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Heat Transfer During Spray Cooling Using Steady Experiments

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Outline

- Project objectives
- Measurements using steady-state experimental apparatus at CINVESTAV, Mexico
- Computational model of Induction heating experiment.
- Spray cooling heat transfer coefficients results
- Conclusions
- Acknowledgements

Project Objectives

i. To study transient and steady-state heat tansfer of nozzle spray cooling

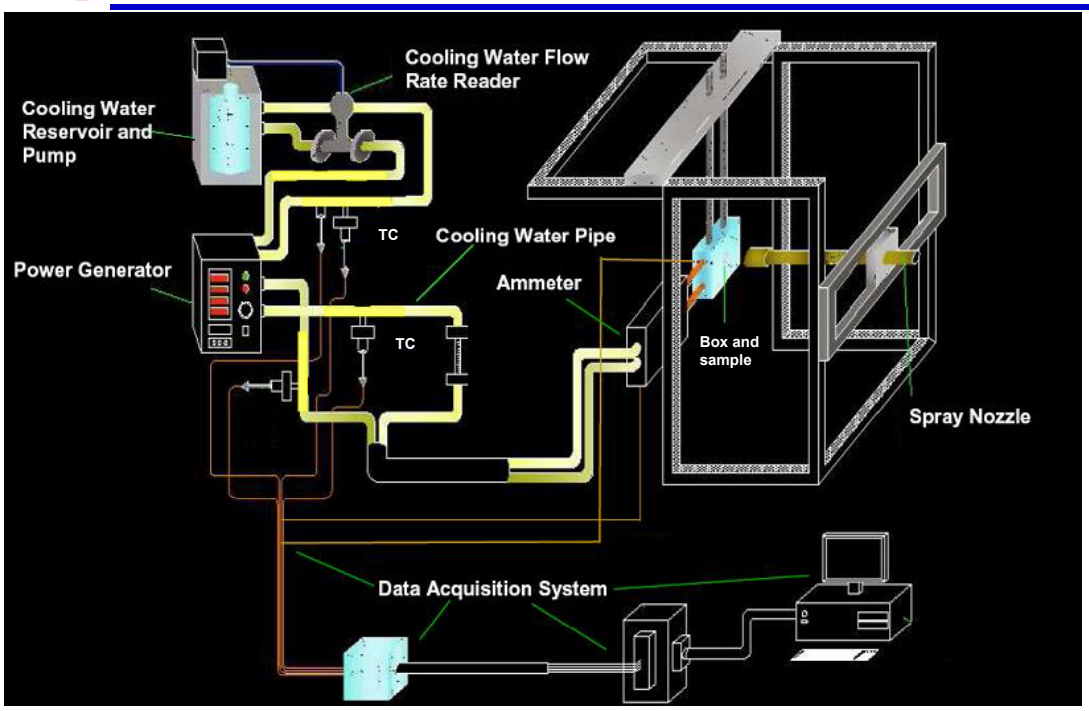
ii. To quantify spray cooling heat transfer coefficients and Leidenfrost effects obtained with air-mist nozzles by interpretation of experiments with computational modeling.

iii. To improve temperature prediction in secondary cooling of the current continuous casting models: Con1D and Cononline with obtained heat transfer coefficients and Leidenfrost effects

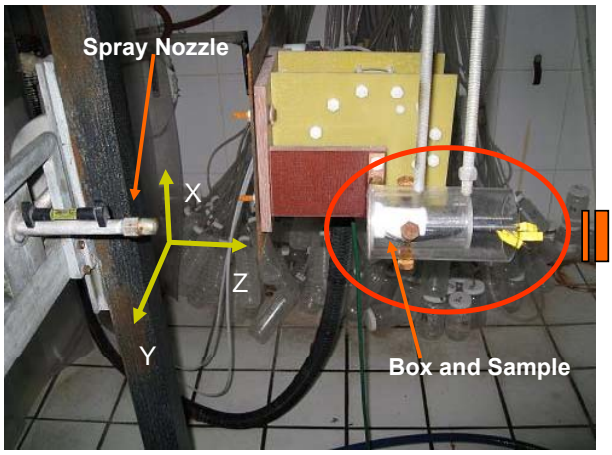
iv. To further validate these two models with industrial trials

v. To improve the casting steel quality by greater control of the strand surface temperature

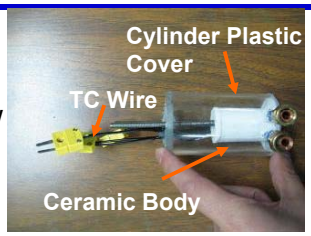
3D Experimental Setup Schematic



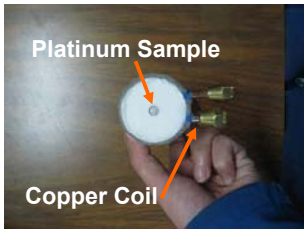
Box and Sample Details



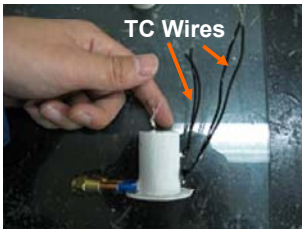
Side View



Top View



Internal View



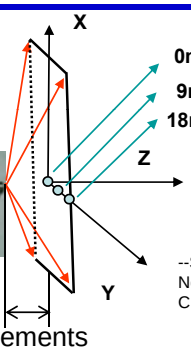
Top View

Side View

Induction Copper Coil

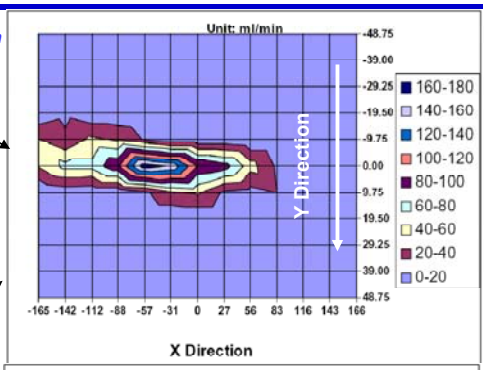
Nozzle Water Flow Rate Footprint Measurements

Nozzle type:
Delevan W19822



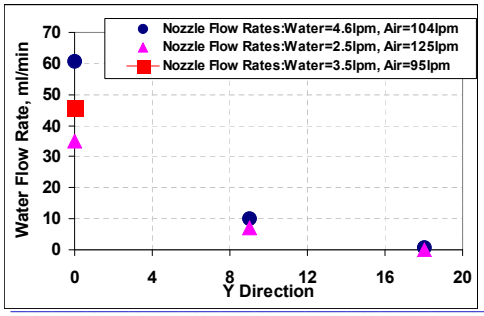
0mm
9mm
18mm

- *Water flow rate: 10.72 lpm*
- *Water pressure: 160 PSI*
- *Air flow rate: 53.99 g/min*
- *Air pressure: 126 PSI*

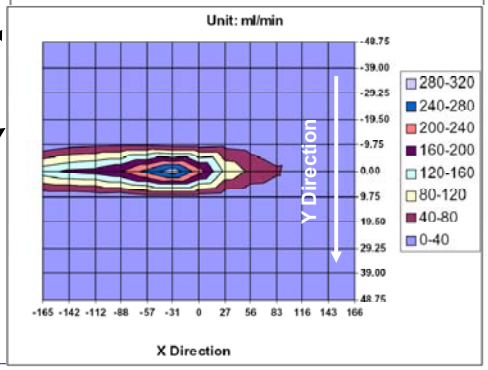


--Sami Vapalahti, et al. Delavan Nozzle Characterization at CINVESTAV,CCC report, 2007

Footprint measurements for the current experiments
(Jun 17, 09~Jul 04, 09)



- *Water flow rate: 10.84 lpm*
- *Water Pressure: 130 PSI*
- *Air flow rate:51.14 g/min*
- *Air pressure: 105 PSI*



Nozzle Spray Impact Measurements

Droplet size distribution

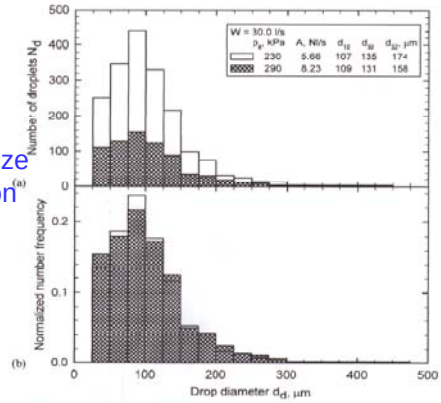


Fig. 4 – (a) Droplet count diameter distributions and (b) normalized droplet count diameter distributions, for two air nozzle pressures.

Droplet velocity

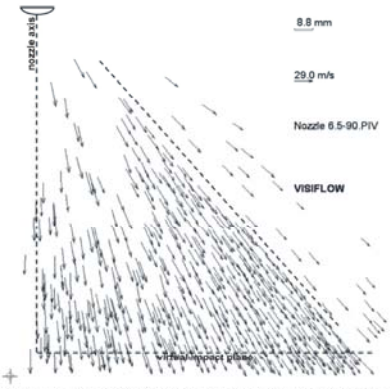


Fig. 8 – Vector plot of the velocities of drops travelling in air-mist jets with W= 30 Lt/min and p_a= 230 kPa

-Hernandez I, Acosta FA, Castillejos AH, et al. Metal Trans B, 39(5), pp: 746-763, 2008

Impact pressure

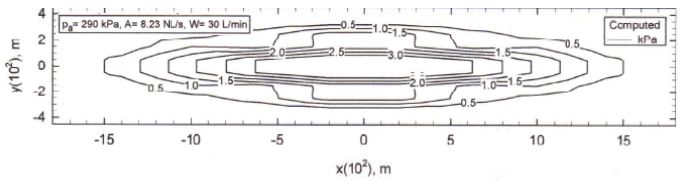


Fig. 14 – computed water impact pressure distributions generated over an impact plane located at 0.175 m from a Casterjet 6.5-90 nozzle operating under the conditions specified.

•Pressure is calculated by using droplet size (mass) and its velocity

Steady Spray Cooling Experiments

Experiment procedure:

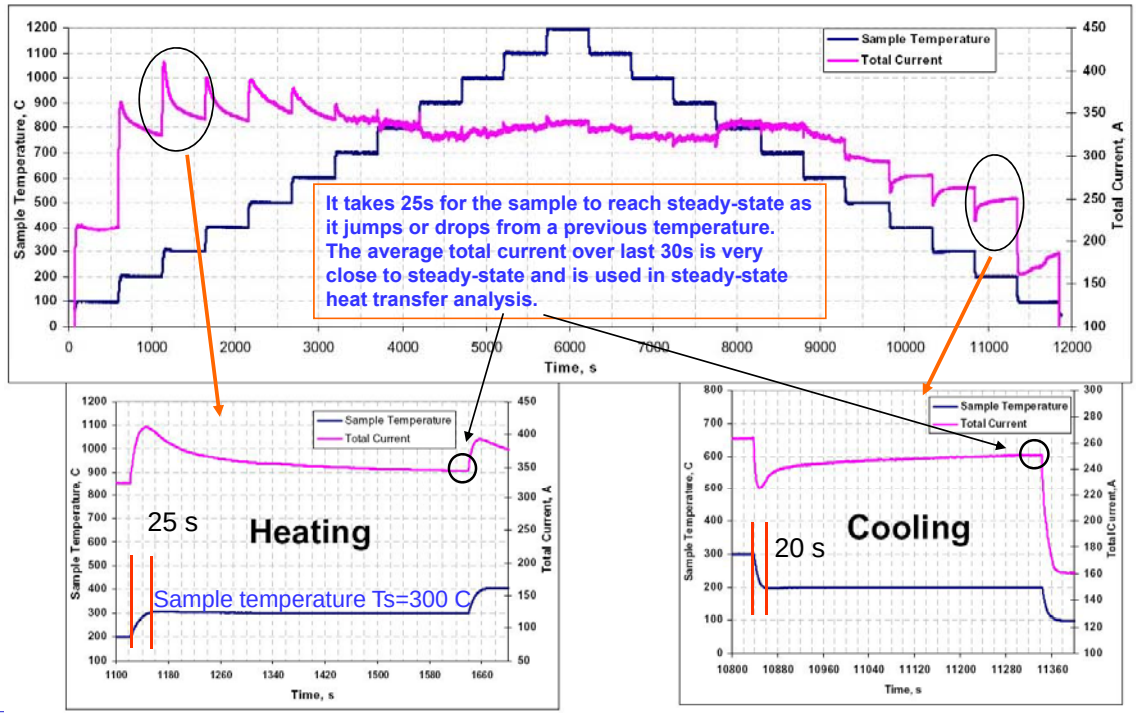
- For each nozzle flow-rate and each nozzle position, the spray-cooled platinum sample is induction-heated with sample temperature controlled from 200 ºC to 1200 ºC and then cooled down from 1200 ºC to 200 ºC with steps of 100 ºC.
- Each sample temperature is held for 8 min.

Recorded Data:

1) Total current through the induction coil.
2) The sample thermocouple temperature (*sample temperature, Ts*).
3) The cooling water flow rate and its temperatures before entering and after leaving the induction coil (*to estimate cooling water temperature*).
4) Water flow rate, water pressure, air flow rate and air pressure through the nozzle.
5) Total applied power for the entire experiment system.
6) Temperatures at selected locations in the ceramic body. (*not reliable*)

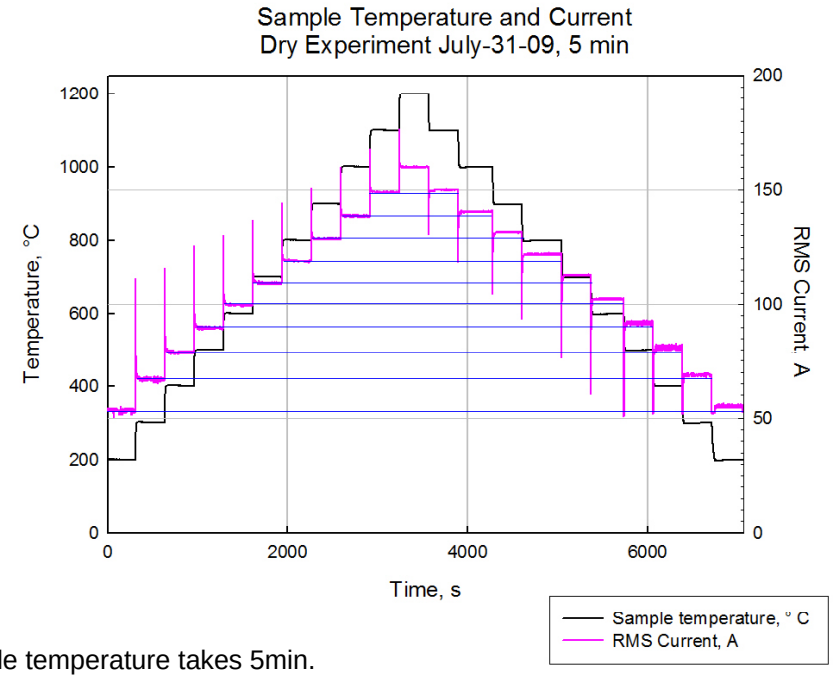
Typical Temperature and Total Current Paths from **Wet** Experiments

Water Flow Rate=4.6lpm, Air Flow Rate=104lpm,Nozzle Centered (June 26, 09)



Typical Temperature and Total Current Paths from **Dry** Experiments

Water Flow Rate=0lpm, Air Flow Rate=0lpm,Nozzle Centered (July-31, 09)



•Each sample temperature takes 5min.

•Steady total current matches very well for heating and cooling, no hysteresis presented.

Induction Heating Model Description

- 2-D axisymmetric induction heating model (AC power electromagnetics and heat conduction) is created by using FEA software: COMSOL Multiphysics. (http://www.comsol.com/)
- Two sets of coupled governing equations are solved (physics modes in COMSOL)
  - ***AC power electromagnetics equation***
    - *combining Maxwell equations, charge conservation, Electromagnetic constitutive equations, Ohm's law*
    - *with temperature-dependent properties*
    - *solve for magnetic potential*
  - ***Heat conduction equation***
    - *with magnetic-potential-dependent heat source and temperature-dependent properties*
    - *solve for temperature distribution*
- Heat is generated by induction heating in the platinum sample and copper coil and mainly removed by spray cooling and cooling water through the coil.

AC Power Electromagnetics Equation

$$\nabla\times(\mu_0^{-1}\mu_r^{-1}\nabla\times\vec{A}_0)-\omega^2\varepsilon_0\varepsilon_r\vec{A}_0=-\sigma\nabla\vec{\Phi}_0-j\omega\sigma\vec{A}_0$$

$\vec{A}_0 = A_0(r,z)\vec{e}_\theta$ for 2-D axisymmetric geometry

Time-Harmonic field Assumption

$$\begin{cases}\vec{A}=\vec{A}_0\,e^{i\omega t}\\ \vec{\Phi}=\vec{\Phi}_0\,e^{i\omega t}\end{cases}$$

Potentials definition

$$\begin{cases}\vec{E}=-\dfrac{\partial\vec{A}}{\partial t}-\nabla\Phi\\ \vec{B}=\nabla\times\vec{A}\end{cases}$$

Constitutive equations

$$\vec{H}=\frac{\vec{B}}{\mu_0\mu_r}$$

--for more details, please refer to Maxwell equations, Charge conservation equation and Ohm's Law

Induced current density amplitude

$$\vec{J}_{ind}=-j\sigma\omega\vec{A}_0$$

Loop current density amplitude

$$\vec{J}_{loop}=-\sigma\nabla\vec{\Phi}_0$$

Total current density amplitude

$$\vec{J}_{tot}=\vec{J}_{ind}+\vec{J}_{loop}$$

Input in COMSOL

$\vec{A}$	magnetic potential
$\vec{A}_0$	magnetic potential amplitude
$\vec{B}$	magnetic field
$\vec{H}$	magnetic flux density
$\vec{E}$	electric field
$\vec{\Phi}$	electric potential
$\vec{\Phi}_0$	electric potential amplitude

Parameters Table

μ_0	permeability of free space
μ_r	relative permeability
ω	angular frequency
ε_0	permittivity of free space
ε_r	relative permittivity
σ	electrical conductivity

Heat Conduction Equation

Transient heat conduction equation

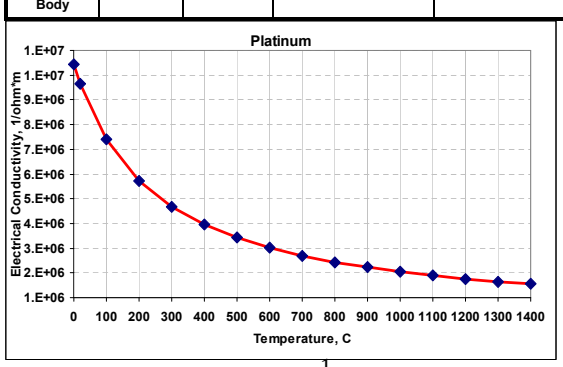
$$\rho C_p \frac{\partial T}{\partial t} - \nabla \bullet (k \nabla T) = Q$$

Q is heat source
(power generated by induction heating)

$$Q = \begin{cases} 0 & \text{for ceramic body} \\ \left|\vec{J}_{ind}\right|^2 / (2\sigma_{Pt}(T)) & \text{for platinum sample} \\ \left|\vec{J}_{tot}\right|^2 / (2\sigma_{Cu}(T)) & \text{for copper coils} \end{cases}$$

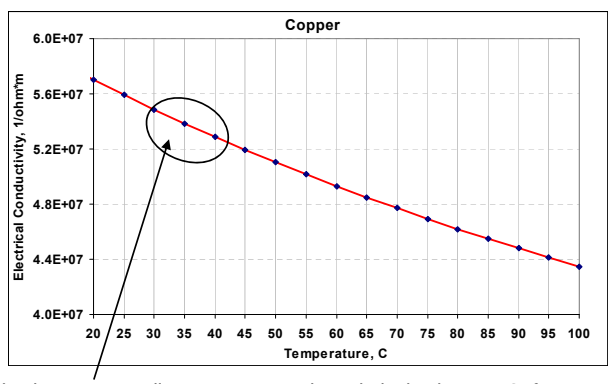
Materials Properties

	Cp (J/kgK)	Density (kg/m3)	Electrical conductivity (1/m*ohm)	Thermal Conductivity (W/m·K)
Copper Coil	385	8960	Temp dependent	400
Platinum	133	21450	Temp dependent	76.6
Cooling Water	4187	988	1	--
Ceramic Body	740	1762	1	0.5



$$\sigma_{Pt}(ohm^{-1}m^{-1}) = \frac{1}{1.04\times10^{-7}(1+0.0038(T(^oC)-20))}$$

--From website:
http://www.platinummetalsreview.com/jmpgm/

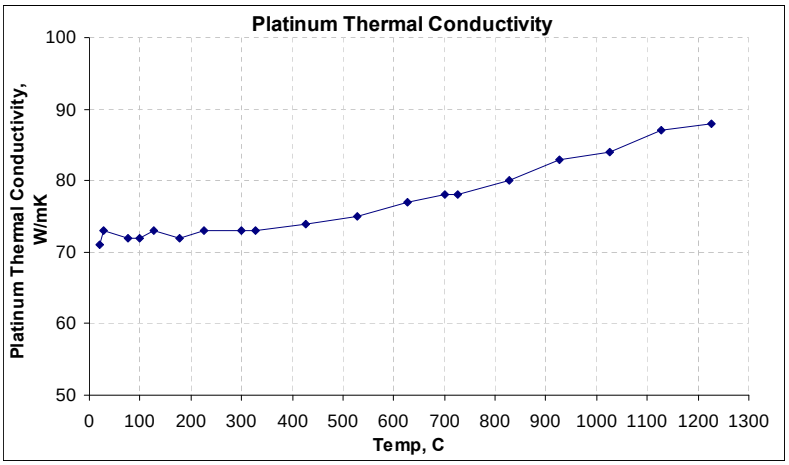


Induction copper coil temperature varies relatively about 5 ^oC for each sample temperature. And the total variation range is 30~45 ^oC. Temperature dependent copper electrical conductivity is unnecessary. A specific value is enough in accuracy for each sample temperature modeling.

$$\sigma_{copper}(ohm^{-1}m^{-1}) = \frac{1}{1.75\times10^{-8}(1+0.0039(T(^oC)-20))}$$

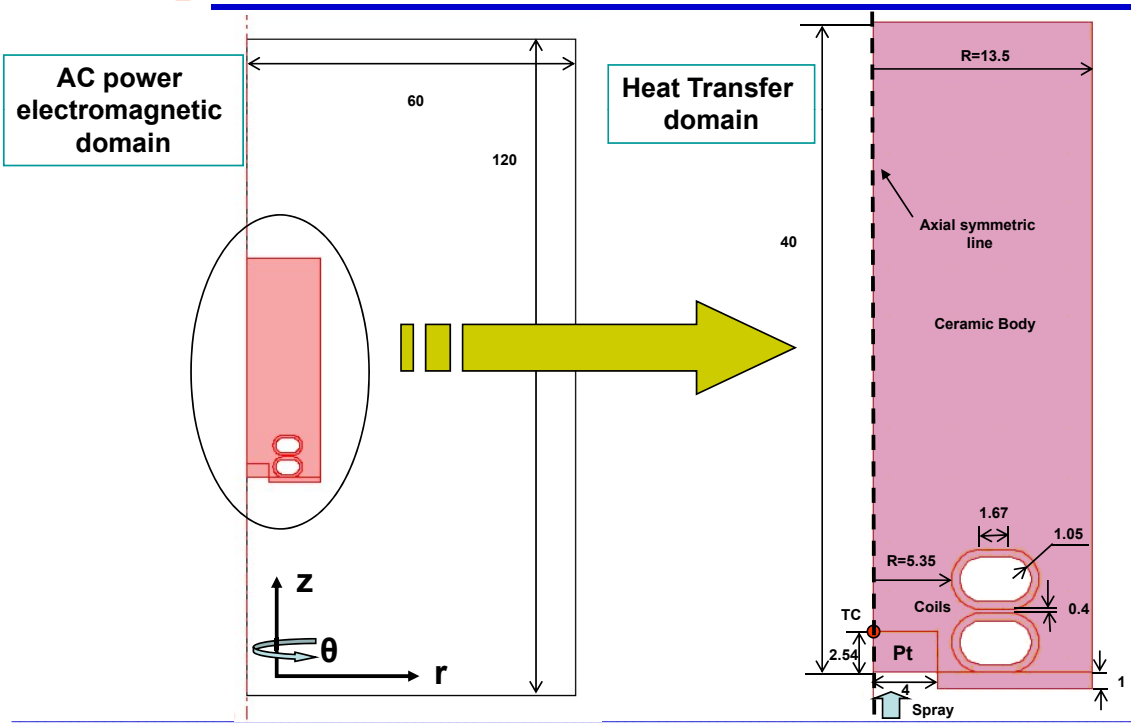
-- From P21, COMSOL MUTIPHYSICS3.5, AC/DC MODULE Model Library

Platinum Thermal Conductivity

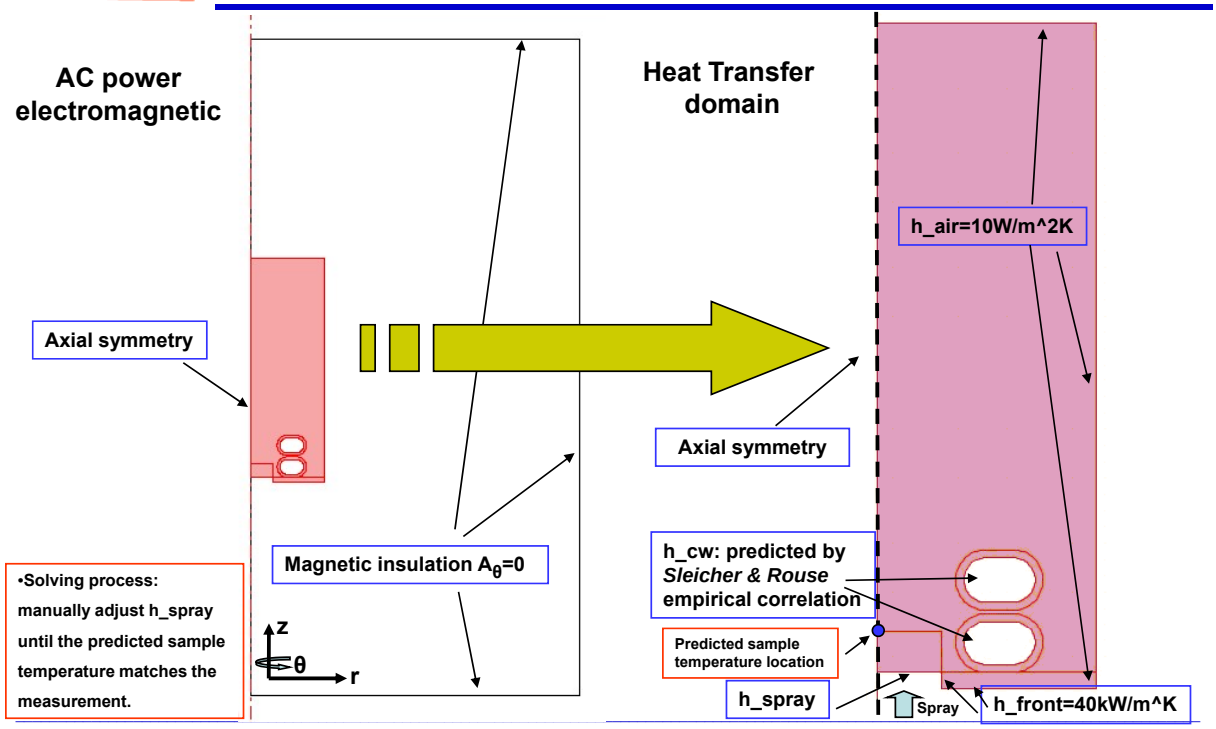


At each sample temperature, the variation of platinum thermal conductivity is relatively very small (less than 4%). Therefore, a specific platinum thermal conductivity value can be used for each sample temperature modeling .

Modeling Domains and Geometry Dimensions (mm)



Boundary Conditions

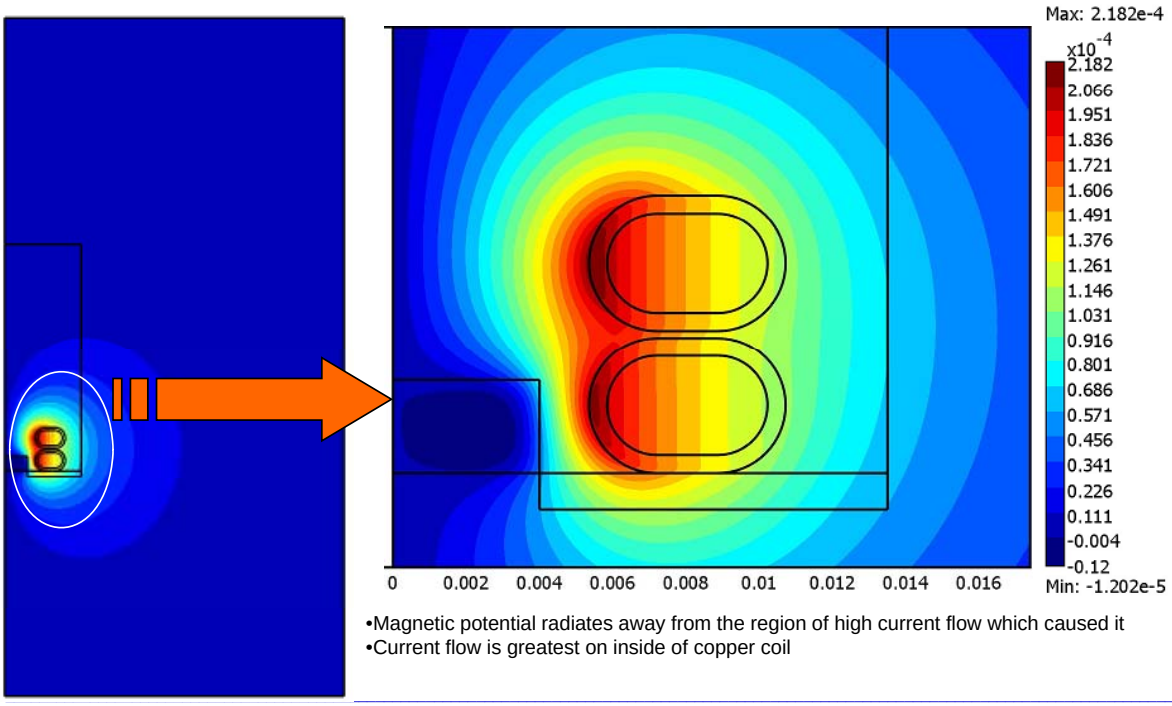


Example Case (Ts=700 ^oC)

- Transient solution to the case with sample temperature Ts= 700 ^oC
- Initial condition: steady-state solution to the previous case
  - Ts =600
  - Total current=486.3 A
- Boundary conditions: refer to slide 16, h_spray=8600 W/m^2K
- Constant total current = 484.6 A (average value of last 30s for Ts=700 ^oC)
- Temp-dependent properties used (slides 13 and 14)
- 2-D axisymmetric induction heating
- Nozzle operating conditions:
  - Water flow rate =4.6lpm
  - Air flow rate = 104lpm
  - Position: X=0mm, Y= 0mm (centered), Z=0mm

Magnetic Potential $A_0(r,z)$ Distribution (Wb/m)

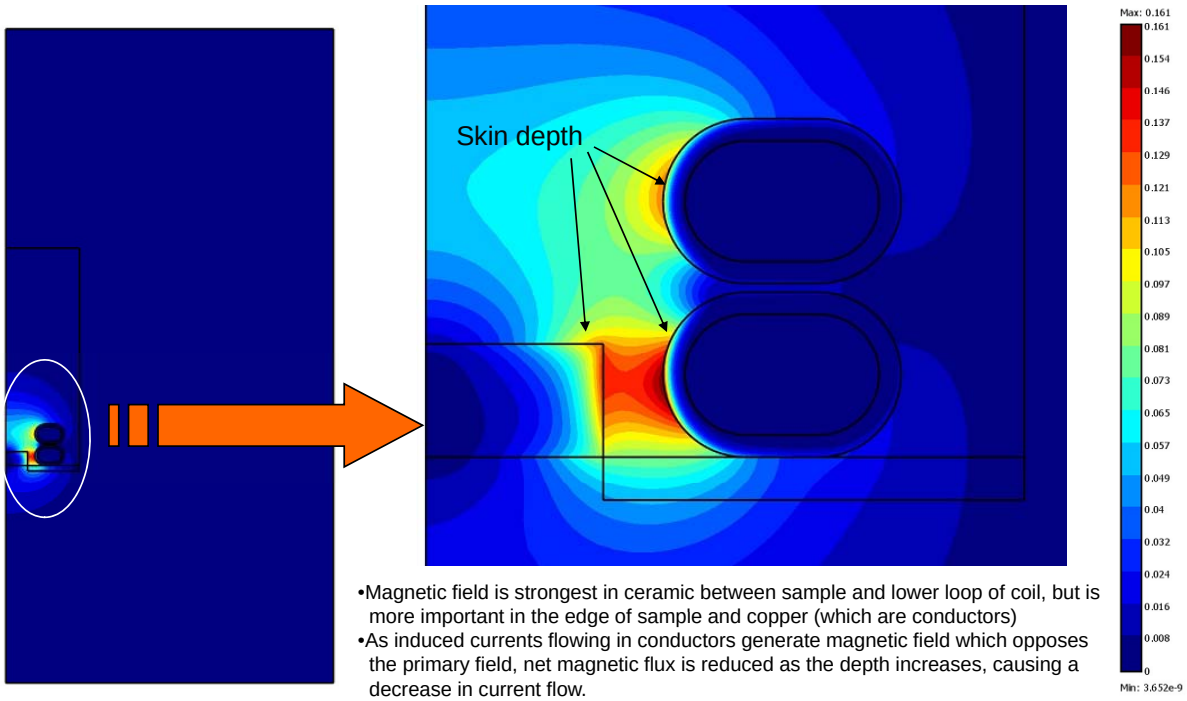
(Case Ts=700°C)



- Magnetic potential radiates away from the region of high current flow which caused it
- Current flow is greatest on inside of copper coil

Norm of Magnetic Flux Density H (Tesla)

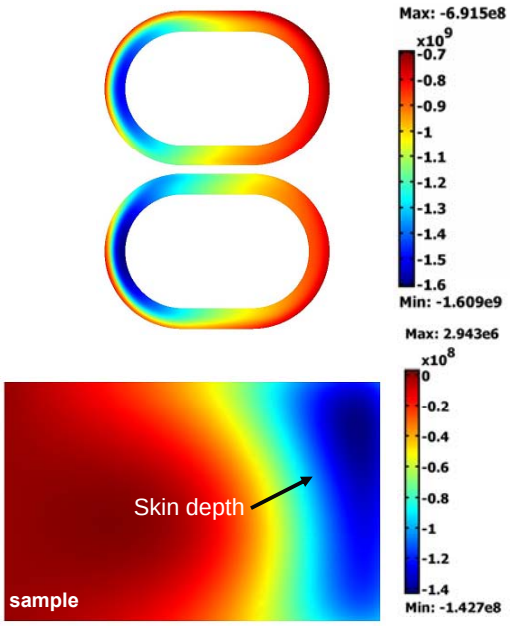
(Case Ts=700°C)



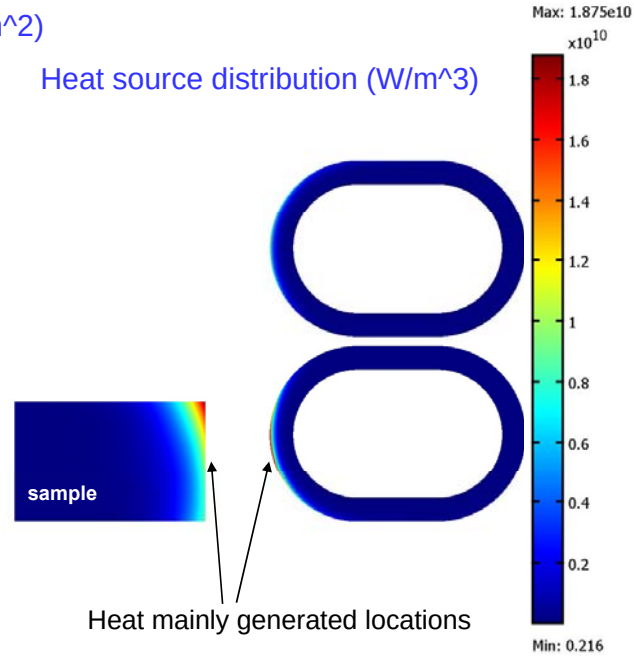
- Magnetic field is strongest in ceramic between sample and lower loop of coil, but is more important in the edge of sample and copper (which are conductors)
- As induced currents flowing in conductors generate magnetic field which opposes the primary field, net magnetic flux is reduced as the depth increases, causing a decrease in current flow.

Induced Current Density Distribution and Heat Source (Case Ts=700°C)

Induced current density distribution (A/m^2)



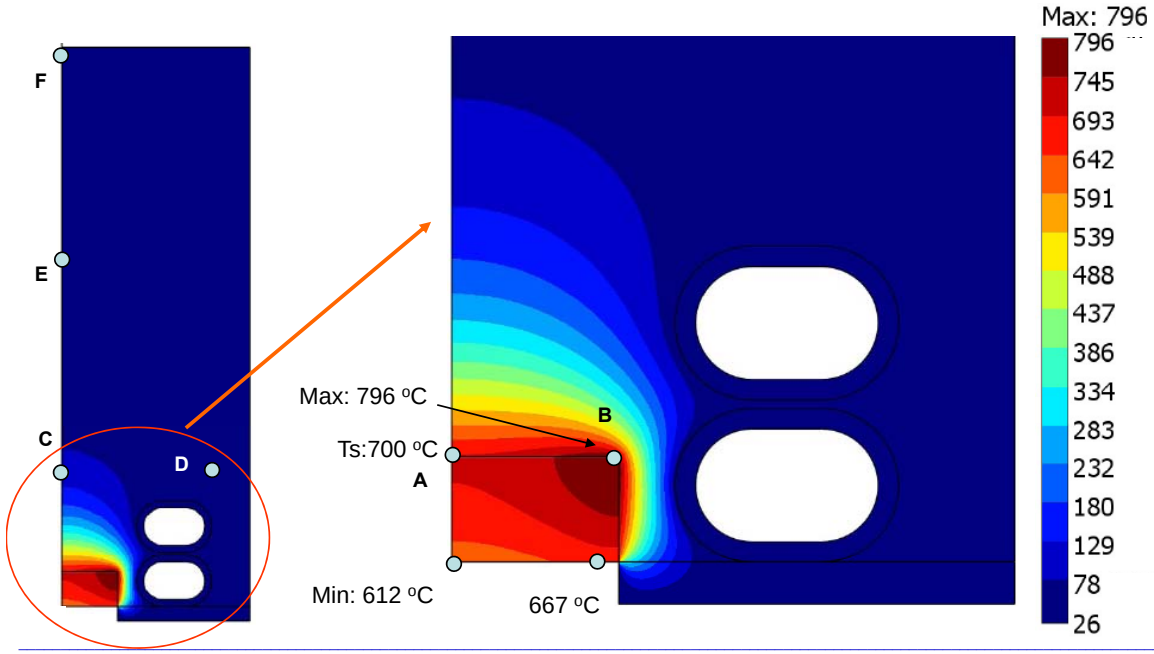
Heat source distribution (W/m^3)



Temperature Distribution

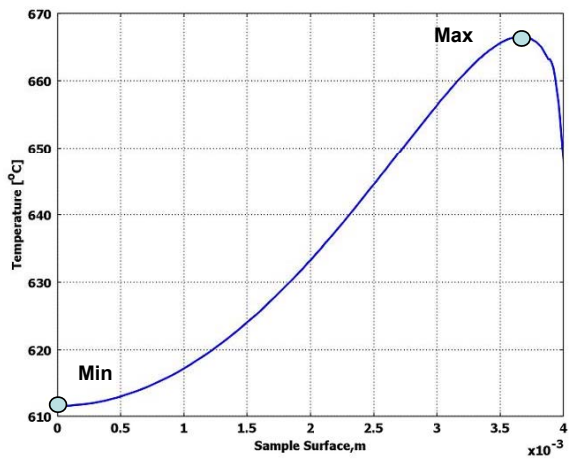
(Case Ts=700°C)

Temperature contour at 480s after initial state of steady-solution to Ts=600 °C case



Sample Front Surface Temperature Distribution

(Case Ts=700ºC)

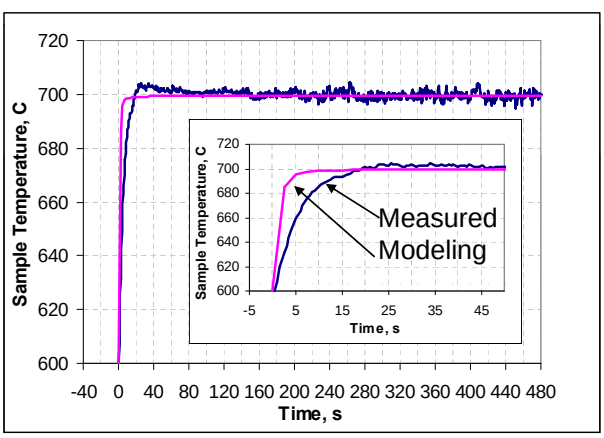


•The temperature along the sample surface is not uniformly distributed.
•The variation is around 55 ºC. The middle temperature value between minimum and maximum temperatures can be used as surface temperature with the associated deviation.

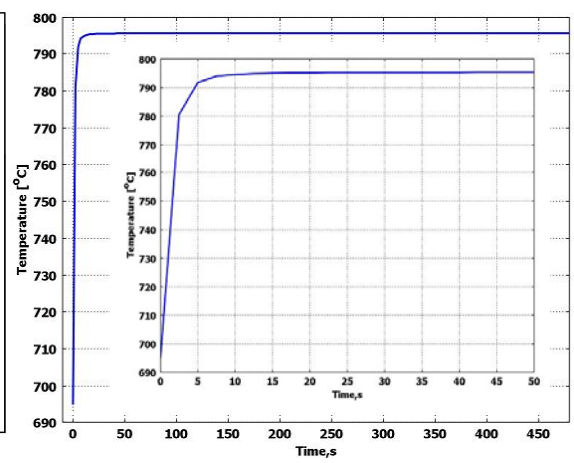
Transient Behavior of Temperature: Point A, B

(Case Ts=700ºC)

Point A located at back center



Point B located at back corner



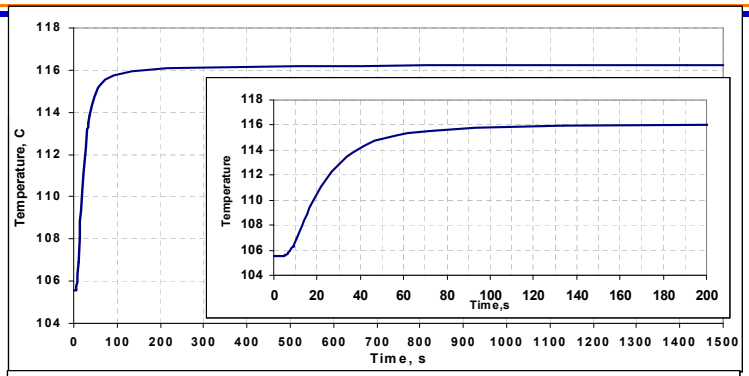
•15 seconds (model) or 25s (measured) for points A and B to reach steady-state

Transient Behavior of Temperature: Point C, D

(Case Ts=700°C)

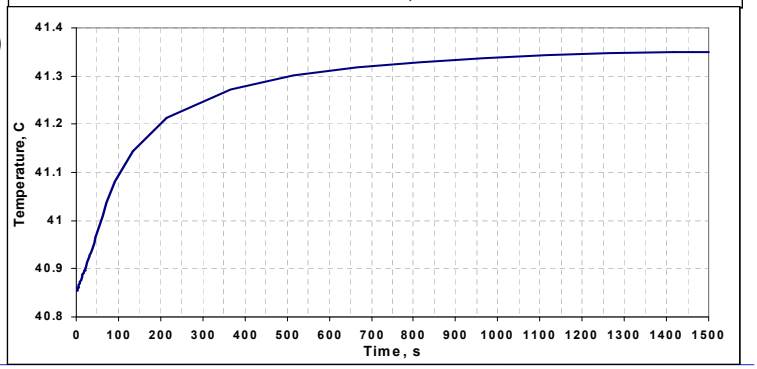
Point C (0,0.009)

140 s for point C to reach steady-state.



Point D (0.012,0.009)

1400 s for point D to reach steady-state.

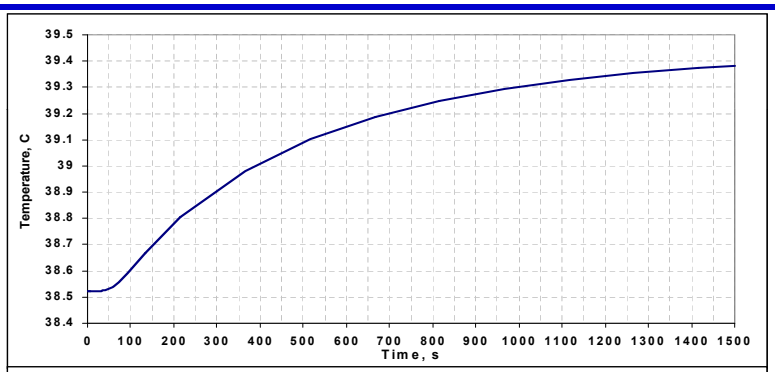


Transient Behavior of Temperature Point E, F

(Case Ts=700°C)

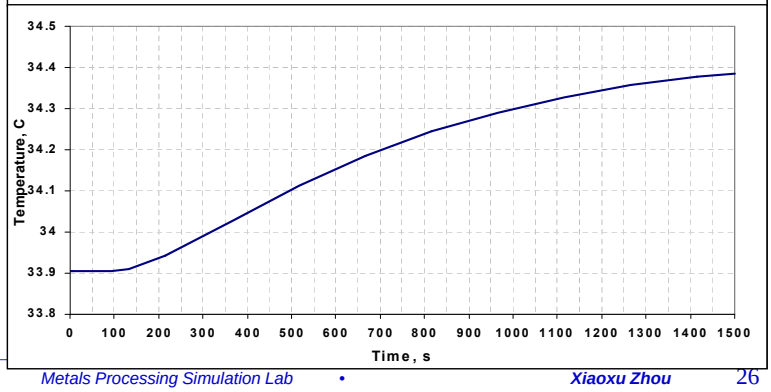
Point E (0,0.025)

More than 1500 s for point E to reach steady-state.



Point F (0,0.039)

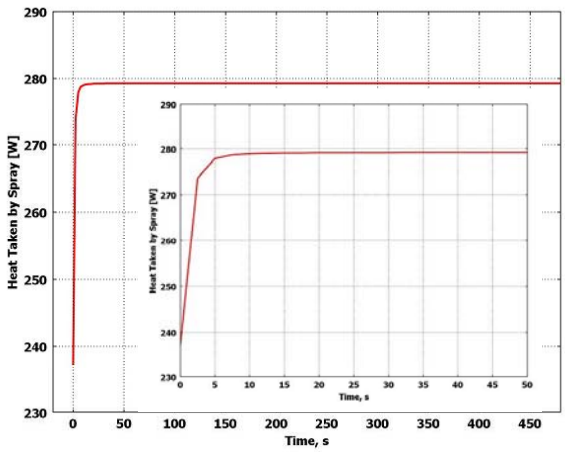
More than 1500 s for point F to reach steady-state.



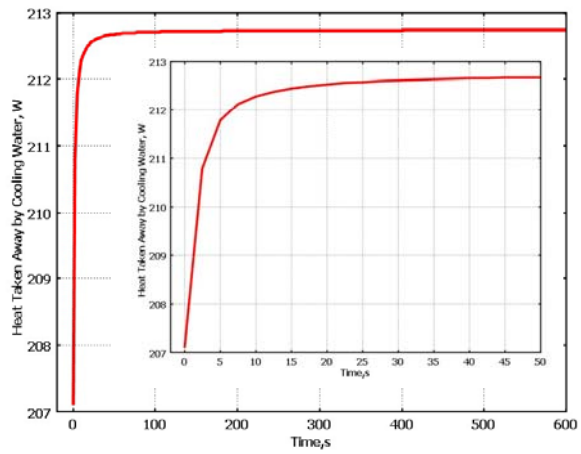
Transient Behavior of Heat Flux

(Case Ts=700ºC)

Heat going to the spray



Heat going to the cooling water



•7 seconds for the heat going to the spray to reach steady-state.
•25 seconds for the heat going to the cooling water to reach steady-state.

Methodology to Determine Heat Transfer Coefficients from Measurement and Model

- Transient heat conduction model results show it takes about 25 s for heat transfer in both sample and copper coil to reach steady state.
- Measured total current and sample temperature turn to steady state by 8 min for each sample temperature in experiments.
- Combining two reasons above. Steady-state heat conduction equation can be used with temperature-dependent material properties to extract heat transfer coefficients. (A lot of computation time can be saved, since it has 23 sample temperatures per heating-cooling cycle)

Steady-state 2-D Induction Heating Model (COMSOL) – Example Input Data

- Nozzle: Y=0mm
- Water flow rate=3.5lpm
- Air flow rate=95lpm
- Jun 26, 09

Ts: sample temperature
I_tot/loop: total current per loop

Boundary Conditions

Ts	I_tot/loop	h_spray	h_cw	h_front	h_air	T_cw	Tcoil
C	A	kW/m^2K	kW/m^2K	kW/m^2K	W/m^2K	K	C
100	292.5	27.50	35.90	40	10	29.4	36
200	443.7	31.00	37.50	40	10	34.1	39
300	472.3	21.80	38.10	40	10	37.1	39
400	487.1	16.20	37.80	40	10	36.3	40
500	489.4	12.70	38.30	40	10	37.6	40
600	481.0	9.93	38.40	40	10	37.8	40
700	452.0	7.20	38.00	40	10	36.8	39
800	454.4	6.20	38.40	40	10	37.9	40
900	436.1	4.85	37.60	40	10	35.7	40
1000	447.1	4.58	38.20	40	10	37.3	40
1100	450.8	4.14	37.90	40	10	36.5	40
1200	466.9	4.10	38.00	40	10	36.7	40
1100	463.2	4.50	38.50	40	10	38.2	42
1000	445.8	4.55	37.30	40	10	37.6	42
900	429.7	4.62	37.70	40	10	38.6	42
800	452.4	6.20	33.40	40	10	37.9	42
700	441.0	6.75	33.20	40	10	37.4	42
600	423.2	7.20	33.40	40	10	38.0	42
500	384.3	6.95	32.80	40	10	36.0	42
400	354.6	7.15	32.50	40	10	35.3	40
300	342.8	9.20	32.30	40	10	34.6	37
200	356.6	17.50	32.40	40	10	34.8	37
100	253.5	19.00	31.70	40	10	32.7	37

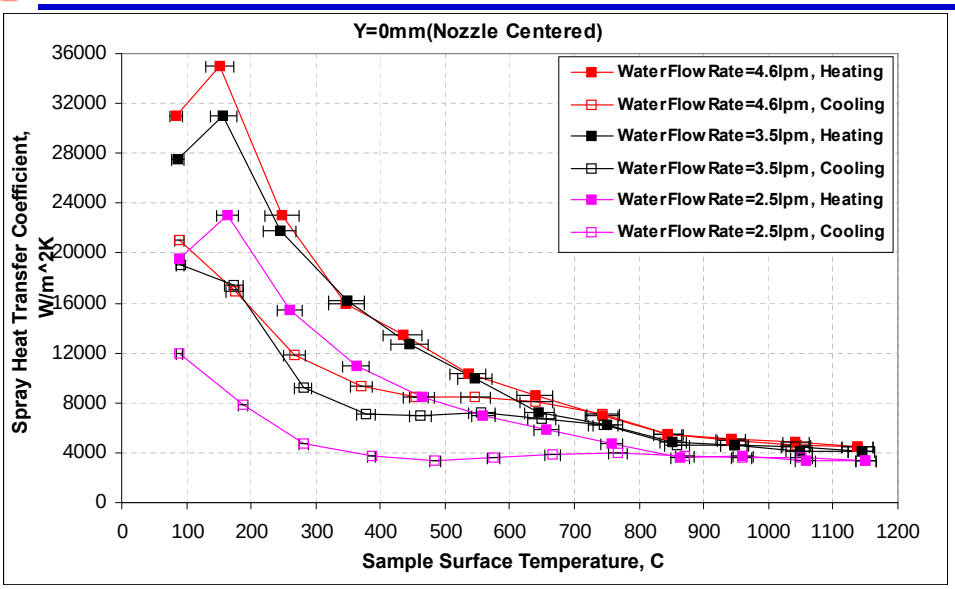
Steady-state 2-D Induction Heating Model (COMSOL) – Example Output Data

- Nozzle: Y=0mm
- Water flow rate=3.5lpm
- Air flow rate=95lpm
- Jun 26, 09

P_loss: heat loss to air and through front window
I_surf_min/max: minimum and maximum temperatures at sample surface

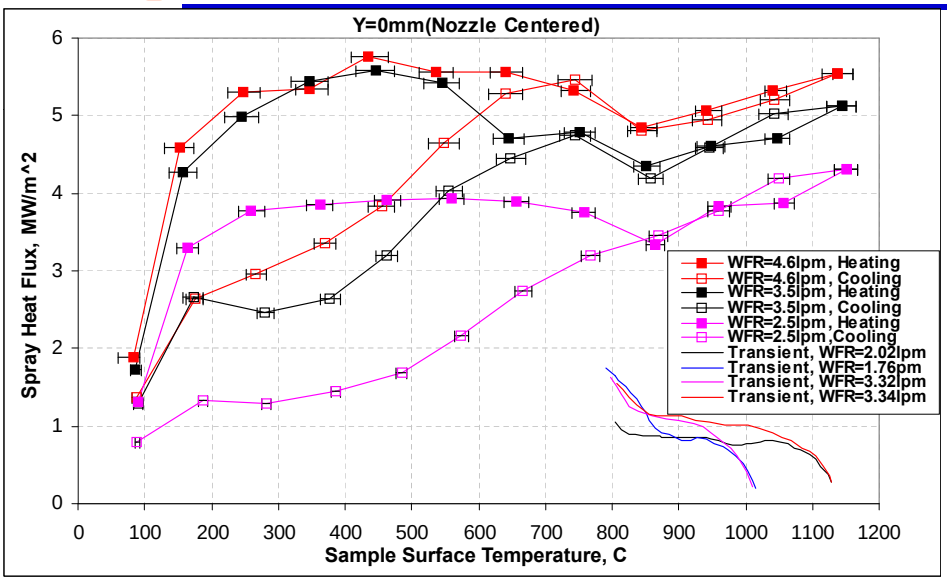
Ts	T_surf min	T_surf_max	Ptot	Pspray	P_loss	Spray heat fllux	Pspray/Ptot	P_loss/Ptot	Ptot(M)	Ptot/Ptot(M)
C	C	C	W	W	W	MW/m^2			W	
100	78	95	161	87	2	1.73	54%	1%	407.5	40%
200	137	177	385	215	5	4.28	56%	1%	1056.0	36%
300	220	270	448	251	7	5.00	56%	2%	1242.3	36%
400	320	375	488	273	9	5.43	56%	2%	1234.3	40%
500	417	474	502	280	11	5.57	56%	2%	1226.2	41%
600	519	572	493	272	12	5.41	55%	2%	1207.3	41%
700	623	668	441	237	14	4.72	54%	3%	1137.5	39%
800	728	774	453	241	16	4.80	53%	4%	1207.5	38%
900	832	872	423	219	18	4.36	52%	4%	1242.8	34%
1000	927	968	450	232	20	4.62	52%	4%	1298.4	35%
1100	1028	1067	462	237	22	4.72	51%	5%	1147.7	40%
1200	1122	1165	501	258	23	5.14	51%	5%	1230.8	41%
1100	1020	1064	489	253	22	5.04	52%	4%	1248.4	39%
1000	926	967	448	231	20	4.60	52%	4%	1086.6	41%
900	840	877	411	211	18	4.20	51%	4%	985.9	42%
800	722	767	449	239	16	4.76	53%	4%	920.0	49%
700	627	670	421	224	15	4.46	53%	4%	927.7	45%
600	536	576	381	203	13	4.04	53%	3%	803.6	47%
500	446	478	308	161	11	3.20	52%	4%	680.2	45%
400	364	392	258	133	9	2.65	52%	3%	606.5	43%
300	268	293	235	124	8	2.47	53%	3%	575.9	41%
200	158	187	248	134	5	2.67	54%	2%	577.5	43%
100	84	97	121	65	3	1.29	54%	2%	321.7	38%

Nozzle Centered--Spray Heat Transfer Coefficients



- Increasing water flow rate increases heat transfer coefficient.
- During heating, HTC peaks around 150~200 C, then decreases as sample surface increases
- During cooling, HTC keeps increasing gradually.
- Hysteresis is shown in heat transfer coefficient curves.

Nozzle Centered--Spray Heat Flux



--Transient results by Sami Vapalahti, etc, Spray Heat Transfer Research at CINVESTAC, P26, CCC report, 2007

- Increasing water flow rate increases spray heat flux.
- Spray heat flux also shows hysteresis
- Leidenfrost temperature is around 850 ^{o}C
- Steady measurement gives higher heat flux than transient measurement

Mechanism of Hysteresis

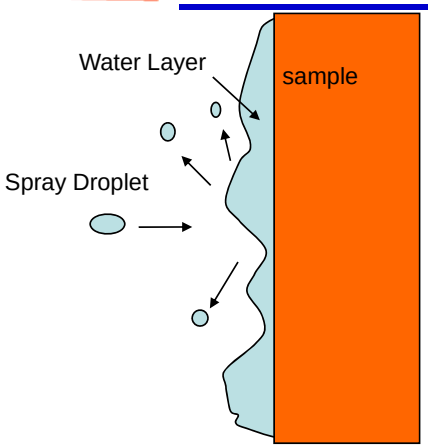


Fig. 1

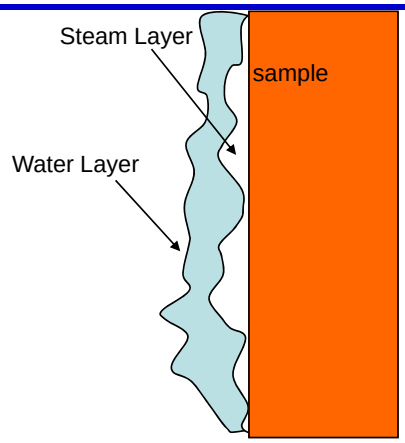


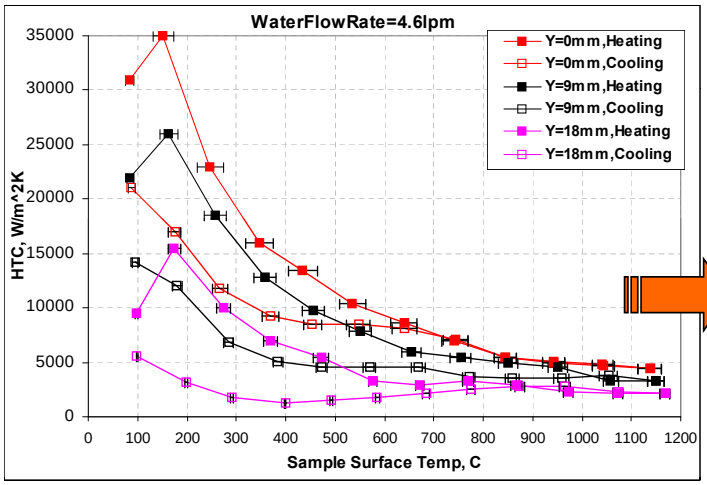
Fig. 2

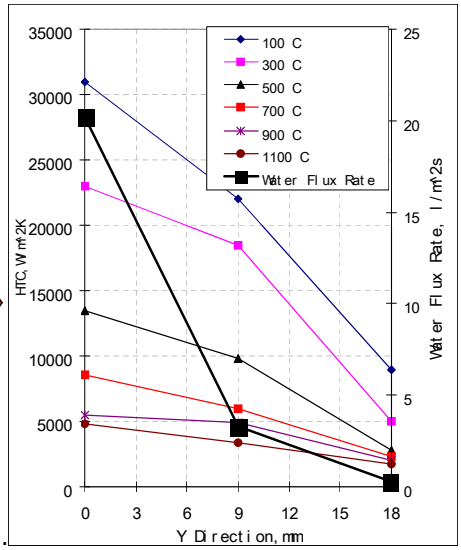
- **Heating experiments:**
  - **spray droplet impinges on water layer, touches surface, boils, and takes heat away. (Fig. 1)**
  - **High heat removal keeps surface cold.**

- **Cooling experiments:**
  - **At high sample surface temperature (>~860oC), a stable steam layer forms on the sample surface. (Fig. 2)**
  - **This steam layer acts as a barrier to heat transfer and decreases heat removal.**
  - **Low rate of heat removal sustains the air gap to low temperatures before droplets finally can penetrate through**

- **Result: difference in heat transfer at intermediate temperatures according to history (heating or cooling)**

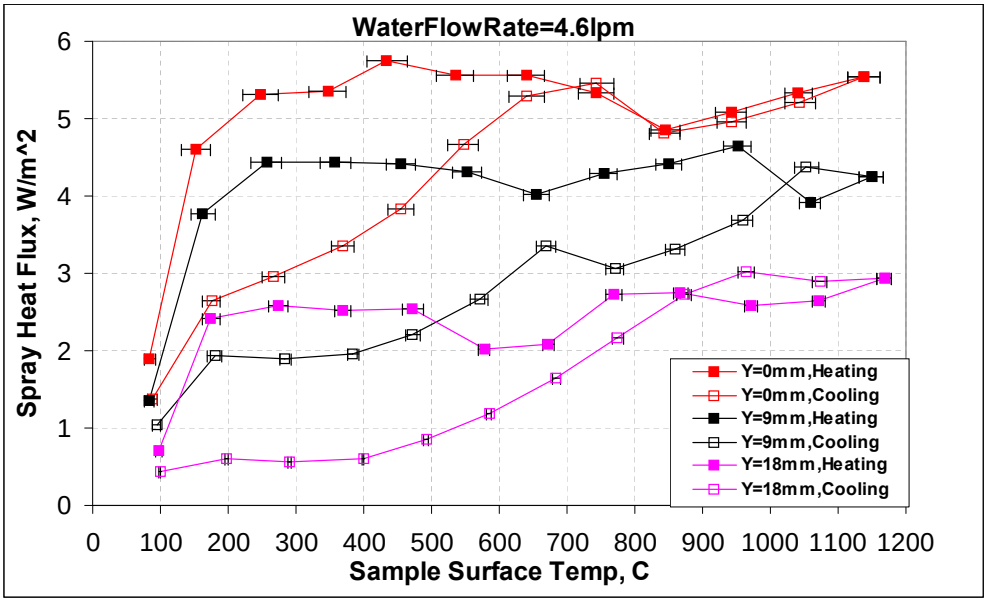
Nozzle Water Flow Rate=4.6lpm --Spray Heat Transfer Coefficients





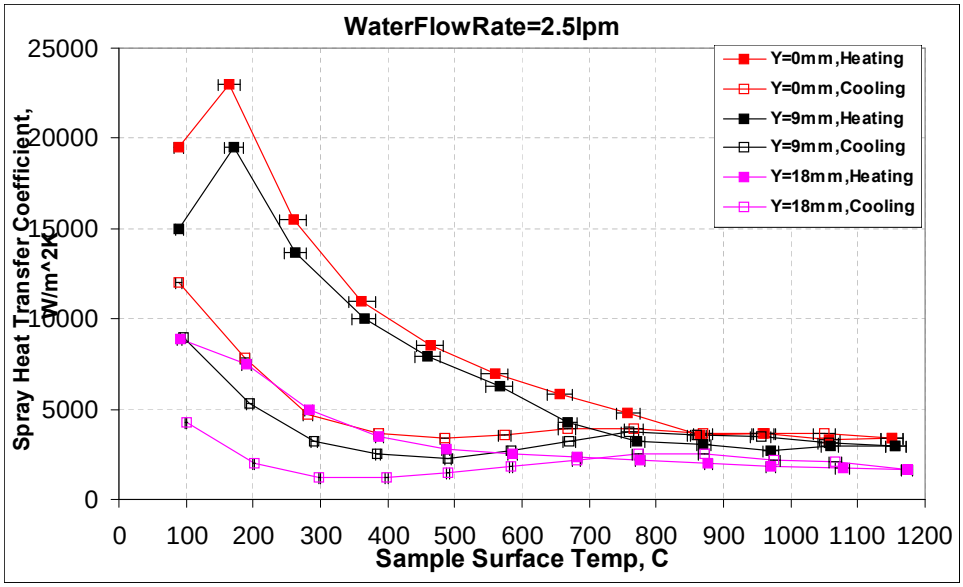
- Hysteresis exists for different location from spray centerline.
- Moving further away from spray centerline decreases HTC.
- Difficult to correlate water flow rate footprint measurements with HTC.
- More details of spray dynamics needed (droplet distribution, size, velocity, etc, --collaboration work at CINVESTAV, Mexico)

Nozzle Water Flow Rate=4.6lpm --Spray Heat Flux



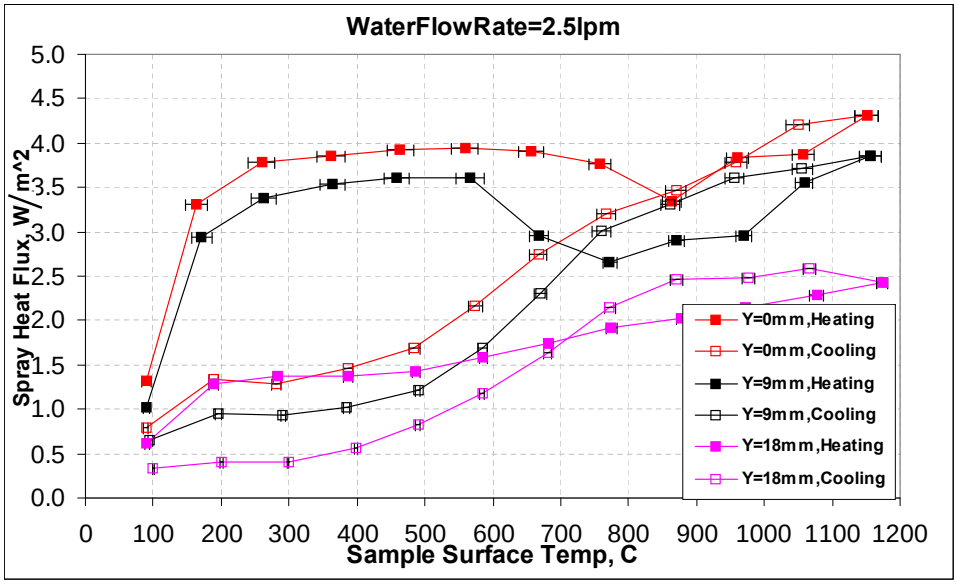
•Moving further away from spray centerline decreases spray heat flux
•Hysteresis is shown in heat flux curves

Nozzle Water Flow Rate=2.5lpm --Spray Heat Transfer Coefficients



•Moving further away from spray centerline decreases HTC.
•Hysteresis is shown in spray heat transfer coefficient curves

Nozzle Water Flow Rate=2.5lpm --Spray Heat Flux



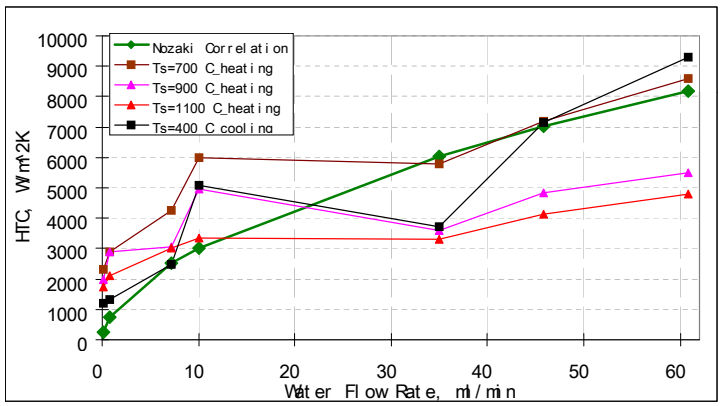
- Moving further away from spray centerline decreases spray heat flux.
- Hysteresis is shown in heat flux curves

Comparison between Nozaki Correlation and Current Results

Nozaki empirical correlation prediction:

$$h_{spray}(W/m^2K)$$
$$= ACQ_w^n(1-bT_{spray})$$
$$= A*1570*Q_w^{0.55}(l/m^2s)(1-0.0075T_{spray}(^oC))$$

- T. Nozaki, ISIJ, 1978, vol.18, pp330-38



Nozaki correlation matches current results at higher flow rate (35~62ml/min) for Ts=700 C_heating.
It is difficult to match at lower flow rate (<5ml/min).

- **A=1 for the figure above**
- **A=0.25 for the steel caster**
- **The difference is likely due to significant surface oxide scale formation, much surface roughness, water quality, etc, in steel caster.**

Conclusions for Experiments and Modeling

- Both AC power electromagnetics and steady-state heat conduction are used to extract spray heat transfer coefficients and heat fluxes.
- Apparatus was modeled for 23 sample temperatures in each heating-cooling cycle.
- Spray heat transfer coefficient and heat flux curves for 3 different nozzle operating condition and 3 different positions from the spray centerline are shown in the report. Heat transfer coefficient varies from 2000W/m^2K to 35000W/m^2K. Heat flux varies from 0.5MW/m^2 to 6MW/m^2.
- Total power loss through cooling to ambient air and front window is relatively low (less than 8% of total heat generated).
- The fraction of power to the spray is around 45~55%.

Conclusions for Practical Results

- Both spray heat transfer coefficient and spray heat flux show hysteresis which likely is related to formation of vapor layer on the sample surface.
- The Leidenfrost temperature (minimum heat flux) is around 840~860 ^{o}C for platinum.
- Heat transfer coefficient around surface temperature 100~600 ^{o}C for heating is much larger (20~50%) than that during cooling, for all operating conditions studied.
- Increasing water flow rate increases spray heat transfer coefficients and spray heat fluxes by 10~60%, for the same nozzle position .
- Moving further away (9mm, 18mm) from the spray centerline decreases spray heat transfer coefficients and fluxes by 10~70%, for the same nozzle operating condition. The decrease is more gradual than the drop in water flow would suggest.
- Heat transfer coefficient decreases as the sample surface temperature goes up from 200 ^{o}C to 1200 ^{o}C, while increasing from 1200 to 100 ^{o}C during cooling.

Conclusions for Comparison with Previous

- Spray heat flux from new steady measurement apparatus developed in this work is much higher than from transient measurement at high sample surface temperature (800 ^{o}C~1150 ^{o}C).

- Spray heat flux from steady measurement can match Nozaki correlation well by using A=1 instead of A=0.25 which is used in steel caster. This is possibly due to significant surface oxide scale formation and much surface roughness in steel caster.

Future Work

- Lab experiments using steel with oxidization layer scale formation which happens in real casting.

- Pyrometer temperature measurement in plant to validate with HTC from lab experiments using steel.

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  (ABB, Arcelor-Mittal, ANSYS-Fluent, Baosteel, Corus, Delavan/Goodrich, LWB Refractories, Nucor, Nippon Steel, Postech, Steel Dynamics.)

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- Other students in Mexico