Device to Measure Surface Velocity in Flowing Molten Steel

ME470 Spring 05 Design Group 8
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Device to Measure Surface Velocity in Flowing Molten Steel

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Why Measure Surface Velocity?

- Validate fluid flow models
  - Water models
  - Computer simulations
- Monitor fluid motion
  - Defects in the final product
    - Surface velocity too fast: inclusions
    - Surface velocity too slow: surface defects, hooks
  - Breakouts
  - Quality monitoring: deviations in flow pattern should require extra inspection of associated steel product
- No reliable method to measure surface velocity exist
Mold Flow

Reasonably constant surface velocity to \( \sim 30 \text{mm} \) depth

Design Constraints

- Probe must withstand \( \sim 1550\degree \text{C} \)
- Must not dissolve or fracture (high thermal shock resistance)
- Account for EM noise and mold oscillations
- Must measure surface velocities between 0 and 0.5 m/s
Approach

- Literature review outlining viable methods
- Choice of methodology and design calculations
- Material selection and prototype construction
- Data acquisition
- Water model calibration, testing, & validation
- Correlate to the steel environment

Eliminated Methods

- Hot wire anemometry
  - Temperature too high
- Heat exchanger
  - Manufacturing complexity
  - Freezing problem
- Paddle wheel
  - Inclusions
  - Freezing problem
- Tracers
  - Inclusions
- Melting spheres
  - Too expensive
- Electromagnetic sensor
  - Tested in steel industry with little success
  - Expensive
  - Electromagnetic interference
- IR Doppler
  - Doesn’t penetrate slag layer
Melting Sphere Method

Abandoned

- Difficult to calibrate
- Requires rebuilding for each use
- Expensive

Images Source: A Novel Technique to Estimate Velocity in Liquid Steel and in Other High Temperature Liquid Metals Argyropoulos et al.

Karman Vortex Method

- Flow past a submerged cylinder in cross flow creates vortices which oscillate probe
- Oscillation frequency increases with velocity

Evaluation of Karman Vortex Method

- Relationship between velocity and frequency:
  \[ V = \frac{f \cdot D}{St} \]
  
  \( f \) = shedding frequency
  \( D \) = diameter of cylinder
  \( St \) = Strouhal number

Poor correlation with water model measurements because:
Vortex shedding vibrations are smaller than natural frequency of current rod system

Comparison With Water Model Measurements

<table>
<thead>
<tr>
<th>Design Variables (Inputs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillation time, ( t_s ) [s]</td>
</tr>
<tr>
<td>Strouhal Number, ( St )</td>
</tr>
<tr>
<td>Diameter of probe, ( D ) [m]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pumping Velocity</th>
<th>Experimental Parameters</th>
<th>Theoretical Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>Output</td>
<td>Input</td>
</tr>
<tr>
<td>( f_m ) [Hz]</td>
<td>( V_m ) [m/s]</td>
<td>oscillations</td>
</tr>
<tr>
<td>35</td>
<td>0.218</td>
<td>64</td>
</tr>
<tr>
<td>45</td>
<td>0.307</td>
<td>69</td>
</tr>
<tr>
<td>55</td>
<td>0.366</td>
<td>66</td>
</tr>
</tbody>
</table>

- Very poor correlation. Why?
- Vortex shedding vibrations are smaller than natural frequency of current rod system
Drag Force on a Sphere

• Porous, spherical probe is submerged in cross-flow
• Velocity dependant drag force causes sphere to displace
• Displacement measured by pressure sensors

Drag Force on a Sphere

• Advantages
  – Capable of measuring 2-D velocity
  – Has been tested in low temperature liquid metal environment with good results
  – Determines local velocity
  – Not a function of depth
  – Easily tested in water model
  – Tolerant to electromagnetic noise

• Disadvantages
  – Not tested in molten steel
  – Complex shape makes for difficulty in manufacturing
  – Drag coefficients not well known for porous sphere
Drag Force on a Cylinder in Cross Flow

- Design:
  - Thin beam: magnifies deflection
  - Thick cylinder: transmits drag force

Same probe could measure drag force and Karman vortex velocity simulataneously

Relationship Between Reynolds Number and Drag Coefficient

- Drag force on cylinder:
  \[ F_D = \frac{C_D \cdot A \cdot \rho \cdot V^2}{2} \]

\[ Re = \frac{V \cdot D_{rod}}{\nu} \]

\[ C_D = 1 + 10 \cdot Re^{-2/3} \]
Drag Force Calculations

- Angular displacement of plate:
  \[ \theta = \frac{1}{E \cdot I} \left[ F_D \cdot x \cdot L + F \left( \frac{L^2}{2} \right) \right] \]

- Deflection of plate:
  \[ d_{\text{plate}} = \frac{1}{E \cdot I} \left[ F_D \cdot x \cdot \left( \frac{L^2}{2} \right) + F_D \cdot \left( \frac{L^3}{3} \right) \right] \]

- Deflection at end of probe:
  \[ d_{\text{probe}} = d_{\text{plate}} + L_{\text{rod}} \cdot \tan \theta \]

Effects of Submersion Depth on Drag Force Displacement

- The maximum deflection occurs at approximately 4 inches for all velocities
- Probe displacement can be considered independent of submersion depth
Initial Design

- Decoupled motion of Karman vortex and drag force
- Two different surface velocity measurements from same device
- Allowed for various thicknesses for bending beams
- Set aside Karman vortex component due to time constraints

Probe and Testing Stand

- Strain Beam
- Probe
- Water Testing Stand
Data Acquisition Setup

- ±15V power supply
- Strain Bridge
- Data Acquisition Hardware

Strain Bridge Schematic

- The gain resistor can be chosen to give the optimal output voltage for data acquisition
Strain Gauges Mounted on Beam

Strain vs. Voltage

- Voltages were measured for known displacements
- Displacements were correlated to strain
- Strain was correlated to voltage

\[ y = 0.0002x \]
\[ R^2 = 0.9993 \]
Surface Velocity increases with Output Voltage

\[ \text{Velocity} = 0.5741 \cdot \text{Voltage}^{0.5101} \]

Water Tunnel
Water Tunnel Calibration

- Water Tunnel has no way of displaying velocity
- A tracer study was conducted to determine the velocity in the water Tunnel

![Graph showing Velocity vs. Motor Frequency]

\[ y = 0.0067x - 0.055 \]

\[ R^2 = 0.9797 \]
Validation of Probe in Water

- Comparison of measured & expected velocity:

<table>
<thead>
<tr>
<th>Voltage [V]</th>
<th>Displacement [m]</th>
<th>Velocity [m/s]</th>
<th>Motor Frequency [Hz]</th>
<th>Velocity [m/s]</th>
<th>Error [%]</th>
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</thead>
<tbody>
<tr>
<td>0.0549</td>
<td>0.00082</td>
<td>0.121</td>
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<td>0.113</td>
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<td>0.0790</td>
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<td>0.105</td>
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<tr>
<td>0.188</td>
<td>0.00320</td>
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<td>0.247</td>
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<tr>
<td>0.238</td>
<td>0.00405</td>
<td>0.267</td>
<td>50</td>
<td>0.280</td>
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<tr>
<td>0.293</td>
<td>0.00503</td>
<td>0.285</td>
<td>55</td>
<td>0.314</td>
<td>8.74</td>
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<tr>
<td>0.350</td>
<td>0.00596</td>
<td>0.313</td>
<td>60</td>
<td>0.347</td>
<td>9.81</td>
</tr>
</tbody>
</table>

\[
y = 0.0067x - 0.055 \\
R^2 = 1
\]

\[
y = 0.0058x - 0.0196 \\
R^2 = 0.9994
\]
Probe Material Selection

Refractory Materials
- Boron Nitride
  - Possible contamination
- Beta Sialon
  - Very expensive
- Tantalum
  - Limited sources
  - Expensive
- Alumina Graphite
  - Ideal (SEN Material)
  - Expensive, difficult to acquire
- Alumina
  - Less expensive than alumina graphite
  - Readily available

Future Steel Testing

- Larger drag force in steel requires thicker strain beam:
  - Large deflections due to increased forces surpass the limits of the beam theory applied
  - Steel testing strain beam should be 1.2 mm thick
- Alumina probe must be preheated to withstand thermal shock
Conclusions

- A device to measure surface velocity of molten steel in the CC mold has been designed
- The device has been validated in a water model and measures surface velocity to within 10% from 0.1-0.4m/sec
- Design features
  - Simple, robust, mechanical mechanism
  - Capable of operating in molten steel
  - Resistant to fluctuations in a range of submersion depths
  - Tolerant to electromagnetic noise
  - Inexpensive

Future Work

- Construct mounting apparatus to suspend device over continuous casting mold
- Test in molten steel environment (quantification of molten steel velocity)
- Validation / comparison with nail-board measurements and modeling predictions
- Further study of Karman vortex method