/h.

4 Numerical Solution and Measurements in Plant

In Table 1 we present data (taken in plant) of the ore temperature at the exit of the cooler (x = 30) for two different values of ore mass flow (20 and 34 tons/h) and two values of water flow rate (50 and 100 m^3/h). We also include the results of the numerical solution. It must be stressed that final temperature is a decreasing function of the water flow rate and an increasing function of the ore mass flow. In fact, if water flow rate is kept constant we see that a change in the ore mass flow leads to important changes in the final ore temperature. The data of table I show that when

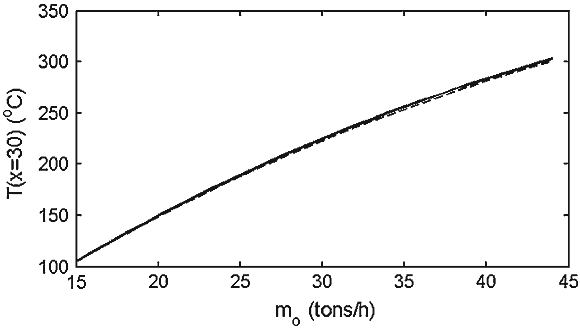

Fig. 3 Final temperature of the ore versus ore mass flow. Continuous curve corresponds to a water flow rate of 50 m^3/h whereas dashed line corresponds to a water flow rate of 100 m^3/h. Both curves are very similar, indicating that, according to the numerical model, the water flow rate has a weak influence in the cooling process

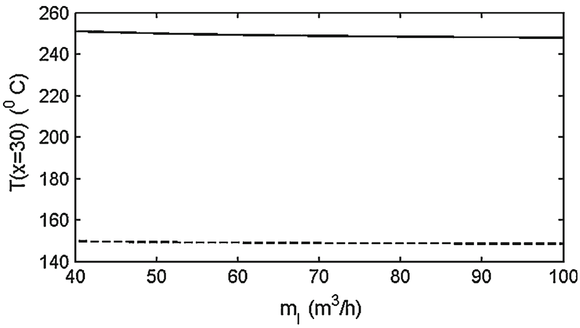

Fig. 4 Curves of final temperature of the ore T(30) versus water flow rate. **a** $\dot{m}_o = 34$ tons/h (*continuous line*) and **b** $\dot{m}_o = 20$ tons/h (*dotted line*). An increase in the water flow rate leads to a small decrease in the final temperature

$\dot{m}_o$ changes from 20 to 34 tons/h the increase of the final ore temperature is greater than 50 °C. The comparison between measurement and numerical solution show an agreement only for the case $\dot{m}_o = 20$ and $\dot{m}_l = 50$. In the remaining cases the model overestimates final ore temperature for more than 10 °C.

The Fig. 3 shows the curves of final temperature of the ore as a function of $\dot{m}_o$ in two cases, $\dot{m}_l = 50\,m^3/h$ (continuous lines) and $\dot{m}_l = 100\,m^3/h$ (dotted line). Both curves are very similar, indicating that an increase in the water flow rate has a weak influence in the cooling of the lateritic ore.

In Fig. 4 we present the curves of the final temperature T(30) versus water flow rate $\dot{m}_l$. The continuous line corresponds to an ore mass flow $\dot{m}_o = 34$ tons/h, while the dashed line corresponds to an ore mass flow $\dot{m}_o = 20$ tons/h. In both cases the increase of the water flow rate from 50 to 100 m^3/h leads (according to the numerical model) to a change of the final temperature T(30) of only few degrees.

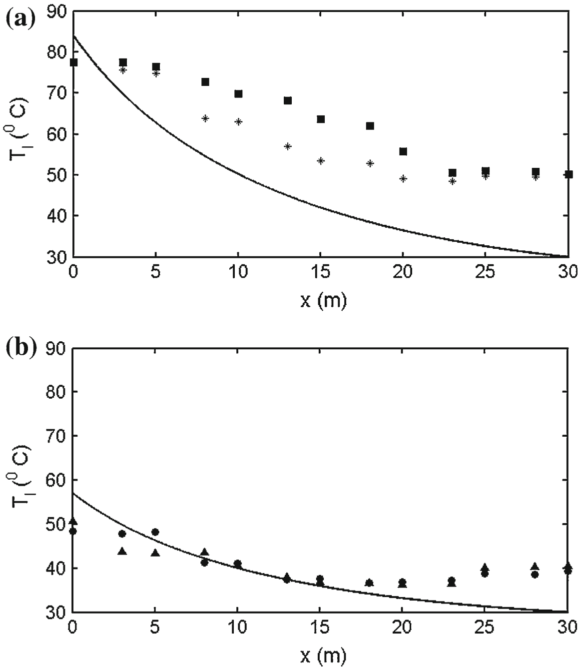

Fig. 5 Data of water temperature T_l versus x. **a** $\dot{m}_o = 34$ tons/h and $\dot{m}_l = 50\,m^3/h$, (□) measurements in the *left side*, (*) measurements in the *right side*, (*continuous line*) data obtained from numerical solution, **b** $\dot{m}_o = 34$ tons/h and $\dot{m}_l = 100\,m^3/h$, (*o*) measurement in the *left side*, (Δ) measurement in the right side, (*continuous line*) data obtained from numerical solution

Some measurements of the water temperature were made at different points along the pool, using PT-100 probes. Temperatures were recorded to the left and to the right of the cylinder (see Fig. 1). We have encountered a difference in data obtained along right and left sides, showing that there is a dependence of the cooling on the angular coordinate. This effect is related to the fact that surface of granular bed does not remain horizontal and also to the existence of discrete avalanches. However differences are only of few degrees and consequently one dimensional model can retain some important features of the cooling process. In Fig. 5 we present the data of water temperature T_l versus x and we include the prediction of the numerical solution. The Fig. 5a shows the temperature profile for an ore mass flow of 34 tons/h and a water flow rate of $50\,m^3/h$. There is an important difference between data obtained from measurement and the prediction of numerical solution, however, prediction of temperature of water at $x = 0$ is close to the experimental value. With respect (Fig. 5b), the ore mass flow and the water flow rate are respectively 34 tons/h and $100\,m^3/h$. The agreement between experimental data and numerical solution is good for $5 < x < 15$. In this case, the temperature of water at $x = 30$ is different from the assumed value $T_a = 30\,°C$.

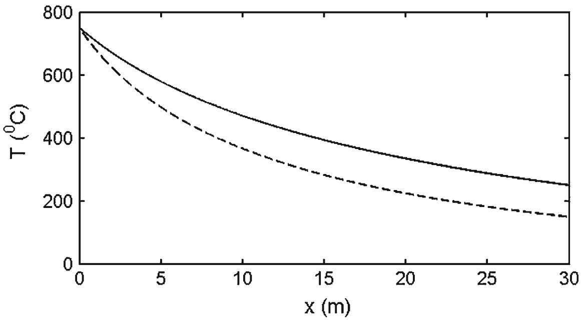

Fig. 6 Temperature profile of the granular bed, $\dot{m}_l = 50\,\text{m}^3/\text{h}$ **a** $\dot{m}_o = 34\,\text{tons/h}$ (*continuous line*) and **b** $\dot{m}_o = 20\,\text{tons/h}$ (*dashed line*). A reduction in the ore mass flow allows to a reduction of the temperature of the ore at the exit of the cooler

Finally, in Fig. 6 we present the ore temperature versus x for water a flow rate equal to 50 m^3/h and two different values of ore mass flow, namely $\dot{m}_o = 34$ tons/h and $\dot{m}_o = 20$ tons/h. In both cases the temperature at x = 0 is 750 °C. But the final temperature is different, for the first case T(30) = 250 °C and for the second case T(30) = 149 °C.

5 Conclusions

In this work we have presented data measured in situ and results of a model for the process of the cooling of lateritic ore occurring during the production of nickel. This simplified model is based on a system of two ordinary differential equations and an algebraic equation. Despite its simplicity the model allows to make some predictions for improving the efficiency of the cooler system. As a result of the numerical simulation we have found that an increase in the mineral flow and a decrease of the water flow rate lead to an increase of the temperature of the mineral at the cooler outlet. Therefore it is recommended to work with flows of mineral of 20 t/h and a water flow rate around 50 m^3/h. On the other side It was found in experimental data that the temperature of the cooler (the rotating horizontal cylinder) have a dependence on the angular coordinate, then an improvement of this model could be the modeling of the cooling process with a system of partial differential equations dependent on two coordinates (x, θ).

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