OBSERVATION OF MOLTEN STEEL FLOW IN SUBMERGED ENTRY NOZZLE

T. Kato, M. Hara, A. Muto, S. Hiraki, M. Kawamoto

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 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,

INTRODUCTION

Argon gas is injected into molten steel stream from upper nozzle, slide gate and/or nozzle to deter submerged entry nozzle (SEN) clogging. Since both entrapment of argon bubble and unstable flow induced by SEN clogging make the slab quality to deteriorate, much effort has been performed to optimize fluid flow in the mold to produce high quality steel [1-8].

Application of electromagnetic force into molten steel flow in the mold and optimizing submerged entry nozzle design is a possible effective measure. Various types of static magnetic field (brake) [3,4], travelling magnetic field [5] and various designs of submerged entry nozzle [6-8] are proposed and installed into commercial continuous caster. Those results are generally based on experimental study with water model and/or numerical simulation of fluid dynamics.

Although fluid flow in the nozzle significantly effects on spouting stream as a source of mold flow, few studies have been done in this field [9,10]. Uneven flow velocity depending on plate sliding direction was clarified [11], however, precise consideration of gas-liquid multi-phase-flow in numerical simulations and replication of steel flow by water models are insufficient to reveal fluid flow in submerged entry nozzle. Whether steel flow inside the nozzle of commercial continuous casting is potential-flow or plug-flow is not clear yet.

In this study, three fluid models, i.e. water model, fusible alloy model and steel flow model are used in order to clarify the fluid flow in the submerged entry nozzle of commercial slab continuous caster. As physical properties of fluid and gas must affects on flow condition, and wettability between nozzle material and fluid affects on gas behaviour[11], three fluid models are used properly. Fluid flow in the nozzle is in-situ observed by fusible alloy model and steel flow model [12].

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EXPERIMENTAL PROCEDURE

Fluid model experimental

Three fluid models, water model, fusible alloy model and molten steel model, are used for the study. The specifications of these models are shown in Tab. 1. Three layered slide gate or its structure are installed in each model, and air or argon gas is injected from upper plate through bores surrounding flow channel. Sliding direction is coincident with mold width in every model and an amount of gate opening is about 70% in stroke. Fluid is supplied into submerged entry nozzle by closed pipe line and circulated in a closed loop in water model and fusible alloy model. 2500kg of molten steel is supplied into nozzle via tundish, as continuous casting process in molten steel model. Gas flow rate was established considering thermal expansion so that volume ratio of gas/fluid must be similar among each model.

Spouting stream behaviour and gas extraction profile in the

Fluid	Water	Fusible alloy	Molten steel
Geometrical scale	*1/1*	*1/4*	*4/9*
Similarity rule	*Froude number* *Reynolds number*	*Froude number*	*Froude number*
Fluid temp.(K)	*R.T.*	*383*	*1830*
Slide gate	*fixed*	*fixed*	*controlled*
Nozzle diameter(mm)	*90*	*22,30,40*	*40,58*
Fluid flow rate(l/min)	*691*	*21.5,17.5,13.5*	*86,94*
Gas	*air*	*argon*	*argon*
Gas flow rate(Nl/min)	*0,30*	*0-1.0*	*0-5.0*

Tab. 1
Specifications of three fluid models used.
Specifiche dei tre modelli di fluido utilizzati.

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 controlled 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 60mm front from nozzle. Nozzle port size is 90mm height and 80mm width. The figure shows horizontal component of velocity when 30Nl/min air is injected into nozzle, corresponding to 5Nl/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 is 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 stream, fluid flow in the nozzle must be important to stabilize mold flow. However, it must be impossible to replicate molten steel flow in the nozzle by water model due to considerable discrepancy of physical properties. Therefore, 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.

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 show 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 collection 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 from upper sliding plate should be brought into nozzle at molten 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.

Observation of fusible alloy model

Fluid flow in the nozzle is in-situ observed by fusible alloy model. Fig. 4 show meniscus height inside nozzle measured under various conditions. Metal flow rate and argon flow rate are vari-

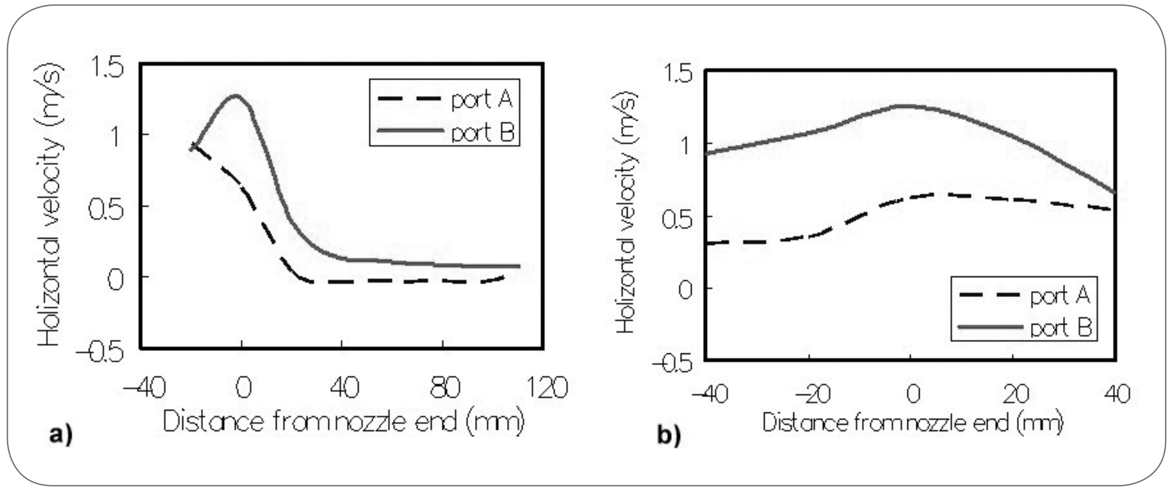

Fig. 1
Comparison of spouting velocity between two opposite ports. a) Vertical profile; b) Horizontal profile.
Confronto delle velocità di getto fra due uscite opposte. a) profilo verticale, b) profilo orizzontale.

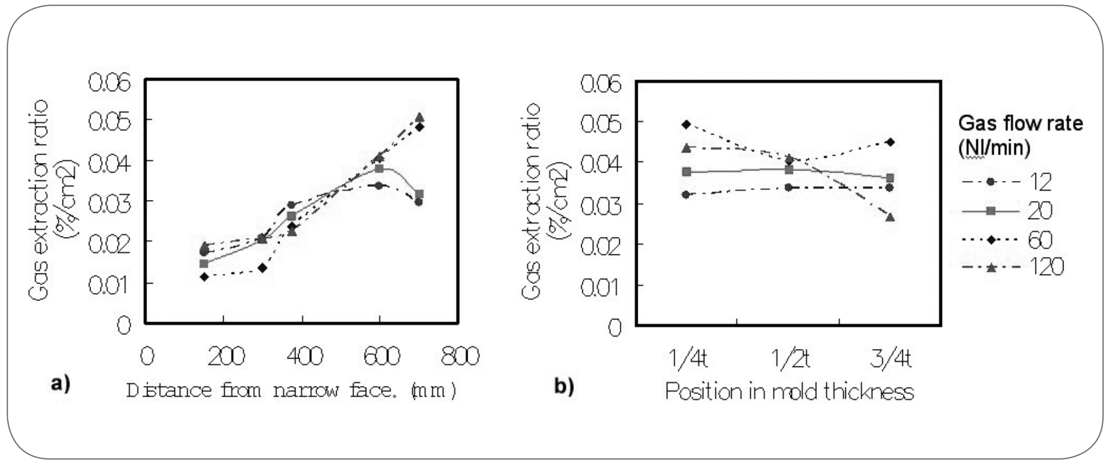

Fig. 2
Distribution of gas extraction from mold meniscus. a) Mold width direction; b) Mold thickness direction.
Distribuzione dell'estrazione di gas dal menisco. a) in direzione della larghezza dello stampo, b) in direzione dello spessore dello stampo.

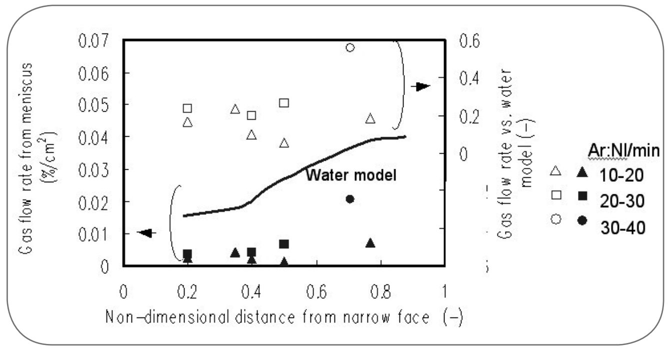

Fig. 3
Distribution of gas extraction in commercial slab caster comparing with water model.
Distribuzione dell'estrazione di gas in un commercial slab caster a confronto con il modello di flusso con acqua.

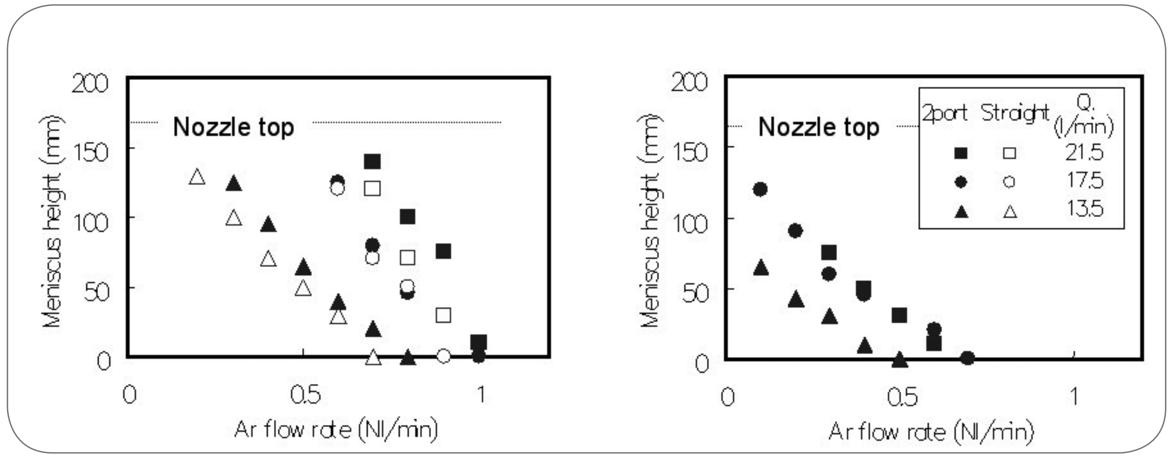

Fig. 4
Meniscus height inside nozzle measured by fusible alloy model. a) 30mm dia.; b) 40mm dia..
Altezza del menisco all'interno dell'ugello misurato nel caso di modello con lega fusibile;a) 30mm; b) 40mm.

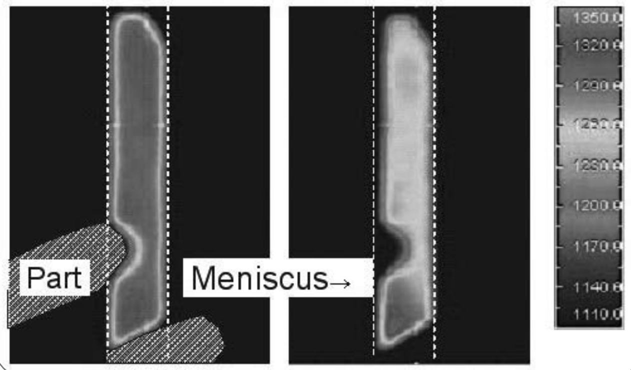

Fig. 5
In-situ observed molten steel flow in the nozzle by thermography. a) Ar:1Nl/min; b) Ar:5Nl/min.
Flusso dell'acciaio liquido nell'ugello osservato in situ mediante termografia. a) Ar:1Nl/min; b) Ar:5Nl/min.

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 gas 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 metal flow rate.
Comparing two nozzle diameters, expansion of nozzle size leads to a drop in meniscus height, and changes 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 design, however, did not give significant effect on flow condition.
It is concluded that meniscus height in submerged entry nozzle is fixed depending on metal flow rate Ql (l/min), argon flow rate Qa (Nl/min) and nozzle diameter D (mm). Nozzle internal pressure is measured and consistent with estimated negative pressure to raise the fluid up obtained by reverse calculation from measured meniscus height [12]. Since gas volume ratio is less than 0.1, density of fusible alloy is assumed as fluid density, ignoring gas volume. Previous studies have reported that internal pressure was negative [14,15] and became higher with an increase in gas flow rate [15], consistent with present data.

Observation of molten steel model

Fig. 5 show in-situ observation of 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, splashes and meniscus in the nozzle could be observed through nozzle material. Meniscus height in the nozzle could be optically and thermally observed and it

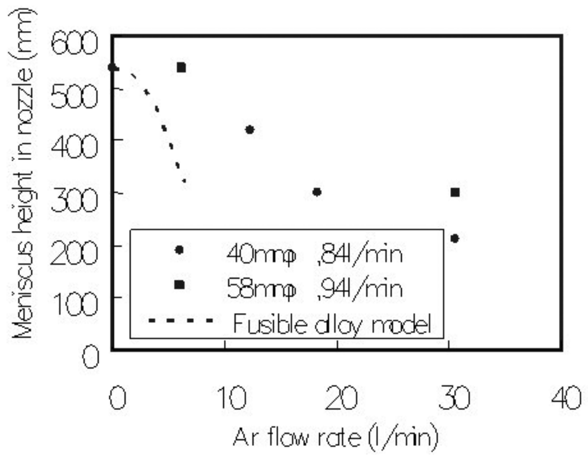

Fig. 6
Meniscus heights measured by molten steel model comparing with fusible alloy model result.
Altezza del menisco misurata nel caso del modello con acciaio liquido confrontato con i risultati del modello con lega fusibile.

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 there seems to be a potential-flow when argon flow rate is 5Nl/min.

DISCUSSION

According to fusible alloy experiment, meniscus height in submerged entry nozzle, is regulated depending on metal flow rate Ql (l/min), argon flow rate Qa (Nl/min) and nozzle diameter D (mm). Equation 1 shows a multiple regression equation obtained by experimental results of fusible alloy model.

$$H = 15.6 \cdot Q_a^{2.02} \cdot Q_l^{-2.80} \cdot D^{3.04} \quad (1)[12]$$

Fig. 6 shows meniscus heights measured in these experiments and at fusible alloy model derived by equation 1. As injected argon gas should heat up to fluid temperature immediately [14], gas volume is expanded more than 5 times in molten steel model compared with its normal volume. In the figure, argon flow rate is transcribed into net volume at experimental temperature considering thermal expansion to compare with the results obtained by fusible alloy model. As argon flow rate increases, meniscus height in the nozzle falls. Argon flow rate at molten steel model is 4 or 5 times larger than fusible alloy model, and this discrepancy corresponds to gas brought ratio into nozzle shown in fig.3. Since argon gas was injected at upper sliding plate in molten steel model, part of gas must float into tundish.
Taking these experimental results into consideration, meniscus height in commercial slab caster is estimated. A throughput of 4.8ton/min is assumed for the estimation. Meniscus height in the nozzle is estimated by equation 1 on condition that metal flow rate Ql is 690l/min and nozzle diameter D is 90mm. Thermal expansion of argon gas and gas brought ratio of 20% into nozzle against injected volume is considered. Experimental results with molten steel model are also converted into commercial caster condition with exponent of equation 1. General argon flow rate of 10-30Nl/min. injected from upper nozzle or upper sliding plate at commercial slab caster makes steel flow in the nozzle plug-flow. It is concluded that in conventional slab caster, submerged entry nozzle must be filled with molten steel and steel flow must be like a plug-flow during usual operation.

CONCLUSIONS

Fluid flow in the submerged entry nozzle was in-situ observed by fusible alloy and molten 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 coincides 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.
(4)Taking these experimental results into consideration, it is concluded that in conventional slab caster, submerged entry nozzle must be filled with molten steel and steel flow must be like a plug-flow during usual operation.

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ABSTRACT

ANALISI DEL FLUSSO DI ACCIAIO FUSO NELLO SCARICATORE SOMMERSO

Parole chiave: acciaio, colata continua, modellazione

Il flusso di acciaio liquido nella lingottiera di colata continua dà luogo direttamente a difetti interni e della superficie della barra, come ad esempio intrappolamento di scorie, inclusioni, e "pinholes". Sono stati effettuati in campo molteplici sforzi al fine di ottenere una maggiore stabilità. Nei processi di colata continua commerciali sono state proposti e sperimentati diversi accorgimenti, come l'applicazione di flussi magnetici (statitci o variabili), e variazioni di forma dell'ugello. Tuttavia pochi studi hanno analizzato il flusso del fluido nello scaricatore sommerso (SEN-Submerged Entry Nozzle) pur essendo questo all'origine del flusso nella lingottiera.
In questo studio, il flusso di fluido nello scaricatore sommerso è stato osservato in situ attraverso un ugello trasparente. Secondo lo studio, il flusso di fluido nello scaricatore sommerso è prevalentemente governato dalla velocità di flusso dell' argon, dalla velocità di flusso del metallo e dal diametro dello scaricatore. L'altezza del menisco nell'ugello è sufficientemente stabile per essere misurata, e diminuendo la velocità di flusso di argon, aumentando la velocità di flusso del metallo e riducendo il diametro dell'ugello è possibile portare il flusso da flusso potenziale a plug-flow.
Da un altro esame, la misura della velocità netta di flusso dell'argon ha evidenziato che il 20% circa di gas argon iniettato dall'upper slide plate viene immesso nell'ugello durante il processo di colata continua. Alla luce dei risultati ottenuti, è stato considerato il flusso di acciaio nello scaricatore sommerso in un impianto convenzionale per la colata di bramme.