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

Wenhua Yu

Energy Systems Division, Argonne National Laboratory

May 9, 2011

Coworkers

David M. France, Jules L. Routbort, and Roger K. Smith

Project ID # VSS057

Overview

Timeline

- Start – April 2010
- Finish – April 2013
- 25% Complete

Budget

- Funding received in FY10 – $100K (DOE)
- Funding received in FY11 – $101K (DOE)
  - Continuing resolution

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

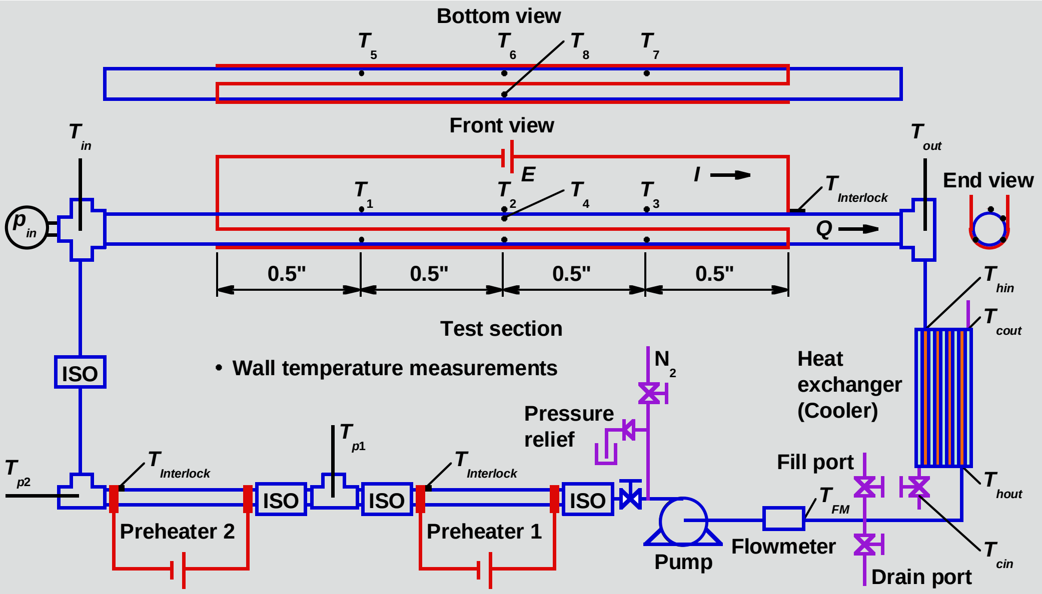
- Overall objective
  - Understand and quantify engine coolant boiling heat transfer in heavy duty trucks for
    - Increase cooling system efficiency with reduced cooling system size
    - Increase engine thermal efficiency through optimized thermal control
- Specific programmatic objectives
  - Experimentally 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 (completed in June 2010)
- June 2010 – Concept design of experimental facility (completed in June 2010)
- June 2010 – Power supply system rewiring (completed in June 2010)
- September 2010 – Detailed design of experimental facility (completed in September 2010)
- December 2010 – Procurement and fabrication of experimental facility components (completed in December 2010)
- December 2010 – Hardware and software of data acquisition system (completed in December 2010)
- March 2011 – Assembly of experimental facility (near completion)
- June 2011 – Checkout, preliminary operation, and heat loss calibration of experimental facility
- September 2011 – Complete single-phase heat transfer tests and analyses
- March 2013 – Complete boiling heat transfer tests and analyses

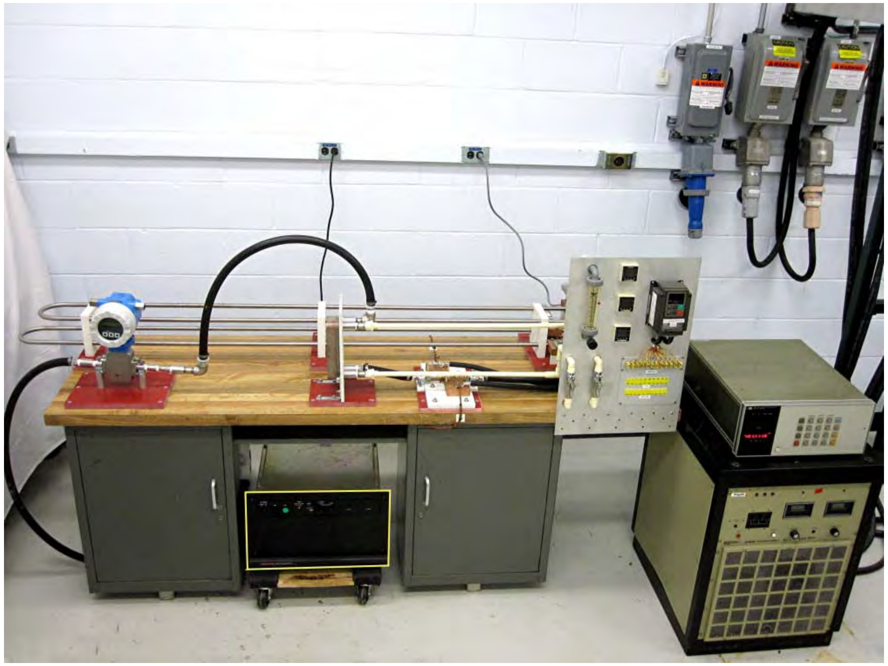
Experimental Approach

- 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
  - Boiling of pure water, 25/75 ethylene glycol/water mixture, and 50/50 ethylene glycol/water mixture
- New applications to very high heat flux boiling conditions in cylinder head



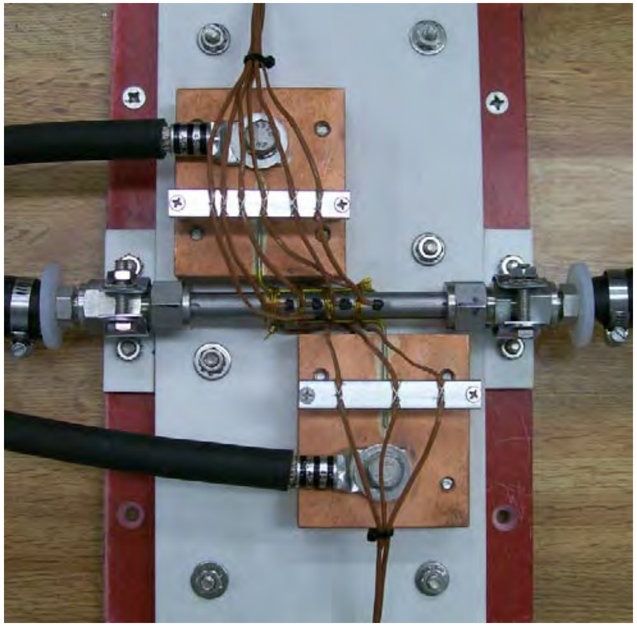
Accomplishments — Experimental Facility Design

- Test section design considerations
  - Size set by head geometry of a 500 hp diesel engine
  - Cast iron material
  - Heating methods and high heat input rates
  - Appropriate instrumentation
- Preheater design considerations
  - 30 C temperature rise
  - Acceptable pressure drop
- Heat exchanger design considerations
  - High heat rejection rates
  - Cooling water discharge
- Pump choice considerations
  - Flow higher than 1.5 m/s
  - Sufficient head
  - Operation temperature up to 110 C
- Balance of system piping
  - Acceptable pressure drop
  - Appropriate test fluid circulation time



Accomplishments — Experimental Test Section

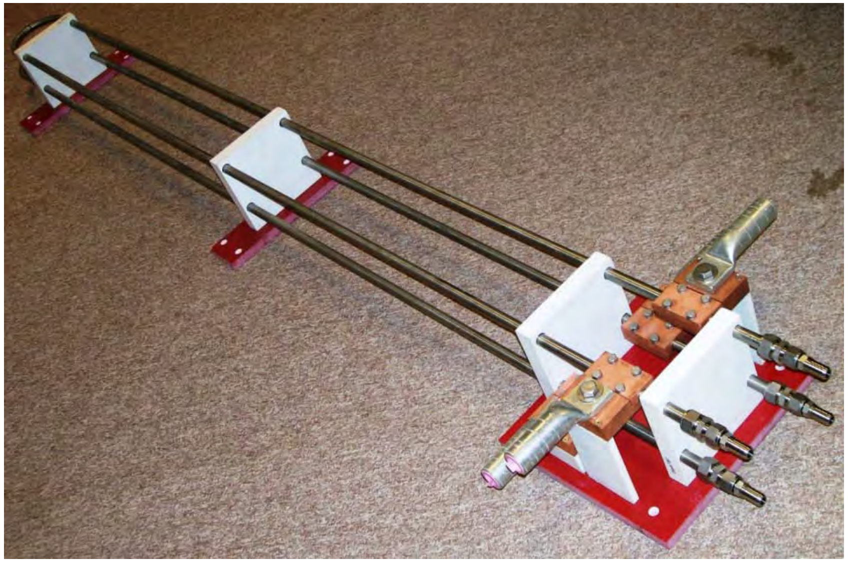
- Design and fabrication challenges
  - Short test section length
  - Enough thermocouples for temperature measurements
  - Half-heated around the test section circumference
  - High heat flux
  - Heating matched to power supply
  - No current through the test section



- Solutions
  - Eight thermocouples installed
    - Along the test section
    - Around the test section circumference
  - Stainless steel wire for half heating the test section
  - Appropriate heating wire size for optimizing power output
  - Electrical insulation for preventing current from flowing through the test section

Accomplishments — Preheaters

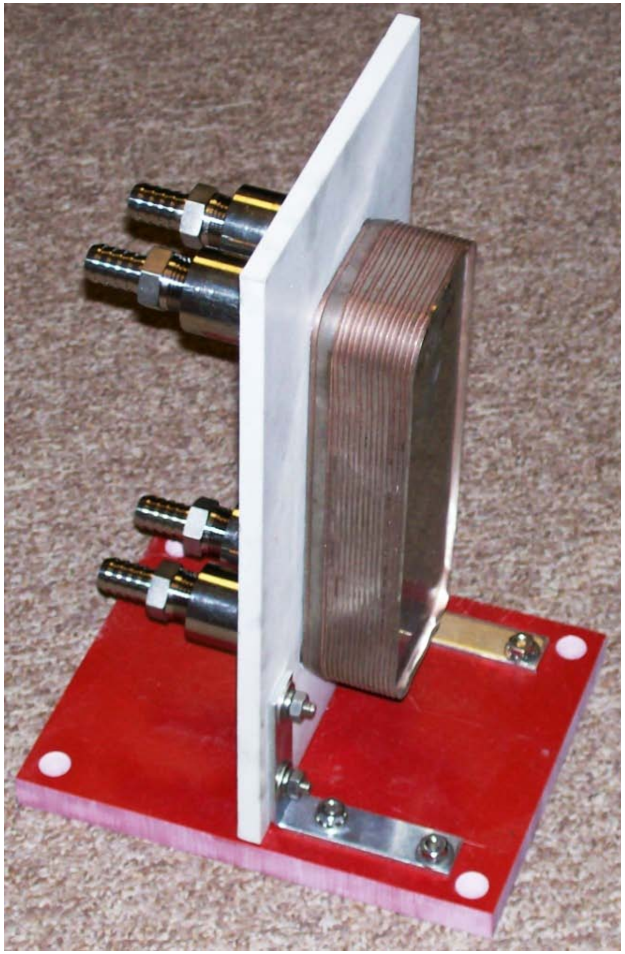
- Design and fabrication challenges
  - High test fluid flowrates
  - Large test fluid volume preheating
  - Maximum power supply output limited



- Solutions
  - Laboratory electrical wiring upgrade for accommodating high current for this project
  - Dual preheater arrangement for utilizing two existing power supplies
  - Double-stacked U-shape preheaters for saving space
  - Appropriate preheater inside diameter for accommodating the design flowrates
  - Appropriate preheater length and wall thickness for optimizing power output

Accomplishments – Heat Exchanger (Cooler)

- Design and fabrication challenges
  - High test fluid flowrates
  - Large amount of heat to be rejected
  - Laboratory tap water as the heat rejection medium



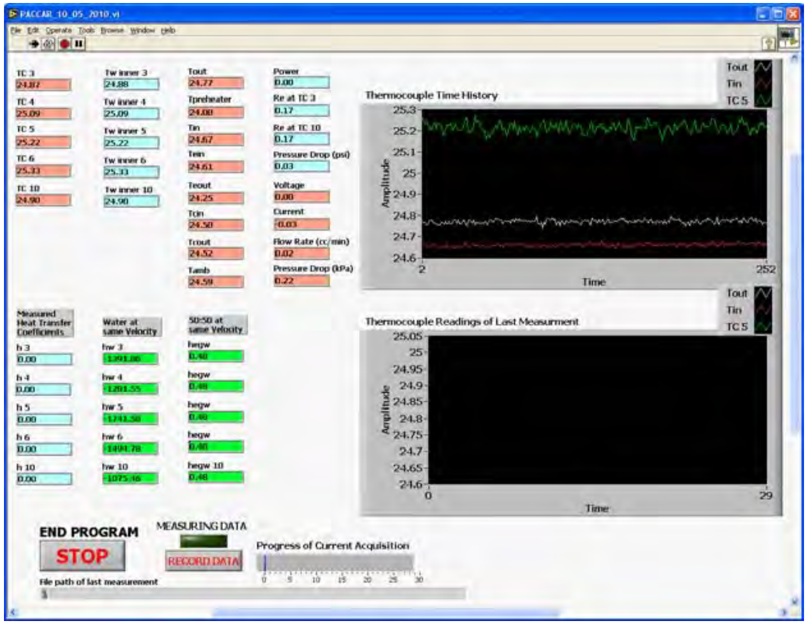
- Solutions
  - Compact plate and frame heat exchanger – for efficiently rejecting large amount of heat
  - Cooling water flowrate ~11 l/min – less than the maximum laboratory tap water flowrate ~22 l/min
  - Cooling water outlet temperature <110 F – acceptable for directly discharging into the drain system

Accomplishments — Instrumentation

- Wall temperatures – eight wall thermocouples along the test section and around the test section circumference
  - For measuring test section wall temperatures and their distributions
  - For calculating boiling heat transfer coefficients
  - For analyzing boiling heat transfer limits (critical heat flux and flow stability)
- Test fluid temperatures – test section inlet and outlet fluid in-stream thermocouples
  - For calculating boiling heat transfer coefficients
- Test section inlet pressures – absolute pressure transducer
- Test fluid flowrates – electromagnetic flowmeter
  - For calculating boiling heat transfer coefficients
- Preheater temperatures – preheater outlet thermocouples
- Test fluid and cooling water temperatures – heat exchanger (cooler) inlet and outlet thermocouples
- Safety interlocks – test section and preheater temperature interlocks

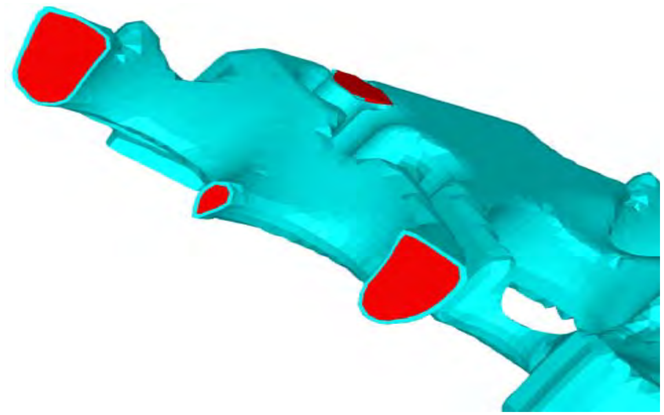
Accomplishments — Data Acquisition System

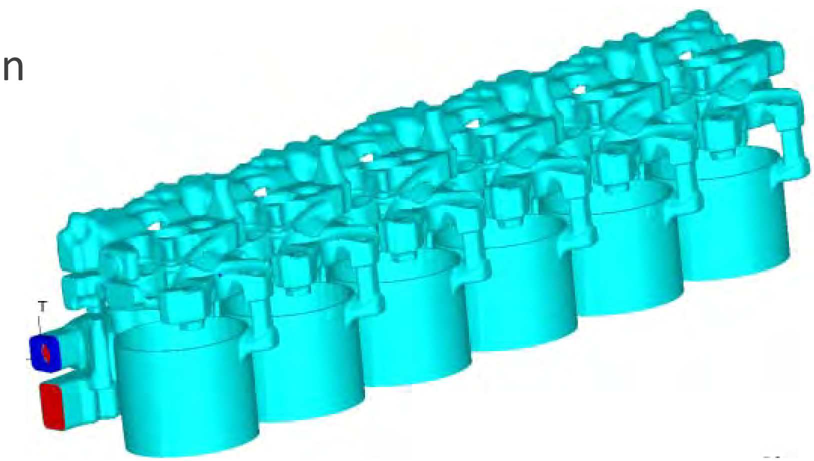
- Data acquisition system hardware
  - Dell Optiplex GX270 personal computer
  - Hewlett Packard HP 75000 Series B Multiplexor
  - Hewlett Packard HP E1347A Thermocouple Relay Mux
- Data acquisition system LabVIEW software
  - On-screen data display
    - Wall and test fluid temperatures
    - Test fluid pressure
    - Test fluid flowrate
    - Heating power
    - Heat transfer coefficients
  - On-screen graphic display
    - Wall and test fluid temperatures
  - On-screen control button display
    - Program start and stop
    - Data record



Collaboration with Other Institutions

- Partner
  - PACCAR/DAF
  - CRADA in place for the joint program
    - With in-kind cost share
- Boiling experimental work
  - To be performed by Argonne National Laboratory
- Computer code optimization and validation
  - To be performed by PACCAR/DAF
- Interpretation and evaluation of results
  - Combined effort





Proposed Future Work

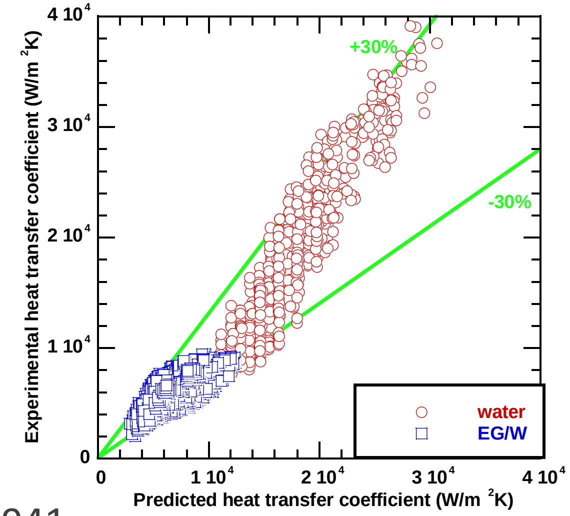
- Continue and complete experimental facility fabrication
- Verify experimental facility
  - Experimental facility checkout
  - Preliminary experimental facility operation
  - Heat loss tests and dependence of the heat loss on the test section wall temperature
  - Data reduction Excel spreadsheet for single-phase heat transfer
  - Single-phase heat transfer tests and comparison between experimental data and predicted results
- Coolant boiling heat transfer tests and experimental data analyses
  - Boiling data reduction procedure and Excel spreadsheet
  - Coolant boiling heat transfer tests
    - Test fluids: pure water, 25/75 ethylene glycol/water, and 50/50 ethylene glycol/water
    - System pressures: 100–400 kPa
    - Flow speeds: <1.5 m/s
    - Test fluid inlet temperatures: from room temperature to slightly subcooled
  - Experimental data comparison, interpretation, and correlation

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
- Accomplished all intended objectives on schedule
  - Currently finishing assembly of experimental facility
- Well positioned for work planned for next year and beyond
  - Experimental facility verification
  - Boiling heat transfer tests
  - Experimental data comparison, interpretation, and correlation
  - Computer code optimization and validation

Accomplishments from the Related Prior Project

- Completed program on boiling of ethylene glycol/water mixtures under various test parameters: system pressure, test section inlet temperature, ethylene glycol concentration, flow direction, and mass flux
- Developed a data reduction procedure for calculating the boiling temperatures along the test section
- Obtained, interpreted, and correlated experimental boiling data
  - Boiling curve
  - Two-phase pressure drop
  - Boiling heat transfer coefficient
  - Critical heat flux and flow stability



- Publications
  - Journal of ASTM International 8 (2011) JAI103378
  - DOE final project report ANL – 10/39 (2010)
  - Experimental Heat Transfer 18 (2005) 243-257
  - International Journal of Multiphase Flow 28 (2002) 927-941
  - Proceedings of VTMS 5 (2001) 205-211