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Quantitative Measurement of Molten Steel Surface Velocity with Nail Boards and SVC Sensor in CC Molds

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Objectives

- **To examine the accuracy of measuring molten steel meniscus velocity using nail boards**
- **To evaluate and compare the following two methods in measuring liquid steel surface velocity,**
  - **using Sub-meniscus Velocity Control (SVC) device**
  - **using nail boards**
- **To validate the numerical models for the turbulent multiphase flow in the mold using nail board/SVC measurements**

Background

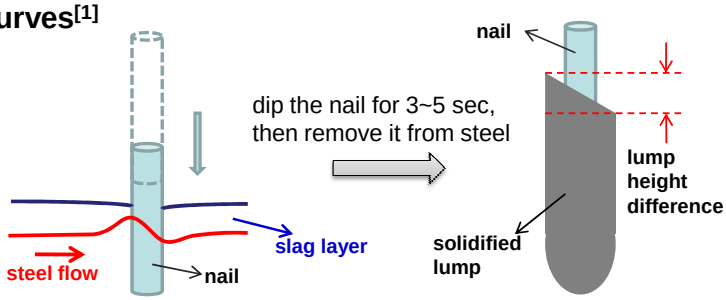
- **Meniscus velocity is critical to the quality of final products in continuous casting process**
- **Difficulty with measuring surface velocity is from:**
  - **liquid metal flow with very high temperature (1550 C or above)**
  - **direct visualization of the liquid steel flow pattern is not available**
- **Methods to quantify surface velocities include:**
  - **Plant measurements using nail boards or other sensor devices**
  - **Mathematical and numerical modeling**
  - **Physical modeling and scaling**

Introduction to Nail Board Measurement

Nail Board with 6 mm ϕ Nail

Procedures:

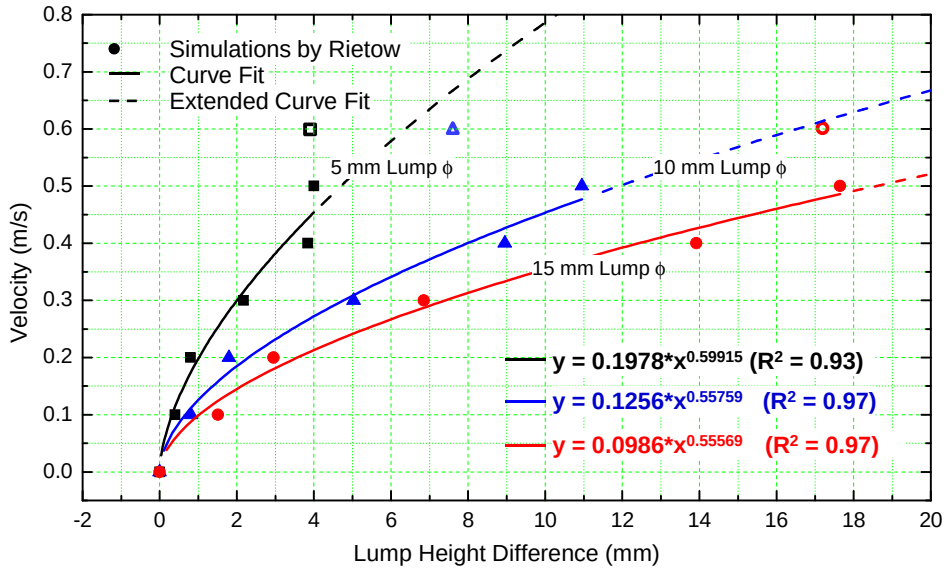
1. **Insert the nail into the surface of liquid steel flow through the slag layer**
2. **Liquid steel runs up on the nail frontal area, and decreases on the other wake region of the nail, as it solidifies into a lump**
3. **The height difference between either side of the lump is measured and converted into surface velocity of liquid steel using the calibration curves[1]**



Ref:
[1] B. Rietow and B. Thomas, Master's Thesis

Lump Height Difference and Calibration Curves

6 mm ϕ Nail and Lump

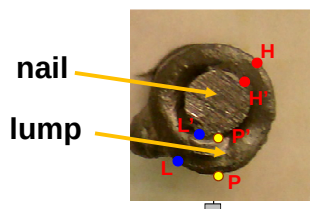


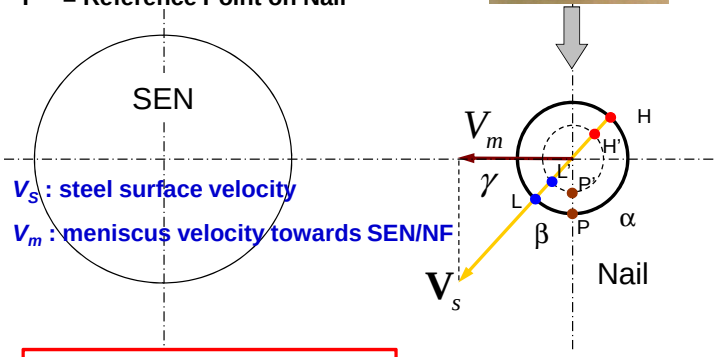
- The meniscus velocity vs. lump height difference curve is extended to predict high surface velocities.
- The lump diameter is usually ranging from 10~15 mm for a 6-mm diameter nail.

Flow Direction and Meniscus Velocity towards SEN/NF

H = High Point on Lump
L = Low Point on Lump
P = Reference Point
(P always faces the operator)

H' = High Point on Nail
L' = Low Point on Nail
P' = Reference Point on Nail





V_s : steel surface velocity

V_m : meniscus velocity towards SEN/NF

Parameters to measure:

d_1 : arc length from point H' to point P' on the nail circumference

d_2 : arc length from point L' to point P' on the nail circumference

d_{lump} : lump diameter

d_{nail} : nail diameter

$$\alpha = \frac{2PH}{d_{lump}} = \frac{2d_1}{d_{nail}}$$

$$\beta = \frac{2PL}{d_{lump}} = \frac{2d_2}{d_{nail}}$$

$$V_m = |\mathbf{V}_s| \cos\left(\frac{d_1 - d_2}{d_{nail}}\right) \Leftarrow \gamma_{avg} = \frac{1}{2}\left[\left(\alpha - \frac{\pi}{2}\right) + \left(\frac{\pi}{2} - \beta\right)\right] = \frac{1}{2}(\alpha - \beta) = \frac{d_1 - d_2}{d_{nail}}$$

Error Estimation for Nail Board Measurements

Final form of meniscus velocity:

$$V_m = \left[\frac{15-d_{lump}}{5}\left(a_1 h_{lump}^{b_1}\right) + \frac{d_{lump}-10}{5}\left(a_2 h_{lump}^{b_2}\right) \right] \cos\left(\frac{d_1-d_2}{d_{nail}}\right)$$

magnitude of surface velocity vector from linear interpolation of the calibration curves: $|\mathbf{V}_s|$

projection from flow direction to meniscus horizontal direction

In current measurement, lump diameter is between 10 mm and 15 mm, close to 10 mm. Parameters a_1, b_1, a_2 and b_2 are constants from the curve fit:

Model Geometry Parameters	Value
a_1	0.1256
b_1	0.55759
a_2	0.0986
b_2	0.55569

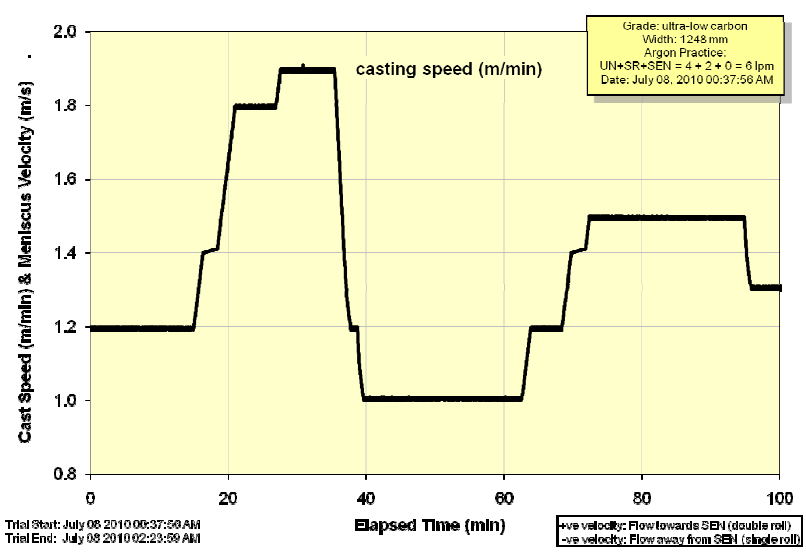
Differentiating the equation above gives the error estimation:

$$dV_m = \frac{\partial V_m}{\partial d_{lump}} d\left(d_{lump}\right) + \frac{\partial V_m}{\partial h_{lump}} d\left(h_{lump}\right) + \frac{\partial V_m}{\partial\left(d_1-d_2\right)} d\left(d_1-d_2\right)$$

$$\begin{aligned} dV_m = & \left| \left[\frac{a_2 h_{lump}^{b_2} - a_1 h_{lump}^{b_1}}{5} \cos\left(\frac{d_1-d_2}{d_{nail}}\right) \right] \right| d\left(d_{lump}\right) \\ & + \left| \left[\frac{15-d_{lump}}{5} a_1 b_1 h_{lump}^{b_1-1} + \frac{d_{lump}-10}{5} a_2 b_2 h_{lump}^{b_2-1} \right] \cos\left(\frac{d_1-d_2}{d_{nail}}\right) \right| d\left(h_{lump}\right) \\ & + \left| \left[\frac{15-d_{lump}}{5}\left(a_1 h_{lump}^{b_1}\right) + \frac{d_{lump}-10}{5}\left(a_2 h_{lump}^{b_2}\right) \right] \sin\left(\frac{d_1-d_2}{d_{nail}}\right) \right| d\left(d_1-d_2\right) \end{aligned}$$

$\rightarrow \pm 0.5\,mm$

Casting Conditions for Trial #1



Description:

1. **Casting speed changes,**
2. **SEN submergence depth keeps constant**
3. **Mold width keeps constant**
4. **Different SEN for strand #1 and strand #2**

Objective:

To study the meniscus velocity change corresponding to the casting speed change.

Devices:

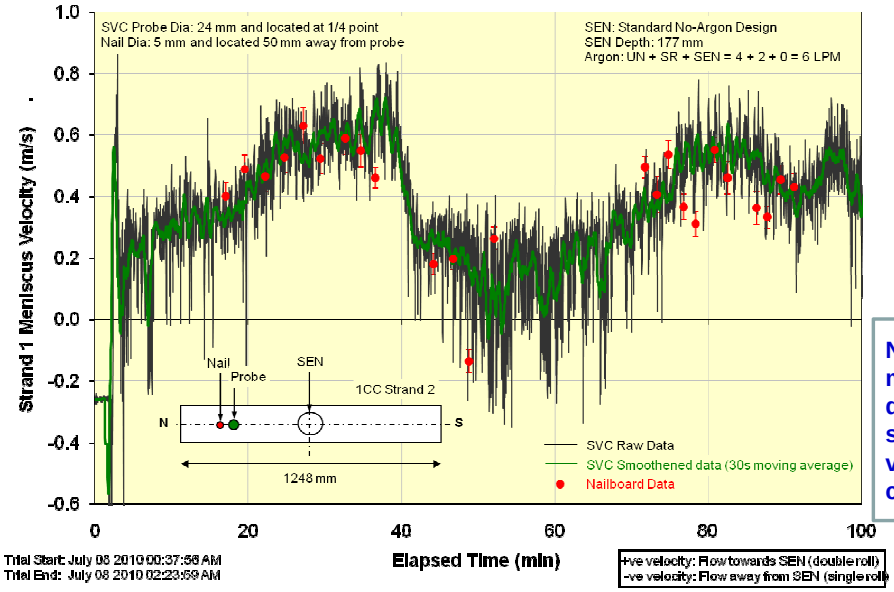
1. **SVC probe**
2. **Nail board**

SEN Submergence Depth: **177** mm

Submergence depth for the SVC probe: **100** mm

SVC VS. Nail Board Measurement

-- Trial #1, Strand #1



SVC VS. Nail Board

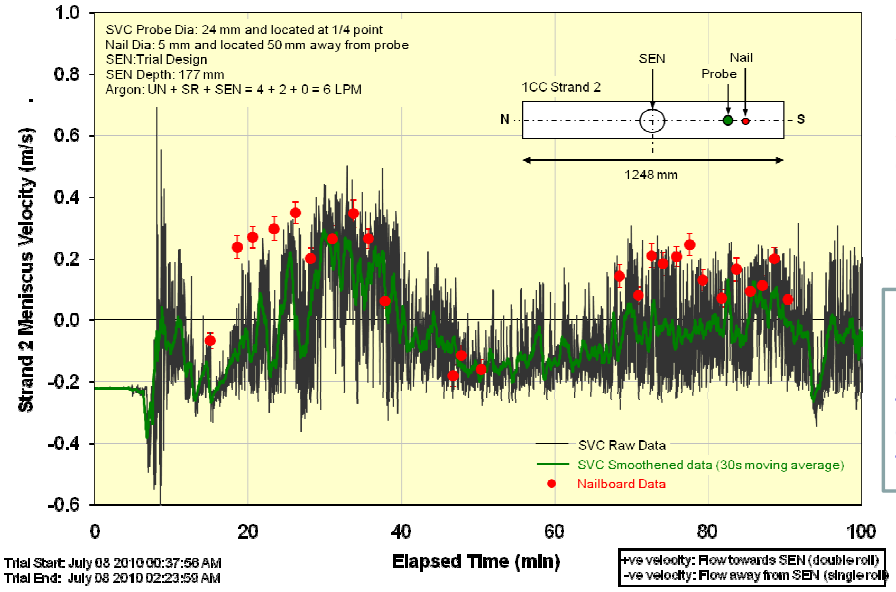
- **Data Type—**
  SVC:
  continuous data
  Nail Board:
  discrete data

Nail board data is nicely matching with the SVC data, both showing the same trend of meniscus velocity change with casting speed.

1. **Meniscus velocity magnitude increases as casting speed increases;**
2. **Double-roll flow pattern increases as casting speed increases;**
3. **At low casting speed (1.0 m/min, between 40~60 min), complex flow pattern exists**

SVC VS. Nail Board Measurement

-- Trial #1, Strand #2



SVC VS. Nail Board

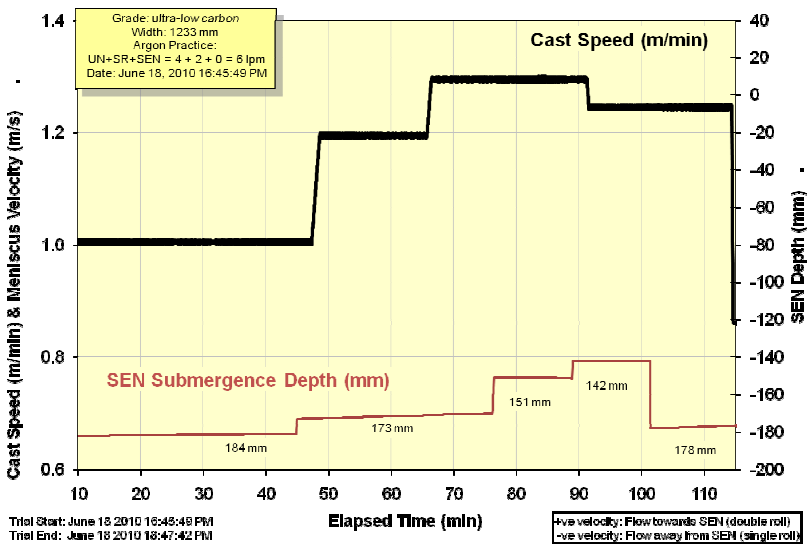
- **Data Type—**
  SVC:
  continuous data
  Nail Board:
  discrete data

Nail board data is nicely matching with the SVC data, capturing both the trend for velocity change and the turbulent transients

1. **Complex flow pattern is observed through the whole process;**
2. **High casting speed tends to increase double-roll flow pattern, while low casting speed tends to cause single-roll flow pattern.**

Casting Conditions for Trial #2

-- Strand #2 with new SEN design



Description:

1. Casting speed changes,
2. SEN submergence also changes
3. Mold width keeps constant

Objective:

To study the meniscus velocity change corresponding to the casting speed change for strand #2 with new SEN design.

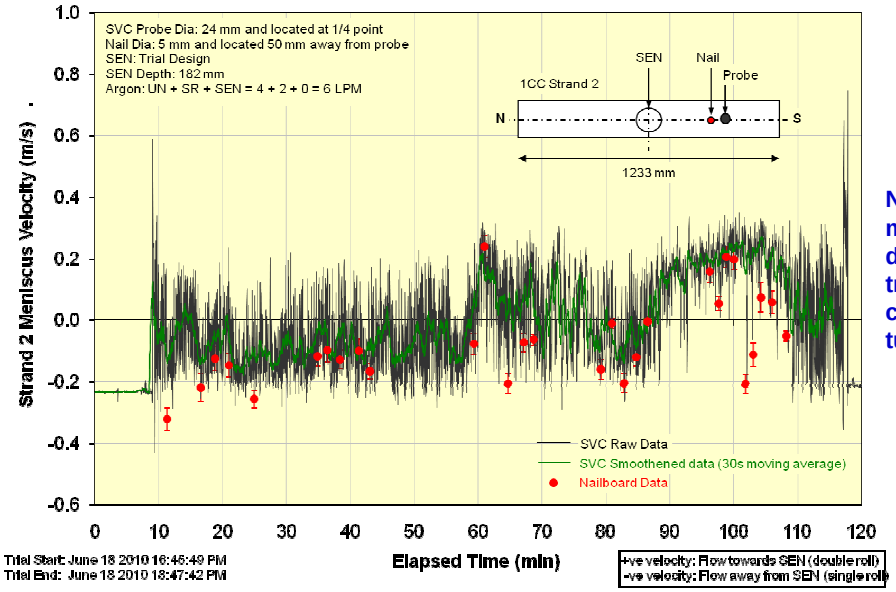
Devices:

1. SVC probe
2. Nail board

Submergence depth for the SVC probe: **100** mm

SVC VS. Nail Board Measurement

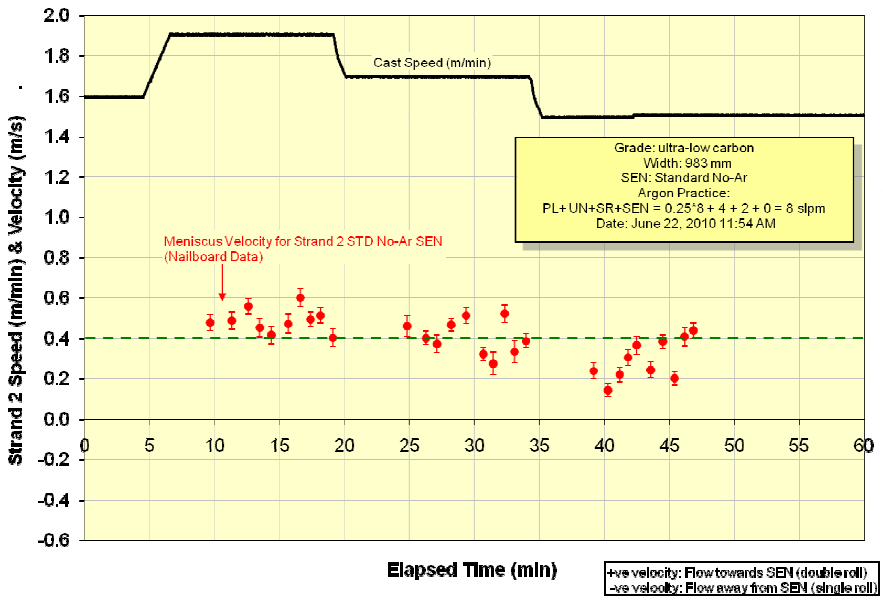
-- Trial #2, Strand #2



Nail board data is nicely matching with the SVC data, capturing both the trend for velocity change and the turbulent transients

1. **Complex flow pattern is observed for most time of the trial with low surface velocities;**
2. **High casting speed tends to make the flow pattern more "double-roll";**
3. **At relatively low casting speed (1.0 m/min, between 10~50 min), the flow pattern tends to be single-roll**

Casting Conditions and Nail Board Results for Trial #3 -- Strand #2, Narrower Mold, Std SEN



Conditions:

1. **Casting speed changes**
2. **SEN submergence keeps constant**
3. **Mold width keeps constant**

Devices:

Only Nail board, the SVC device is not able to be placed into the mold due to the limited space

SEN Submergence Depth: **186** mm

Submergence depth for the SVC probe: **100** mm

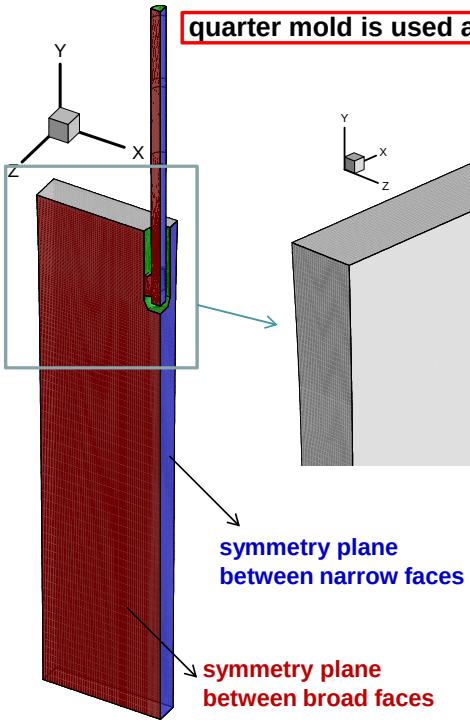
Cases for Numerical Simulation

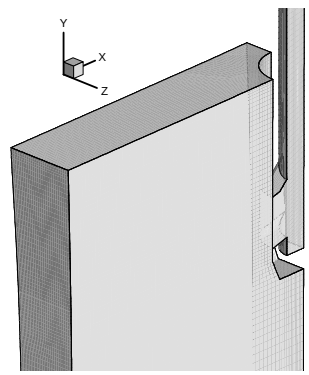
For this narrower mold, three cases from Trial #3 are set up for CFD simulations, and the inlet boundary conditions are listed below:

Mean argon bubble diameter: 2.5 mm

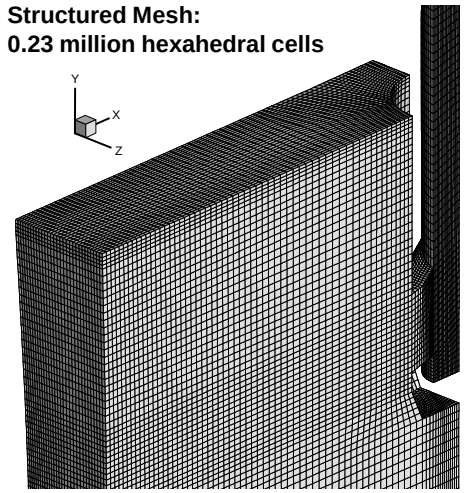
Process Parameters	Values
Casting Speed (m/min) & Steel Flow Rate (m^3/s)	CASE 1: 1.90 m/min, $6.861*10^{-3}$ m^3/s CASE 2: 1.70 m/min, $6.138*10^{-3}$ m^3/s CASE 3: 1.50 m/min, $5.416*10^{-3}$ m^3/s
Argon Injection at Stopper-Rod Tip	2.0 SLPM, 12.276 LPM at 1823 K, ($2.046*10^{-4}$ m^3/s) Volume Fraction for: CASE 1: 0.02896 CASE 2: 0.03226 CASE 3: 0.03640
Argon Injection at Upper Tundish Nozzle	4.04 SLPM, 24.798 LPM at 1823 K, ($4.133*10^{-4}$ m^3/s) Volume Fraction: 1 Velocity: 0.04385 m/s
Argon Injection at Plate	8.03 SLPM, 49.289 LPM at 1823 K ($8.215*10^{-4}$ m^3/s) (Assume ¼ gas has entered the SEN, $2.054*10^{-4}$ m^3/s) Volume Fraction: 1 Velocity: 0.02456 m/s
Liquid Steel/argon gas Velocity at Inlet	CASE 1: 1.5993 m/s CASE 2: 1.4357 m/s CASE 3: 1.2722 m/s

Domain Geometry and Mesh





Structured Mesh:
0.23 million hexahedral cells



Model Geometry Parameters	Value
Mold Width (m)	0.983
Domain Length (m)	2.500
Mold Thickness at Meniscus (m)	0.225
SEN Outer/Inner Diameter (m)	0.130/0.075
SEN Submergence Depth (m)	0.186

Computational Details and Boundary Conditions

Computational Details and B.C. Settings:

Models and Schemes	Name
Turbulence Model	k-epsilon with std. wall function
Multiphase Model	Eulerian Model
Model for Shell Growth	Mass and Momentum Sink at shell
Gas Escaping from Meniscus	Mass and Momemtum Sink for Argon Phase
Advection Discretization	2st order upwinding for k-epsilon model

Parameters for the transient run:

Time marching scheme	1st order implicit, 0.05 sec time step
Time before collecting statistics	20 sec
Time for the stats	20 sec

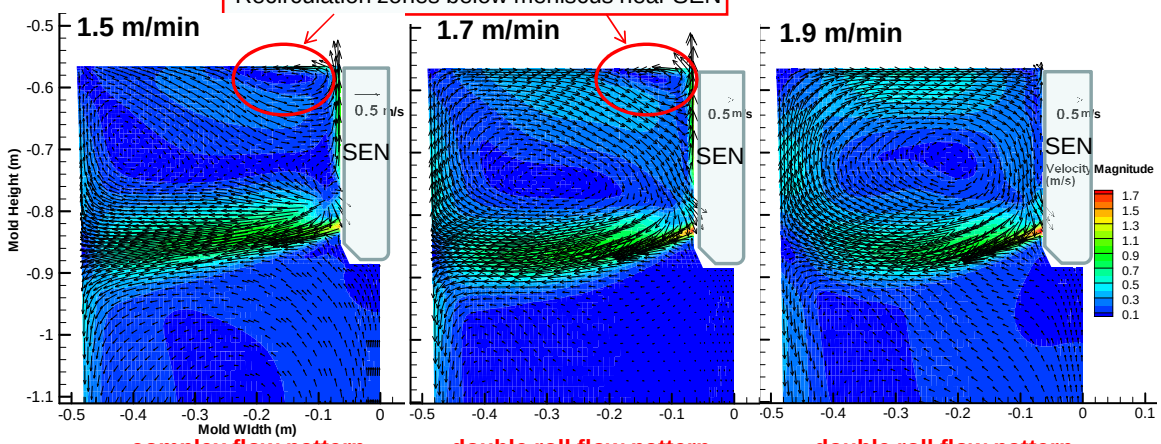
Domain Boundaries	B.C.	Domain Boundaries	B.C.
Meniscus	No-Slip Wall (slag layer)	Outlet	Pressure Outlet

Steel Velocity Distribution in the Mold

Casting speed:

Steel velocity distribution at center plane between broad faces

Recirculation zones below meniscus near SEN



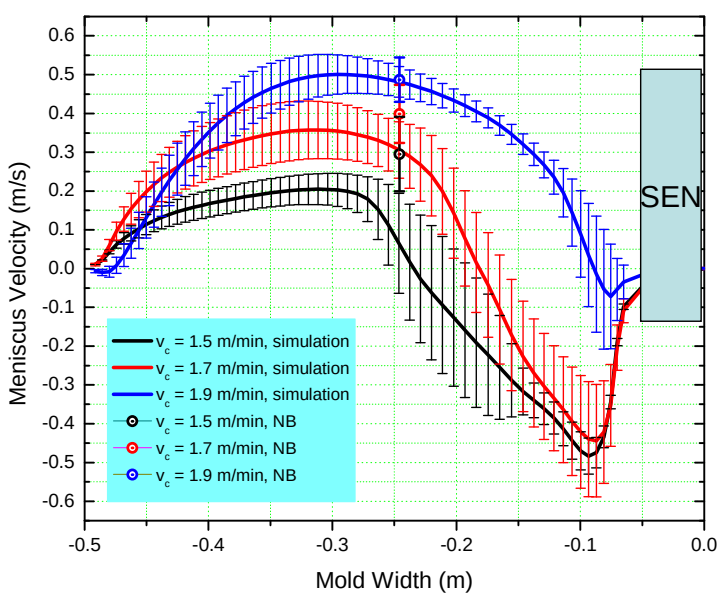
complex flow pattern | **double roll flow pattern** | **double roll flow pattern**

Increasing casting speed will:

1. **reduce gas momentum along outer SEN**
2. **bend the liquid steel jet towards meniscus**
3. **increase liquid steel surface velocity (more double roll)**

Vector plots show liquid steel mean velocity over 20 sec

Comparison with Nail Board Data



- **Reasons for not matching measurement at lower casting speeds:**

  -- RANS model tends to over-predict gas volume fraction at upper port exit region, thus generates higher drag force near outer SEN, which increases "single-roll" flow

  -- No-slip B.C. at top surface in CFD models is not quite appropriate

  -- Thicker boundary layers at lower casting speeds

Velocity profiles are taken at 2 mm below top surface

Lines: Mean Horizontal V

Error Bars: RMS Mean V

Conclusions –1

- By matching the data with SVC results, nail board measurement is able to capture both the mean velocity trend and the turbulent transients for the surface flow of the liquid steel, thus it can be used to quantify the meniscus steel velocity in CC molds, with the error estimated;

- Observation from the measured data shows
  - meniscus velocity increases with casting speed;
  - complex flow pattern exists for cases with medium casting speeds (~1 m/min for 1200 mm mold width)
  - low casting speeds tend to generate single-roll flow patterns, while high casting speeds tend to generate double-roll flow patterns in the mold (due to argon injection)

Conclusions –2

- Compare the two methods to measure surface steel velocity:
  - SVC:
    - generates continuous meniscus velocity data, showing the details of the flow
    - expensive device to use
    - measures the steel velocities at some distance beneath meniscus
    - usually velocity at only one point on the surface can be obtained
  - Nail board:
    - gives limited discrete data points, recording instantaneous meniscus velocities
    - cheap measurement, convenient to use
    - measures exactly the meniscus steel velocity
    - easy to obtain the velocity profile from several points

Acknowledgement

- **Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Corus, LWB Refractories, Nucor Steel, Nippon Steel, Postech, Posco, ANSYS-Fluent)**

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