# CRADA with PACCAR
# Experimental Investigation in Coolant Boiling in a Half-Heated Circular Tube


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May 16, 2012


Coworkers

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Project ID #
VSS079

# Overview

## Timeline

- Start – April 2010
- Finish – April 2013
- 60% Complete

## Budget

- Funding for FY10 – $100K (DOE)
- Funding for FY11 – $235K (DOE)
- Funding for FY12 – $300K (DOE)
  - Received $150K

## Barriers

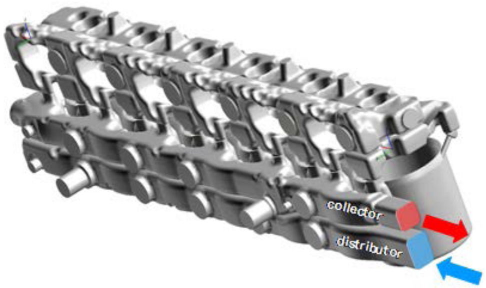
- Barriers
  - Constant advances in technology
  - Computation models and design and simulation methodologies
  - Lower component volumes and weights, smaller cooling system size, fewer parasitic energy losses, and higher engine thermal efficiency

## Partners

- PACCAR (CRADA) – in-kind cost share

# Objectives/Relevance

- Overall objective
  - Understand and quantify engine coolant boiling heat transfer in heavy duty trucks for
    - Increase cooling system efficiency with reduced cooling system size
    - Increase engine thermal efficiency through optimized thermal control
- Specific programmatic objectives
  - Experimentally determine boiling heat transfer rates and limits in the head region of heavy duty truck engines
  - Develop predictive mathematical models for boiling heat transfer coefficients
  - Provide measurements and models for development/validation of heavy duty truck engine computer code
- Relevance to Vehicle Technologies Program
  - Reduce parasitic energy losses
    - Reduce size, weight, and pumping power of cooling systems
  - Increase engine thermal efficiency
    - Optimize engine cooling
    - Improve engine temperature gradients
  - Overcome barriers
    - Technology advances in coolant boiling
    - Computational model improvement for heavy duty truck engine analysis

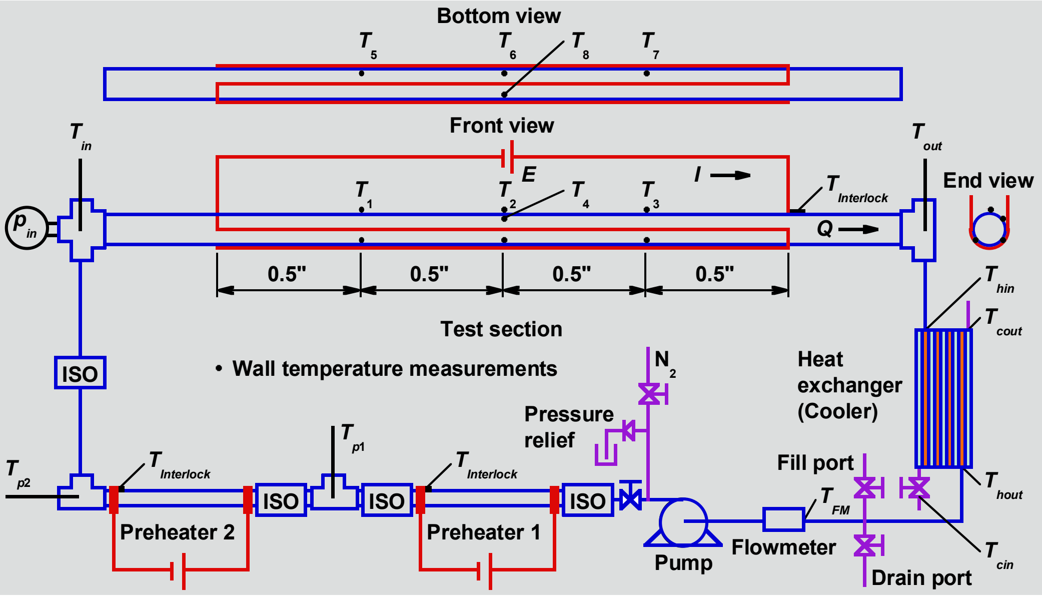


# Milestones

- June 2010 – Selection of experimental parameters, concept design of experimental facility, and power supply system rewiring (completed)
- September 2010 – Detailed design of experimental facility (completed)
- December 2010 – Procurement and fabrication of experimental facility components and  hardware/software for DAS (completed)
- March 2011 – Assembly of experimental facility (completed)
- June 2011 – Checkout, preliminary operation, and heat loss calibration of experimental facility (completed)
- September 2011 – Single-phase heat transfer tests and analyses (completed)
- March 2012 – Initial subcooled boiling heat transfer tests (completed)
- Sept 2012 – Tests and analyses of subcooled boiling in water, 50/50 mixture, and 25/75 mixture over a range of flowrates and subcoolings
- March 2013 – Boiling heat transfer tests and analyses, comparisons with exiting prediction equations, and modifications as required

# Experimental Approach

- New experimental facility based on Argonne National Laboratory unique experience with boiling of 40/60, 50/50, and 60/50 ethylene glycol/water mixtures
  - Simulation of cylinder head in a 500 hp diesel engine
  - Geometry, flow, and energy simulation (inside diameter=11 mm, length=51 mm, flow speed=1.5 m/s)
  - Boiling of pure water, 50/50 ethylene glycol/water mixture, and 25/75 ethylene glycol/water mixture
- New applications to very high heat flux boiling conditions in cylinder head

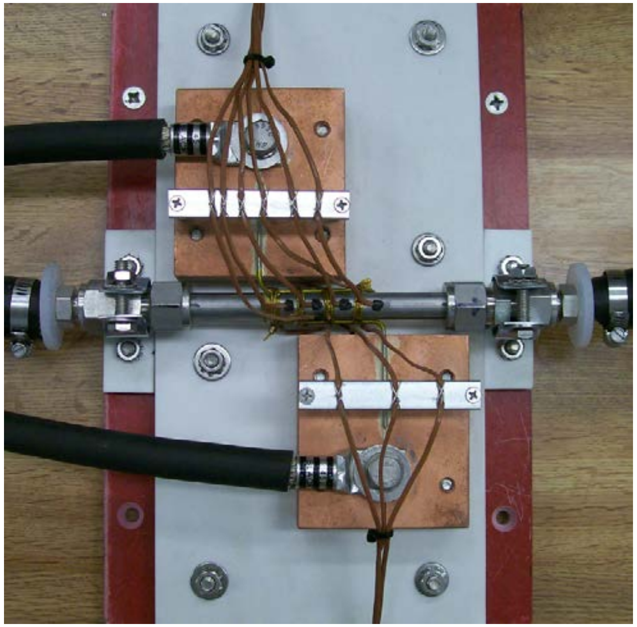


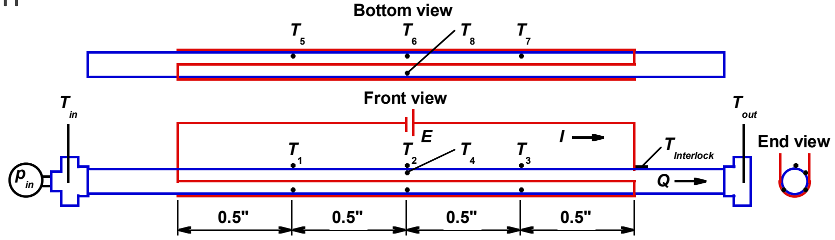
# Accomplishments – Experimental Test Facility

- Key parameters for experimental test facility
  - Test section – round cast iron tube with 11 mm inside diameter and 51 mm length
  - High fluid flowrate – up to 1.5 m/s
  - Heating –half heated test section, high heat flux for preheating and test section heating
- Key solutions for test facility design and fabrication challenges
  - Preheaters
    - Dual preheating arrangement, Double-stacked U-shape preheaters
    - Appropriate preheater length and wall thickness for optimizing power output
  - Heat exchanger (cooler)
    - Compact plate and frame heat exchanger
    - Efficiently rejecting large amount of heat
  - Pump
    - Enough pump head and flowrate range
    - Operation temperature up to 110 C
  - Balance of system piping
    - Acceptable pressure drop
  - Data acquisition system
    - LabVIEW program
    - On-screen data display
    - On-screen graphic display – temperature curves
    - On-screen control button display

# Accomplishments – Experimental Test Section

- Key design and fabrication challenges
  - Short test section length
  - Half-heated around the test section circumference
  - High heat flux
  - No current through the test section
- Test section heating solutions
  - Stainless steel wire for half heating the test section
  - Appropriate heating wire size (diameter and length)
    - For optimizing power output
  - Electrical insulation
    - No current flowing through the test section
- System instrumentation
  - Eight wall thermocouples installed
    - Along the test section
    - Around the test section circumference
  - Test fluid temperatures – test section inlet and outlet fluid in-stream thermocouples
  - Other temperature measurements and interlocks
  - Test section inlet pressures – absolute pressure transducer
  - Test fluid flowrates – electromagnetic flowmeter



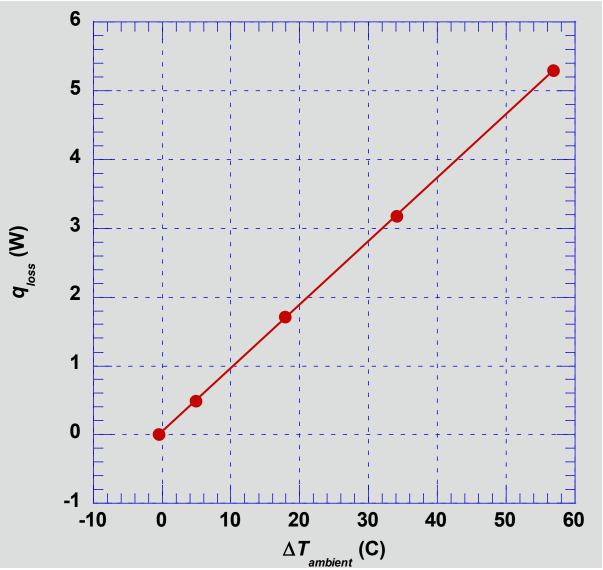


# Accomplishments – Heat Loss Calibration

- Well-insulated experimental test section
  - Minimized heat loss to the environment
    - Heat loss is not negligible during flow boiling heat transfer experiments because of the relatively high driving temperatures

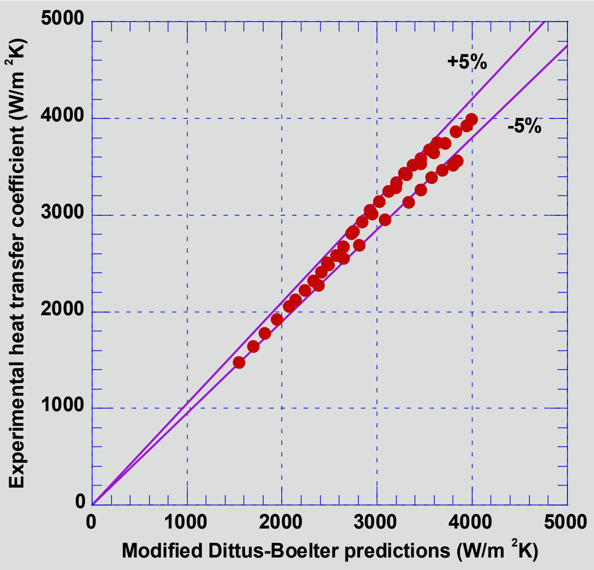
- No flow heat loss tests
  - Applied five power inputs to bring its wall temperature to selected levels
    - Corresponding heat loss=applied power

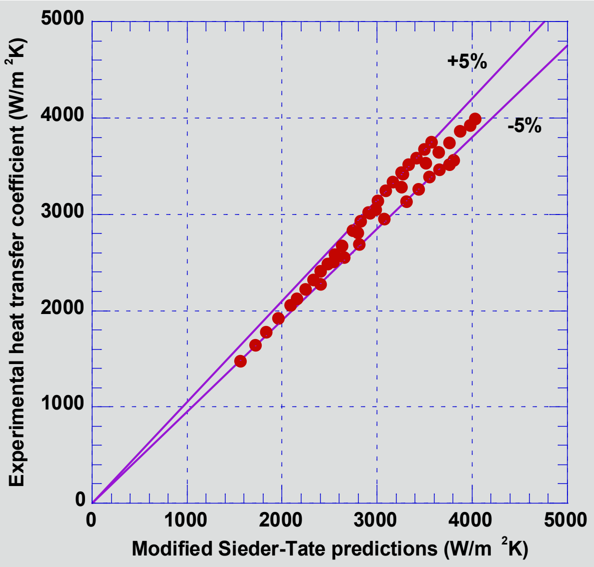
- Heat loss characteristics
  - Minimized heat loss
    - Expected to be less than 1% of the applied power
  - Linearly depended on driving temperature difference
    - Predicted well with the fitting equation
  - Incorporated into the data reduction procedures
    - For single-phase heat transfer tests
    - For boiling heat transfer tests



# Accomplishments — Single-Phase Heat Transfer

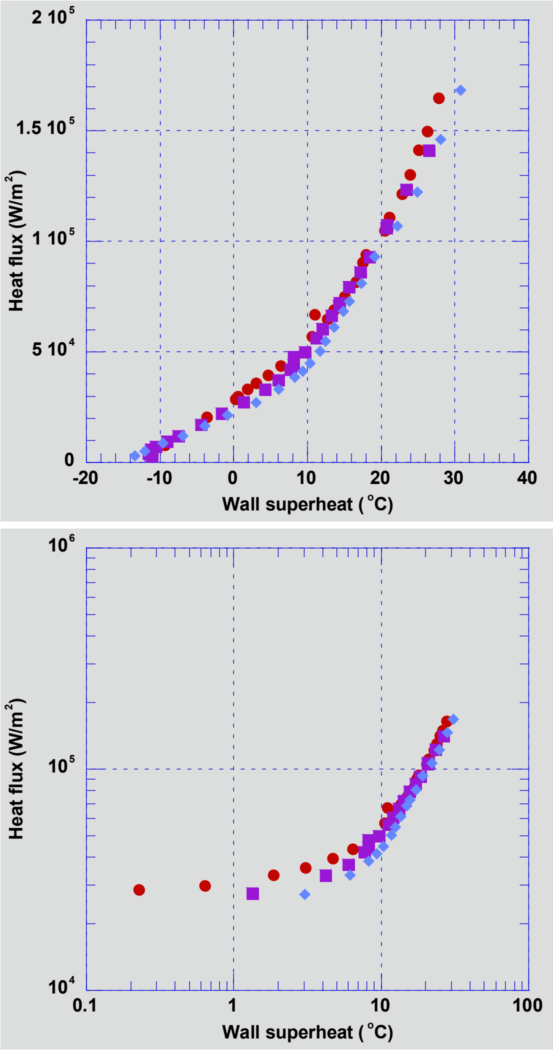
- Single-phase heat transfer experimental parameters
  - Wall temperature: 35–85 C
  - Fluid temperature: 20–75 C
  - Reynolds number: 2400–42000
  - Prandtl number: 2.35–6.90
  - Flow velocity: 0.22–1.47 m/s
    - Covering boiling flowrate range
- Modified Dittus-Boelter equation
  - $h=0.4020Re^{0.4465}Pr^{0.4}(k/d)$
- Modified Sieder-Tate equation
  - $h=0.4920Re^{0.4326}Pr^{1/3}(\mu_{fluid}/\mu_{wall})^{0.14}(k/d)$
- Single-phase heat transfer coefficients
  - Very well predicted by the modified equations
  - Most experimental data within ±5% ranges



# Accomplishments — Two-Phase Flow Boiling Curve

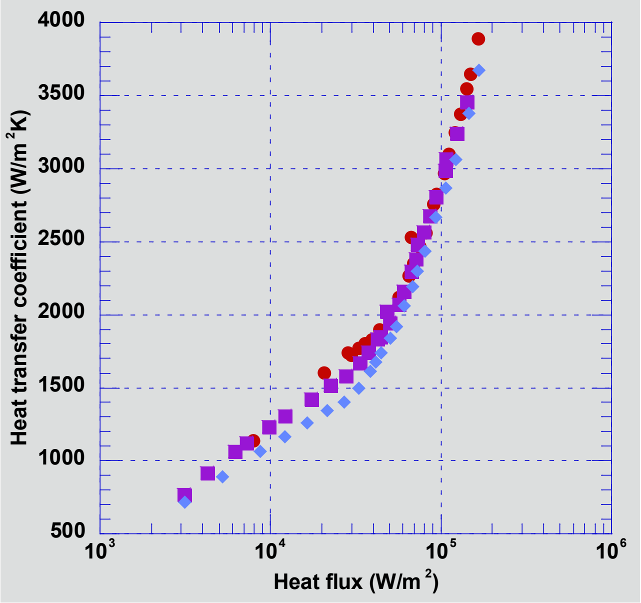
- Bulk fluid temperature
  - Lower than fluid saturation temperature
    - Subcooled boiling
- Wall temperature
  - Higher than fluid saturation temperature
- Wall superheat
  - Increases with the heating power input
  - Two slopes
    - Single-phase: small increase in heat flux → large increase in wall superheat
    - Two-phase boiling: similar increase in heat flux → lower increase in wall superheat
  - Up to approximate 30 C
- Boiling curve
  - Generated for water (to be extended over a range of flowrates and subcoolings and to ethylene-glycol/water mixtures – see Proposed Future Work)



# Accomplishments — Two-Phase Heat Transfer

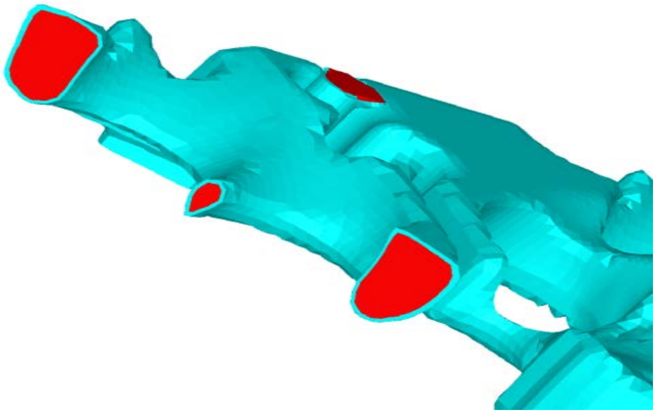
- Two-phase subcooled boiling experimental parameters
  - Wall temperature: 90–140 C
  - Fluid temperature: approximate 85 C
  - Subcooling: approximate 16 C
  - Reynolds number: 4000
  - Prandtl number: 2.10
  - Flow velocity: 0.125 m/s

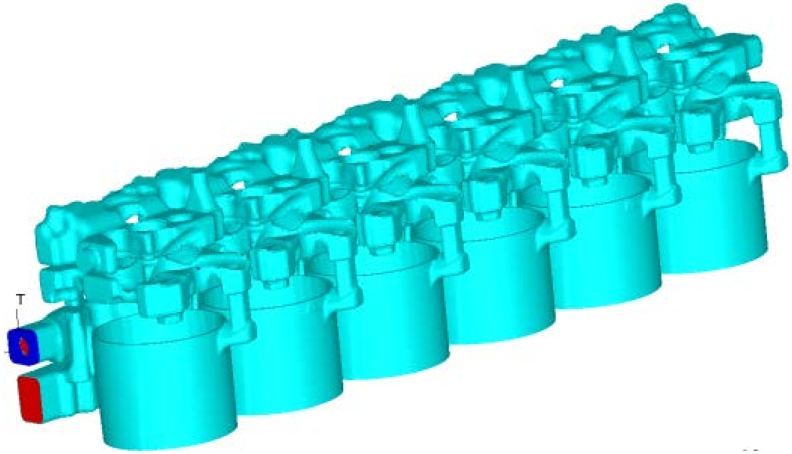
- Heat transfer coefficients under current conditions
  - Two different trends versus heat flux
    - Single-phase convection dominant
    - Two-phase boiling dominant
  - Initial boiling at heat flux approximate 40000 W/m $^2$
  - Boiling heat transfer coefficient up to 4000 W/m $^2$ K



# Collaboration with Other Institutions

- Partner
  - PACCAR/DAF
  - CRADA in place for the joint program
    - With in-kind cost share
- Boiling experimental work
  - PACCAR/DAF: specifying test parameters
  - Argonne: performing experimental work
  - Argonne and PACCAR/DAF: exchanging technical and project progress information
- Computer code optimization and validation
  - PACCAR/DAF: performing code optimization and validation
  - Argonne and PACCAR/DAF: exchanging technical information
- Interpretation and evaluation of results
  - Combined effort of Argonne and PACCAR/DAF





# Proposed Future Work

- Coolant boiling heat transfer tests
  - Test fluids: pure water, 50/50 ethylene glycol/water mixture, and 25/75 ethylene glycol/water mixture
  - Flow speed range up to 1.5 m/s
  - Test fluid subcooled temperature levels

- Experimental data analyses
  - Boiling data reduction procedure and Excel spreadsheet
  - Experimental data comparison, interpretation, and correlation
    - Comparison between the experimental data and the theoretical predictions
    - Interpretation of experimental data (heat transfer coefficients and possible critical heat fluxes)
    - Correlation of boiling heat transfer coefficients

- Computer code optimization and validation

# Summary

- Completed concept and detailed designs of experimental facility with specified test section size, test section material, test fluid flowrates, heating method, and heat rates
  - Successfully resolved many technical challenges in design
- Designed and fabricated/purchased experimental facility components including test section, preheaters, heat exchanger (cooler), fluid pump and controller, power supply controller, and instrumentation
  - Successfully overcame many technical challenges in fabrication
- Completed heat loss calibration and single-phase heat transfer tests of experimental facility and initiated boiling tests
  - Successfully developed single-phase predictive equations
- Accomplished all intended objectives on schedule
  - Currently running boiling heat transfer tests
- Work planned for next year and beyond
  - Boiling heat transfer tests
  - Experimental data comparison, interpretation, and correlation
  - Computer code optimization and validation