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DETAILED MODELING OF A METAL DISTRIBUTOR BY MEANS OF A COMBINED NUMERICAL AND PHYSICAL APPROACH

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Abstract

By means of detailed measurements it is shown that the outflow characteristics of the commonly used glass cloth type metal distribution bag are strongly influenced by the deformation of the bag. This deformation is caused by the dynamic interaction between the flexible bag and its surrounding flow field. As a consequence, accurate prediction of the fluid flow in the liquid pool cannot be performed if the distortion of the distribution bag is not taken into account. In this article a method is presented to incorporate the influence of the distortion of the flexible bag on the flow. In this method results from water model measurement are used as input for the numerical modeling. These measurements represent in an implicit manner the entire interaction of the flexible distribution bag with the flow field. The modeling results then show that using the measured input leads to a different and more accurate prediction of the mixing in the sump compared to a more conventional method of modeling.

Introduction

During casting of ingots or billets, the flow pattern in the liquid pool strongly influences the distribution of alloying elements over the cross section. Consequently the properties of the solidified product will be influenced by this flow pattern. Therefore, with respect to alloying element distribution, control over the flow in the liquid pool gives the possibility to improve the product quality.

Considering this flow pattern, two main driving forces can be distinguished. The first is the buoyancy force caused by both temperature differences and concentration differences. Therefore solidification process and the cooling directly interact with the mixing in the sump. The second cause for flow is the inertia force introduced by the liquid metal inlet. During casting of large ingots and billets the flow in the sump is dominated by this inlet flow. In order to control the inlet flow floats, nets or flexible metal distributor bags are used. At present, the latter option, the flexible distribution or combo-bag, is the most frequently used due to its low cost and ease of use in the cast house.

For the design and modification of the flexible distributor, knowledge is required of how the flow pattern in the liquid pool is altered by the design. To that end, several numerical models have been developed which are capable of calculating the fluid flow in the sump and solidification of the material. These models require input for the metal distribution at the inlet. So far most of these numerical models consider the metal distribution bag as a stiff box [1,2,3]. At the top of this box metal enters the domain though a narrow tube, the so-called spout. The metal leaves the box through a set of openings, which can be positioned at the side or bottom of the box depending on the design of the distributor. The distribution of the metal into the liquid pool is assumed to be only dependent on the position and size of these openings. However, in reality the flexible distributor dynamically interacts with the flow in the sump and the flow entering from the spout. Therefore, the distributor deforms considerably in operation and changes for different casting conditions. Consequently, the outflow of the distorted combo-bag changes significantly with respect to the un-deformed situation as implemented in the models. In reality, the flow patterns in the sump will be completely different compared to those predicted by models, which consider the bag as being stiff. The prediction of elemental distribution over the ingot-cross section will also deviate from that found in reality.

From a point of view of computational effort, detailed modeling of the combo bag deformation is not feasible. The dynamic interaction between the flexible bag and the flow field, in combination with detailed modeling of solidification calls for a very fine mesh and a detailed description of the physics. Therefore, within the present article a hybrid method is described for detailed modeling of the distribution bag. Here, the outlet characteristics of the distribution bag are measured during water model experiments and these measurements are used as input/inlet conditions for the numerical model. The numerical model then calculates, by using this input, the flow in the sump and the related solidification process. In this paper, the experimental method is presented as well as the methodology for implementation in the numerical model. A section discussing the dynamics of the flexible distribution bag quantifies the need for this approach using detailed flow measurements. Finally the results are presented showing the effect of using the measured distribution bag outlet characteristics as input for numerical model. These results are compared with the results obtained with the more conventional modeling approach.

Methodology

<u>Water modeling measurement of the distribution bag outlet</u>

Within the water model temperature differences are not present, resulting in the absence of buoyancy effects. Therefore, one can argue the usefulness of a water model simulation with respect to the aluminum-casting situation in which temperature differences are present. However, in the liquid metal flow, the buoyancy force does not play an active role in every region. The relative importance of the buoyancy term can be expressed by means of the following ratio of dimensionless numbers

$$\frac{Gr}{Re^2} = \frac{\Delta TLg\beta}{U_0^2}$$

where *Gr* is the Grashof number, *Re* the Reynolds number, ΔT the local temperature difference, *L* a length scale typically the height of the distribution bag, *g* the gravity constant, β the volumetric expansion coefficient, and U_0 the velocity at the inlet. For very small values of this ratio the influence of buoyancy can be neglected while for very large values the buoyancy effects are dominant. Considering a typical casting situation this value is of the order 10^{-1} in the region of the metal entranc. Therefore, the influence of the buoyancy force can be neglected and the results of the water model are a good representation of the process taking place during aluminum casting. Looking deeper into the liquid pool, the situation changes completely. There, the typical velocity is in the order of 1 cm/s giving a dimensionless ratio in the order of 1-10. Consequently buoyancy forces can no longer be neglected. Water modeling results showing the mixing and transport in the sump then have a limited predictive value.

Considering the situation at the distribution bag outlet, casting parameters still need to be scaled properly. Therefore, for both situations the Reynolds numbers should be equal. Considering the properties of aluminum and water, this scaling can be accomplished by increasing the speed in the water model by a factor of about 2.

For the measurements of the distribution-bag output a full-scale water facility was used. In order to model the presence of the solidification front, transparent plates were positioned inside a plexiglas water tank. The plates were densely perforated allowing on every position of the plate a homogeneous outflow equal to the casting speed. At the inflow a flexible distribution bag was positioned. The quantitative measurement of the flow leaving the distribution bag was performed by using the image analysis technique PIV (Particle Image Velocimetry, see reference 4)). The flow was visualized by adding small particles to the flow. These particles were visualized by using a 5 Watt Argon Ion laser system which illuminates a 2D slice of the domain. The particles illuminated in this slice were recorded using a digital camera system.

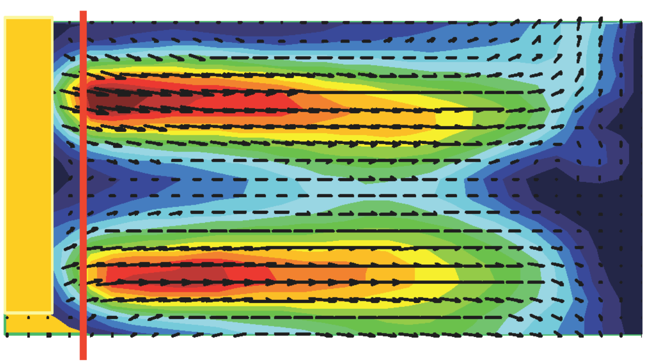

Figure 1 : Outflow from the distribution bag's front opening measured in plane 1 (see figure 2). The values along the red line are later used as input for the numerical model.

The sequence of images captured by the camera system was processed using image correlation techniques to provide a sequence of vector fields representing the 2D time dependent outflow from of the distribution bag. A typical example of such a measurement is presented in figure 1.

By changing the orientation of the illuminated slice from slice 1 to 2 (see figure 2) the third component of the velocity was obtained.

An evaluation of the vector field over the entire volume was obtained by measuring in each orientation (1 and 2) on at least 10 parallel positions. This resulted in a full 3D scan of the volume in the vicinity of the outflow opening. Due to the time difference between the measurements in each plane, the 3D vector field in the volume can only be deduced when the average velocity value of a measurement is considered. Therefore, all results as presented in the next sections were time average values of the velocity field. Finally the distribution bag outflow was evaluated by considering only a small part of the measured volume. To that purpose, a plane parallel to the outflow opening was selected which was positioned close to the distribution bag outlet. Typically such a plane is situated about 1 to 2 cm in front of the distribution bag outlet.

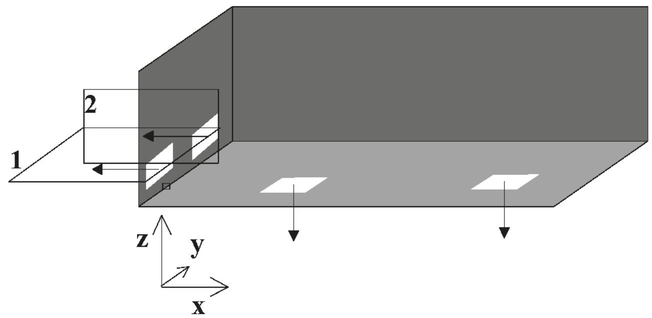

Figure 2: The distribution bag geometry and measuring planes defined at the distribution bag outlet. The planes are defined at the front opening but the definition also applies for the bottom opening

<u>Implementation and numerical model</u>

The measurement results were used as boundary conditions for the numerical simulation. As one can understand, it is not possible to measure exactly at the outflow edge of the distribution bag, Therefore, the values measured just in front of the distribution bag were used (see vertical (red) line in figure 1). In order to compensate for this shift, the distribution bag is therefore chosen to be slightly larger in the numerical domain.

The numerical domain then starts at the boundaries at which the velocities were measured. These boundaries were represented by the rectangular box at the top of the domain (figure 3). The colors on the rectangular box represent the velocity at the inflow. This velocity varies between 0 m/s and approximately 0.1 m/s. For the simulation of the solidification process a single phase or mixture model was used. This approach is embedded in the commercial CFD package CFX version 4.4.

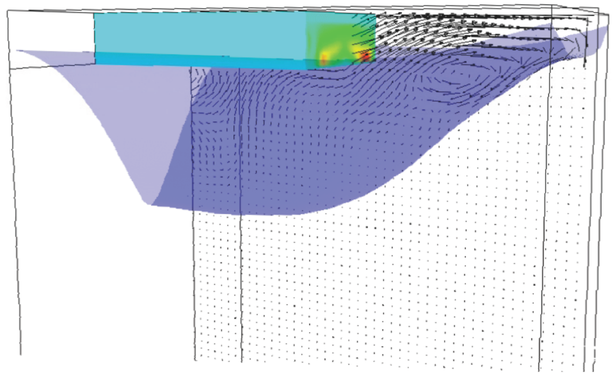

Figure 3: Characteristic result from the numerical simulation in with water model simulations results used as input

Characterization of the flexible distribution bag outflow

The first question to be answered was whether the outflow of the distribution bag was influenced by the casting conditions. A full-scale glass fiber distribution bag was mounted inside the water model. In order to quantify the outlet, several parameters were varied. The results showed that the volume/mass flow at the inlet appears to have the strongest influence on the outflow of the distribution bag. Therefore, in this paper only the results of two different volume flows are presented (Table 1).

Table 1: Model parameters.

Case	Mold width (mm)	casting speed (mm/min)	Corresponding water flow (m^3/hr)
1	1070	46	1.4
2	1070	92	2.8

Outlet front opening

For the first set of measurements the outflow at the front opening was measured. The plane in which the outlet is considered is situated about 2 cm in front of the actual distribution bag outlet.

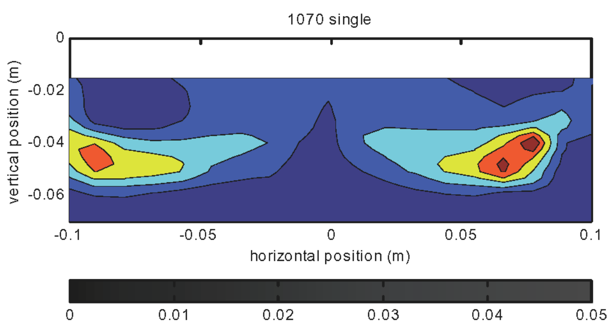

Figure 4: Contour plot of velocity in the front opening for a volume throughput of 1.4 m^3/h. The plane under investigation was orientated in y-z direction. The velocity is in m/s.

Considering the characteristics of the flow within this region, this small shift will have no major influence on the results. Therefore the measurements can be considered as valid measurements for describing the distribution bag outflow.

The first measurement was for the case of a volume flow equal to 1.4 m^3/hr. Although the outlet opening was a slit over the full length, the outflow is far from homogenous cross the opening (

Figure 4). Most of the material leaves at the sides of the distribution bag, in the form of two jets. The intensity and direction of these jets will have a strong influence on the flow field generated in the sump.

In the second experiment the volume flow was doubled. The velocity pattern changed only slightly (Figure 5). The outflow jet positions are shifted more to the sides and top with respect to the previous case. Consequently, a slightly different flow pattern in the sump is expected. Furthermore the jets have a more confined shape resulting in a more intense jet structure.

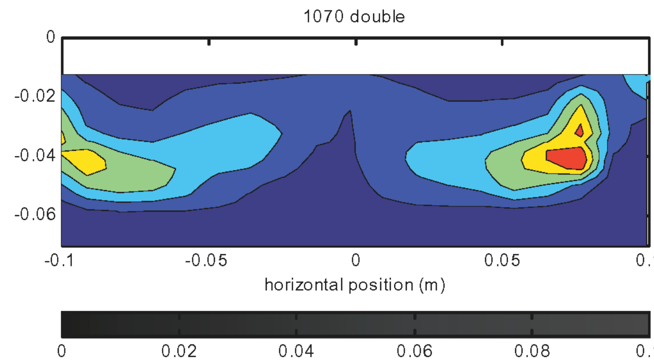

Figure 5: Contour plot of the velocity for a volume throughput of 2.8 m^3/hr. The velocity is in m/s.

Outlet bottom opening

The second outlet flow to be quantified was the bottom opening. In the distribution bag two bottom openings are positioned on the center line, each at about 1/3 of the bag length (Figure 2). These openings have a rectangular shape with dimensions of 5x5 cm^2.

The first set of experiments was performed for a volume flow equal to 1.4 m^3/hour. The result (Figure 6) shows the outflow of the square bottom opening. The right hand side of the picture is positioned closest to the end of the distribution bag.

The strongest outflow appears on the right hand side of the opening with a peak slightly off-axis of the opening. However, over a considerable area an outflow is observed. Comparing the maximum outflow velocity and surface area with those as found in the front opening (Figure 4), about 10% of the total volume flux goes, for this casting situation, through the bottom opening area.

For a double volume flow (2.8 m^3/hr), the outflow through the bottom opening changes completely. Figure 7 shows that more than 75% of the outflow area almost no velocity is detected. Only in the right hand side of the opening is a strong outflow observed. The magnitude of this outflow is about twice the value of that found for the 1.4 m^3/hour case. For this typical case it is estimated that the volume flow through the bottom opening is approximately 5% of the total volume flow.

In conclusion, for varying metal throughput the outflow of the distribution bag dynamically responds to these changes. These changes should be incorporated in the modeling input or description.

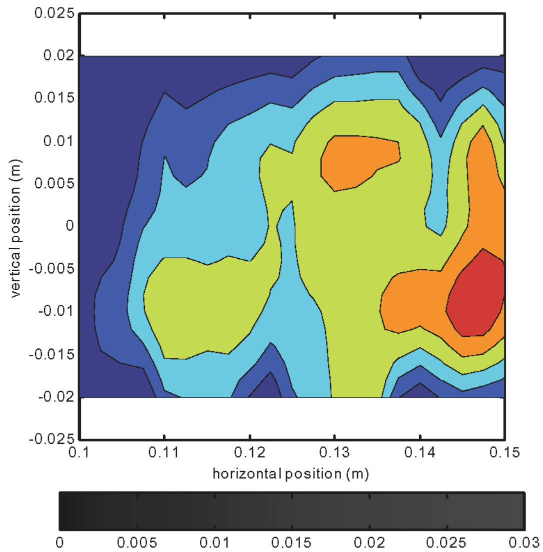

Figure 6: Measured outflow from the bottom opening for a flow rate of 1.4 m^3/hour. The velocity is in m/s.

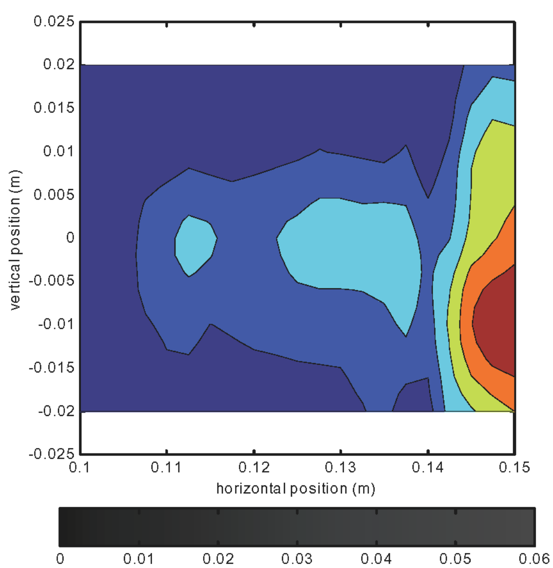

Figure 7: Measured outflow from the bottom opening for a flow rate of 2.8 m^3/hour (The velocity is in m/s)

Numerical modeling

In this section *two cases* are considered and compared which will elucidate the effect of using measurement results as input for the numerical model.

In the first case the flow in the distribution bag and in the ingot was fully modeled. Consequently, the walls of the distribution bag and the interior of the bag were part of the computational domain. Furthermore, an additional inlet tube was defined which allows the metal flow into the distribution bag. The sides of the distribution bags were modeled as stiff walls. The pressure difference over these walls therefore had no influence on the shape of the distribution bag. In the remainder of the text this undeformed distribution bag geometry is referred to as *case 1*.

In the second case, in order to improve reliability of the casting simulations, the velocity measurements from the water model were used as input for the numerical simulations. By following this approach the distortion of the distribution bag and its effect on the flow patterns was implicitly taken into account. In the remainder of the text this case is referred to as *case 2*.

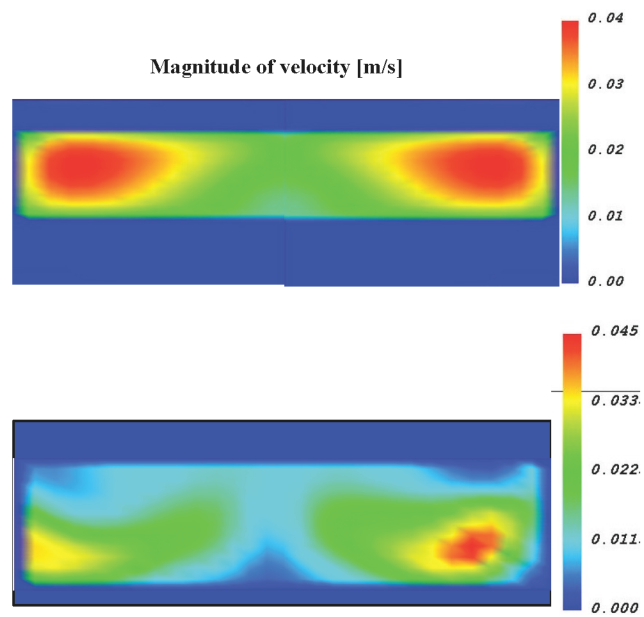

Figure 8: Modeled (top) and measured (bottom) outlet velocities at the front opening of the distribution bag (velocity in m/s)

Of primary interest is the difference between the measured outflow and that obtained for the fully modeled distribution bag. In the results showing the outlet from the front opening (Figure 8) the following major differences can be observed.

- The calculated outflow is more evenly distributed over the entire outflow opening while in the measurements some confined outlet jets can be found.
- Due to the deformation of the bag the height of the outflow region is about 25% larger for the measured results

- The measured front outflow shows a strong asymmetry in the pattern while the calculated outflow is perfectly symmetric.

Also in the outflow of the bottom opening a large difference can be found between the results. Figure 9 shows the vector field at the outlet seen from below. The calculated flow field contains both flow vectors into and out of the distribution bag. The inward flow is almost absent in the measured flow pattern. The measured outflow has a more homogeneous distribution and has a strong forward outlet component. This forward component is almost absent in the calculated flow pattern.

As the outlet profile influences the flow pattern in the sump, both cases will be considered. In the first comparison the flow just below the surface of the liquid aluminum is considered (Figure 10). Note that in this figure only a quarter of the surface area is presented.

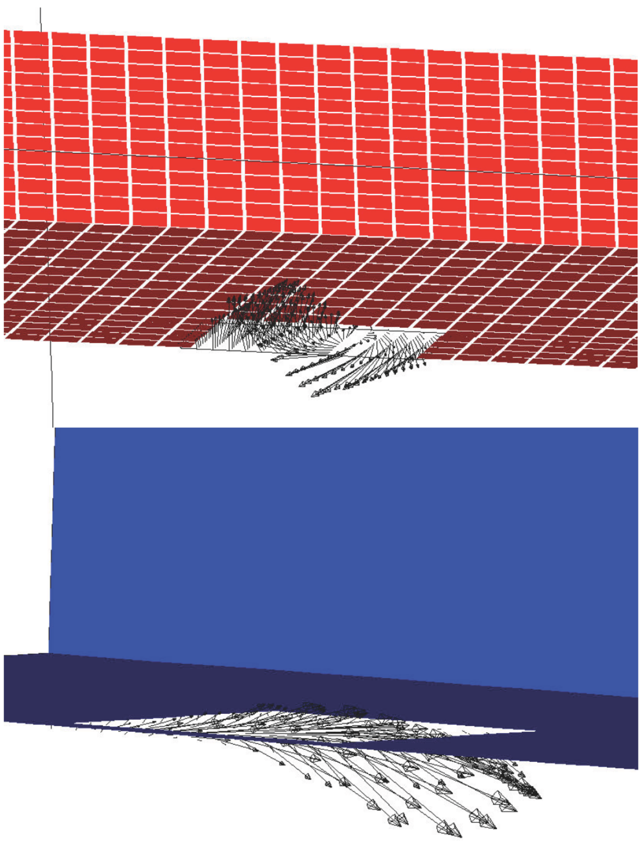

Figure 9: Modeled (top) and measured flow pattern at the bottom opening of the distribution bag at a casting speed of 45 mm/min

Comparing these results the following differences between case 1and case 2 can be observed:

- In case 1 (distribution bag fully modeled) the flow in front of the distribution bag is deflected more strongly to the sides. In the results for case 2 the flow is directed more strongly in the forward direction.
- In the results for case 1 a circulation region appears close to short edge of the domain (see the red ellipse in the upper drawing). This recirculation area is absent in the results for case 2
- In case 2 a recirculation area appears just outside the distribution bag (blue ellipse). This recirculation area is absent in the results from case 1

Both differences are most likely caused by the different inflow patterns. As already shown in figures 4 and 5, two confined jets were present in the outflow. Due to these jets the flow is directed strongly in the forward direction. On the other hand the calculated outflow is more evenly distributed over a larger area and will therefore have a tendency to slow down much faster and will deflect faster in the transversal direction. Conclusions with respect to edge and corner feeding will be different depending on which result is considered.

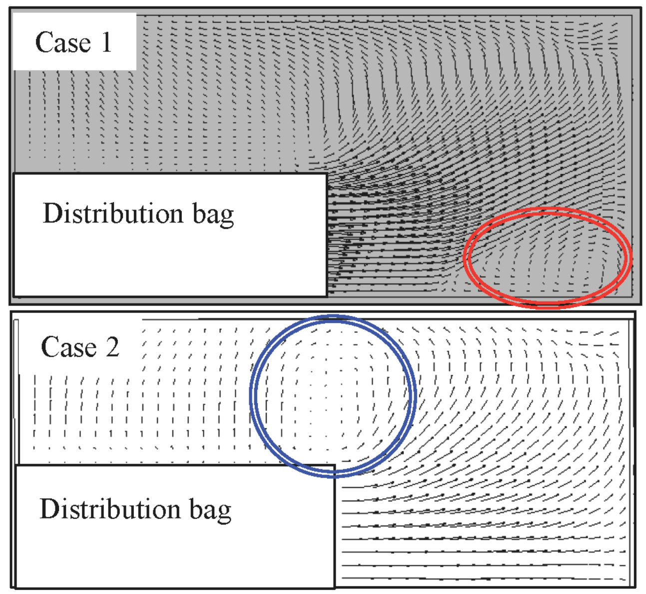

Figure 10: Flow pattern approximately 25 mm below the top surface of the liquid aluminum. The top figure shows the results for the fully modeled case, the bottom figure shows the results for the case where measurements were used as input at a casting speed of 45 mm/min.

The flow patterns in a cross section through the liquid pool are shown in Figure 11. The flow pattern in such a cross section will give information about the mixing and the transport of alloying elements in the sump. Accurate prediction of this transport phenomenon is important for accurate prediction of macro segregation.

Considering the results obtained from case 1 (fully modeled) and case 2 (implemented measurements) the following major differences can be observed:

- For case 1, the outflow of the distribution bag and the subsequent flow towards the side edge takes place in a smaller and thinner area. Therefore, the flow below the oxide layer will be stronger. In case 2 this flow takes place in a larger area.

- Once the material arrives at the edge of the domain it is almost fully reversed for case 1 and flows backwards almost horizontally (red arrow in top figure). For case 2 the flow is along the solidification front (blue arrow in bottom figure). Therefore, the predicted mixing and transport processes in this region for both cases are totally different.

- Below the bottom opening a stronger flow field and mixing can be observed for case 2. Therefore, the mixing and the transport of alloying elements will be different. Consequently the predicted macro segregation will differ strongly. The driving force for this difference is the outflow from the bottom opening. Whereas for case 1 the bottom opening hardly influences the flow pattern in the center region, for case 2 a greater influence can be observed.

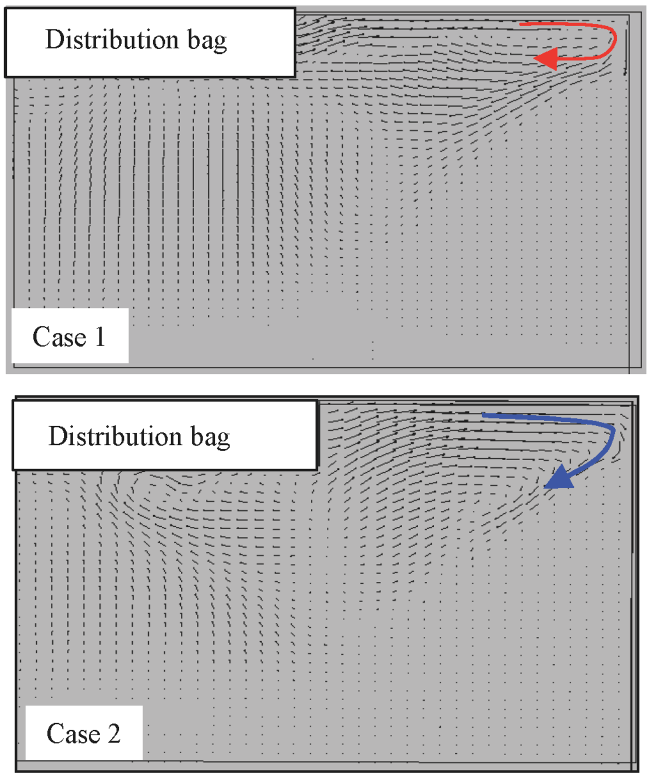

Figure 11: Flow pattern on the center of the ingot . For the casting speed 45 mm/min was chosen.

The results above clearly show that a major difference exists between the outflows of the combo bag as measured and calculated. Due to this difference the predicted flow pattern in the liquid pool is entirely different and conclusions with respect to surface turbulence and macro segregation will be different for the two cases.

Discussion

In the previous sections it was shown that full modeling of the distribution bag by means of a stiff box will result in an entirely different outflow from the distribution bag compared to the measured one. The cause for this difference is the flexible character of the distribution bag as shown in Figure 12. Considering the situation when the distribution bag is unloaded, the bottom surface is almost flat. Once an inlet flow from the spout is introduced, a strong impingement in the center of the distribution bag bottom will cause a deflection of the bottom. Consequently the flow will follow the deformed shape of the bottom and will have a different outflow direction at both the front and bottom openings. As the casting speed increases, the impingement and momentum transfer at the bag center increase, which results in a changed shape of the bag. Again this will cause a deflection of the flow pattern at the bottom and front opening. Consequently the driving force for mixing in the liquid pool will be changed, resulting in a modified flow pattern in the liquid pool. This change in flow pattern will also have an influence on the distribution bag geometry, but it is expected that this is only a second order effect.

Conclusions

The results presented, show that the flexible combo bag dynamically interacts with the fluid flow in and around the bag. The volume flow through the distribution bag (which is of course directly linked to the casting speed) has a major influence on the outflow from the distribution bag. It was observed that for increasing volume flow the outflow is directed more upwards and the proportion of outflow from the bottom opening increased.

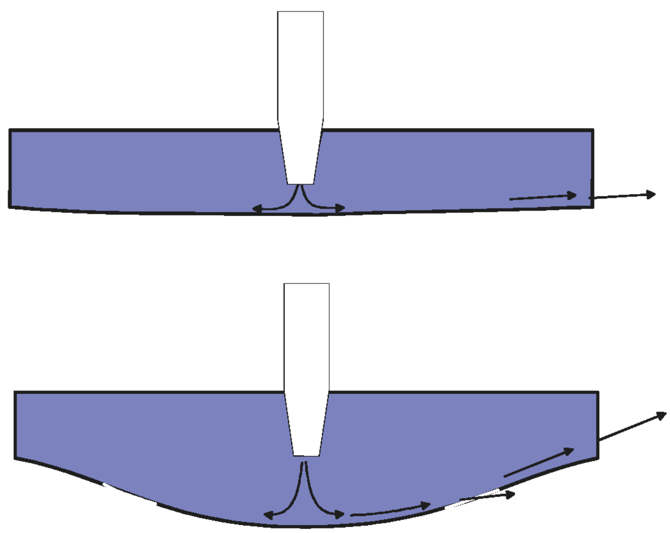

Figure 12: Schematic representation of the distribution bag deformation due to the flow from the spout. For low casting speed (top figure) and high casting speed (low figure)

The measured outflow from the distribution bag was used as input for modeling the fluid flow behavior in the liquid pool. These results were compared with the case in which the ingot as well as the entire distribution bag was modeled. The outflow of the distribution bag, as calculated by the latter method, was different from the one as measured. Consequently the flow pattern in the liquid pool as predicted by the fully modeled case differed significantly from the results obtained by the model in which measurements were used as input. The latter results are considered to be more accurate as the measured input implicitly represents the dynamic interaction of the flow with the distribution bag.

Considering the dynamic interaction between the flow and the distribution bag it can be understood that fully modeling this interaction is far too complicated. Calculation of this process calls for modeling of the small process details as well as the large-scale effects. A short cut to overcome detailed modeling of the deformation effects of the flow is measuring the outflow of the bag as presented in this article. The measurements will implicitly represent all detailed interaction effects between the flow and the distribution bag and are therefore the most accurate input for modeling the fluid flow behavior in the liquid pool.

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