Validation of Fluid Flow and Solidification Simulation of a Continuous Thin-Slab Caster

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  (computing time and use of CFX)

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  (water model and plant measurements)

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  (finite element analysis of the mold)
**Objective**

Validate fluid flow and solidification models with extensive measurements:

- velocities within the liquid pool  
  (from water models)
- temperatures measured in the molten steel pool  
  (plant trial)
- temperatures measured in the copper mold walls  
  (mold thermocouples)
- heat flow rate  
  (heat balance on the mold cooling water)
- thickness of the solidified steel shell  
  (from breakout shell measurements)
The Continuous Casting Process

- Ladle
- Molten Steel
- Tundish
- Submerged Entry Nozzle
- Mold
- Meniscus
- Liquid Pool
- Support roll
- Spray Cooling
- Solidifying Shell
- Metallurgical Length
- Torch Cutoff Point
- Strand
- Slab

B.G. Thomas
Thin Slab Casting Mold

- Inlet Nozzle
- Copper Wide Face
- Steel Cassette Water Box
- Narrow Face
- Meniscus Ferrostatic Loading
- Molten Steel
- Outer Radius Side
- Inner Radius Side
- Solidified Shell
- Casting Direction
- Clamping Force
- Footroll
Fluid Flow Model

3D Domain and Mesh of ¼ of Liquid Pool:

- Includes 3-port nozzle
- Standard high-Re K-ε turbulence model and wall laws
- Solidification front (boundary): liquidus temperature
- Predicts velocities and superheat distribution
3-D K-ε Simulation

Water Model
Water Model Flow

Velocity Along Flowing Jet (Calculated and Water Model Measurements)
Molten Steel Temperature (Model Validation)

Pour

1559 °C

1520 °C

1502 °C Liquidus

56°C superheat

Superheat (°C)

Distance below the Meniscus (mm)

Profile Location

SEN

Middle Point

NF

Measurement Position

Model

Probe (insertion)

Probe (withdrawal)
Superheat Flux Profiles

(Calculated Around the Exterior of the Strand Surface)
Temperature Contours in 3-D Portion of Mold Wall

- Temperature range from 70 °C to 307 °C
- Heat flux density \( q = 2.5 \text{ MWm}^{-2} \)
- Thermal conductivity \( k = 315 \text{ Wm}^{-1}\text{K}^{-1} \)
- Heat transfer coefficient \( h = 54 \text{ kWm}^{-2}\text{K}^{-1} \)
- Water slot temperature \( T_w = 25 \text{ °C} \)
- Hot face and cold face indicated
- Thermocouple position noted
Instrumented Mold (106 Thermocouples)
Heat Flux and Cooling Water Heat Balance

Heat Flux (MWm$^{-2}$) vs. Distance below Meniscus (mm)

Unit: °C

<table>
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<tr>
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<th>Steady state</th>
<th>Breakout shell</th>
<th>CON1D predicted</th>
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<tr>
<td>Wide Face</td>
<td>6.12</td>
<td>6.28</td>
<td>5.61</td>
</tr>
<tr>
<td>Narrow Face</td>
<td>7.98</td>
<td>8.28</td>
<td>8.22</td>
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</table>
Temperatures Down Mold Walls
(Calculated and Measured at Thermocouple Locations)

Wide Face

Narrow Face

CON1D calculation offset: 4.5mm

10.3mm
Solidification and Heat Transfer Model: CON1D

- 1-D transient finite-difference model of solidifying steel shell
- 2-D steady-state heat conduction within the mold wall
- detailed treatment of interfacial gap including mass and momentum balances on slag layers
- uses superheat flux from flow model
- predicts:
  - shell thickness down the mold
  - temperature in the mold and shell
  - slag layer thicknesses (solid & liquid)
  - heat flux down the mold
  - mold water temperature rise
  - ideal taper of mold walls
Solid Fraction Effect on Steady-state Shell Thickness

![Graph showing the effect of solid fraction on steady-state shell thickness. The graph plots shell thickness against distance below the meniscus. Different solid fractions (fs=0, fs=0.1, fs=0.3, fs=0.7, fs=1.0) are represented by distinct lines on the graph. For fs=0, the shell thickness increases gradually with distance. As the solid fraction increases, the rate of increase in shell thickness also increases, indicating a stronger effect of solid fraction on shell thickness.](image-url)
Section through slab showing longitudinal crack that started breakout

Narrow Face

Centerline
Casting Conditions & Simulation parameters

- Casting Speed: 1.524m/min
- Pour Temperature: 1563 °C (61 °C superheat)
- Slab Size: 984mm*132mm
- Mold Length: 1200mm
- Nozzle Submerge depth: 127mm
- Mold Powder Consumption Rate: 0.48kg/m²
- Mold Thickness: wide face 35mm; narrow face 25mm
- Steel Grade: 434 Stainless Steel
- Inlet Cooling Water Temperature: 25 °C
- Fraction Solid for Shell Thickness Location: 0.1
Events during breakout

- Estimated liquid level
- Bottom of breakout hole
- Mold exit
- Top of breakout shell
- Measured liquid level

Distance below steady-state meniscus (mm)

Time (s)

$0 \quad 500 \quad 1000 \quad 1500 \quad 2000 \quad 7120 \quad 7140 \quad 7160 \quad 7180 \quad 7200 \quad 7220 \quad 7240 \quad 7260$

$0 \quad 2000$

$t_0 - 57$

$t_0 - 50$

$t_0 - 40$

$t_0 - 30$

$t_0 - 20$

$t_0 - 10$

$t_0$

Top of breakout shell

Measured liquid level
Shell Thickness Along Wide Face (WF)
(Calculated Compared with Breakout Shell Measurements)
Shell Thickness Along Wide Face (WF)
(Calculated Compared with Breakout Shell Measurements)
Shell Thickness Along Narrow Face (NF)
(Calculated Compared with Breakout Shell Measurements)

![Graph showing shell thickness along narrow face with distance below meniscus and solidification time.]
Model Applications

These validated modeling tools can now be applied to study related phenomena of practical significance in a quantitative manner, which include:

- ideal taper of the mold walls to match the shell shrinkage,
- critical shell thickness to avoid breakouts,
- behavior of flux layers in the interfacial gap,
- crack formation,
- relationships between mold wall temperatures and events in solidifying shell to enable online quality prediction.
Conclusion

- An efficient model of 3-D turbulent flow, heat transfer and solidification in a thin slab caster has been developed, featuring one-way coupling between
  - K-ε flow model (CFX) and
  - 1-D transient model of heat transfer in the mold, interface, and solidifying steel shell (CON1D).

- The accuracy of this modeling approach has been demonstrated by comparison with
  - experimental measurements of fluid flow in the liquid pool,
  - temperature in the molten steel,
  - temperature in the copper mold walls,
  - temperature increase of the cooling water, and
  - breakout shell thickness.