CCC ANNUAL REPORT

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Heat Transfer During Spray Cooling Using Steady Experiments

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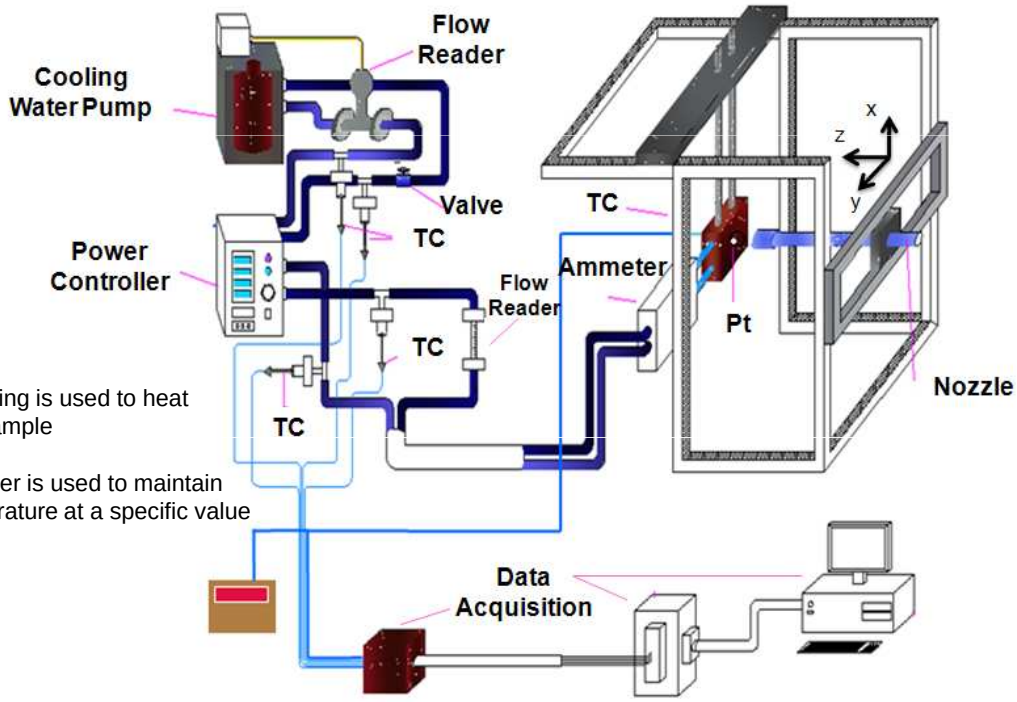
Project Objectives

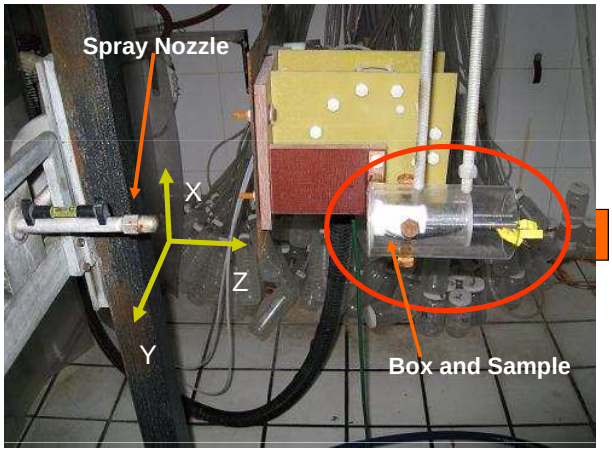
- Quantify spray water cooling heat transfer rate
  - by interpretating steady experiments with computational modeling
- Improve secondary-cooling zone temperature-prediction in continuous-casting of steel
  - CON1D, CONONLINE
- Better control of steel quality
  - Uniformly-distributed temperature in slab

Schematic of Experiment Setup



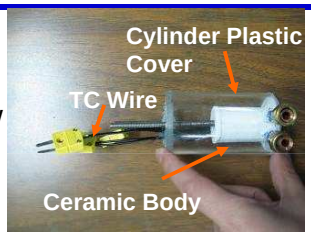
- Induction heating is used to heat up platinum sample
- Power controller is used to maintain sample temperature at a specific value

Setup Details

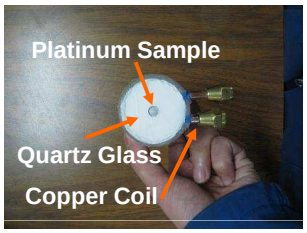


Top View

Side View



Top View



Induction Copper Coil

- Plastic cover and quartz glass are used to keep spray water from ceramic body, only exposing front surface of platinum sample to the water

Steady Spray Cooling Experiments

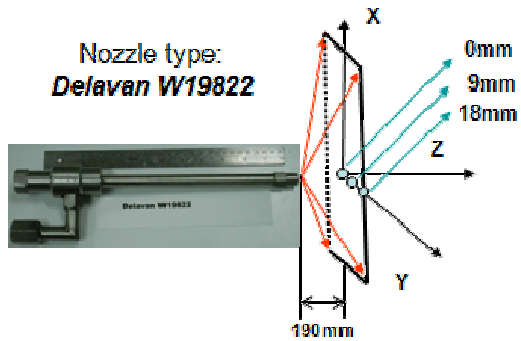
Experiment procedure:

- Pt sample is induction-heated with sample TC temperature (***Ts***) controlled in stages of 100, 200, …, 1100, 1200, 1100, …, 200, 100 °C. Each *Ts* stage takes 8 min.

  Heating — Cooling

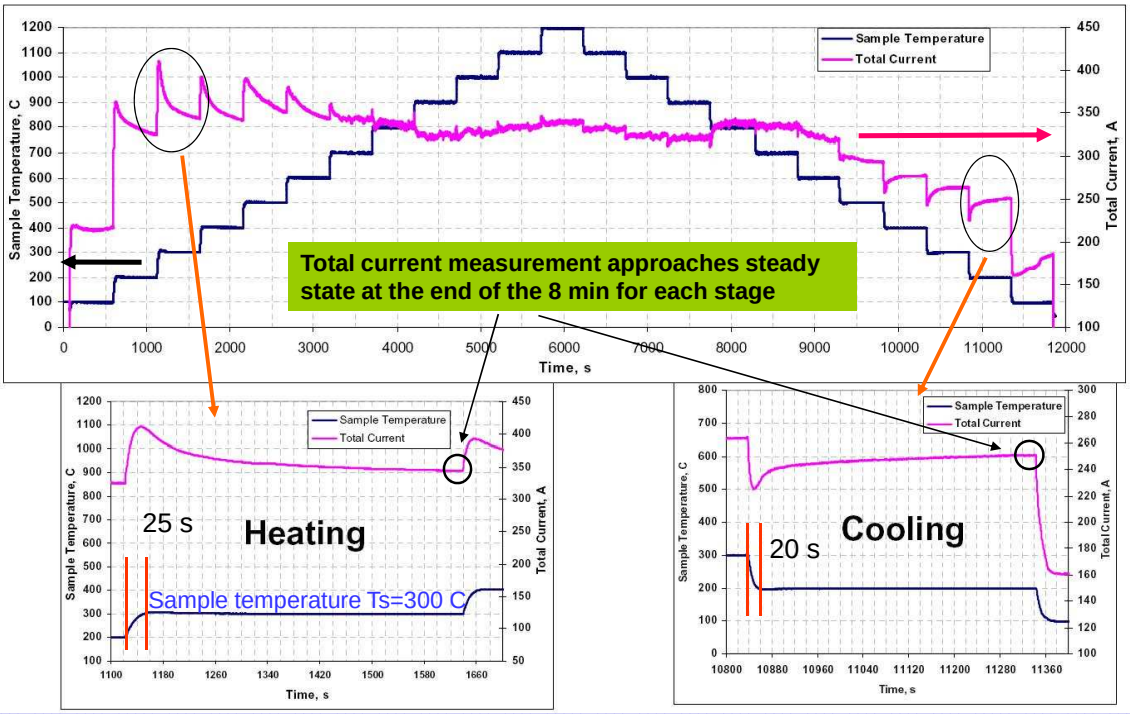
- Two types of experiments:
  - wet (spray is on)
  - dry (spray is off)

- Sample locations during spraying:



Typical Ts and I_{tot} Measurements from Wet Experiment

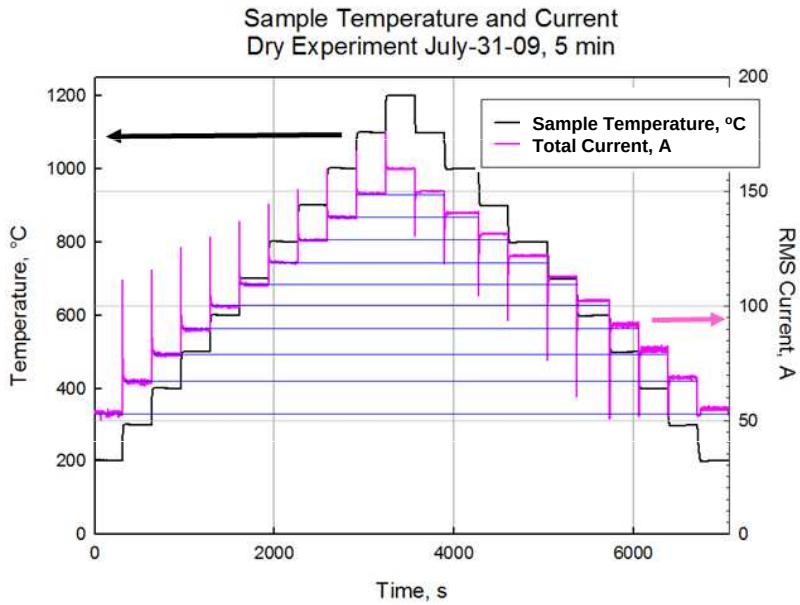
Water Flow Rate=4.6lpm, Air Flow Rate=104lpm,Nozzle Centered (June 26, 09)



Typical Ts and I_{tot} Measurements from

Dry Experiments

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



•Each sample temperature stage takes 5 min.
•Steady total current stays almost the same for heating and cooling, no hysteresis presented.

Induction Heating Modeling

Electromagnetics equation

Induced current density, J_{ind}

$$-\frac{1}{\mu}\nabla^2\mathbf{A} = -\underbrace{j\omega\sigma(T)\mathbf{A} + \mathbf{J}_{ext}}$$

Total current density, J_{tot}

A	Magnetic potential
ω	angular frequency
μ	permeability
ε	permittivity
σ	electrical conductivity
j	Complex unit square root of -1

Heat conduction equation

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

Q (Heat Source)	Material Type
0	Non-conductive (***air, ceramic, water***)
$\lvert\mathbf{J}_{tot}\rvert^2/(2\sigma(T))$	Conductive, with $\mathbf{J}_{ext}$ (***copper coil***)
$\lvert\mathbf{J}_{ind}\rvert^2/(2\sigma(T))$	Conductive, without $\mathbf{J}_{ext}$ (***platinum***)

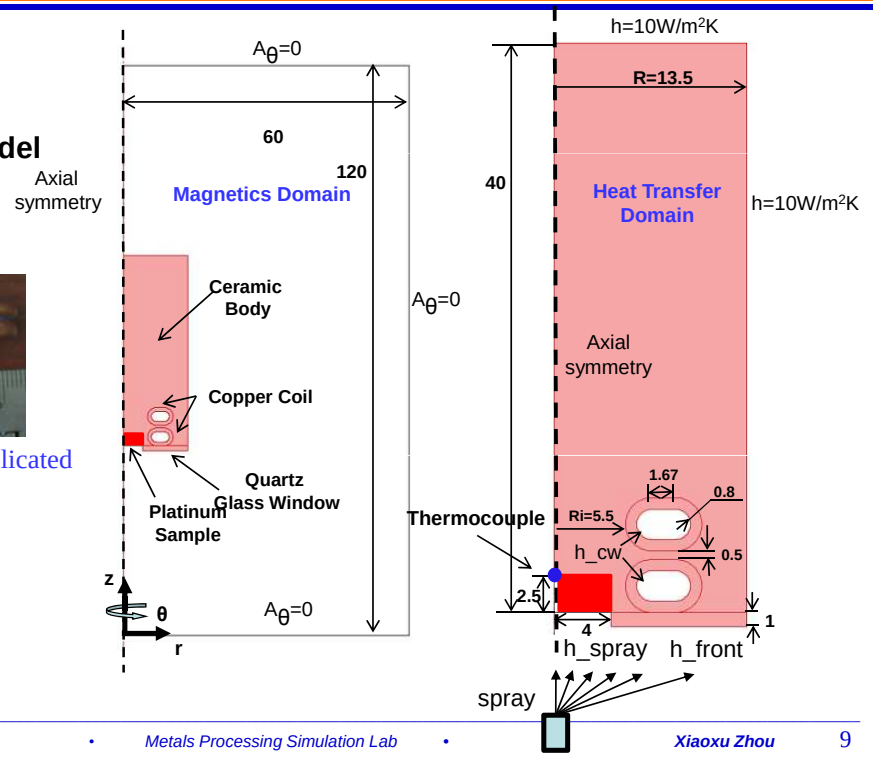
- Two equations are fully coupled via ***T*** and ***A***
- Commercial package **COMSOL** is chosen to do simulation

Modeling Domains and Boundary Conditions

Unit: mm

2D Axi-symmetric model

- Induction coil shape is complicated
- It consists of 1.5 loops
- Model needs calibration



Materials Properties

Table. 1 Electrical and Thermal Material Properties*

	Specific Heat (J/kg·K)	Density (kg/m³)	Electrical Conductivity (1/m·ohm)	Thermal Conductivity (W/m·K)
Copper	385	8960	$5.7\times10^{7}/(1+0.0039(T-20))$	400 (25 °C~150 °C)
Platinum	133	21450	$9.6\times10^{6}/(1+0.0038(T-20))$	$71.86+0.0015T+1.0118\times10^{-5}T^{2}$
Water	4187	988	0	---
Ceramic	740	1762	0	???

•Ceramic thermal conductivity is missing, which requires model calibration too.

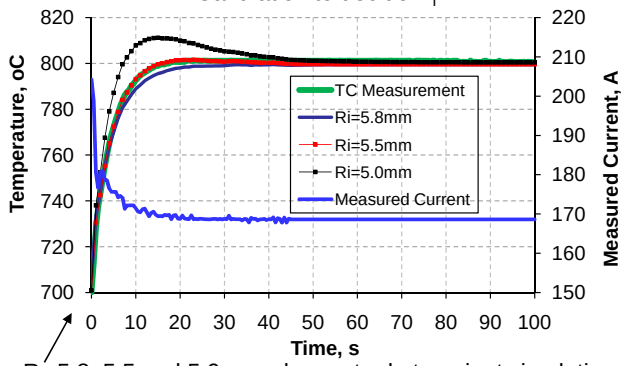
Table. 2 Temperature-dependent Platinum Emissivity*

Temperature, °C	100	500	1000	1500
Emissivity	0.05	0.1	0.15	0.19

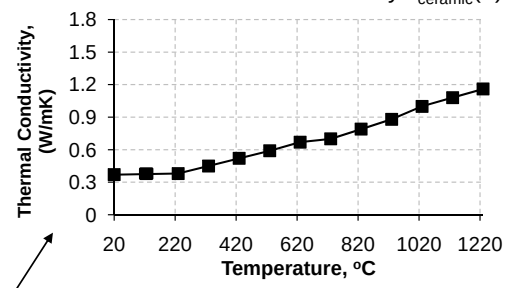
*http://www.platinummetalsreview.com

Model Calibration by Dry Experiment to Decide R_i and $k_{ceramic}(T)$

Calibration to decide R_i



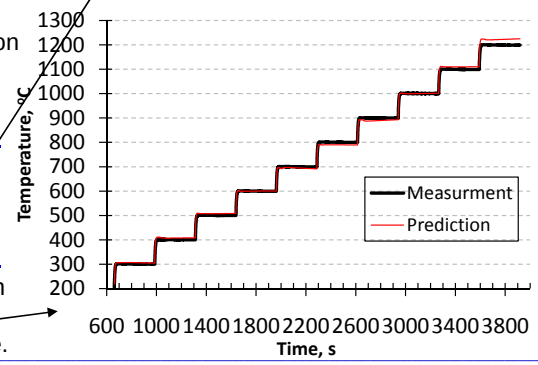
Calibration to obtain ceramic thermal conductivity $k_{ceramic}(T)$



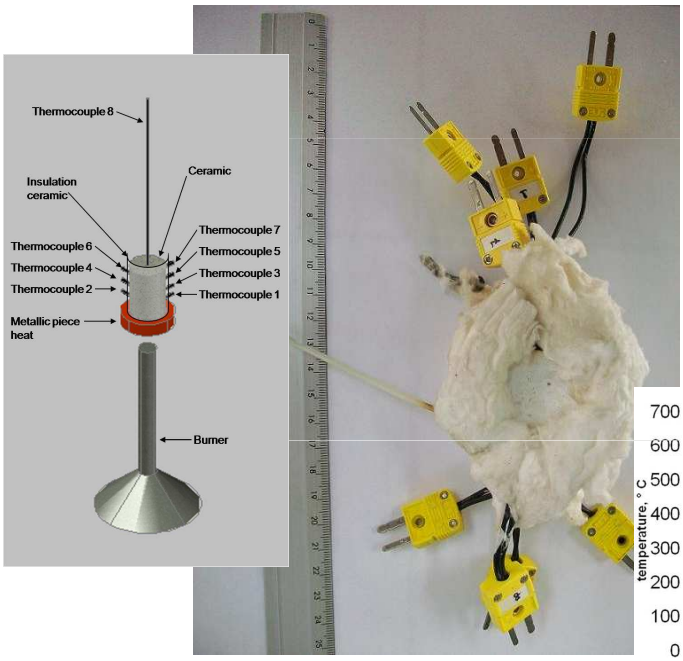
- R_i=5.8, 5.5 and 5.0 mm chosen to do transient simulation for dry experiment from 700 °C to 800 °C.
- R_i=5.5 mm gives the best match of temperature with transient measurement

❖ R_i=5.5mm used in calibrating model to get $k_{ceramic}$
❖ $k_{cermaic}(T)$ is obtained by matching each TC measurement from 100 °C to 1200 °C in steady state dry experiment simulation.

1. Comparison between TC measurement and prediction from transient dry experiment simulation.
2. good match; R_i=5.5mm and $k_{ceramic}(T)$ are good to use.

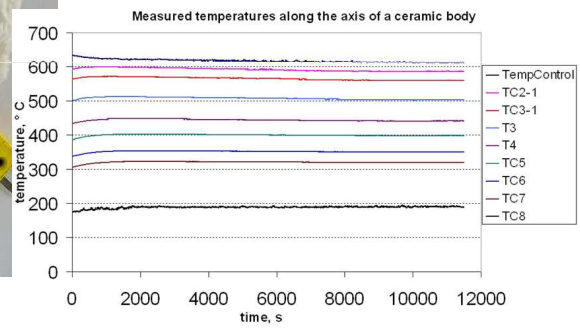


Side Experiment for Validating Calibrated Ceramic Thermal Conductivity

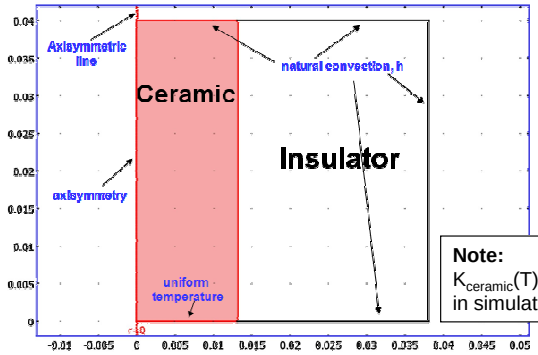


- Cylindrical ceramic body resting on a thin metallic sheet
- Sheet is heated up by a Bunsen burner
- Top surface is exposed to natural convection in the laboratory environment
- The lateral surface is isolated
- Steady temperature profile along the axis is measured by 9 TCs

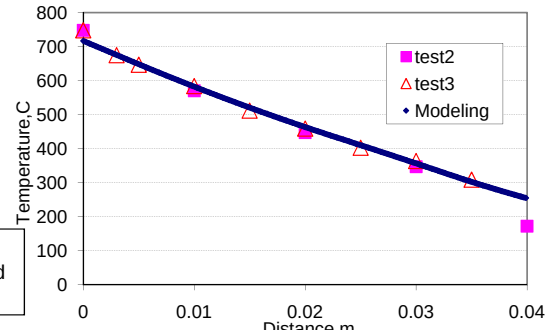
TC	Location, mm	TC	Location mm
1	3	5	20
2	5	6	25
3	10	7	30
4	15	8	40

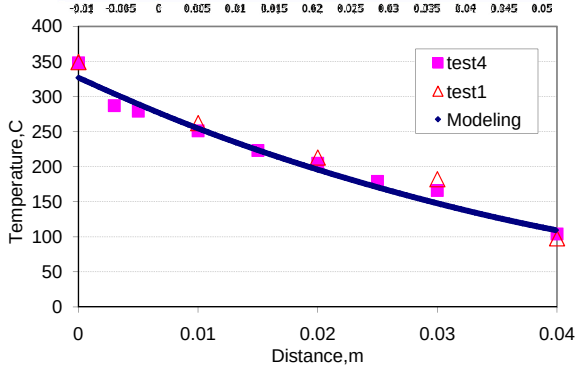


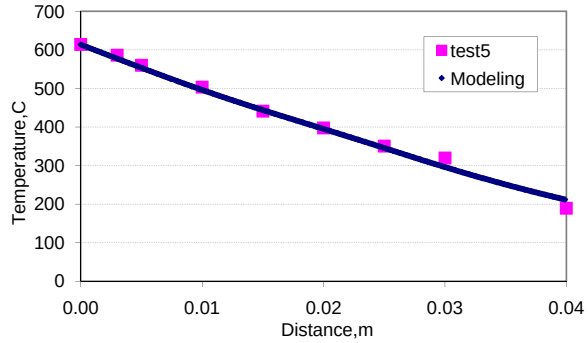
Side Experiment Modeling and Validation Results



Note:
$K_{ceramic}(T)$ used in simulations







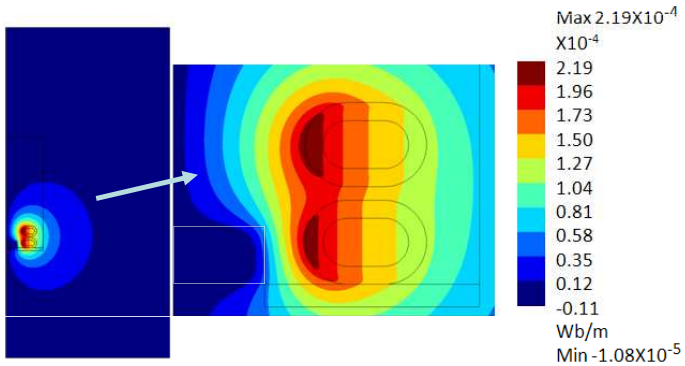
Example Case Modeling to Extract HTC

- Methodology:
  - steady-state simulation
  - adjust h_spray to match temperature prediction with TC measurement

- Conditions
  - Ts=700 ^{o}C
  - total current = 484.6 A
  - h_spray = 7100 W/m^{2}K
  - h_cw = 2.96e4 W/m^{2}K
  - h_front = 5500 W/m^{2}K
  - nozzle
    - water flow rate = 4.6lpm
    - air flow rate = 104lpm
    - position: X=0mm, Y= 0mm (centered), Z=0mm

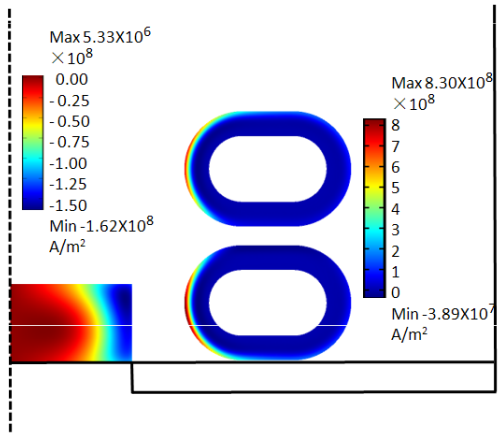
Magnetic Potential Distribution and Total Current Distribution

Magnetic potential distribution



- Magnetic potential radiates away from the region of high current flow which caused it
- Magnetic potential can only penetrate into the sample at a very small distance ~ 0.4mm (skin depth)

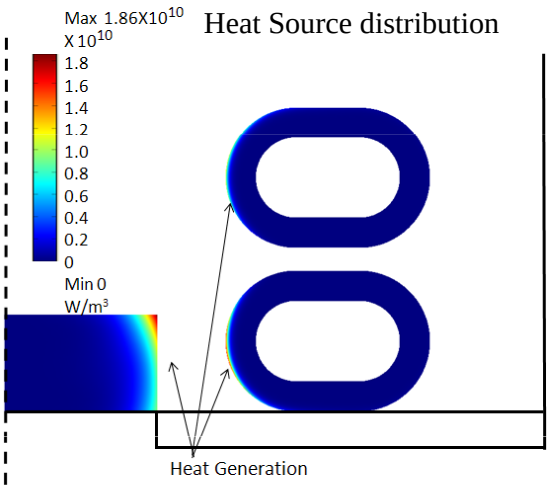
Total Current distribution



- Induced current is stronger at the right side of the sample, while total current is stronger at the left side of the coil.

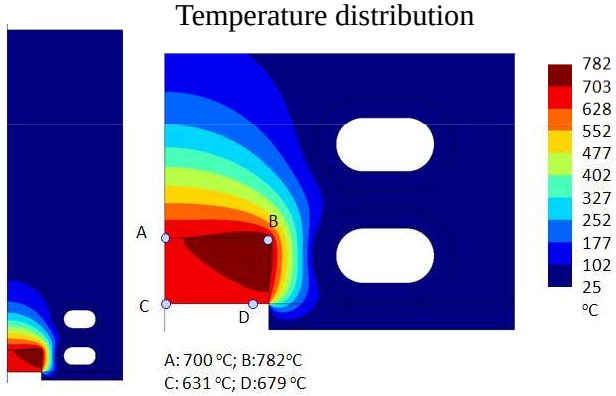
Heat Source Distribution and Temperature Distribution

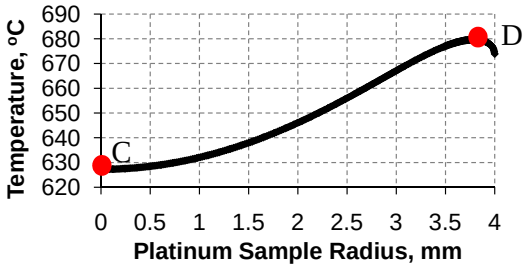
Heat Source distribution



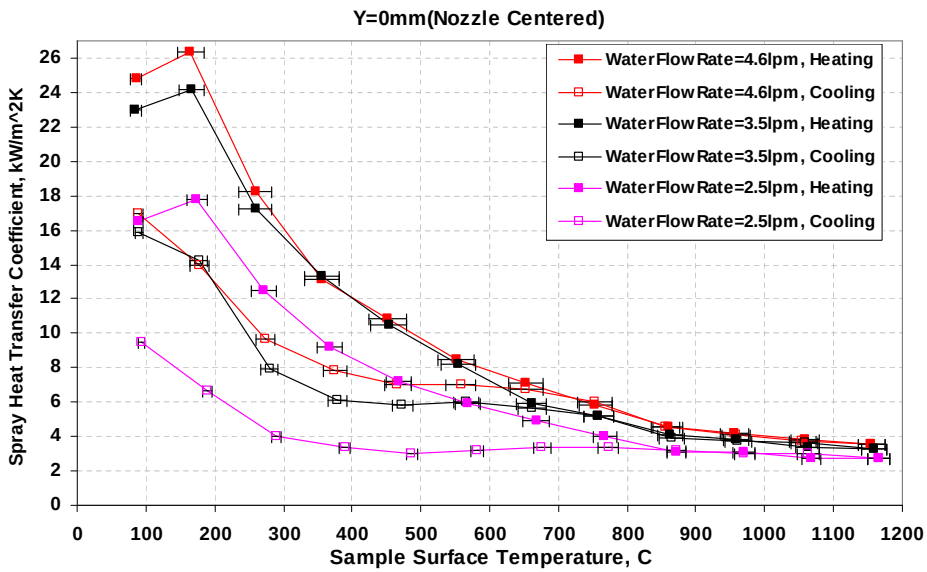
Heat Generated, W		Heat Out, W	
Sample	264.49	Spray	229.14
		Coil	206.22
Coil	186.19	Window	14.96
		Natural convection	0.44
Total	450.68	Total	450.76

Temperature distribution



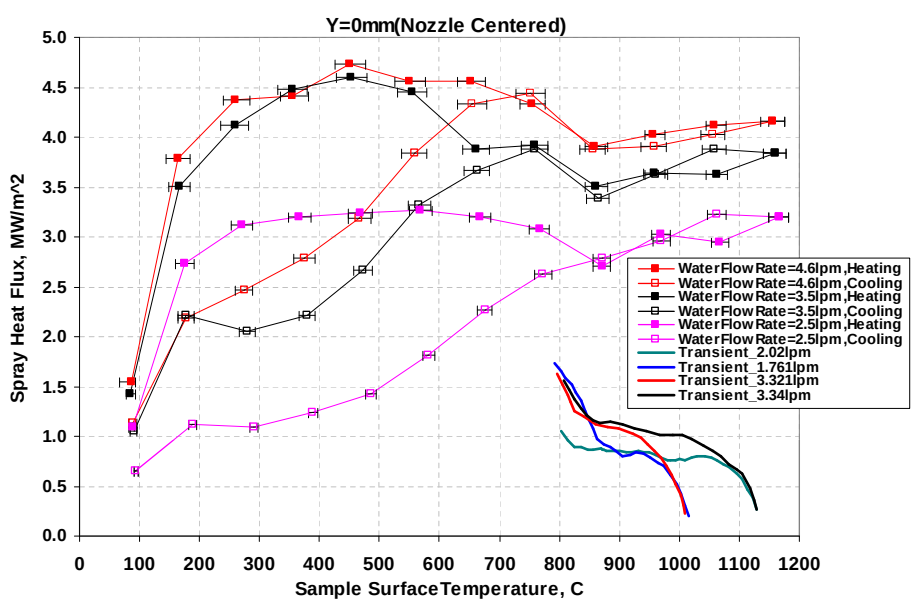


Nozzle Centered
Spray Heat Transfer Coefficients



- 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. **HTC is independent of temp at temp >850 C**

Nozzle Centered--Spray Heat Flux



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

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

Mechanism of Hysteresis

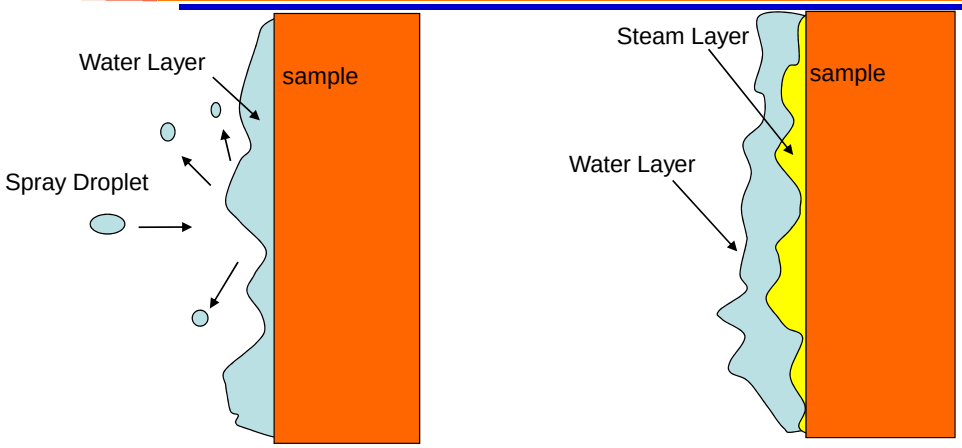


Fig. 1 Fig. 2

•**Heating process:**

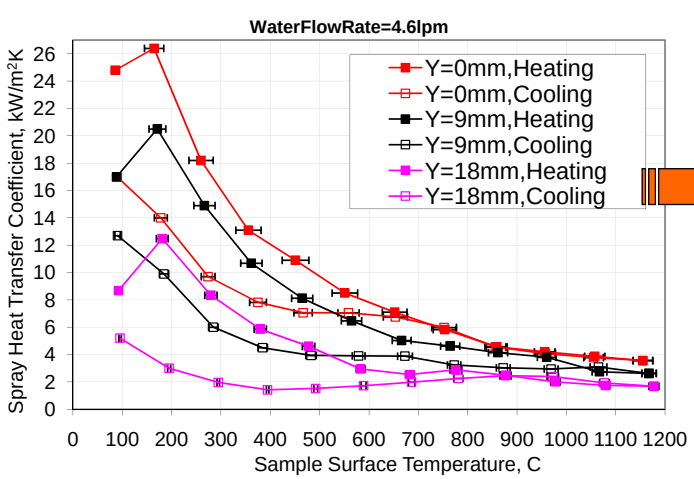
- **•spray droplet impinges on water layer, touches surface, boils, and takes heat away. (Fig. 1)**
- **•High heat removal keeps surface cold.**

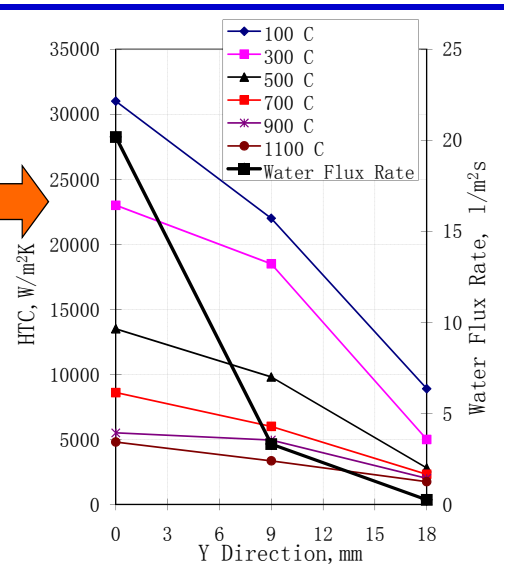
•**Cooling process:**

- **•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)**

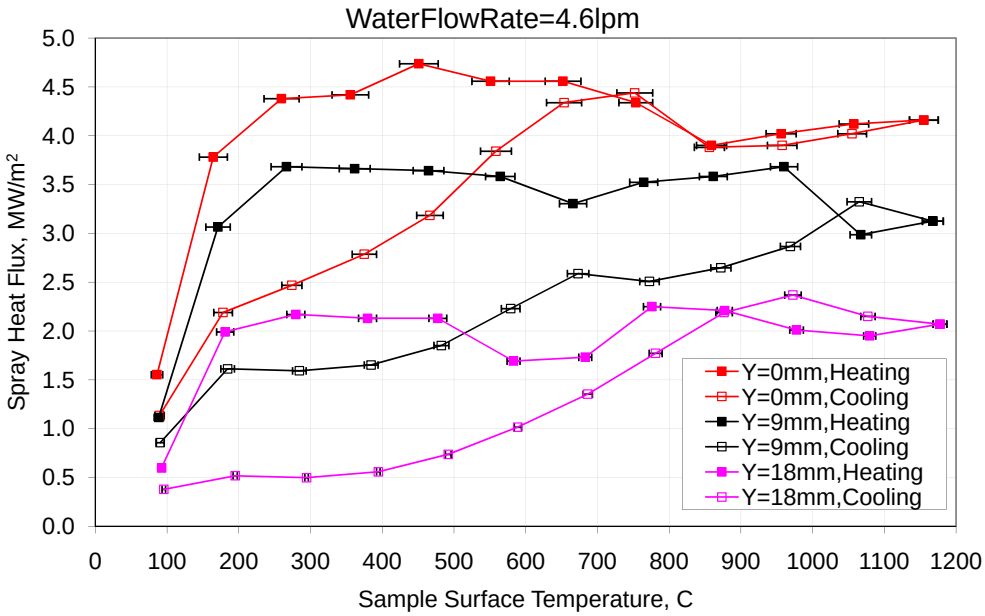
Nozzle Water Flow Rate=4.6lpm --Spray Heat Transfer Coefficients





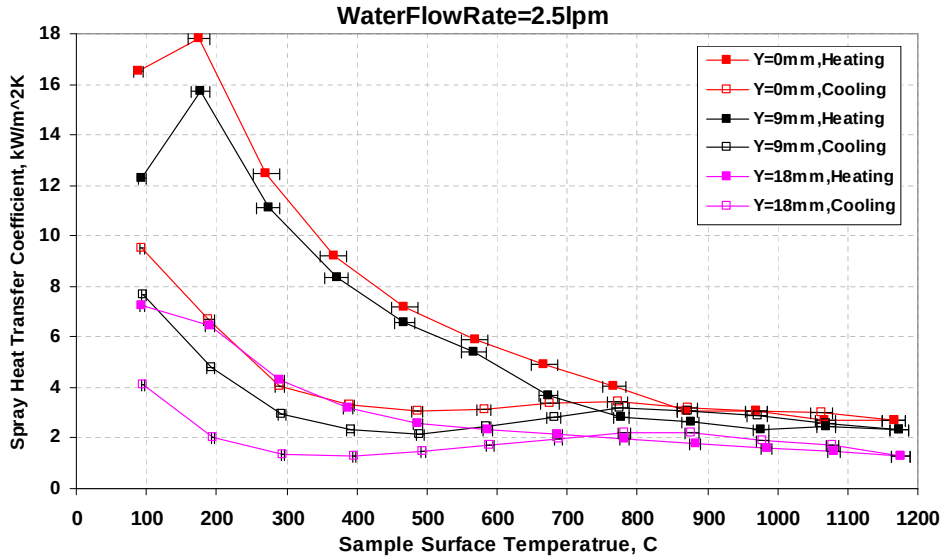
•Hysteresis exists for different location from spray centerline.
•Moving further away from spray centerline decreases HTC.
•Difficult to correlate water flow rate footprint measurements with HTC.
•More details of spray dynamics needed (droplet distribution, size, velocity, etc, --collaboration work at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

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



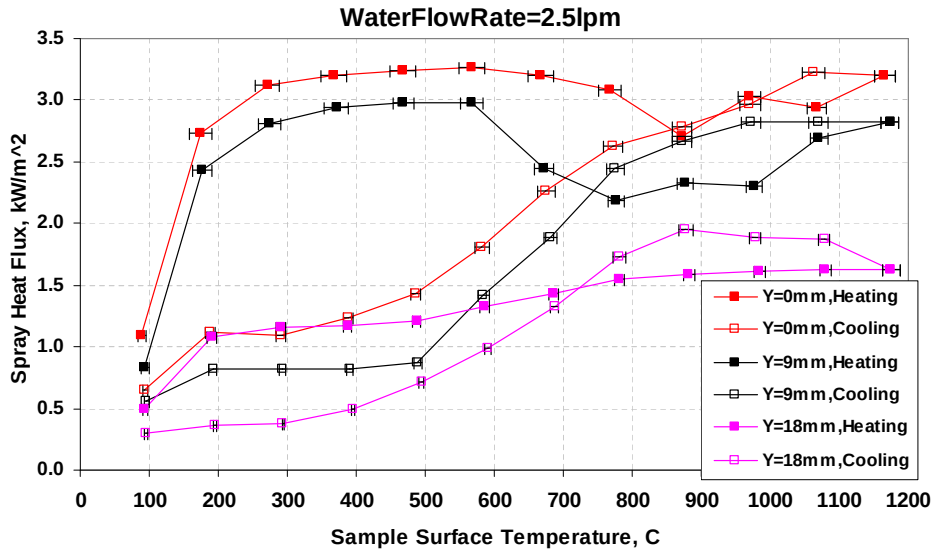
•Moving further away from spray centerline decreases spray heat flux
•Hysteresis is shown in heat flux curves

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



•Location closer to the center gives higher heat transfer coefficient.
•Hysteresis is shown in spray heat transfer coefficient curves

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



•Location closer to the center gives higher spray heat flux
•Hysteresis is shown in heat flux curves

Conclusions for Experiments and Modeling

- This report presents a new technique combining experimental measurements with computational modeling to obtain local heat fluxes of water spray cooling a platinum sample for various nozzle operating conditions.
- Apparatus (induction heating) 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^{2}K to 35000W/m^{2}K. Heat flux varies from 0.5MW/m^2 to 6MW/m^2.
- Total power loss to the ambient air and the front quartz glass window is relatively low (less than 8% of total heat generated).
- The fraction of power going 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 from 200 ^{o}C to 1200 ^{o}C, while increasing from 1200 to 100 ^{o}C during cooling.

Plant Observations and Measurements Compared with Prediction by CON1D

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Plant Measurements at Nucor
(Whale and Pyrometer Measurements)

Three cases of whale / no whale (Nucor Dec 9, 2003)

	Case 1	Case 2	Case 3
Casting Speed (ipm)	146	157	146
Spray Pattern	1	1	6 (less water)
Plant Observation	No Whale	No Whale	**Whale**

Two cases of pyrometer measurements (Case 4-1, low spray; Case 4-2, high spray) (Nucor Jan 13, 2006)

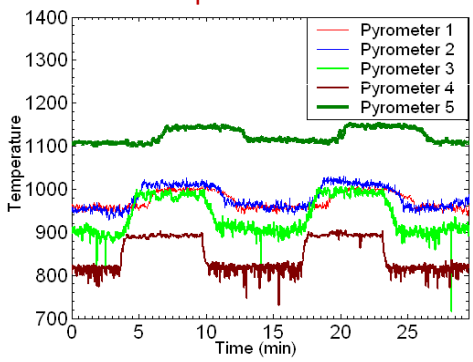
A. Caster operation conditions

Parameter	Value
Time	Jan. 13, 2006, 16:10-16:40 hrs.
Casting Speed	142.1 ipm (3.61 m/min)
Spray Pattern	Pattern 4 (low spray) , 7 (high spray)
Caster	South
Pouring Temp	1547.8 °C

B. Pyrometers locations

Pyrometer	Distance from Meniscus, mm
1	3866.1
2	6015.3
3	8380.0
4	11385.0
5	13970.0

C. Experimental data*



*Amar's CCC annual meeting 2006

Simulation Details

Note:

- Wedged-hat spray heat transfer coefficients are used *
- Spray widths come from Sami's experimental footprint measurements*
- Measured mold heat flux from the Nucor plant is used
- Superheat=0(no superheat flux, but initial temperature starts from pouring temperature)

spray width (m)	spray length (m)
1.640	0.078
0.987	0.148
0.987	0.160
1.008	0.170
1.620	0.176
1.680	0.204
1.680	0.212

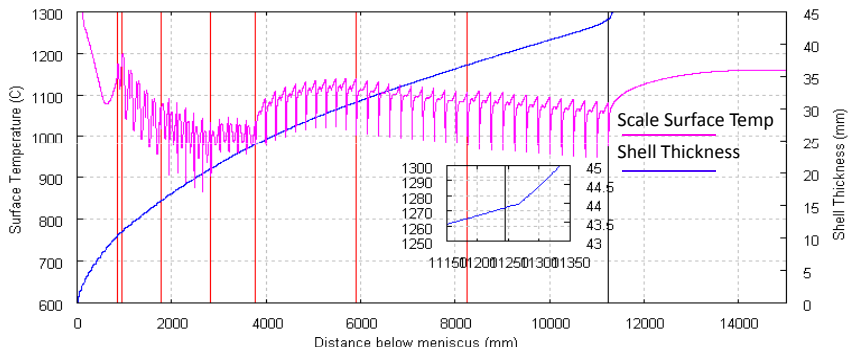
Calibrated spray HTC functions

Spray HTC tuning parameters					
z1	z2	z3	h1	h2	h3
0.08	0.50	0.92	0.20	1.50	0.20
0.20	0.50	0.80	0.30	1.90	0.30
0.35	0.50	0.65	0.60	2.10	0.60
0.20	0.50	0.80	0.70	2.20	0.70
0.40	0.50	0.60	0.50	1.80	0.50
0.12	0.50	0.88	0.20	1.00	0.20
0.30	0.50	0.70	0.20	1.00	0.20

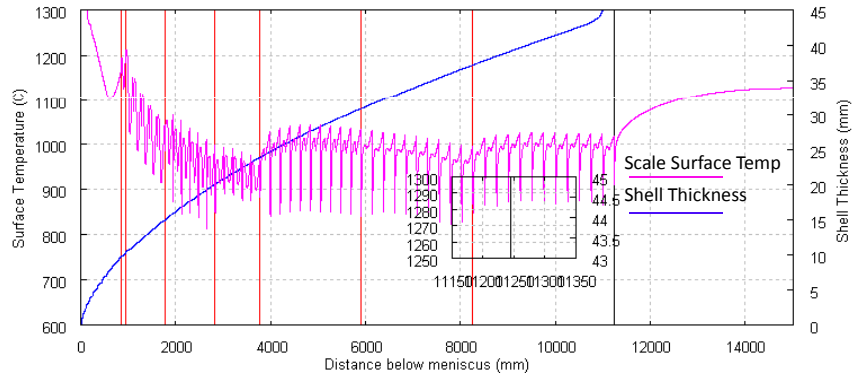
*Sami Vapalahti, 2006 CCC Meeting Report: Delavan Nozzle Characterization at CINVESTAV

Whale Formation Prediction by CON1D

Case 3
Whale

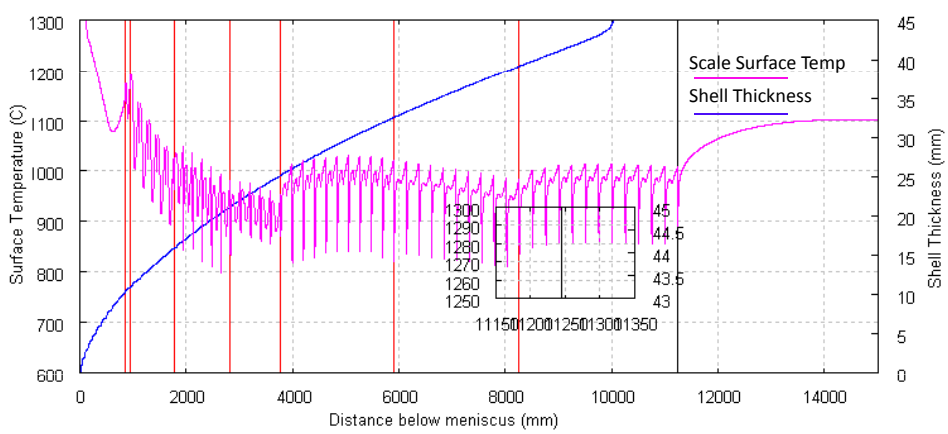


Case 2
No Whale



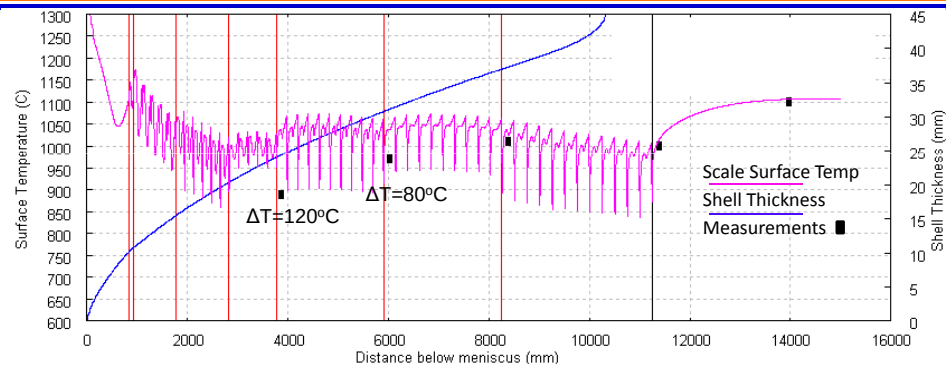
Whale Formation Prediction by CON1D

Case 1
No Whale

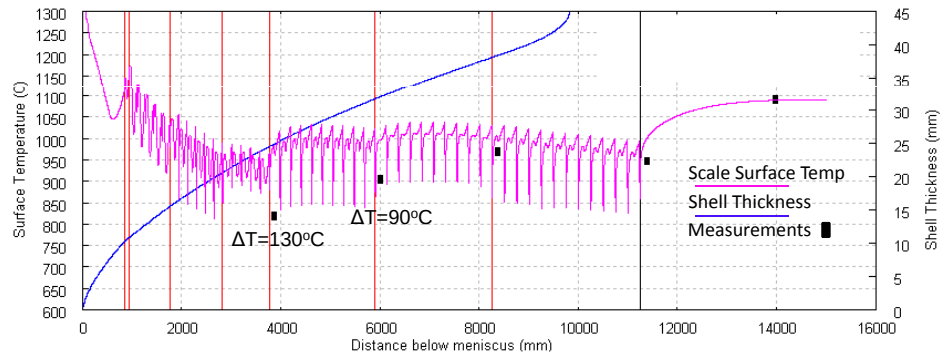


Strand Surface Temperature Prediction by CON1D and Comparison with Measurements (black dots)

Case 4-1
(low spray)



Case 4-2
(high spray)

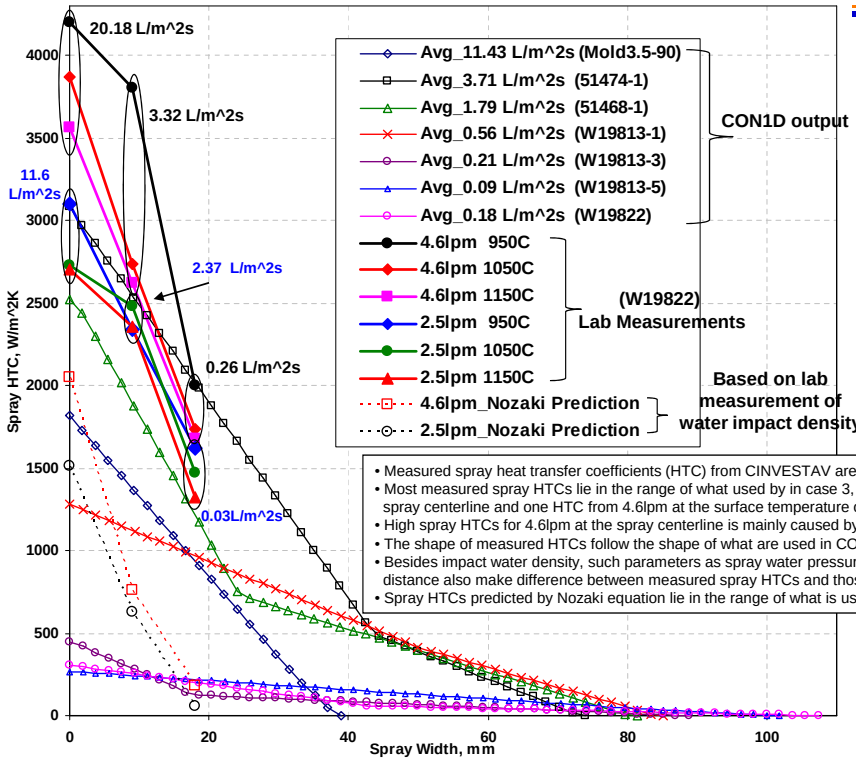


Discussion

- Good match with observation of whale formation.
- Good match with last three pyrometers.
- Bad match with the first two pyrometers, may due to dense steam.

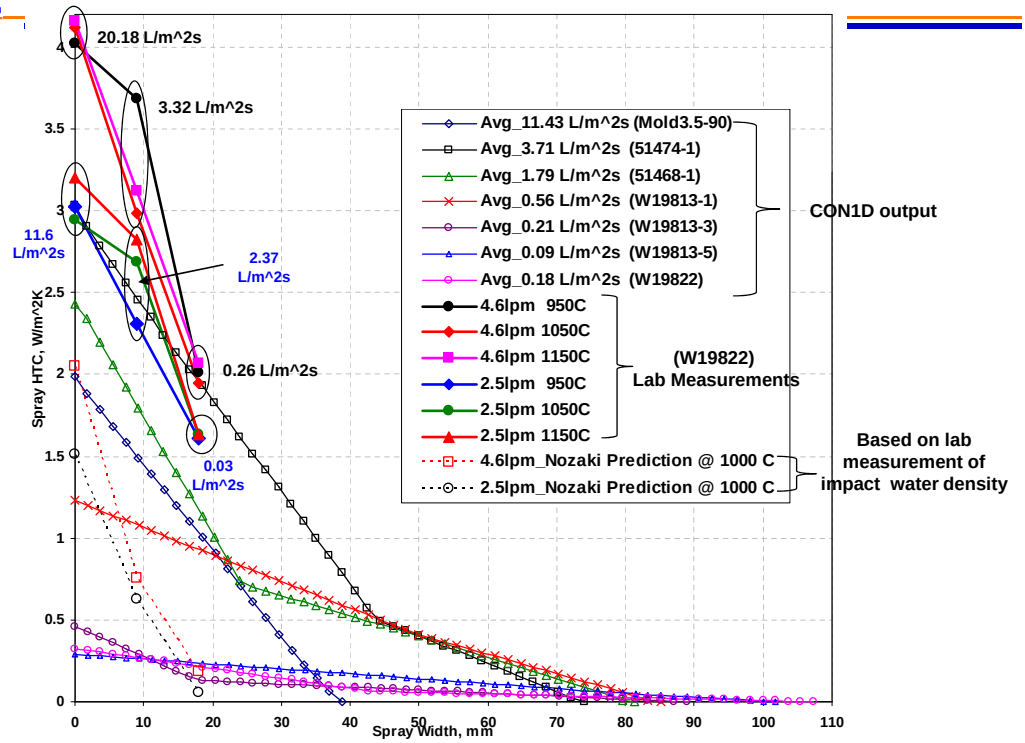
- Possible method to make simulation match better:
  - Include a scale layer in CON1D
    - scale layer is always observed in casting,
    - scale layer decreases heat transfer rate, increases metallurgical length,
    - scale layer surface temperature should be lower than steel surface temperature,
  - lower scale surface temperature and longer metallurgical length is favorable in the current simulations.
  - scale effect is studied in the next talk.

Spray HTC Comparison



- Measured spray heat transfer coefficients (HTC) from CINVESTAV are compared with those used by CON1D in case 3.
- Most measured spray HTCs lie in the range of what used by in case 3, except HTCs from 4.6lpm experiments at the spray centerline and one HTC from 4.6lpm at the surface temperature of 950 ºC.
- High spray HTCs for 4.6lpm at the spray centerline is mainly caused by the high impact water density (20.18L/m²s).
- The shape of measured HTCs follow the shape of what are used in CON1D, except the ones from 4.6lpm at 950 ºC.
- Besides impact water density, such parameters as spray water pressure, air pressure, nozzle type and nozzle standing distance also make difference between measured spray HTCs and those used in CON1D.
- Spray HTCs predicted by Nozaki equation lie in the range of what is used in CON1D.

Spray Heat Flux Comparison



Summary

- Calibrated spray HTC functions in CON1D are able to match whale observations and the last three pyrometers measurements, but not do well in matching the first two pyrometer measurements.

- Most measured spray HTCs lie in the range of what are used by in case 3, except HTCs from 4.6lpm experiments at the spray centerline and one HTC from 4.6lpm at the surface temperature of 950°C.

- The shape of measured HTCs follow the shape of what used in CON1D, except the ones from 4.6lpm at 950 ^{o}C.

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