A fluid flow of molten steel in continuous casting mold directly results in slab surface and internal defects, such as slag entrapment, inclusions, and pinholes. Much effort was made on the field to stabilize it. Application of various electromagnetic forces and various nozzle designs are proposed and applied to commercial continuous casting process. However, few studies have looked at fluid flow in submerged entry nozzle even if it is a source of flow in the mold.

In this study, fluid flow in submerged entry nozzle is in-situ observed through transparent immersion nozzle by a fusible alloy model and a molten steel flow model. According to the experiment, fluid flow in submerged entry nozzle is dominated by argon flow rate, metal flow rate and nozzle diameter. Meniscus height in the nozzle is stable enough to measure, and decreasing argon flow rate, increasing metal flow rate and reducing nozzle diameter leads the flow from potential-flow to plug-flow.

Another examination, measurement of net argon flow rate through mold meniscus revealed that about 20% of argon gas injected from upper slide plate is brought into nozzle at continuous casting process. Taking these results into consideration, fluid flow in submerged entry nozzle in conventional slab caster is considered.

KEYWORDS: submerged entry nozzle, fluid flow, fusible alloy, water model, gas injection.
mold depending on slide gate, argon gas flow rate and fluid flow rate is examined by water model. Influences of the fluid flow rate, argon gas flow rate and nozzle inner diameter on fluid flow behaviour in submerged entry nozzle were in-situ observed by fusible alloy model and molten steel model. Measurement of argon flow rate through mold meniscus Solution of net argon flow rate brought into nozzle is important to solve fluid flow in the nozzle. Argon gas gushing out of the mold meniscus is measured at previously mentioned water model and commercial caster. Gas extracted from mold meniscus is collected through 50mm diameter glass container and gas volume was simply measured in water model, whereas it is collected through 100x100mm square steel cap and immediately analyzed the composition in molten steel model. Net argon gas flow rate gushing out of mold meniscus is calculated from the analysis. In commercial caster, mold size was 270mm x 1400-1600mm and casting rate was 1.5m/min, and gas flow rate was controled 10-40Nl/min. On the other hand, in water model, mold size was 270mm x 1400-1600mm and gas flow rate was between 12-120Nl/min. In the model, gas was injected into closed loop. All of injected gas must be brought into nozzle by force, which is different from commercial caster.

**EXPERIMENTAL RESULTS**

**Water model experiment**

Fluid flow velocity profile of spouting stream was measured by a propeller current meter in front of both nozzle ports; port A and B. Velocity was measured vertically and horizontally, and a time-averaged liquid velocity was obtained from every 0.5s data for 60s duration. Fig. 1 shows an example of fluid velocity comparing two ports measured at 80mm front from nozzle. Nozzle port size is 90mm height and 60mm width. The figure shows horizontal component of velocity when 30Nl/min air is injected into nozzle, corresponding to 30Nl/min argon injection into molten steel considering thermal expansion. The velocity is obviously faster at the lower part of nozzle port as usual results with bifurcated nozzle. It is important to note that spouting velocity by no means equal to each port, and asymmetric spouting stream is recognized in the mold. In the process, channel at sliding gate must deviate from SEN axis. Many experiments under various conditions revealed that this asymmetric stream is related to a channel direction at sliding gate. Although spontaneous periodical fluctuation appears, this asymmetric stream is obvious. Similar results are obtained when fluid flow rate changes or gas injection is turned off. Even structure above nozzle gives significant effects on spouting direction regardless of fluid material. That injected gas distribution is much alike in the mold width direction depending on fluid flow rate, gate diameter and gas injection rate etc., the 20% seems appropriate value at conventional steel system. Although the gas ratio brought into nozzle should vary depending on fluid flow rate, gate diameter and gas injection rate etc., the 20% seems appropriate value at conventional slab operation considering meniscus behaviour when argon gas is injected directly into submerged entry nozzle wall compared with when it is injected from upper sliding plate.

**Argon gas extraction from meniscus**

It is necessary to clarify net argon flow rate brought into nozzle in order to know actual flow condition in the nozzle. Therefore, argon gas extracted from mold meniscus is measured by water model and commercial caster. Fig. 2 shows a distribution of gas extraction from mold meniscus by 1/1 water model under various gas flow rate. Gas flow rate is indicated as volume ratio by unit meniscus area against injected volume. Gas extraction increase in the vicinity of nozzle, as in the previous work [8,13], and is almost even toward mold thickness. When gas flow rate increases, gas extraction in the vicinity of nozzle tends to increase. However, almost similar distribution is obtained in all conditions in spite of gas flow rate. As gas is injected into closed loop in the model, all of the gas is brought into submerged entry nozzle. A rough approximation of gas extraction profile and integration of it with respect to meniscus area, leads a gross value of almost 100%. Extracted gas is also collected in commercial slab caster at various positions toward mold width. Fig. 3 shows a distribution of gas extraction in commercial slab caster comparing with water model. In the continuous casting process, part of argon might elude into tundish. Then, collected gas volume is obviously more in water model and fusible alloy model, in which gas is injected into closed channel, than commercial slab caster. Although buoyancy force and other physical properties are significantly different between water and molten steel, these results indicate that injected gas distribution is much alike in the mold width direction regardless of fluid material. Open marks in the figure show gas extraction ratio compared with water model. When much gas is injected into nozzle, gas extraction near the nozzle became large. However, net argon flow rate at commercial slab caster is one-fourth or fifth compared with water model. According to these experiments, about 20% of argon gas injected

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**Table 1**

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Water</th>
<th>Fusible alloy</th>
<th>Molten steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical scale</td>
<td>1/1</td>
<td>1/4</td>
<td>4/9</td>
</tr>
<tr>
<td>Similarity rule</td>
<td>Froude number</td>
<td>Froude number</td>
<td>Froude number</td>
</tr>
<tr>
<td>Fluid temp. [K]</td>
<td>R.T.</td>
<td>385</td>
<td>1830</td>
</tr>
<tr>
<td>Slide gate</td>
<td>fixed</td>
<td>fixed</td>
<td>controlled</td>
</tr>
<tr>
<td>Nozzle diameter [mm]</td>
<td>30</td>
<td>22-40, 40</td>
<td>40, 60</td>
</tr>
<tr>
<td>Fluid flow rate [l/min]</td>
<td>691</td>
<td>21.5, 17.5, 13.5</td>
<td>86.94</td>
</tr>
<tr>
<td>Gas</td>
<td>air</td>
<td>argon</td>
<td>argon</td>
</tr>
<tr>
<td>Gas flow rate [Nl/min]</td>
<td>0.30</td>
<td>0-1.0</td>
<td>0-5.0</td>
</tr>
</tbody>
</table>

**Fig. 1**

Comparison of spouting velocity between two opposite ports. a) Vertical profile; b) Horizontal profile. Confronto delle velocità di getto fra due uscite opposte: a) profilo verticale, b) profilo orizzontale.

**Fig. 2**

Distribution of gas extraction from mold meniscus. a) Mold thickness direction; b) Mold width direction. Distribuzione dell'estrazione di gas dal menisco. a) in direzione della larghezza dello stampo, b) in direzione dello spessore dello stampo.

**Fig. 3**

Distribution of gas extraction in commercial slab caster comparing with water model. Distribuzione dell'estrazione di gas in un commercial slab caster a confronto con il modello di flusso con acqua.

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Meniscus height measured by molten steel model compared with fusible alloy model result.

According to fusible alloy experiment, meniscus height in submerged entry nozzle, is regulated depending on metal flow rate Qm (m³/min), argon flow rate Qa (Nl/min) and nozzle diameter D (mm). The flow rate of molten steel in the nozzle is estimated by equation 1 on condition that metal flow rate Qm is assumed for the estimation. Meniscus height in the nozzle is compared with fusible alloy model. As argon flow rate increases, meniscus height in the nozzle falls. Ar gas flow rate should heat up to fluid temperature immediately [14], gas volume is expanded more than 5 times in molten steel model compared with fusible alloy model, and this discrepancy corresponds to gas brought ratio into nozzle shown in fig. 5. Since argon gas was injected at upper sliding plate in usual operation, the injection of argon gas from upper sliding plate makes steel flow in plug-flow during usual operation.

**REFERENCES**


**Colata continua**

**Memorie >>**

ed at a nozzle size of 30mm and 40mm in inner diameter. Huge bubbles originated from accumulated in nozzle are discharged only at the beginning. Then Ar bubbles of 2-3mm are calmly extracted from whole mold meniscus. Although many splashes of metal are seen in the nozzle, metal meniscus inside nozzle is stable enough to measure its height. When meniscus height reaches to the top of nozzle, nozzle is filled with metal and flow as plug-flow. In water model, it is impossible to realize a potential-flow under the condition corresponding to commercial operation. However, both plug-flow and potential-flow are emerged with fusible alloy depending on experimental condition. Increasing argon flow rate and decreasing metal flow rate leads to a drop in meniscus height. Change in meniscus height with argon flow rate seems almost linear under each nozzle size. When bifurcated nozzle is used, meniscus height in nozzle is slightly raised due to channel resistance. A nozzle model was employed to observe molten steel flow in the nozzle by thermography. These figures are taken under argon flow rate of 1Nl/min and 5Nl/min at same steel flow rate. The nozzle could withstand thermal shock and high temperatures, and molten steel flow, meniscus and meniscus in the nozzle could be observed through nozzle material. Meniscus height in the nozzle could be optically and thermally observed and it falls with an increase of argon flow rate. The nozzle was filled with molten steel and there seems to be a plug-flow at lower argon flow rate of 1Nl/min, while temperature was uneven and seems to be a potential-flow when argon flow rate is 5Nl/min.

**DISCUSSION**

In situ molten steel flow in the nozzle by thermography. a) Ar:1Nl/min; b) Ar:5Nl/min.

Fluid flow in submerged entry nozzle is in-situ observed by fusible alloy and meniscus steel model. Net argon flow rate extracted from mold meniscus was also measured. Results obtained by present works are summarized as follows. (1) In fusible alloy model experiment, both potential flow and plug flow emerged depending on argon flow rate, metal flow rate and nozzle diameter. Decreasing of argon flow rate, increasing of metal flow rate and reducing of nozzle diameter led to a rise of meniscus height in nozzle. Nozzle internal pressure measured during flowing was negative and coicides with estimated value to raise the fluid obtained by reverse calculation from measured meniscus height. (2) Molten steel flow could be observed through transparent immersion nozzle. Both potential-flow and plug-flow also emerged depending on argon flow rate. (3) According to measurement of net argon flow rate through mold meniscus, gas distribution extracted from mold meniscus is similar among water, fusible alloy and molten steel. About 20% of argon gas injected from upper sliding plate is brought into nozzle at commercial slab continuous caster. The injection of argon gas from upper sliding plate is necessary to raise the fluid obtained by reverse calculation from measured meniscus height. It is concluded that meniscus height in submerged entry nozzle is slightly raised due to channel resistance. A nozzle model was employed to observe molten steel flow in the nozzle by thermography. These figures are taken under argon flow rate of 1Nl/min and 5Nl/min at same steel flow rate. The nozzle could withstand thermal shock and high temperatures, and molten steel flow, meniscus and meniscus in the nozzle could be observed through nozzle material. Meniscus height in the nozzle could be optically and thermally observed and it falls with an increase of argon flow rate. The nozzle was filled with molten steel and there seems to be a plug-flow at lower argon flow rate of 1Nl/min, while temperature was uneven and seems to be a potential-flow when argon flow rate is 5Nl/min.

**CONCLUSIONS**

In situ molten steel flow in the nozzle by thermography. a) Ar:1Nl/min; b) Ar:5Nl/min.

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