Heat Transfer During Air-Mist Spray Cooling

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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 Ts and $I_{\text{tot}}$ Measurements

Water Flow Rate=4.8lpm, Air Flow Rate=104lpm, Nozzle Centered (June 26, 09)

Total current measurement approaches steady state at the end of the 8 min for each stage.

Heat Source Distribution and Temperature Distribution

Heat Source Distribution

Temperature Distribution

Sample heating: 18.6%
Spray cooling: 17.2%
Energy losses to cooling water circuit and environment: 68.3%
Coil heating: 13.1%
Nozzle Center Spray Heat Transfer Coefficients

Y=0mm (Nozzle Centered)

- 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.

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 = 4.6 lpm
-- 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 $T_w$ 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)
Droplet Parameter Measurements

For a given nozzle, water flow rate, and air pressure, measure distributions of droplet:
- Size
- Velocity
- Weber number

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.
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 +/-25% of prediction

![Graph](image)

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 \( \sim 650 \) °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)


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