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Numerical Simulation of the Liquid-Gas Interface Shape in the Shot Sleeve of Cold Chamber Die Casting Machine

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A mathematical model has been developed to simulate the flow pattern of molten metal and to predict the liquid-gas interface shape in the shot sleeve of a cold chamber die casting machine during the injection stage. The flow pattern in the shot sleeve is known to be closely related to the extent of gas entrapment of molten metal in the sleeve during the injection operation. In this study, a Variable Spacing Even Mesh (VSEM) method is proposed to incorporate with a computational fluid dynamics technique, named SOLA-MAC, to simulate the flow pattern in the shot sleeve. SOLA-MAC can deal with free surface flow problems while the VSEM method is used to handle the problem where the space in the shot sleeve keeps decreasing as the plunger moves to push the molten metal. The model is then tested on the shot sleeve of a cold chamber die casting machine. Four plunger speeds are tested to demonstrate the effects on the flow pattern of molten metal in the shot sleeve. The critical speed found in this study is 38 cm/s and it is close to the reported critical speed under the conditions that the space between the plunger and the sleeve end is 5 cm in diameter and 30 cm in length, and the fill ratio is 50%. As the plunger speed is slower than the critical speed, the wave front propagates along the sleeve faster than the plunger and reflects against the end wall of the sleeve. The remaining air in the shot sleeve is entrained as the wave front enters to the gate. As the plunger speed is higher than the suggested critical speed, the melt is immediately pushed higher in front of the plunger and forms a surge. The surge traps air in the early stage of the injection process.

Keywords die casting, fluid flow, numerical simulation, plunger

1. Introduction

The die casting process has many advantages, such as high production rate and good surface finish. It, however, has its disadvantages. One of the problems is gas porosity in the casting, which makes the casting unsuitable for further heat treatment. The mechanical properties of the casting suffer from the gas porosity and lack of heat treatment.

For die casting produced by a cold chamber die casting machine, molten metal is first poured into the shot sleeve. The plunger then moves to push molten metal to flow in the shot sleeve, enter the runner and gating system in the cavity, and fill the cavity in the die. As the casting solidifies, the die opens and the casting is ejected from the die. It is known that the entrapment of air/gas will result from undesirable flow patterns during filling. The entrapped air/gas bubbles in the molten metal will be sources of gas porosity in the casting after mold filling and solidification. Two places are most prone to the entrapment of air/gas during filling. One is in the die cavity and the other is in the shot sleeve. The flow of molten metal in the die cavity is pretty much dependent on the design of the running and gating system. The flow of molten metal in the shot sleeve, however, depends on the die casting operation; mainly the setting of plunger speeds (Ref 1, 2).

For the die casting operation, a calculated amount of molten alloy is poured into the shot sleeve and partially fills the sleeve as shown in Fig. 1. The initial fill level in the sleeve is called the fill ratio. To minimize air entrapment, the molten metal injection process usually consists of three stages. The first stage is the so-called slow speed stage when the plunger moves slowly in the shot sleeve to push the molten metal to fill the sleeve and then enter the die. Then, during the high speed stage, the plunger moves rapidly and molten metal is squeezed into the die cavity through narrow ingate(s). Finally, it is during the intensification stage where pressure is inserted onto the casting by the plunger. The slow speed stage is responsible for the gas entrapment in the shot sleeve.

Molten metal is initially at rest horizontally in the sleeve, and then the plunger starts to move slowly. As the plunger proceeds, the molten metal is pushed high in front of the plunger and gradually fills the sleeve and enters the die. The main concern in this study is how plunger speed in the slow speed stage affects the way molten metal fills the sleeve before it enters the die. There are two main features for this kind of flow problem: the movement of the free surfaces of the molten metal and the domain where the molten metal flow keeps decreasing.

Previous work (Ref 2) has shown that there is a critical plunger speed, which can raise the wave caused by plunger motion to fill the shot sleeve with less air entrapment. If the plunger reaches a speed higher than this critical speed, the wave front might roll over and cause air entrapment. If the plunger does not reach the critical value, the wave might reflect against the end wall of the sleeve and trap air in the molten metal. The

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influence of plunger speed, acceleration, and filling ratio on the injection process has been studied theoretically by Faura et al. (Ref 1), Garber (Ref 3), Tszeng and Chu (Ref 4), and Thome and Brevick (Ref 5). Experimental studies have been carried out by Garber (Ref 3) and Duran (Ref 6).

It is known to be very difficult to observe/measure the fluid flow phenomena of molten metal during the filling of a casting mold/die (Ref 7). Significant efforts have been made to numerically simulate the filling pattern in a mold/die cavity (Ref 8-10). The similarity between die filling and sleeve filling is that they are both fluid flow problems with free surface movement and the location of the melt changes rapidly. The main difference between sleeve filling and die filling is that for die filling, the space for the molten metal to flow and fill is fixed while for sleeve filling, the flow domain keeps decreasing because of the plunger movement. The moving boundary problem was first accounted for in the heat transfer phenomena at the interface between ice and water. The technique was later applied to study the melting of polar ice (Ref 11). A literature survey shows that there are essentially two approaches to numerically handle the moving boundary problem (Ref 12-13).

The first approach is called the Fixed Grid Method. The proper number of elements, mesh spacing, and time step are chosen before the numerical simulation and remain unchanged throughout the simulation of the concerned process. Muehlbauer and Sunderland applied the method to a heat transfer problem (Ref 14). Bankhoff applied the method to a heat transfer and diffusion problem (Ref 15). The disadvantages of the method are that the moving boundary cannot be clearly defined and numerical solutions become unstable when the boundary moves from one element to another.

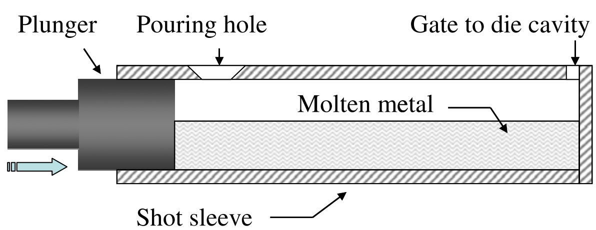

Fig. 1 Schematic representation of the shot sleeve of a die casting machine

The second approach is called the Variable Grid Method. The mesh spacing and time step are adjusted to respond to the computational need during the numerical simulation. There are two ways to make the adjustments. Douglas and Gallie adjusted the time step to assure that the boundary moves one element distance for each time step (Ref 16). Murray and Landis separately adjusted the spacing of the elements on both sides of the boundary to keep the time step constant (Ref 17), meaning that the element spacing on one side of the boundary will decrease while that on the other side will increase. This treatment has the problem of numerical instability when the element spacings on the two sides differ too much. Gupta further modifies this treatment by adjusting (decreasing or increasing) only the spacings of the elements near the fixed wall boundaries and keeping the element spacings near the moving boundary unchanged (Ref 18). They applied the method to study the heat transfer phenomena during phase transformation and the diffusion of oxygen in absorbing tissues. Schematic illustrations of the three mesh systems are shown in Fig. 2.

In this study, an algorithm called the Variable Spacing Even Mesh (VSEM) method, which is a modification of the Landis's meshing technique, is proposed to account for the moving boundary problem when a plunger moves in the shot sleeve. A mathematical model is then developed to incorporate the VSEM method and the SOLA-MAC (Ref 8) technique to numerically simulate the flow pattern of molten metal in the shot sleeve of a cold chamber die casting machine during the injection operation.

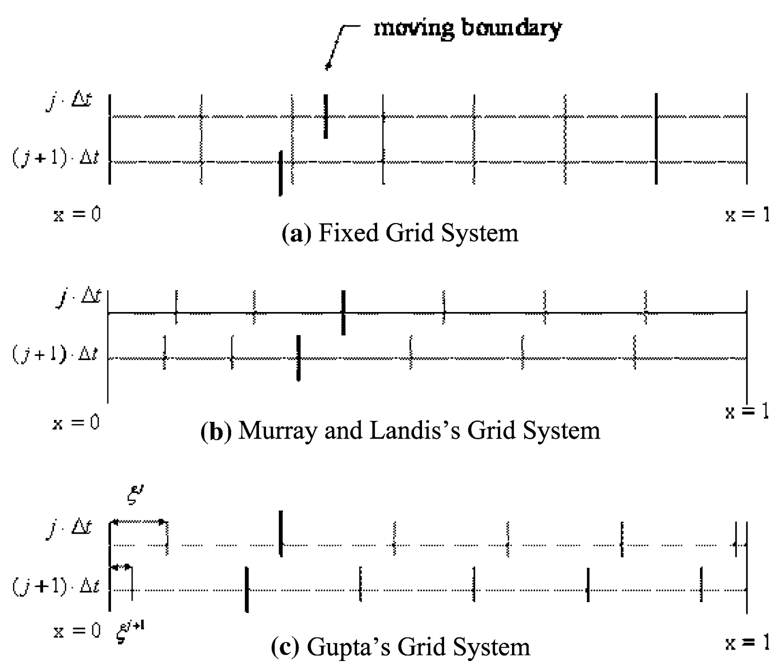

Fig. 2 Schematic illustrations of the three different grid systems

2. Mathematical Model

2.1 Highlight of SOLA-MAC Technique for Die Filling

For die filling, the space for molten metal to flow and fill is fixed. Flow of molten metal during die filling is highly transient; the amount and location of the melt change. Calculation of the location of molten metal must be an integral part of the computational techniques used to model it. A family of computational techniques named MAC, SMAC, SOLA-VOF and others are well suited for handling these problems. Although they differ from each other in the way that they keep track of the location of the free surface and satisfy the free surface boundary conditions, they are based on similar principles. The techniques in the MAC family are believed to be capable of appropriately handling the free surface problems of concern and by using rather simple algorithms, they are efficient in computation.

The SOLA-MAC technique uses a finite difference scheme for the mathematical analysis of fluid flow problems. Like most numerical techniques, it first divides the simulation domain into a mesh system; that is, the configuration of the die cavity under consideration is divided into a number of subdivisions called cells. The field variables, such as the velocity components in the x and y directions, are located at the center of the four sides of a mesh element, and the pressure and viscosity terms are located at the center of the staggered mesh system. A set of imaginary markers are introduced into the system to represent the location of the fluid at any instant. The cells are designated as full, surface, or empty based on the locations of the fluid markers and the nature of their surrounding cells. A full cell is the one that contains at least one fluid marker and all of its neighboring cells also contain fluid markers. A surface cell contains at least one marker but has at least one neighbor without a fluid marker. An empty cell is any cell with no fluid marker. Collectively, the full cells constitute the interior regions and the surface cells constitute the surface region.

The velocity field of the moving fluid domain can be calculated by the application of fluid dynamics principles. In the interior region, the fluid dynamics principles to be obeyed contain the continuity equation and momentum equation. When solving these equations, a SOLA scheme is used. In the surface region, the continuity equation, however, does not hold in the state of zero divergence because the flow domain may be expanding or shrinking in the surface region. Instead, the following conditions should be satisfied on the free boundaries: (a) stress tangential to the surface must vanish; and (b) stress normal to the surface must balance the externally applied stress.

Accurate application of the free surface boundary conditions requires accurate prediction of the free surface orientation, which is difficult to obtain with the MAC method. Without resolving the surface orientation, the technique proposes some simplifications to the treatment of the free surface boundary conditions. Next, the fluid markers are moved according to the calculated velocity field to represent the new location of the fluid domain. The procedure can be repeated from the beginning, when the die is empty, until it is filled. Details of the technique can be found in Ref (8).

2.2 Description of Variable Spacing Even Mesh (VSEM)

For shot sleeve filling, the space in the shot sleeve keeps decreasing because of the plunger movement. To simulate the filling process, mesh generation is first made for the space of the shot sleeve between the plunger and the end of the sleeve. Instead of having a fixed mesh system throughout the whole simulation period, the VSEM method is applied to generate a new mesh system at each time step.

Before the calculation for each time step, the VSEM method first calculates the distance of the plunger movement for the previous time step, assuming the plunger moves with the speed of U_{wall}. During the time step of δt, the displacement of the plunger is

$$\Delta X_{\text{wall}} = U_{\text{wall}} \cdot \delta t = X_n(a_1) - X_n(a_1'), \quad \text{(Eq 1)}$$

where $X_n(a_1)$ is the coordinate of the location of the plunger (with the coordinate of the sleeve end defined as 0) at time a_1 and $X_n(a_1')$ is the coordinate of the new location of the plunger at time a_1'. Since the number of elements remains unchanged, the element spacing in the direction of the plunger movement must be decreased. The shortening of the element spacing in the direction of the plunger movement can then be calculated.

$$\Delta x_{\text{wall}} = \frac{\Delta X_{\text{wall}}}{n} = \frac{X_n(a_1) - X_n(a_1')}{n}, \quad \text{(Eq 2)}$$

where Δx_{wall} is the shortening of the element spacing and n is the number of elements. Figure 3 shows schematically how the new element spacing is calculated from the old one. As the new element spacing is determined, a new mesh system can be generated. Again, the field variables as well as the fluid markers, are designated at the appropriate locations of the new mesh system. Finally, the new liquid-air interface is defined for the new time step. It should be noted, however, that the new positions where the field variables are housed are slightly shifted from the old ones as shown in Fig. 4. The values of the field variables at these new positions must then be re-determined. For example, the velocity component in the x direction in the new mesh system can be differentiated simply form the two neighboring cells in the old mesh system.

$$U_{i-1} = \frac{U_i' \cdot [XI(i+1) - XIq(i)] + U_{i-1}' \cdot [XIq(i) - XI(i)]}{\Delta x}, \quad \text{(Eq 3)}$$

where the superscript of (′) denotes the velocity variables at the old time step and the subscript of (q) denotes the x coordinates at the new time step. $XI(i+1)$ and $XI(i)$ are the x coordinates of the boundaries of elements $i + 1$ and i, respectively. Δx is the element spacing at the old time step.

Again, the interior region and the surface region are differentiated in the new mesh system based on the new flow configuration. Fluid dynamics principles and boundary conditions are again applied to calculate the new field variables for the new time step and to move the markers accordingly as described in Section 2.1. The movement of the plunger in each time step is limited to be less than half the length of an element in the x direction. It should be noted that the number of markers in the computational system remains unchanged throughout the whole calculation cycle since the amount of molten metal in the shot sleeve is fixed in the slow speed injection stage. The procedure is repeated from the beginning, when the molten metal in the sleeve is at rest to the next stage, when the molten metal is pushed to move until the sleeve is filled. Detailed description of operation procedures of the program can be seen in Fig. 5.

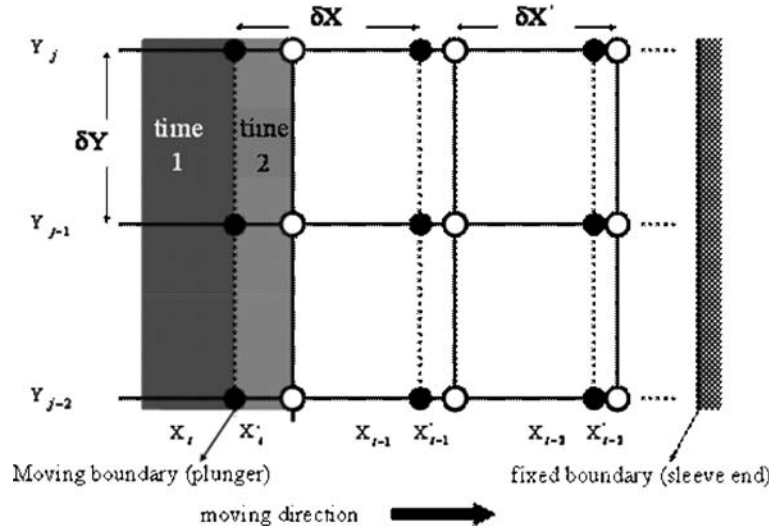

Fig. 3 Schematic illustration of how new element spacing, $\delta x'$, is calculated from the old one, δx

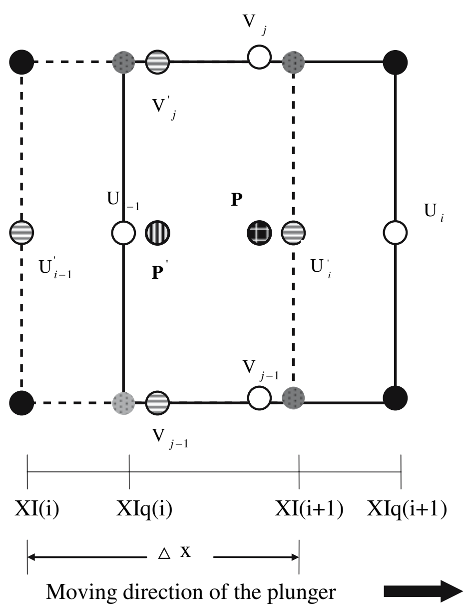

Fig. 4 The positions of the field variables for the old time step and the new time step

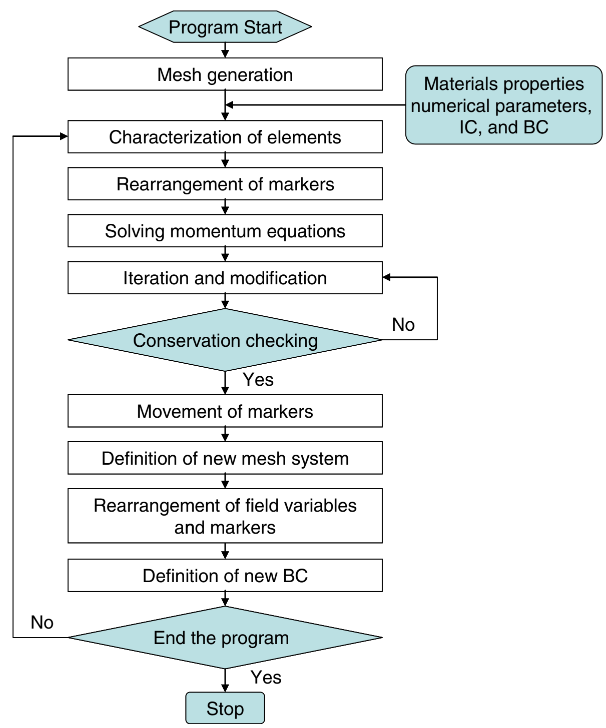

Fig. 5 A flowchart detailing the operation of the program

3. Test Results and Discussion

The developed model was tested on the filling operation of the shot sleeve of a cold chamber die casting machine and is considered isothermal. The plunger was on the left, the sleeve end was on the right and there is a gate connected to the runner system of the die. The space between the plunger and the sleeve end was 5 cm in diameter and 30 cm in length, and the fill ratio was 50%. Before the numerical analysis, the grid-independency of the system was simply checked using a different number of grids. The system was finally divided into 100×42 elements in consideration of grid-independency and calculating efficiency. Several plunger speed settings were used for the slow speed injection stage to study the effects of plunger speed on the flow pattern in the shot sleeve.

3.1 Filling Pattern for a Low Plunger Speed

The first plunger speed tested was 25 cm/s, which is slower than the reported critical speed of 41 cm/s (Ref 2). The simulated flow patterns are shown in Fig. 6. As the plunger starts to move, the molten metal is pushed high and a surge is formed right in front of the plunger. This can be seen in Fig. 6(a). When the plunger moves further, the surge grows longer as shown in Fig. 6(b). Then, a wave starts to form as the molten metal in the surge moves faster than the plunger. This can be observed in Fig. 6(c). Figure 6(d) shows that the wave moves ahead as the plunger keeps pushing. After that, the molten metal is pushed high against the sleeve end and up to

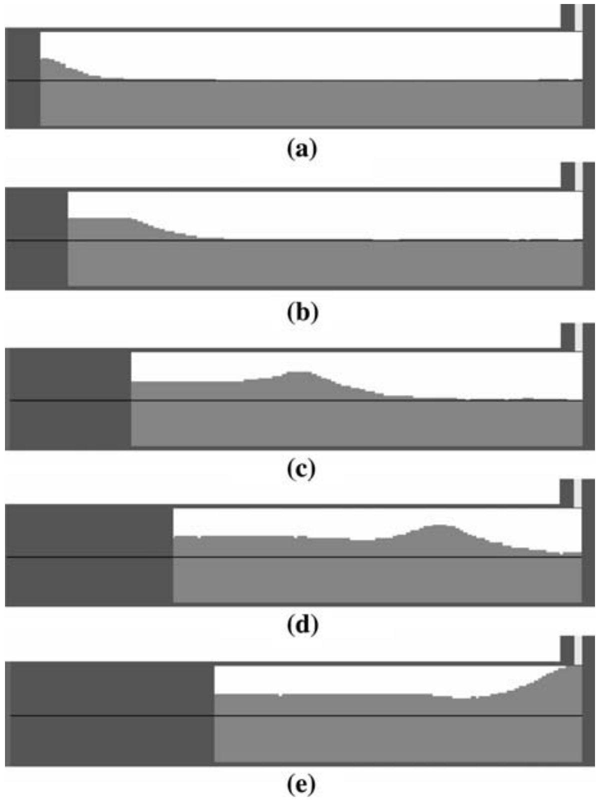

Fig. 6 The flow patterns of molten metal in the shot sleeve for a plunger speed of 25 cm/s at various instants during filling

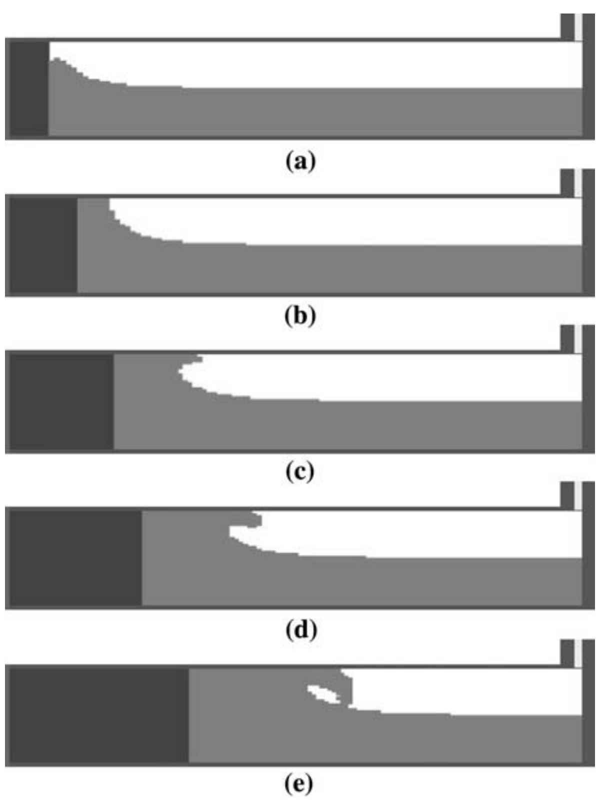

Fig. 7 The flow patterns of molten metal in the shot sleeve for a plunger speed of 60 cm/s at various instants during filling

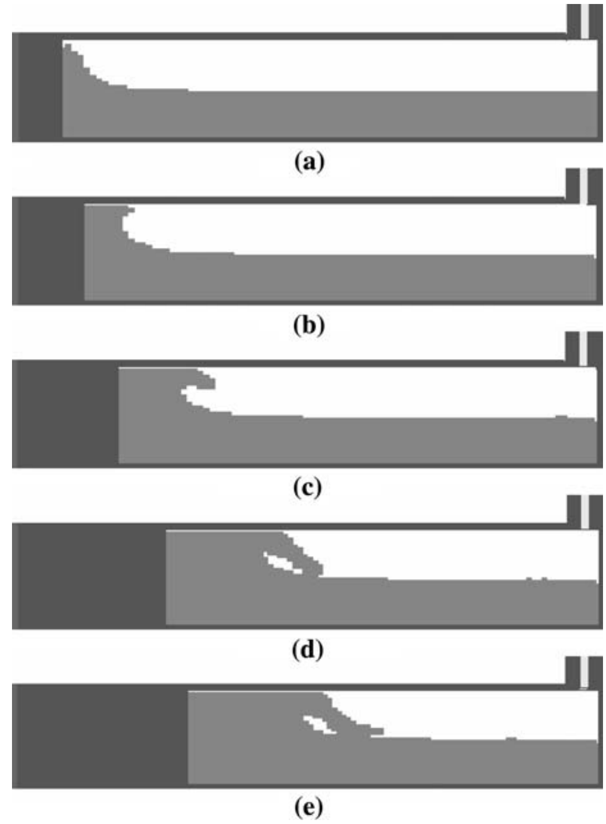

Fig. 8 The flow patterns of molten metal in the shot sleeve for a plunger speed of 100 cm/s at various instants during filling

the sleeve top. From Fig. 6(e), it can be easily seen that the air between the moving plunger and the melt wave is encircled and trapped. It is obvious that air entrapment will occur in this case.

3.2 Filling Pattern for a High Plunger Speeds

For plunger speeds of 60 and 100 cm/s, both higher than the reported critical speed of 41 cm/s, the simulated flow patterns during filling of the sleeve are shown in Figs. 7 and 8, respectively. Both of the results show that the molten metal is pushed high against the plunger as the plunger starts to move. When the plunger moves further, the molten metal is pushed even higher against the plunger. An instant later, the molten metal is pushed even higher and up against the sleeve top. As the plunger keeps pushing, the molten metal near the sleeve top is seen to drop as can be seen in Figs. 7(c) and 8(c). Figures 7(e) and 8(e) show that the dropping melt also moves rapidly along the plunger moving direction and circles an empty space. It is then obvious to see that molten metal engulfs a significant amount of air in the early stage of the filling operation.

3.3 Filling Pattern for the Critical Plunger Speed

Several tests were conducted in this study around the suggested critical speed of 41 cm/s. The authors found that the best setting of plunger speed in the slow speed stage is 38 cm/s at the conditions that the plunger diameter is 50 mm and 300 mm in length, and the fill ratio is 50%. As shown in Fig. 9, the molten metal is pushed high and forms an ideal wave front to push the air/gas out of the shot sleeve smoothly during the whole stage. There is no obvious air entrapment in the molten metal in the shot sleeve.

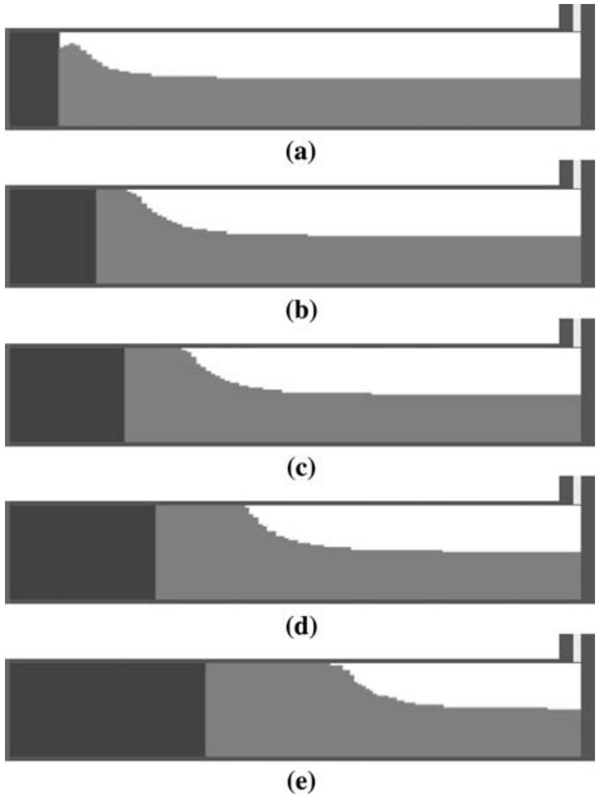

Fig. 9 The flow patterns of molten metal in the shot sleeve for a plunger speed of 38 cm/s at various instants during filling

4. Summary

The characteristics for the filling of molten metal in the shot sleeve of a cold chamber die casting machine during the slow speed injection stage are the movement of the free surface of the molten metal and the domain where the molten metal flows keeps decreasing. In this study, a VSEM method is proposed to incorporate with a previously developed computational fluid dynamics technique, named SOLA-MAC, to handle the flow problems with a moving boundary of fluid domain.

The developed model was tested under various plunger speed settings, with a plunger diameter of 50 and 300 mm in length, and a fill ratio of 50%. The best setting for the slow speed stage was found to be slightly lower than the suggested critical speed. This might be due to the limitations of the 2D model. The cross section of the shot sleeve perpendicular to the injection direction is circular and the 2D model cannot consider the side wall effect. If the plunger speed is deliberately slower or higher than the critical speed, the problem of air entrapment occurs during the filling stage of die casting operation. The simulated results show that in both cases the problem of air entrapment occurs, though they differ in the way how air is trapped in the molten metal during the filling of the shot sleeve.

It has been proved that the VESM method can successfully treat the moving boundary problem of the filling phenomena in the shot sleeve of the die casting process. However, because of the limitation of the SOLA-MAC method, as well as the 2D system, it is difficult to precisely predict the orientation and shape of the liquid-gas interface. To obtain precise data and consider the effects of all operation parameters, however, future work is required to develop a 3D analysis system with a better surface tracking method as well as its experimental validation.

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