ANNUAL REPORT 2005

Meeting date: June 1, 2005

Measuring Mold Top Surface Velocities Using Nailboards

Bret Rietow &
Brian G. Thomas

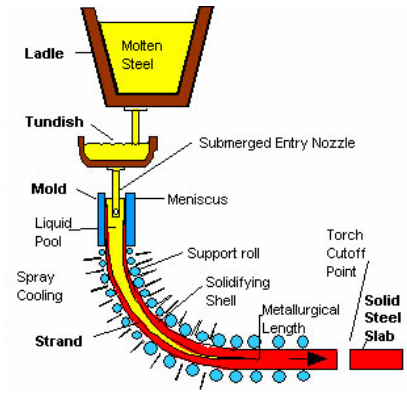
Department of Mechanical & Industrial Engineering
University of Illinois at Urbana-Champaign

Acknowledgements

- National Science Foundation
  - Grant NSF-GOALI DMI 01-15486
- Continuous Casting Consortium at UIUC (Nucor, Postech, LWB Refractories, Accumold, Algoma, Corus, Labein, Mittal Riverdale)
- National Center for Supercomputing Applications (NCSA) at UIUC

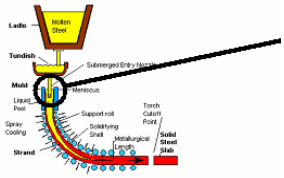
Introduction

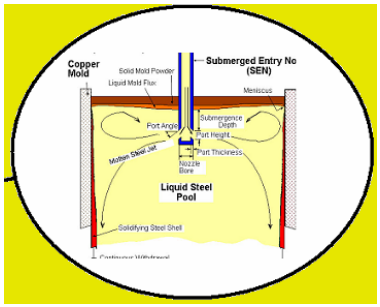
- Continuous Casting Process



Introduction (cont.)

- Top Surface Velocity
  - Greatly influences the amount of inclusions
    - Entrapped gas bubbles
    - Solid inclusions
  - Surface Quality





Motivation

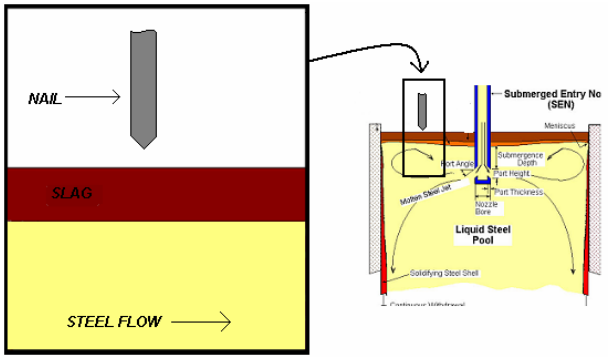
- Is there a way to measure the top surface velocity?
- Benefits
  - CC operators will have more information about their process
    - Allows for better control of CC product
  - Model calibration
  - Helps researchers measure molten flow velocities

Current Flow Measurement Devices

- Flow Meters
  - Useless in high-temperature environment of molten steel
- Tracer Techniques
  - May alter composition of metal
  - Flow is not always horizontal
- Pitot Tube
  - Metal solidifies and clogs up inlet
- Visualization Methods
  - Slag layer prevents any optical device from “seeing” the flow surface
- Electromagnetic Devices
  - Have not been shown to transmit through the slag layer
- Strain-measured Probe
  - Requires a solid base
- Vortex-Frequency Probes
  - Expensive
  - Requires a steady base

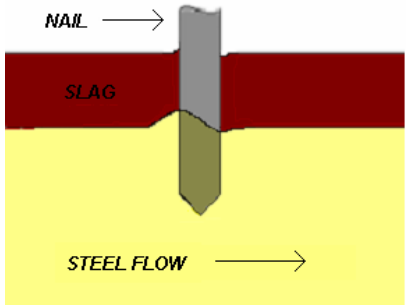
Proposed Method

- Free surface piercing object
  - Insert object into flowing molten steel



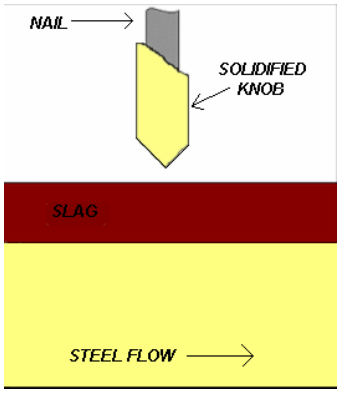
Proposed Method (cont.)

- Free surface piercing object
  - Fluid height will increase on flow-facing side of object; decrease on opposite side



Proposed Method (cont.)

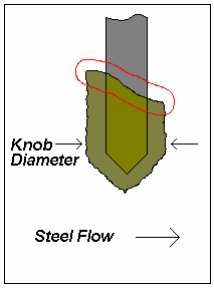
- Free surface piercing object
  - Solidified metal will have a characteristic profile with respect to the nail



Proposed Method (cont.)

- Find a relation between:
  - Knob profile/Leading edge runup
  - Knob diameter
- Molten Steel Velocity

- Advantages
  - Non-intrusive to CC process
  - Inexpensive
  - Easy!
  - Fast (setup, data acquisition, etc…)



Governing Equations

- Main Phenomenon - FREE SURFACE FLOW
- Reynolds-Averaged Navier Stokes equation:

$$\frac{\partial \overline{u_i}}{\partial t} = -\frac{\partial \overline{u_i}\,\overline{u_j}}{\partial x_j} + \frac{\partial}{\partial x_j}\left\{ \nu \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \right\} - \frac{\partial \overline{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j}$$

- Continuity Equation: $\frac{\partial \overline{u_i}}{\partial x_i} = 0$

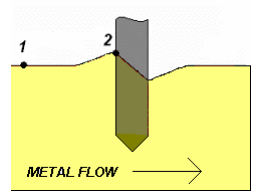
Assumptions

- Treat molten steel as an incompressible fluid
- Steady flow (no waves, disturbances, etc.)
- Standard K-ε model for turbulence
- Isothermal
- No heat/mass transfer to nail (Flow field is established faster than solidification)
- Diversion of flow under nail DOES NOT affect free surface flow

Estimation

- Bernoulli Equation

$$p + \tfrac{1}{2}\rho V^2 + \rho g h = const.$$



- Relation: $$Runup = \frac{V^2}{2g}$$

Program Selection

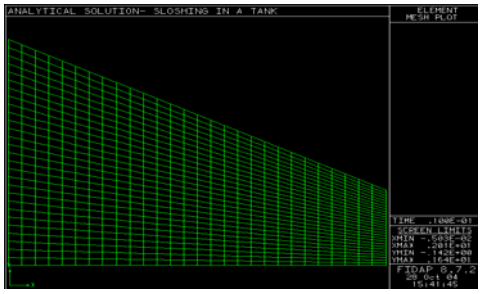
- FIDAP
  - Solves free surface problems accurately
    - Utilizes the spines technique
    - Incorporates surface tension effects into model
  - University has access to program

FIDAP/Analytical Comparison

- 2-D Transient Free Surface Sloshing in a Container (Wu et al, 2000)
- Analytical Equation-

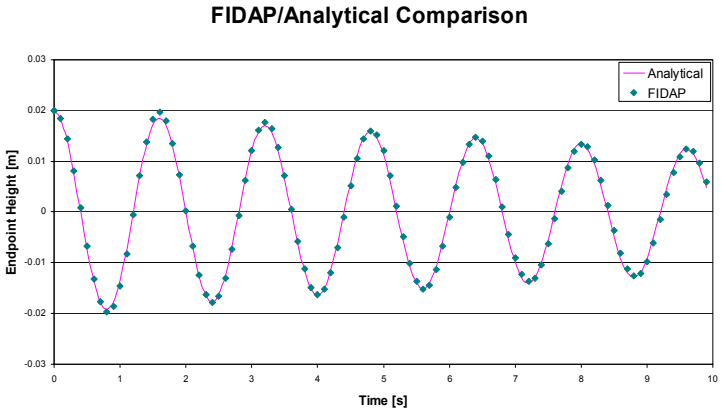
$$\frac{\eta(t)}{\eta_0} = 1 - 2\kappa \operatorname{Re} \sum_{i=1}^{2} \frac{A_i \left\{ -\gamma_i e^{(-1+\gamma_i^2)\nu k_2^2 t} \left[1 + erf(\gamma_i k_2 \sqrt{\nu t}) \right] + \gamma_i + erf(k_2 \sqrt{\nu t}) \right\}}{1 - \gamma_i^2}$$

- Mesh-



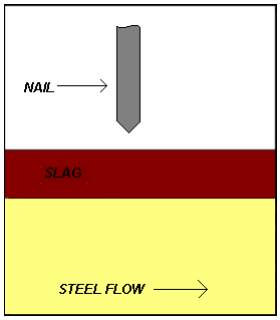
FIDAP/Analytical Comparison (cont.)

- Results-



FIDAP Simulations

- 1. No-Slag layer model
  - Simplified model – gain experience in FIDAP
  - Comparison with experimental
  - measurements in water



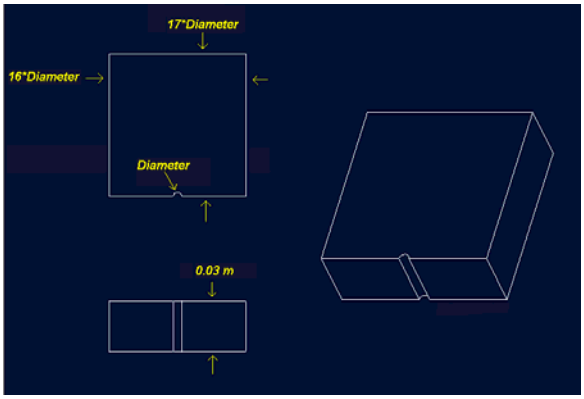
- 2. Slag layer model
  - More accurate to real-life scenario

FIDAP Solution Procedure

- First step- Steady state, fixed free surface run
  - Obtain initial conditions for transient free surface run
- Second step- Transient free surface run
  - Input results from first run
  - Convergence to steady state solution is not possible in one time step
  - Allows for observance of intermediate free surface motion before steady state is reached

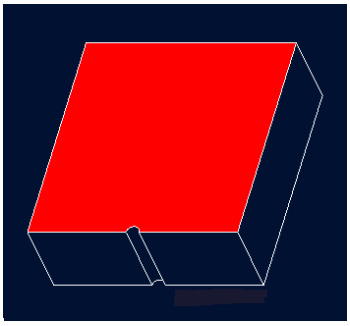
No-Slag Model Domain

- Utilize Symmetry
- Diameter
  - 0.005 – 0.02m
- Velocity
  - 0.1-0.5 m/s



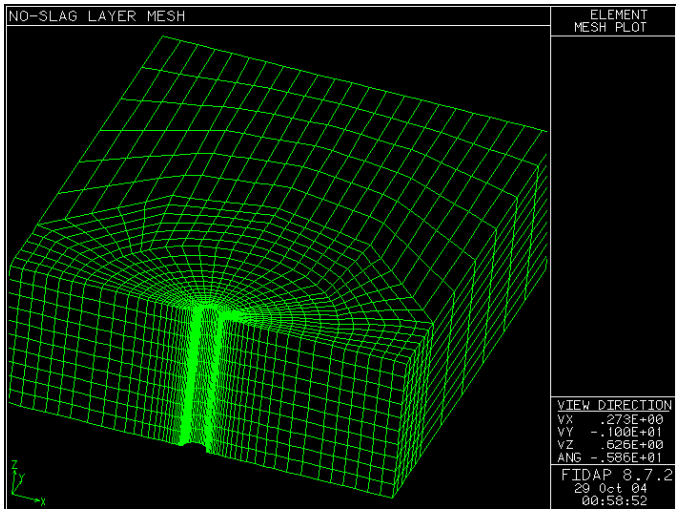
No-Slag Boundary Conditions

- Zero velocity along nail surface
- Zero normal velocity on symmetrical surface
- UX=free stream velocity,
  UY=UZ=0 for Inlet
- Zero normal velocity on vertical wall opposite of nail
- Zero normal velocity on bottom surface
- Zero shear stress on top surface
- Remaining BC's: zero velocity gradient at boundaries



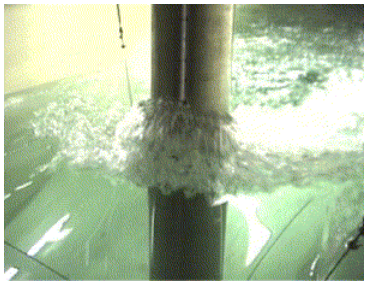
No-Slag Layer Model

- Mesh



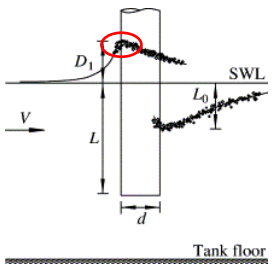
No-Slag/Experimental Comparison

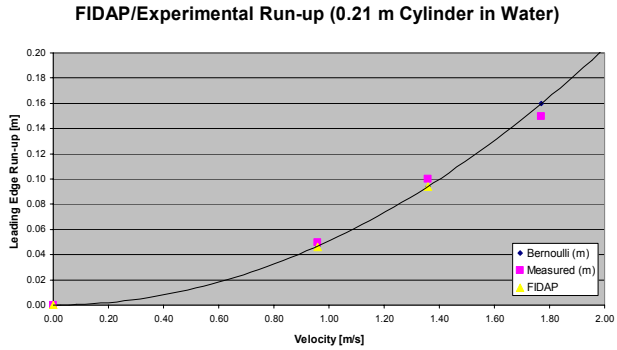
- Chaplin et al (2003)- Steady flow past vertical surface-piercing cylinder



No-Slag/Experimental Comparison

- Leading Edge Run-up Comparison

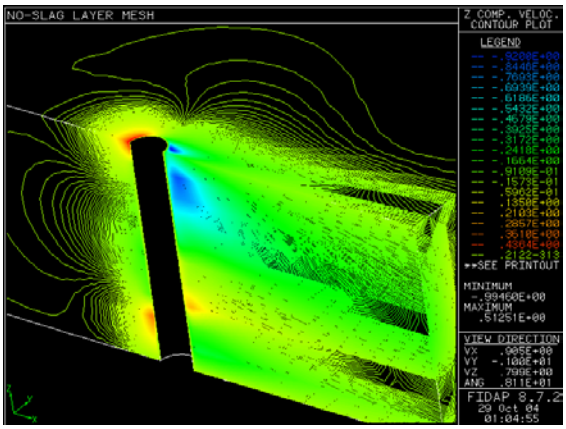




FIDAP IS ACCURATE!

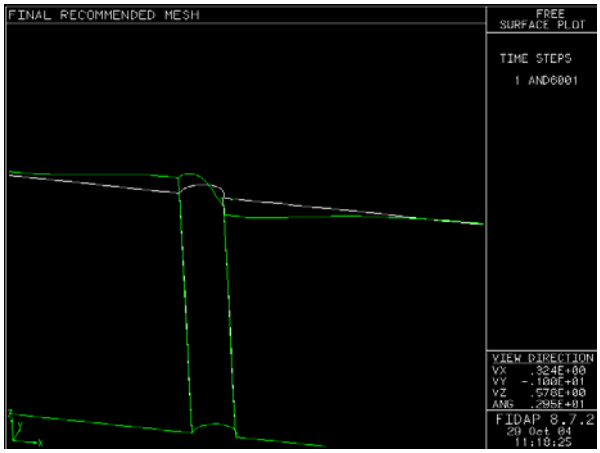
No-Slag FIDAP Model

- First Step- Fixed free surface run



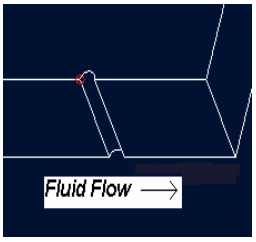
No-Slag FIDAP Model

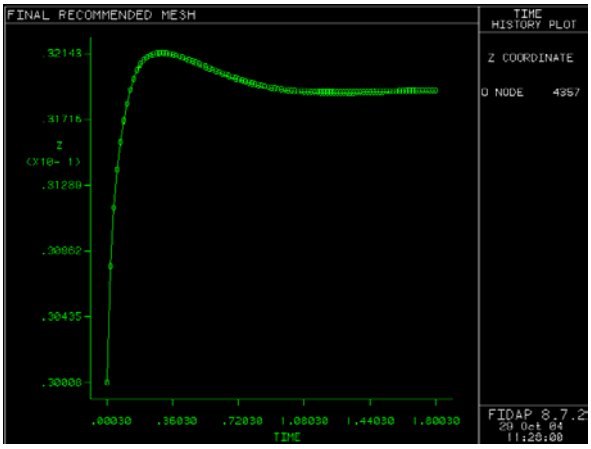
- Second Step- Transient free surface run
  - 6000 time steps
  - dt=0.0003 s
  - Tot. Sim. Time 1.8 s



No-Slag FIDAP Model

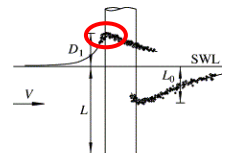
- How do you know steady state has been achieved?

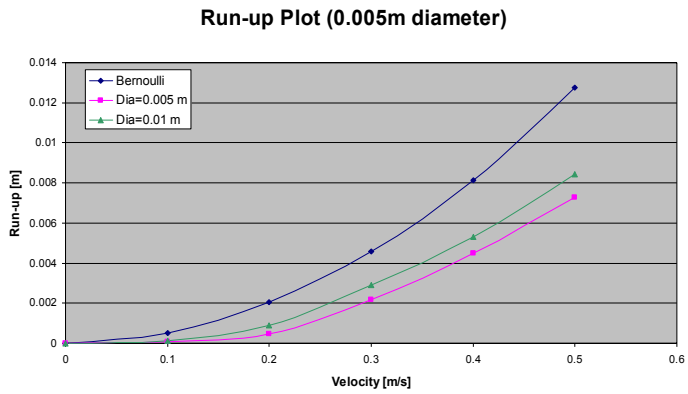




No-Slag Results

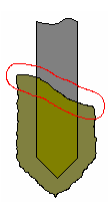
- Run-up on leading edge of nail

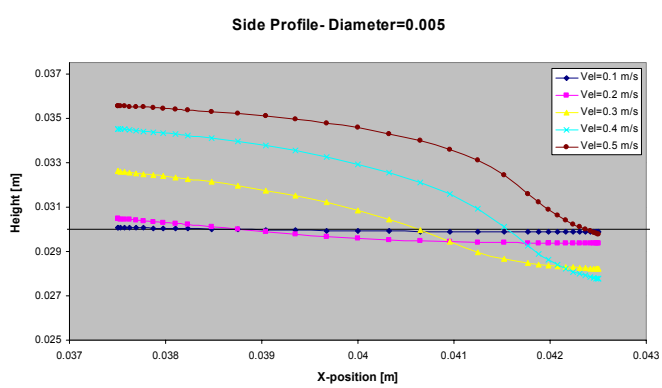




No-Slag Results

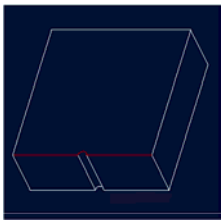
- Profile

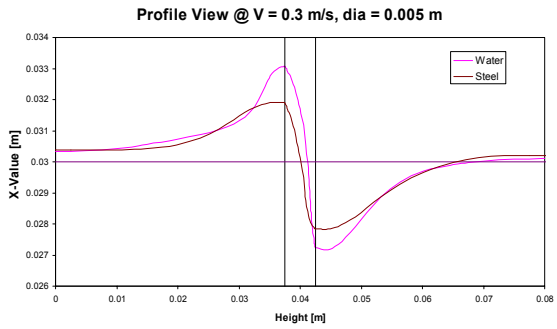




No-Slag Results

- Why not just perform water-model tests?
  - Water and molten steel have similar Re
- Different surface tensions!

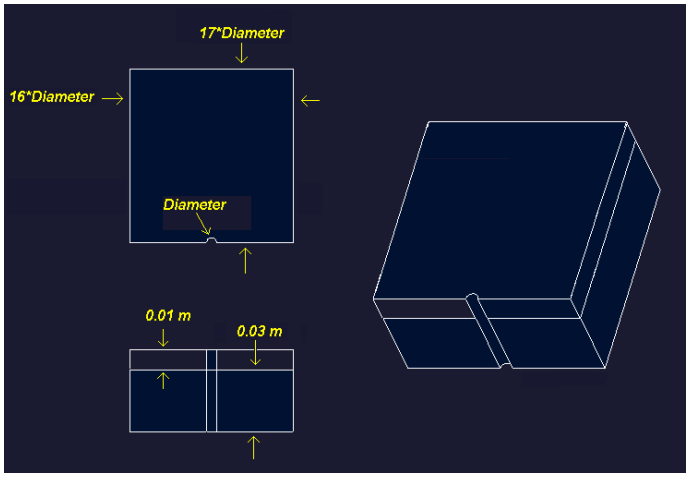




No-Slag Results

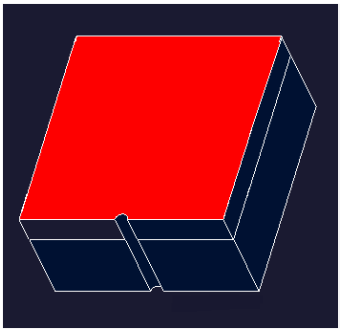
- FIDAP Difficulties
  - GUI is not very user-friendly
    - Input file is preferred over GUI commands
  - Convergence is DIFFICULT to achieve
    - Factors involving convergence
      - Mesh size
      - Time step
      - RELAXATION FACTORS
  - Educational Tech Support is NOT helpful

Slag Model Domain



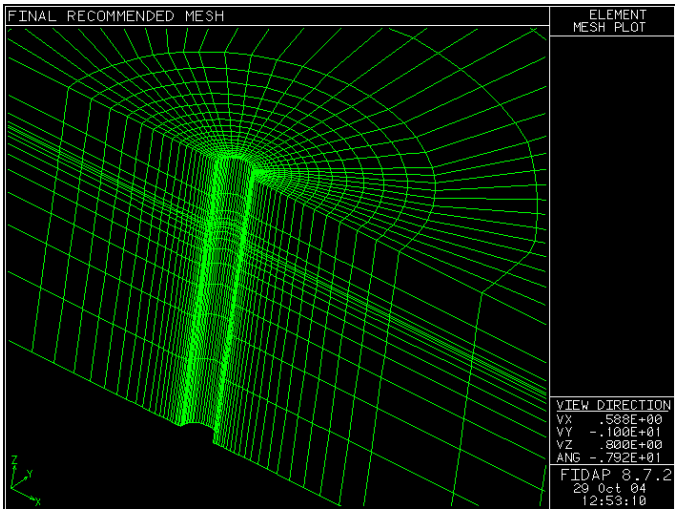
Slag Boundary Conditions

- Same B.C.'s as No-Slag model
- Top surface of slag layer has zero velocity



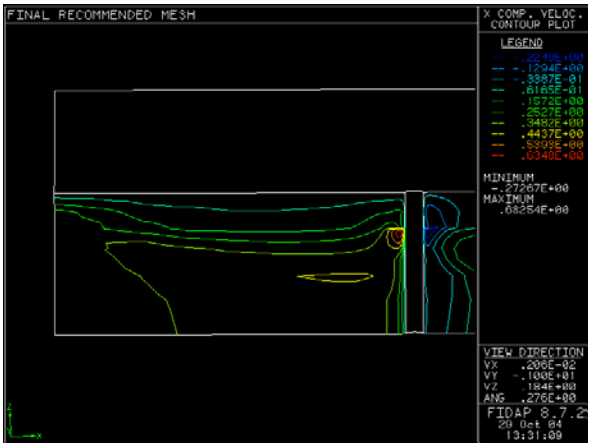
Slag Layer Model

- Mesh



Slag FIDAP Model

- First step- fixed free surface run

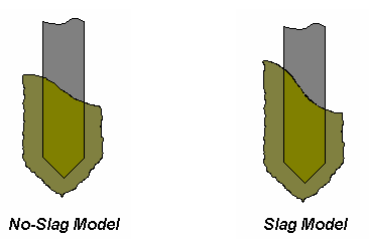


Slag FIDAP Model Current Work

- Finalize boundary conditions to match real world scenario
- Determine appropriate upstream distance to ensure fully developed flow before reaching the nail
- Set appropriate parameters to achieve convergence

Slag FIDAP Model Current Work

- Expecting a more pronounced profile using slag layer than from no-slag model
  - Result of lessened density variation across top surface of molten steel



Final Deliverable

- Use slag model data to create reference manual
  - Measure knob diameter
  - Fit top knob surface to profile templates