Simulation of Sliding Nozzle Gate Movements for Steel Continuous Casting

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(Received on February 28, 2001; accepted in final form on May 29, 2001)

The slab surface quality is generally known to deteriorate when the casting speed fluctuates during the continuous casting of steel. The mold powder on the meniscus is more likely to be entrapped in the molten steel undergoing molten steel flow fluctuations due to a casting speed change. As the casting speed is controlled by the sliding nozzle (SN) gate movement, an investigation into the effect of such SN gate movement on the molten steel flow would be useful. In this study, the molten steel flow in a mold was numerically simulated during partial opening/closing of the SN gate by a certain distance at a constant speed. The deforming mesh model was used to consider the geometry change in the simulation. The validity of this model was confirmed by comparison with the results of a water model simulation experiment.

When the SN gate is partially opened/closed, the steel mass flow rate is increased/decreased accordingly. At the SN gate and the SEN ports, the transitional time required to reach a steady flow is several seconds after the commencement of SN gate movement. At the meniscus, an even much longer time is required to reach a steady flow.

KEY WORDS: steelflow; castings; quality control; simulation; sliding nozzle; submerged entry nozzle; deforming mesh model.

1. Introduction

A common problem in continuous casting of steel is that a slab produced when the casting speed fluctuates is relatively inferior in quality. In order to pursue a lower rejection rate of slabs, it is important to improve the quality of such a slab. The casting speed is controlled by the sliding nozzle (SN) gate movement, and an investigation into the effect of such SN gate movement on the molten steel flow would be useful. In this study, the molten steel flow in a mold was numerically simulated during partial opening/closing of the SN gate by a certain distance at a constant speed. The deforming mesh model was used to consider the geometry change in the simulation. The validity of this model was confirmed by comparison with the results of a water model simulation experiment.

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KEY WORDS: steelmaking; castings; quality control; simulation; sliding nozzle; submerged entry nozzle; deforming mesh model.

2. Numerical Simulation Method and Validity

2.1. Numerical Simulation Method

In order to examine the transitional molten steel flow during SN movement, numerical simulation using the deformation mesh model was performed. The deforming mesh model can be used to simulate the flow in a vessel whose shape varies with time when the shapes before and after changing are topologically equivalent, i.e. any new control volume is not produced throughout the calculation. The conservation equations contain terms for the effect of volume change of the domain and the grid moving velocity. J is defined as a measure of the change of material volume and varies such that:

\[ \frac{\partial J}{\partial t} = -\frac{V^{n+1} - V^n}{\Delta t} \sum_i (v_i S_i) \]
where, \( n \) and \( n+1 \) indicate discrete time values, \( S_i \) is the \( i \)th boundary segment of the control volume surface, \( V \) is the volume of the mesh element and \( v_i \) is the grid moving velocity component.

The mass conservation equation and the momentum equation for the deforming mesh model are given in Eqs. (2) and (3), respectively.

\[
\frac{1}{J} \frac{d}{dt} \rho J u_j + \frac{\partial}{\partial x_j} \rho (u_j v_j) = 0 \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2)
\]

\[
\frac{1}{J} \frac{d}{dt} \rho J u_j + \frac{\partial}{\partial x_j} \rho (u_j v_j) u_i = - \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} (\tau_{ij} + \tau_{ji}) + S_k \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots (3)
\]

where, \( \rho \) is the specific density, \( u_i \) is the flow velocity component, \( p \) is the pressure, \( \tau_{ij} \) is the molecular stress tensor, \( \tau_{ij} \) is the Reynolds stress tensor and \( S_k \) is the source term. \( d/dt \) is defined as the total derivative. These equations are solved by means of a finite volume method.

In a continuous casting mold, the Reynolds number can be estimated from the dimensions of the SEN port. The order of magnitude is about \( 10^5 \), which makes it necessary to consider the effects of turbulence. The two-equation \( k-\varepsilon \) model is used as a turbulence model. The boundary wall on the mold is assumed to be hydro-dynamically non-slip, and the boundary wall at the meniscus is assumed to be slip. In this paper, all calculations are performed in 2-dimensional geometry for the sake of simplicity. The inlet boundary condition is set as equivalent to flow velocities of the corresponding 3-dimensional model. SN gate is moved by the same distance as the corresponding 3-dimensional model. For convenience of discussion in subsequent sections, we will refer to the mass flow rate as the value based on a unit slab thickness of 1.0 m.

At first, a steady state calculation is carried out with the initial SN gate position fixed. Then a time-dependent calculation is carried out with the SN gate moving. This is done by the deforming mesh model method. The time step of this calculation is 0.01 sec. The calculation grid is also interpolated using the same time step, \textit{i.e.} 0.01 sec. The solution convergence criterion for each time step is that the normalized residual sum for each solution variable decreases to \( 10^{-4} \). The solutions converged well at each time step.

2.2. Water Model Experiment

In order to check the validity of numerical simulation, a water model simulation experiment of 1/3 actual plant scale was also carried out. The experimental apparatus is illustrated in Fig. 1. From a buffer vessel referred to as “tundish”, water is fed into a simulated continuous casting mold through the SN gate and the SEN. It is then drained off from the bottom of the mold and pumped up to the tundish again. The SN gate is moved by an actuator and flow rate is dependent on the SN gate position. The flow valve is controlled by reference to a measurement of the pressure at the bottom of the mold such that the meniscus level is maintained at a certain level.

The flow velocity is measured at the bottom edge of both SEN ports simultaneously by electromagnetic velocity sensors. The response time of this sensor is 0.05 sec. The response time is defined as the time required to detect a change in velocity up to 63%. The sampling frequency is 135 Hz.

The nozzle shape is shown in Fig. 2. Two different configurations were used for the bottom of the nozzle; pentroof and pool. Both are commonly used in actual casting. We will refer to the side pulling the SN gate as “A” and the opposite side as “B” hereafter for convenience.

Experimental conditions are listed in Table 1. The SN gate is never opened or closed completely. In this experi-

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**Table 1.** Water model experimental condition.

| Slab Size width[mm] × thickness[mm] | Slab Size width[mm] × thickness[mm] | Slab Size width[mm] × thickness[mm] |
|-----------------------------------|-----------------------------------|-----------------------------------|
| 550 × 73                          | 550 × 73                          | 550 × 73                          |
| SN moving speed[mm/sec]           | SN moving speed[mm/sec]           | SN moving speed[mm/sec]           |
| 13.3                              | 13.3                              | 13.3                              |
| SN moving time[sec]               | SN moving time[sec]               | SN moving time[sec]               |
| 0.45                              | 0.45                              | 0.45                              |
| SN gate position [mm]             | SN gate position [mm]             | SN gate position [mm]             |
| 17                                | 17                                | 17                                |
| Percentage of gate area open[\%] | Percentage of gate area open[\%] | Percentage of gate area open[\%] |
| 29.5                              | 29.5                              | 29.5                              |
| Water throughput [L/min]          | Water throughput [L/min]          | Water throughput [L/min]          |
| 50                                | 50                                | 50                                |

**Fig. 1.** Schematic view of water model experimental apparatus.

**Fig. 2.** SN and SEN shape. (a) pentroof, (b) pool.
moment, the most “open” SN gate position is 17 mm from the fully opened position, creating a large aperture, while the most “closed” position is 23 mm. From the most “open” position to the most “closed” position or vice versa, the SN gate is moved at a constant speed and is then fixed at the two extreme positions. **Figure 3** shows the position of the SN gate plate and SN gate movement with time.

### 2.3. Comparison of Calculation Results and Water Model Experimental Results

The validity of numerical simulation was checked by comparing the simulation results with the water model results. Numerical simulation was performed under the same conditions as the water model experiment. **Figure 4** shows the computational geometry.

**Figure 4.** Computational geometry.

As an example, **Fig. 5** shows a large-scale picture of the flow velocity vectors in the region around the SN gate, when in the “open” position. The water flow passing through the SN gate is deflected and subsequently the water mainly flows near side A.

**Fig. 5.** Flow velocity vectors around SN gate.

**Fig. 6.** Flow velocity change with SN gate movement (pentroof configuration). (a) from “close” to “open”, (b) from “open” to “close”.

As an example, **Fig. 5** shows a large-scale picture of the flow velocity vectors in the region around the SN gate, when in the “open” position. The water flow passing through the SN gate is deflected and subsequently the water mainly flows near side A.

The flow velocity change at the bottom edge of the SEN port is shown in **Fig. 6** for pentroof SEN configurations. Positive velocity indicates flow in a direction from the SEN port towards the narrow face of the mold wall. The horizontal axis shows elapsed time from the start of the SN gate movement. Experimental data is plotted with smooth lines.
and calculated data is plotted with symbols. The calculated flow velocity change gradient is the same as the experimental one. In addition, both experimental and calculated flow velocities at port A are higher than that at port B. This is due to the flow deflecting around the SN gate.

Figure 7 shows the flow velocity change at the bottom edge of the SEN port for pool SEN configurations. Calculation data and experimental data are in agreement with each other concerning the general shape of the velocity change curve. As is known, the fluctuation with a pool bottom configuration is larger than that of pentroof bottom configuration. Therefore, in the water model a lot of turbulence fluctuation is observed. However, over an elapsed time of 2 sec, the value of experimental flow velocity at port A is still higher than that at B for the majority of this period, although it is sometimes lower. In the calculation, as the time averaging procedure, the two-equation $k$–$\varepsilon$ model, is used, the flow velocity at port A is always higher than that at port B.

3. Numerical Simulation of Actual Plant

As the validity of calculation results was confirmed, numerical simulation of the actual plant conditions could be carried out to investigate the transmission time delay of the SN gate moving effect on flow characteristics. Geometry of calculation is similar to that used in the water model experiment, however, the scale of numerical simulation is about three times larger than that of the water model. The SN gate is moved from the most “open” position to the most

| Table 2. Conditions of numerical simulation. |
|------------------------------------------------|
| Case1-1 | Case1-2 |
| Mold width[mm] | 1030 | |
| Distance from SN plate to SEN port[mm] | 580 | |
| SN moving speed[mm/sec] | 30 | 60 |
| SN moving time[sec] | 0.33 | 0.17 |
| SN gate position 1[mm] | 20 | 20 |
| Percentage of gate area open[%] | 73 | 59 |
| Corresponding molten steel throughput [t/h/min] | 5.5 | 4.8 |

3.1. Transitional Time at the SN Gate

Calculation conditions are listed in Table 2. Cases involving two different SN gate moving speeds are calculated. A chart of the SN gate position and graphs of mass flow rate and mass flow acceleration at the SN gate are shown in Figs. 8(a)–8(c). As the SN gate is moved toward closing, mass flow rate decreases gradually. After the SN gate movement is ceased, mass flow rate continues to change

Fig. 7. Flow velocity change with SN gate movement (pool configuration). (a) from “close” to “open”, (b) from “open” to “close”.

Fig. 8. Mass flow rate change at the SN gate. (a) SN movement with time, (b) mass flow rate, (c) mass flow acceleration.

“closed” position. A pool bottom nozzle is selected for the simulation.
until eventually reaching a steady state. The time delay of mass flow rate change can be seen in Fig. 8(c). Mass flow acceleration peaks when the SN gate movement ceases. After that, mass flow acceleration gradually returns to zero. The elapsed time from this peak to zero mass flow acceleration corresponds to the time delay. About 5 sec is needed to reach a steady mass flow rate after commencement of SN gate movement. The flow transitional time from one steady flow condition to another is almost constant and does not vary with the SN gate moving speed. However, the SN gate moving speed does affect the mass flow acceleration. When the SN gate moving speed is higher, the mass flow acceleration is larger.

Flow velocity and flow acceleration at the center of the SN gate aperture are shown in Figs. 9(a) and 9(b). The aperture of the SN gate is reduced with the SN gate movement. Therefore, although the mass flow rate decreases as we have seen, flow velocity increases at first. After a certain time, flow velocity starts to decrease and gradually reaches a steady flow velocity. From Fig. 9(b) it can be seen that after the SN gate movement stops, flow acceleration becomes negative rapidly and then returns to zero, i.e. a steady flow velocity, in around 5 sec. This transitional time of flow velocity is the same as that of mass flow rate. Although the SN gate moving speed does not affect the transitional time, it affects the mass flow acceleration in a similar way to the mass flow rate. It should be noted that after the SN gate movement, the steady flow velocity is higher than the initial flow velocity although mass flow rate is decreased.

### 3.2. Transitional Time at the SEN Ports

Previously, it was found that even if the SN gate moving speed changes, the transitional time from one steady state to another is not affected at the SN gate. In this section, flow change at the SEN ports is investigated. The calculation conditions of Table 3 are used. Calculations are performed for three different SEN length cases. From the bottom edge of the SN gate plate to the SEN port is 330 mm, 580 mm and 830 mm respectively.

Change of mass flow rate emerging from both SEN ports should be the same as that at the SN gate due to the mass conservation law. However, it is important to investigate the change in imbalance in the flow from the two ports of the SEN. Figure 10 shows a plot of the ratio of port A mass flow rate to the total mass flow rate. For all cases, this ratio is always under 0.5. This can be explained with reference to Fig. 11, the velocity profile at the SEN port under initial conditions \((t=0)\) for the 580 mm case. The molten steel flow is deflected around the SN gate and subsequently the molten steel mainly flows near side A as we have seen. Therefore, maximum flow velocity at port A is higher than that at port B around the bottom edge of the SEN port.
port. However, flow velocity at the upper edge of port A is lower than that at port B due to the strong re-circulation. As a result, mass flow rate at port A is always smaller than that at B.

From Fig. 10, it can be seen that the ratio of port A flow rate to total flow rate is always nearer to 0.5 when the SEN is longer. Figure 12 shows contours of flow velocity in the SEN. Flow velocity magnitude is indicated by gray scale. From white to black, flow velocity magnitude increases. It is found that the “flow jet” constriction at the SN gate is dispersed downstream. A longer SEN has a larger distance over which to disperse the “flow jet”.

Again, focusing on Fig. 10. A large change in flow imbalance at the SEN ports occurs at around 2sec. In order to evaluate the effect of using different SEN lengths, the largest rate of change of flow imbalance has been found and marked with circles on each of the three curves in Fig. 10. The elapsed time until this point is greater for the longer SEN. The difference in values of elapsed time to these points is about 0.6 sec between those of the shortest and longest SENs and is referred to as $\Delta t$. This can be explained by considering molten steel travelling time from the SN gate to the SEN port. Maximum “flow jet” velocity at the SN gate is about 0.9 m/s under initial conditions ($t=0$) for these cases. Therefore, molten steel travelling time is estimated as 0.37 sec and 0.92 sec for the shortest and longest SENs respectively. It is considered that the difference between these figures, i.e. 0.55 sec indicates the time delay, $\Delta t$. Although the time when the largest rate of change of flow imbalance occurs at the SEN ports is related to the travelling time from the SN gate to the SEN port, time delay, $\Delta t$ between cases of different SEN lengths is small. Also, the time required to return to a steady mass flow rate at SEN port is almost the same as that at the SN gate, i.e. 5 sec after commencement of SN gate movement. Therefore, time delay, $\Delta t$ is not significant when the longer SEN is applied. Considering that unbalanced flow causes powder entrapment, a longer SEN would be better than a shorter SEN.

3.3. Transitional Time at the Meniscus

So far, flow at the SN gate and the SEN ports during SN gate movement has been discussed. In this section, meniscus flow change needs to be taken into consideration because mold powder is entrapped from the meniscus. In particular, it has been reported that the meniscus flow velocity at a distance of 1/4 mold width from the narrow side wall has a significant effect on the slab quality. Calculation conditions are the same as those in Table 2. Figure 13(a) shows the meniscus flow velocity at the 1/4 mold width position plotted against time. SN moving speed is 60 mm/s. Meniscus flow velocity is gradually reduced to a steady flow with time.

In order to check the change of meniscus flow velocity in more detail, the meniscus flow acceleration at the same position is shown in Fig. 13(b). As the SN gate is moved toward closing and the aperture of the SN gate is reduced,
meniscus flow velocity increases during the first 0.17 sec in the same way as the flow velocity at the SN gate. Then it decreases rapidly and the local minimum of meniscus flow acceleration appears at around 1.1 sec. At one point meniscus flow acceleration approaches the zero line, then it is reduced again and has a minimum around 7.4 sec. After that, it finally reaches zero.

It is considered that the minimum peak is related to the molten steel flow in the mold. The molten steel flows from the SEN port to the narrow face of the mold and diverges at the narrow face of the mold wall. After the divergence, some of it flows upward and some of it flows downward. After the upward molten steel flow reaches the meniscus, it is redirected away from the narrow face toward the mold center moving close to the meniscus. Maximum “flow jet” velocity at the SN gate is about 0.9 m/s under initial conditions ($t=0$). Molten steel travelling time from the SN gate to the SEN port is estimated as 0.64 sec for the 580 mm SEN length case. The molten steel travelling time from the SEN port to the meniscus at the 1/4 mold width position can be estimated using the results of the water model experiment conducted by Teshima et al.\textsuperscript{16}. They provided an empirical formula to calculate the trajectory of molten steel “flow jet” from the SEN port to the narrow side wall and maximum impinging jet velocity on the narrow face of the mold wall. From this formula, travelling distance from the SEN port to the meniscus at the 1/4 mold width position is estimated to be 1.97 m. Maximum impinging jet velocity on the narrow face of the mold wall is estimated to be 0.27 m/s. If this velocity magnitude is assumed to remain constant from the SEN port to the meniscus at the 1/4 mold width position, the molten steel travelling time from the SEN port to the meniscus at the 1/4 mold width position can be calculated as 7.82 sec. Total travelling time from the SN gate to the meniscus at the 1/4 mold width position is 7.82 sec. This estimated time should be similar to the elapsed time at which a minimum in meniscus flow acceleration will appear after the SN gate movement ceases. In fact, this estimated time, 7.82 sec, is almost the same as calculated time, 7.4 sec. Therefore, it is considered that the flow change at the SN gate is transmitted to the 1/4 mold width position by the main stream of “flow jet” from the SN gate.

From Fig. 13(b), it can be seen that about 35 sec is needed to reach a steady flow at the 1/4 mold width position near the meniscus. This is quite large compared to the SN gate moving time. In the actual casting process, the SN gate position is varied toward the “open” or “closed” positions by reference to a measurement of the meniscus level fluctuation. As the effect of one action of SN gate movement lasts about 35 sec, flow change in the actual process will be more complicated.

The meniscus flow velocity and flow acceleration at the 1/4 mold width position are shown in Figs. 14(a) and 14(b) for the lower SN moving speed case, 30 mm/s. The general profiles of these curves are similar to those of the higher SN moving speed case in Fig. 13. The only remarkable difference is the magnitude of the first peak in the meniscus flow acceleration curve. The origin of this first peak is the flow acceleration peak shown in Fig. 9(b) and a higher SN gate moving speed results in greater flow acceleration. This means that the flow change at the SN gate is transmitted to the meniscus directly. There is no clear indication that mass flow acceleration has led to mold powder entrapment so far. However, large mass flow acceleration might be a cause of fluctuation in flow and level at the meniscus and induce mold powder entrapment in the molten steel. Studying the relationship between mass flow acceleration and mold powder entrapment will be necessary in the future.

4. Conclusion

The deforming mesh model numerical calculation was applied to investigate the effect of SN gate movement on
the molten steel flow in a mold. From the results, the following conclusions can be drawn.

(1) At the SN gate, when the SN gate is moved, the molten steel flow starts to change instantaneously. The flow continues to change for about 5 sec after the commencement of SN gate movement. A higher SN gate moving speed results in greater flow acceleration, although the time required to reach a steady flow is not affected by the SN gate moving speed.

(2) At the SEN ports, the time when the largest rate of change of flow imbalance occurs is related to the travelling time from the SN gate to the SEN port. The time delay between cases of different SEN length is less than one second. To alleviate unbalanced flow, it is better to have a long SEN.

(3) There is a large time delay between the flow change at the SN gate and the meniscus flow change. This is mainly caused by the flow travelling time from the SN gate to the meniscus. The time required for the meniscus to return to a steady flow state is 35 sec after the commencement of SN gate movement.

The following subjects remain to be studied in future works.

1) A more detailed 3-dimensional analysis.
2) A study of flow characteristics as SN gate varies toward the “open” or “closed” positions continuously which would correspond more accurately with the actual casting process.
3) An investigation of the relationship between mass flow acceleration and mold powder entrapment.

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