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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

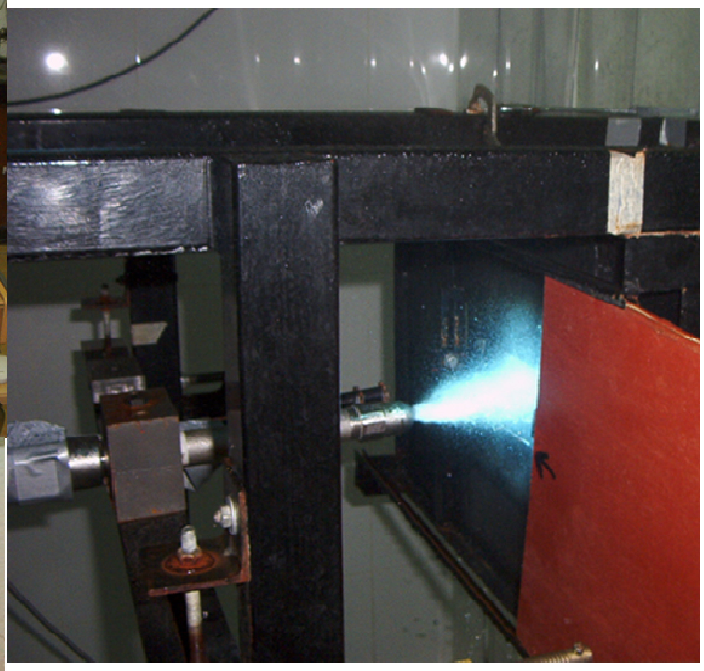
Outline

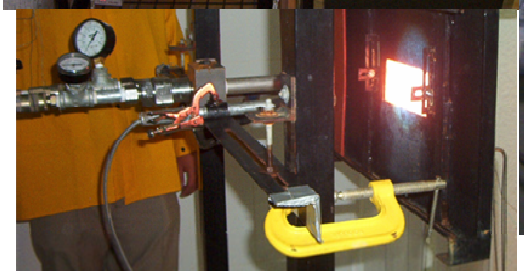
- Goals
- Transient experiments (Vapalahti's previous work - 2006 CCC meeting)
- Steady state experiments
  - Experiment setup
  - Previous experiments
  - Current experiments
- Conclusion
- Future work

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





Transient Measurements

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

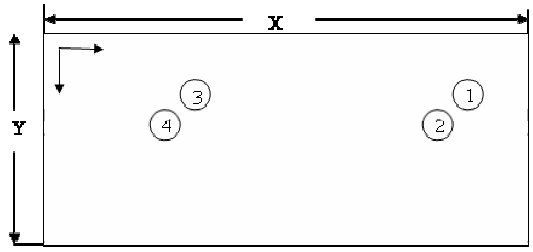
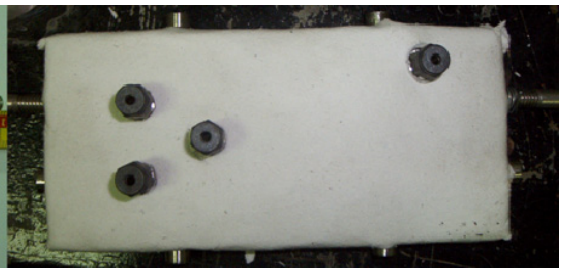


PLATE 3	lxl	lyl	dz	X	Y	L	L-dz
1	130.6	25.2	11.6	168.5	76.5	12.95	1.45
2	129.4	35.8	11.5				1.45
3	70.0	25	11.5				1.45
4	60.3	41.6	11.5				1.45

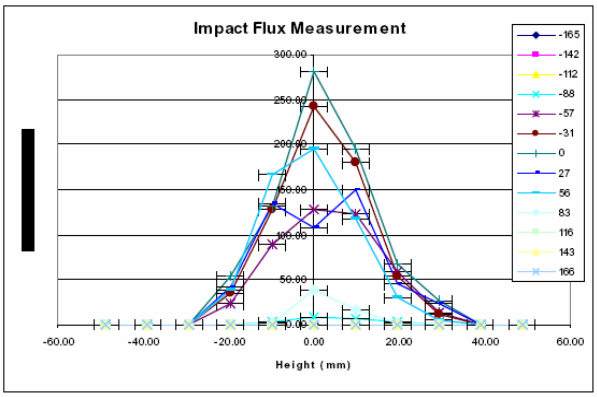
PLATE 4							
1	134.6	25.6	11.8	168.5	77.0	12.95	1.15
2	129.9	34.9	11.8				1.15
3	69.9	26.0	11.6				1.35
4	60.5	38.9	11.6				1.35

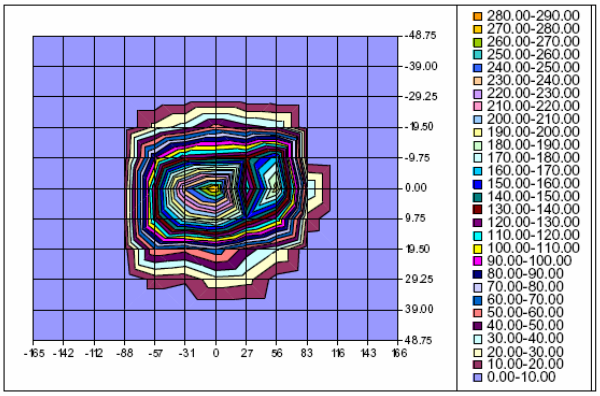
PLATE 5							
1	134.4	25.7	12.1	168.0	76.0	12.05	0.75
2	129.5	35.9	11.9				0.95
3	69.6	25.3	11.8				1.05
4	59.3	40.6	11.9				0.95



Typical water flux distribution on the steel plate(obtained by footprint measurement)

Impact flux density: L/m²s



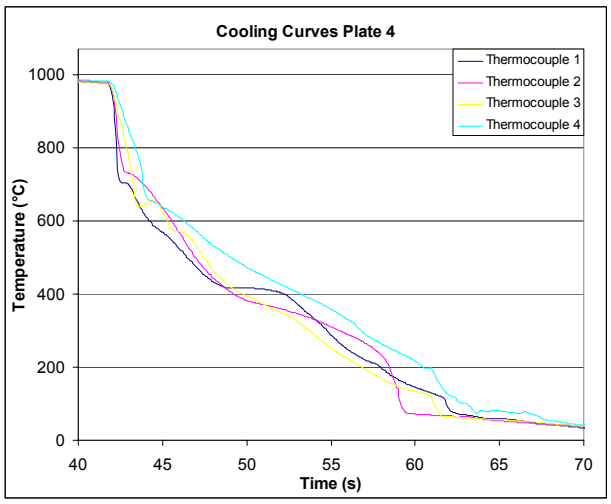


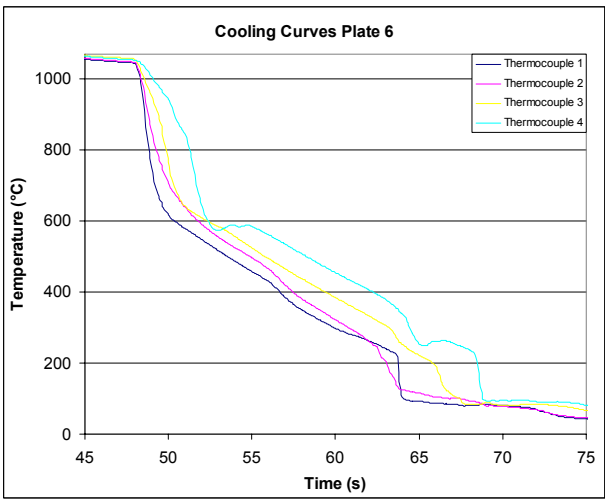
Nozzle type: Delavan 51474-1

-Vaphalahti's 2006 CCC annual meeting report

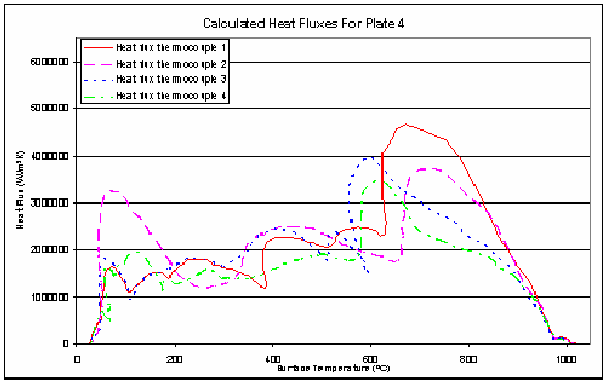
Cooling curves

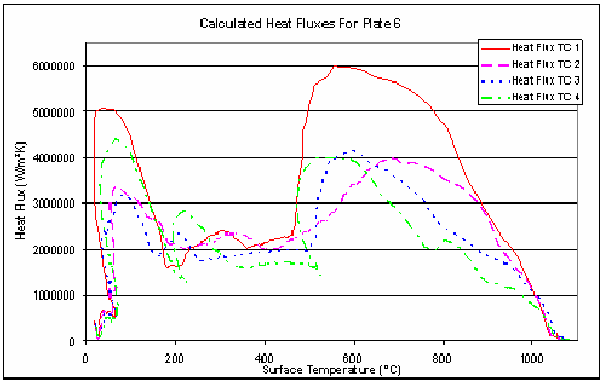
Plate	To (°C)	Pa (kg/cm²)	Pw (kg/cm²)	Qa (grams/min)	Qw (l/min)	Water T (°C)	Note
4	975	3.5	3.8	625.11	30.75	22	
6	1050	3.6	3.8	625.8	30.78	24	Smooth



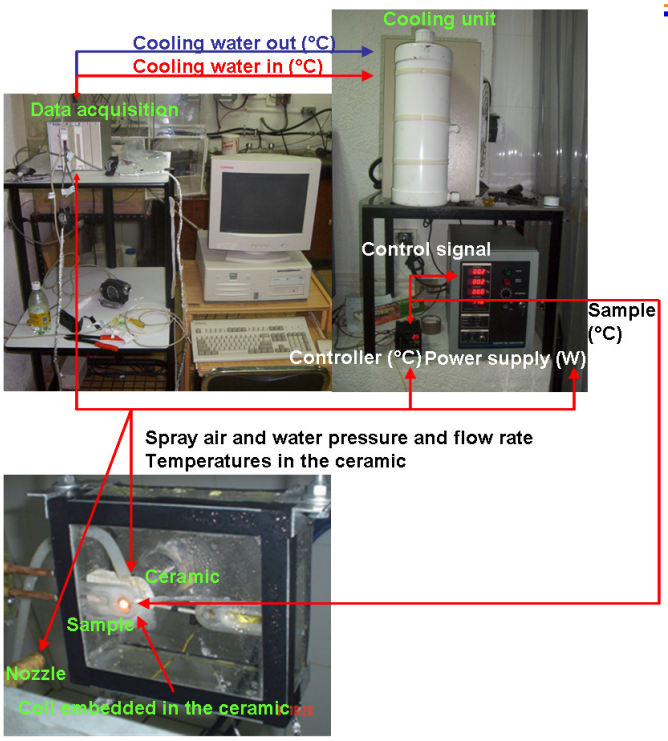


Heat flux calculated by inverse model

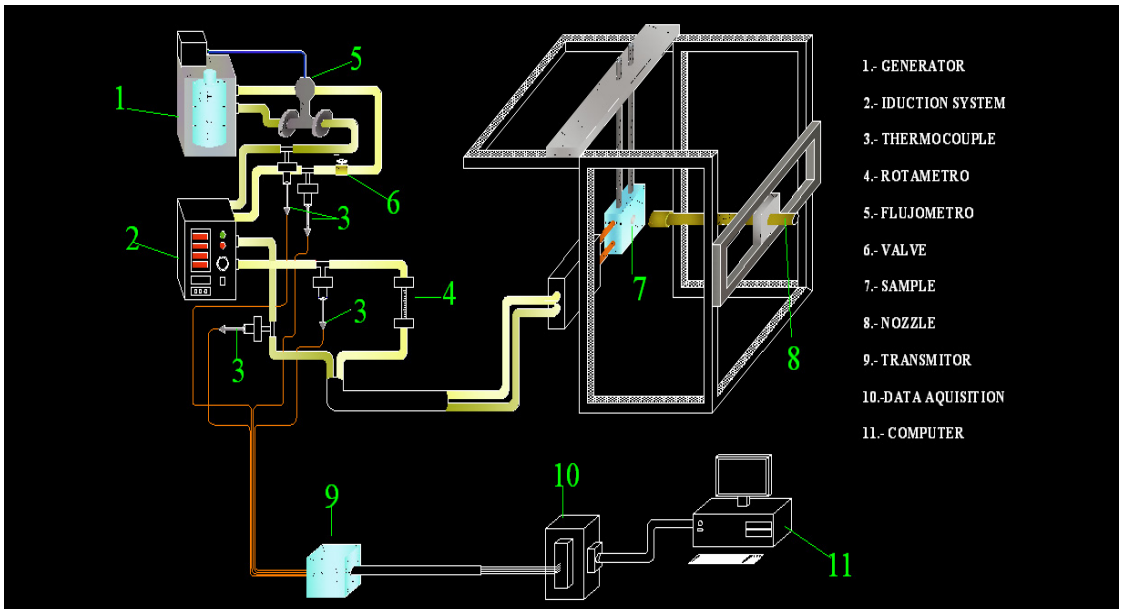




Steady state experiment--Setup

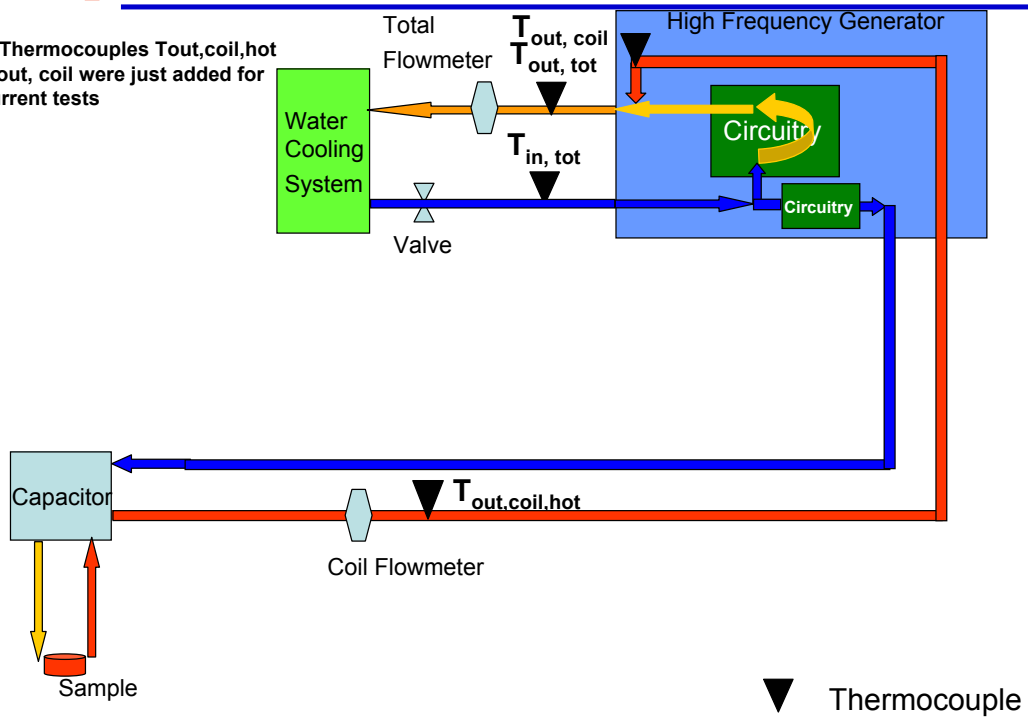


Current experiment--Setup (3D schematic)

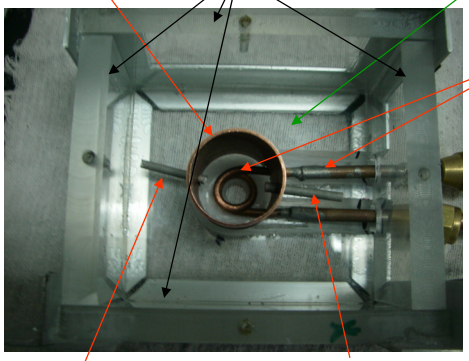


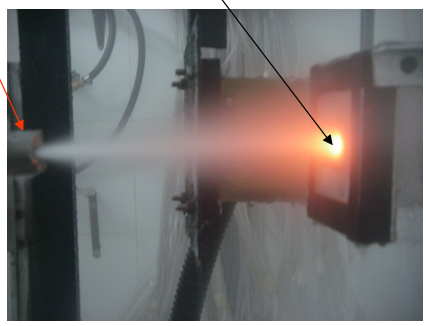
Schematic of induction Heating System

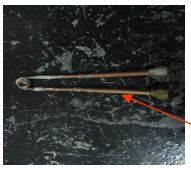
Note: **Thermocouples Tout,coil,hot and Tout, coil were just added for the current tests**



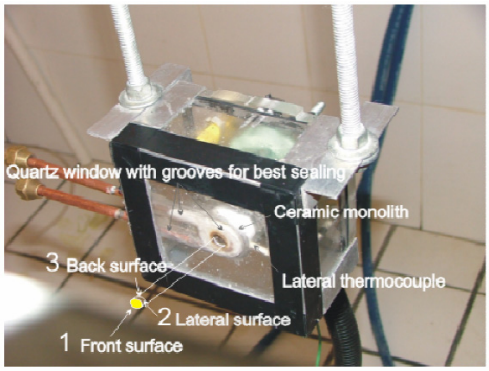
Plastic-walled **Box** (containing induction coil in ceramic block, sample, and thermocouples)

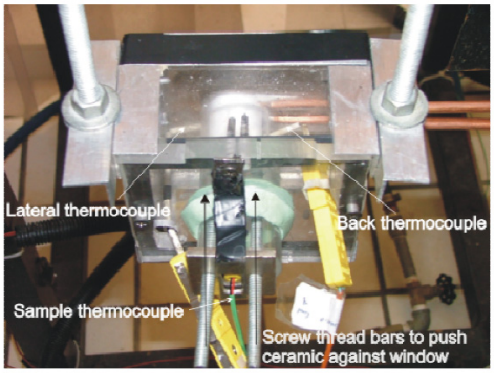




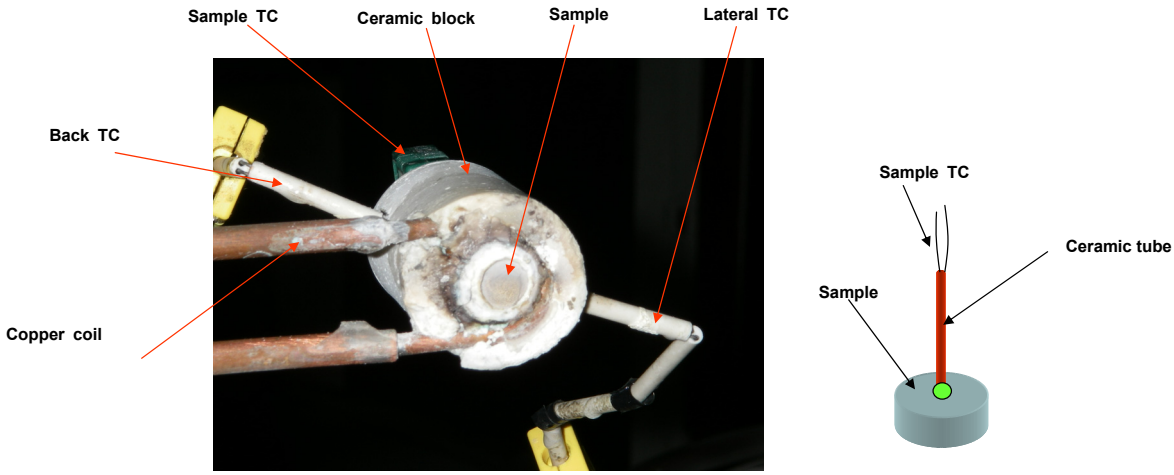


Assembled box



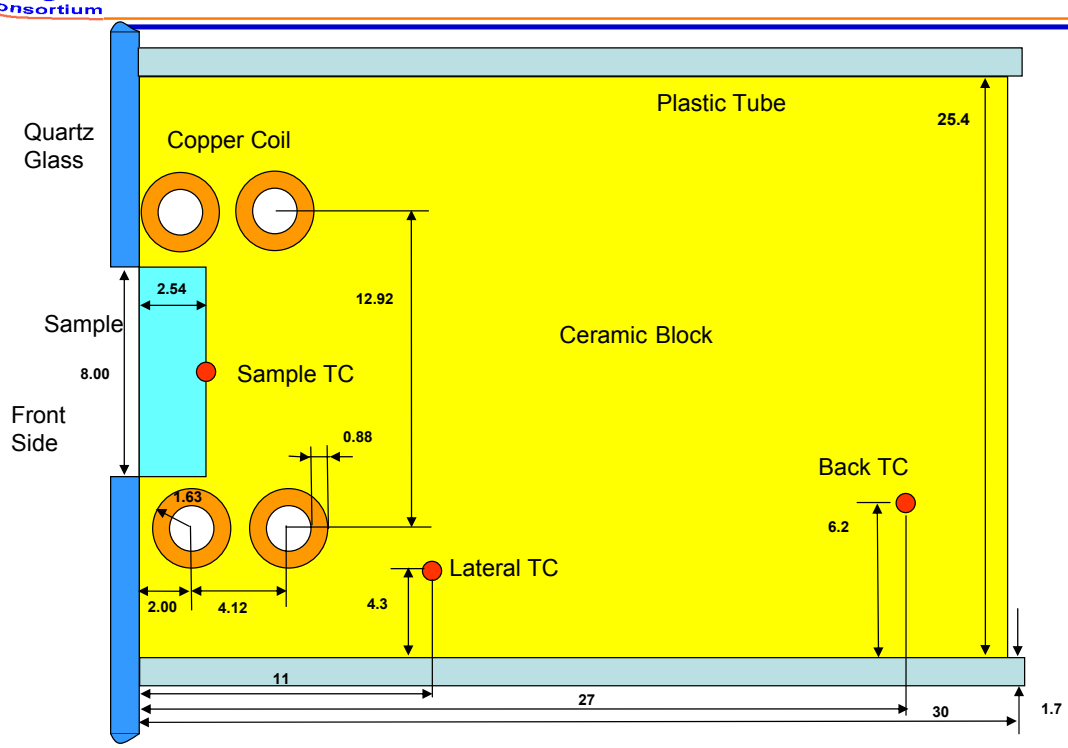


Current Ceramic block

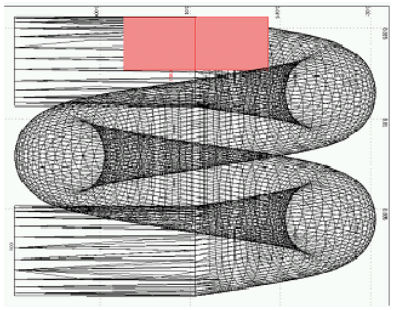


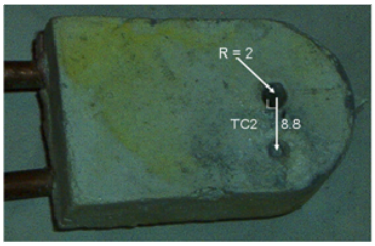
•Induction is applied on the surface of the sample parallel to the coil and heat is generated on the surface within the skin depth of the system

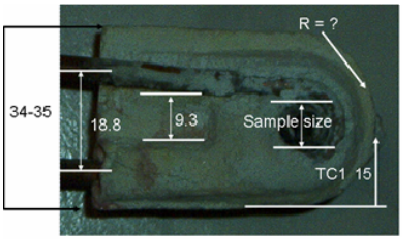
Schematic of ceramic block

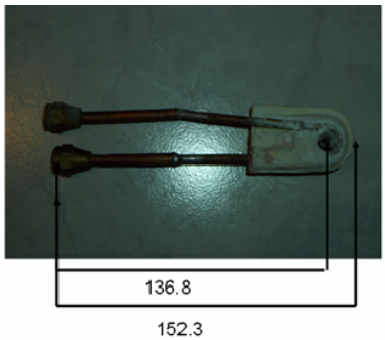


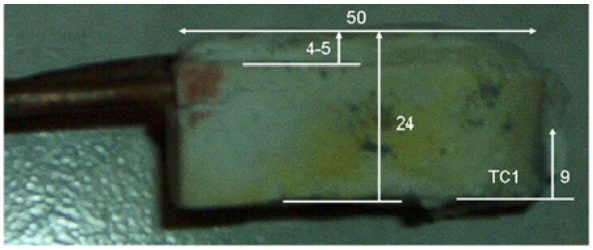
Previous coil, TC and ceramic block











Previous heat analysis

Heat balance:

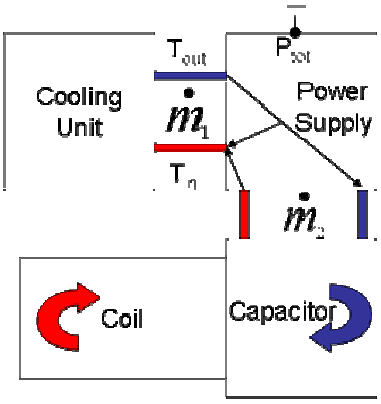
$P_{tot}=P_{water}+P_{sample}+P_{air\&components}$

Assumption for heat analysis:

The power loss to water and sample is a constant fraction of total power.

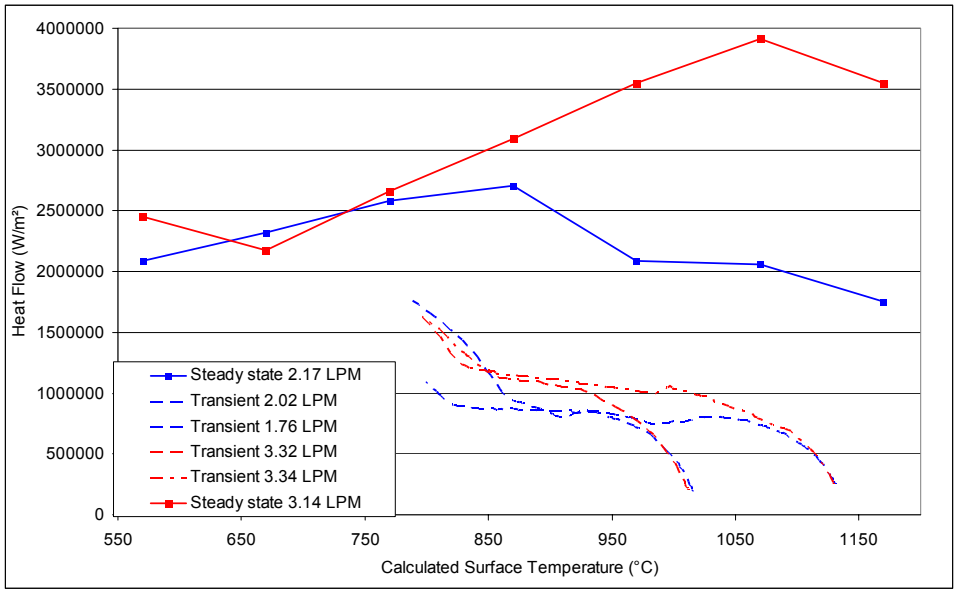
$P_{sample}=f \cdot P_{tot}$

$P_{sample}=P_{spray\ water}+P_{conduction\ to\ ceramic\ block}$



Previous experiment results

- Steady state and transient results with similar conditions:



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**

cases	A1	A2	A3	A4
Water flow rate (lpm)	3.0	6.0	6.0	12.0
Air flow rate (gpm)	650	650	325	625
Temp path	Heating (100-1300)	Heating (100-1300)	Heating (100-1300)	Heating (100-1300)

•**Nozzle type: Delavan W19822**

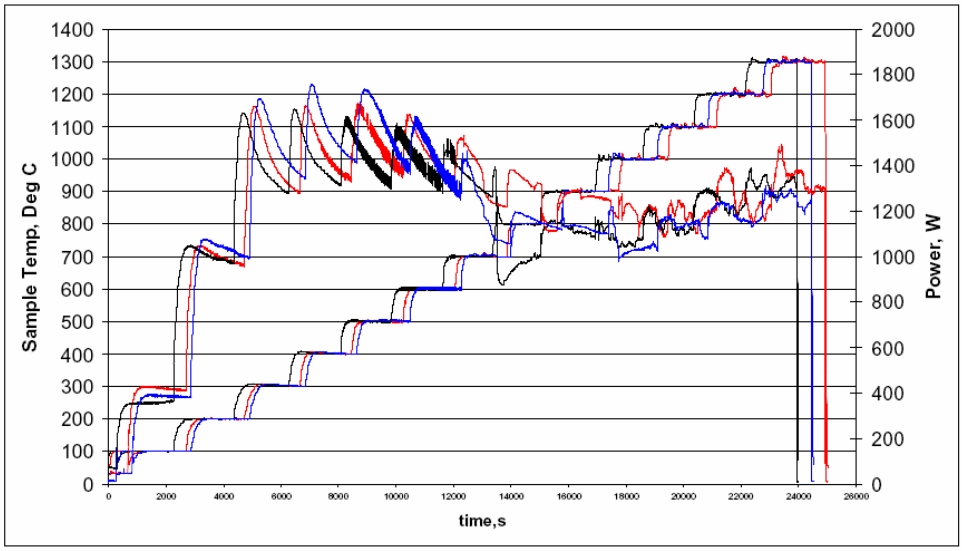
cases	B1	B2	B3
Water flow rate (lpm)	4.6	2.0	4.6
Air flow rate (gpm)	104	125	104
Temp path	Heating	Heating	Heating-Cooling-Heating

Case A1: power vs. time

- Water flow rate:3 lpm
- Air flow rate: 650 gpm
- Nozzle: ss-6.5-9
- 5 min for each temp

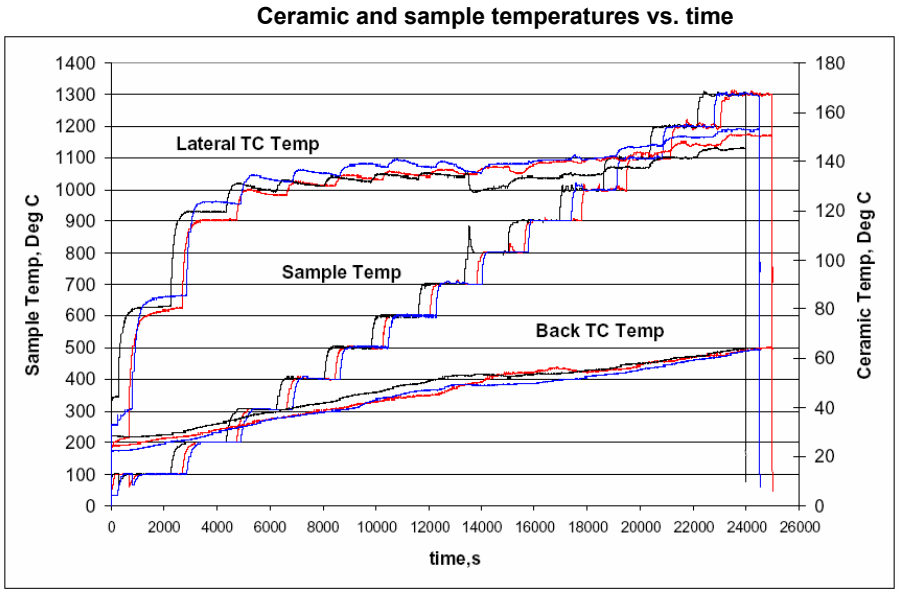
Repeat case A1 3 times to show reproducibility

Total power and sample temperature vs. time



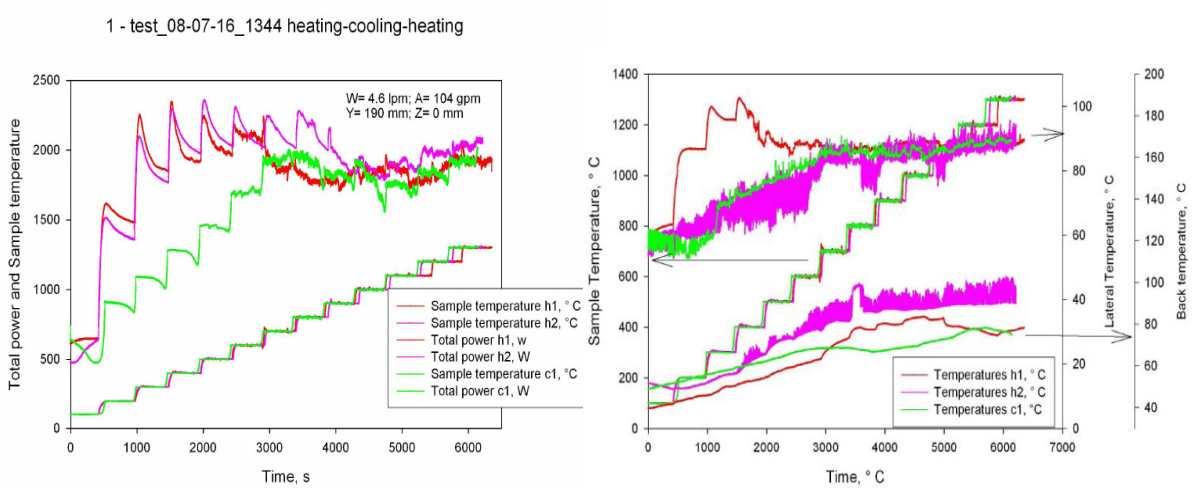
Note: large power on heating to 300C; level to 600C; then drop-off

Case A1: ceramic temps vs. time



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

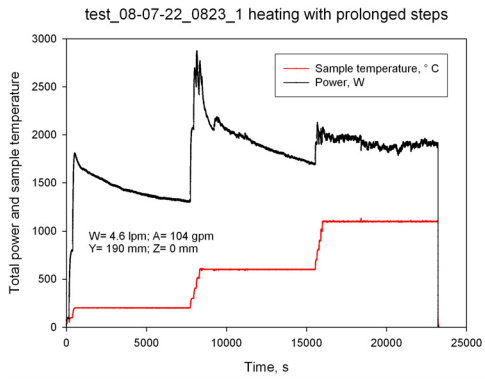
Heating-cooling-heating (Case B3)

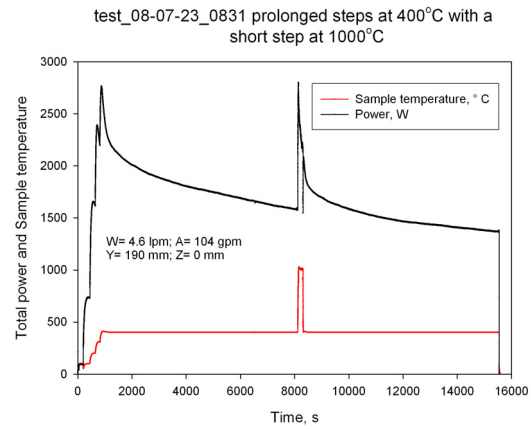


Note: The power gives almost the same behavior during heating, but much lower in cooling.

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

$$\frac{\rho V C_p}{h A_s} \sim \frac{1762 kg/m^3 \times (\pi \times \frac{25.4^2}{4} \times 11 \times 10^{-9} m^3) \times 0.74 \times 10^3 J/kgK}{10 W/m^2 K \times (\pi \times 25.4 \times 11 \times 10^{-6} m^2 + 2 \times \pi \times \frac{25.4^2}{4} \times 10^{-6} m^2)} \sim 7.4 \min$$

$$B_i = \frac{h L_c}{k} \sim 0.004 << 1$$

- Time constant for ceramic block from front to the back TC

$$\frac{\rho V C_p}{h A_s} \sim \frac{1762 kg/m^3 \times (\pi \times \frac{25.4^2}{4} \times 27 \times 10^{-9} m^3) \times 0.74 \times 10^3 J/kgK}{10 W/m^2 K \times (\pi \times 25.4 \times 27 \times 10^{-6} m^2 + 2 \times \pi \times \frac{25.4^2}{4} \times 10^{-6} m^2)} \sim 9.4 \min$$

$$B_i = \frac{h L_c}{k} \sim 0.01 << 1$$

Preliminary heat conduction analysis

Heat transfer equation:

$$k \nabla^2 T + S = 0$$

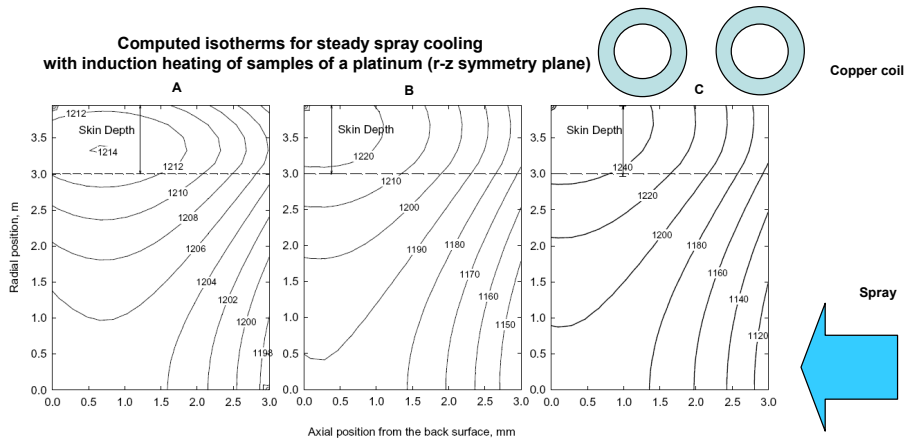
Power density generated by induction heating:

$$P_v = \rho_e J^2$$

Skin depth:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

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



-Prof. Humberto's simulation by CONDUCT

- **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.**

	Case A	Case B	Case C
Sample TC temp, Deg C	1205	1186	1190
Max/min temp on surf, Deg C	1206/1196	1174/1144	1170/1110

	Sample used in tests	Sample here
Radius (mm)	**4**	**4**
thickness (mm)	**2.53**	**3**

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