NUMERICAL STUDY FOR THE ANALYSIS OF DEFECTS IN METAL INJECTION MOLDING PROCESS

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Abstract

Metal injection molding (MIM) is a complex manufacturing process which is used for producing complex-shaped parts of various materials. The MIM is a combination of four sequential technological processes which has an effect on the quality of the final parts. If the molding step is made with a poor mould design or unsuitable chosen injection parameters, it will results defects. These defects can be rectified by optimizing process parameters and mold design with trial and error technique. The main purpose of this paper is to present the results of the numerical simulation of mold filling by casting the liquid metal (aluminum) in a metal mold. The influence of some processing parameters such as cooling time, injection temperature, injection pressure and flow rate on the defects generated after cooling the liquid metal have been investigated. The finite element method (FEM) is used in the numerical simulation to solve the set of governing equations using Ansys software. The volume of fluid (VOF) approach is used for tracking moving free surfaces during the cooling process.

Keywords: *Metal injection molding; numerical simulation; finite element method; volume of fluid approach*

1. INTRODUCTION

Metal Injection Molding (MIM) is a most common manufacturing process for producing small and complex metallic parts (Barriere et al. 2000). The feedstock is injection moulded in the desired shape by heating in the mould machine and hot ramming it under pressure into the tool cavity (Cysne Barbosa 2011). MIM process is a combination of four sequential technological processes – mixing, injection moulding, debinding and sintering. Fig.1 shows schematically the production process during metal injection molding. All the steps of the MIM process have an effect on the characteristics of the final parts (Bergink et al. 2009). If the molding step is made with a poor mould design or unsuitable chosen injection parameters, it will results defects. On the other hand, defects, such as voids, sink marks, weld lines and density variation can form if the molding parameters are not properly specified (Zhoushun et al. 2003). Some of the process parameters can be distinguished as the most important ones, such as the temperature inside the barrel, the injection temperature, the mould temperature, the charging volume, the injection volume flow rate, the injection pressure, the holding pressure and the holding time (Cysne Barbosa 2011). During the sintering process (last step of MIM), the powder particles are joined together at high temperatures. The size of the pores is reduced and the density of the part reaches from 94 -99 % of the theoretical density (Lin et al. 1991). The traditional method for determining the process parameter is to try and correct again and again because of the complexity. The melt feedstock is a kind of non-Newtonian fluid and its flow in the channel and the mould cavity is unsteady and nonisothermal (Zhen-xing et al. 2008). Computational simulation is an effective measure in studying the mold-filling process in metal injection molding because of the complexity of process and the nonlinearity of the governing equation and material properties (Ahn et al.2009). Indeed, it has been widely reported that computational fluid dynamics (CFD) analysis can provide valuable information to mold designers and manufacturers (Chen et al. 1999; Samanta et al.2008; Shih et al. 2001). Zheng et al. (2008) used the Hele-Shaw flow model to describe approximately the mold cavity, the mathematical equations was solved by means of the finite element/finite difference hybrid method using the Moldflow software. They reported that the flow rate has an important effect on the filling course in powder injection modeling. The Moldflow software was also used by Hsu et al. (2004) to

conduct a numerical study to find the effect of molding conditions to the shrinkage of aspheric lenses. Wei et al. (2014) studies the effects of filling patterns on the powder–binder separation during powder injection molding. They found that the filling mobility variable was proportional to the velocity of feedstock and inversely proportional to the viscosity of feedstock. Pequet et al. (2002) studied the defects formation during solidification of Al alloy using ABAQUS and showed that most of the defects formed where the metal solidified last. Shaha & Haque (2010) reported that the solidification rate of molten metal in the sand mould depends on the thermal conductivity of the mould material, casting design and the direction of heat-flow into the mould wall. In the present study, we investigate the defects generated during the filling process of a complex cavity. For this purpose, a numerical analysis based on Finite Elements/ Volume Of Fluid (FE/VOF) method and ANSYS software were applied for simulation of the flow of molten Aluminum (Al) metal during mold filling.

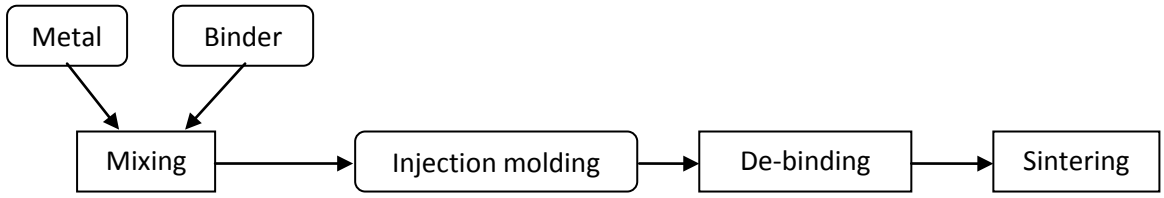


Fig 1 Metal Injection Molding Process

2. MATHEMATICAL FORMULATION

The molten metal is assumed with a rheological behavior (Newtonian fluid). In the VOF method, the cell containing a fluid is governed by the conservation of mass, conservation of momentum and conservation of energy equations (Abdellah El-hadj et al. 2010; Crochet et al. 1984; Lapidus et al. 1982):

The conservation of mass or continuity equation is:

$$\vec{\nabla} = \left(C_k . \vec{V}\right) = 0 \qquad (1)$$

Eq. (1) is the general form of the mass conservation equation and is valid for incompressible and compressible flows.

Conservation of momentum (Navier-Stockes) is described by:

$$\frac{\partial(C_k.\vec{V})}{\partial t} + \left(C_k . \vec{V} . \vec{\nabla}\right)\vec{V} = \frac{-C_k}{\rho}\vec{\nabla}\mathrm{p} + C_k \nu \nabla^2 \vec{\mathrm{V}} + \frac{C_k}{\rho}\vec{\mathrm{F}}_\mathrm{b} \qquad (2)$$

Where $\vec{V}$ is the velocity vector, ρ is the density, p is the pressure, C_k is called fraction of fluid volume, ν is the kinematic viscosity and t the time. $\vec{F}_b$is the body force applied to the fluid.

According to the VOF method, the fraction of fluid volume C_k is used for the all domain where its value indicates the presence or the absence of the fluid (Hirt & Nichols 1981). We attribute the value of 1 for a point occupied by the metal and 0 in the other domain part. The mean value in the element k presents the function of the fluid volume occupied by the metal (Zirari et al. 2010 & Hamid 2008):

$$C_k = \begin{cases} 0 & \text{inside the fluid} \\ 0 < C_k < 1 & \text{contain a free surface} \\ 0 & \text{empty cell} \end{cases}$$

The element with a value of C_k between 0 and 1 is containing the free surface or the interface. For all points of the domain, it is necessary to solve the transport equation:

$$\frac{dC_k}{dt} = \frac{\partial C_k}{\partial t} + V.\nabla C_K \quad (3)$$

Energy conservation can be expressed as:

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{V}.\vec{\nabla}T\right) = \nabla(\lambda \nabla T) + \eta\dot{\gamma}^2 \quad (4)$$

Where ρ is the density, C_p is the specific heat, λ is the thermal conductivity, T is the temperature, η is the viscosity of the metal and $\dot{\gamma}$ is the shear rate.

3. NUMERICAL SIMULATION

ANSYS software was used to simulation the mold filling in Metal injection molding. Some initial conditions were established such as temperature, pressure and VOF in the elements of the mesh. Through FEM, the velocity and pressure fields were obtained from the conservation of mass (Eq. 1) and momentum (Eq. 2) equations. The temperature is determined from the resolution of the energy conservation equation (Eq. 4) in the region occupied by the fluid.

The properties of the metal and sand mold used in the calculation, are given in Table 1.

The 2D-geometry and dimensions of casting mold and the mesh we chose for the calculus are resented in Fig. 2. The geometry of mesh element is quadrilateral form.

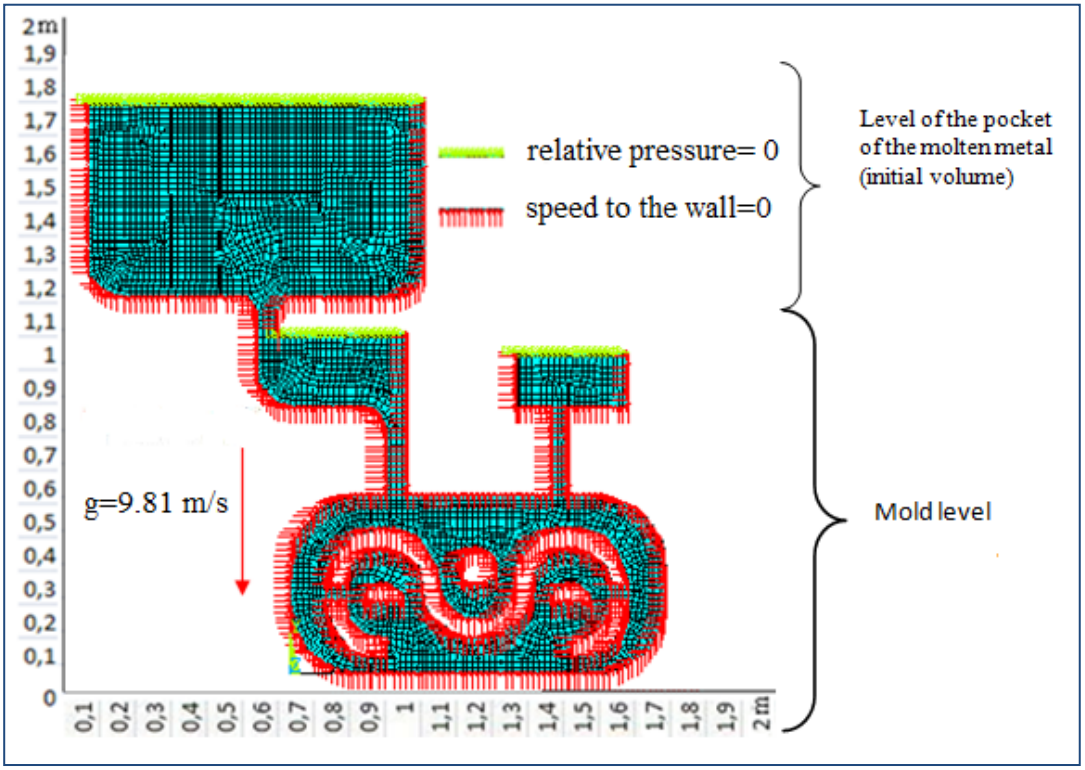


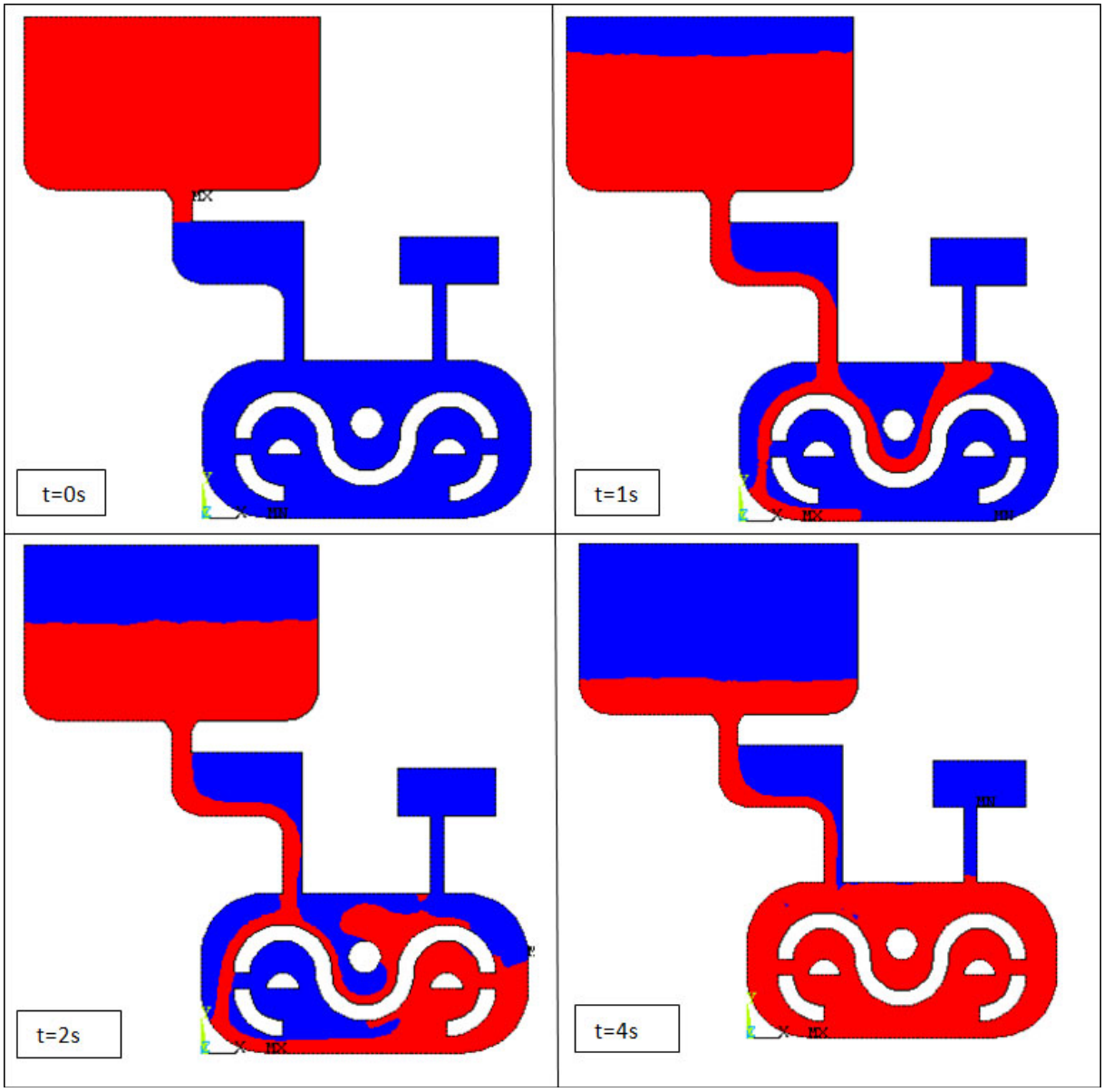
Fig. 2 Geometry and the 2D mesh of the model.

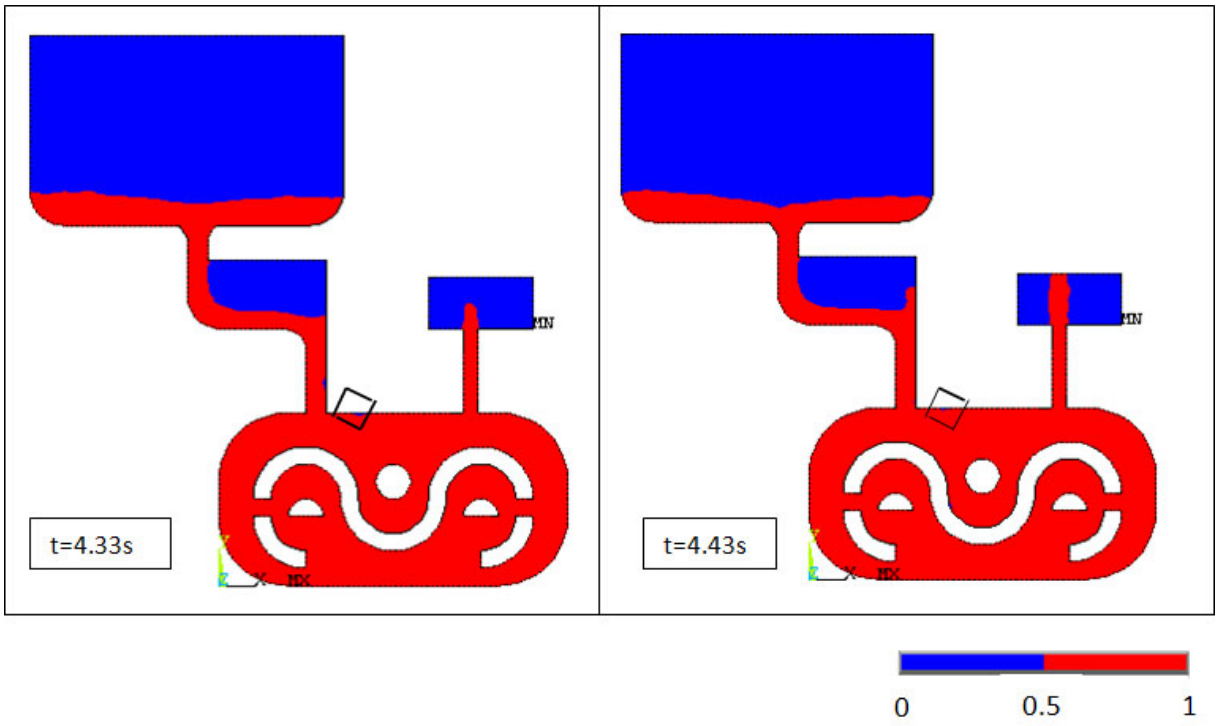
Table 1. Aluminum and Sand properties

Properties	Solid metal	Liquid metal	Sand mold
density, ρ (kg/m^3)	2570	2400	1520
thermal conductivity, λ (W/m.K)	220	110	0.65
specific heat, C_p (J/kg K)	1100	1100	987
viscosity, η (kg/ms)	-	0.02	-

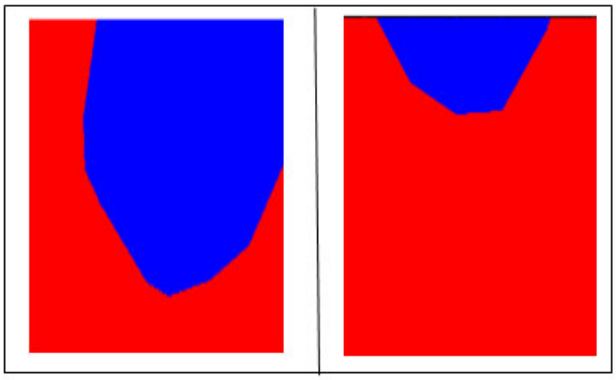
4. RESULTS AND DISCUSSION

In Fig. 3 are shown the filling sequences at six times: 0, 1, 2, 4, 4.33 and 4.43 s. The red color corresponds to the metal and the blue represents the air.





(a)



(b)

Fig. 3. (a) Views of the fluid configuration at different filling time: 0, 1, 2, 4, 4.33 and 4.43 s. (b) Zoom of the defects area.

The visualization of Fig.3 (a) shows that after filling the mold (t> 4.33 s), the cavity still presents some cavities occupied by air. Indeed, the presence of air bubbles in the cavity represents a filling defect that makes the major problem for molded articles. Fig. 3 (b) shows the zoom of the two areas of defects t = 4.33s and t= 4.43s.

To observe the influence of air bubbles on the metal flow during the mold filling process, we have also studied, as a function of filling time the evolution of the temperature, the velocity and the pressure of the fluid at three fixed points in the cavity. The position of the three fixed points is represented in Fig. 4.

The evolution of the temperature, the velocity and the pressure as a function of filling time are shown in Fig. 5, Fig. 6 and Fig. 7, respectively.

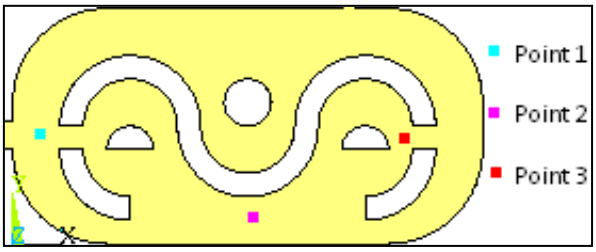


Fig. 4. Position of the three fixed points on the imprint

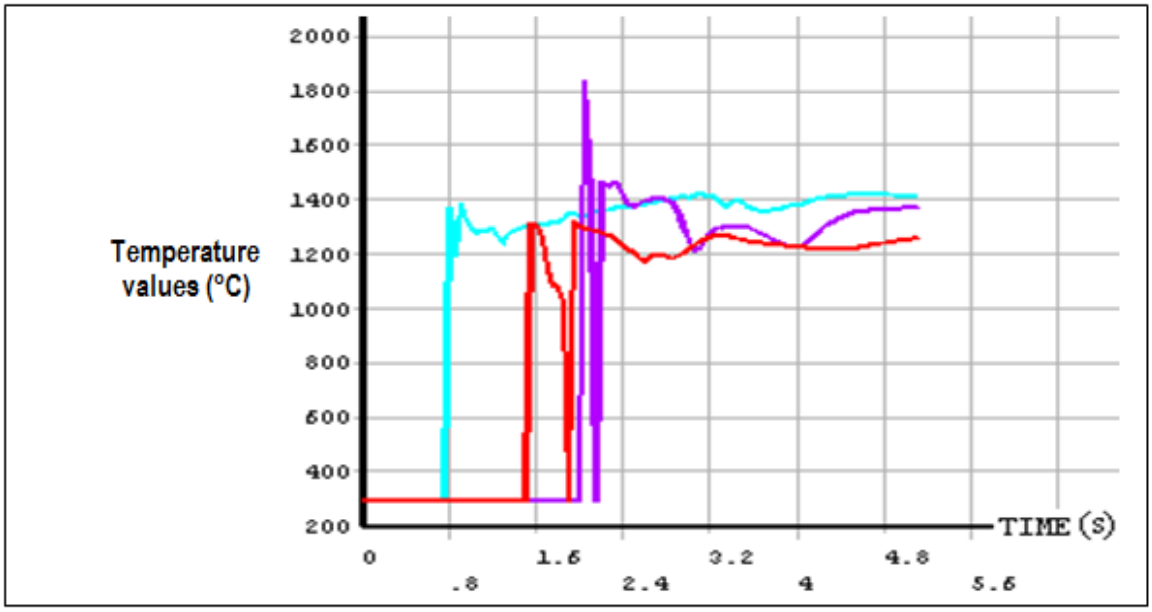


Fig. 5 Evolution of the temperature as function of filling time at the fixed three points

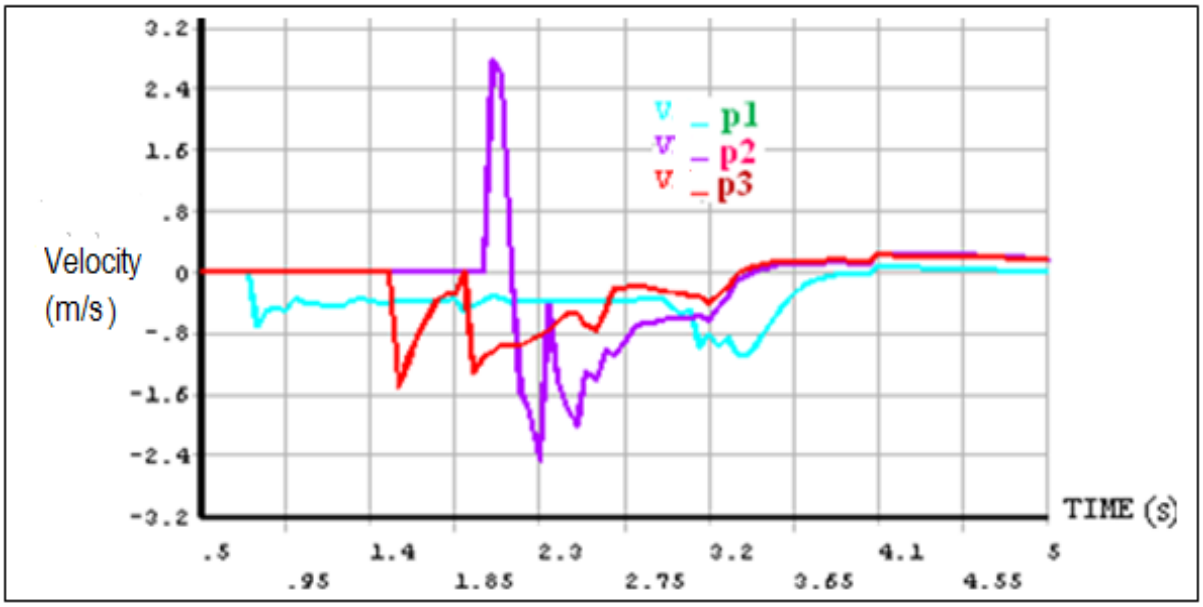


Fig. 6 Evolution of the velocity as function of filling time at the fixed three points

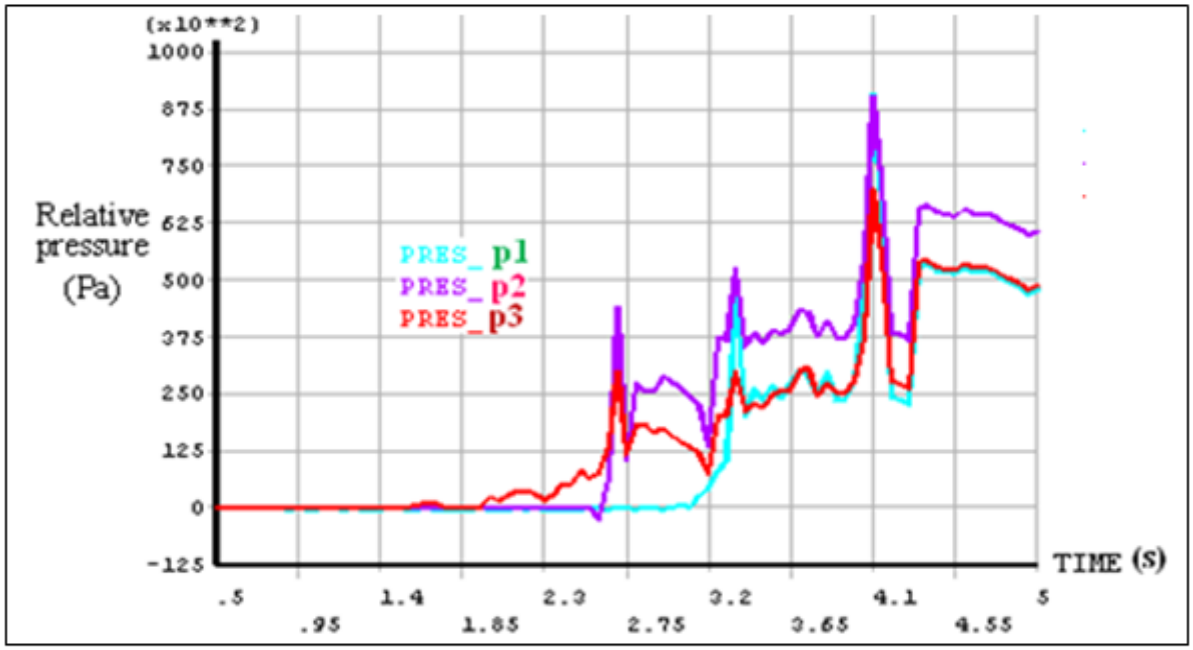


Fig. 7. Evolution of the relative pressure as function of filling time at the fixed three points

From Fig. 5, it is clear seen that the temperature at the point 1 remains constant for filling time less than 0.8 s and when t is approximately equal to 0.8 s, it is shown that the temperature increases dramatically and after that remains constant. The increase of the temperature is due to the fact that the metal attained the point 1 after 0.8 s. For the point 2, we observed that the metal attained this point after 1.5 s, but it is also noticed that at this point the temperature decreases rapidly. This drop in temperature may be due to the presence of air bubbles which prevents the progress of the fluid flow in the cavity. This interpretation is also confirmed by the evolution of the fluid velocity at this point, in fact, it is clearly seen in Fig. 6 that the fluid velocity decreases rapidly and reaches a value of 0 for t = 1.9 s. The same observation is noted for the point 2, indeed, the temperature increases when the fluid reaches this point and then decreases due to the presence of air bubbles that dampen the movement of the fluid.

In order to see the influence of the metal casting conditions on product quality, we have added a pouring ladle after the reservoir simulating molten metal. This configuration is shown in Fig. 8. The casting ladle has the advantage of separating the two fluids at the entrance of the mold due to the difference of densities, the air rises to the surface of the liquid metal and wins the atmosphere. The simulation results are presented in Fig. 9. As can be seen, after 4.43 s of filling time there are no air bubbles in the cavity of the mold. Compared to the first configuration (Fig.2), One can conclude that the presence of the pouring ladle offered the advantage for the evacuation of air bubbles from the cavity and then the amelioration of the product quality.

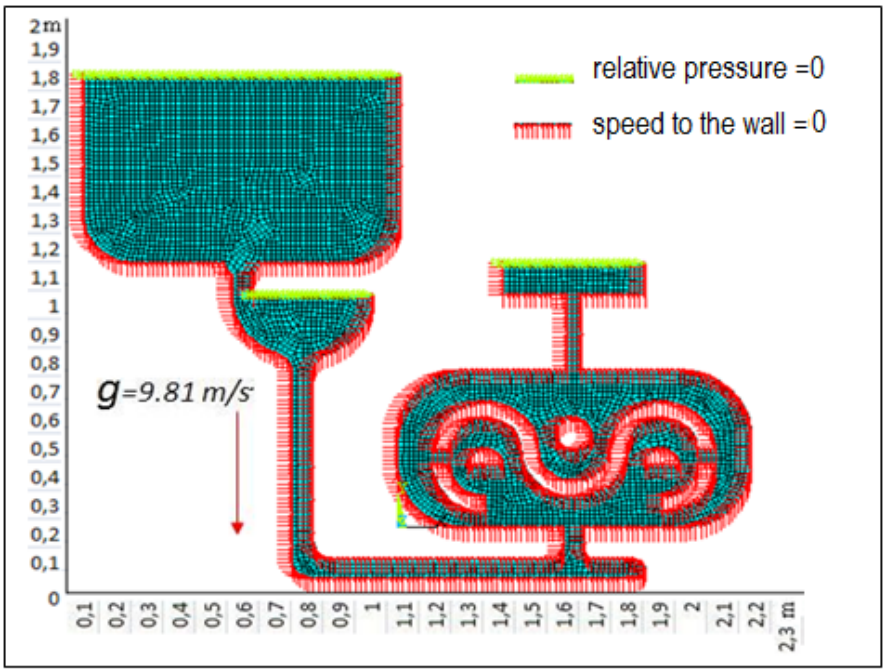
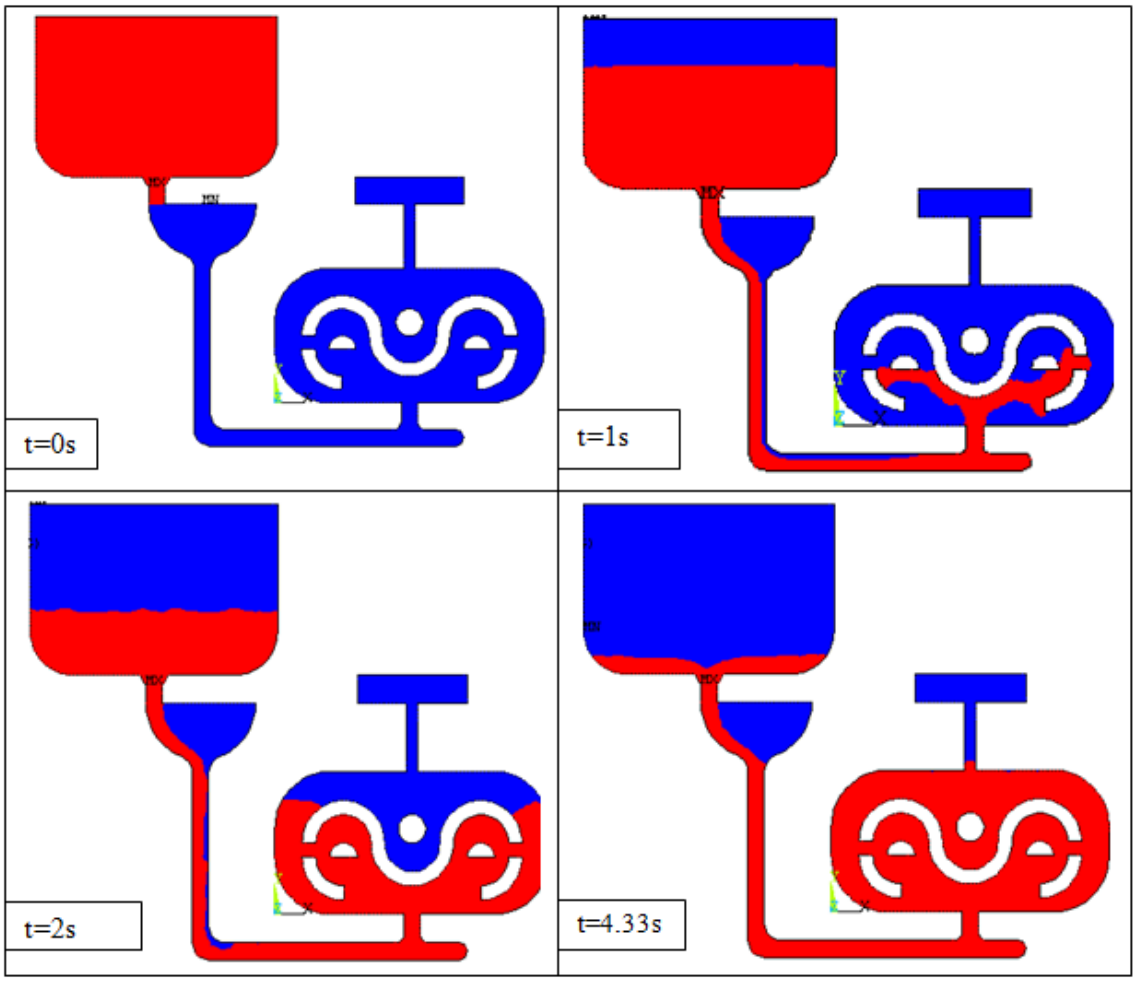


Fig. 8. Geometry and the 2D mesh of the model with the presence of a casting ladle



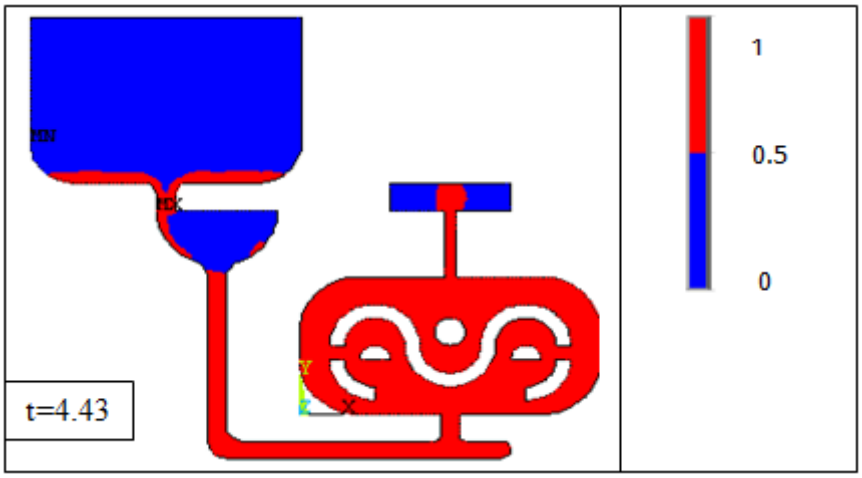


Fig. 9. Geometry and the 2D mesh of the model with the presence of a casting ladle

CONCLUSION

The finite element and the volume of fluid methods were used to simulate and visualize the mold filling process. In a first case, we used the configuration of the mold without pouring ladle. The numerical simulation results and the visualization of the cavity after complete filling of the mold showed the presence of air bubbles which reflect defects in the product. These results were also confirmed by the study of the evolution of the characteristic parameters of the metal flow, namely, the temperature, the velocity and the pressure. In a second numerical experiment, we adopted a configuration with a pouring ladle. The visualization of temporary sequences mold filling up to 4.43 seconds has proved more better results, in effect, the pouring ladle is involved in the evacuation of air bubbles and thus to improve the quality of the product.

NOMENCLATURE

Latin letters

C_p	specific heat (J/kg K)
C_k	fraction of fluid volume
F_b	body force (N)
λ	thermal conductivity (W/m.K)
p	Pressure (N/m^3)
t	Time (s)
T	Temperature (°C)
V	Velocity (m/s)

Greek symbols

ρ	density of the metal (kg/m^3)
ν	kinematic viscosity (m^2/s)
η	viscosity (kg/ms)
$\dot{\gamma}$	shear rate.

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