Argonne NATIONAL LABORATORY

# *Efficient Cooling in Engines with Nucleate Boiling*

*D. M. France, W. Yu, and J. R. Hull*

*April 2006*

THE UNIVERSITY OF CHICAGO

*A U.S. Department of Energy laboratory managed by The University of Chicago*

Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

# *Meeting the goals of the 21CT Truck Partnership*

- Demands of higher heat rejection require new cooling methods

- Objective of this work is to develop such methods that will enable reduced cooling system sizes, hence smaller frontal areas, and reduced aerodynamic drag for increased fuel economy

# *Project Overview*

- Current heavy vehicle engine cooling system design
  - Using liquid ethylene glycol/water coolant
  - Size based on worst condition--summer grade
  - Problems removing sufficient heat from head region
- Two-phase cooling advantages for heavy vehicles
  - Reduced coolant system size by more efficient cooling
  - Reduced coolant pumping power (parasitic energy reduction)
  - Increased heat removal rates in problem head region
- Heavy vehicle application
  - Design to high heat load (worst) conditions to limit two-phase
  - Continue to use ethylene glycol/water coolant
  - Focus on small coolant passage in head region
  - Study both horizontal and vertical coolant passage orientations

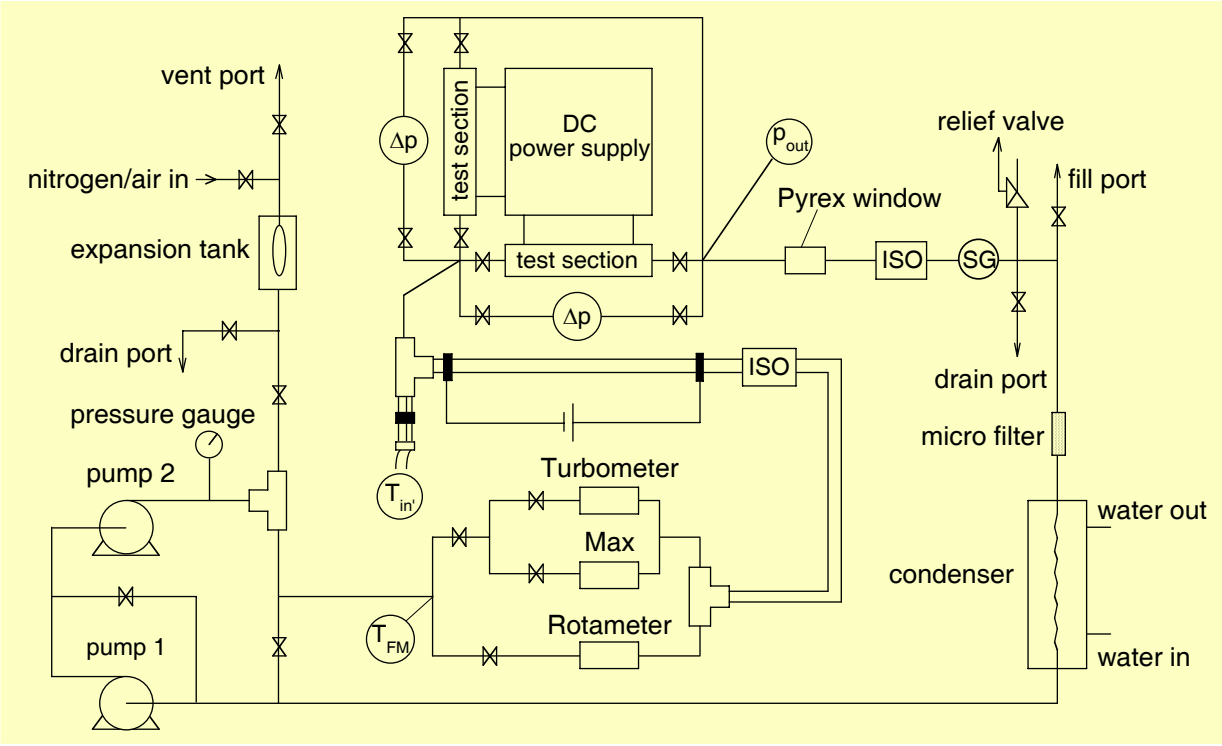
# Objectives

- Investigate potential of two-phase flow in engine cooling applications with focus on head region
- Determine heat transfer rates and pressure drops of two-phase flow in engine cooling applications
  - Boiling of binary coolant mixtures
  - Boiling in small head-region coolant passages
  - Preprogram results almost non-existent for combination of binary mixture (ethylene glycol/water) and small channels
  - Argonne's experience for single component fluid boiling in small channels formed the basis for more advanced binary boiling work
- Determine limits on two-phase boiling heat transfer (occurrence of critical heat flux and flow instability)
- Correlate data for use in engineering/design applications
- Transfer work to industry

# Approach

- Experimentally determine heat transfer rates and critical heat fluxes in small channels with water and ethylene glycol/water mixtures
  - Design, fabricate, and utilize a unique experimental facility
  - Develop accurate data reduction procedures including component composition of liquid and vapor
- Study the impact of vertical versus horizontal flow on two-phase heat transfer
- Perform experiments with alternative fluids

# Experimental Facility Schematic




***The experimental apparatus is a closed-loop system consisting of two pumps, a flowmeter set, an accumulator, a preheater, two (horizontal and vertical) experimental test sections, and a condenser.***

# Horizontal and Vertical Two-Phase Flows

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

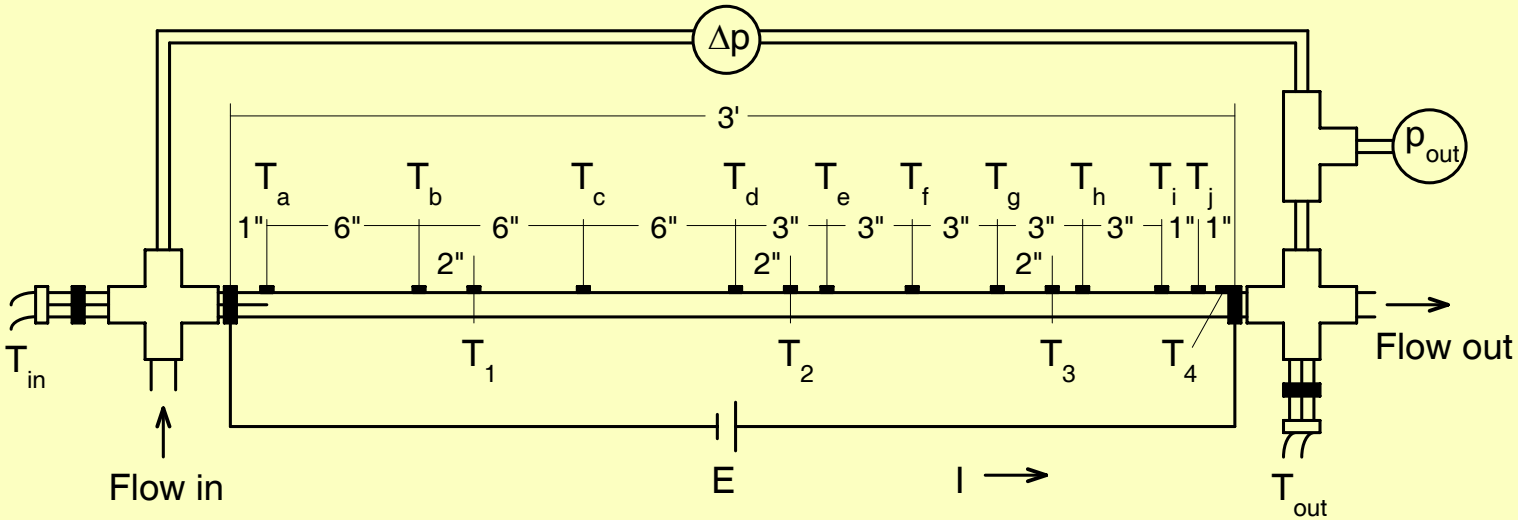
# Horizontal and Vertical Test Sections

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

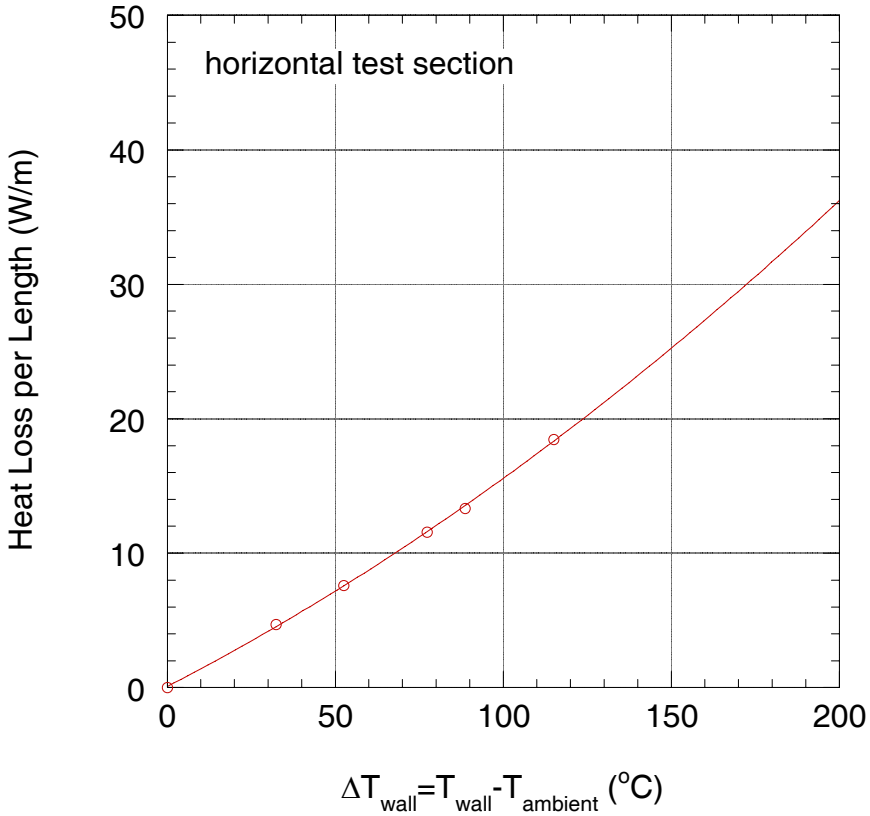
***The test section, fabricated from 2.98-mm-inside-diameter Type 316 stainless steel tubing, is resistance-heated with a DC power supply. During the experimental tests, ten wall temperatures, inlet and outlet fluid temperatures, outlet fluid pressure and overall pressure drop across the test section, and voltage drop across the test section and current through the test section were measured.***

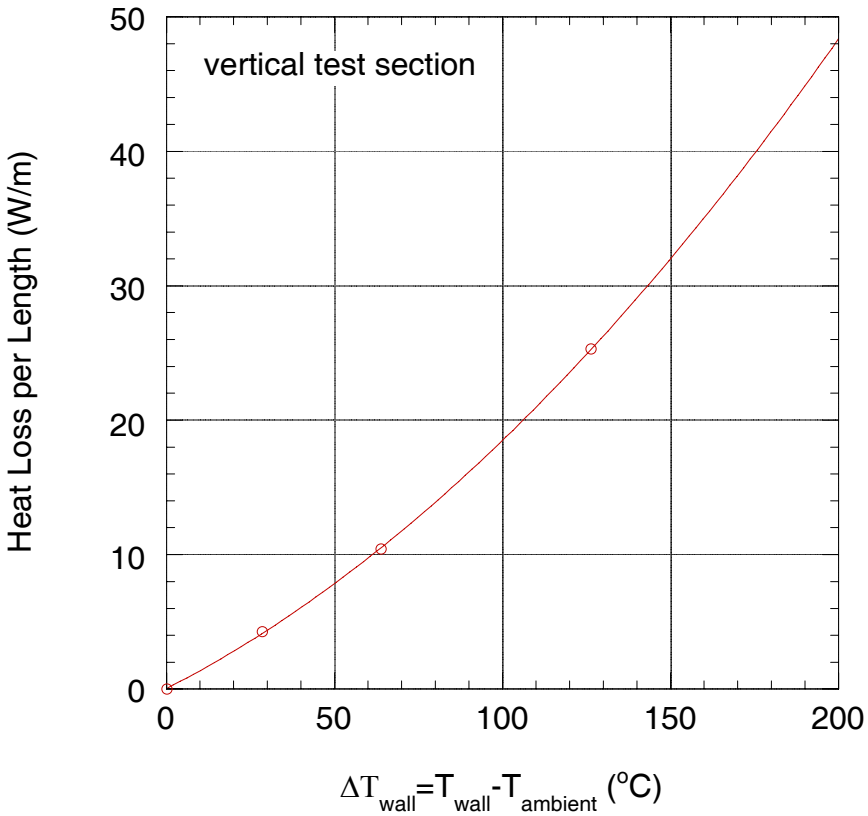
# Test Section Details




$T_a$, $T_b$, ..., $T_j$ : Test section wall temperature
$T_{in}$: Inlet temperature
$T_{out}$: Outlet temperature
$T_1$, $T_2$, $T_3$, $T_4$: Temperature interlock
$p_{out}$: Outlet pressure
$\Delta p$: Pressure drop across test section
E: Voltage drop across test section
I: Current through test section

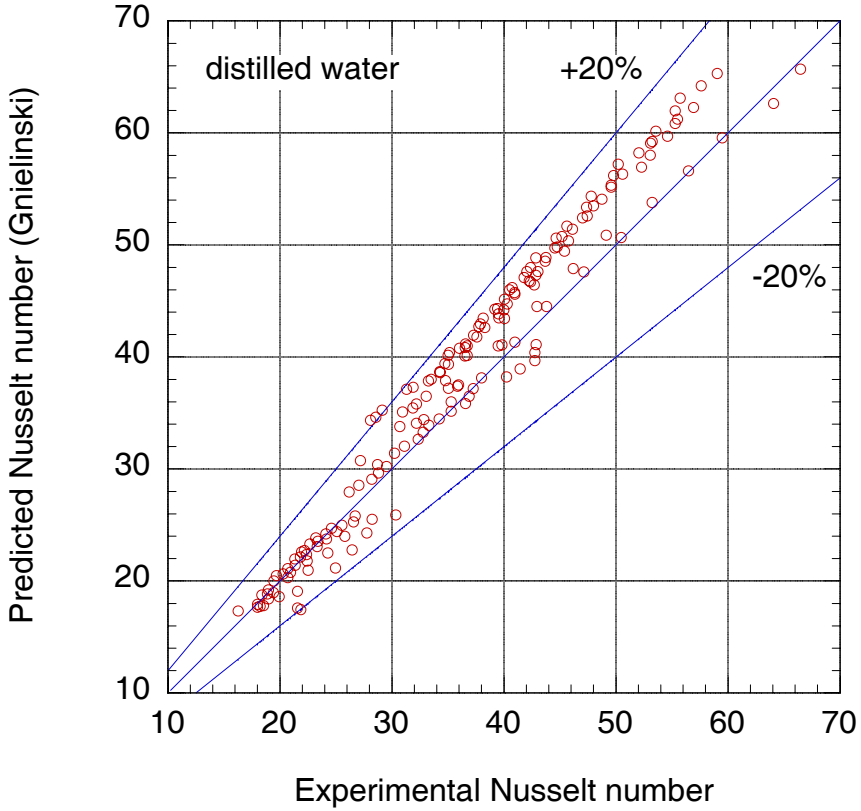
# Experimental Test Section Heat Losses

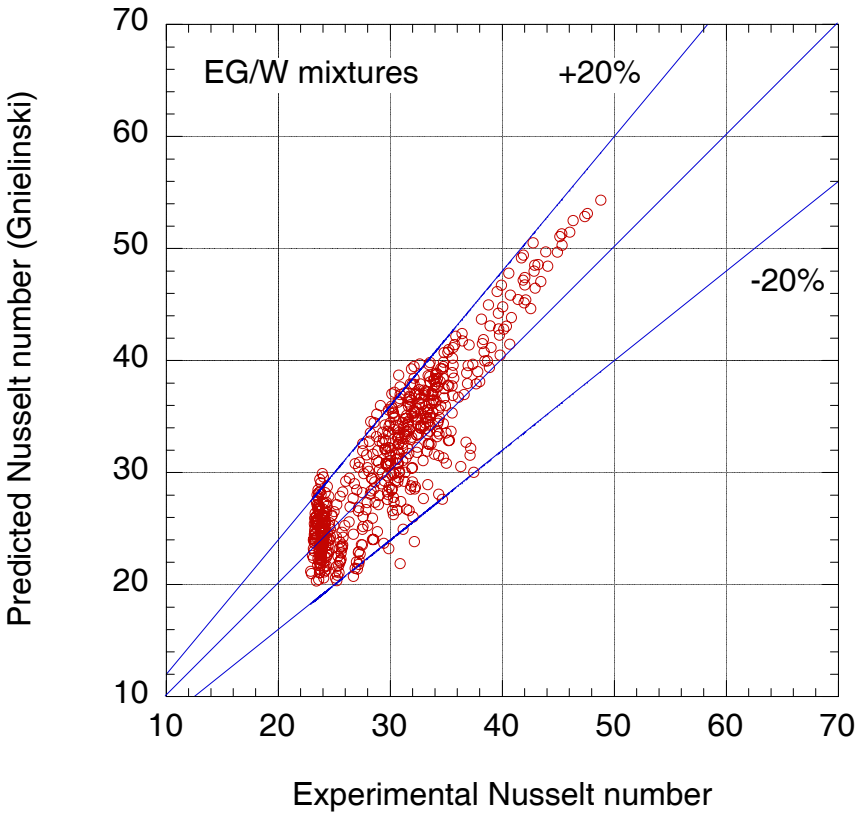



***The experimental test sections were well insulated thermally from the atmosphere to minimize heat losses to the environment. The test section heat losses were less than 1% of the applied heat in all two-phase heat transfer tests.***

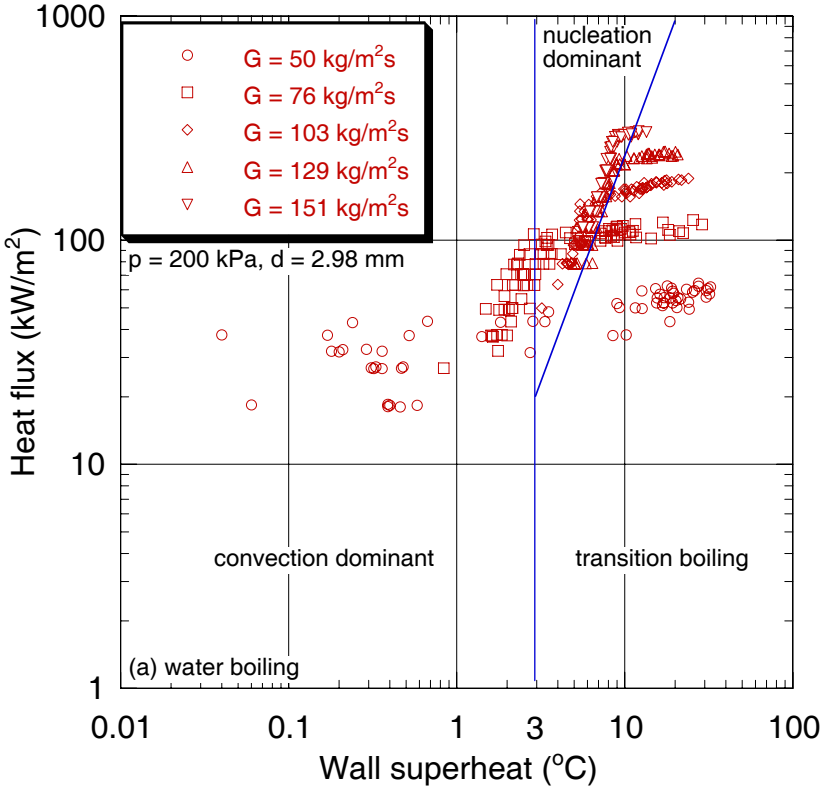
# Single-Phase Heat Transfer Comparison

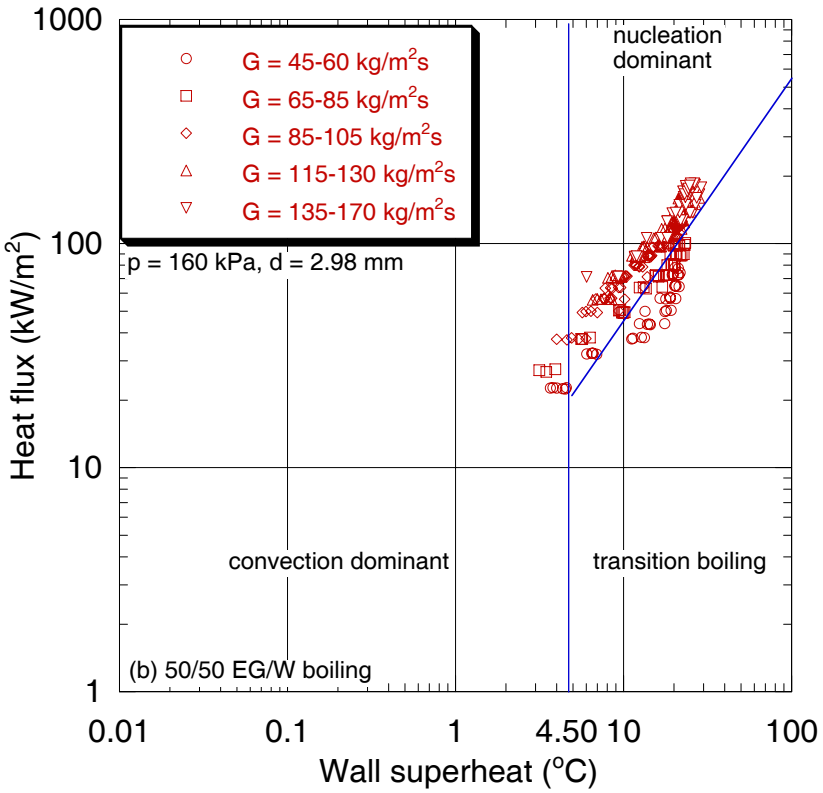



***Almost all experimental data are within ±20% of the predictions. These single-phase heat transfer test results serve as validation of the accuracy of the instrumentation, measurements, data acquisition, and data reduction procedures.***

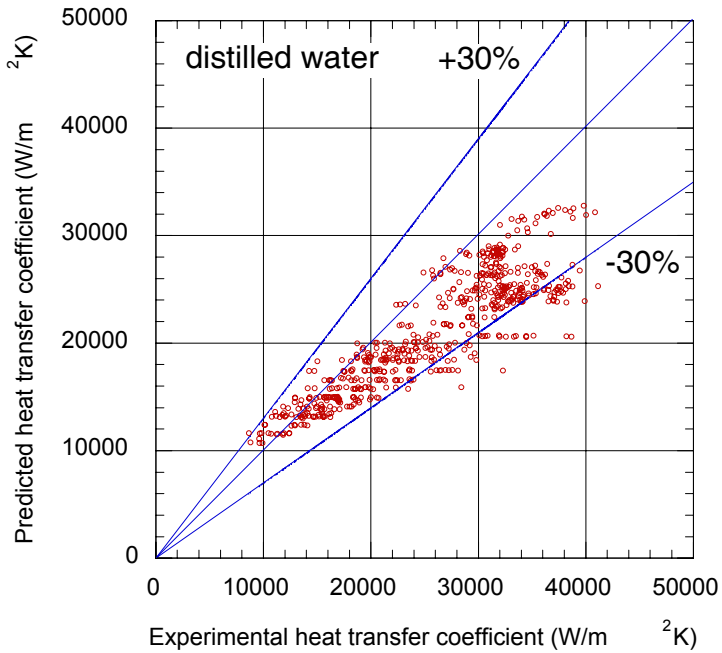
# Horizontal Flow: Three Flow Boiling Regions

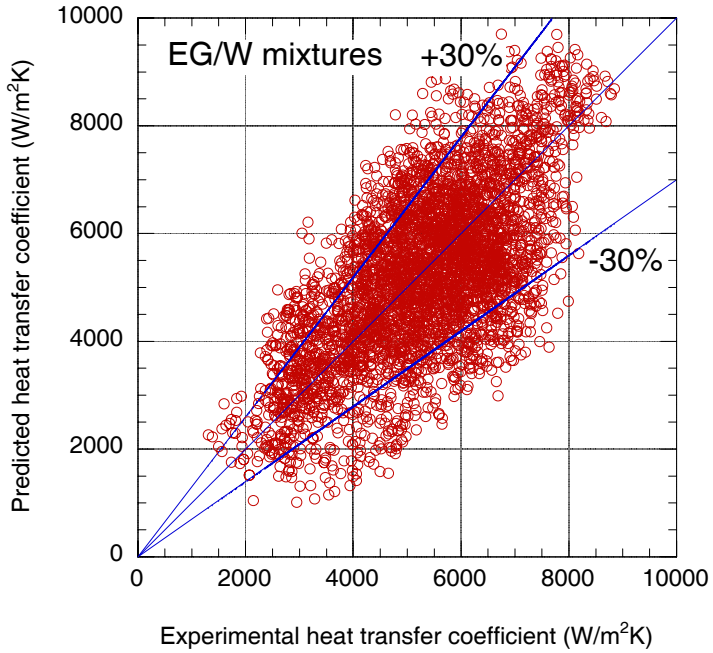



***In the present study, the heat flux in the nucleation-dominant boiling region was correlated as a function of the wall superheat because the boiling heat transfer data of water and ethylene glycol/water mixtures displayed a strong trend that the heat flux is dependent on the wall superheat but almost independent of the mass flux and inlet subcooling.***

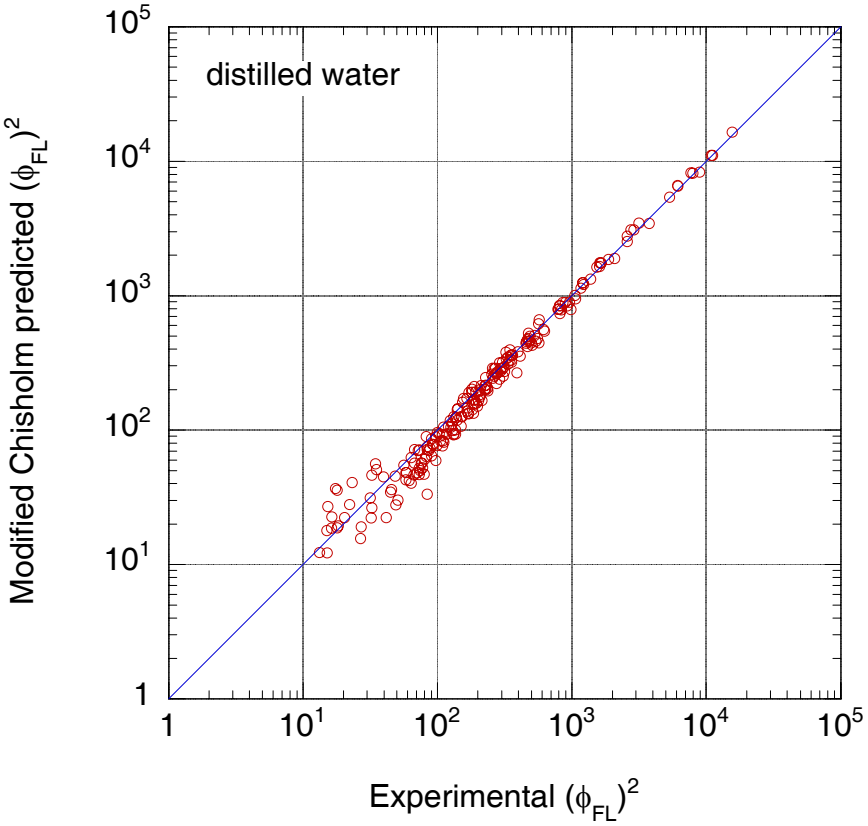
# Horizontal Boiling Heat Transfer Coefficient

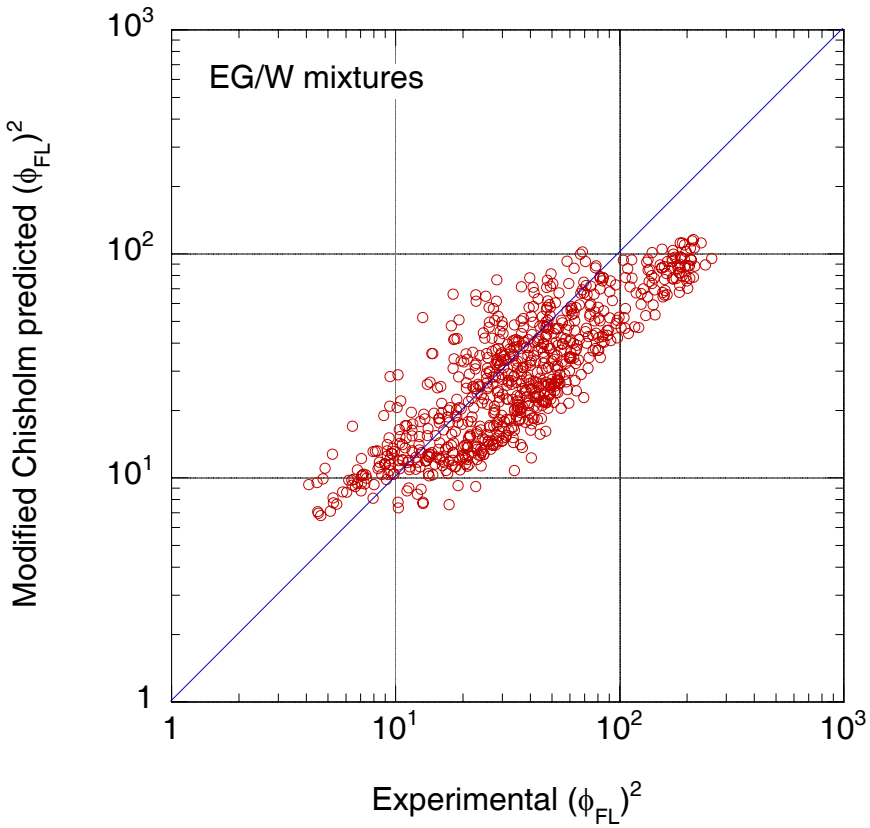



***The new developed correlation, a function of the mixture volume fraction, boiling number, Weber number, density ratio, and viscosity ratio, predicts the data well and most of the predicted values are within ±30% of the experimental data.***

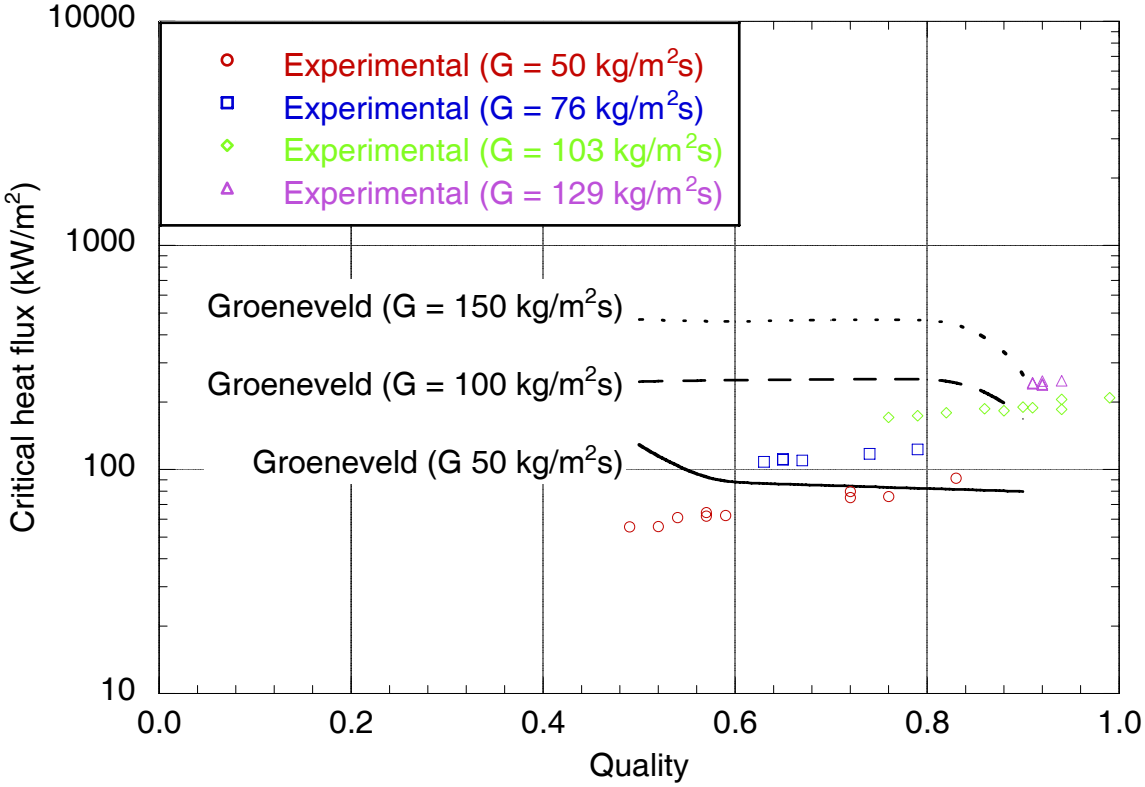
# Horizontal Flow: Frictional Pressure Gradient



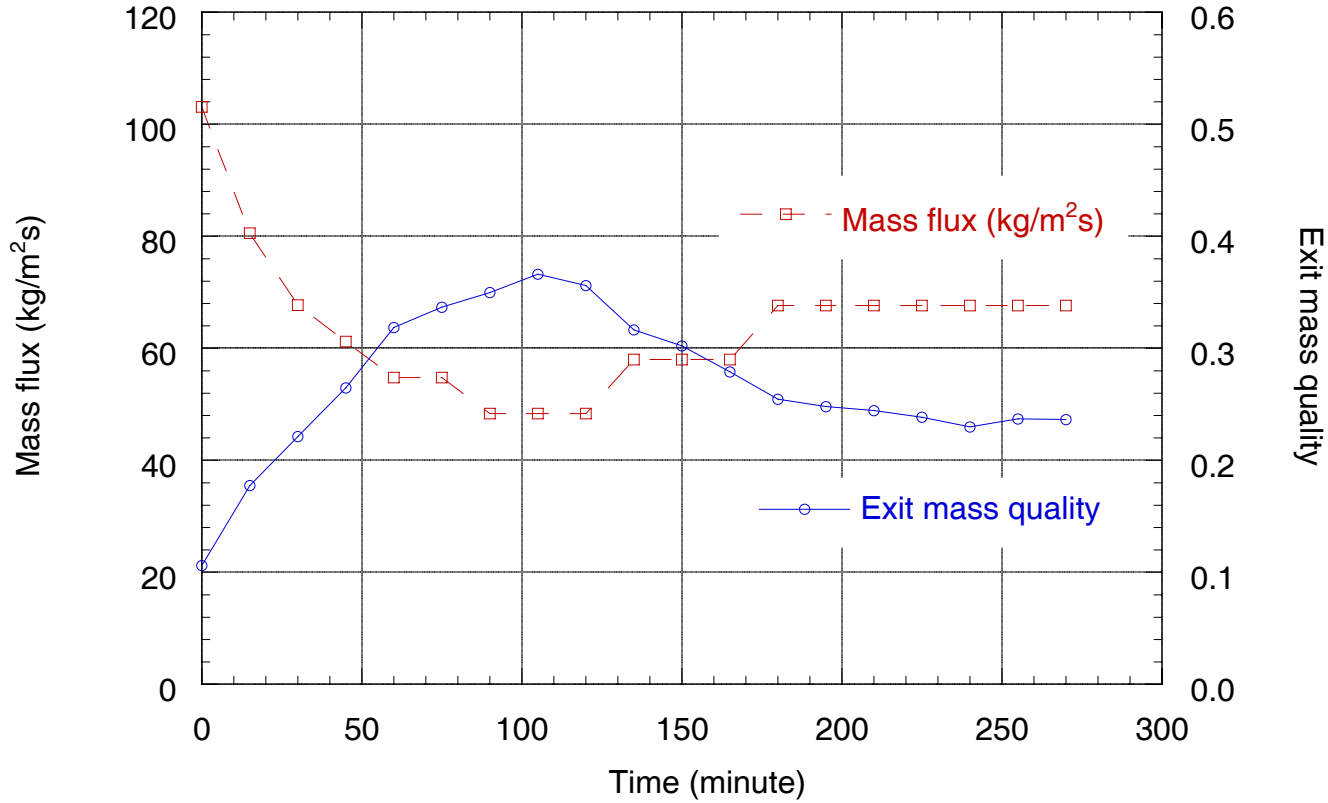

***Two-phase frictional pressure gradients of water and ethylene glycol/water mixtures are in reasonable agreement with the predictions of ChisholmÕs correlation. Modified ChisholmÕscorrelations improve the predictions of pressure drop data of water and ethylene glycol/water mixtures.***

# Horizontal Flow: Critical Heat Flux




***Critical heat fluxes of water boiling occurred at relatively high qualities between 0.5 and 1.0, which are higher than those found in large tubes; the CHF quality was found to decrease with decreased mass flux, which is opposite to that found in larger tubes. The Groeneveld-Cheng-Doan method provides an approximation of the CHF of the present study with correct trends for small tubes.***

# Horizontal Flow: Flow Rate Stability




***The boiling heat transfer of ethylene glycol/water mixtures is mainly limited by flow instability rather than critical heat fluxes. Tests show that stable long-term two-phase boiling flow is possible for ethylene glycol/water mixtures as long as the mass quality is less than a certain critical value (approximately <0.2).***

# Sample Peer Recognition of Program Results

***The first general journal paper form the program***

***Two-phase pressure drop, boiling heat transfer, and critical heat flux to water in a small-diameter horizontal tube***
***International Journal of Multiphase Flow, June 2002***

***received 21 citations July 2002 through December 2005 (unusually high number representative of pioneering work) including prominent researchers:***

***G. Hetsroni***
***I. Mudawar***
***S. G. Kandlikar***

## *Summary (Horizontal Flow)*

- ***Development of these engineering design data will enable more use of nucleate boiling in heavy vehicle cooling systems, thus reducing cooling system size and parasitic pumping losses***

- Measured two-phase frictional pressure gradients are in reasonable agreement with the modified Chisholm correlation
- Measured two-phase heat transfer rates are very high for both water and ethylene glycol/water mixtures and are in good agreement with the developed general correlation.
- Flow rate is stable at low mass qualities (<0.2) for ethylene glycol/water boiling
- There is a good potential for stable engine cooling at qualities <0.2

## *Future Work*

- Study the impact of flow directions on boiling heat transfer
  - Perform boiling heat transfer tests with distilled water
  - Perform boiling heat transfer tests with ethylene glycol/water mixtures

- Perform systematic experiments with alternative fluids (e.g. NPG, Cabot fluids)

- Investigate higher engine temperatures with higher ethylene glycol concentrations in coolant

# 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

$$F_v = \frac{9p_W(p_m - p_{EG})}{31p_m(p_W - p_{EG}) - 22p_W(p_m - p_{EG})}$$

$$x = \frac{31F_m(p_W - p_{EG}) - (9 + 22F_m)(p_m - p_{EG})}{31F_v(p_W - p_{EG}) - (9 + 22F_v)(p_m - p_{EG})}$$

$$T_{mi} = T_{mo} - \frac{\dot{Q}/\dot{m} + \left[F_{vi} i_{fgWi} + (1 - F_{vi}) i_{fgEGi}\right] x_i - \left[F_{vo} i_{fgWo} + (1 - F_{vo}) i_{fgEGo}\right] x_o}{\left[F_m C_{pWl} + (1 - F_m) C_{pEGl}\right]}$$

# Heat Transfer Prediction/Correlation

- Boiling ethylene glycol/water mixtures in small channels

$$h = 135000\left[1 + 6(0.5 - V)(1 - V)\right](\mathrm{BoWe}_l^{0.5})^{0.5}\left[(\rho_l/\rho_v)^{-0.5}(\mu_l/\mu_v)^{0.7}\right]^{-1.5}$$

- Predictions at various ethylene glycol/water mixture concentrations

| *water (%)* | *ethylene glycol (%)* |
|---|---|
| *100* | *0* |
| *60* | *40* |
| *50* | *50* |
| *40* | *60* |