Development of Nanofluids for Cooling Power Electronics for Hybrid Electric Vehicles

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Project ID: VSS112

Sponsored by L. Slezak (Vehicle System Optimization)

Overview

Timeline

- Project start FY11
- Project end FY14
- 90% complete

Budget

- FY11 = $150K (DOE)
- FY12 = $225 K (DOE)
- FY13 = $75 K (DOE)
- FY14 = $350 K (DOE)

Barriers

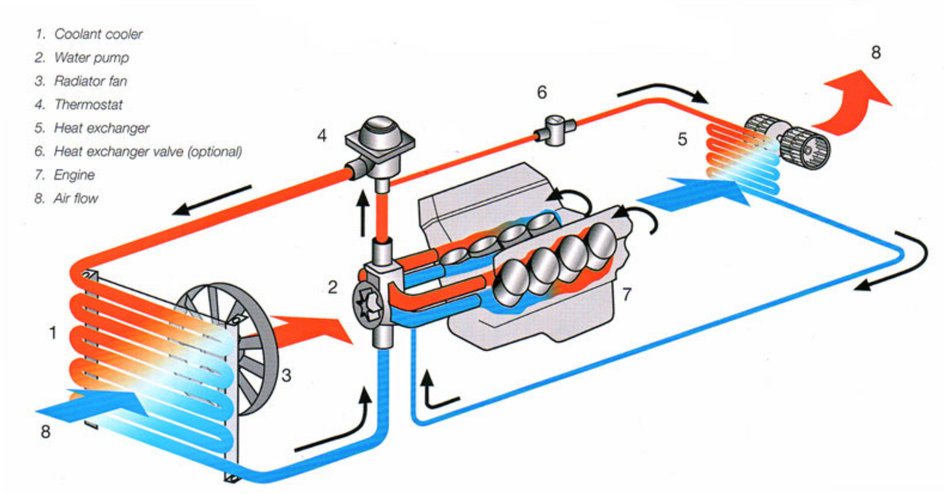
⇒ Development of effective, affordable nanofluid
⇒ High viscosity, low suspension stability
⇒ System clogging, erosion of parts
⇒ Manufacturability of nanofluid
⇒ Need for demonstration in conditions similar to HEV
⇒ Industrial acceptance of technology

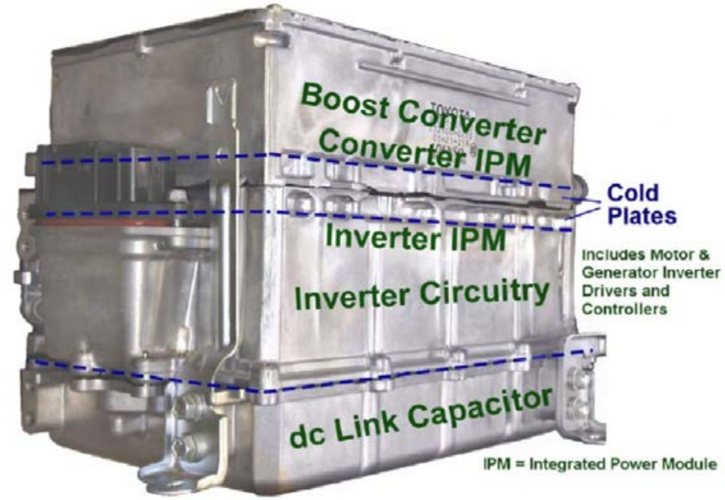
Partners

- XG Sciences in development of graphite-based ethylene glycol/water nanofluids
- Dynalene in characterization of heat transfer properties
- PACCAR, Hussmann Corp., and Castrol BP have expressed interest in the technology

State of the art Power Electronics (PE) cooling

TWO cooling systems are currently used for Hybrid Electric Vehicles:





1) **higher** temperature system for cooling combustion engine

2) **lower** temperature system for cooling power electronics

DOE goals:

- eliminate the lower temperature cooling system, such that all cooling is done with a single higher temperature cooling system
- heavy vehicle cooling – improved heat transfer - system and weight reduction

Liquid cooling vs. heat sink

Increasing heat fluxes and power loads require efficient and reliable heat dissipation

http://en.wikipedia.org/wiki/Heat_sink

Improved heat dissipation

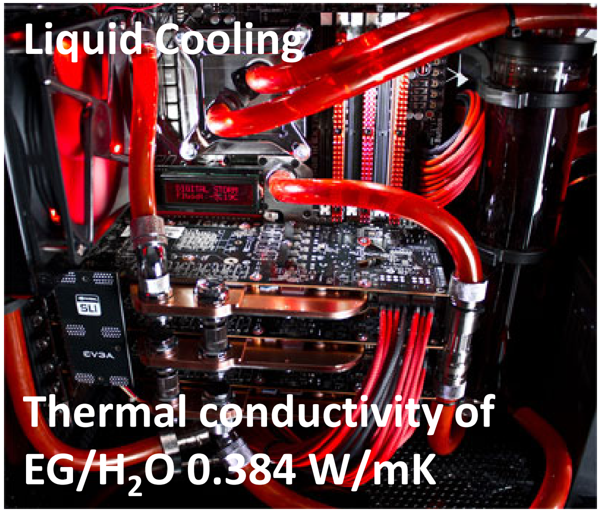


Image Credit: Digital Storm

Further improvements to liquid cooling could be done by using advanced coolant

Nanofluids are liquids with nanometer or submicron size particles dispersed

NANOFLUIDS have proven ability to increase thermal conductivity and heat transfer of liquids

Promising for reducing the size, weight and number of heat exchangers for power electronics cooling

Prior Nanofluid Research

Thermal Conductivity Mechanisms

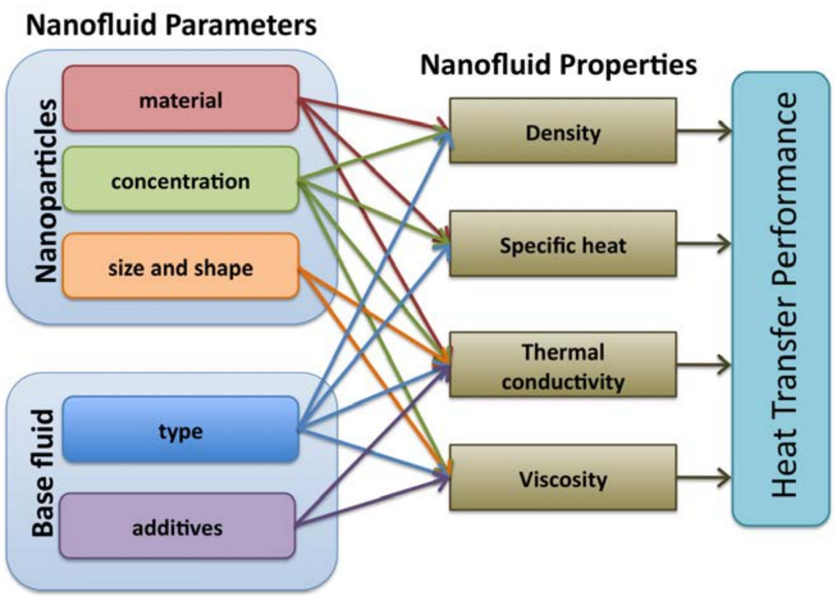
- Effective Medium Theory
- Micro-convection
- Fluid layering
- Extended agglomerates
- Surface plasmon enhancement

Ceramic Nanofluids

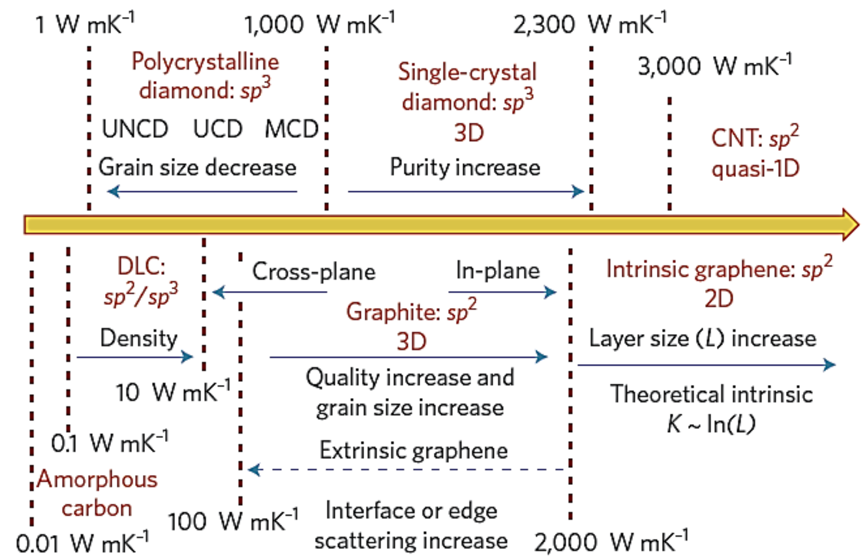
Metallic Nanofluids

Carbonaceous nanofluids

Nanofluid Engineering Approach



Thermal Conductivity of Carbon Materials



A.A. Balandin, Nature Nanomaterials, 2011, V.10, 569-581

Objectives:

- Conduct assessment of using nanofluids to cool power electronics in HEVs, namely:
  - *Use heat transfer analysis to determine the requirement for nanofluid properties that would allow eliminating the low temperature cooling system in HEVs*
  - *Develop nanofluid formulations with defined set of thermo-physical properties*
  - *Identify and address engineering issues related to use of nanofluid(s)*
  - *Experimentally evaluate the heat transfer performance of the developed coolant fluids*

- Target power electronics cooling in HEVs, but also address the thermal management issues related to heavy vehicle

- Capitalize on our prior work on nanofluid development, in particular, nanofluid engineering approach

Relevance

- Elimination of a low temperature cooling system
- Reduction in weight and cost
- Other benefits of the technology:
  - Improved efficiency and reliability of power electronics at higher operating conditions
  - Increased lifetimes of the power electronic components

Approach

FY11

Perform a heat transfer analysis of power electronics cooling package

Determine the magnitude of enhancement in thermal properties of a nanofluid required to eliminate lower temperature cooling system

FY12/FY13

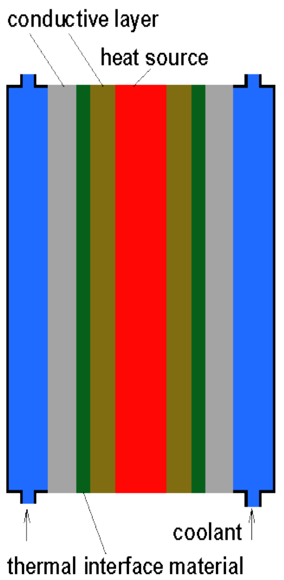
Using nanofluid engineering approach to formulate and optimize suspensions to meet the property requirements defined by thermal analysis

FY13/FY14

Process scale-up & test performance of formulated nanofluid in heat transfer loop

Examine fouling, pumping power, and erosion with nanofluid under actual heat exchanger conditions

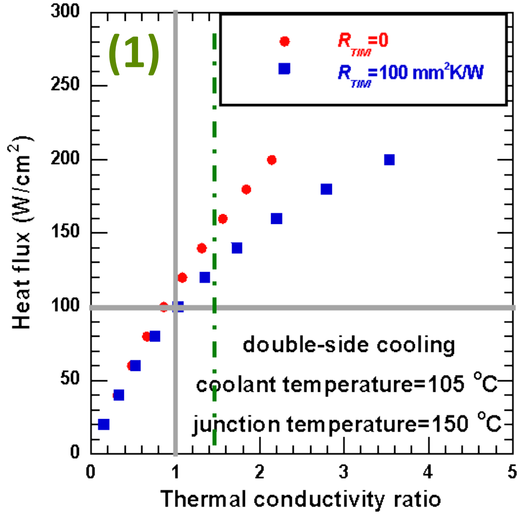
FY12 Accomplishments: Thermal analysis



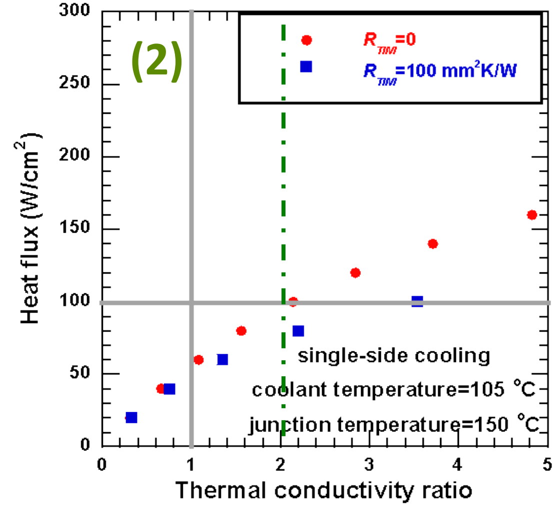
Input from NREL group

Schematic of the power electronic module for thermal analysis

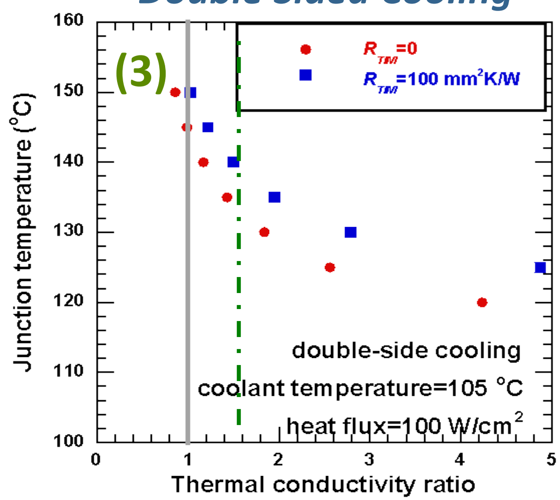
Heat Flux– Double Sided Cooling



Heat Flux – Single Sided Cooling



Junction Temperature – Double Sided Cooling



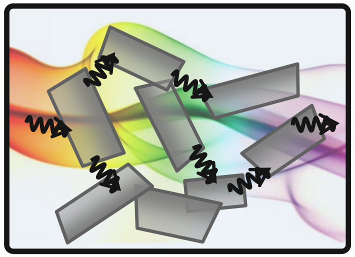
Conclusions:

- (1) TC ratio of 1.5 increases heat load by ≈50% with thermal interface material (TIM) and by ≈ 70% without TIM
- (2) TC ratio of 2 without TIM is sufficient to eliminate the low temperature system
- (3) TC ratio of 1.5 decreases semi-conductor junction temperature to ≈ 139°C with TIM and to ≈ 135°C without TIM

Accomplishments: Nanofluid development criteria

- Thermal conductivity ratio > 1.5
- Low viscosity => low pumping power
- Low cost
- Suspension stability

Percolation => High thermal conductivity



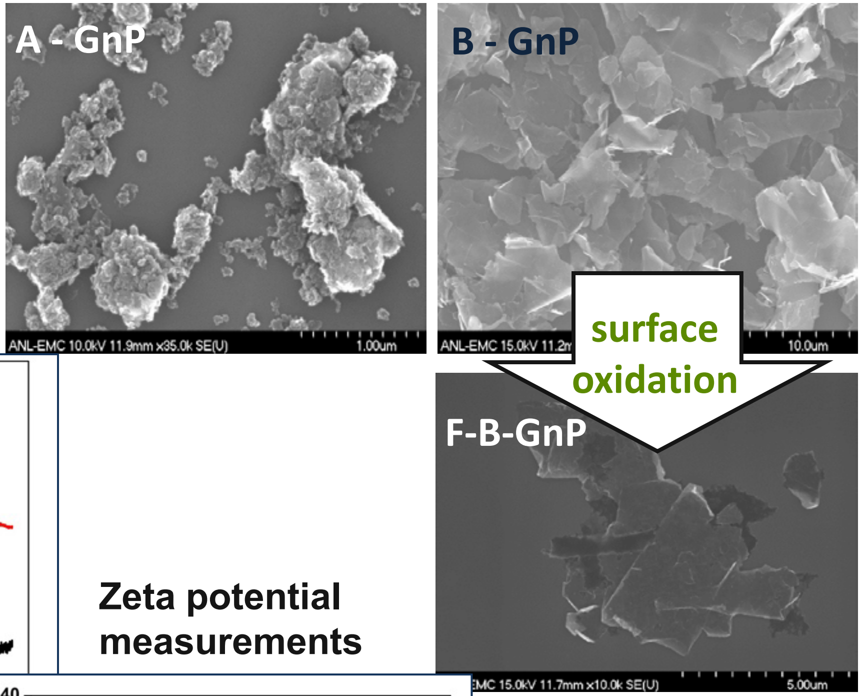
Nanofluid (*nf*) is more efficient than base fluid (*0*) when

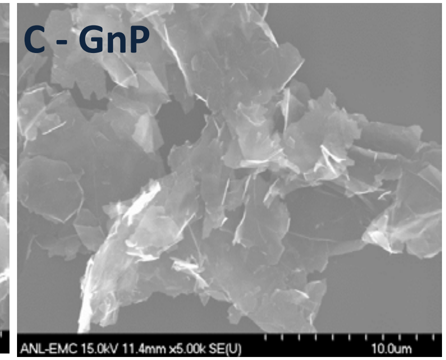
$$h_{nf} / h_0 > 1$$

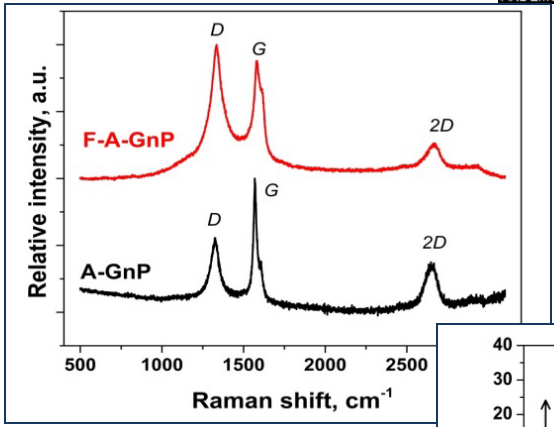
W. Yu et al., *Appl. Phys. Lett., 96, 2010, 213109*

FY 13 Accomplishments: Study of shape effects and surface functionalization of Graphite nano-Platelets (GnP)

Commercially available graphitic nanomaterials (currently \$100/lb and projected \$20/lb)

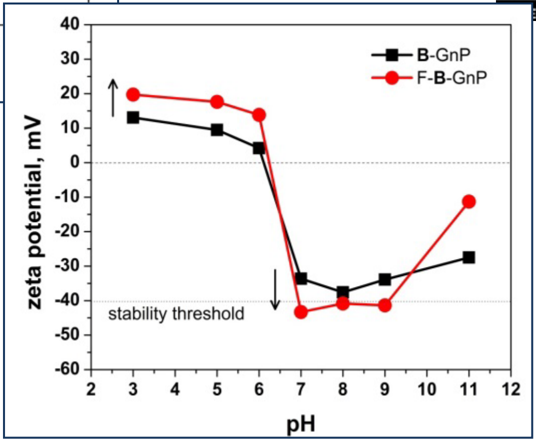


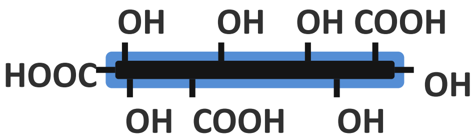




Raman spectroscopy

Zeta potential measurements





Graphite/GO core/shell platelets

Conclusions:

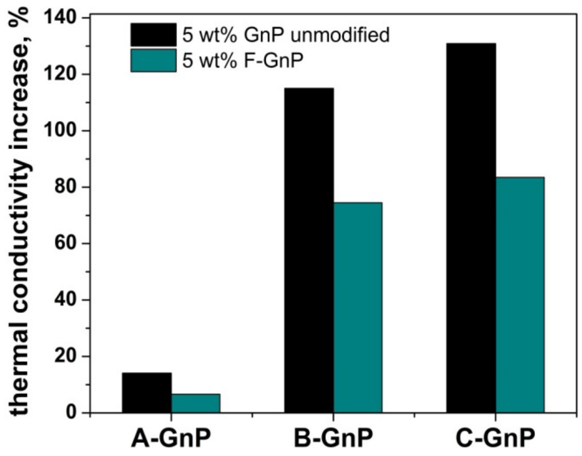
Surface functionalization creates core-shell structures and helps to improve suspension stability

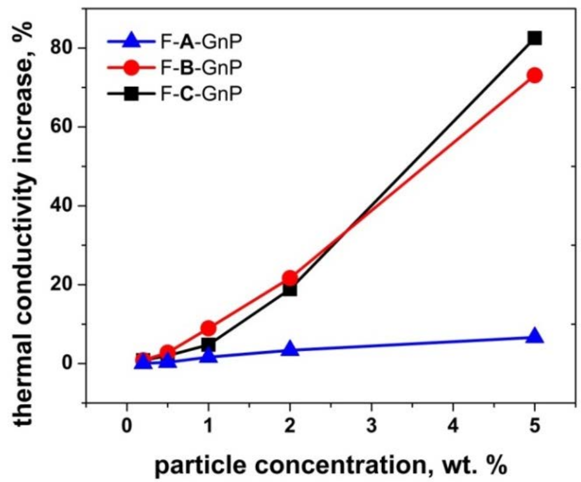
FY13 Accomplishments: Thermo-physical properties of GnP in EG/H_2O nanofluid

Conclusions:

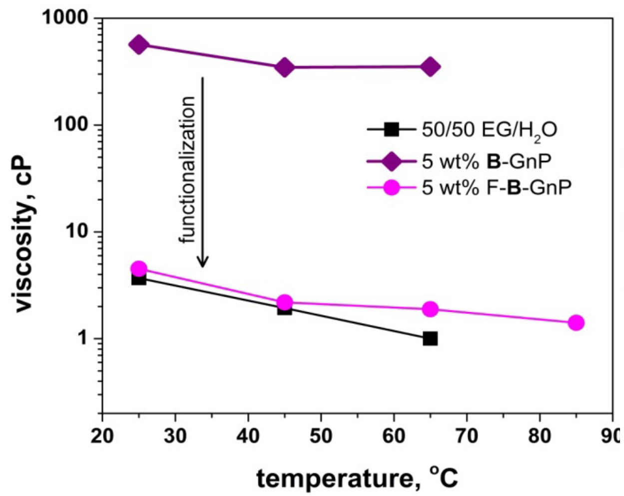
- Surface functionalization partially degrades thermal conductivity increase (~45% less), but dramatically lowers viscosity (> 100 times less viscous)
- GnP with larger diameter and thickness show higher thermal conductivity increases and viscosities at same concentrations
- Diameter/thickness are critical for viscosity (optimum geometry is needed)

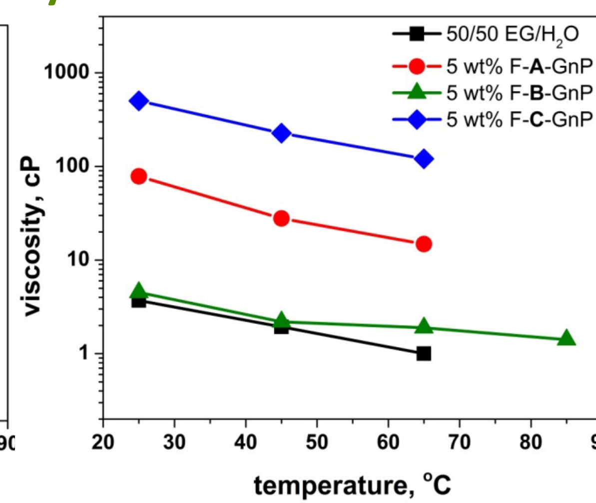
Thermal Conductivity Results





Viscosity Results





FY13 Accomplishments: Evaluation of nanofluid in Laminar and Turbulent flow

- Thermal conductivity ratio ~1.8 (variation in concentration can bring it up or down)
- => **goal of k_{nf}/k_0 >1.5 is met**
- At 75-90% increase in thermal conductivity viscosity increase only ~ 10-40% (vs. 2000% of original GnP suspension)

Conclusion:

Developed nanofluid F-B-GnP in EG/H_2O is beneficial (h_{nf}/h_0>1) in both Laminar and Turbulent flow regimes with ~80% and ~35% improvements in heat transfer coefficients correspondingly

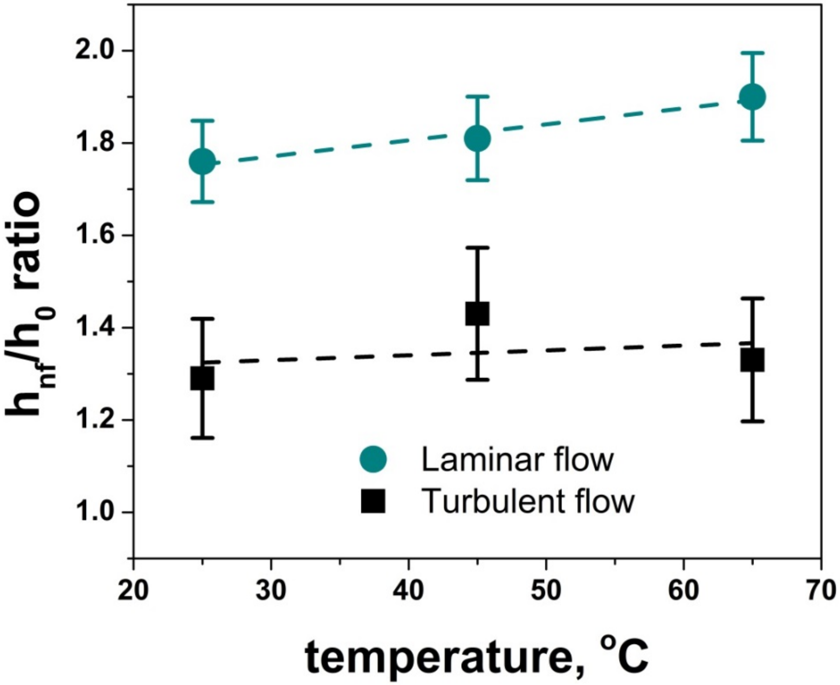
Laminar flow $h \propto k$

k – thermal conductivity

Turbulent flow

$$h \propto \rho^{4/5} c_p^{2/5} \mu^{-2/5} k^{3/5} V$$

ρ – density
c_p – specific heat
μ – viscosity
V – flow velocity



Top level cost analysis

The cost analysis was not possible until the composition of nanofluid coolant was finalized.

- 5wt% of GnP in EG/H2O
- Cost of raw GnP material 1kg ~ $20
- added cost ~ $1/L is it a lot?
- Retail antifreeze $10-30/gal ~$5/L

GnP additive will add 20% to the cost of the coolant per volume,
However savings come on the side of:

- Reduced volume of coolant required (20-50% less)
- Reduced size of the radiator, simpler and cheaper single cooling system (10-50% less)
- Reduced weight of the vehicle (~1-2%)
- Increased fuel efficiency

FY 14 Tasks

Task 1: Optimize the GnP nanofluid preparation procedure for scale-up

Task 2: Prepare nanofluid in quantities sufficient for heat transfer test (~1 gal.)

Task 3: Demonstrate the efficiency of nanofluid coolant in close to real heat exchanger conditions

Task 4: Test fouling, erosion, and pumping power of the nanofluid coolant in close to real heat exchanger conditions

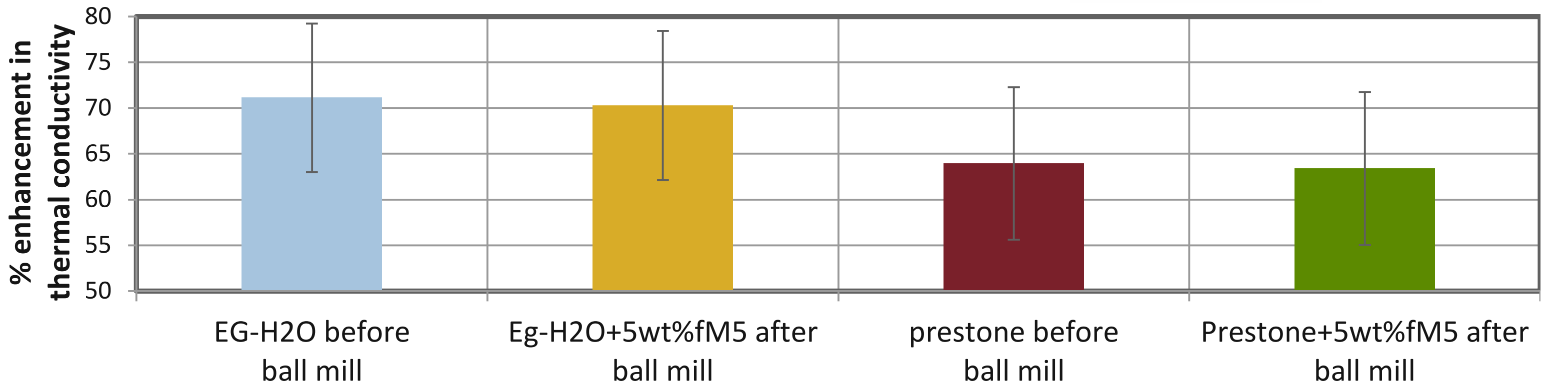
Task 1. Optimize the GnP nanofluid preparation procedure for scale-up

APPROACH:

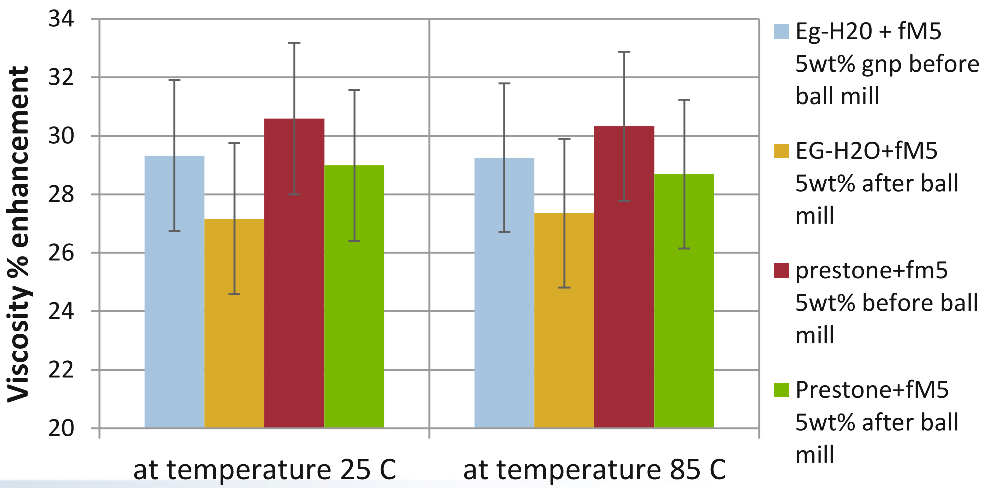
- Investigated effects of ball milling on thermo-physical properties.
- Studied the effect of GnP additive on properties of commercial Preston® 50/50 coolant.

STATUS: TASK CONCLUDED

RESULTS:



- Additives in Prestone coolant slightly interfere with our graphitic additives – providing ~7% lower thermal conductivity and ~4% higher viscosity at all other variables being the same.
- Ball-milling decreases viscosity by ~3%, while thermal conductivity is not affected. Therefore ball-milling is a beneficial step for improving the heat transfer.



Task 2. Scale-up of nanofluid preparation in quantities sufficient for heat transfer test

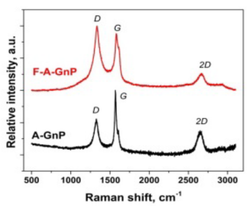
APPROACH:

Surface modification treatment

Dispersion of nanomaterials in the base fluid

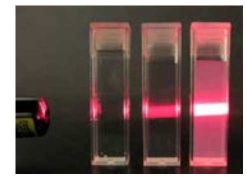
Characterization of nanofluid properties

0.1L => 5L



F-GnP nanomaterials **quality control** (SEM, Raman, TGA)

Dispersion **quality control** (zeta potential, DLS)



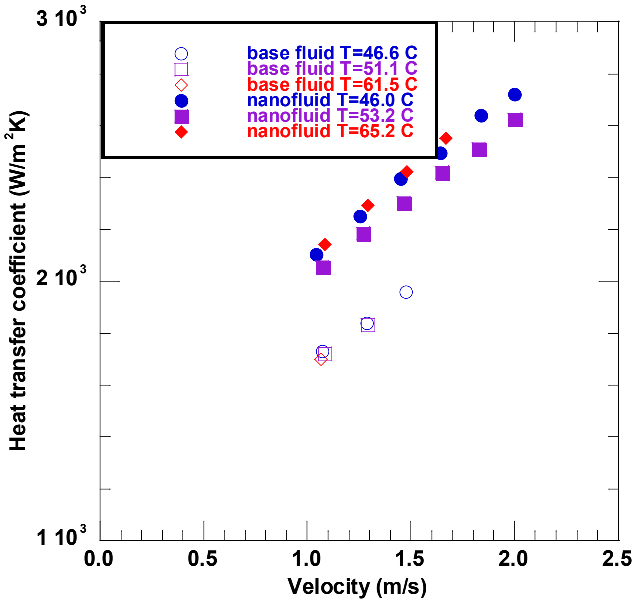
RESULTS :

- Prepared several 0.5L batches of f-GnP nanofluids, revealed sensitivity of the nanofluid properties to the fluid parameters (concentration, pH, degree of surface functionalization). Introduced **quality control steps** for the scale-up process.
- Multiple adjustments have been made to the process to achieve the properties of the small batch on the larger 0.5L scale.

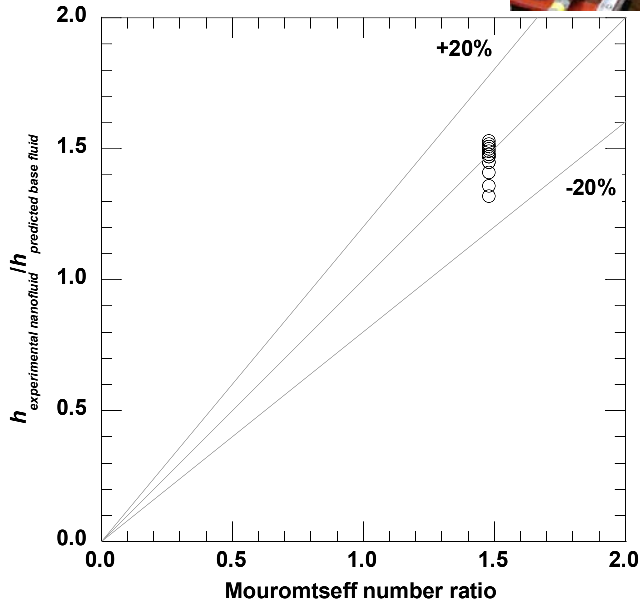
Task 3. Demonstrate the efficiency of nanofluid at real heat exchanger conditions

APPROACH: Apparatus allows measuring experimental heat transfer coefficient at various temperatures and flow rates

RESULTS : Heat transfer coefficients were measured in laminar flow regime for the fluid with as-projected thermal conductivity but viscosity slightly higher than the small batch nanofluid.



Experimental heat transfer coefficients in laminar flow (for laminar flow with Reynolds number Re<2000)



Experimental nanofluid heat transfer coefficient enhancement between 1.32 and 1.53 with an average of 1.46 compared to Mouromtseff number ratio (for laminar flow with Reynolds number Re<2000) estimated to be 1.48.

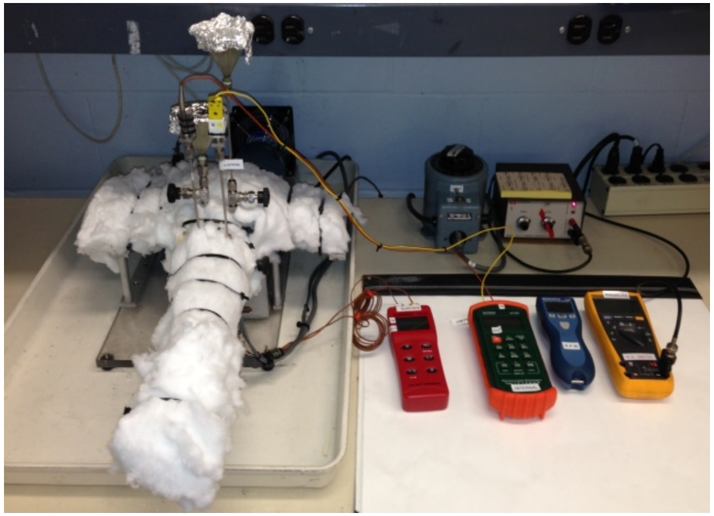
Task 4. Test fouling and erosion of the nanofluid coolant in close to real heat exchanger conditions

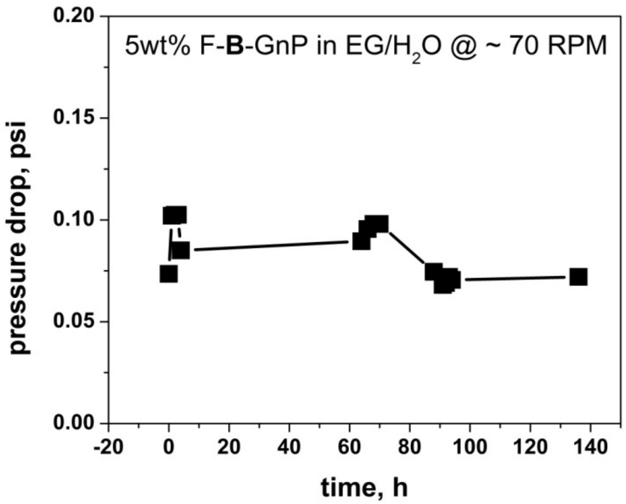
APPROACH:

- Evaluation of fouling/clogging within pipes/channels
- Pressure drop measured as a function of time & temperature
- Flow rates are maintained as those in a radiator cooling system

RESULTS:

room temperature test: No clogging observed after hundreds of hours of testing

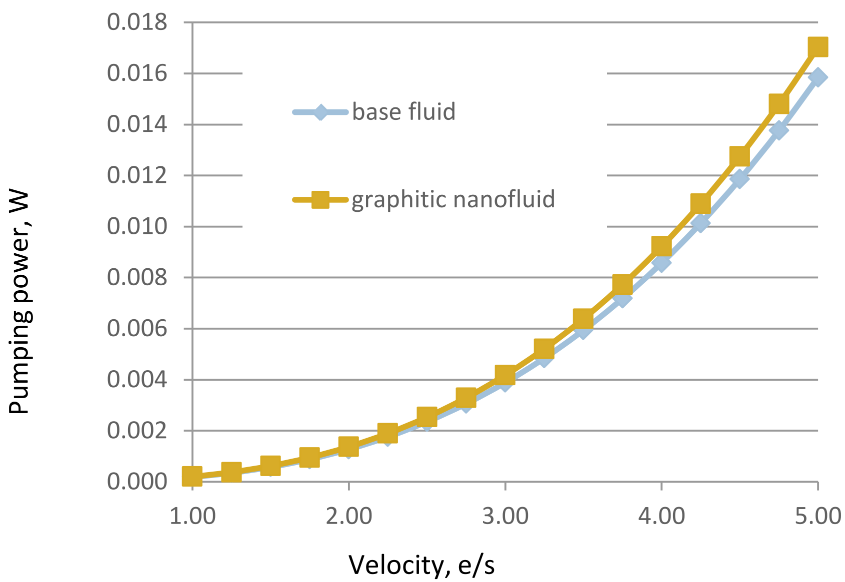


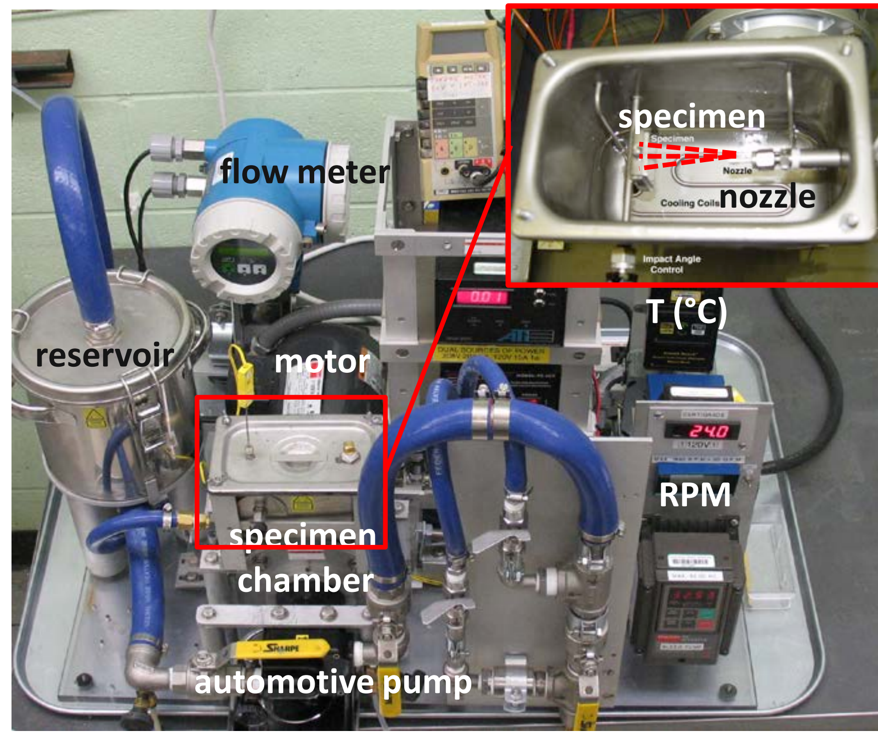


Task 4. Test fouling and erosion of the nanofluid coolant in close to real heat exchanger conditions

APPROACH: Apparatus determining erosion of target material at fixed angle & velocity and measuring power required to pump nanofluids and the base fluids

RESULTS: **Calculated pumping power for GnP nanofluid vs. EG/H_2O base fluid from properties**





Estimated pumping power penalty ~7.5% more for nanofluid vs. EG/H_2O base fluid

Technology-to-Market Efforts

- 3 Patent Applications
- Signed NDA with Dynalene Inc.
- Dynalene had evaluated previous nanofluid coolant

- Other commercial interest:

Hussmann Corporation (refrigeration systems manufacturer)

HUSSMANN®
CORPORATION

Summary

- Analysis of power electronics cooling system allowed establishing criteria for efficient nanofluid coolant such as thermal conductivity ratio of more than 1.5.
- Such enhancements are possible with graphitic nanoparticles that are commercially available at reasonable costs (20% added cost to coolant)
- Graphitic nanofluids in 50/50 mixture of ethylene glycol and water showed:
  - morphology dependent thermal conductivity;
  - 50-130% increases in thermal conductivity at 5 wt.% (room temperature) – possibilities for dramatic improvement in liquid cooling
  - nanoparticle surface treatment provides better dispersion stability, lower viscosity, and higher thermal conductivity
  - enhanced performance with temperature
- The optimized and scale-up nanofluid tested in a heat transfer loop, fouling and erosion tests to assure the commercial viability of the GnP nanofluid technology
- NDA signed and technology transfer process is in progress