Spray heat transfer research
at Cinvestav, Mexico

Xiaoxu Zhou (MS Student), Sami Vapalahti (Ph.D. Student), Humberto Castillejos E. (Prof.), F. Andres Acosta G. (Prof.), Alberto C. Hernandez B. (PHD Student), José Manuel González de la Cruz (MS Student), Brian G. Thomas

Laboratory of Process Metallurgy, Cinvestav, Mexico
Department of Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

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• Laboratory of Process Metallurgy, CINVESTAV, Mexico
Outline

• Goals
• Transient experiments (Vapalahti’s previous work - 2006 CCC meeting)
• Steady state experiments
  – Experiment setup
  – Previous experiments
  – Current experiments
• Conclusion
• Future work

Goals

• To study dynamics of spray heat transfer
  – Comparison between steady state and transient results to understand phenomena related to both cases
• To quantify heat transfer coefficients and Leidenfrost effects obtained with air-mist spray nozzles
• To implement obtained information to current heat transfer models
• Validate heat transfer models with industrial trials
Transient equipment

The plates were produced and measured for actual locations of the thermocouples and the thermocouples are attached

<table>
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<th>M</th>
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<th>R</th>
<th>y</th>
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Typical water flux distribution on the steel plate (obtained by footprint measurement)

Impact flux density: L/m²s

Nozzle type: Delavan 51474-1

-Vaphalahti’s 2006 CCC annual meeting report

Cooling curves

<table>
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<th>Plate</th>
<th>To (°C)</th>
<th>Pa (kg/cm²)</th>
<th>Pw (kg/cm²)</th>
<th>Qa (grams/min)</th>
<th>Qw (l/min)</th>
<th>Water T (°C)</th>
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<td>625.8</td>
<td>30.78</td>
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Cooling Curves Plate 4

Cooling Curves Plate 6
Heat flux calculated by inverse model

Steady state experiment--Setup
Current experiment--Setup
(3D schematic)

Schematic of induction Heating System

Note: Thermocouples Tout, coil, hot and Tout, coil were just added for the current tests
Plastic-walled **Box** (containing induction coil in ceramic block, sample, and thermocouples)

**Plastic tube mold used to form ceramic block**

**Plastic side wall**

**Quartz frontal wall**

**Copper coil**

**Nozzle**

**Sample**

**Induction heating Copper coil**

Assembled box

**Quartz window with grooves for best sealing**

**Ceramic monolith**

**Lateral thermocouple**

**Sample thermocouple**

**Screw thread bars to push ceramic against window**
Current Ceramic block

Induction is applied on the surface of the sample parallel to the coil and heat is generated on the surface within the skin depth of the system.

Schematic of ceramic block
Previous coil, TC and ceramic block

Heat balance:
\[ P_{\text{tot}} = P_{\text{water}} + P_{\text{sample}} + P_{\text{air\&components}} \]

Assumption for heat analysis:
The power loss to water and sample is a constant fraction of total power.

\[ P_{\text{sample}} = f \cdot P_{\text{tot}} \]
\[ P_{\text{sample}} = P_{\text{spray water}} + P_{\text{conduction to ceramic block}} \]
Previous experiment results

- Steady state and transient results with similar conditions:

![Graph showing calculated surface temperature and heat flow](image)

Current experiment

- Heat sample for prescribed temperature path (control power by sample TC)

- Record:
  - sample temperature,
  - ceramic temperature (lateral and back),
  - four water temperatures in the pipes,
  - total power input.
Tests  
(May 15, 2008 – July 15, 2008)

• Nozzle type: ss-6.5-9

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<th>A4</th>
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<td>6.0</td>
<td>6.0</td>
<td>12.0</td>
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<tr>
<td>Air flow rate (gpm)</td>
<td>650</td>
<td>650</td>
<td>325</td>
<td>625</td>
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<tr>
<td>Temp path</td>
<td>Heating (100-1300)</td>
<td>Heating (100-1300)</td>
<td>Heating (100-1300)</td>
<td>Heating (100-1300)</td>
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• Nozzle type: Delavan W19822

<table>
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<td>Temp path</td>
<td>Heating</td>
<td>Heating</td>
<td>Heating-Cooling-Heating</td>
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Case A1: power vs. time

Repeat case A1 3 times to show reproducibility

Total power and sample temperature vs. time

Note: large power on heating to 300C; level to 600C; then drop-off
Case A1: ceramic temps vs. time

Note: nearby ceramic heats rapidly until sample is 300°C, then approximately level; far-away ceramic slowly heats throughout tests.

Heating-cooling-heating (Case B3)

Note: The power gives almost the same behavior during heating, but much lower in cooling.
Other recent cases

Heating for a long time at 200 °C, 600 °C, 1100 °C

ceramic block thermal time constant

- Time constant for ceramic block from front to the lateral TC
  \[ \rho V C_p \sim \frac{1762 \text{kg} / \text{m}^3 \times (\pi \times \frac{25.4^2}{4} \times 11 \times 10^{-9} \text{m}^3) \times 0.74 \times 10^7 \text{J/kgK}}{10W / \text{m}^2 \text{K} \times (\pi \times 25.4 \times 11 \times 10^{-6} \text{m}^2 + 2 \times \pi \times \frac{25.4^2}{4} \times 10^{-6} \text{m}^2)} \sim 7.4 \text{min} \]
  \[ B_i = \frac{hL_c}{k} \sim 0.004 \ll 1 \]

- Time constant for ceramic block from front to the back TC
  \[ \rho V C_p \sim \frac{1762 \text{kg} / \text{m}^3 \times (\pi \times \frac{25.4^2}{4} \times 27 \times 10^{-9} \text{m}^3) \times 0.74 \times 10^3 \text{J/kgK}}{10W / \text{m}^2 \text{K} \times (\pi \times 25.4 \times 27 \times 10^{-6} \text{m}^2 + 2 \times \pi \times \frac{25.4^2}{4} \times 10^{-6} \text{m}^2)} \sim 9.4 \text{min} \]
  \[ B_i = \frac{hL_c}{k} \sim 0.01 \ll 1 \]
Preliminary heat conduction analysis

Heat transfer equation:
\[ k \nabla^2 T + S = 0 \]

Power density generated by induction heating:
\[ P_v = \rho_v J^2 \]

Skin depth:
\[ \delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \]

- The quasi-parallel isotherms can be achieved, in all cases, in a central region located within: \( 2 < z < 3 \) mm and \( 0 < r < 2 \) mm
- The higher melting point and superior oxidation resistance of platinum are desirable advantages when heating the sample at the high temperatures.

### Computed isotherms for steady spray cooling with induction heating of samples of a platinum (r-z symmetry plane)

Conclusions

- The new system has a high reproducibility.
- The steady-state analysis actually has transient components which take many minutes to heat up.
- Significant power is lost to ambient air and cooling water, which must be accounted for using more TCs.
- The ceramic block shape complicates the analysis of heat transfer.
- Cooling requires much less power than heating, which means hysteresis effect might exist.
- The previous heat-flow models are not quite reasonable: more accurate modeling is needed before heat extraction can be accurately quantified.
Future work

• Construct a more accurate model to quantify heat transfer coefficients obtained with air-mist spray nozzles
• To implement obtained information to Con1d models
• Validate heat transfer models with industrial trials