Development of Nanofluids for Cooling Power Electronics for Hybrid Electric Vehicles

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Project ID#: VSS112

Vehicle Technologies - Annual Merit Review – May 15, 2013

Overview

Timeline

- Project start FY11
- Project end FY14
- 65% complete

Budget

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

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

Supported by L. Slezak (Vehicle System Optimization), J. Gibbs (Propulsion Materials), and S. Rogers (APEEM)

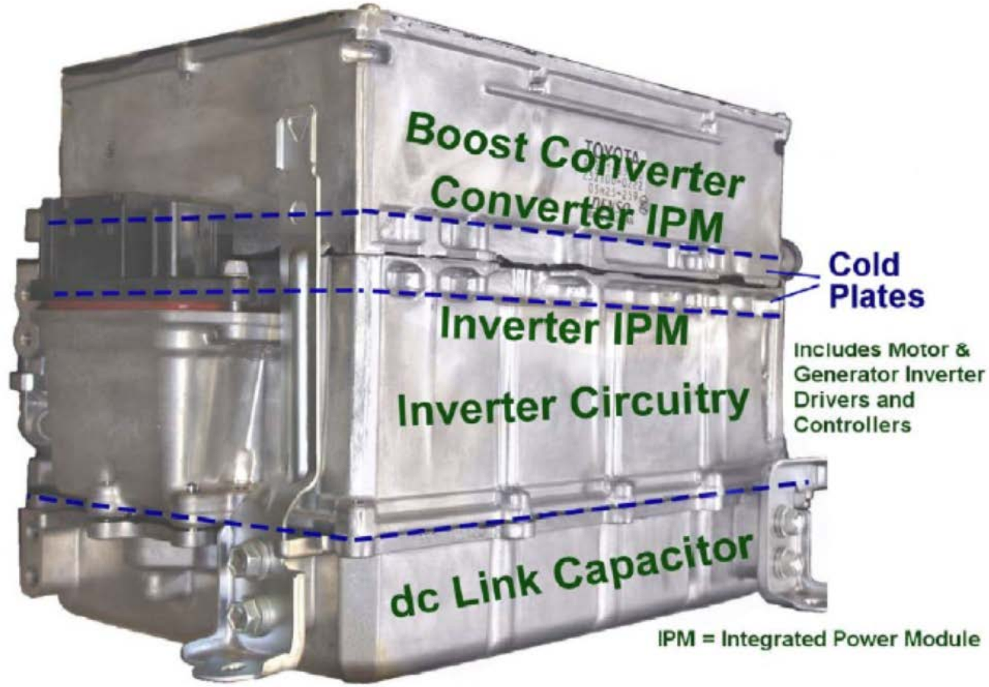
State of the art

TWO cooling systems are currently used for hybrid electric vehicles (HEVs):

1) higher temperature system for cooling the gasoline engine

2) lower temperature system for cooling the power electronics

DOE goal: Eliminate the lower temperature cooling system, such that all cooling is done with a single higher temperature cooling system



Nanofluids are liquids with nanometer or submicron-size particles dispersed

NANOFLUIDS have <u>proven</u> ability to increase thermal conductivity and heat transfer

→

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

Relevance

- Elimination of a low temperature cooling system
- Power electronic modules can operate at high powers or smaller footprints
- Reduction in size & weight of power electronics, consequently reduced costs
  - current costs ~$30/kWh, target is $8/kWh by 2020
- Secondary benefits of the technology:
  - improved efficiency and reliability of power electronics at higher operating conditions
    - smaller inverters delivering same level of power to motor
  - increased lifetimes of the power electronic components ($$ savings)

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

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(s) in heat transfer loop

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

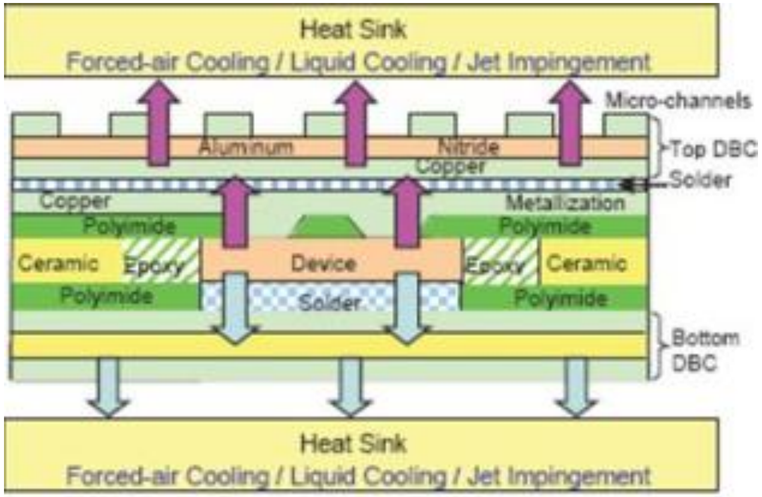
Project Milestones

- FY12 *(all completed)*
  - Identify critical barriers
  - Complete thermal analysis to identify the desired coolant properties
  - Initiate collaborations
  - Develop graphite/graphene-based nanofluid suspensions
  - Design, build, and calibrate fouling, erosion, and pumping power test rigs
  - Conduct preliminary pumping power experiments

- FY13
  - Continue thermo-physical characterizations of the developed coolant (ongoing)
  - Complete fouling tests at ambient and elevated temperatures (ongoing)
  - Determine the overall efficiency of the coolant based on properties (completed)
  - Conduct comparative cost analysis of the nanofluid coolant as compared to the baseline
  - Undertake process scale-up to produce 5 gal. of coolant for heat transfer testing

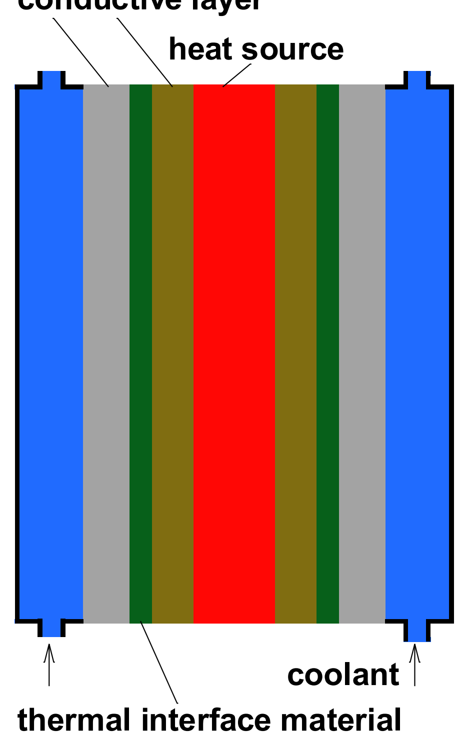
Some of the coolant property evaluation is being done with our industrial collaborators.

Accomplishments: Thermal analysis



Concept of double-sided cooling for IPEM

http://www.cpes.vt.edu/public/showcase/intdoublesided.php



Schematic of the power electronic module modeled for 1-D thermal analysis

Analysis conducted for:

- single or double-sided cooling
- with and without thermal interface material (TIM)

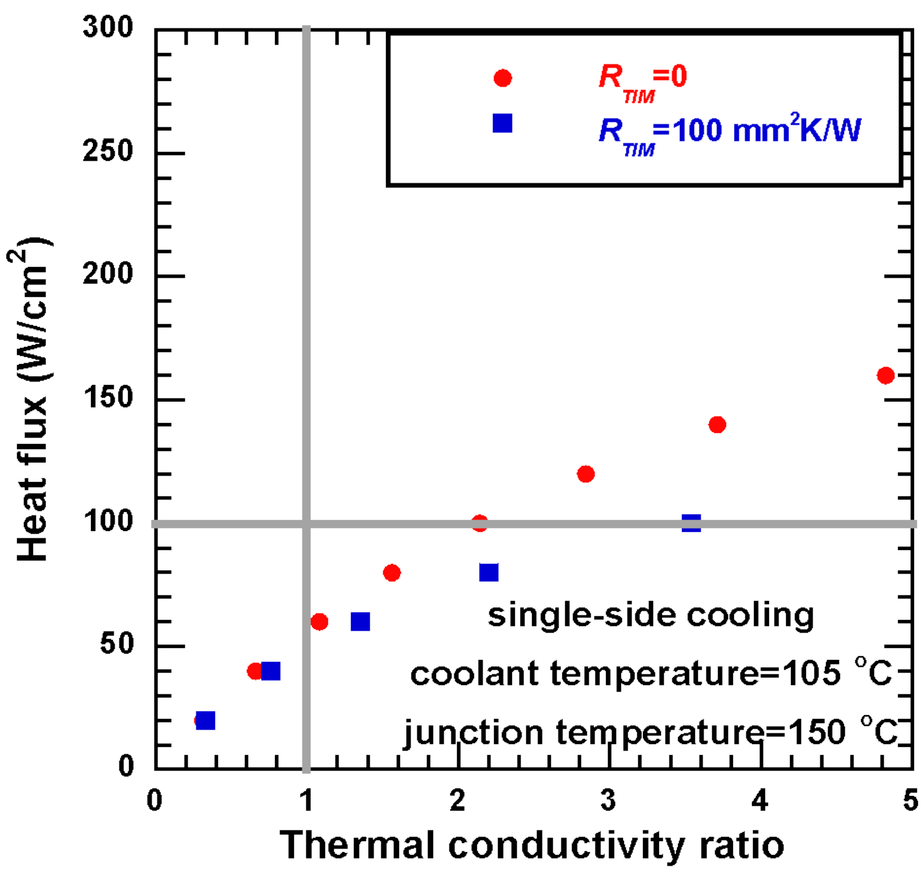
Boundary conditions

- heat flux 100 W/cm^2, junction temperature 150°C, coolant temperature 105°C
- heat flux 100 W/cm^2, coolant temperature 105°C

Refs.: M. O'Keefe & K. Bennion (2007), K. Bennion & K. Kelly (2009).

Accomplishments: Thermal analysis

Heat Flux – Single-Sided Cooling

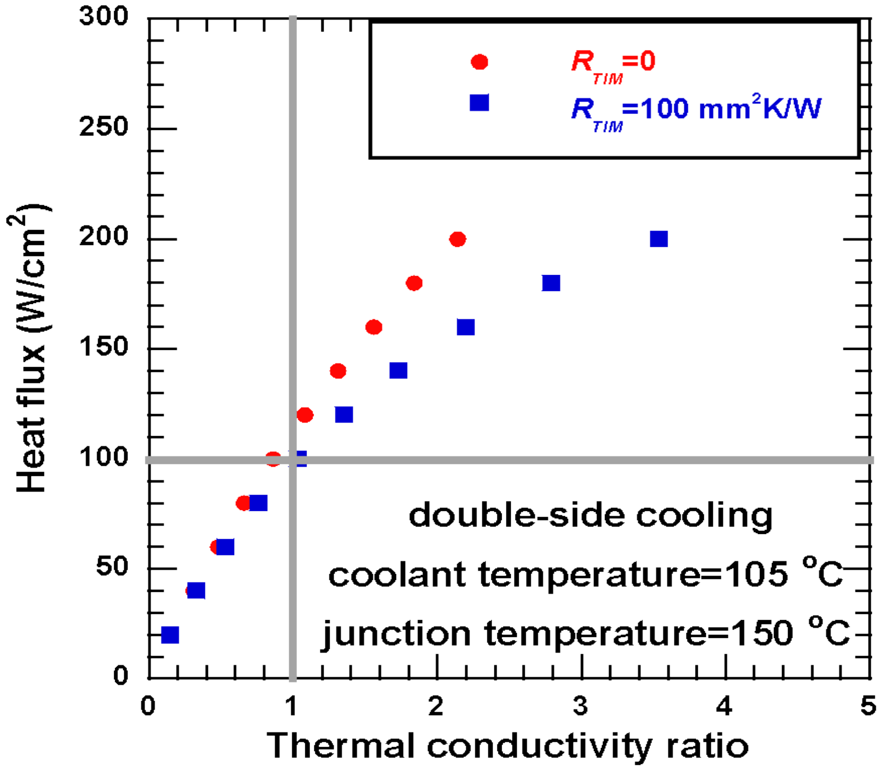


R_{TIM} = thermal resistance of interface material

Nanofluid with TC ratio of 2 without TIM is sufficient to eliminate the low-temperature coolant system.

Accomplishments: Thermal analysis

Heat Flux – Double-Sided Cooling

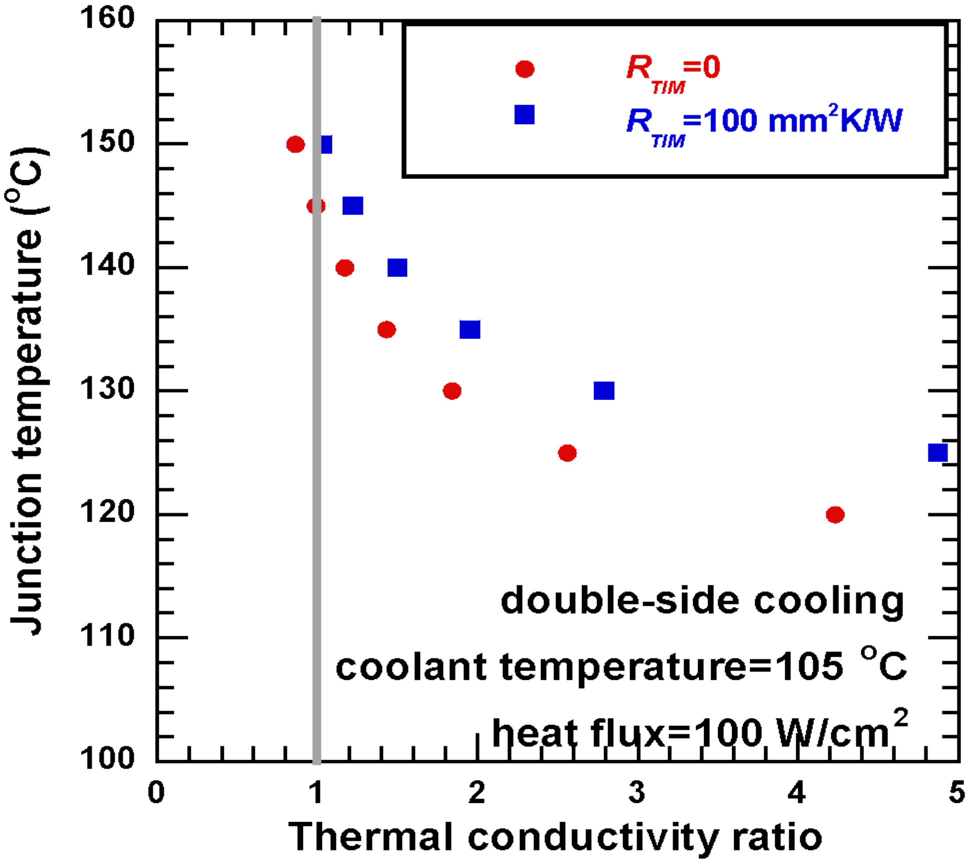


R_{TIM} = thermal resistance of interface material

Thermal conductivity ratio of nanofluid (TC) to base fluid of 1.5 increases heat load by ≈50% with thermal interface material (TIM) and by ≈ 70% without TIM.

Accomplishments: Thermal analysis

Junction Temperature – Double-Sided Cooling



R_{TIM} = thermal resistance of interface material

A nanofluid with 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

Figures of merit for evaluation of nanofluid cooling efficiency:

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

Efficiency:

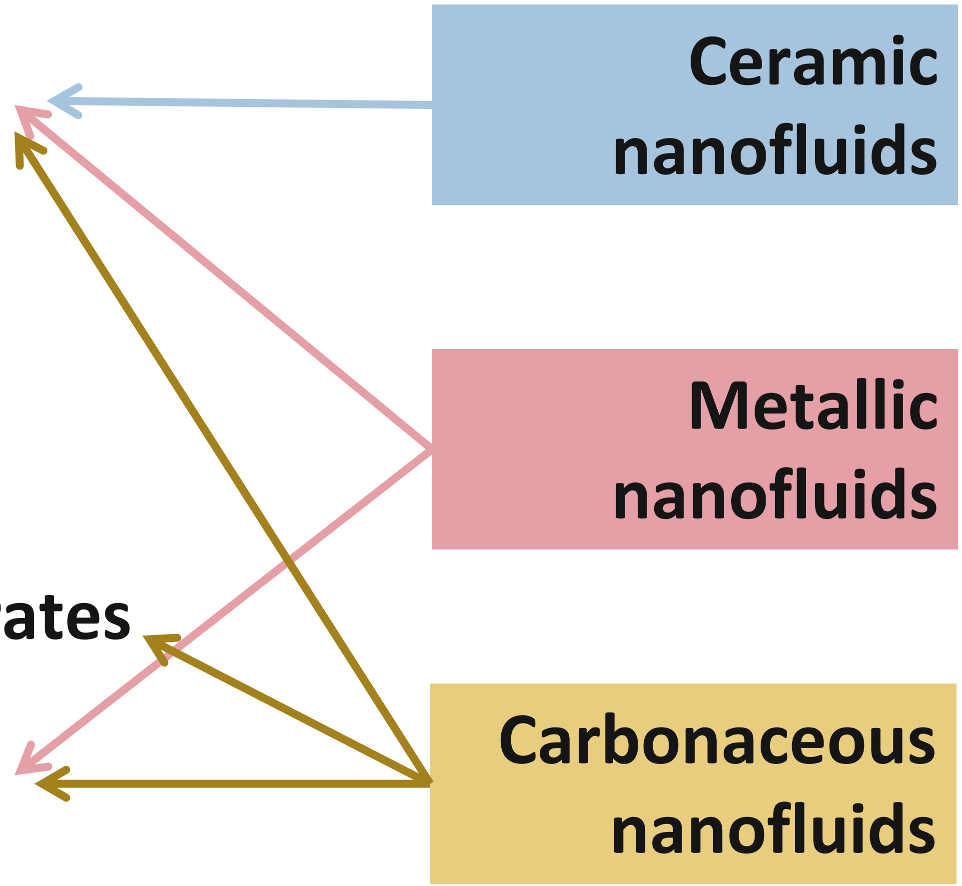
$$h_{nf} / h_0$$

nf beneficial at >1

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

Accomplishments:
Thermal conductivity mechanisms in nanofluids

- Effective medium
- Micro-convection
- Fluid layering
- Extended agglomerates
- Surface plasmons

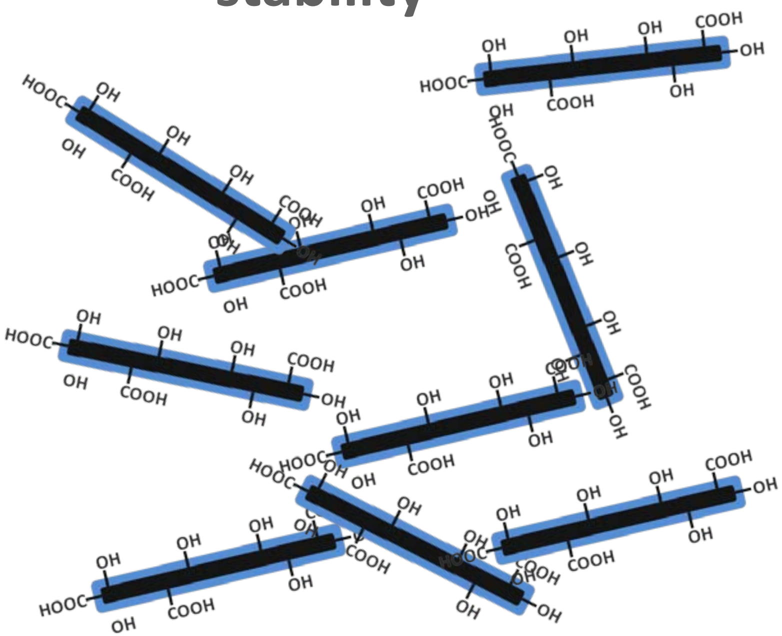


Focus of this work has been on graphitic/graphene-based fluids.

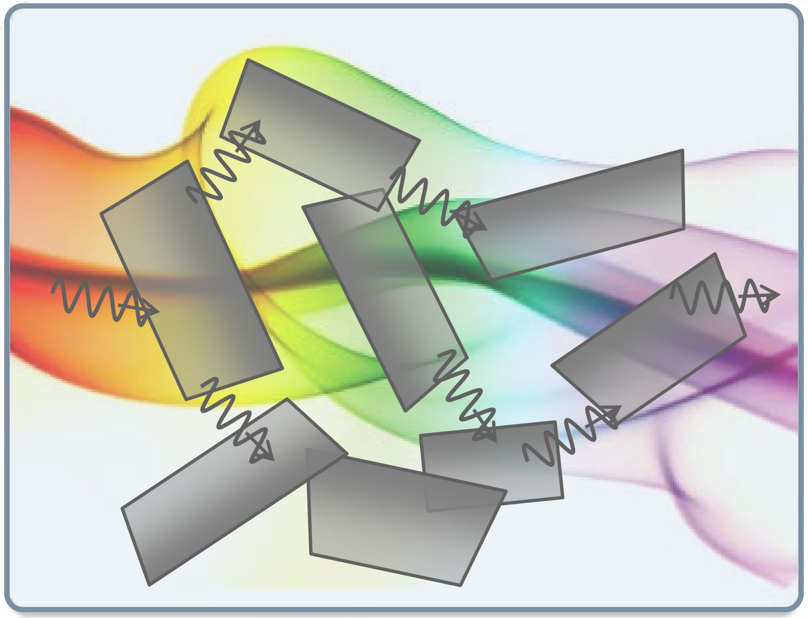
Yu et al., *J. Nanoscience and Nanotechnology, 10, 2010, 1-26.*

Accomplishments: Why should graphitic nanofluids work?

Electrostatic repulsion => good dispersion stability

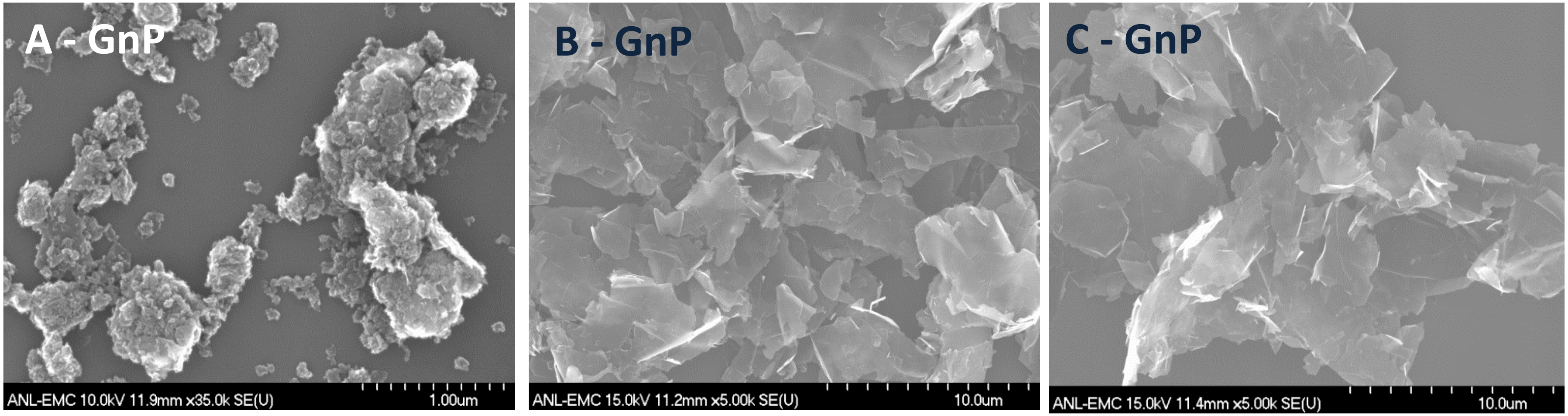


Percolation => High thermal conductivity

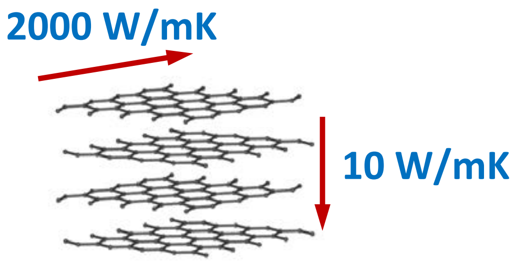


Fluid stability and thermal conduction mechanisms are unique for this system.

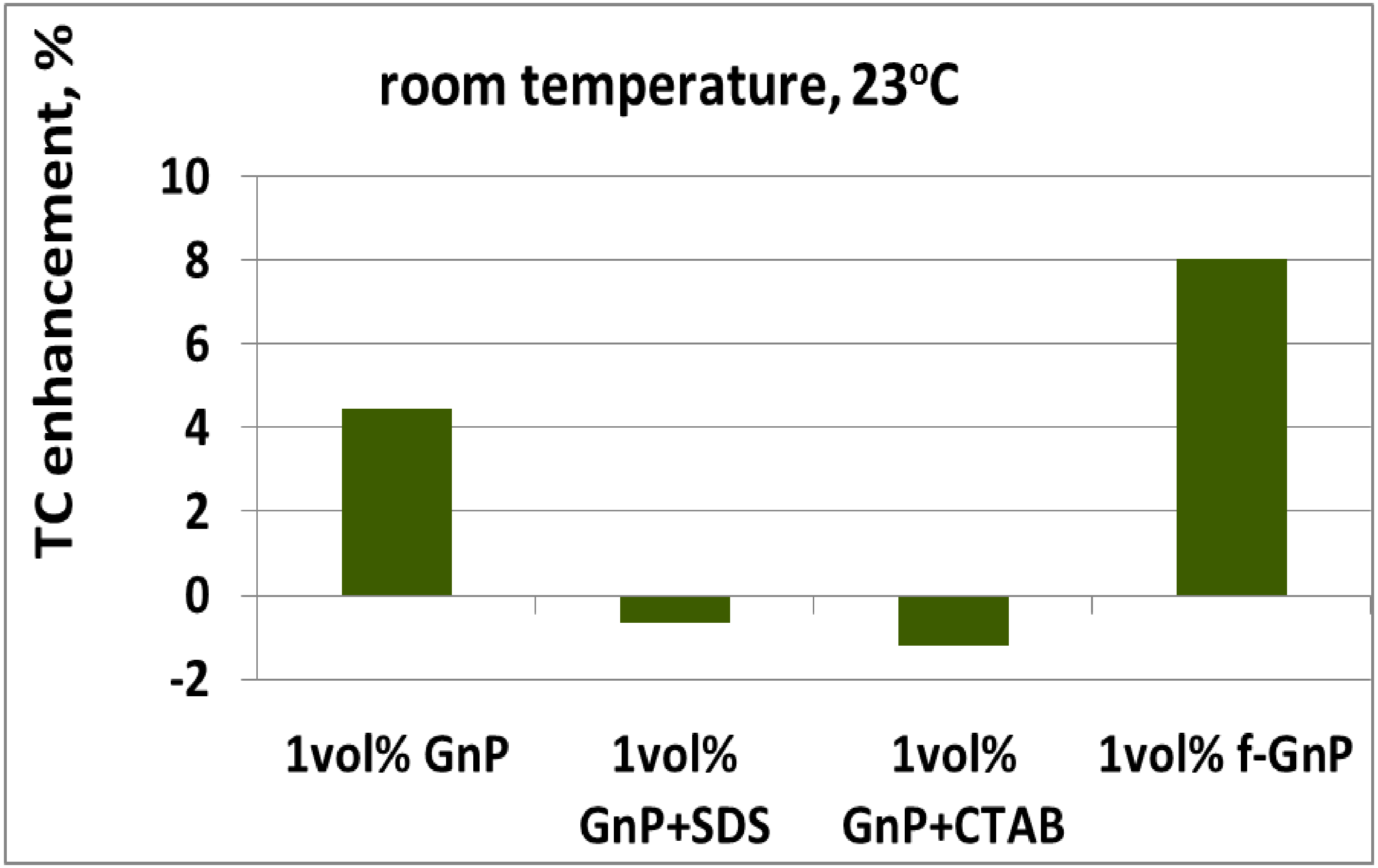
Accomplishments: Nanoparticle selections - graphite nano-platelets (GnP)



- Multilayer graphene (or nano-graphite flakes)
- Commercially available in large scale
- Low cost of graphitic nanomaterials
- Variations in diameter/thickness **=>** **study of shape effects**
- Poor dispersibility in water and ethylene glycol (EG)/water mixtures **=>** **need for surface functionalization**



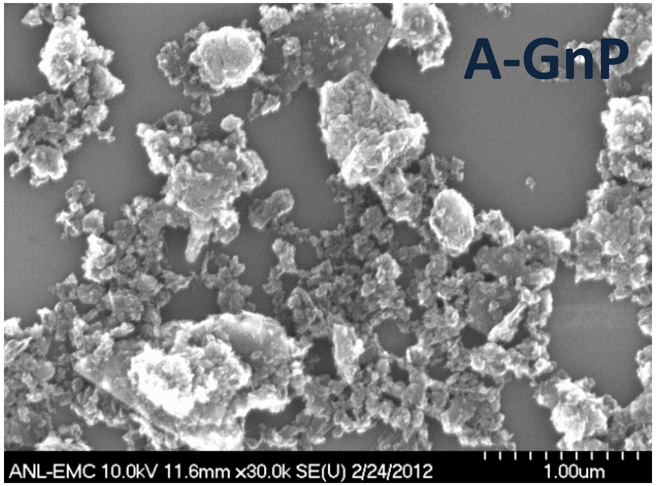
Accomplishments: GnP dispersion in H_2O – *stability*



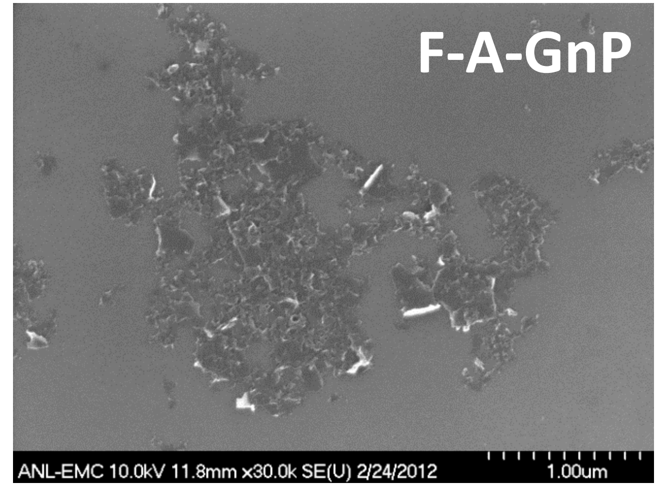
Surfactants (CTAB and SDS) provide good suspension stability but DETRIMENTAL to thermal conductivity in H_2O base fluid. Surfactants are NOT the way to go.

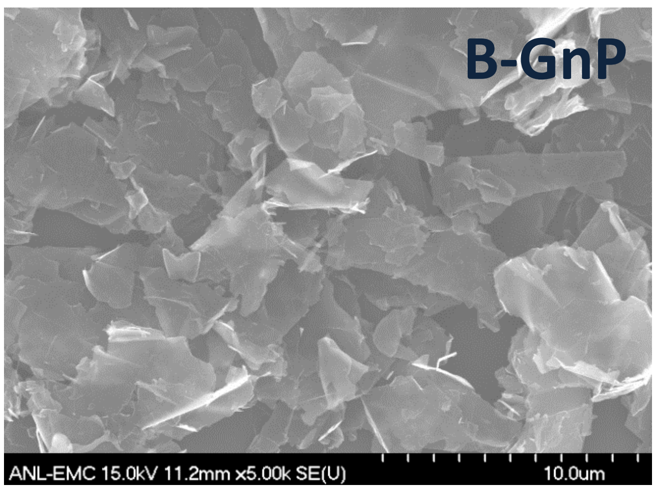
Accomplishments: GnP surface functionalization

BEFORE | **AFTER**

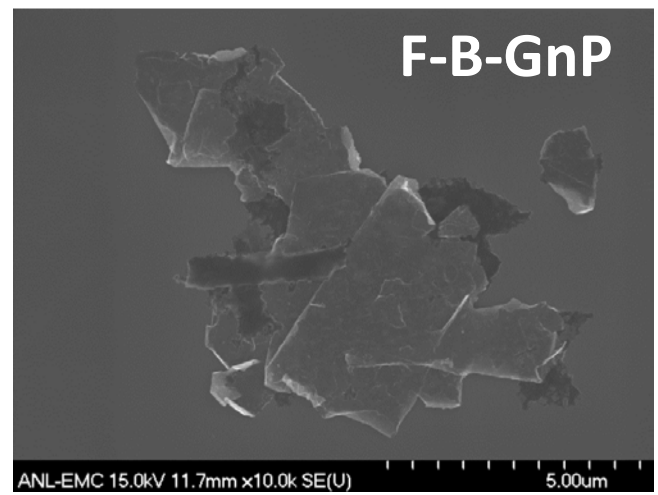


surface modification





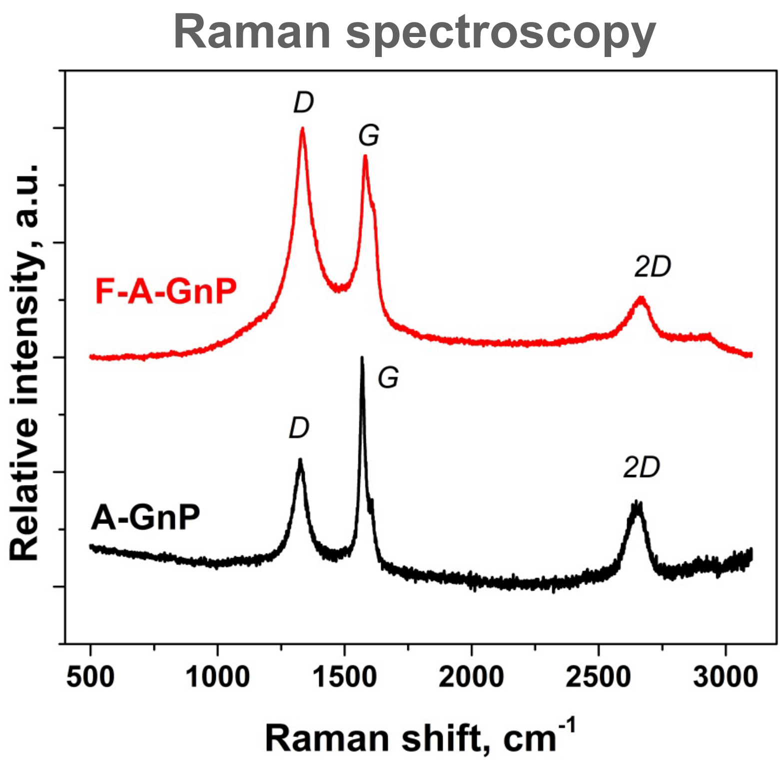
surface modification

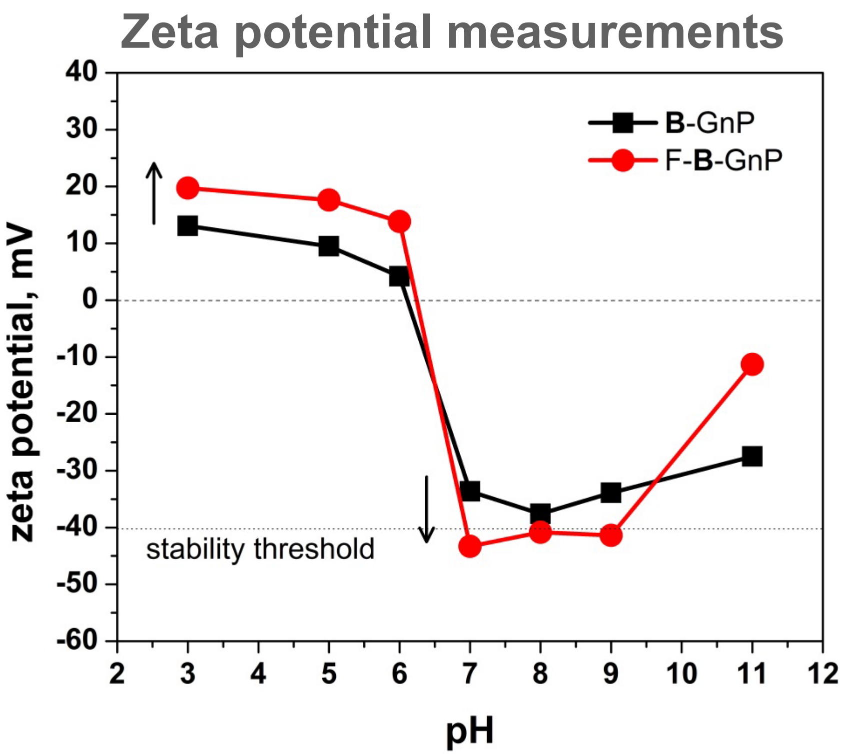


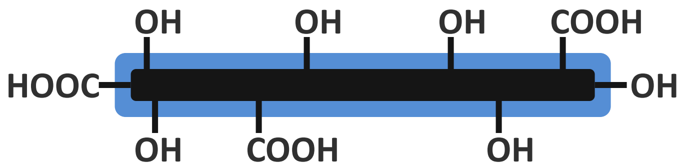
Hydrophobic
(agglomeration, poor dispersibility)

Hydrophilic
(good dispersion in EG/H_2O)

Accomplishments: Change in surface chemistry



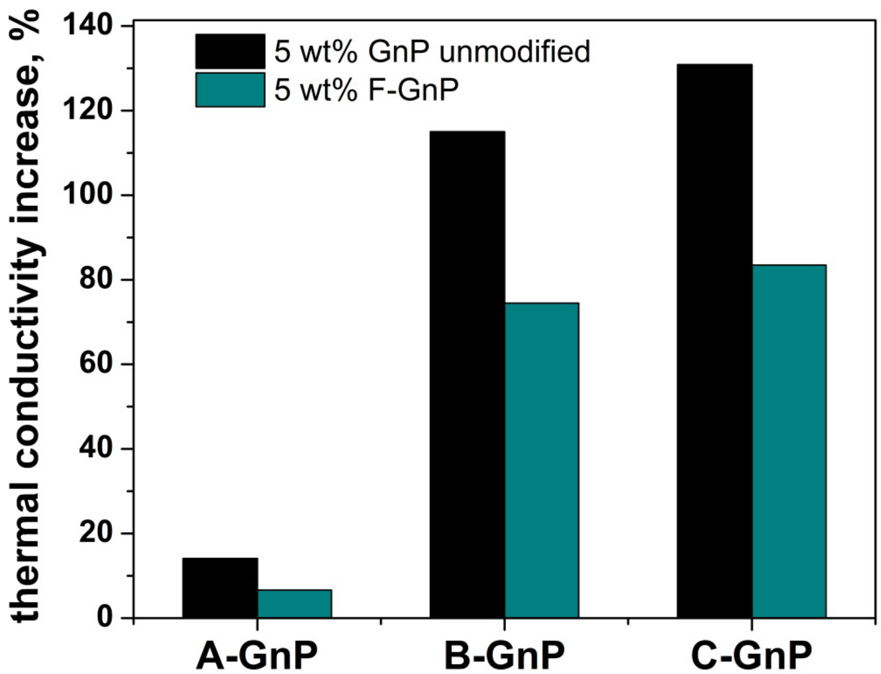


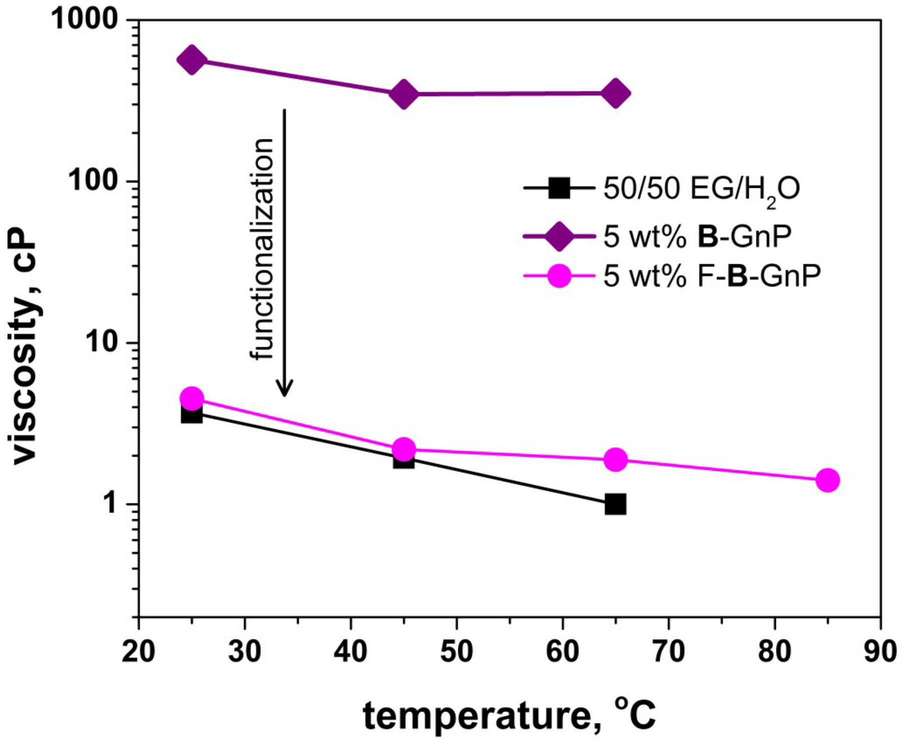


GO/graphite core/shell platelets

Surface functionalization increases surface concentration of hydroxyl and carboxylic groups/charges (zeta potential), engaging electrostatic stability of suspension.

Accomplishments: Thermo-physical properties of GnP in EG/H_2O nanofluid: *effect of surface functionalization*

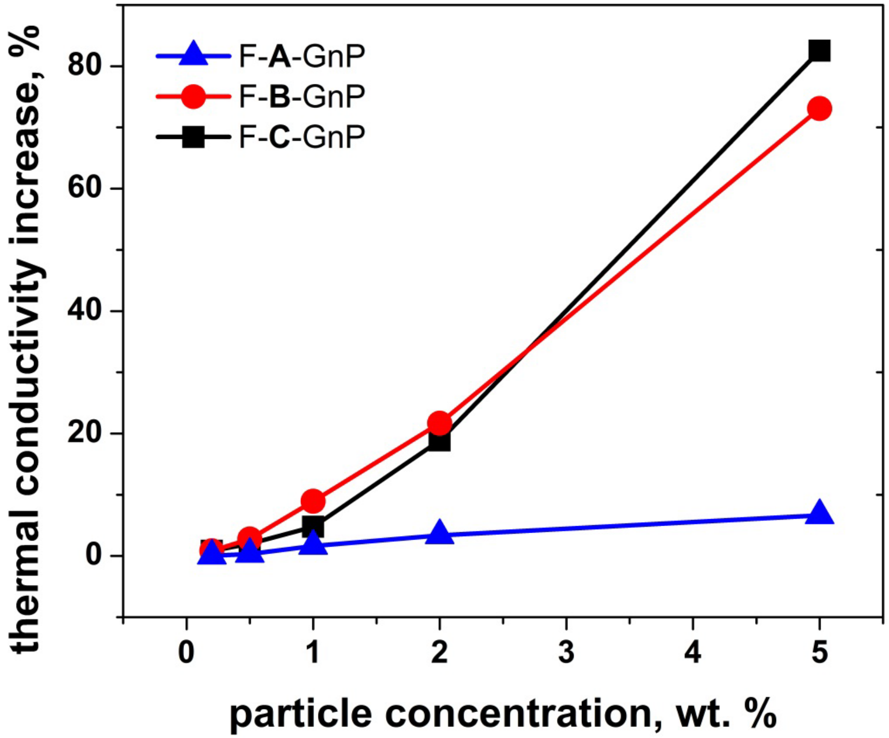


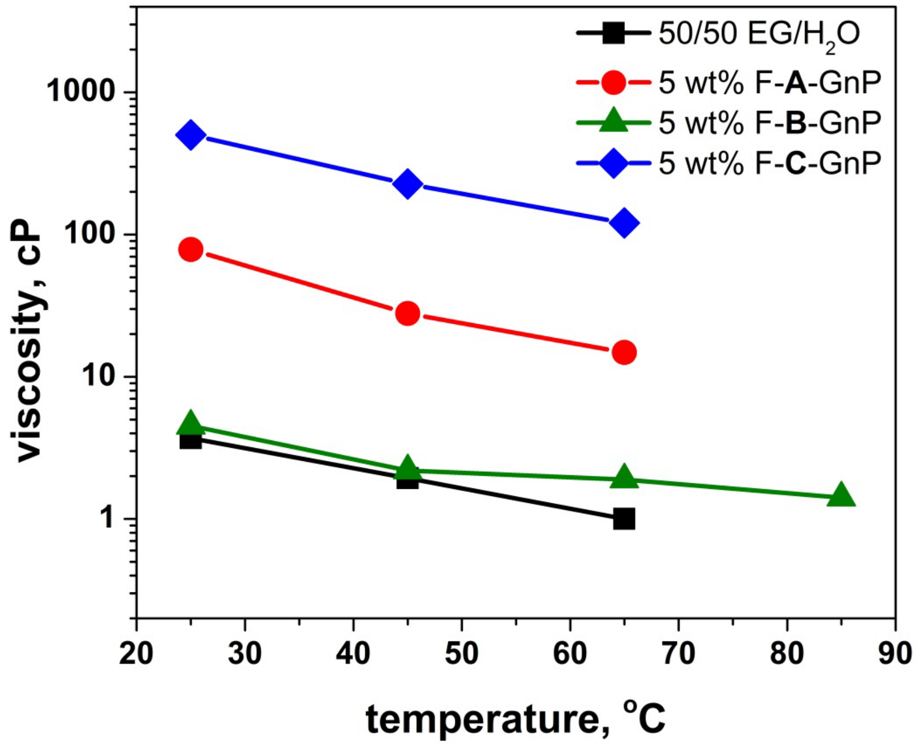


Surface functionalization to some extent degrades thermal conductivity increase (~45% less).

Surface functionalization dramatically lowers viscosity (> 100 times less viscous).

Accomplishments: Thermo-physical properties of GnP in EG/H_2O nanofluid: - *effect of particle shape/morphology*



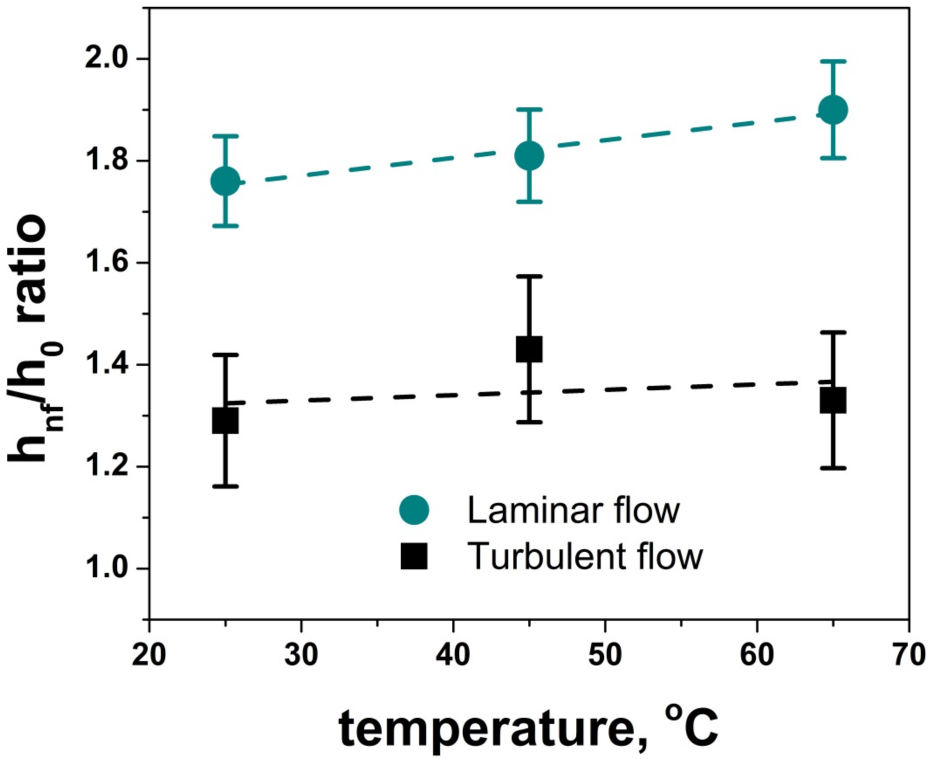


GnP with larger diameter and thickness show higher thermal conductivity increases (confirmation of percolative mechanism).

GnP diameter/thickness is critical for viscosity (optimum geometry is needed).

Accomplishments: Figure of merit evaluation of 5 wt% (~ 2.25 vol%) F-B-GnP in EG/H_2O nanofluid in laminar and turbulent flow

- Thermal conductivity ratio ~1.8 (variation in concentration can bring it up/down) => **Goal of >1.5 is met.**
- Viscosity increase is only ~ 10-40% (vs. 200 times of original GnP suspension).

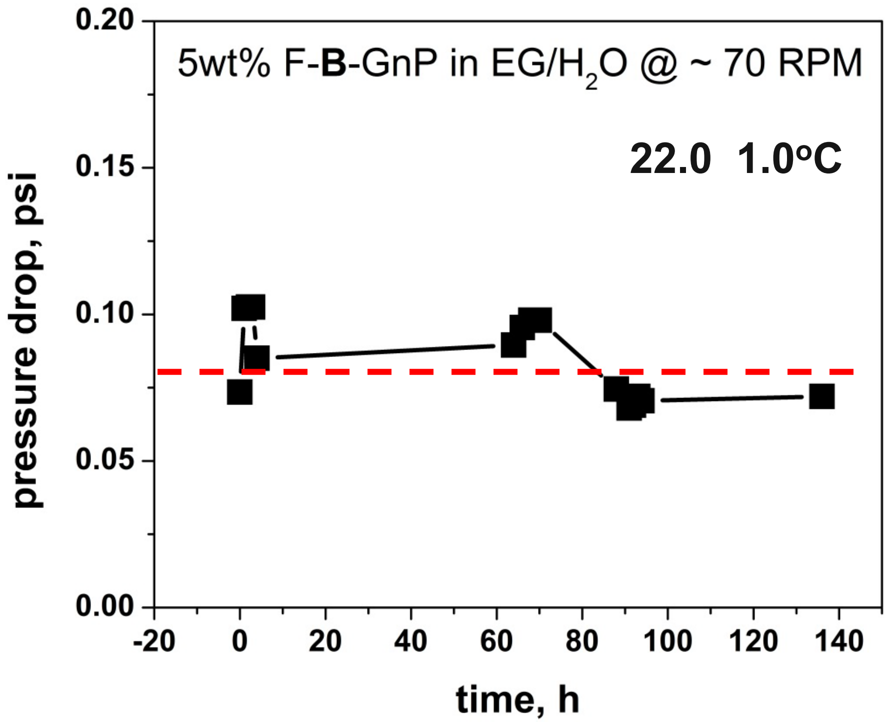


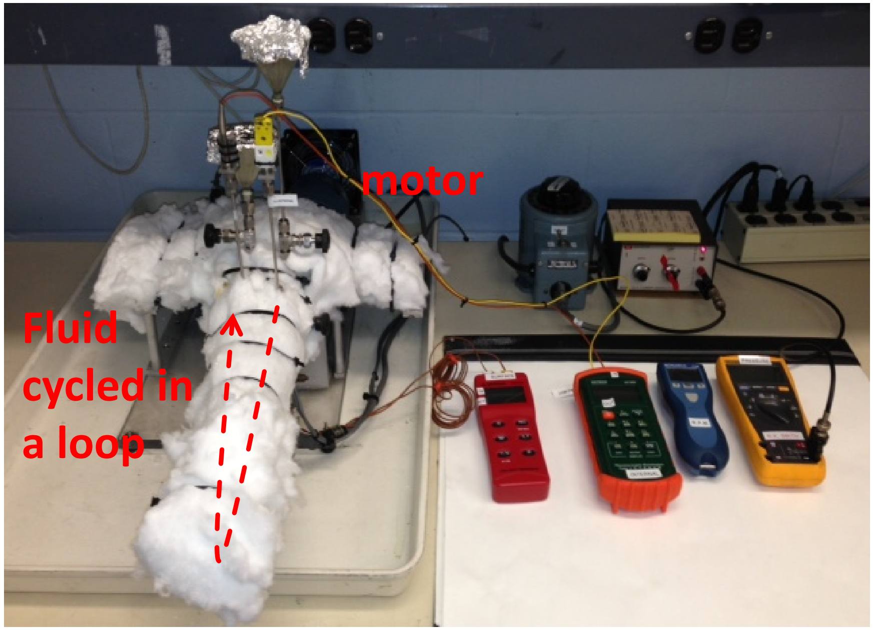
Efficiency criteria: NF is beneficial at h_{nf}/h_0 >1.

Developed F-GnP in EG/H_2O nanofluid that is beneficial in both laminar and turbulent flow regimes.

Accomplishments: Fouling test system

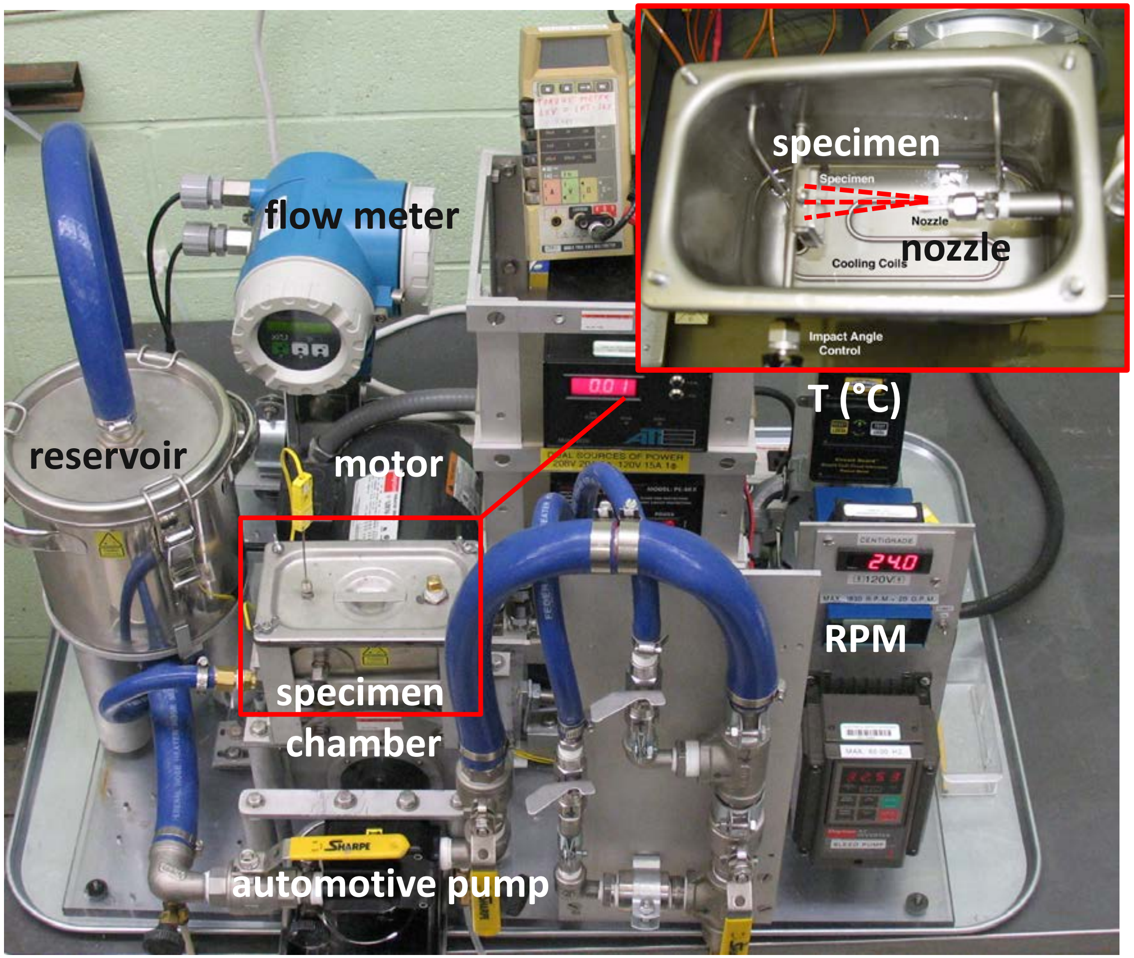
- Evaluated fouling/clogging within pipes/channels
- Measured pressure drop as a function of time & temperature
- Maintained flow rates equivalent to as those in a radiator cooling system





No clogging observed after hundreds of hours of testing.

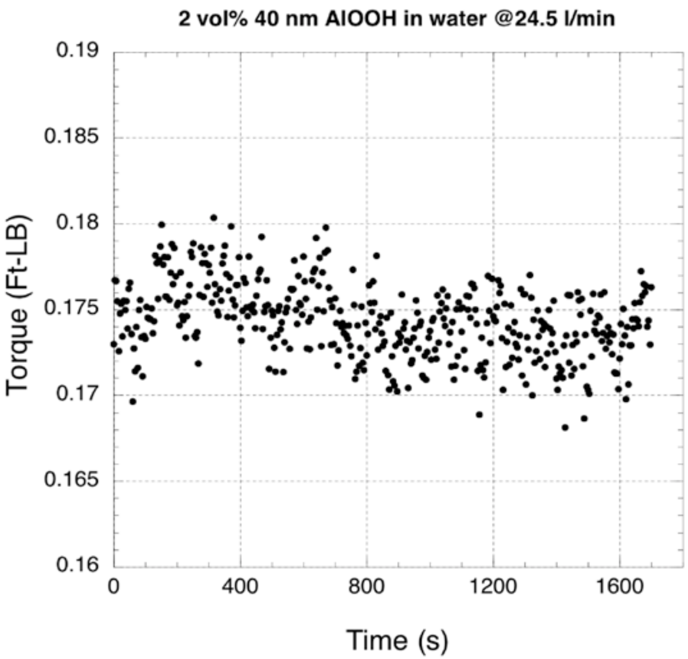
Accomplishments: Erosion/pumping power apparatus



Experiments from this apparatus provide critical data for corroboration of predictive pumping powers calculated from nanofluid property measurements.

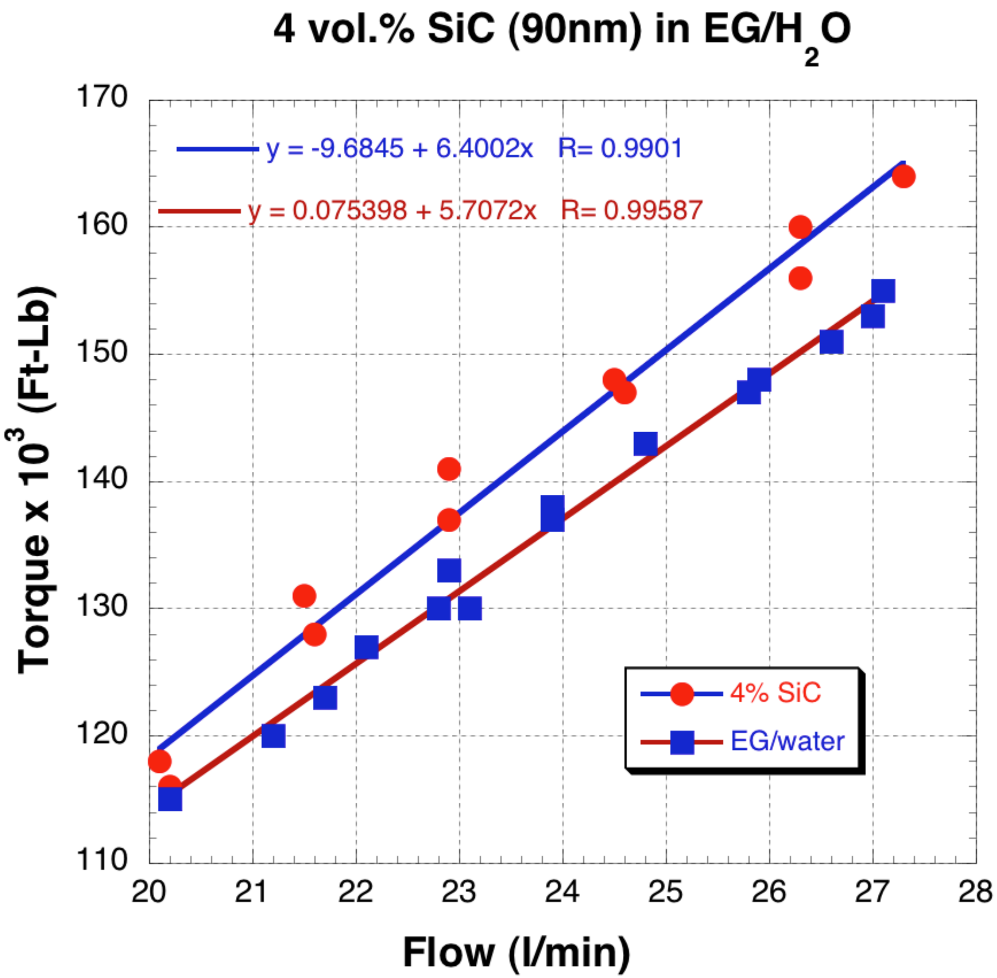
<u>Apparatus allows one to:</u>

- Study erosion of target material at fixed angle & velocity
- Measure power required to pump nanofluids and the base fluids using a torque-meter installed on shaft connecting pump and motor



***Routbort et al.**, J. Nanopart. Res., 2011, 13, 931-937*

Accomplishments: Pumping power evaluations



Nanofluid in EG/H_2O	Experimental relative increase in torque, %	Calculated relative increase in torque, %
2.2 vol% 29 nm SiC	9.3	8.7
4.0 vol% 90 nm SiC	5.3	6.5

Routbort et.al. *Ceramics Engineering and Science Proceedings, 32 (10), 2011,147.*

Experimentally measured pumping power is in good agreement with predictions.

Path forward

- Optimize the GnP nanofluid preparation procedure for scale-up
- Prepare nanofluid in quantities sufficient for heat transfer test (~1-5 gal.)
- Demonstrate the efficiency of nanofluid coolant in close to real heat exchanger conditions
  - heat transfer as a function of velocity, and pressure drop
  - temperature of 65°C, 85 C and 105°C
- Test fouling and erosion of the prospective nanofluid coolant in close to real heat exchanger conditions (temperature, flow rate, etc.)
- Conduct comparative analysis of costs and efficiency of the new technology to the baseline & other state-of-the-art coolants

Conclusions

- 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.
- Graphitic nanofluids in 50/50 mixture of ethylene glycol and water showed:
  - morphology-dependent thermal conductivity;
  - thermal conductivity ratio between 1.5 and 2.3 at 5 wt.% nanoparticles (room temperature) – possibilities for dramatic improvement in power electronics cooling
  - better dispersion stability, lower viscosity, and higher thermal conductivity due to surface chemistry/functionalization
  - enhanced performance with temperature
- Optimized and scaled-up nanofluid(s) will be used for tests in a heat transfer loop, as well as fouling and erosion tests, to assure the commercial viability of the nanofluid technology.