Interaction of a flexible combo bag with the flow in a DC aluminium casting

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1 Abstract

In the latest years different kind of combo bags were introduced in the DC aluminium casting to give better production quality. In order to achieve better the understanding of the process, a numerical model was build to model both the hydrodynamic of the flow and the evolution of the bag. Different bags are investigated: one rigid, one flexible and one elastic. This investigation needs to predict the fluid/structure interaction by considering a full coupling between the liquid flow hydrodynamic and the deformation of the bag. To achieve this goal, the movement of the bag surface is modelled though the introduction of particles markers. The particles are allowed to move according to a dynamic law using an assumed flow-bag drag interaction. Additional elastic forces are introduced between neighbour particles in order to reach a specific elasticity and flexibility.

2 Introduction

In the seventies fibreglass bags were used when the automatic DC casting process were invented. Their purpose lies mainly in the molten metal distribution and in the macro-filtration of refractory particles. These fibreglass fabric bags are often called “combo bags (CB)” for DC sheet ingot casting. The way that the CB distributes the flow is important for the solidification structures of the final cast ingot. A poor bag design or malfunction of the feed system can result in the formation of coarse-grained regions. From experiences, the metal distribution is not only influenced by the bag geometry but also by its lattice structure and material properties [1-4]. The lattice structure controls the size of eddies that can cross the bag, turbulences originated from the inlet are then strongly damped. Since it can be considered as a permeable “porous membrane”, the main effect is the creation of a pressure drop between both sides of the membrane [3-4]. It was already noticed that the permeability of the bag is a key parameter in the distribution pattern of the metal [2-4]. At high temperature the fibreglass become more flexible, and in response to the flow pressure the shape of the CB bag can then be strongly deformed [5-8]. The shape developed by the bag can be estimated only after the end of the casting. During the process it is very difficult to describe the mechanical behaviour (shape, movement, vibration) of the bag. Simulation of the elasticity of the bag is even more important since fibre strength is considerably reduced with high temperatures. At casting temperature (~ 700^{o}C), a glass fibre retains only 15% of its original strength [5,6].

The aim of the current work is to build a model that could predict the interaction between the molten liquid flow and the bag shape. However modelling fluid/structure interactions is one of the challenges of the last decades. In the present configuration the porosity of the bag can be considered as an additional difficulty. The choice is made here to use particle markers to model the shape evolution and the porosity of the bag. The temperature dependence of the bag and liquid material properties are not yet considered

3 The model

3.1 The geometry and flow dynamic

The calculation domain used in this mathematical investigation is shown in Fig.1. The geometrical parameters are listed in Table 1. A flexible bag is put at the entry of the flow into the mould region. The flow velocity **U** is predicted with the full transient Navier-Stokes equations. The CFD package FLUENT is used for the hydrodynamics. Since we also intend to study the influence of the bag on small flow structure, no turbulence model is used. An additional force corresponding to the drag generated by the presence of the bag is added to the Navier-Stokes equations. The expression of the drag is detailed in Eq. 2.

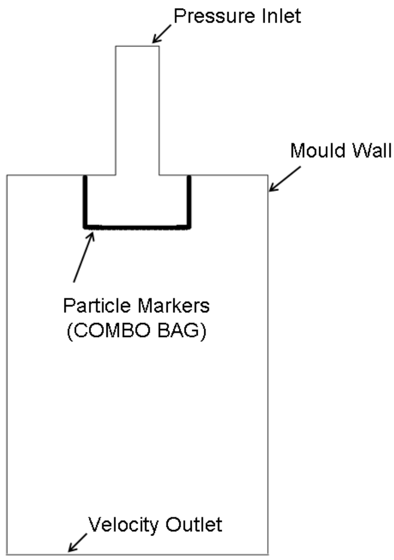


Figure 1: Calculation domain.

Table 1: Parameters for the calculation

Outlet velocity	1 mm/s
Inlet width	10 cm
Mould width	60 cm
Mould Height	85 cm
Length of the bag	40 cm

3.2 The dynamic of the bag structure

The bag shape is modelled with moving particle markers. Since we are in a 2D configuration, the bag is then equivalent to a chain of particles. Each particle indexed with (*i*), represents a piece of the combo bag surface with a masse m_i. The distance between neighbouring particles represents the lattice space of the bag, through which the melt can flow. The motion of the particles is allowed to mimic the motion of the deformation of the bag. The velocity $\mathbf{V}_i$ of each particle is controlled by the balance of the forces applied to it, which includes the drag from the flow (**D),** the elasticity (**F)** and the flexibility forces (**T**) from the solid lattice:

$$m_i \frac{\partial \mathbf{V}_i}{\partial t} = \mathbf{D}_i + \mathbf{F}_{i,i-1} + \mathbf{F}_{i,i+1} + \mathbf{T}_{i,i-1,i-2} + \mathbf{T}_{i,i+1,i+2} \quad (1)$$

The drag force depends on the size specification of the bag fabric, such as its thickness, the shape and size of the holes. A drag law was determined for the fabric type 34 L [2]:

$$\mathbf{D}_i = 2.6 \cdot 10^3 \mu \left\| \mathbf{V}_i - \mathbf{U} \right\|^{1.9165} \frac{\mathbf{V}_i - \mathbf{U}}{\left\| \mathbf{V}_i - \mathbf{U} \right\|}, \quad (2)$$

where μ is the liquid viscosity. In opposite to classical porous media, the pressure drop associated with this drag force is highly non linear. This is a strong indication that the drag force results more from the momentum impact on the bag than from a friction effect.

The elasticity law must be expressed in order to conserve the distance between two neighbour particles, so that a constant total surface of the bag is conserved. A Hooke's law of elasticity is used, it states that the stress is directly proportional to the displacement:

$$\mathbf{F}_{i,j} = k(\mathbf{X}_{i,j} - d_0 \frac{\mathbf{X}_{i,j}}{\left\| \mathbf{X}_{i,j} \right\|}), \quad (3)$$

where d_0 is the desired distance between neighbouring particles, k the spring constant, and $\mathbf{X}_{i,j}$ is the vector linking position between particle i and j. This force is supposed to apply only between neighbour particles (Eq. 3). As shown in Fig.2 the distance between particles 1 and 2 is smaller than d_0, hence they push against each other. The distance between neighbouring particles 2 and 3 is larger than d_0, hence they pull towards each other.

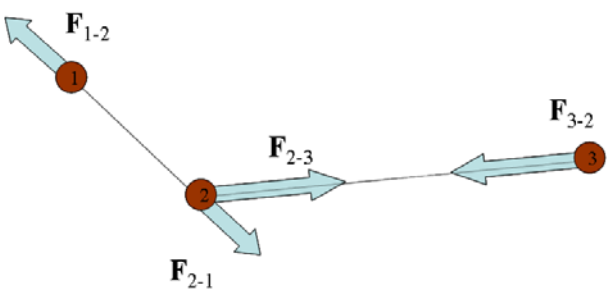


Figure 2: Elastic force

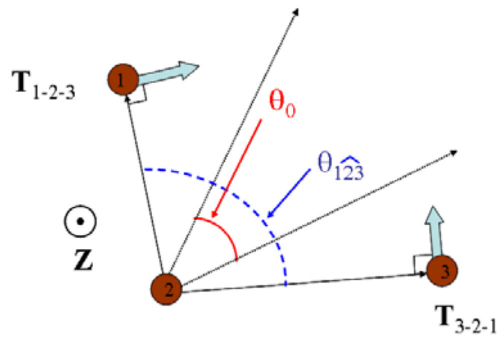


Figure 3: Flexibility force

The flexibility force increases with the local bending of the original bag shape. It can be expressed as a function of the angle formed by three neighbouring particles:

$$\mathbf{T}_{i,j,k} = q(j-i)(\theta_{\hat{ijk}} - \theta_0) \frac{\mathbf{X}_{j,i} \otimes \mathbf{Z}}{\left\| \mathbf{X}_{j,i} \right\|}, \quad (4)$$

where $\theta_{\hat{ijk}}$ is the angle between the three particle positions (i,j,k), θ_0 is the desired angle, q the angular relaxation constant, and **Z** the unit vector in the z direction. This force is a torque acting in a perpendicular direction to the elastic force **F.** As shown in Fig.3 the angle $\theta_{1\hat{2}3}$ is larger than the desired angle θ_0,a force is then applied to particle 1 and 3 to decrease $\theta_{1\hat{2}3}$.

By varying magnitude of k and q, different king of solid structure can be modelled. A non moving and rigid bag can be obtained by using extremely large values for k and q. A non elastic and flexible bag can be model by using large value for k, and 0 for q. If the properties of the bag are temperature dependant or non uniform, the elastic constants are varying with position $(\mathbf{k}_{i,j}; q_{\hat{ijk}})$.

4 Results

A very large number of configurations can be investigated by using various (*k q*) values. In the present work only three cases are explored, the choice of parameters are presented in table 2. For the present work 90 particle markers are introduced, which means that there are 91 holes along the bag, through which the liquid can flow. Two additional particles fixed on the mould wall, are introduced to model the ends of the particles chain.

Table 2: Elastic constants for the investigated cases

Bags	k	q	$\theta_{i\hat{j}k}$
Rigid and rectangular	10^8	10^4	$\theta_{i\hat{j}k} = \pi$ (sides) $\theta_{i\hat{j}k} = \pi/2$ (corners)
Non-elastic but flexible	10^8	0	-
Elastic and low flexibility	10^6	10^2	$\theta_{i\hat{j}k} = \pi$

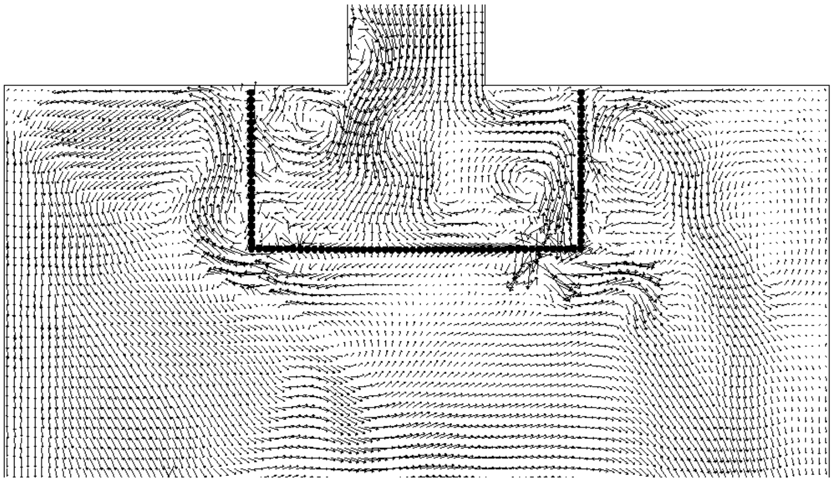


Figure 4: Flow configuration of the rectangular rigid bag

4.1 Rectangular rigid bag

In order to obtain an almost solid bag, for example made with steel, very large values must be fixed for both *k* and *q*. We can then model a bag that will not be influenced by the aluminium liquid flow. The results show that the flow is very turbulent and the flow distribution is non-uniform. The reason is that the presence of fixed corners induces the occurence of small eddies within the bag. After having passed the membrane, the flow is still unstable but usually presents much larger flow structures than inside the bag.

4.2 Non elastic and flexible bag

In this case we want a bag that strictly conserves its dimension, but has no preferred shape. The flow can modify its shape according to the pressure field. The results show that the bag develops an almost stable round bag (Fig.5). The flow is more stable than in the previous case. Inside the bag the flow is symmetric and characterised by the presence of two large eddies around the main jet coming from the inlet. Outside the bag small eddies exists, created by the non uniformity of the mass flow rate crossing the surface of the bag. At some stages the calculations predict some shape modification due to the impacting of external eddies (Fig. 6). However the bag recovers its shape quickly, typically within 4 seconds.

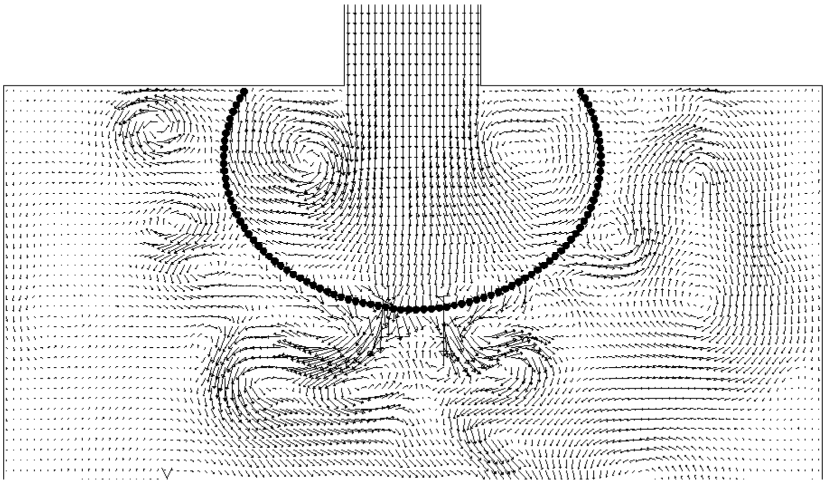


Figure 5: Instantaneous configuration of the flexible bag

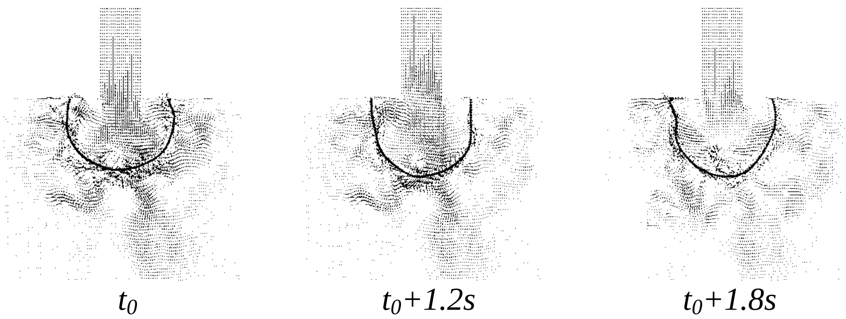


Figure 6: Shape change of the flexible bag

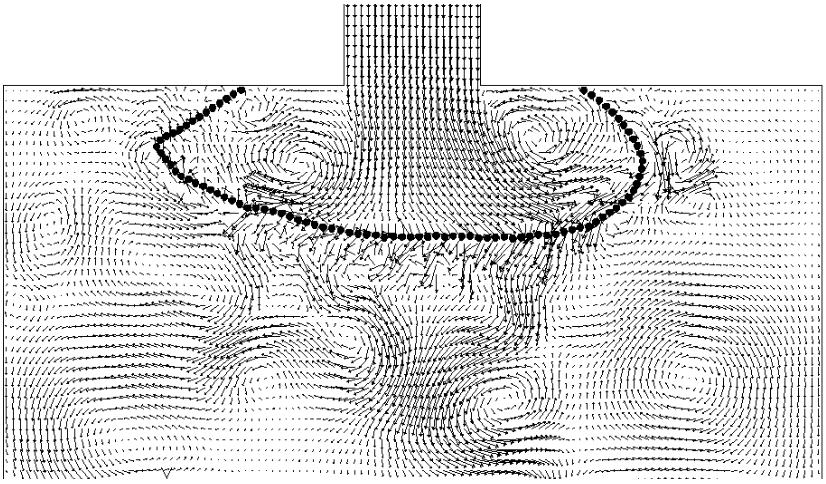
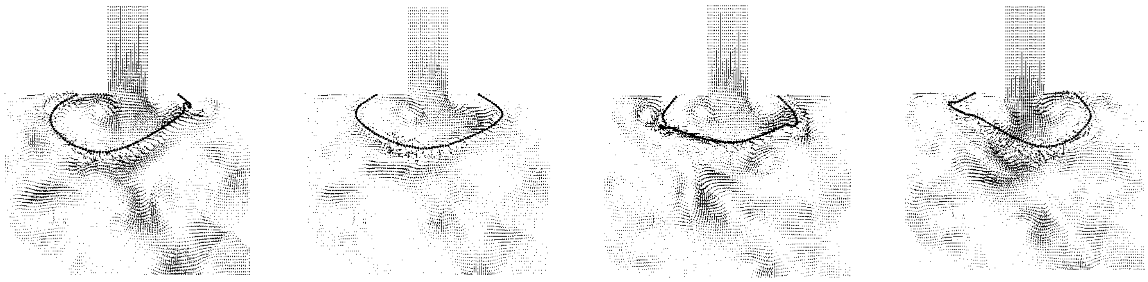


Figure 7: Instantaneous configuration for the elastic bag

4.3 Elastic and moderate flexibility bag

We consider now the case of an elastic bag which can extend its surface. The imposed flexibility force tends to flatten the surface the bag. Under some extend, the flow can modify the size and the shape of the bag (Fig. 7). The results show the existence of a strong interaction between the flow and the bag. The bag oscillates from left to right with a period of about 2 s. (Fig. 8). The oscillation is not very regular, some chaotic behaviour is also present. Compared to the two previous cases, it can be noticed that the distance between the particles is no more uniform. As the results of this non uniformity of the porosity, the liquid metal prefers to flow at positions where the distance between the particles is the largest (Fig. 7). The stretched part of the surface is mainly localized in the bottom, where the jet impinges the bag. The left and the right parts of the bag are more folded than stretched. At its largest extend the total surface of the bag has been found to be only stretched by 13 %. But at some positions the inter distance between the particles was increased by up to 35%.



t_0 $t_0+0.6s$ $t_0+1.2s$ $t_0+1.7s$

Figure 8: Some successive instantaneous configuration for the elastic bag

5 Conclusions

A numerical model was built to simulate the interaction of a combo bag with a flow in a DC casting system. The model uses the concept of marker particles to simulate the movement of a unit surface of the bag. Drag generated by the interaction with the flow, as well as the solid properties of the bag were used to predict the dynamics. Three different configurations were investigated, a rigid rectangular bag, a nonelastic-flexible bag, and an elastic bag. By comparing the three cases the most stable was found to be the flexible and non elastic one. The rectangular and the elastic ones produced strong flow turbulences. However further investigation must be performed in order to correctly estimate the impact of each bag on heat transfer, and on solidification. The present work has shown the possibilities offered by this numerical model for simulating complex fluid-bag interactions. Many different configurations can be considered, in particular a bag whose properties can change with temperature. For the future a 3D model is under preparation.

6 References

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