Efficient Cooling in Engines with Nucleated Boiling

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Thermal Management – Project Organization

Nanofluid Development for Engine Cooling Systems
FWP 49424/49386 Agreement # 16822

Erosion of Materials
FWP 49113/49381
Agreements
#9416/15529

Nucleated Boiling
FWP 49425
Agreement # 14758

Overview

Timeline

- Project start FY06
- Project end FY12
- 40% complete

Budget

- Total project –
  see Project ID #
  vss_13_routbort
- Nucleated Boiling
  – FY08 = 200k (DOE)
  – FY09 = 200k (DOE)

Barriers

- Reduction of cooling system size including radiator, pump, tubing and hoses; aerodynamic drag; and parasitic energy losses by engineering engine coolant boiling under high heat load conditions needing
  - -Coolant boiling heat transfer coefficients
  - -Coolant two-phase pressure-drop data
  - -Acceptable boiling limits of
    - * Critical Heat Flux
    - * Flow Instability

Partners/Interactions

- PACCAR (CRADA in progress)
- Major vehicle & engine manufacturers

Nucleated Boiling

- **Develops the controlled boiling of coolant, in large engines, under high heat load conditions, leading to reduction in energy usage through reduction of cooling system size, and parasitic energy uses and losses**

Dr. Sid Diamond, Mid-America Truck Show, photo by Routbort

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Why Boil Engine Coolant?

- **Under maximum heat load conditions**
  - Boiling of coolant often occurs in engines
    - *Cooling system is oversized to avoid boiling*
  - Engineering for coolant boiling
    - *Take advantage of high heat transfer rate resulting from boiling to*
      - Reduce coolant pump size and power
      - Reduce size of cooling system tubing and hoses
      - Allow for precision engine cooling
    - *Has potential to*
      - Reduce radiator size
      - Reduce aerodynamic drag
      - Improve thermal efficiency

Objectives

- Investigate potential of two-phase flow in engine cooling applications.
- Provide data and design methods for engine applications.
- Determine limits on two-phase heat transfer (occurrence of critical heat flux and/or flow instability).

Milestones

- **FY08 *(completed)***
  - **Test facility modifications**
    - ***Vertical test section expansion***
    - ***Flowmeter changes***
  - **Water vertical boiling/data analyses**
- **FY09**
  - **Complete liquid water testing and flowmeter calibration, 1Q-FY09**
  - **Complete vertical water boiling tests and analyses, 2Q-FY09**
  - **Ethylene glycol/water mixture vertical boiling/data analyses, 4Q-FY09**

Potential Barriers

- A data base for boiling heat transfer in 50/50 ethylene glycol/water engine coolant is nonexistent.
- Effective and accurate mathematical analyses based on flow boiling physics are necessary for transferring the experimental data into design correlations for boiling engine cooling systems.
- Boiling limits for CHF and flow stability must be in acceptable ranges including safety margins.
- Experience with engine cooling systems designed to utilize boiling heat transfer

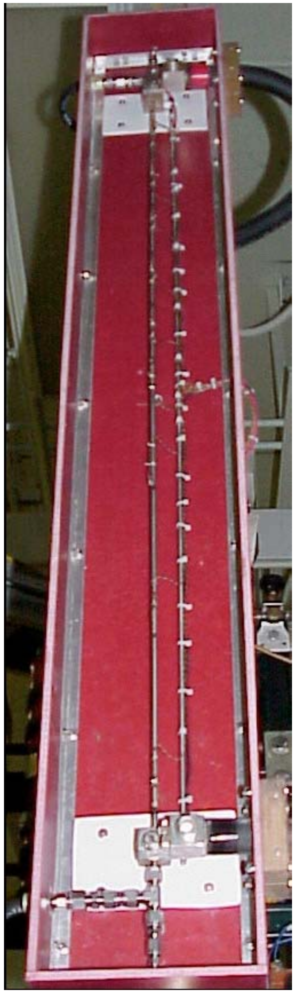
Approach

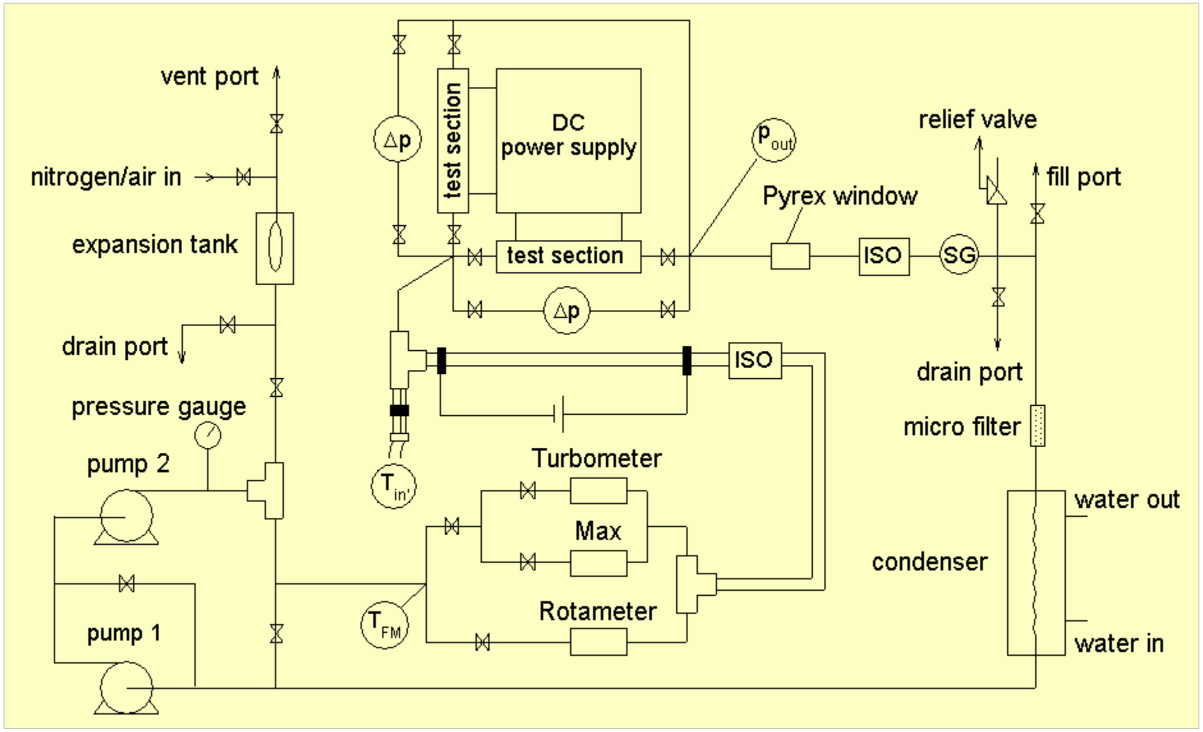
- Experimental data are correlated into equations for two-phase boiling pressure drop and heat transfer.

- Two-phase boiling heat transfer limitations are established from the experimental data.

- Computer simulations are used to predict the performance of boiling heat transfer in real engine cooling systems.

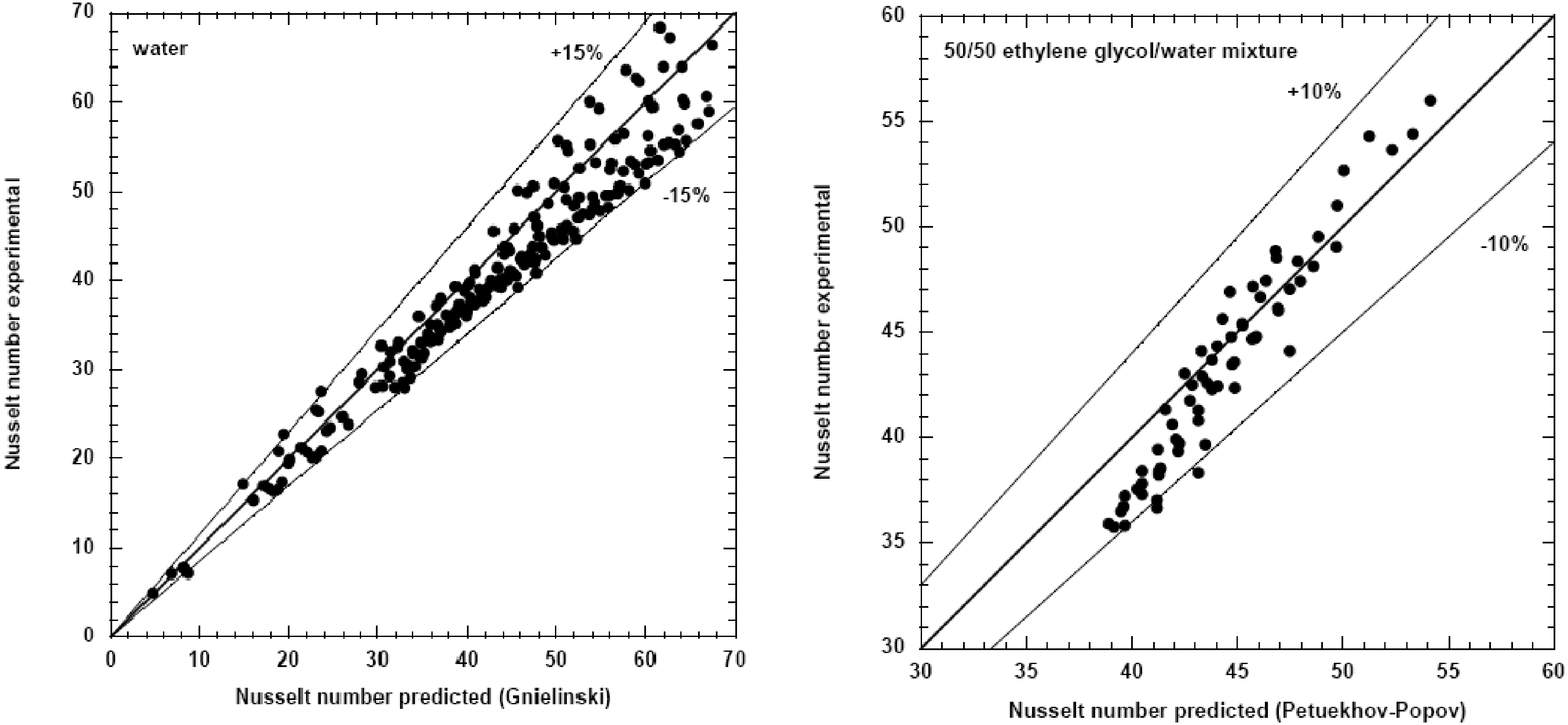
Vertical Test Section & Experimental Facility





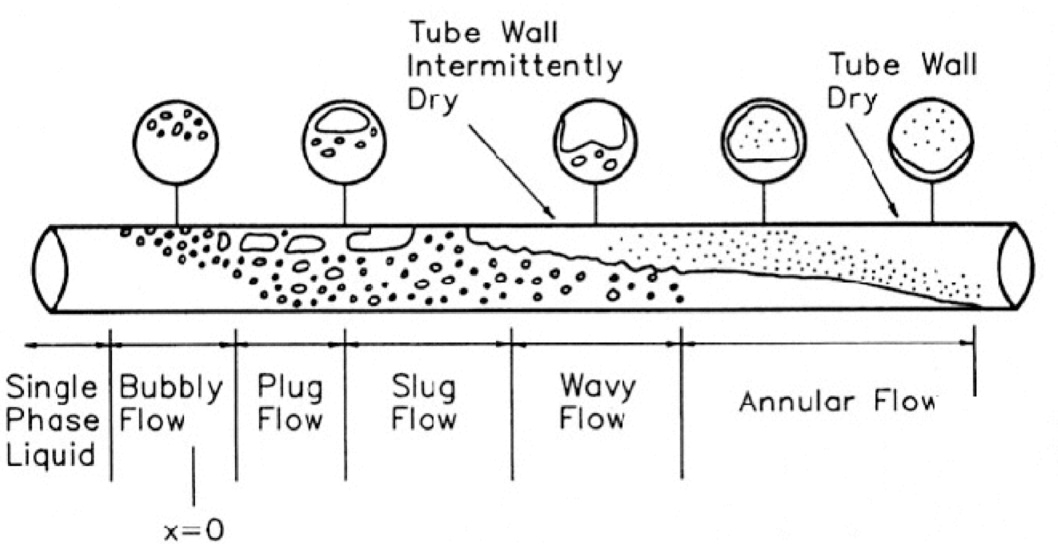
The experimental facility is a closed loop system consisting of pumps, flowmeters, an accumulator, a preheater, horizontal and vertical test sections, and a condenser.

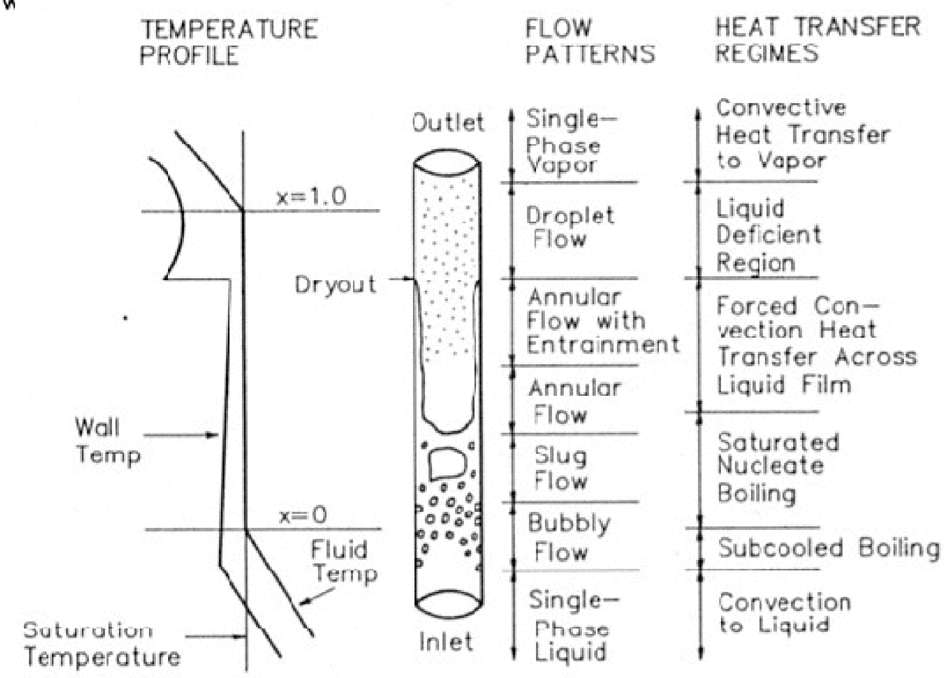
Vertical Liquid Flow – System Verification



Both, water and 50/50 EG/water mixture, well predicted by standard correlation equations

Horizontal and Vertical Two-Phase Flows





Data Reduction

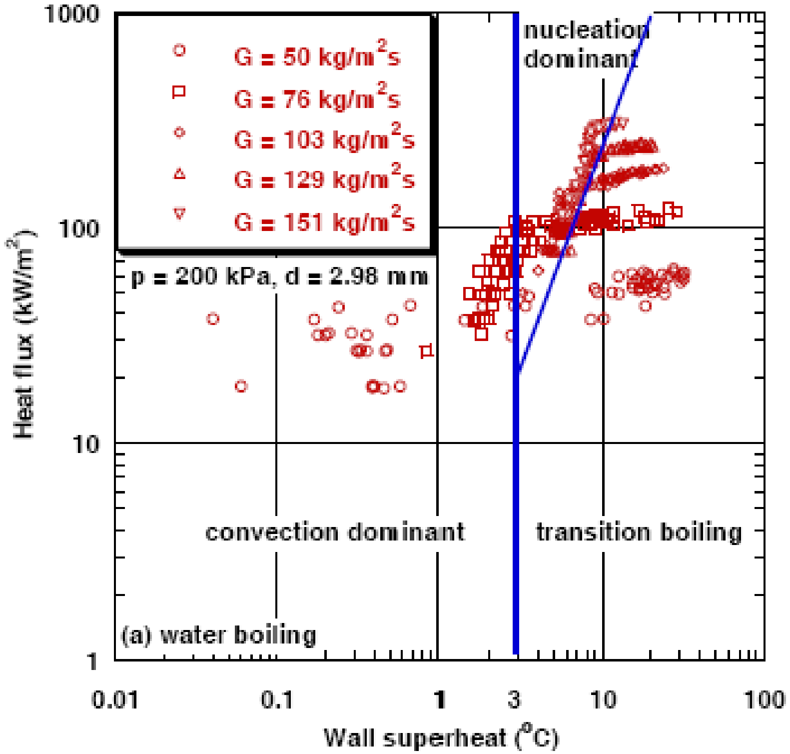
- **Evaluation of concentration, quality, and temperature**
  - **Other investigators**
    - ***Average rather than local fluid temperature***
    - ***Linear temperature assumption***
  - **Present work: local thermodynamic equilibrium calculation**

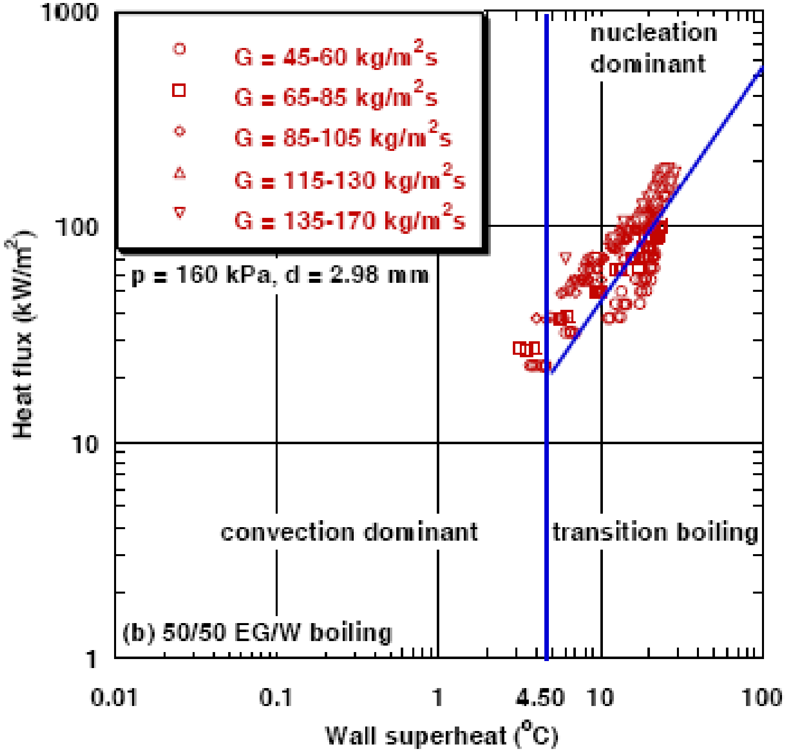
$$F_{EGv} = \frac{31(p - p_{Wsat})p_{EGsat}}{p(31p_{EGsat} - 9p_{Wsat}) - 22p_{EGsat}p_{Wsat}}$$

$$x = \frac{\left[p(31p_{EGsat} - 9p_{Wsat}) - 22p_{EGsat}p_{Wsat}\right]\left[(31 - 22F_{EG})p - 9F_{EG}p_{EGsat} - 31(1 - F_{EG})p_{Wsat}\right]}{279(p - p_{EGsat})(p - p_{Wsat})(p_{EGsat} - p_{Wsat})}$$

$$T_{in} = T_{out} - \frac{\Delta q/\dot{m} + \left[(1 - F_{EGvin})i_{fgWin} + F_{EGvin}i_{fgEGin}\right]x_{in} - \left[(1 - F_{EGvout})i_{fgWout} + F_{EGvout}i_{fgEGout}\right]x_{out}}{(1 - F_{EG})C_{pWl} + F_{EG}C_{pEGl}}$$

Horizontal Flow: Flow Boiling Regions & Dependencies





Heat flux in the nucleation-dominant boiling region shows strong dependence on wall superheat and minimal dependence on mass flux. A single equation was developed that predicts data for: water; refrigerants; and EG/W 50/50, 40/60, 60/40, all supporting the dependences identified.

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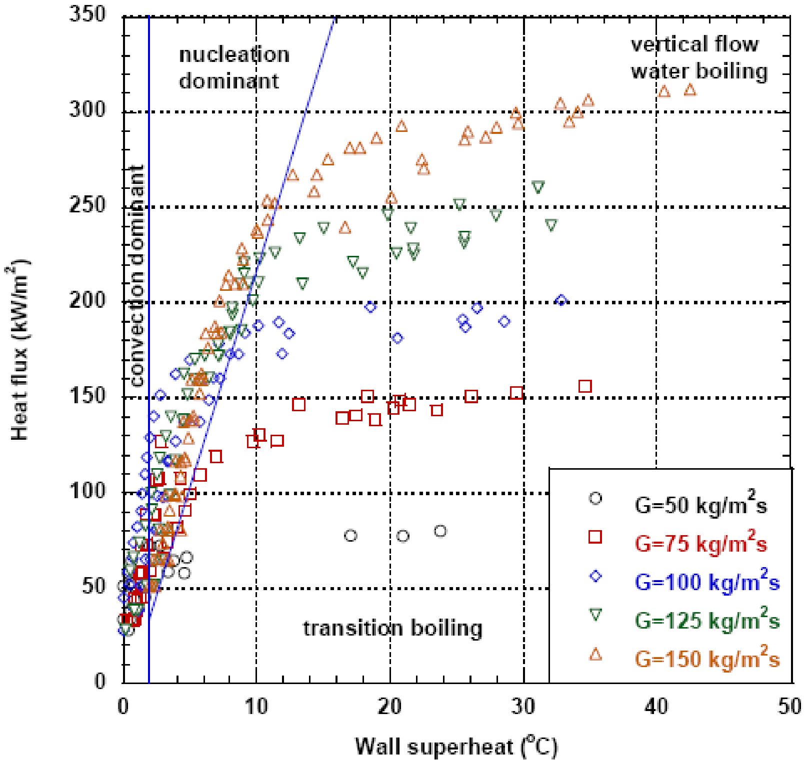
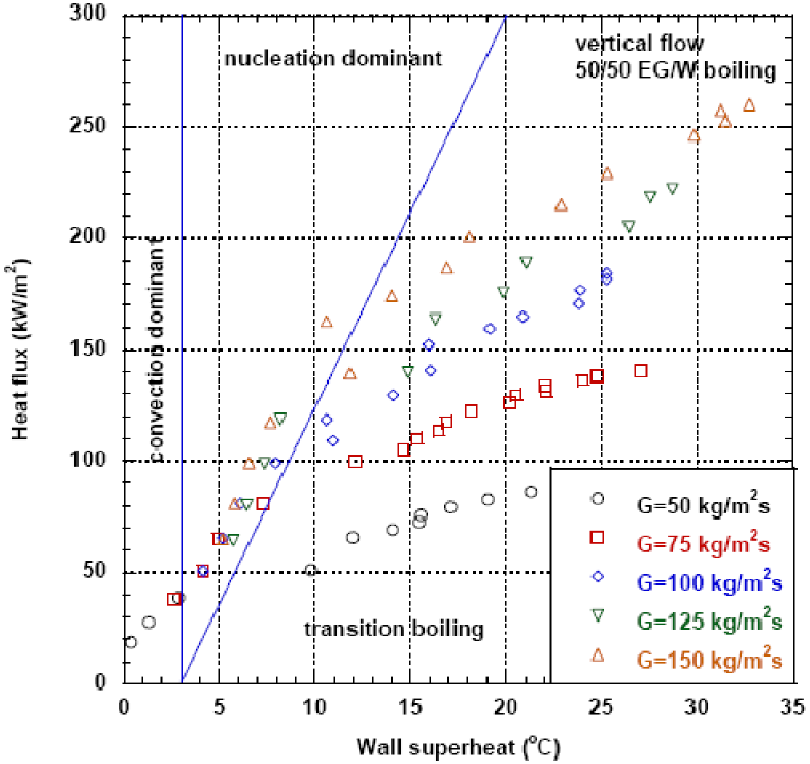
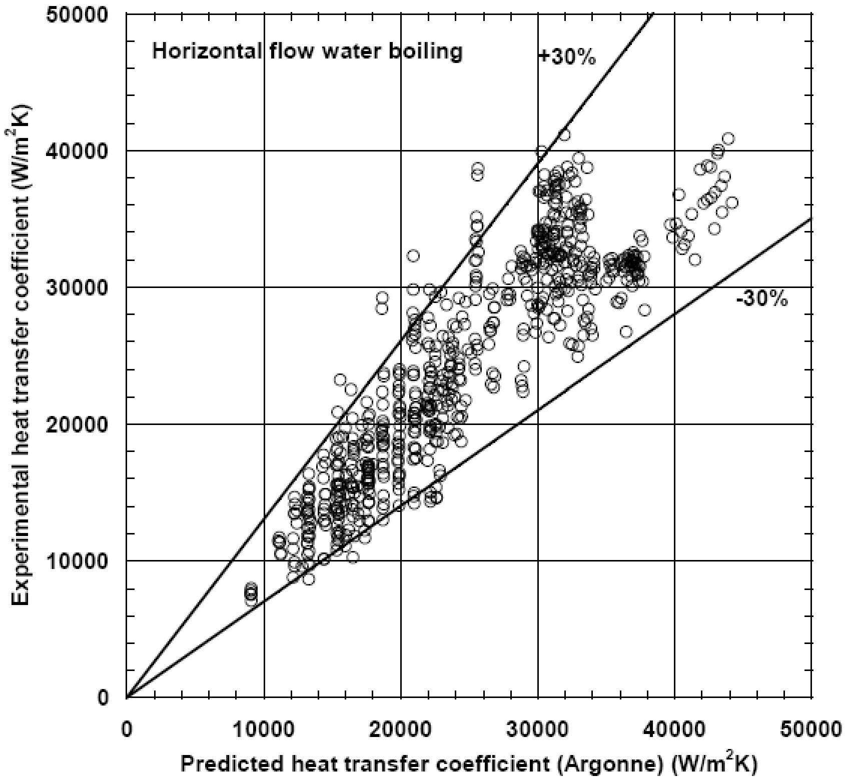
Vertical Flow: Flow Boiling Regions & Dependencies

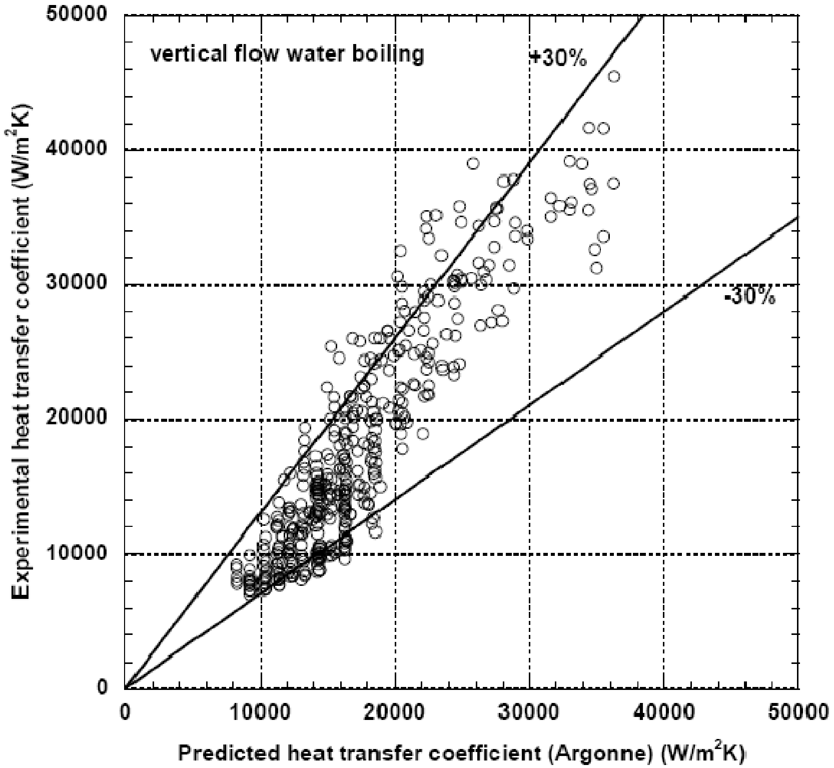




Similar to horizontal flow, heat flux in the nucleation-dominant boiling region shows strong dependence on wall superheat and minimal dependence on mass flux. Boiling region differences are clear on this linear plot.

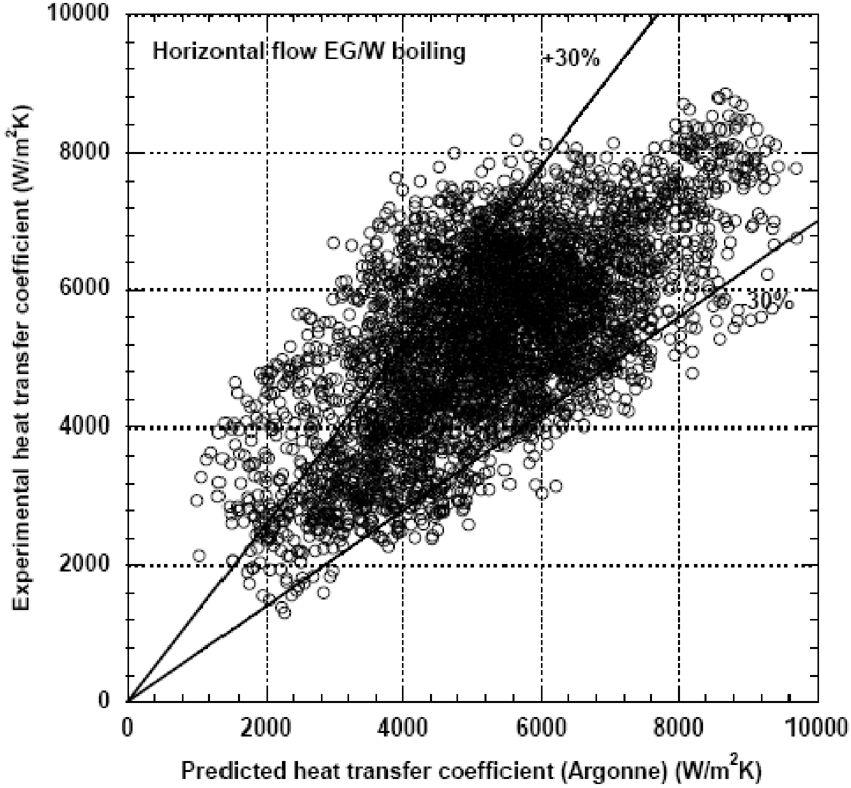
Horizontal & Vertical Boiling Water: Heat Transfer Coefficients & Predictions

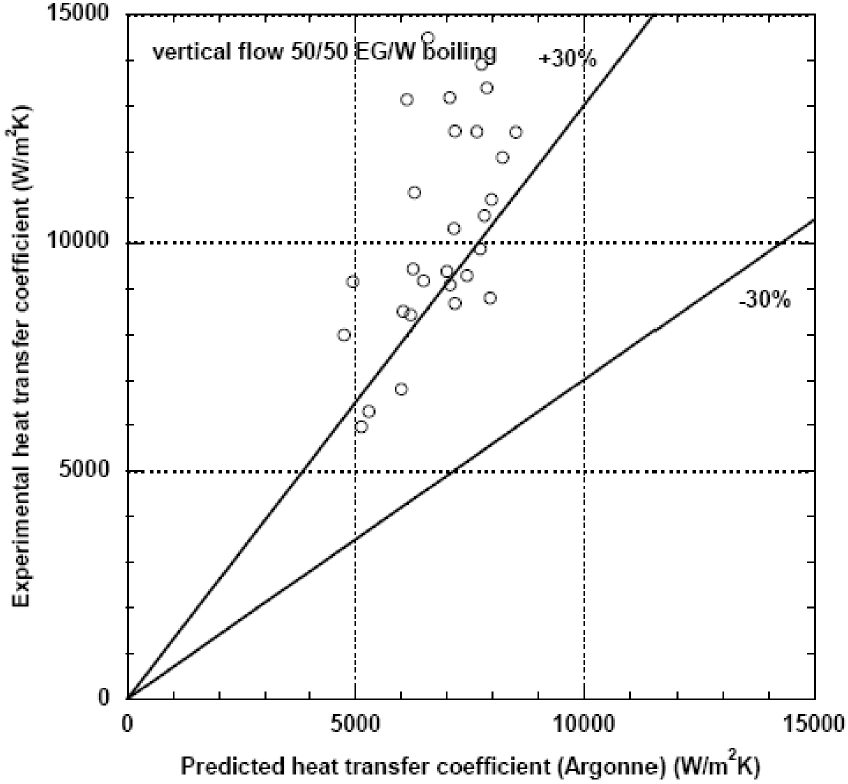




Boiling water data predicted equally well for horizontal and vertical flow using ANL equation developed from horizontal data for boiling water, ethylene glycol/water, & refrigerants.

Horizontal & Vertical
Boiling of Ethylene Glycol/Water mixtures: Heat Transfer Coefficients & Predictions





Vertical boiling experiments are in progress; preliminary indications are that vertical flow boiling heat transfer rates are greater than horizontal.

Horizontal Boiling Heat Transfer Coefficient

$$h/h^{*} = [1 + 6V(V - 0.5)](\mathrm{BoWe}_l^{0.5})^{0.5}\left[(\rho_l/\rho_v)^{-0.5}(\mu_l/\mu_v)^{0.7}\right]^{-1.5}$$

- Predicts data for
  - Ethylene glycol & water concentrations
    - 50/50
    - 60/40
    - 40/60
  - Water
  - Refrigerants 12 & 134a
- Characteristic heat transfer coefficient $h^* = 135\ \mathrm{kW/m^2K}$
- $h_{boiling}$ is 5-10 times larger than h_{liquid}

Path Forward

- Results to date have been excellent for engine applications
- Horizontal flow boiling of mixtures (completed)
  - High heat transfer rates
  - Good application limits
- Vertical flow boiling of mixtures (in progress)
  - Differences from horizontal accentuated in small channels
  - Separate data analysis/correlation required
- Combined results for horizontal & vertical flows required for engine application