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Measurement of Transient Meniscus Flow in Steel Continuous Casters and Effect of Electromagnetic Braking

Seong-Mook Cho[1], Hyoung-Jun Lee[1], Seon-Hyo Kim[1],
Rajneesh Chaudhary[2], Brian G Thomas[2],
Duck-Hee Lee[3], Yong-Jin Kim[3], Woong-Ryul Choi[3],
Sung-Kwang Kim[3], Hui-Soo Kim[3]

1. Department of Materials Science and Engineering, Pohang University of Science and Technology, Pohang, Kyungbuk, South Korea
2. Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, IL, USA
3. Steelmaking Department, POSCO Gwangyang Works, South Korea

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Abstract:

Unstable meniscus flow leads to slab surface defects during continuous casting of steel, due to level fluctuations and vortex formation, which causes entrapment of argon bubbles and mold flux. Applying electromagnetic fields across the liquid steel pool, such as the “double-ruler” or “FC-mold” braking system, has been commercialized to stabilize meniscus flow. Plant measurements were performed using nail boards to quantify meniscus flow in a typical steel slab-casting mold with a slide gate system. The shape of the meniscus level, the surface velocity, and the direction of meniscus flow, are all quantified with time and location by analyzing the shape of the skull of solidified steel that encases each dipped nail. The results reveal interesting insights into time-variations of the flow pattern, which cannot and should not be detected with a standard mold-level sensor used for flow control. Further, the effect of applying the electromagnetic braking field on the flow pattern is revealed.

Introduction

Continuous casting is used to manufacture over 90% of steel in the world [1] so it is essential to understand and optimize this process to minimize defects. Most of the defects affecting slab quality are associated with surface flow in the mold [2]. Surface level variations caused by excessive surface velocity can entrain slag inclusions resulting in both surface and internal defects in the product [3-5]. Thus, it is important to optimize the surface flow velocity to reduce the defects of steel slabs. Many efforts have been made to optimize nozzle geometry [6] and caster operation to achieve an optimal and stable mold flow pattern. Adding electromagnetic force to the steel fluid flow may improve the ability to control fluid flow in the mold. Commercial systems include static local-, single-ruler-, double ruler-, and moving electromagnetic fields. The FC (Flow Control)-mold braking system consists of two rectangular magnets across each wide face that create a double-humped magnetic field that is roughly constant through the mold thickness. This type of EMBR (Electromagnetic Brake) system aims to stabilize the jet flowing from the SEN ports. Plant measurements of meniscus flow are important to investigate the electromagnetic effects on flow in the mold.

Many researchers have suggested different methods to measure surface velocity. Iguchi et al. developed an electromagnetic non-contact sensor to measure surface velocity of the molten metal flow [7]. Kubota suggested a method that uses an immersed bar to quantify surface velocity by measuring the angle of inclination of the bar by the flow [8]. Nail board measurements suggested by Dauby et al [9] have been commonly used to measure slag thickness and flow direction due to their convenience and efficiency. Rietow and Thomas extended this method to acquire velocity information. They suggested a relation between steel surface velocity and solidified skull height difference measured on a dipped nail [10].

The measurements using nail board are efficient to measure the level and surface velocity at the many positions across the meniscus both with and without electromagnetic braking. Electromagnetic sensor methods may be adversely affected by induced magnetic fields, and the immersed refractory bar is expensive and sometimes difficult to employ due to space restrictions. The nail-board method was successfully used by Cukierski and Thomas to validate their computational fluid flow model with electromagnetic braking effects [11].

This work applies nail board measurements to investigate time variations in surface velocity and level in a commercial steel continuous caster to gain new insight into transient turbulent flow in the mold. Measurements are made at different times and locations, both with and without the effect of a double-ruler electromagnetic braking force.

Measurement and Procedure

Measurements were performed using nail board sets, as shown in Fig. 1. Each wood nail board has two rows of ten 5mm-diameter stainless steel nails, spaced 50mm apart, centered between the SEN (Submerged Entry Nozzle) and the NF (Narrow Face). Thus, each line of nails parallel to the wide face was 55mm from the mold midplane. Figure 2 shows more details about the nail board, and its stable positioning above the oscillating mold using stainless-steel rods for support. Six trials each were performed with (FC-on) and without (FC-off) electromagnetic braking. For each trial, the nail board was dipped into the molten steel pool for 3 seconds, with 1 minute between each trial. A time gap of 30 minutes was given between the FC-on and FC-off trials, to allow plenty of time for the new flow pattern to stabilize.

Table I provides details of the casting conditions, flow control system, nozzle and mold dimensions of the continuous caster, and the FC-current applied during the measurements.

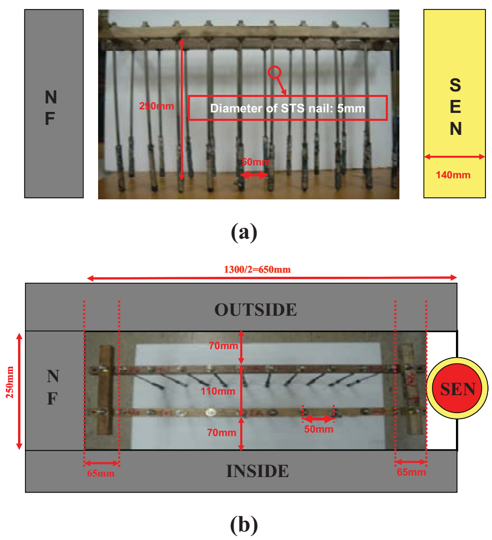


Figure 1. Schematic of nail board set : (a) front view, (b) top view

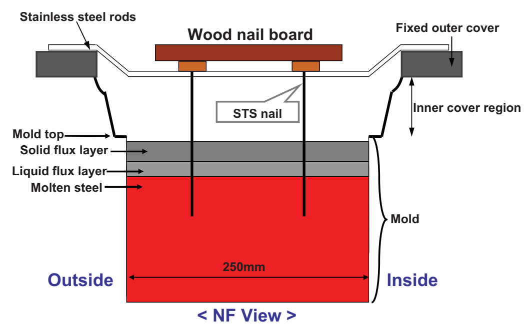


Figure 2. Position of nail board in mold (side view)

Table I. Measurement conditions

Steel flow rate		552.5 LPM
Casting speed		1.70 m/min
Argon gas injection rate		9.2 SLPM (1atm and 273K)
Flow control system		Slide-gate
Nozzle	Bottom type	Well bottom
	Port angle	52 to 35degree step angle at the top, 45 degree angle at the bottom
	Port area	80mm (width) x 85mm (height)
	Bore diameter(inner/outer)	90 (at UTN top) to 80 (at bottom well) mm / 140 mm
Mold	Width	1300 mm
	Thickness	250 mm
EMBr Current	FC off	Upper: 0A, Lower: 0A
	FC on	Upper: 300A, Lower: 300A

After dipping the nail board into the steel liquid pool and removing it, the steel skulls that solidified on the end of each nail were measured and converted to meniscus surface level, flow direction, and surface velocity. Surface level was measured by recording the average distance of each skull from the wood plate. The flow direction is recognized by the orientation of the wave, which is pushed up highest where the steel flow impinges on the nail, as shown in Fig. 3. The difference between the maximum and minimum skull heights around the perimeter of each nail was converted to meniscus velocity using the relation between flow velocity and skull height given in Fig. 4 from Rietow and Thomas [10]. Both inner and outer skull height differences were measured to give two meniscus velocities for each nail and averaged. This required accounting for the different diameters of the outer skull (always ~10mm) and the inner skull at the nail surface (constant 6mm).

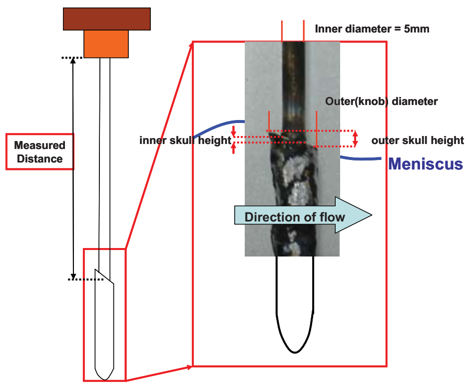


Figure 3. Sample nail with solidified skull

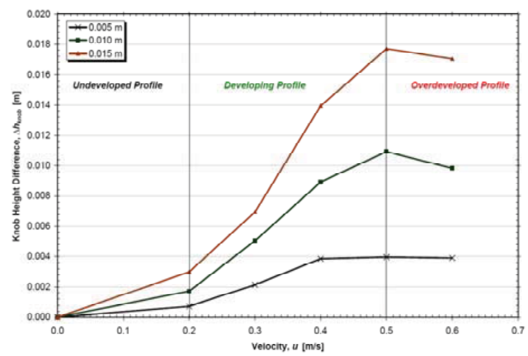
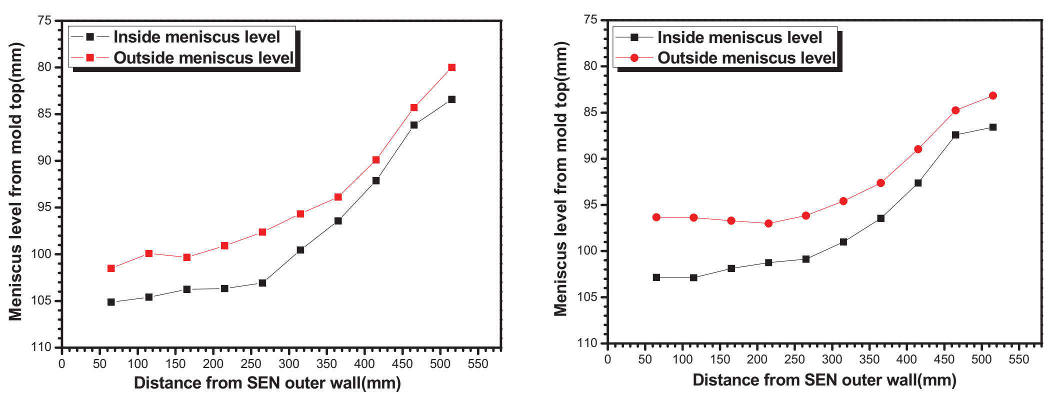


Figure 4. The relation between surface velocity and skull height difference [10]

Results and Discussion

Six meniscus level profiles collected over 5-minute time intervals were averaged for both EMBr (FC-on) and non-EMBr (FC-off) conditions. The asymmetric level profiles between the inside and outer-radius sides of the mold indicate asymmetric flow caused by the asymmetric opening area of the slide-gate flow control, and time variations due to turbulence. Time-averaged meniscus level profiles are shown in Fig. 5. Generally, the surface level is raised higher near the NF, and falls lower near the SEN, which indicates a classic double-roll flow pattern in the mold. The average surface level is flatter with electromagnetic braking on.



(a) **(b)**

Figure 5. Time-averaged meniscus level : (a) FC off , (b) FC on

The surface level fluctuates with time showing a sloshing pattern. The instantaneous surface level profiles used to create Fig. 5 are shown in Figs. 6 and 7, for conditions of FC-off and FC-on respectively. The changing level profiles show evidence of a least 2 periodic oscillations over the 5-min time interval for FC off and at least 3 with FC on. The target level point for the standard mold-level sensor is shown as a blue cross symbol and is roughly satisfied in all cases. These results reveal that a standard mold-level sensor can be used to control a stable meniscus level when properly positioned at the central "node". Naturally, this sensor cannot detect the level variations which exist in other regions of the mold surface.

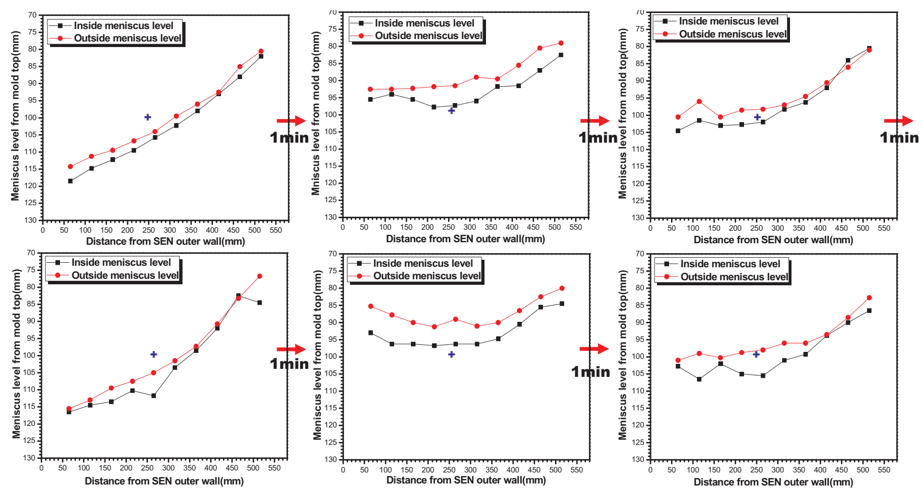


Figure 6. Time progression of level variations measured with FC-off

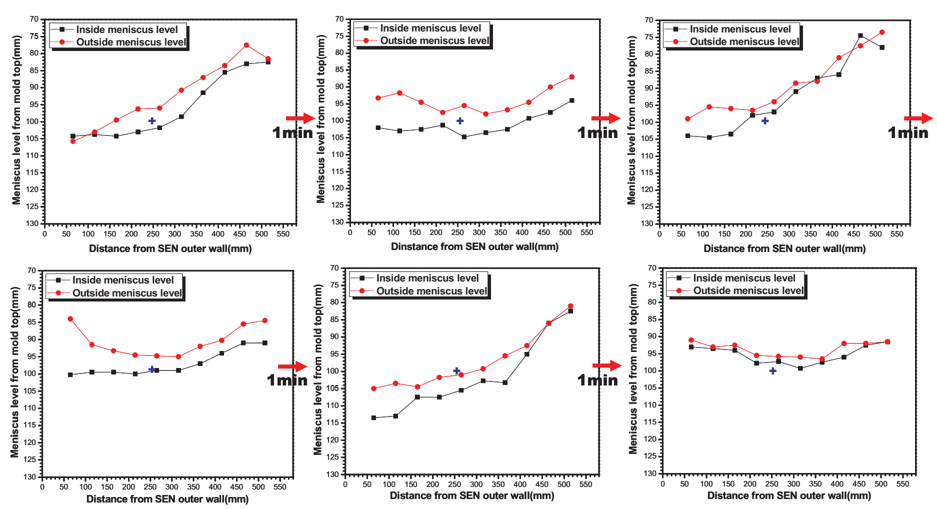
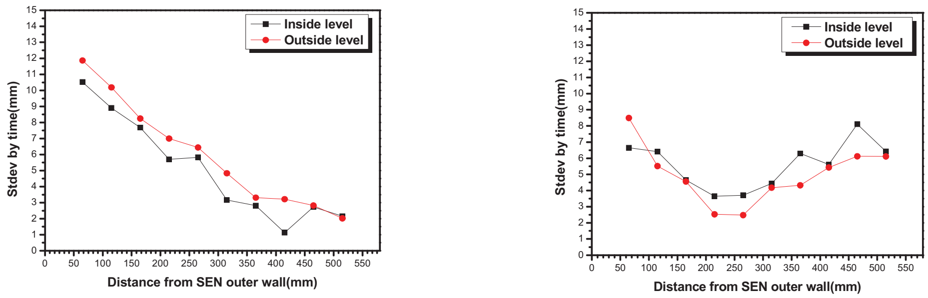


Figure 7. Time progression of level variations measured with FC-on

The standard deviation of the levels measured at each nail over the 5-min. time interval was calculated and plotted in Fig. 8. The smallest time fluctuations (indicating stable nodes) are observed closer to the NF with FC off and at the region midway between SEN and NF with FC on. These characteristic level variations are consistent with the wave behavior in Fig. 9.



(a) **(b)**

Figure 8. Comparison of time-average variations of measured level: (a) FC off , (b) FC on

(a) **(b)**

Figure 9. Schematic of level variation mechanism: (a) FC off , (b) FC on

To visualize the transient evolution of the surface flow pattern with time, flow direction and velocity magnitudes are represented by vector arrows at each time in Figs. 10 and 11 for FC-off and FC-on respectively. Both conditions indicate a classic double roll flow pattern, with surface flow towards the SEN. With FC off, surface flow is slightly biased towards the inside radius. Surface flow with FC-on shows more random variations for the chaotic turbulent flow.

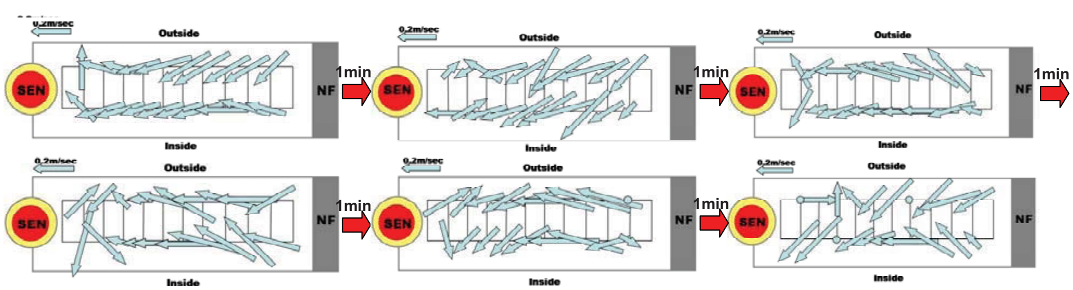


Figure 10. Time-evolution of flow pattern with FC off

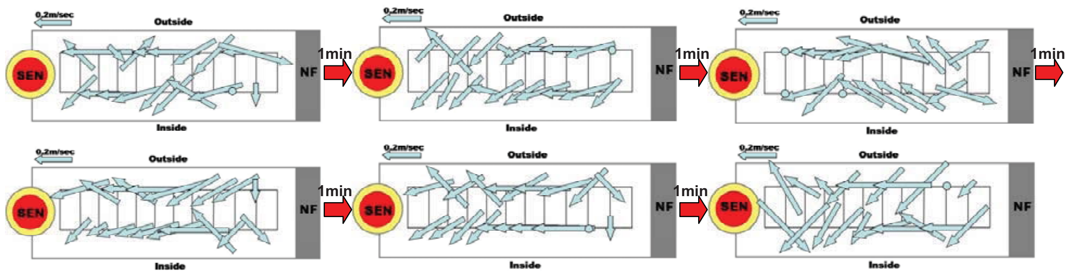


Figure 10. Time-evolution of flow pattern with FC on

Time-averaged surface velocity vectors were calculated by splitting the measured velocity magnitudes into x and y components as shown in Fig. 12 and averaging each velocity component at each nail. Flow vectors were plotted from calculating the flow direction and velocity magnitude from the averaged components.

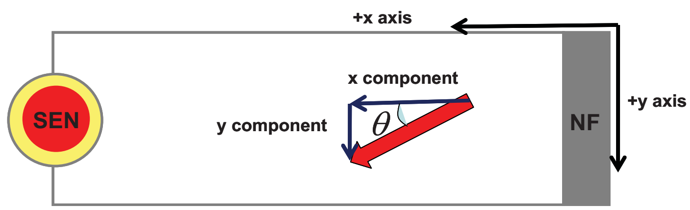
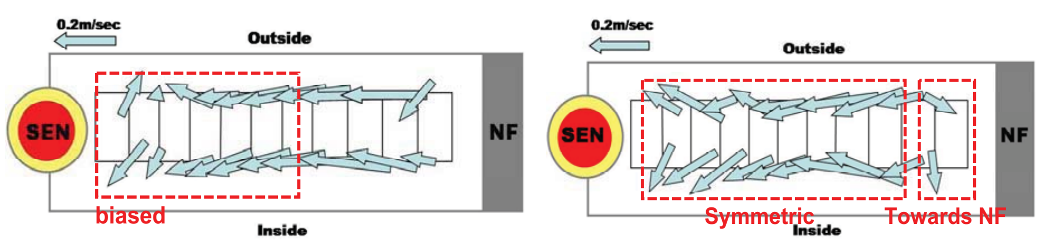


Figure 12. Quantifying average surface velocity vectors

The resulting time-averaged flow patterns are shown in Fig. 13. Meniscus flow shows a slightly biased pattern with FC off and a more symmetric pattern with FC on. With EMBr (FC-on), flow near narrow face goes towards the narrow face. This flow suggests that the electromagnetic field causes a change in flow circulation in the upper corner of mold. Electromagnetic forces also appear to slightly suppress the asymmetric flow towards the inside radius, giving a more symmetrical surface flow pattern. Chaotic flow variations caused by turbulence is more dominant than these effects, however, so more research is needed.



(a) **(b)**

Figure 13. Time-averaged flow pattern : (a) FC off , (b) FC on

Conclusions

- Nail board experiments offer an efficient method to measure meniscus level and velocity.
- Surface meniscus level, velocity and flow pattern appear to be transient with strong periodic sloshing, which is changed by electromagnetic forces.
- A standard mold level sensor can best be used to control meniscus level when positioned near a relatively stable "node" position in the surface level.
- In reality, the surface level in the mold fluctuates greatly with time variations that cannot be detected with standard mold level sensors.
- Electromagnetic forces of a double-ruler (FC-mold) braking system makes the meniscus level profile slightly flatter, with slightly slower and more symmetrical surface velocities.

Acknowledgements

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