Physical Modeling of a Sampler Filling for Molten Steel

Zhi ZHANG,1) Anders TILLIANDER,1) Manabu IGUCHI2) and Pär JÖNSSON1)

1) Department of Materials Science and Engineering, Royal Institute of Technology, Brinellvägen 23, 100 44 Stockholm, Sweden. 2) Division of Materials Science and Engineering, Graduate School of Engineering, Hokkaido University, West 8, North 13, Kita-ku, Sapporo 060-8628 Japan.

(Received on April 10, 2009; accepted on June 22, 2009)

In recent years, much attention has been paid to determining not only the composition, but also the inclusion characteristics from liquid steel samples extracted from a ladle or a tundish. Here, a crucial point is that the steel sampler is filled and solidified without changing the inclusion characteristics that exist at steel making temperatures. Therefore, one of the first steps to investigate is the flow pattern inside samplers during filling in order to obtain a more in-depth knowledge of the sampling process. In this paper, this is done using physical modeling of a lollipop-shaped sampler. More specifically, particle image velocimetry was employed to capture the flow field and calculate the velocity vectors during the entire experiment. The filling rate at the pin part of the sampler was varied during the experiments. It was found that due to the geometry change at the transition from the inlet pin to the body part of the sampler, the flow is very chaotic at the initial filling stage. Furthermore, vortexes are formed in the water sampler vessel during all the fillings and the height of the vortex center varies with the filling rate. Overall, it was found that the flow patterns in the lollipop-shaped sampler vessel can be characterized into three distinct flow regions: the upper vortexes region, the lower horizontal flow region and the middle nozzle flow region.

KEY WORDS: physical modeling; flow pattern; vortex; PIV; sampler.

1. Introduction

The requirements for steel grades with improved material properties are increasing due to, for example, demand for lighter steel constructions with the same or better performance than heavier ones. Therefore, it is a necessity to make cleaner steel with respect to inclusion characteristics. Non-metallic inclusions are inevitably present in liquid steel. However, they should be removed to the largest possible degree before solidification for the majority of the steel grades in order to improve the material properties of the final product. Therefore, it is very important for the steelmakers to know how to ensure the achievement of good cleanliness at the stages of secondary steelmaking, from furnace to mold. In order to determine the most representative liquid steel sampling parameters to optimise the correlative inclusions populations’ assessment, a good understanding of the flow field in the sampler is desirable.

The major sampling technique used presently is the liquid steel sampling procedure. The molten steel sample is extracted into a steel sampler mold through an inlet pin. The sampler is manually or automatically immersed into the molten steel. Sometimes, argon gas is flushed through the sampling during the immersion of sampler in the melt and the pressure is set to balance the ferrostatic pressure at the sampling depth. 1) The argon gas is used to make sure that no top slag enters the sampler during immersion of the sampler through the top slag, which is located on top of the steel bath. As soon as the inlet of mold has reached the position of a predetermined depth, a pressurised gas is introduced by an ejector connected to the handle of the sampling rod to invert the argon flow. As a consequence, the filling of the sampler, which is also partly caused by the ferrostatic pressure, is carried out under controlled conditions. After holding of about 3 to 5 s, the sampler rod is lifted vertically from the melt.

In order to obtain a more in-depth knowledge regarding the filling of production steel samplers it is necessary to understand the fluid flow inside the sampler. This together with the turbulent characteristics of the flow will especially influence the growth of the inclusions during sampler fillings. Overall, a change of inclusion size distribution and composition during filling should be avoided in order to determine the true inclusion characteristics in steel at steelmaking temperatures.

In this work, water model experiments have been carried out to study the fundamental characteristics of flow fields inside a lollipop-shaped sampler. A lollipop-shaped sampler used was scaled up to create an experimental sampler. During the experiments, water was injected through a cylindrical inlet pin connected to the bottom center of the sampler body. Several different flow rates were applied to study the flow pattern under different filling conditions. The flow fields were determined using a Particle Image Velocimetry (PIV) system. The experimental work is described in the first part of the paper. Thereafter, the results are presented and discussed.
2. Experimental Work

Physical modeling was done to study the flow field during the filling of a lollipop-shaped sampler.

2.1. Sampler Dimension and Experimental Setup

As a base for the construction of a physical model of a lollipop-shaped sampler, the dimensions from a production steel sampler were used. A sketch of the lollipop-shaped sampler including important dimensions is shown in Fig. 1. A production sampler typically has a 31.6 mm diameter of the body part (Φ), a 6 mm diameter of the inlet pin (d_m) and a thickness of 12 mm (W). This is a relatively small geometry that is quite difficult to study using physical modeling. Thus, it is necessary to scale up the size of the water model in order to simplify the experiments.

In these experiments, the different flow rates were calculated according to the Froude number similarity:

\[ \text{Frm,s,r} = \text{Frm,m} \] .................................(1)

where Frm,s,r is the modified Froude number in a production sampler and Frm,m is the modified Froude number in the physical model of a sampler. Calculations of the Froude number should be considered according to three different regions in a filled lollipop-shaped vessel as shown in Fig. 2.

Thus, the modified Froude number 2) should be expressed as follows:

- Region I: Inlet of mold
  \[ Fr_{m,m,1} = \frac{Q_L^2}{g \cdot D_m^3} \] .................................(2)

- Region II: Middle of mold
  \[ Fr_{m,m,2} = \frac{Q_L^2}{g \cdot D_h^3 \cdot H_L} \] .................................(3)

- Region III: Surface of liquid in the mold
  \[ Fr_{m,m,3} = \frac{Q_L^2}{g \cdot D_h^5} \] .................................(4)

In Eqs. (2)–(4), the first subscript ‘m’ refers to the modified Froude Number; the second ‘m’ refers to that the Froude Number is applied in the water mold and the last digital term refers to the different regions defined in Fig. 2 of the entire mold. Q_L is the flow rate of the water injection, d_m is the inner diameter of the cylindrical inlet pin, H_L is the depth of the bath and D_h is the hydraulic diameter. The last term is defined as six times the ratio of volume to surface area (see Appendix):

\[ D_h = 6 \frac{V}{A} \] .................................(5)

The physical model was designed according to the calculations of the modified Froude number in different regions. First, the modified Froude numbers were calculated for a production sampler. It was assumed that the inlet velocity was 0.16 m/s by referring to a previous paper. Then, the geometry of the lollipop-shaped vessel was used to calculate the flow rate needed. In this work, the Froude number in Region II is considered to be important for the modeling of flow pattern. The calculated Froude numbers in Region II Frm,m,2 from the experiment data in turn is 3.76×10^{-4}. Therefore, the similarity criteria are applied to this region. The resulting Froude number and the flow rate for the physical model were 3.84×10^{-4} and 20.21 L/min, respectively. However, it should be pointed out that a limitation of this study was the capacity of the water pump, where the upper limit of the flow rate was 24 L/min. Moreover, flow rates other than the calculated value were also used in the experiments to investigate the flow patterns for different flow rates. Thus, a similarity of the Froude number by using the modified Froude number in the physical model Frm,m to calculate the real velocity in the inlet pin of a steel sampler was applied.

Based on the calculations of a Froude number similarity between a production sampler and a physical model sampler the dimensions given in Table 1 were used in the construction of the physical model. The vessel was made of transparent acrylic resin. It should be noted that due to the fact that the vessel was scaled up, similarities with respect to other important dimensionless numbers such as the Reynolds number could not be fulfilled. However, it was judged to be more important to consider the modified Froude number, since it allows a better modeling of what is actually the fluid flow in the real production sampler. The
different flow rates used for PIV measurement are shown in Table 2. The flow rate which corresponds to a production sampler is marked with a bold text.

2.2. Measurements of Flow Fields

Measurements of flow fields were carried out using a Twins Ultra PIV system. This system uses a Charge-Coupled Device (CCD) MEFAPLUS Camera with a speed of 30 fps to capture the flow containing small particles on a selected plane. Before carrying out the experiments, water is mixed with fluorescent seeding particles in order to capture the flow fields. The size of one particle is $\Phi 15 \mu m$ with a density of 1.1 g/cm³. When the plane is illuminated by two short duration laser flashes (green-colored laser, Nd:YAG), a double exposure of flow field is captured through the CCD camera to the computer. Then flow fields can be calculated by comparing the two photos through PIV software. In this work, the middle plane of the vessel is illuminated by the laser flash at the right side. The CCD camera is set in the front of the vessel, so that the front view of the flow patterns has been obtained. A schematic plot of the whole measurement system is shown in Fig. 3.

3. Results

Figure 4 shows the mean velocity distributions in the middle of a lollipop-shaped vessel at different filling times for an average flow rate of 20.21 L/min. The nozzle which connects the cylindrical inlet pin is located at the bottom center of the circular body. As can be seen from the plots, the flow in the middle of the vessel is directed upwards due to the strong injection from the pin-part of the sampler. In addition, two vortexes are created on each side of the vertical flow. Moreover, these two vortexes are the two completely separated vortexes with the ends at the surface wall in the front and back of the vessel. (Due to the three-dimensional turbulent eddy motion, it could be observed from an isotropic view.) The formation of vortexes is caused by the strong circulation created after the injected flow has reached the liquid/gas surface and thereafter is directed towards the circular wall of the vessel. The velocity distribution beneath the two vortexes shows clearly that water flows horizontally toward the middle vertical velocity flow region to complete the circulations (Figs. 4(a) and 4(b)). As the sampler is being filled, the bath depth increases. Then, the centers of vortexes will also shift from their original position. Moreover, the size of the vortexes is changed so significantly that more than half of the flow field makes up the circulation region.

Figure 5 depicts the flow pattern in the middle of the lol-

| Trials | Flow rates in the water vessel [L/min] | Froude Number | Flow rates in a real sampler [L/min] | Corresponding velocity in a real sampler [m/s] |
|--------|--------------------------------------|---------------|-------------------------------------|---------------------------------------------|
| 1      | 6.14                                 | 3.549E-05     | 0.0833                              | 0.0491                                      |
| 2      | 8.29                                 | 6.469E-05     | 0.1125                              | 0.0663                                      |
| 3      | 10.37                                | 1.012E-04     | 0.1407                              | 0.0829                                      |
| 4      | 12.32                                | 1.429E-04     | 0.1672                              | 0.0985                                      |
| 5      | 14.24                                | 1.909E-04     | 0.1932                              | 0.1139                                      |
| 6      | 16.31                                | 2.504E-04     | 0.2213                              | 0.1304                                      |
| 7      | 18.27                                | 3.142E-04     | 0.2479                              | 0.1461                                      |
| 8      | 20.21                                | 3.845E-04     | 0.2742                              | 0.1616                                      |
| 9      | 22.14                                | 4.614E-04     | 0.3004                              | 0.1771                                      |
| 10     | 23.87                                | 5.364E-04     | 0.3239                              | 0.1909                                      |
lipop-shaped vessel at different filling times for a mean flow rate of 8.29 L/min. A comparison with the data presented in Fig. 4 shows that the filling flow rate is more than 50% smaller. This is realistic since the mean flow rate was decreased from 20.21 to 8.29 L/min. Based on the data presented in Fig. 5 and data from other experiments, some characteristic flow field regions can be identified. Specifically, the following three regions were identified: vortexes, vertical flow field and horizontal flow field, as shown in the sketch in Fig. 6. However, in the early stage of filling, circulations are formed near the bath surface. This is caused by the injection flow through the nozzle and also a small cross sectional area in the lower region of the sampler. As a result, a small hump is formed at the initial filling, but it is quickly immersed into the rising free surface. This observation is different from what was seen in the flow pattern shown in Fig. 4, which shows a high velocity field in the top of the vertical flow pattern due to the high flow rate. Centers of vortexes also shift from the region near the surface to a deeper region.

Humps were observed since the process of filling a sampler can be considered as a typical bottom filling of an empty vessel with a constant fluid flow and a time-dependent rising surface. It is known that the height of the hump will decrease with increasing the free surface of water. On the other hand, the measured maximum heights of the hump during each filling process increases with an increased flow rate. These results are in agreement with those obtained by Hallgren et al., who have extensively studied the hump formation during filling of ingots. Figure 7 shows a linear relation between the maximum heights of hump and various flow rates, and their relation can be expressed as follows:

$$h = 3.11Q - 24.31 \quad (12 < Q < 22) \quad \ldots \ldots \ldots \ldots (6)$$

where $h$ [mm] is the maximum height of a hump and $Q$ [L/min] is the flow rate.

Figure 8 depicts the velocity magnitudes at different heights of a lipop-shaped vessel at a specific filling time. Data for a 18.27 L/min and a 20.21 L/min flow rate are presented in Figs. 8(a) and 8(b), respectively. From the figures it is clear that the velocity has the highest magnitude in the middle vertical flow region above the nozzle in comparison to other regions. In addition, the velocity magnitudes' profiles are very similar at different filling heights and different flow rates. It can also be seen that at a similar height level but different flow rates, the velocity magnitude is higher due to a higher flow rate. For instance, $H=74$ mm in Fig. 8(a) and $H=72$ mm in Fig. 8(b) represent flow rates of 18.27 L/min and 20.21 L/min, respectively. Furthermore, at the height of $H=93$ mm in Fig. 8(a) and $H=109$ mm in Fig. 8(b), which are much close to the height of vortex center, the velocities are relatively smaller in Region III (defined in Fig. 6) compared with the other regions. It is also clearly shown that the velocity magnitude has a higher value at the lower height level, especially in the vertical flow region in the middle of the sampler.

The comparison of velocity magnitudes of different flow rates at the same height of vessel are shown in Fig. 9.
Fig. 7. Maximum height of humps at different flow rates.

Fig. 8. Velocity magnitude on different height of a lollipop-shaped vessel.

for a 62 mm and a 109 mm height are presented in Figs. 9(a) and 9(b), respectively. In addition, both plots are obtained at the end of the filling periods. As seen in both plots, the higher flow rate tends to generate a higher velocity magnitude in the middle vertical flow fields at both the same height level. Moreover, the velocity magnitude decreases from a lower to a higher height level by comparing the plots shown in Figs. 9(a) and 9(b) at the same flow rate. The velocity magnitudes also decrease in Region III (defined in Fig. 6) as the height increases. More specifically, the velocity magnitude near the wall region tends to have a higher magnitude than its nearby region at a height of 62 mm, as shown in Fig. 9(a). This phenomenon could be explained by the small cross sectional area compared with a higher level region that has a bigger cross sectional area. When the fluid flows from a higher level to a lower level, the velocity will increase due to a cross sectional area reduction (below the center of the water vessel).

Figure 10 shows the relationship between the ratios of height of vortex center to the height of free surface \((h/H)\) at different flow rates. Because different flow rates lead to different filling times to the same amount of volume, the data are obtained at the end of each filling process. As can be seen from the plot, a trend is that the ratio decreases with an increased flow rate. This means that the vortex region will expand into Region III (see Fig. 6) with an increased flow rate. Furthermore, that the height of the vortex center will increase slower than that of the free surface. This is because at the end of each filling process, the free surface area will decrease due to the circular cross section of sampler vessel and the increasing height of free surface (above the center of the water vessel). Also, a higher flow rate can as-
sist to lead to a fast rising free surface. Moreover, the free surface and vortex recirculations can be stabilized by a larger free surface area as shown in Fig. 6(a). The wave frequency on the surface is observed that it is increasing with an increasing height (above the center of water vessel, the area of surface will decrease according to an increasing height). For example, approximately from a frequency of 2 Hz at the center height of the water vessel to a frequency of about 2.5 Hz at the 80% of height of free surface, for a flow rate of 18.27 L/min. A larger area in the flow is preferred by the vortex recirculation if the free surface area is small. Thus, the center of vortex is switched into a larger area in Region III.

4. Discussion

Vortices or recirculation flows can be difficult to observe at the very beginning of any filling processes. This is especially for the filling of samplers during the first two seconds when the flow enters the main sampler body. This is caused by the chaotic flow which is formed due to the sudden geometry change when the water is transferred from the
Based on the above presented results it is clear that the sampler filling times should be reduced according to their increased filling rate. This relationship is shown in Fig. 11. More specifically, it can be seen that the filling time is 4 s for a flow rate of 24 L/min. Furthermore, it increases exponentially to 18 s for a 6 L/min flow rate. Here, it is interesting to note that Ericsson et al. have reported that a filling velocity of 0.45 m/s is typical for a real production sampler that is solely filled due to the ferrostatic pressure. Furthermore, that the filling velocity for a production sampler using argon and a back pressure is approximately around 0.2 m/s. From Fig. 11 it can be predicted that the corresponding filling times for sampling in the experimental water vessel is 2 s and 4.3 s, respectively. The relationship between the filling times and the corresponding flow rate can be expressed as the following equation:

\[ t = -0.0038 \times Q^3 + 0.2239 \times Q^2 - 4.6111 \times Q + 39.078 \quad (5 \leq Q \leq 25) \] ........................(7)

Additionally, the available velocity magnitude data obtained by the water experiment can be used to calculate the Reynolds number, which is known as the critical parameter to determine the transition between a laminar and turbulent flow. It can be expressed as follows:

\[ \text{Re} = \frac{\rho Du}{\mu} \] ..........................(8)

where \( \rho \) is the density of liquid, \( D \) is the hydraulic diameter of jet, \( u \) is the flow velocity and \( \mu \) is the dynamic viscosity. Figure 12 depicts the calculated Re using an average velocity in Region II of a lollipop-shaped vessel at different flow rates at both 62 mm and 109 mm heights. All the calculated Re values for the region exceed 2000, which is the critical value for the transition between a laminar flow and turbulent flow. Moreover, the Reynolds number will increase with an increased flow rate. This indicates that no laminar flow exist in the vertical flow region.

As shown in the above results, flow fields vary for different filling conditions. It is obvious that a higher flow rate, for example, 20.21 L/min, could lead to a more turbulent flow pattern and more fluctuations on the free surface. It can also be predicted from Fig. 12 that the Reynolds Number will increase 220% from a low flow rate of 12.24 L/min to a higher flow rate of 20.21 L/min with increasing the flow rates at the same height level of 109 mm. One phenomenon that is inconvenient to observe by the PIV system is the flow pattern on planes parallel to the surface, which can be chaotic within the plane. A chaotic flow pattern formation in one aspect is due to the transition of shape differences between the cylindrical inlet pin and the sampler vessel. This should be mentioned here, because from a metallurgical point of view, the geometry change has a great impact on the flow pattern. This, in turn, will influence the distribution of inclusion particles due to the collision by turbulence. The particles’ collision and growth has been extensively studied by Söder et al. Larger fluctuations on the free surface are observed as waves when applying a higher flow rate. The frequency of the surface wave is approximate 2 Hz. On the surface, they represent the uneven height that waved surface is higher on one side of the sampler vessel and lower on the other. Moreover, the flow field beneath the surface will be changed due to this fluctuation. As shown in Fig. 4(b), the flow jet from the center bottom inlet pin of the sampler is not directly straight upwards near the surface. Instead, it follows the wave flow to bend as the flow change. In addition, positions of the vortex center will vary with the changing of fluctuations. It is also observed that an undisturbed free surface shown in Fig. 5 is formed due to a lower flow rate of 8.29 L/min.

From a metallurgical point of view, the formation of hump on a free surface is in most cases harmful for the metallurgical process. It should be pointed that the formation of a hump during the filling of a sampler can lead to some entrapment of air. Then, in turn, the sample will be destroyed since the entrapped air will react with elements with a high affinity to oxygen under the formation of new inclusions. Moreover, it also possible to form pores or porosities if the amount of air entrapped is large and the solidification of the steel is fast.

In summary, a laminar flow is desirable in order to represent the correct distributions of inclusions inside a liquid steel sample. This is due to the fact that a turbulent flow, which is characterized by fluctuating velocity fields, will destroy the original distributions of inclusions during filling and solidification of the sampler. However, based on the results of this study it can be concluded that it is impossible to avoid the turbulence because of the geometric design of
commercial samplers that can lead to turbulence formations. Moreover, in order to reduce the influence of turbulence, it is important to decrease the velocity magnitude of molten steel when extracting from ladles into the sampler. Presently, the water model representing the liquid steel filling (Fig. 4) shows very disturbed flow patterns. For a better undisturbed and calm flow pattern, as shown in Fig. 5, with a flow rate of 8.29 L/min, flow fields are good for representing the original inclusions distributions as well as the compositions. The velocity in the production sampler in turn will have a value of 6.63 cm/s according to the Froude number similarity. However, a too small flow rate is not realistic for the sample extracting because of the solidification of liquid steel. Then, the pre-solidified steel in the inlet pin will block the flow to the main sampler body.

5. Conclusions

Flow fields inside lollipop-shaped samplers during the filling processes have been investigated using physical modeling. The flow patterns are captured by a PIV system. Different flow rates between 6 and 23 L/min have been applied through the inlet pin at the bottom center of the vessel. It has been concluded that the smaller inlet velocity, the less turbulent is the flow. In general, a more laminar flow will lead to a smaller hump formation during the initial filling as well as a calmer filling of a sampler. The most important specific conclusions from this study may be summarized as follows:

(1) Due to the geometries change from the inlet pin to the main body and high flow rates applied, the flow is very chaotic at the initial filling stage, especially during the first 2 s;
(2) Humps are observed during the filling of samplers. The height of hump will decrease with a increased water free surface and its maximum height measured will linearly increase with an increased flow rate, as illustrated by Eq. (6);
(3) The filling time was found to decrease with an increased flow rate, as can be calculated using Eq. (7);
(4) Vortexes are formed in the vessel during the filling and the height of the vortex center varies with different filling conditions;
(5) Flow patterns in the middle of the lollipop-shaped vessel can be characterized into three distinct flow regions: i) an upper vortexes region, ii) a lower horizontal flow region and iii) a middle nozzle flow region.

It is the research groups’ ambition to extend this work to mathematically model the filling of a sampler using both water and steel as liquids. Here, it should be noted that when modeling the filling and solidification of a steel sampler it is important to determine the lowest possible filling velocity that is possible to use without causing that pre-solidified steel may block the path of the incoming flow, resulting in an unfinished filling.

Acknowledgements

The authors wish to thank the European Union for financial support under the contract number RFSR-CT-2007-0005.

REFERENCES

1) T. Hansen, P. Jönsson, S. Lundberg and K. Törresvoll: Steel Res. Int., 77 (2006), No. 3, 177.
2) K. Kawakami, M. Iguchi and K. Ishido: Tetsu-to-Hagané, 92 (2006), No. 5, 2543.
3) O. Ericsson: KTH Licentiate Thesis, (2009).
4) L. Hallgren, S. Takagi, A. Tilliander, S. Yokoya and P. Jönsson: Steel Res. Int., 78, (2007), No. 3, 254.
5) M. Söder, P. Jönsson and L. Jonsson: Steel Res. Int., 75 (2004), 128.

Appendix

It is well known that the hydraulic diameter for a two-dimensional (2D) case, for example, considering a circular with a diameter of $D$, the expression for its area $A$ and peripheral length $P$ are as follows:

$$ A = \frac{\pi}{4} D^2 \quad \text{.................(A-1)} $$
$$ P = \pi D \quad \text{...............(A-2)} $$

The ratio between Eqs. (7) and (8) is:

$$ \frac{A}{P} = \frac{D}{4} \quad \text{.................(A-3)} $$

Thus, the hydraulic diameter for a 2D case can be expressed as:

$$ D_h = 4 \frac{A}{P} \quad \text{...............(A-4)} $$

Applying the same theory, for a three-dimensional (3D) case, we consider a spheroid with a diameter of $D$. The volume $V$ and total surface area $S$ can be expressed as:

$$ V = \frac{\pi}{6} D^3 \quad \text{.................(A-5)} $$
$$ S = \pi D^2 \quad \text{...............(A-6)} $$

The ratio between Eqs. (11) and (12) yields:

$$ \frac{V}{S} = \frac{D}{6} \quad \text{...............(A-7)} $$

Thus, the hydraulic diameter for a 3D case can be expressed as:

$$ D_h = 6 \frac{V}{S} \quad \text{...............(5)} $$