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MEASUREMENT OF MOLTEN STEEL SURFACE VELOCITY WITH SVC AND NAIL DIPPING DURING CONTINUOUS CASTING PROCESS

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Abstract

Surface velocity of the molten steel is critical to final product quality during the continuous casting of steel. Plant experiments using two different new sensors, Sub-meniscus Velocity Control (SVC) devices and nail dipping, are performed to evaluate their performance, and to quantify liquid steel velocities at locations 50 mm apart on the surface of ArcelorMittal Dofasco's No. 1 continuous caster under different casting conditions, including different throughputs and mold widths. Correlation between the height difference of the solidified lump on the nail and surface velocity is confirmed and extended. Reasonable agreement between the two sensing methods of surface velocity is obtained, both in trends and magnitudes for both time-averaged velocity and transient flows. The effects of casting speed, mold width, and gas volume fraction on meniscus velocity are also discussed.

Introduction

In continuous casting (CC) process, molten steel flow in molds cannot be directly observed or measured using conventional flowmeters due to the opaque slag layer on top (Fig. 1) and high temperature of liquid steel inside. Information of liquid steel flow patterns in mold could be achieved from meniscus steel velocities which can be measured. The liquid steel surface velocity is also a key factor that affects the final product's quality: too high a surface velocity induces excessive turbulence and shear instability at slag-steel interface and increases the possibility of slag entrainment[2,3]; too low a surface velocity results in lack of heat transfer near narrow face and meniscus regions, which further leads to hook formation and entrapment of slag or inclusion particles[4,5,6]. Thus it is of great significance to measure and control meniscus steel velocities in the mold during CC process.

Various methods to measure liquid steel velocities have been developed and reported[7~16]. Mass Flow Control (MFC) sensors were imbedded behind mold walls, and liquid steel velocities were measured by computing the time delay of signals recorded by the two probes, which was caused by a change of induced electromagnetic current by flow variation as liquid metal traveled through the magnetic field[7]. This expensive technique was implemented to only measure velocities near the shell and around meniscus where the molten steel flow is more uniform[8].

Argyropoulos[9, 10] *et al.* developed a method to measure the liquid metal velocity by measuring the time needed to melt a metal sphere immersed in liquid bath of the same metal with three sensing wires imbedded at the sphere center. The sphere melting time is related to the local liquid velocities as well as the superheat contained. Mathematical models were also developed to predict the time required for the sphere to melt under different flow conditions. This sphere melting method needs a new sphere with all sensing wires imbedded for every trial, thus is very expensive for industrial use.

The methods mentioned above adopt complicated multi-physics procedures such as magnetohydrodynamics and heat transfer coupled flow to quantify the molten steel velocity. These methods are much more expensive to use and complicated to analyze the data obtained. On the other hand, simpler methods using basic fluid mechanics principles were also developed.

The Karman vortex probe was developed by Iguchi *et al.*[11,12,13] to measure the liquid steel velocities near meniscus based on the linear relationship between molten steel velocity and the shedding frequency of Karman's vortex streets formed behind the cylindrical probe immersed in the mold. This method only works well for one-dimensional flows. Other shapes of the probe were also tested in plant trials, and the triangular shape was confirmed most accurate in measuring low steel velocities (down to ~0.05 m/s) provided the direction of the flow is known[13]. The probe used in this method requires a rigid support to filter the noises in the signal. However, other sources generating the noise might not be prevented with this method.

Kubota[14] *et al*. utilized a simpler technique with a rod dipped into the molten steel, and the deflection angle of the rod and the torque acting on it were measured. These quantities were then transformed into surface steel velocities. The SVC technique[15] used in the current work operates via a similar principle.

A much simpler method to measure meniscus steel velocities using nail boards was pioneered by Dauby[1] *et al*. at LTV steel, then further developed and utilized by Thomas[16-18] *et al*. In addition to measuring instantaneous surface steel velocities in the mold and the direction of flow, the nail board method also provides extra information such as thickness of the slag layer, and the meniscus liquid level profile across the top surface.

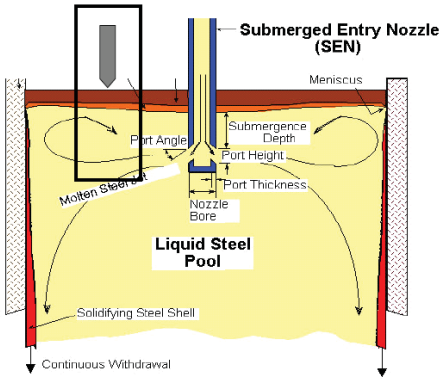

Fig. 1 Surface Slag Layers and CC Process[1]

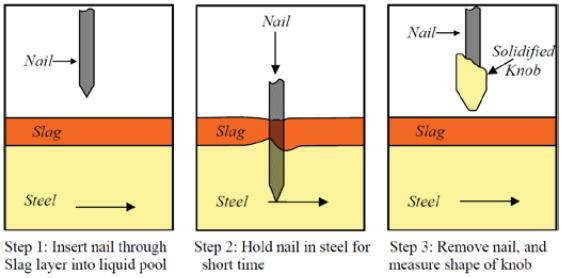

Fig. 2 Procedures for Nail Board Test[17]

For both nail board and single nail dipping tests, nails are inserted into molten steel for 3~5 seconds, then removed, and lumps form due to the solidification of the liquid steel and slag around the nails, as shown in Fig. 2. As molten steel flows past the nail, liquid steel builds up at the impinging point on the nail lump as it solidifies, and all kinematic energy is converted into

potential energy at the stagnation point. Liquid steel level drops at the opposite side of the nail lump due to the lower pressure at the wake region. This deformation of the meniscus is recorded by the shape of the solidified lump, as shown in Fig. 3. By investigating the lump shape and lump height difference between the facing-flow side and its opposite side, the magnitude and direction of the surface steel velocity can be determined. CFD models for nail dipping tests were developed by Rietow and Thomas[18] to study the liquid steel flow past a nail with a liquid slag layer on top using FIDAP. The standard k-ε model was employed to describe turbulence, and the SPINE method was used to track the slag/steel interface. The surface tension and gravity effects were also taken into account by the model. Further details of this computational model are provided elsewhere[19]. Correlation between the lump height difference and the surface steel velocity magnitude was established by performing parametric studies, as shown in Fig. 4.

Fig. 3 Nail and Lump

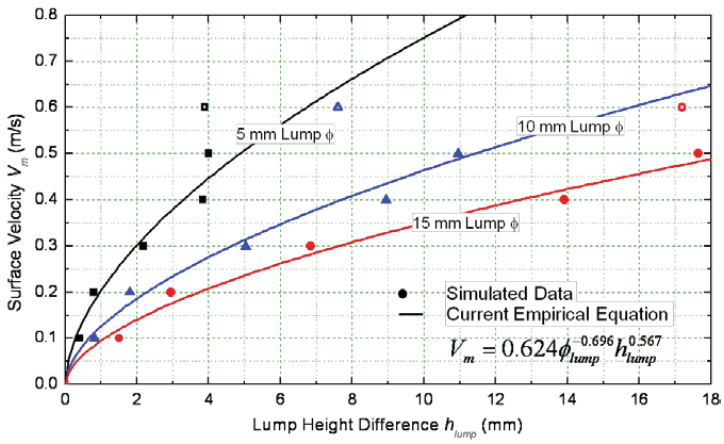

Fig. 4 Curves to convert nail lump height difference into velocity magnitude

The simulation results marked as hollow symbols in Fig. 4 suggest a drop of lump height difference at a free stream velocity of 0.6 m/s for all three lump diameters investigated, indicating that lump height difference does not always increase with liquid steel surface velocity. The maximum lump height difference from the simulation results occurs around a surface steel velocity of 0.5 m/s for all three lump diameters. However, the maximum lump height difference measured in practice was found to exceed the simulated maximum lump height difference significantly. Assuming possible convergence issues with the computational model at high free stream velocities, the simulated data above 0.6 m/s surface velocities are neglected, and a curve fit of rest data points is performed using a simple power law relation. The fitted curves are further extended to take into account cases with large lump height differences, as shown in Fig. 4 with the dashed lines.

In the present work, two sensor techniques, Sub-meniscus Velocity Control (SVC) device and nail dipping, are used together to measure the surface velocity in No. 1 continuous caster mold at ArcelorMittal Dofasco. The extended curve fit of Rietow's simulation results is utilized to quantify the liquid steel surface velocity from measured lump height difference. Use of nail dipping as a simple sensor is shown to be a reliable method to measure the liquid steel surface transient velocities from the comparisons.

Results and Discussion

In current work, meniscus velocities were measured from two plant trials at ArcelorMittal Dofasco's No. 1 continuous caster. Both SVC and nail dipping measurements were performed in the first trial on strand 1, in order to compare and evaluate the two sensing methods. The SVC probe has a diameter of 25 mm, and was inserted at a depth of 100 mm below meniscus at quarter point of the mold. The instantaneous velocities were measured and recorded with a sampling frequency of 1 Hz. Instead of using a row of nails fixed in a board to measure liquid steel meniscus velocities at multiple locations, a single nail with a diameter of 6 mm was inserted about 50 mm closer to the narrow face than the SVC probe for each measurement time. The location for dipping the nail was chosen so that the two sensing methods were measuring velocities at almost the same location at meniscus, and also that the steel flow at meniscus was not disturbed much by the SVC probe or the nail. For the sign convention of meniscus velocity, positive meniscus velocities indicate flow towards the SEN, and negative velocities indicate flow away from the SEN towards the narrow face. The process conditions and sensing methods used in measurements for these trials are listed in Table I for the standard SEN. The complete history of the changing casting speed for the first trial is shown in Fig. 5(a).

Table I. Processing Parameters for Two Trials

Trial #	Mold Width (mm)	Mold Thickness (mm)	Sensing Methods	SEN Depth (mm)	Gas Injection Rate (SLPM)
1	1248	225	SVC + Nail	177	6
2	983		Nail	185	

Comparison of SVC and nail dipping measurements

The change of casting speed with time for trial #1 is shown in Fig. 5(a), and steel meniscus surface velocity histories monitored by SVC and nail dipping are shown in Fig. 5(b). In addition to the instantaneous SVC data for surface velocity, Fig. 5(a) also shows a 30-second moving average velocity during the trial. The locations in the top of the mold where the nail and SVC probe were inserted are also given in the figure. The error bars for the nail dipping test results are obtained by performing an error analysis, assuming an uncertainty of 0.5 mm during the lump height difference measurements.

It is observed from Fig. 5(b) that the SVC data and nail dipping results match closely with each other. Furthermore, most nail dipping measurements match the moving average of the SVC data. At a few points, the nail dipping results fall outside the moving average, but still always fall within the range of the instantaneous SVC data. Perhaps the velocities from the nail dipping measurements are slightly less than the SVC data. This might be expected, considering that the SVC probe extends to 100mm below the surface and measures an average over that range. The nail dipping test measures velocity closer to the surface, which should be lower, owing to the drag effect from the slag layer.

Effects of Casting Speed and Mold Width on Meniscus Velocity

The steel meniscus surface velocities measured by both the SVC and nail dipping methods illustrate the same trends with casting speed change. At the high casting speed of 1.9 m/min, Fig. 5 shows the average meniscus velocity with the standard SEN design reaches around +0.6 m/s, which suggests a strong double-roll flow pattern in the mold. At the medium casting speed of 1.4 m/min, meniscus velocity is always positive (0.3 to 0.5 m/s), which indicates a consistent

double-roll flow pattern in the mold. At the low casting speed of 1.0 m/min, meniscus velocities appear both positive and negative, indicating a complex flow pattern, with variable reversing flows where neither method is expected to be particularly accurate.

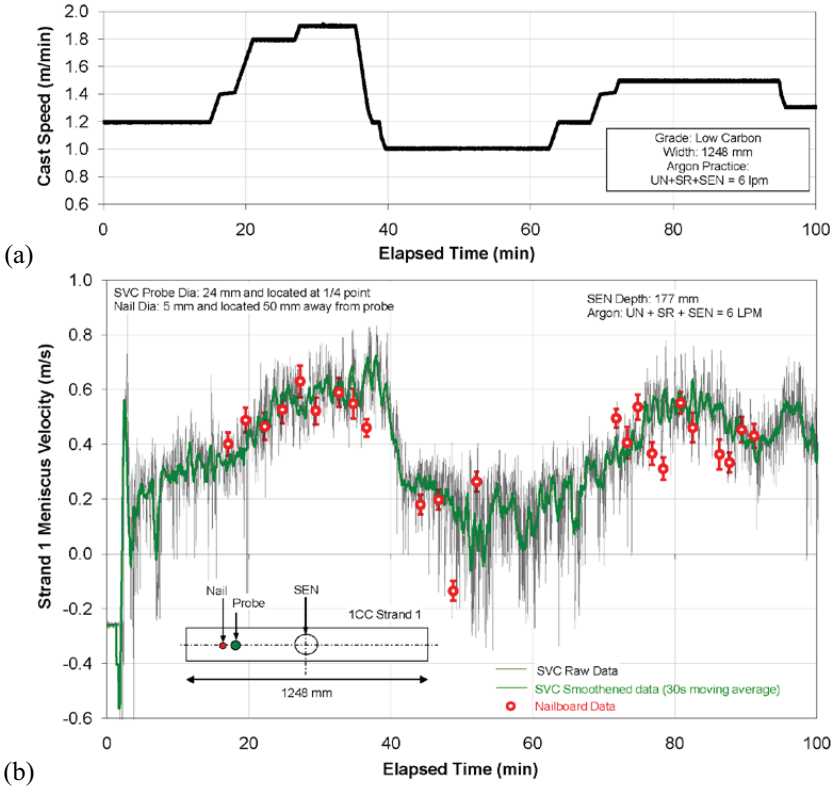

Fig. 5 Casting Speed Change in Trial #1 and Measured Meniscus Velocity
(a) Casting speed change; (b) Meniscus Velocity History from SVC and Nail Dipping.

For trial #2 with the narrower mold width (983 mm), the SVC device could not fit into the mold due to lack of supporting system within the limited space at meniscus region, so only nail dipping tests were performed in this trial. Three casting speeds (1.9 m/min, 1.7 m/min and 1.5 m/min) were tested during this trial. Ten nail samples were taken for each casting speed. The SEN submergence depth is 185 mm. Results from nail dipping measurements are shown in Fig. 6, together with the SVC and nail dipping test data from trial #1.

For a constant mold width, higher casting speed has two effects: increasing SEN mean velocity at port exit and lowering gas volume fraction. Both effects encourage higher surface velocities. From Fig. 6, these effects are clearly shown that average meniscus steel velocity increases almost linearly with casting speed for both trials.

For a constant casting speed, Fig. 6 suggests that surface velocities in the 983 mm mold width (nail dipping) are lower than in the 1248 mm mold width (both tests). Larger mold widths lead to higher throughputs, which increases SEN velocities. However, this increase in SEN velocity does not necessarily cause higher surface velocities because the distance for the jet to travel from SEN port exit to meniscus also increases, so the momentum of the jet diffuses more. The result is complicated because mold width also affects gas volume fraction, as discussed in the section

below. Note that the range for variation of instantaneous velocities in trial #1 from SVC decreases as casting speed increases, which suggests a more stable flow in the mold for higher casting speeds with double-roll flow patterns.

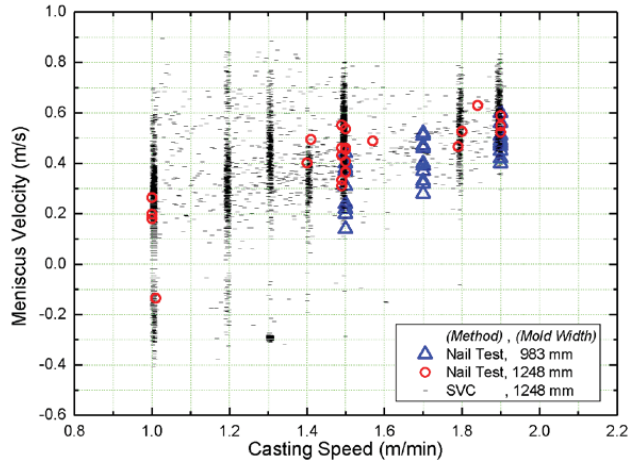

Fig. 6 Casting Speed Effects on Measured Meniscus Velocity

Effects of Gas Volume Fraction on Meniscus Velocity

Besides factors such as casting speed and mold width, gas injection is another critical factor that affects the flow patterns in the mold and meniscus velocities. Though the argon gas flow rate remains the same for both trials at different casting speeds, the gas volume fraction is actually varying according to throughput. Because gas expands at higher temperatures, the gas injection rate will be ~5X higher in the mold than at room temperature (STP). Gas volume fractions were calculated via the ideal gas law using the ferrostatic pressure and temperature values at port exit.

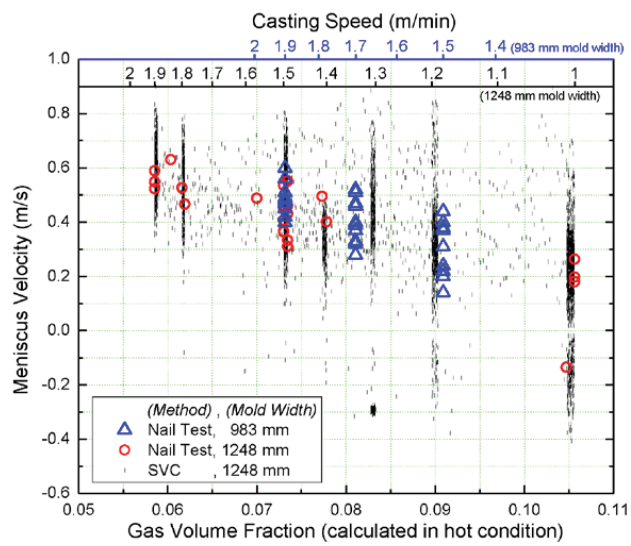

Fig. 7 Gas Volume Fraction (calculated in hot condition) Effect on Meniscus Velocity

The effect of calculated gas volume fraction on surface velocity measured for both trials is shown in Fig. 7. The meniscus velocities decrease almost linearly with increasing gas volume fraction, and show no influence of mold width. This observation suggests that injected argon gas has a more important effect on steel flow patterns in the mold than width. Gas rising from SEN port exit drags steel upward, which generates surface velocities away from SEN, and tends to make a single-roll flow pattern. For higher casting speeds, steel throughput is higher, and the gas volume fraction is lowered. Then a double-roll flow pattern is more likely to occur.
Thus, the trend for increasing gas volume fraction to cause a transition of flow pattern from double-roll to complex flow is clearly shown in Fig. 7. Finally, all three sets of measurements from both trials match consistently with the same trends.

Conclusions

Two different velocity probes for measuring surface velocity in molten steel were tested and compared in a commercial steel slab casting mold, leading to the following conclusions:

1. A reasonable match between SVC measurements and nail dipping tests has been achieved using a new correlation between lump height difference and meniscus steel velocity, based on a curve fit of previous simulation data.
2. The SVC system can provide reliable continuous surface velocity measurements in molten steel and successfully validated the nail dipping tests in the current work. Though only discrete data points can be obtained by nail dipping tests, nail dipping is a simple, reliable, and capable method of measuring slag layer thickness and capturing instantaneous meniscus steel velocities as well as flow directions at multiple locations. Thus, nail dipping is a powerful tool to quantify meniscus velocities and to study flow in the mold for industrial applications.
3. Based on velocity measurements at the mold quarter point using both methods, surface velocity increases with increasing casting speed and/or decreasing gas volume fraction, as the flow pattern tends towards double-roll. The effect of increasing mold width is complicated because it increases port velocity, increases travel distance, and decreases gas fraction, with a net effect of increasing surface velocity.

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