Jim Evans Honorary Symposium
Edited by: Ben Q. Li, Brian G. Thomas, Lifeng Zhang, Fiona M. Doyle and Andrew P. Campbell
TMS (The Minerals, Metals & Materials Society), 2010

EFFECT OF STOPPER-ROD MISALIGNMENT ON ASYMMETRIC FLOW AND VORTEX FORMATION IN STEEL SLAB CASTING

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Keywords: Keywords: continuous casting; entrapment; mold powder; water model; mold

Abstract

Vortices forming near the slag-steel interface in the mold can entrap inclusions and cause defects in continuous casting of steel slabs. Lab experiments employing a 1/3rd scale water model were performed to quantify the effects of stopper rod asymmetry on vortex formation. Three stopper-rod placements (aligned, front-misaligned and left-misaligned) were considered. Vortex formation was visualized with a high speed camera by placing sesame-seed tracer on the surface, which enables counting the number and detecting the location of vortices with time. Impeller flow probes were adopted to measure velocity profiles near the surface. Misaligning the stopper-rod placement induces asymmetric flow, resulting in asymmetric surface velocity, velocity variations, and turbulent kinetic energy. These factors influence vortex frequency and location among four zones near the SEN. Most vortices form at the left regions beside the SEN with a left-misaligned stopper-rod. Vortices form more preferentially at outside regions with a front-misaligned stopper-rod.

Introduction

Continuous casting is used to manufacture over 90% of steel in the world so there is great incentive to understand and optimize the process to minimize energy consumption and defects. Most defects in the rolled product are slivers caused by inclusions being trapped in the solidifying shell in the mold. These inclusions come from entrained slag due to excessive surface velocity or vortexing [1,2], alumina particles from the tundish, or reoxidation and clogging inside the nozzle. Because steel quality depends greatly on turbulent flow in the mold, many efforts are made to optimize nozzle geometry and operation to achieve an optimal and stable mold flow pattern. Asymmetric flow in the mold is one of the main phenomena attributed with causing inclusion entrapment [3-5]. Steel flow rate into mold is usually controlled by either a stopper rod or slide-gate system. Flow from slide-gate nozzles is inherently asymmetric and produces either strong swirl or different flow on the right and left sides of the mold, depending upon the orientation of slide-gate. Stopper-rod control is gaining popularity because it offers symmetric flow, assuming it is aligned. The effect of stopper-rod misalignment is the subject of this study. The stopper rod could be misaligned by many causes such as: accidental faulty placement; buoyancy forces from the difference of density between light stopper-rod ceramic and heavy steel; deformation of the stopper-rod supporting beam by radiant heat from the steel; and drag force from steel flow across the bottom of the tundish.

This work investigates the effect of stopper-rod misalignment on steel flow in the mold. Specifically, the effect of both front-back and left-right stopper misalignment on surface velocity and vortex formation is measured using water model experiments. Many previous successful studies of mold fluid flow have been done using water models [3-8]. The current study applies water model experiments to quantify the effect of stopper-rod misalignment on both asymmetric flow and asymmetric vortex formation.

Experimental Apparatus and Procedure

Experiments were performed using a 1/3rd scale water model, shown in Figure 1. The model consists of a tundish, stopper-rod, Submerged Entry Nozzle (SEN), and mold. Vertical movement of the stopper-rod controls the water flow rate from the tundish through the SEN into the mold via changing the size of the annular gap between the stopper end and the bottom of the tundish where it curves into the SEN. Water exits holes in the bottom of the mold to a holding water bath and is pumped continuously back up to the tundish. The mold has straight walls, so the effects of the solidifying shell are neglected, but this should have negligible effect on the surface behavior for this thick-slab caster model. Single-phase flow was adopted, so the possible effects of argon gas-bubble injection were not studied. The nozzle has typically bifurcated, 35-degree down-angled rectangular ports, with further details given elsewhere [9]. Table I provides details of the casting conditions, nozzle and mold dimensions of this 1/3rd water model. Three different cases of stopper-rod location were studied as shown in Figure 2:

1) "aligned", where the stopper is carefully centered above the SEN with an average minimum annular gap of 1.92mm,
2) "2-mm front misaligned", where the stopper displaced towards the inside radius wide-face to give annular gaps of 0.29mm minimum (front) and 3.56mm maximum (back) and
3) "2mm-left misaligned", with misalignment towards the left narrow face by this same amount

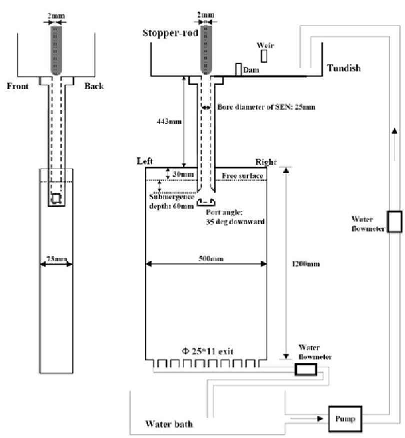


Figure 1. Schematic of 1/3rd scale water model

Table I. Experimental conditions with nozzle and mold dimensions

Water flow rate		34.4 LPM
Casting speed		0.917 m/min
Nozzle	Bottom type	Well bottom
	Port angle	35 degree
	Port area	23.3 mm(width) x 26.7 mm(height)
	Bore diameter(inner/outer)	25 mm/43 mm
Mold	Width	500 mm
	Thickness	75 mm
	Length	1200 mm
Stopper-rod location		Aligned(Center), 2mm misaligned(Front and Left)

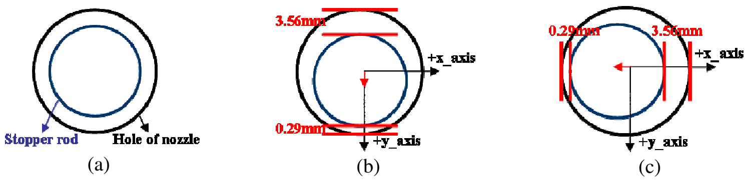


Figure 2. Top view showing location of stopper-rods in : (a) aligned, (b) 2mm front misal igned and (c) 2mm left misaligned cases

Velocity measurements were performed using two impeller-type probes located at 150mm from the narrow faces and 15mm down from the free-surface to record instantaneous velocity signals for 2000sec, as shown in Figure 3. To aid visualization, sesame seeds were used as tracer particles and vortex phenomena were recorded with a high speed camera. After recording, vortices were counted in four regions near the SEN, as shown in Figure 4. The number of vortices in each region was divided by the time interval to calculate the local formation frequency.

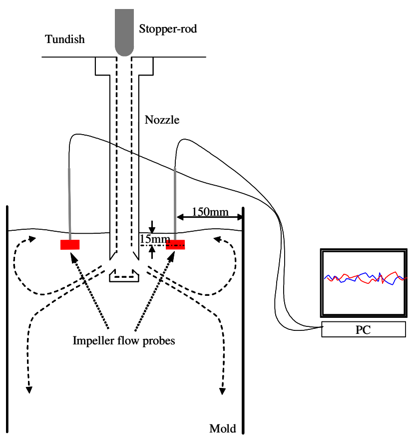


Figure 3. Position of impeller velocity probes in a mold

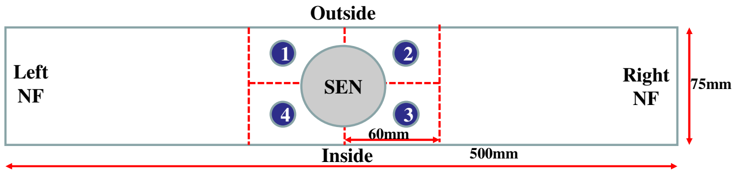


Figure 4. Mold regions where vortices are counted (top view)

Experimental Results and Discussion

Flow in the mold exhibits a classic double-roll pattern with free surface flow from the narrow faces towards the SEN. Instantaneous surface velocity signals were analyzed to see the effect of stopper-rod misalignment on surface flow. Figure 5 shows instantaneous velocity histories with different stopper-rod locations at the two probe positions. Based upon these instantaneous signals, mean surface velocities and turbulent kinetic energy were calculated and given in Table II. Horizontal velocity towards SEN in aligned and front misaligned cases is quite symmetric on right and left sides. Significant difference between velocities on right and left is seen in the left-misalignment case. Turbulent kinetic energy is symmetric in all cases. The difference in mean velocity is important because it clearly causes vortex formation. Greater differences in mean velocity cause more vortices.

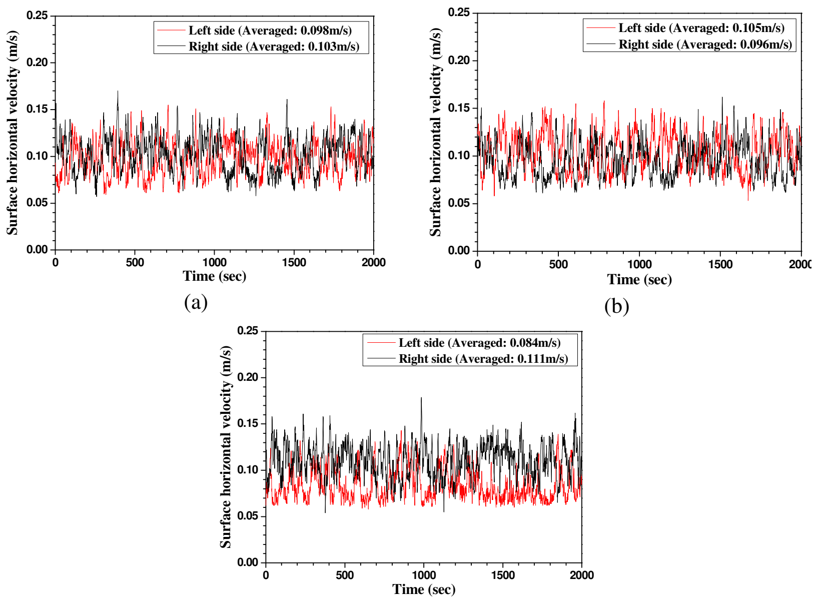


Figure 5. Instantaneous surface velocity measured in (a) aligned, (b) 2mm front misaligne d and (3) 2mm left misaligned stopper-rod cases

Table II. Comparison of averaged velocity magnitude and turbulent kinetic energy

		Left side		Right side	
		Avg. velocity magnitude (m/sec)	Turbulent kinetic energy ($x10^{-04}$ m^2/sec^2)	Avg. velocity magnitude (m/sec)	Turbulent kinetic energy ($x10^{-04}$ m^2/sec^2)
Aligned		0.098	4.72	0.103	5.30
Misaligned	Front	0.105	5.52	0.096	5.07
	Left	0.084	4.04	0.111	4.88

To quantify how often the right side velocity towards the SEN is faster than the left side, (asymmetric fraction), the number of data points recorded by the 2 probes in 2000s were divided according to which side was faster and given in Table III. For the left-misaligned case, this asymmetric fraction was bigger on the right side, which also had higher average variation (difference between velocities) and maximum variation. Furthermore, the magnitude of the variations correlates closely with a difference in vortex frequency. The aligned and front-misaligned cases show random variations, which are due to turbulence.

Table III. Comparison of asymmetric fraction, average variation and maximum variation

	Position of stopper-rod		Left side > Right side	Left side < Right side
Speed Frequency # of data points in 2000s (fraction, %)	Aligned		878 (44.0%)	1122 (56.0%)
	Misaligned	Front	1175 (58.5%)	825 (41.5%)
		Left	365 (18.5%)	1635 (81.5%)
Average variation (m/sec)	Aligned		0.024	0.029
	Misaligned	Front	0.031	0.022
		Left	0.017	0.037
Maximum variation (m/sec)	Aligned		0.071	0.093
	Misaligned	Front	0.091	0.087
		Left	0.066	0.113

Almost all vortices form within 60mm from the mold center in the four regions defined in Figure 4. Vortices at 1st and 3rd region rotate counter-clockwise and at 2nd and 4th region rotate clockwise, as shown in Figure 6(a) and (b). Some vortices penetrate deep near the nozzle port and entrap seeds from the surface into the jet leaving the nozzle port, as shown in Figure 6(c). After entering the jet, the entrapped seeds flow with the jet towards the narrow faces.

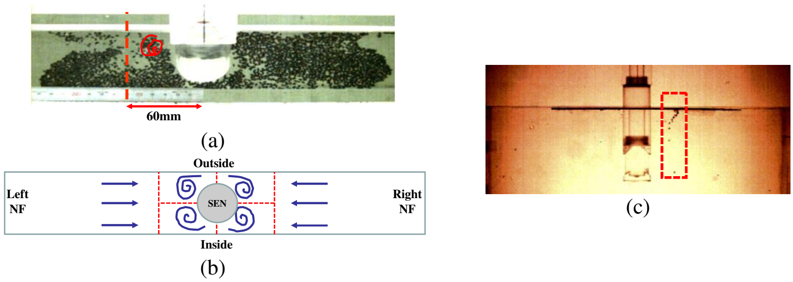
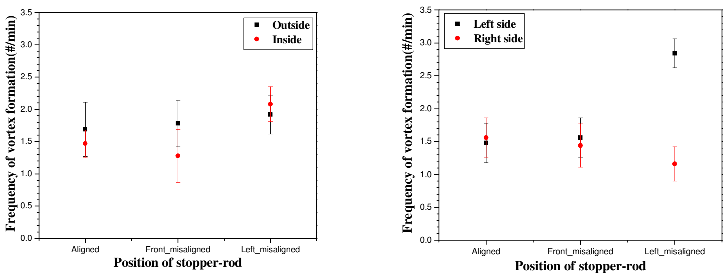


Figure 6. Visualized vortex formation (a) top view, (b) schematic and (c) front view

The frequency of occurrence of vortices at the back (1st and 2nd) regions were added and compared with the vortex frequency at the front (3rd and 4th) regions in Fig. 7(a) and Table IV to see the effect of front-back asymmetric flow. As expected, significant asymmetry is observed in the front misaligned case between the inside (front) and outside (back) radii. Similarly, the vortex formation frequencies at the left (1st and 4th) regions were added and compared with the vortex frequency at the right (2nd and 3rd) regions in Fig. 7(b) and Table V to see the effect of right-left asymmetric flow. As expected, significant left-right vortex asymmetry is observed in the left misaligned case. Twice as many vortices are observed on the left side for the left misalignment case, relative to other cases. These vortices are caused by the velocity difference between the left and right side, which causes flow through the gap between the SEN and the mold, and vortex shedding on the downstream side. Even with perfect alignment, 3 vortices per minute are observed total, which matches the total for front misalignment. These are due to random velocity variations caused by turbulence.



(a) (b)

Figure 7. Vortex frequency comparing (a) inside and outside, (b) left and right sides

Table IV. Comparison of vortex frequency between inside and outside

Vortex frequency(#/min)	Aligned	Misaligned	
		Front	Left
Outside region	1.64	1.72	1.92
Inside region	1.40	1.28	2.08
Difference	0.24	0.44	0.16
Total	3.04	3.00	4.00

Table V. Comparison of vortex frequency between left region and right region

Vortex frequency(#/min)		Left region	Right region	Difference	Total
Aligned		1.48	1.56	0.08	3.04
Misaligned	Front	1.56	1.44	0.12	3.00
	Left	2.84	1.16	1.68	4.00

Conclusions

1. Minor misalignment of the stopper-rod induces significant mean flow asymmetry in the mold and in turn causes significant increase in the incidence of vortices.

2. Most of the vortices form in four regions close to the SEN in all cases.
3. Instantaneous velocity asymmetries due to turbulence cause vortices even in the aligned stopper rod case, though their frequency is low. Velocities on right and left are ~symmetric.
4. Left misalignment causes strong mean flow from right to left on the surface thus forming more vortices on the left side of SEN.
5. Front misalignment seems to cause front-back asymmetry in the velocity with more vortices forming in the outside region.
6. Velocity asymmetry on the free surface correlates well with vortex formation, showing that the difference in velocity flowing past the SEN is responsible for vortices.

Acknowledgements

The authors thank POSCO and Shin-Eon Kang, POSCO Technical Research Laboratories for providing the water model. Support from the Continuous Casting Consortium, University of Illinois at Urbana-Champaign, POSCO, South Korea (Grant No. 4.0002397.01) and the National Science Foundation (Grant No. DMI 07-27620) is gratefully acknowledged.

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