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Overview of

Thermal Management

Jules Routbort
Energy Systems Division
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Coworkers:
E. Timofeeva, D. Smith, D. France, W. Yu, D. Singh, and R. Smith

Project ID # vss_13_routbort

Vehicle Technologies – Annual Review – May 18-22, 2009

*Sponsored by **Systems Optimization**, and **Propulsion Systems Materials**, & partial support from Michelin, Saint Gobain, Tardec, and the Industrial Technology Program, CRADA with PACCAR*

Project Organization

Nanofluid Development for Engine Cooling Systems
Control of Thermal Conditions Underhood
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* ≈ 4.1 M
  - DOE ≈ 3.2 M
  - Contractor ≈ 0.9 M
- FY08 ≈ 1.0 M (DOE)
- FY09 ≈ 1.3 M (DOE)

Barriers

- Reduction of radiator weight, aerodynamic drag, and parasitic energy losses by engineering stable nanofluids having
  - -High thermal conductivities
  - -High heat transfer
  - -Low viscosity
  - -Environmentally friendly
  - -Result in no damage to radiator materials

Partners

- Tardec/WFO
- Saint Gobain-cost share
- Michelin WFO & cost-share
- PACCAR (CRADA in progress)
- Industrial Technologies Program (DOE)

**supports five programs in thermal management (FY06-FY09)*

Thermal Management

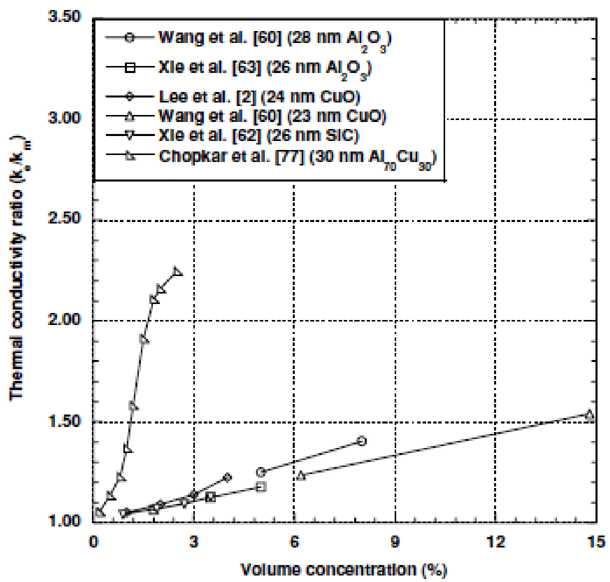
- Thermal management of heavy vehicle engines and support systems is a technology that addresses reduction in energy usage through improvements in engine thermal efficiency and reductions in parasitic energy uses and losses

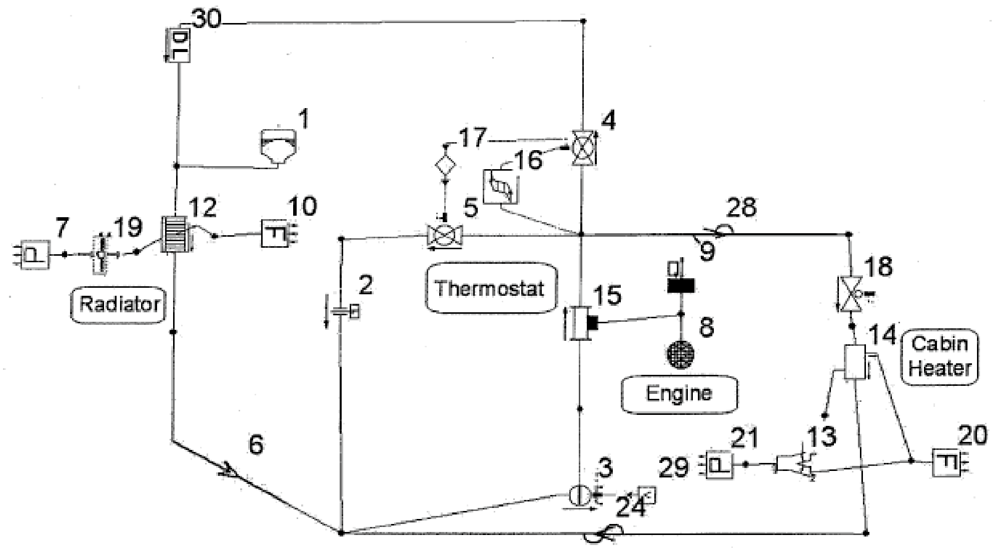
Dr. Sid Diamond, Mid-America Truck Show, photo by Routbort

With permission from PACCAR

Why Nanofluids?

- Enhanced thermal conductivity
- Enhanced heat transfer coefficient? $h \propto k^{0.6}$
- CFD of a Cummins 500 hp engine using an "ideal" nanofluid indicated a 5% reduction in radiator size (SAE-2007-01-2141)





Objectives

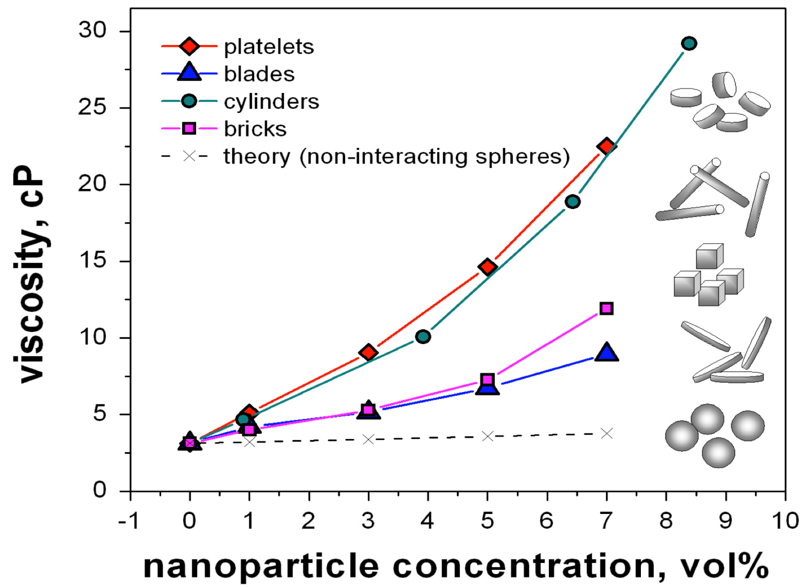
- This work addresses the possibilities of using nanofluids or other cooling schemes to increase the efficiency of heat rejection in cooling applications thereby reducing the heat exchanger size, weight and possibly shape.
- Components of this interrelated program are:
  - Development and characterization of nanofluids, (Poster)
  - Experimental measurements and theoretical analysis of heat transfer characteristics of nanofluids (Poster)
  - Investigation of the erosion effects of nanofluids (Poster)
  - Nucleated boiling of ethylene glycol/water (Poster only).

Milestones

- FY08 *(all completed)*
  - Identify critical barriers
  - Initiate collaborations
  - Thermal and viscosity characterization of some potential promising nanofluids produced by industry and ANL
  - Heat transfer measurements of most promising
  - Comparison of theory/experiments
- FY09
  - Nanofluid viscosity modification without changing thermal properties
    - *Particle shape/size*
    - *Surface chemistry*
  - Explore nanoparticles with higher thermal conductivities
  - CFD to determine nanofluid optimum thermal properties
  - Measure erosion and pumping power
  - Develop further collaborations with industry
    - *Heat transfer of nanofluids*
    - *Evaporative cooling for high heat loads*

Potential Barriers

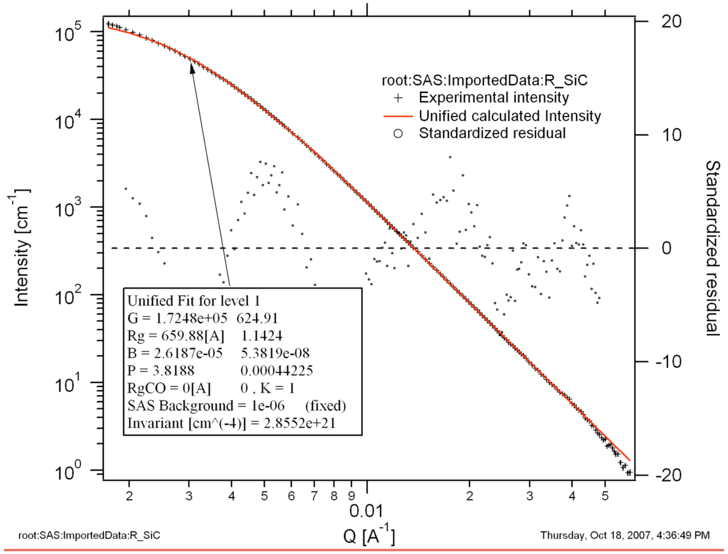
- Viscosity
- Segregation (settling)
- Lack of general predictive theory for thermal properties
- Possible damage to radiator systems/materials
- Cost effective manufacturing (scale up from laboratory)



Approach

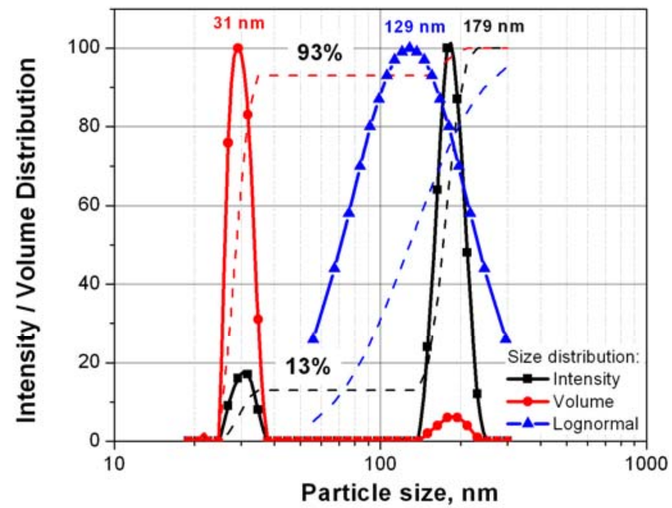
- Use existing theories and extensive experimental results to select nanoparticles that when dispersed in ethylene glycol-water might have the best cooling performance with little or no penalty on pumping
- Compare experimental results of thermal conductivity, viscosity, heat transfer to theory, modify theory, if required
- Continue to improve thermal properties while using chemistry to reduce viscosity
- CFD on diesel engine cooling systems to calculate thermal properties of ANL nanofluids required to reduce size and weight reduction of radiator
- Collaborate with industry to demonstrate efficiency of nanofluids

Characterization of Size/Shape of Nanoparticles

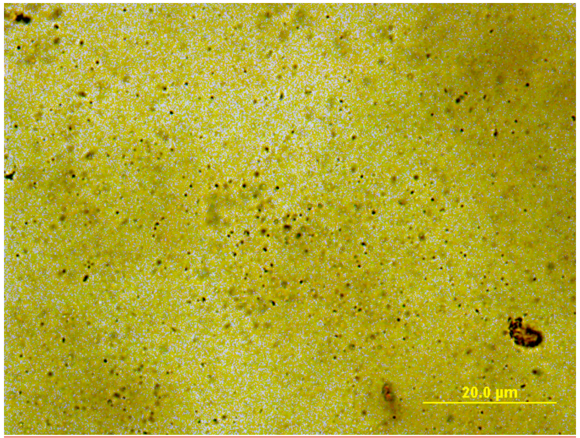


SiC/H_2O

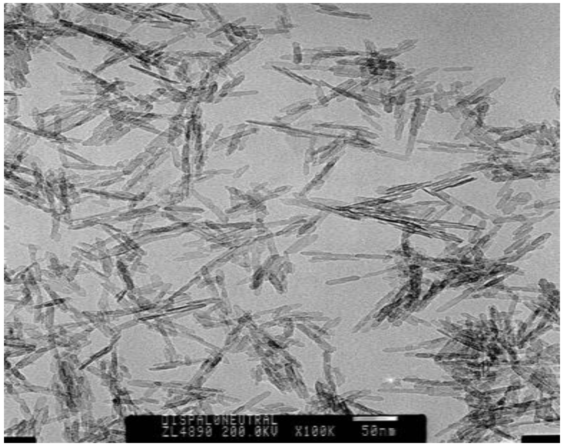
SAS (170 nm)



DLS (179 nm)

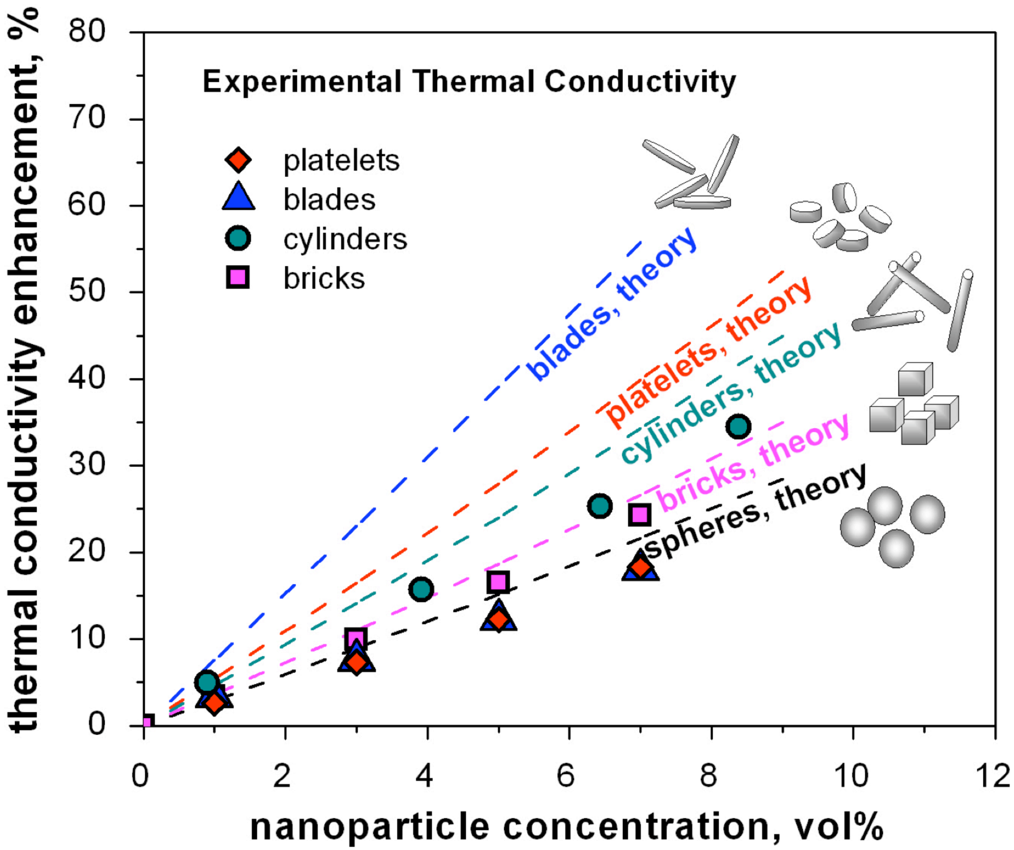


Optical



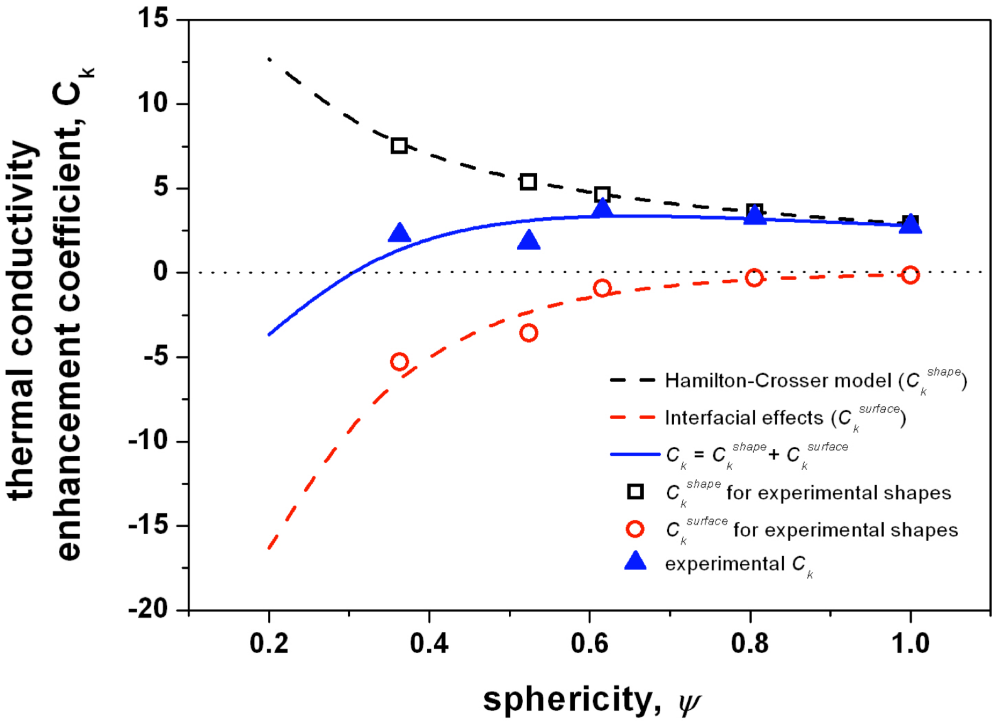
TEM $Al_2O_3/EG/H_2O$

Thermal Conductivity Enhancement - Al_2O_3 in EG-H_2O



Hamilton-Crosser: $$\frac{k_{eff}}{k_0} = \frac{k_p + (n-1)k_0 + (n-1)(k_p - k_0)\phi}{k_p + (n-1)k_0 - (k_p - k_0)\phi}$$

Interfacial Resistance – Al_2O_3 in EG-H_2O

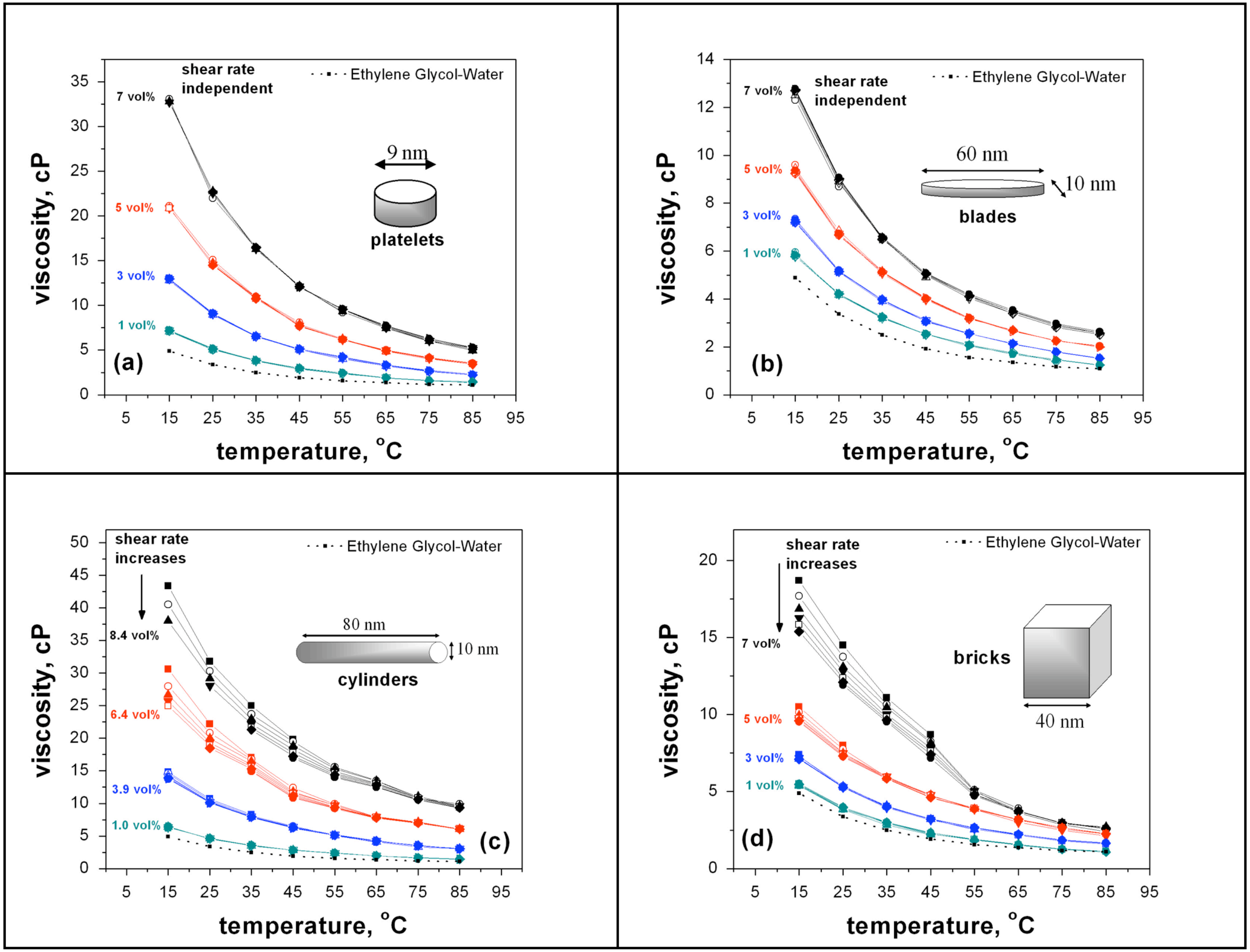


Assume Kapitza resistance proportional to surface area

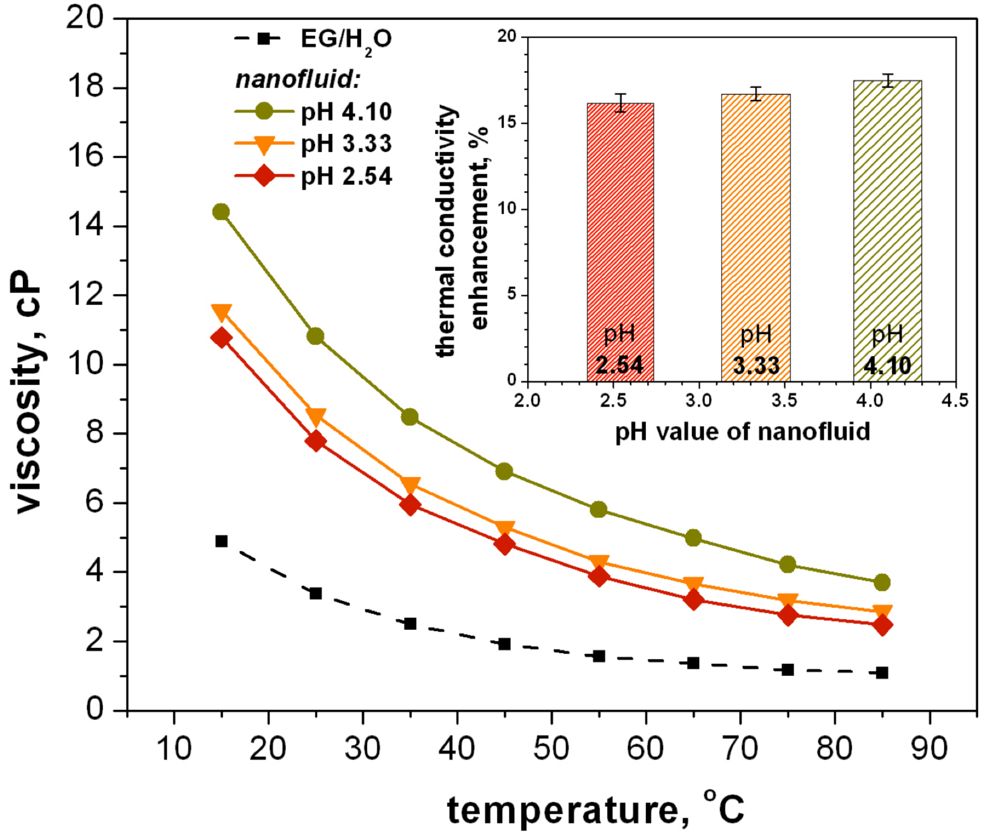
$$C_k^{surface} = -f \cdot l_k \qquad \frac{k_{eff}}{k_0} = 1 + (C_k^{shape} + C_k^{surface})\phi$$

$R_k = 4.4 \times 10^{-9} m^2K/W$

Viscosity (Shape, Shear rate, Concentration & Temperature)



Viscosity also depends pH (data for cylinders)

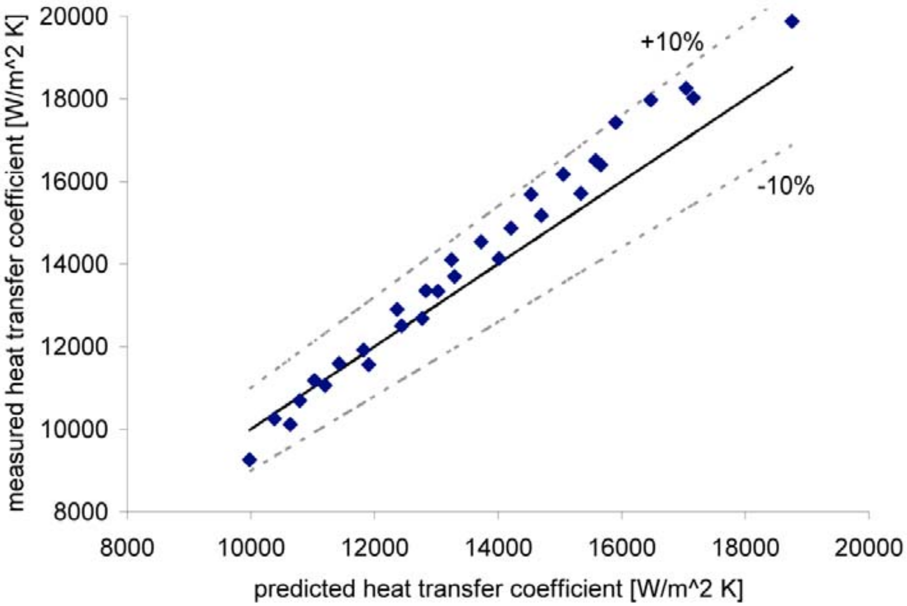


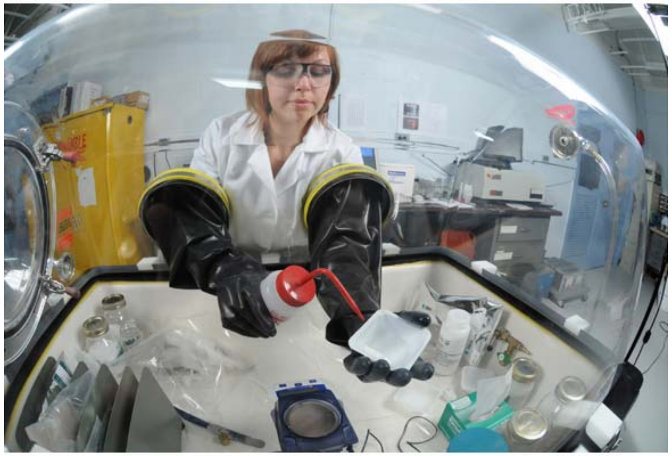
NB–pH modification changed η by 30%

$$\eta = \eta_o \exp(E_a / RT)$$

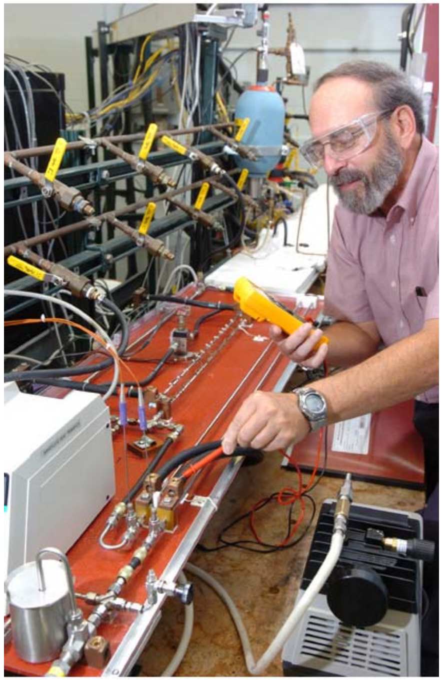
As pH gets further from isoelectric point, higher charged surfaces, more repulsion between nanoparticles, less interaction, reflected in parameters derived from Arrhenius equation

Heat transfer coefficient 50% EG–50%H_2O



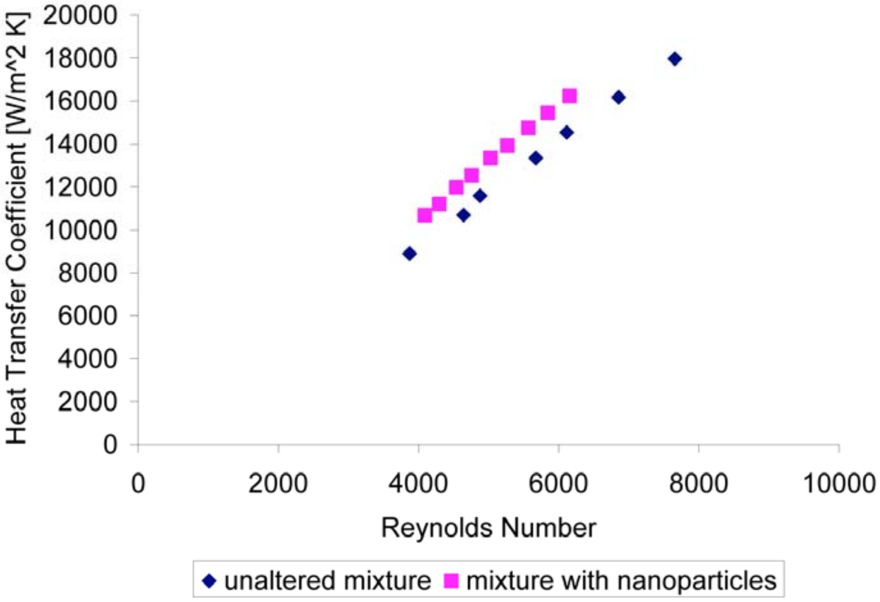


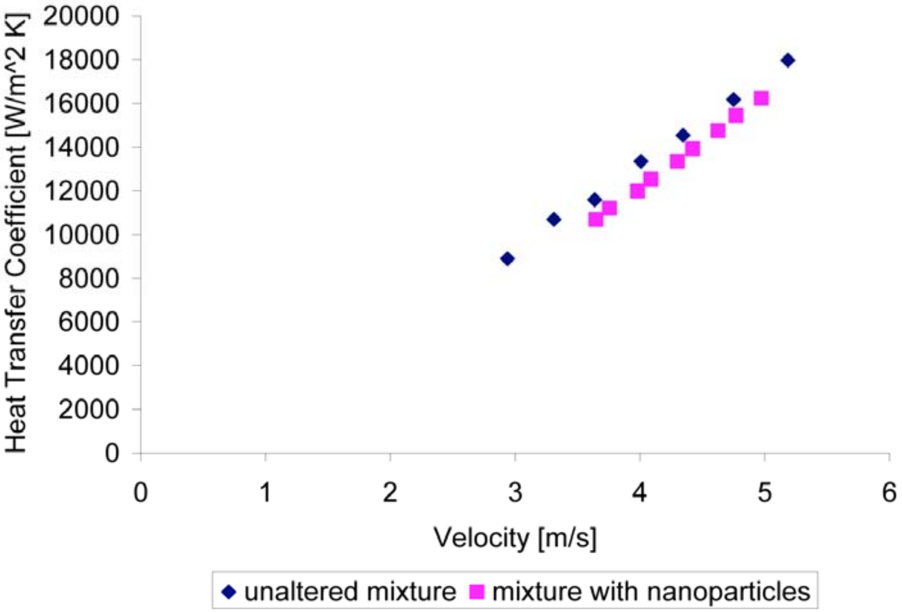
Nanofluid preparation



Apparatus

Heat Transfer Coefficient –SiC (3.7 vol.% in EG/H_2O Nanofluid





$h_{nano} > h_{unaltered}$ (R_e=constant, but $h_{nano} < h_{unaltered}$ (V=constant)

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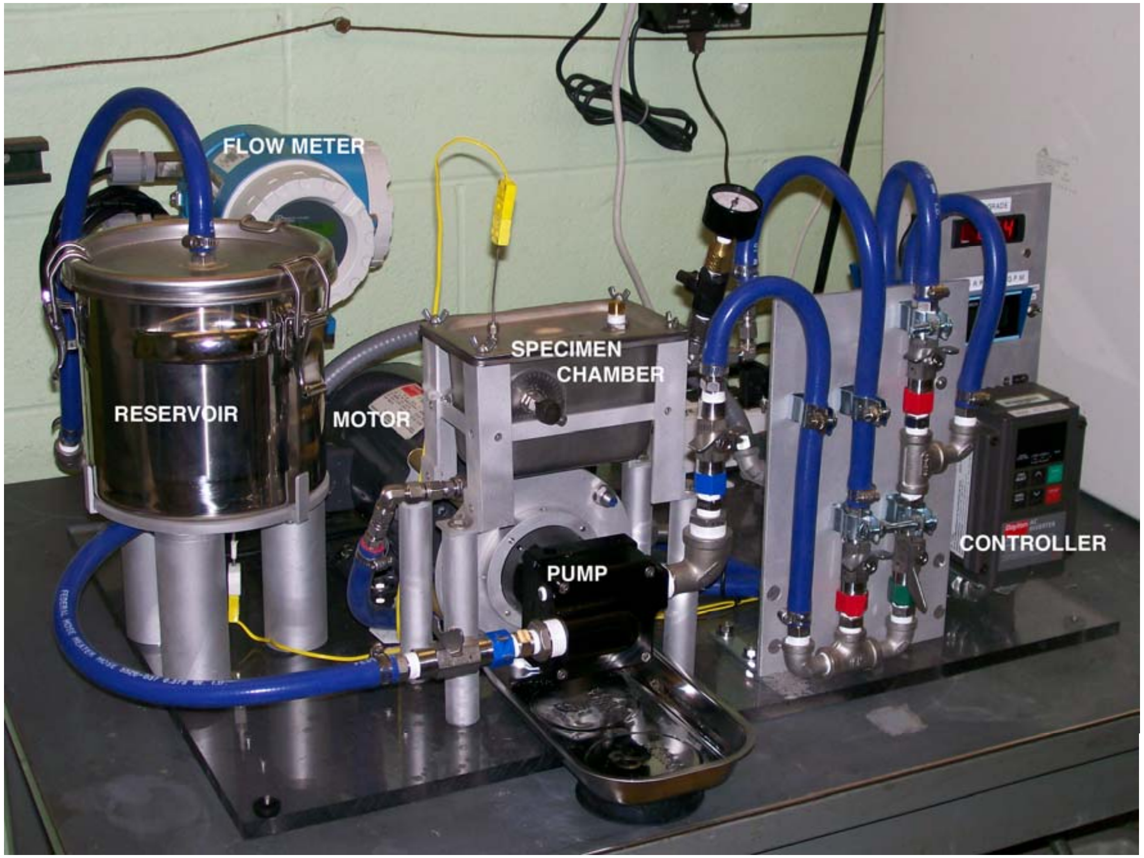
Erosion



Erosion of radiator or pump materials could be show-stopper! New apparatus will allow measurements of both target materials at fixed angle and velocity, as well as erosion of automotive commercial water pump, and power measurements. Thus far, erosion of Al3003 is not a "killer".

Future Work – Path Forward

- Nanoparticles with higher TC
  - Metals
  - Intermetallics
- Viscosity modification
  - Particle shape/size
  - Surface chemistry
- Heat transfer coefficient
- CFD simulations
- Comparison of base fluid to nanofluid using small scale heat exchanger
- Full scale cooling application with industrial partner
- Air side heat removal (Pending funding)

Conclusions

- We have identified the critical barriers for the use of nanofluids for cooling applications
- Using lessons learned, we have identified a viable path forward

Questions?

Please spend some time viewing our posters for more details and technical accomplishments