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Heat Transfer During Air-Mist Spray Cooling

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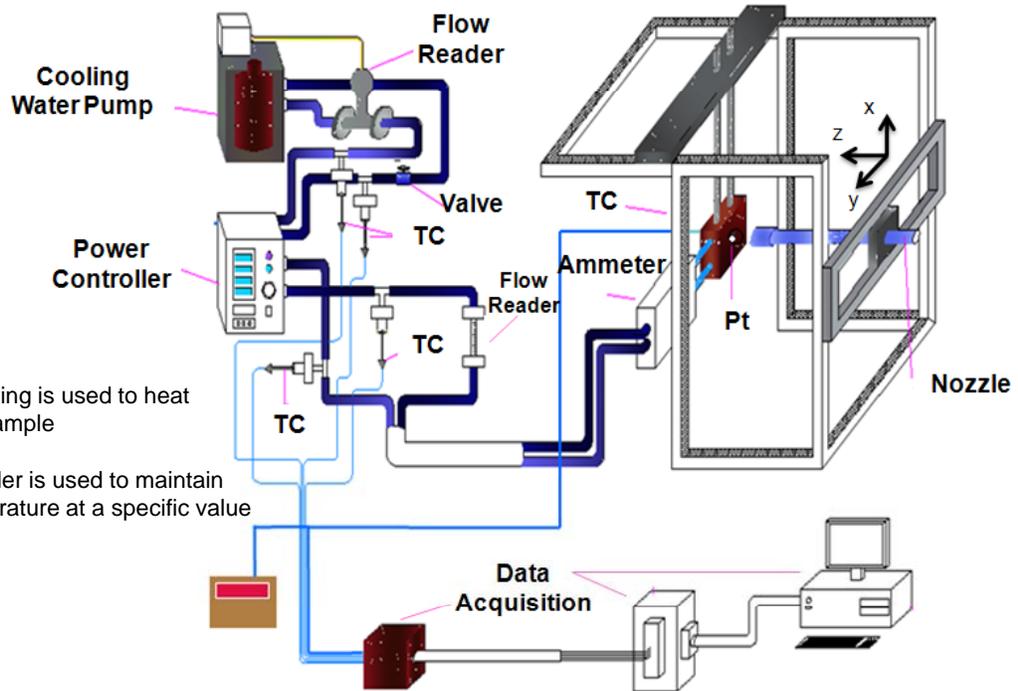


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Project Objectives

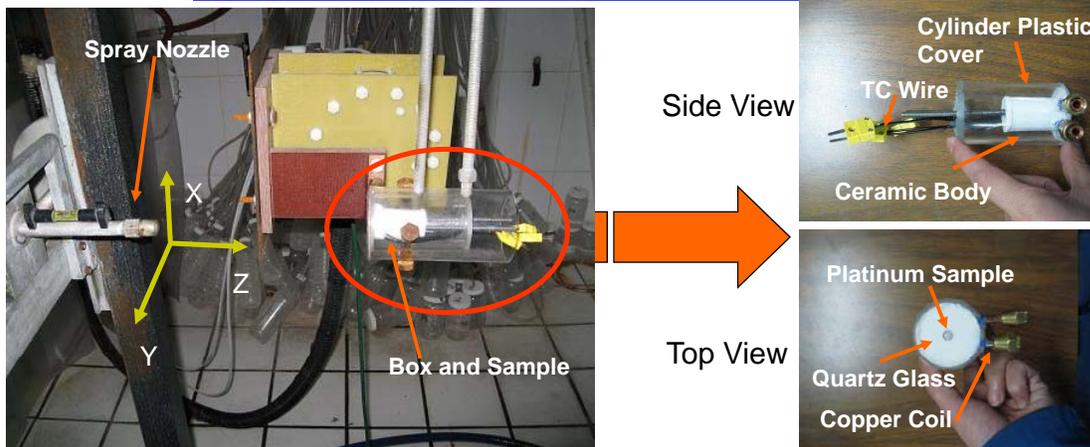
- Quantify heat transfer rate during air-mist spray cooling:
 - measure: size, velocity, flow rate, and impact density distributions of water droplets from commercial nozzles spraying air-water mists
 - interpret steady-state heat-transfer measurements with computational models
 - develop empirical heat flux relation based on fundamental water droplet parameters

Steady Heat Transfer Measurement



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

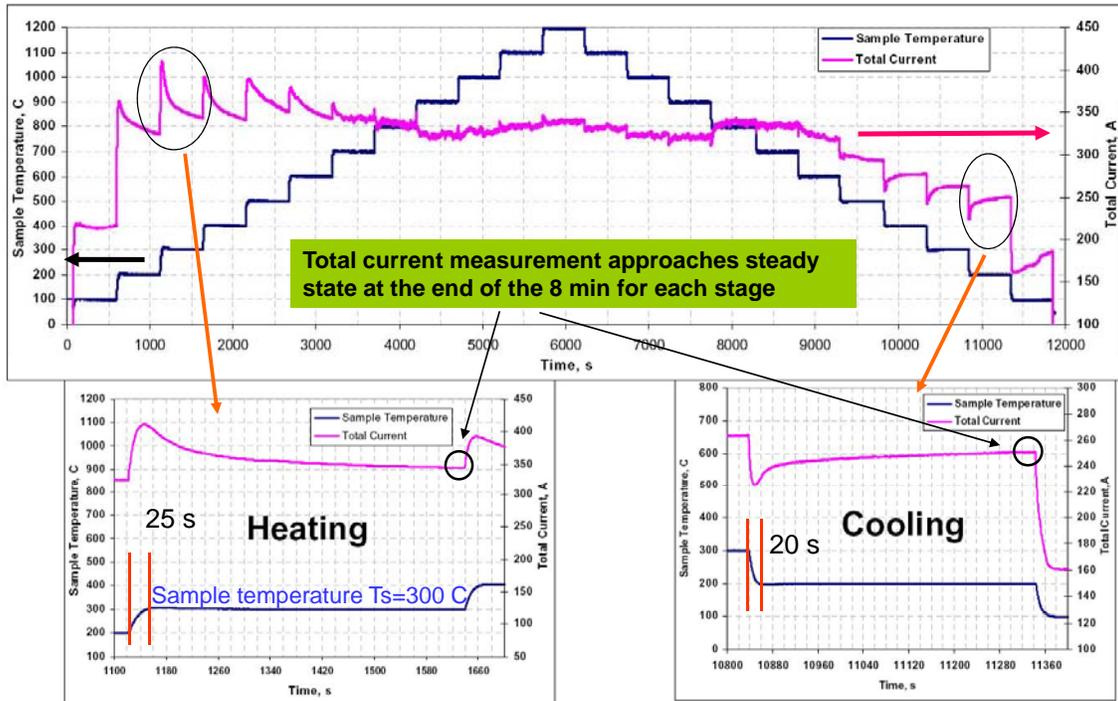
Experiment Details



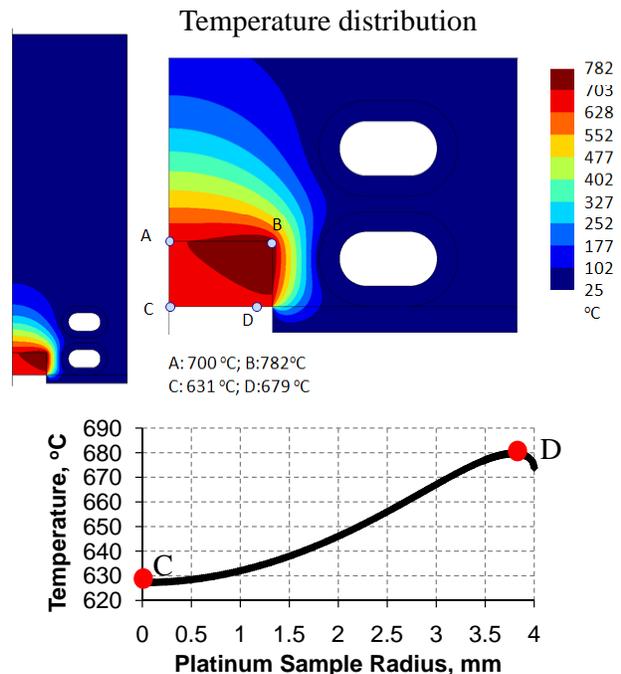
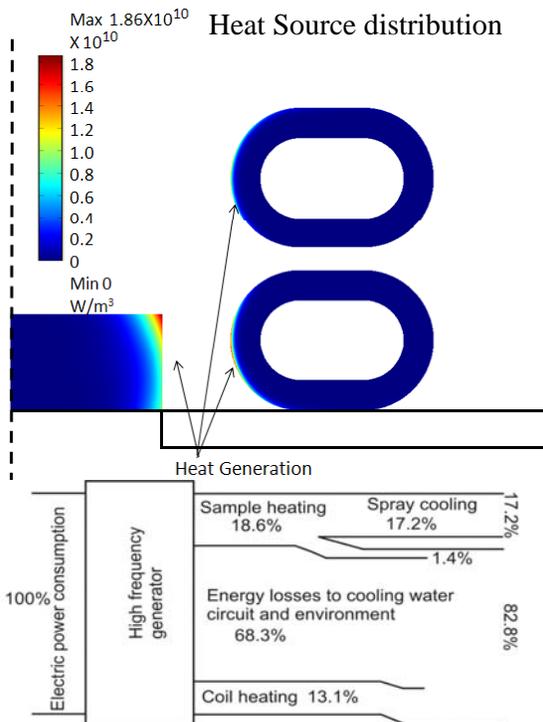
- Plastic cover and quartz glass are used to keep spray water from ceramic body, only exposing front surface of platinum sample to the water

Typical T_s and I_{tot} Measurements

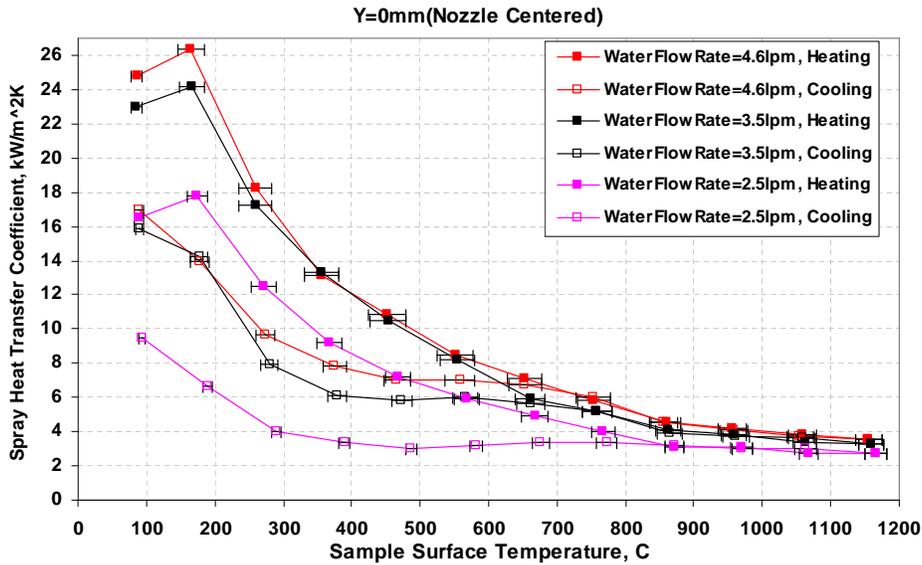
Water Flow Rate=4.6lpm, Air Flow Rate=104lpm, Nozzle Centered (June 26, 09)



Heat Source Distribution and Temperature Distribution

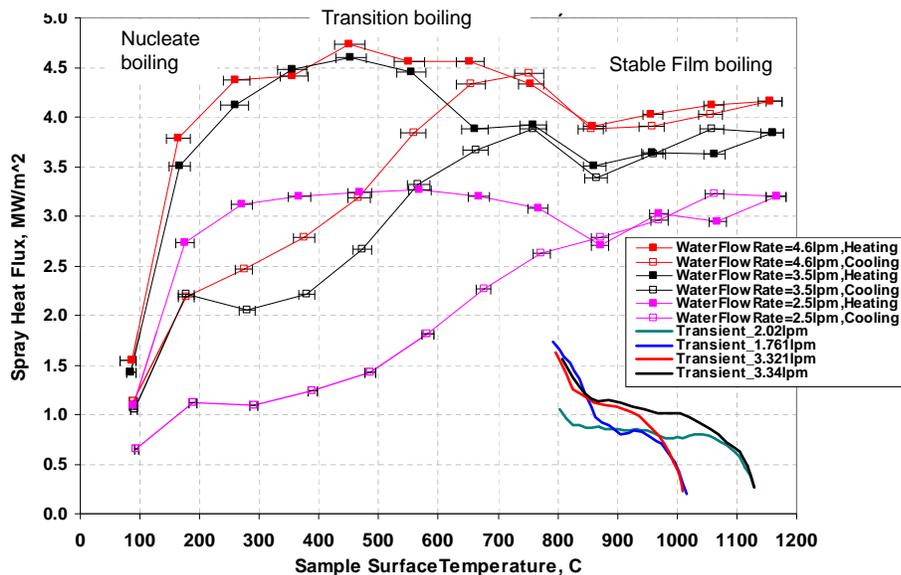


Nozzle Center Spray Heat Transfer Coefficients



- 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**

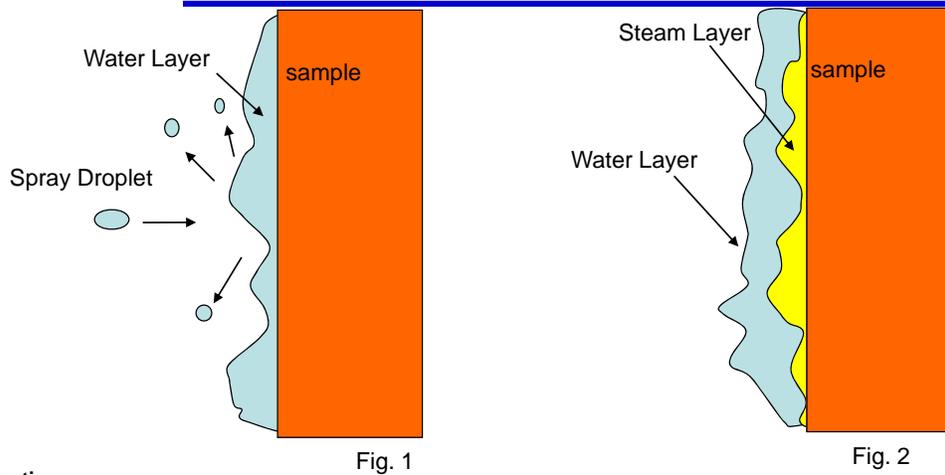
Nozzle Centered - Spray Heat Flux



- Increasing water flow rate increases spray heat flux.
- Heat transfer almost independent of temperature above ~850 °C
- Hysteresis is observed below Leidenfrost temperature ~850 °C
- Steady measurement gives higher heat flux than transient measurement

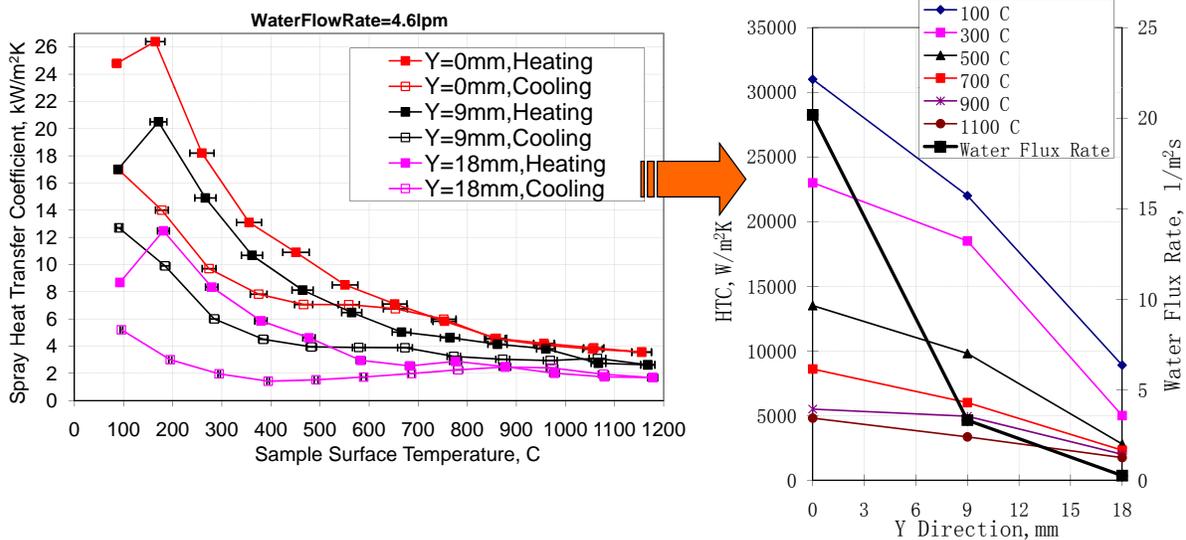
--Transient results by Sami Vapalahti, etc, Spray Heat Transfer Research at CINVESTAC, P26, CCC report, 2007

Mechanism of Hysteresis



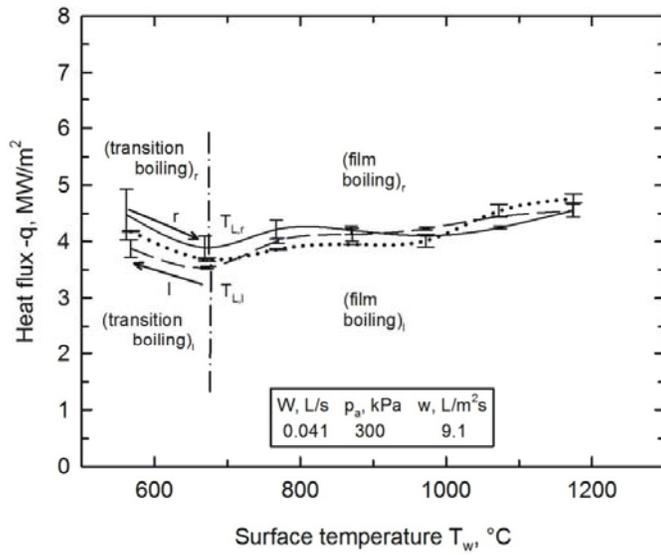
- **Heating process:**
 - spray droplet impinges on water layer, touches surface, boils, and takes heat away. (Fig. 1)
 - High heat removal keeps surface cold.
- **Cooling process:**
 - At high sample surface temperature (>~860°C), a stable steam layer forms on the sample surface. (Fig. 2)
 - This steam 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)

Heat Transfer in Film-Boiling Regime



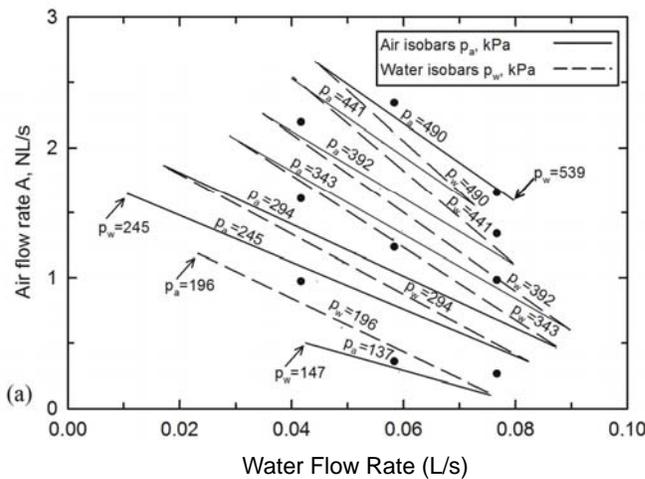
Stable

No hysteresis

Almost independent of surface temperature

Fig. 11. Boiling curves for thermal loops with T_m 600-1200-600°C (—; - -) and for thermal paths 1200-600°C (.....).

Flow-rate and Pressure of air and water are related in a nozzle



Operating Diagram (Delavan W19822 nozzle)

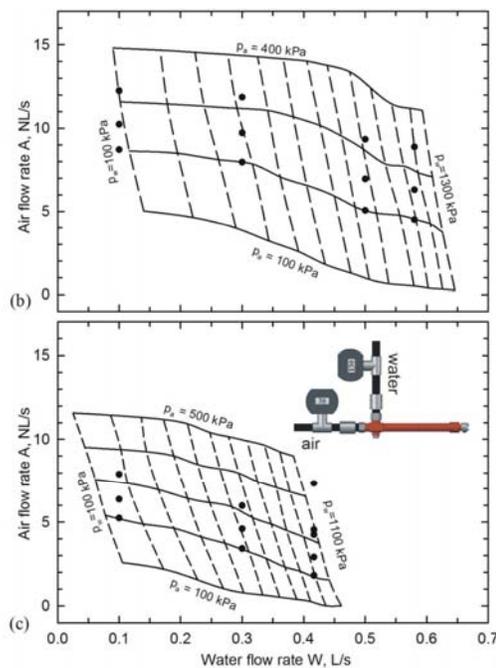


Fig. 1. Operating diagrams of nozzles: (a) W19822, (b) Casterjet 1/2-6.5-90 and (c) Casterjet 1/2-5-60, determined in the laboratory. The experimental conditions are denoted by the dots.

Droplet Parameter Measurements

For a given nozzle, water flow rate, and air pressure, Measure distributions of droplet:

- Size
- Velocity
- Weber number

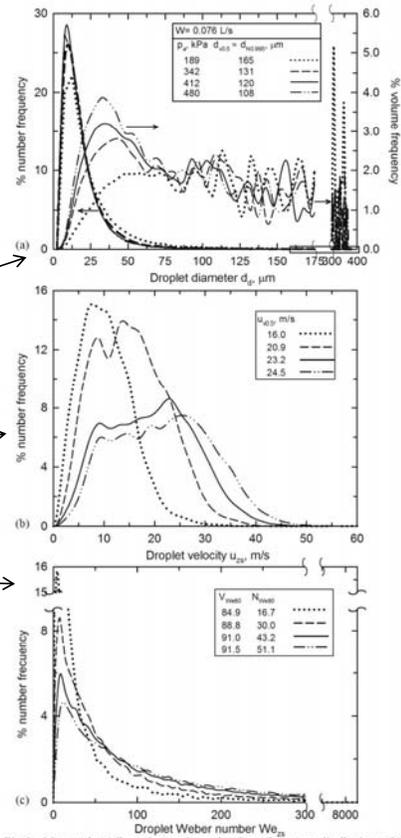


Fig. 3. Measured: (a) Drop size number and volume frequency distributions, (b) drop velocity number frequency distributions and (c) drop Weber number frequency distributions, obtained with a W19822 nozzle operating at different p_a and a single W . The curve types in the different plots are according to the p_a in (a).

Measure water flux and impact density maps

For a given:
 - nozzle,
 - water flow rate, and
 - air pressure

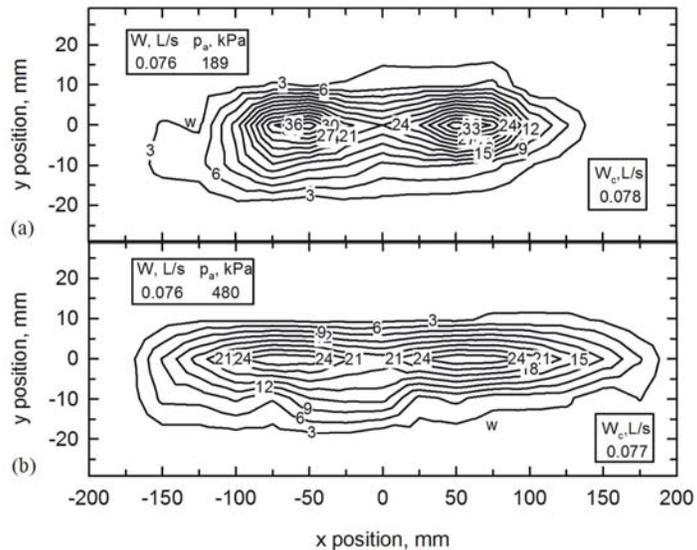


Fig. 6. Water impact density maps for a constant water flow rate and two air inlet pressures with a W19822 nozzle.

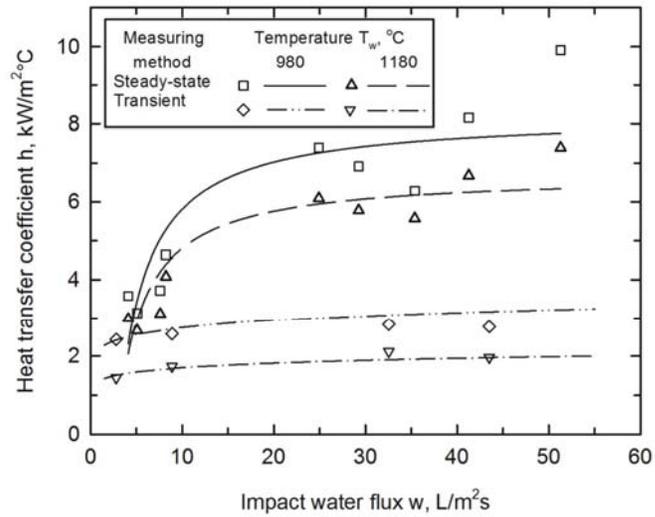


Fig. 11. Comparison between steady-state and transient measurements of heat transfer coefficients as a function of w for two T_w , obtained with a Casterjet 1/2-6.5-90 nozzle with p_a and $W \sim 250$ kPa and ~ 0.5 L/s, respectively.

New Correlations

Heat Flux (W/m²)

$$-q = 0.307 w^{0.319} u_z^{0.317} T_w^{0.144} d_{30}^{-0.036}$$

Heat Transfer Coefficient (W/m²K)

$$h = 379.93 w^{0.318} u_z^{0.330} T_w^{-0.895} d_{30}^{-0.024}$$

w = local water flux density (L/m²s)

u_z = volume-weighted mean droplet velocity (m/s)

T_w = surface temperature (K)

d_{30} = volume-mean droplet diameter (mm)

Agreement of fit:

96% of h measurements fall within $\pm 25\%$ of prediction

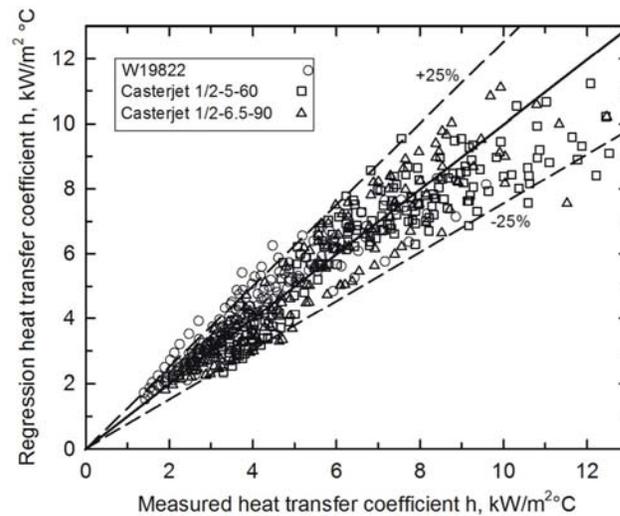


Fig. 10. Comparison between measured and correlation-calculated heat transfer coefficients for all nozzles and conditions (506 results) from 750 to 1200 °C.

Conclusions

- Spray heat transfer coefficient and heat flux show hysteresis likely related to formation of vapor layer on sample surface.
- Heat transfer in stable film boiling regime above ~ 650 °C experiences no hysteresis, (above Leidenfrost temperature)
- New correlation to predict air-water spray mist **heat transfer** has been developed based on fundamental droplet parameters: flux density, size, velocity, & surface temperature
- New correlation fits measurements for 3 different nozzle types and many different water-flow and air-pressure conditions
- New correlation shows heat transfer depends mainly on **water flux density**, with **velocity** also important, but is almost independent of **surface temperature** & droplet **size**.

References (for further details)

- C.A. Hernández, J.I. Minchaca, A.H. Castillejos, F.A. Acosta, X. Zhou, and B.G. Thomas, “Measurement of Heat Flux in Dense Air-Mist Cooling: Part I. A Novel Steady-State Technique”, CCC Report 201101, Aug. 18, 2011.
- C.A. Hernández, J.I. Minchaca, A.H. Castillejos, F.A. Acosta, X. Zhou, and B.G. Thomas, “Measurement of Heat Flux in Dense Air-Mist Cooling: Part II. The Influence of Mist Characteristics on Heat Transfer”, CCC Report 201102, Aug. 18, 2011.
- X. Zhou, Heat Transfer During Spray Water Cooling Using Steady Experiments, MS Thesis, University of Illinois, 2009.

Acknowledgements

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