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Effect of the Density of Molten Metal on the Raining Phenomenon in Horizontal Centrifugal Casting

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Abstract

In this work the influence of the density of the molten metal on the emergence of the raining phenomenon in the horizontal centrifugal casting process is numerically studied. Transient 2D numerical simulations were carried out using Computational Fluid Dynamics software. Three molten metals with different density, namely aluminum, iron and lead, and three angular frequencies, namely 50, 66 and 77 rad/s were considered. It is found that the density of the molten metal significantly affects the emergence, transient or permanent, of the rain phenomenon. However, the magnitude and duration of the rain phenomenon depend on the angular frequency of the rotating mold. Likewise, since gravitational forces affect the metal according to its density, the value of the critical rotation speed of the mold is also affected.

Keywords

Angular Frequency, Centrifugal Force, Computational Fluid Dynamics, Critical Rotation Speed, G Factor, Horizontal Centrifugal Casting, Molten Metal Density

1. Introduction

In the horizontal centrifugal casting process a molten metal is poured into a horizontal rotating mold. The metal can be ferrous or non-ferrous. Due to the centrifugal force, the molten metal is projected towards the walls of the mold, and if the rotation speed of the mold reaches a critical value, a homogeneous layer of molten metal is formed on the walls. After the metal solidifies, a tubular-shaped product is obtained. According to [1] around 15% of the total cast products are obtained by centrifugal casting. The products obtained by centrifugal casting are relatively free of gases and porosity. Because nonmetallic inclusions and dissolved gases accumulate on the interior surface of the product, they can be easily removed by machining [2]. Furthermore, metallurgical and mechanical properties such as grain size and tensile strength can be efficiently changed by manipulating process parameters such as rotation speed, metal pouring temperature, mold temperature, and filling time, among others [3].

The forces involved in the centrifugal casting process are centrifugal forces, gravitational forces, Coriolis forces and surface tension forces [4]-[6]. However, in the literature it is considered that the most important ones are the first two, that is, the gravitational and the centrifugal forces. The relationship between centrifugal and gravitational forces is commonly known as G Factor [1] [7]. In order for the tubular product obtained with horizontal centrifugal casting to have a homogeneous thickness, it is considered that the G Factor value must be between 60 and 80 [4] [8]. Centrifugal forces, determined by the angular frequency and the rotation speed of the mold, define the value of the G Factor and exert a fundamental influence on the flow of fluids inside the rotating mold and on the mechanical and metallurgical properties of the product. A low angular frequency causes the so-called raining phenomenon due to the prevalence of the gravitational forces on the centrifugal forces, and the molten metal falls from the upper part of the mold to the bottom [9] [10]. Consequently the thickness of the solidified tubular piece is not homogeneous. On the other hand, if the angular frequency is very high, strong vibrations of the mold are generated [5] and high tensile stresses are produced in the product, causing longitudinal cracks and a worsening of the mechanical properties [9] [10]. The angular frequency and the mold rotation speed that produces a homogeneous product thickness and optimal metallurgical and mechanical properties, ω_c and N_c, respectively, have received various names in the literature, namely, optimum speed [10], critical rotation speed [4], critical angular speed [11], optimum spinning speed [12], and so on. The critical rotation speed of the mold N_c mainly depends on the type of metal to be cast and its physical properties, namely density and viscosity, the diameter of the mold, the thickness of the piece. N_c can also be affected by the temperature and thermal properties of the molten metal, mold temperature, metal volume fraction, and filling time [3].

Many of the published works on centrifugal casting are focused on analyzing the effect of the mold rotation speed on the mechanical and metallurgical properties of the cast pieces, and on the solidification process of the molten metal. These works have been experimental in nature or using computer simulations. In [1] different mold rotation speeds are used to optimize the tensile strength and elongation of an AlSi alloy. In [13] the effect of process variables on the microstructure and mechanical properties of an AZ80 magnesium alloy is studied. In [9], a 2D numerical model based on the shallow water model is proposed to simulate the solidification of a molten metal in a horizontal centrifugal casting process, considering gravitational, Coriolis and viscous forces, and a radial heat transfer of the metal layer towards the walls of the mold. In [4] the flow of liquid metal inside the mold is experimentally studied using different mold rotation speeds below and above the critical speed. The authors report that with rotation speeds below or above the critical one, the final pieces lack uniformity and have decreased mechanical properties.

In some works, the effect of the mold rotation speed and the physical properties of a fluid on the stability of fluid flow and the rain phenomenon in rotating horizontal cylinders are studied. In [11] the behavior of a liquid in a rotating horizontal cylinder is analyzed experimentally. The authors consider the angular velocity of the cylinder, the volume fraction of the liquid in the mold, and the length and diameter of the cylinder on the stability of the liquid, and report the presence of oscillations and waves that move along the axis of the cylinder. In [10] [14] the authors have experimentally identified three types of flow in the centrifugal casting: Ekmann flow ($N < N_c$), Couette flow ($N = N_c$), and Taylor flow ($N > N_c$). For tin $N_c = 600$ rpm. Laminar and turbulent flows have been reported through experiments for a liquid in rotating horizontal cylinder in [11]. According to these authors, laminar flows occur for high values of the G Factor and low values of the volume fraction of the liquid. On the contrary, turbulent flows occur for low values of the G Factor and high values of the volume fraction. In [3] N_c is numerically determined, and a value of 700 rpm is reported. According to these authors, filling time of the mold with the molten metal should be moderate to ensure that the centrifugal casting process is uniform and stable. In [15] the influence of the angular velocity, the viscosity of the molten metal and the roughness of the mold walls on the distribution of the metal inside the mold of a horizontal centrifugal casting is numerically studied. In the above work it is reported that for a 0.2 m diameter mold with molten steel, the appearance of the rain phenomenon is avoided if $\omega > 77$ rad/s or $N > 735$ rpm, which correspond to a G Factor of 60.

Unfortunately, few works systematically analyze the effect of the physical properties of the molten metal on the raining phenomenon. In [15] the effect of viscosity on the emergence of the above phenomenon for molten steel in a horizontal centrifugal casting is analyzed by two of the present authors. Three values of viscosity are considered, namely 0.002, 0.0067 and 0.01 kg/(m·s) for three different values of the angular frequency and the G Factor. Using 2D Computational Fluid Dynamics simulations, the above authors report that a high viscosity of the molten metal contributes to the metal being distributed more homogeneously on the walls of the mold and to a more even thickness of the cast part. This effect seems to be very important in the early stages of the process, however at high mold angular frequency and long casting times the influence of viscosity is less relevant. The aforementioned authors conclude that the raining phenomenon disappears for molten steel for G Factor values greater than 60, which for a 0.2 m diameter mold corresponds to an angular velocity of 77 rad/s and a rotation speed of 735 rpm.

In this work, the effect of the density of the molten metal on the emergence of the raining phenomenon is studied. Three molten metals with different densities were considered, namely aluminum, iron and lead. 2D transient numerical simulations were carried out using Computational Fluid Dynamics software. A run time of 10 s was set for the three metals considering a trilateral mesh of 7300 elements and an integration step of 0.001 s. The mold angular frequencies considered were 50, 60 and 77 rad/s, which correspond to 478, 573 and 735 rpm of rotation speed, respectively, and 26, 37 and 60 values of the *G* Factor, respectively, for a 0.2 m diameter cylindrical mold. A roughness of 0.0005 m was assumed for the mold walls in all cases.

2. Numerical Modeling

To study the effect of the density of the molten metal on the raining phenomenon, Computational Fluid Dynamics (CFD) software was used. Transient 2-dimensional numerical simulations were carried out to observe the phase distribution within the rotating mold. Two phases were considered, namely molten metal and air. A run time of 10 s and a time step of 0.001 s were applied. The turbulence model used was the standard K-ε model, and the Volume of Fluid model was employed to simulate two-phase flow [16]. A moving wall with a rotational motion ω of 50, 60, and 77 rad/s was established, and a wall roughness of 0.0005 m was set. The diameter of the rotating mold D was set at 0.2 m. To observe the effect of molten metal density on the raining phenomenon, three metals were considered, namely aluminum, iron and lead, whose densities are 2357, 7100 and 10678 kg/m^3, respectively [17]. The *G* Factor and the mold rotation speed N in rpm were calculated through the following expressions:

$$G = \frac{D\omega^2}{2g} \tag{1}$$

$$N = 42.3\sqrt{\frac{G}{D}} \tag{2}$$

In Eq. (1) $g = 9.81$ m/s^2 is the gravity acceleration. **Table 1** shows the rotation speeds and the *G* Factor associated with the angular velocity considered in the numerical simulations:

The molten metals used in the numerical simulations and their respective densities are shown in **Table 2**.

Table 1. Rotation speeds and *G* Factors associated with the angular velocity considered in the numerical simulations.

Ω, rad/s	N, rpm	G, dimensionless
50	478	25.5
60	573	36.7
77	735	60.4

Table 2. Densities of the molten metals considered [17].

Metal	Density, kg/m^3
Aluminum	2357
Iron	7100
Lead	10,678

3. Results and Discussion

2D transient CFD numerical simulations were carried out in which the angular frequency of the mold and the density of the molten metal were varied. The results are shown graphically to observe the distribution of phases within the mold and the presence or absence of the raining phenomenon. A simulation time of 10 s was established considering that during this time a stable state is reached in the casting process. Even though the time step was 0.001 s, the results were saved every second to observe the evolution of the phase distribution. The graphical results are shown according to the gradual increase in the angular frequency and the metal density. The times from the beginning of the casting chosen to present results were 1, 5 and 10 seconds.

Figure 1 shows the numerical results of the phase distribution for aluminum, with density of 2357 kg/m^3. The angular frequency is shown in the rows and the time in the columns. The continuous presence of the raining phenomenon (RP) can be observed for an angular frequency of 50 rad/s, which corresponds to a G Factor of 25.5, regardless of the time elapsed. For an angular frequency of 60 rad/s, which corresponds to a G Factor of 36.7, the presence of the phenomenon is still significant for a time of 5 s. However, for this angular frequency the RP disappears completely when 10 s has elapsed. The disappearance of the RP at 60 rad/s, with a G Factor value of 36.7, is not consistent with what was reported in [4] [8] where it is established that a G Factor value greater than 60 is needed to avoid the RP. **Figure 1** also shows that for an angular frequency of 77 rad/s, with a G Factor of 60.4, the RP disappears much faster, and for a time of 10 s there is already a homogeneous distribution of the metal inside the mold and an even thickness of metal in the casting. The anomaly of the absence of RP for molten aluminum for G Factor values less than 60 may be due to the low density of aluminum, in which gravitational forces act with less intensity precisely because of its low density. Apparently, the low density of aluminum affects the value of the critical rotation speed N_c. That is, the critical rotation speed appears to decrease as the density of the molten metal decreases.

The results for iron, whose density is 7100 kg/m^3, are displayed in **Figure 2**. The permanent presence of the RP can be observed for angular frequencies of 50 and 60 rad/s. For an angular frequency of 77 rad/s the emergence of the RP is only transient and disappears for times greater than 5 s. Lead, whose results are shown in **Figure 3**, has a behavior similar to that of iron. For angular frequencies of 50 and 60 rad/s, which correspond to G Factor values of 25.5 and 36.7, respectively, the presence of RP is permanent, and becomes transient and disappears for an angular frequency of 77 rad/s, with a G factor of 60.4 [4] [8]. These results are consistent with what was expressed above, in the sense that the density of the molten metal affects the value of the critical rotation speed, and the opposite is also valid: high densities should increase the value of N_c.

A summary of the results presented here is shown in **Table 3**. This table seeks to answer the following question: under what values of the rotation speed and density of the molten metal considered here does the rain phenomenon occur permanently? As could be seen in the numerical results shown in this work, the rotation speed and the density of the molten metal decisively influence the critical rotation speed, and consequently these parameters can decide the temporary or permanent emergence of the raining phenomenon.

Table 3. Permanent emergence of the raining phenomenon.

Ω, rad/s	N, rpm	G Factor, dimensionless	Aluminum, $\rho = 2357$ kg/m^3	Iron, $\rho = 7100$ kg/m^3	Lead, $\rho = 10{,}678$ kg/m^3
50	478	25.5	Yes	Yes	Yes
60	573	36.7	No	Yes	Yes
77	735	60.4	No	No	No

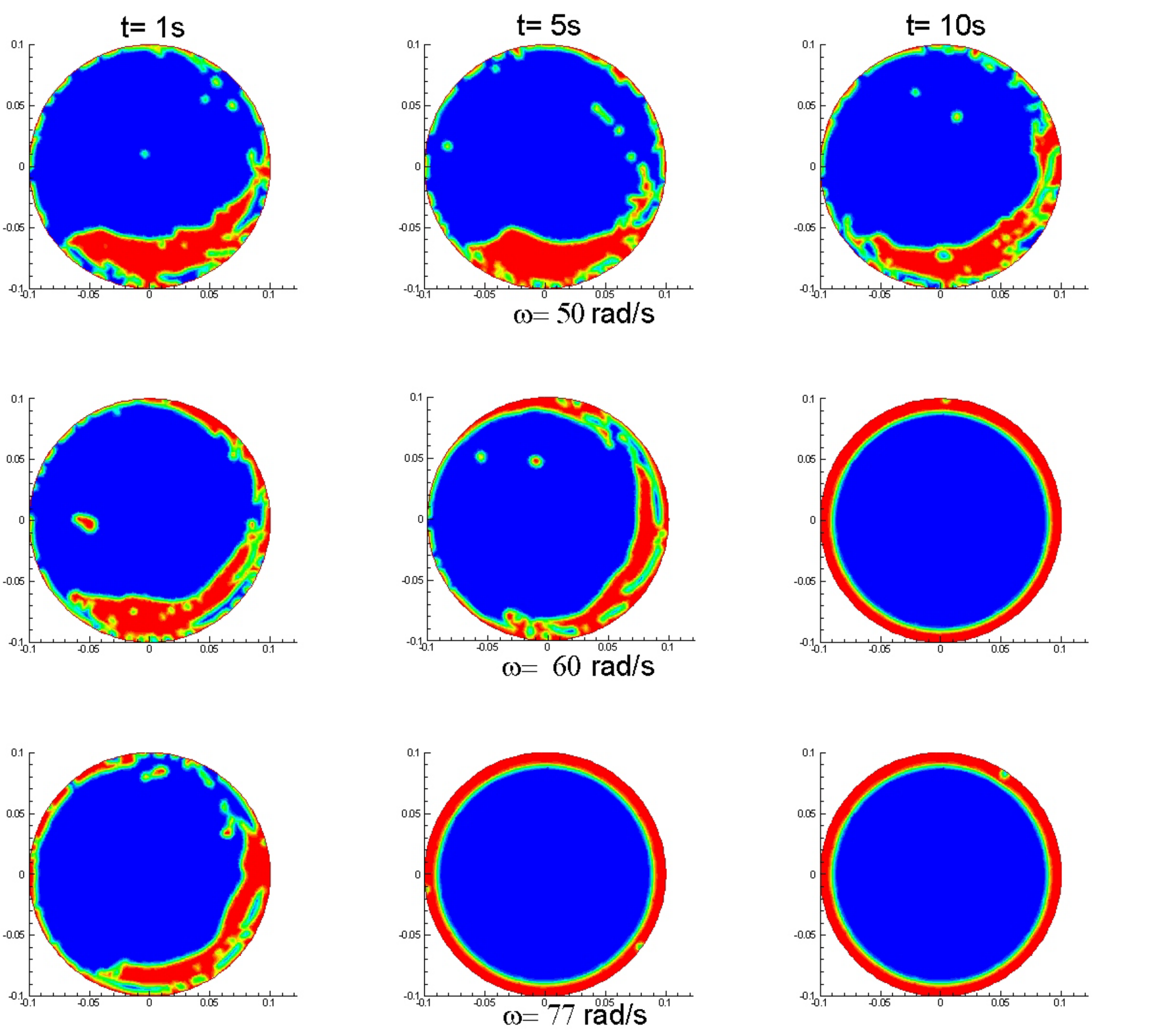

Figure 1. Phase distribution and raining phenomenon for aluminum. The units are given in meters.

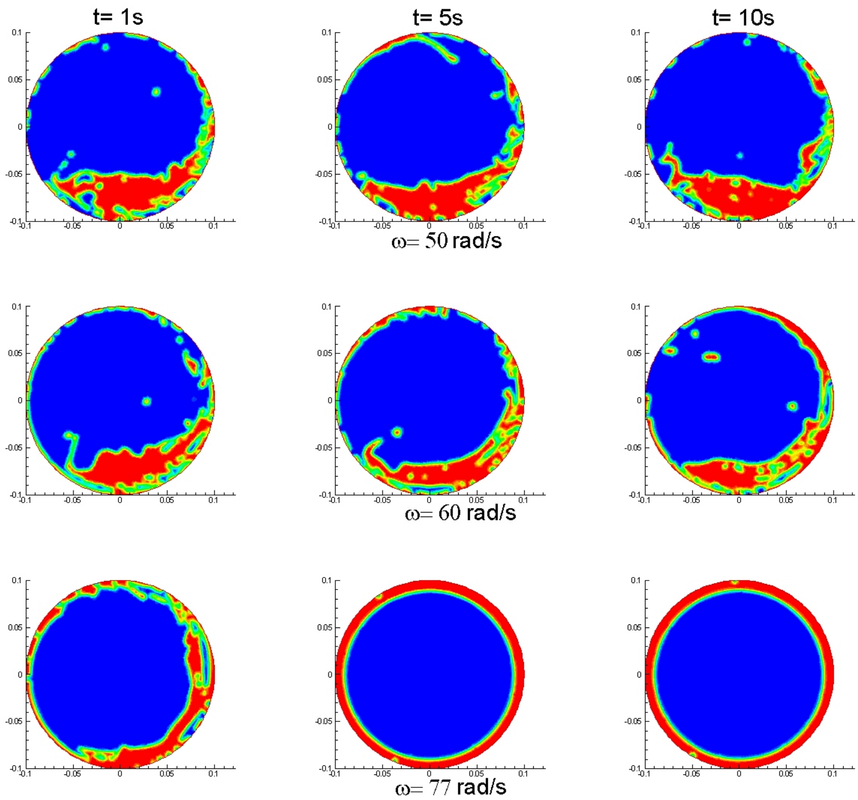

Figure 2. Phase distribution and raining phenomenon for iron. The units are given in meters.

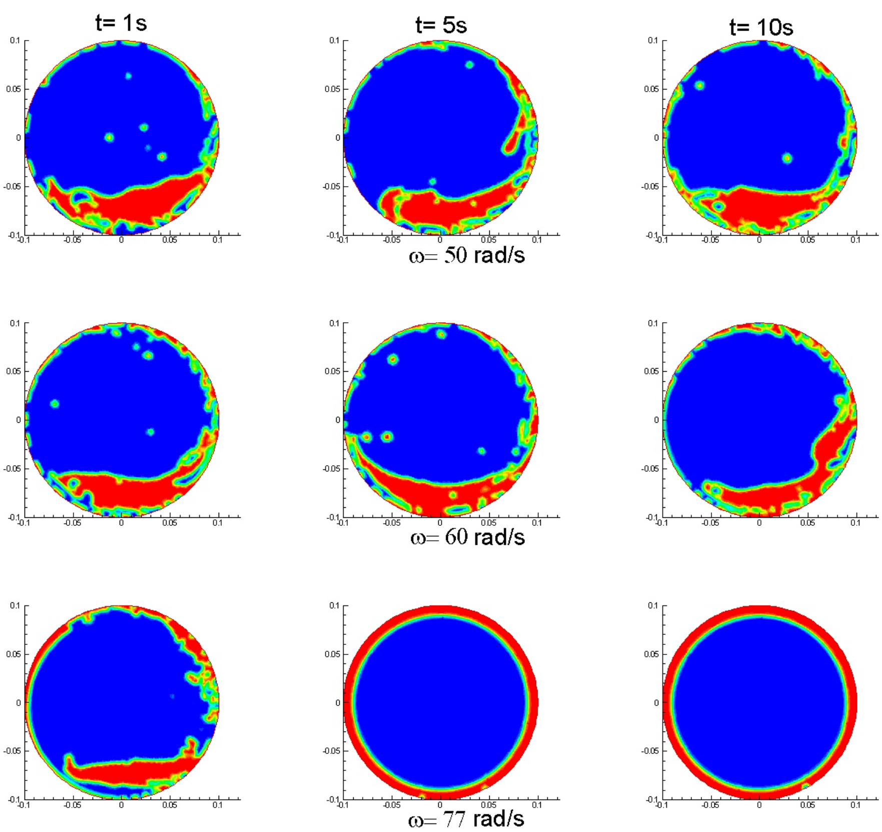

Figure 3. Phase distribution and raining phenomenon for lead. The units are given in meters.

4. Conclusions

With the objective of determining the influence of the density of the molten metal on the emergence of the raining phenomenon in the horizontal centrifugal casting process, 2D transient numerical simulations were carried out using Computational Fluid Dynamics software. The results allow us to observe the phase distribution inside the rotating mold and check whether the thickness of the cast casting is uniform. Three molten metals with different density, namely aluminum, iron and lead, and three angular frequencies, namely 50, 66 and 77 rad/s, were considered. From the analysis of the numerical results the following conclusions can be derived:

1) The density of the molten metal decisively affects the emergence of the raining phenomenon.

2) Due to the lesser action of gravitational forces on metals with low density, these metals present the raining phenomenon at lower values of the G Factor.

3) The effect of molten metal density on the raining phenomenon is more marked for high values of density.

4) The effect of the molten metal density on the emergence of the rain phenomenon is less important as the angular frequency of the rotating mold increases.

5) Consequently, the critical value of the mold rotation speed decreases if the density of the molten metal decreases. The opposite is also true, that is, the critical value of the mold rotation speed increases with the increase in the density of the molten metal.

Conflicts of Interest

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

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