Engineering Nanofluids for Efficient Heat Transfer

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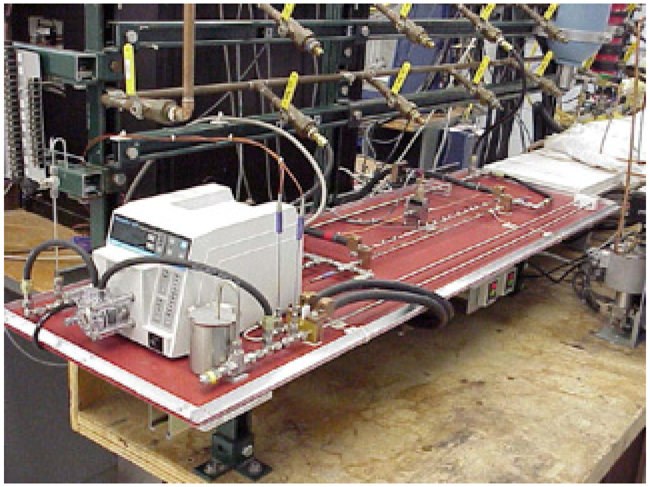
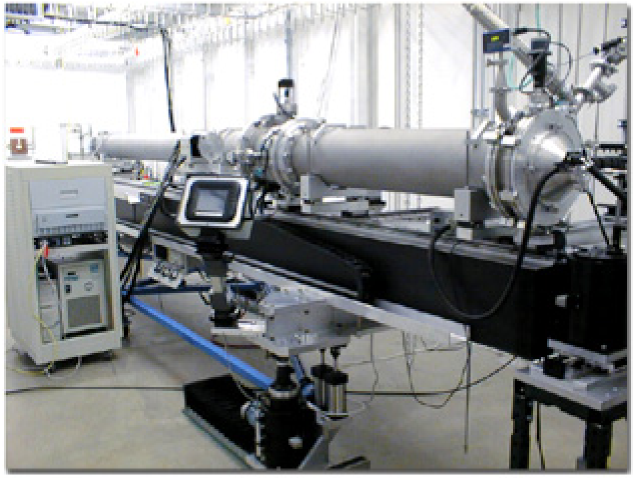


Heat transfer apparatus



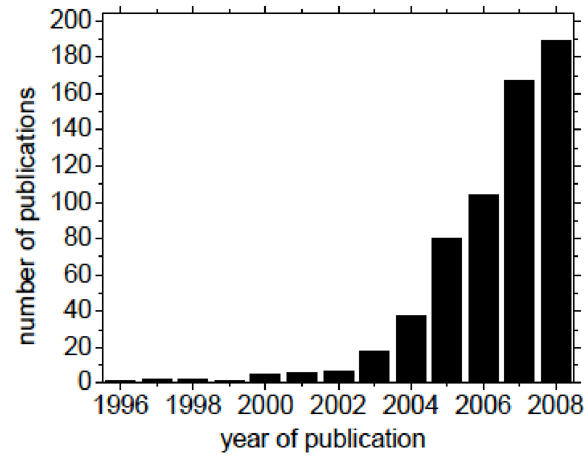
SAXS set-up at the Advanced Photon Source (ANL)

Institute of Physics, Chinese Academy of Sciences, October 21, 2011

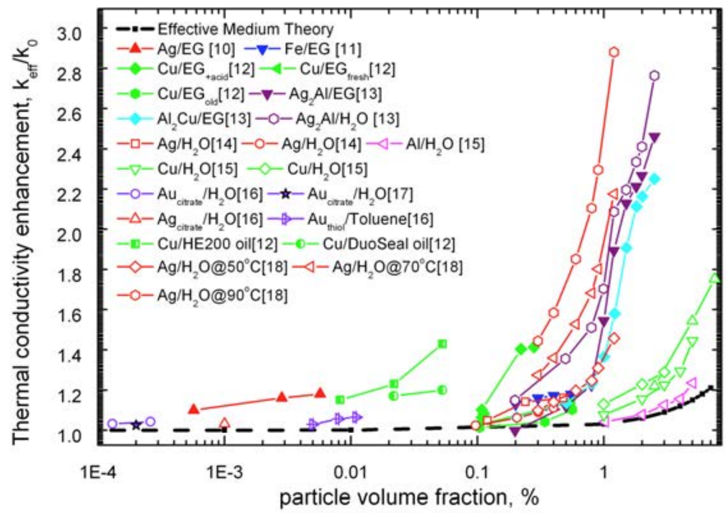
Outline

- Engineering Nanofluids – Important Properties Illustrated with SiC and Al_2O_3 nanoparticles in H_2O and EG/H_2O
  - Thermal conductivity
  - Viscosity
  - Heat Transfer
  - Erosion
  - Clogging
  - Pumping Power Penalty

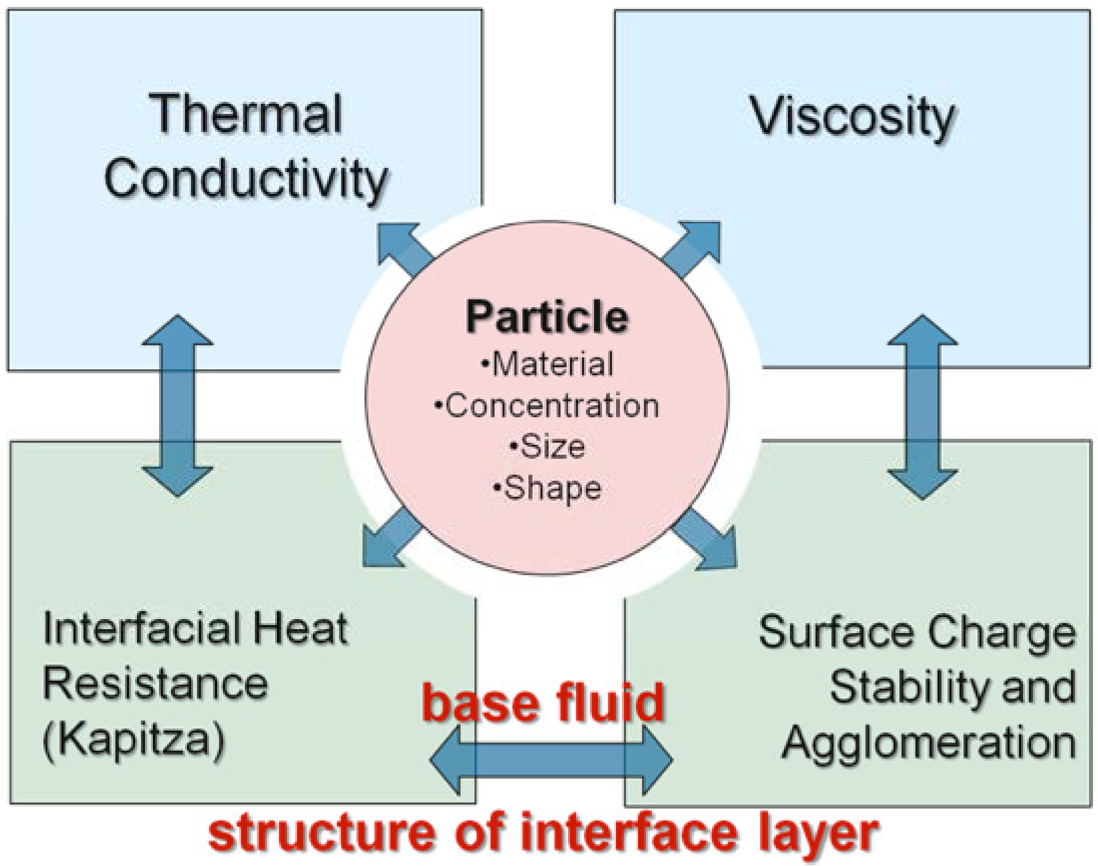
2009 – 314
2010 – 332



- Application for Cooling Power Electronics
- Graphite/Graphene based Nanfluids
- Summary



Nanofluids are a multivariable system



Highlights

- Understand how to engineer nanofluids (NF) for optimization of heat transfer
  - Thermal conductivity of NF depends on particle shape, size, concentration, chemistry of fluid, and thermal conductivity of nanoparticle
  - Relationship between thermal conductivity and heat transfer (in laminar and turbulent regions)
  - Measured power required to pump NFs and compared to theoretical
  - Measured erosion of NF on radiator materials (have observed NONE)
  - Developed apparatus to measure clogging/fouling (have observed NONE)

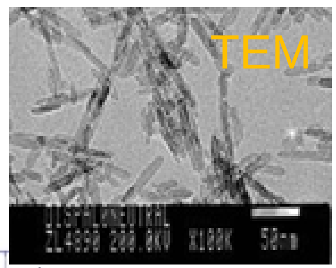
Experimental Approach:

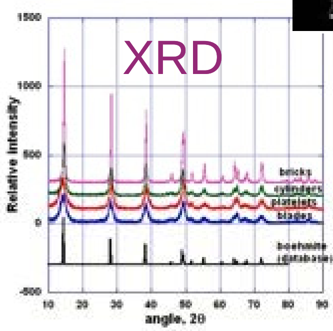
- Optimization of material properties for nanofluid manufacturing

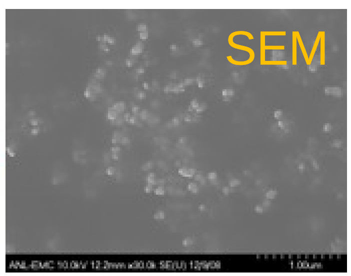
Effect of
- Particle shape
- Particle size
- Base fluid effect
- Additives

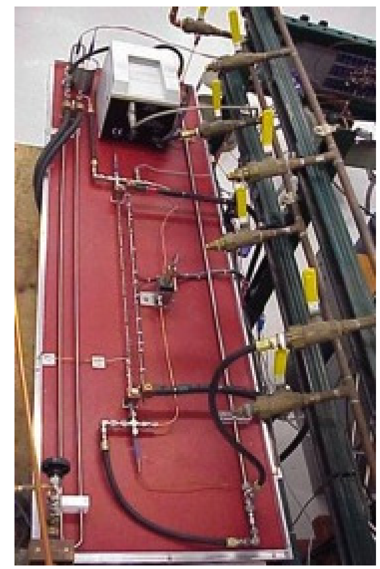
on
- Thermal Conductivity
- Viscosity

→ **Heat transfer coefficient**



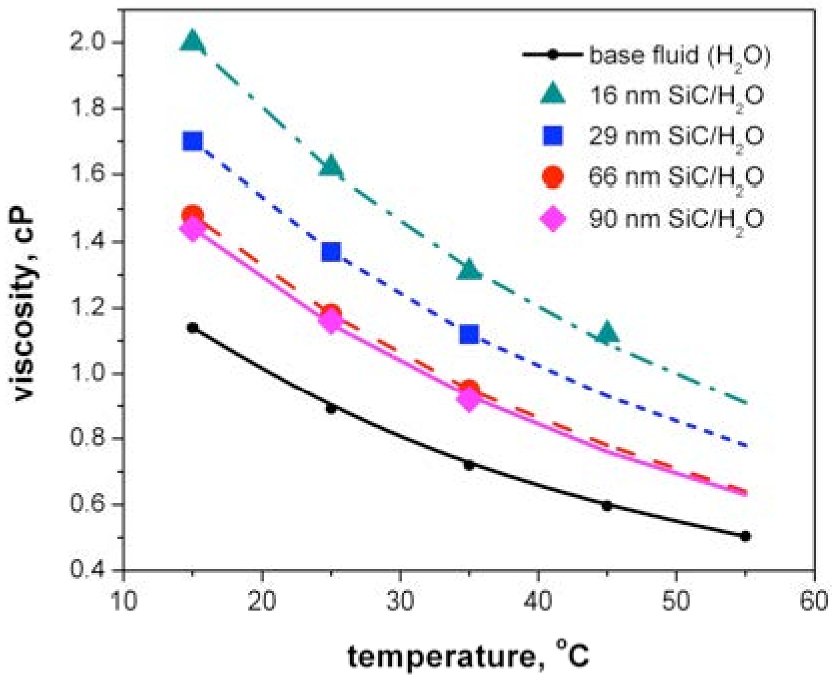




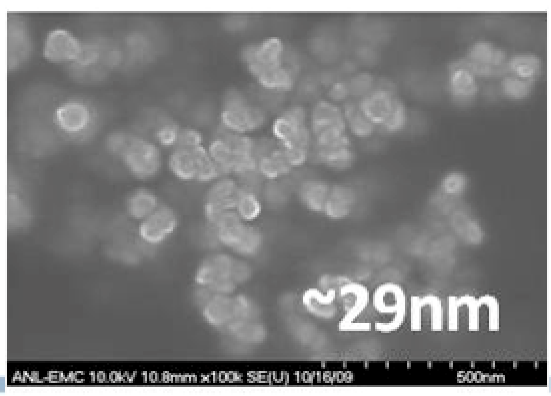


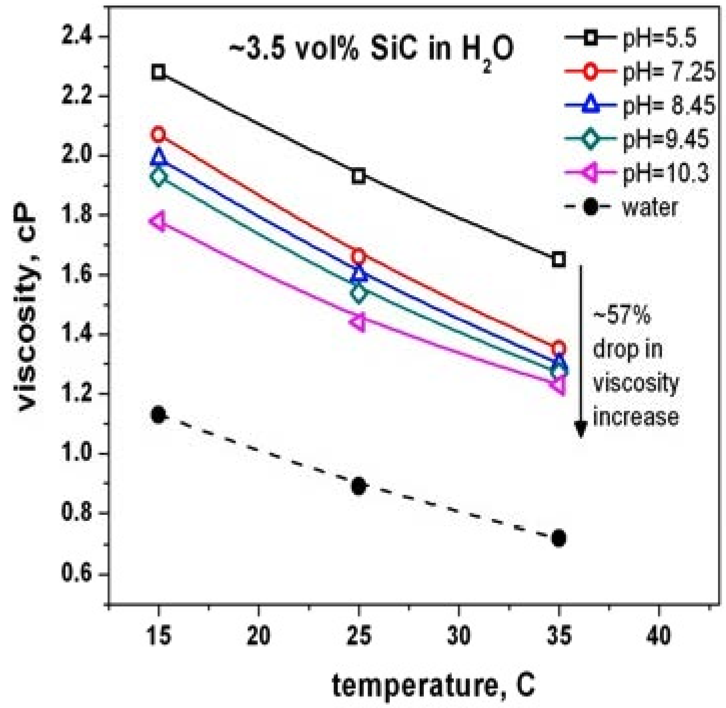
- Testing of nanofluid performance at various temperatures

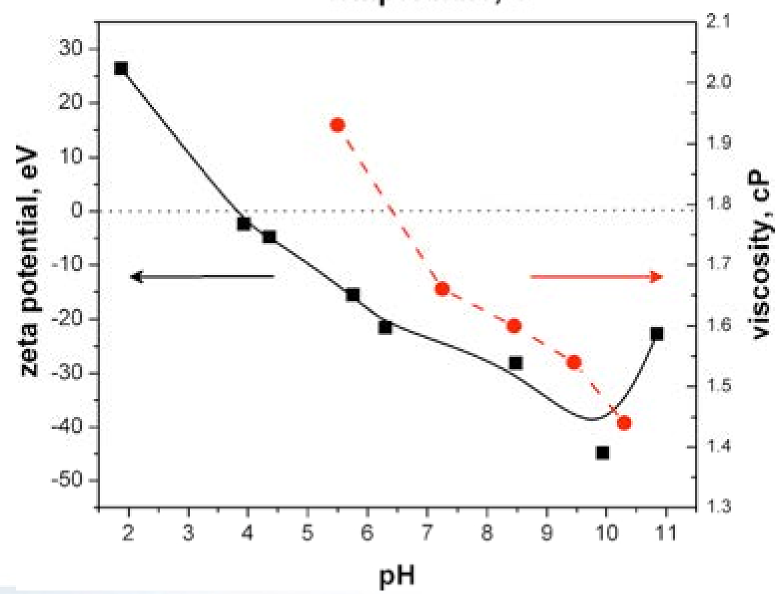
Viscosity Modification – SiC



Particle Size effect on viscosity

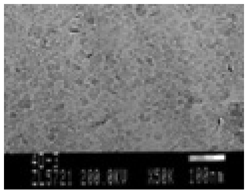


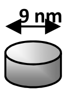




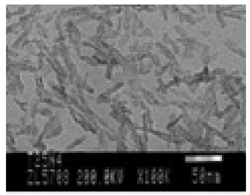
Particle Shape Effects Boehmite (AlOOH) in 50% EG-50% H_2O

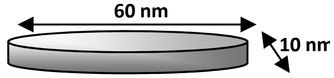
Platelets



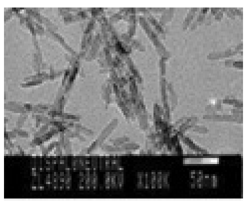


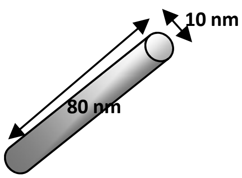
Blades



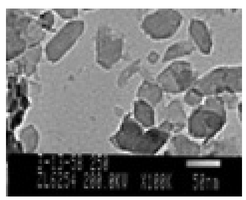


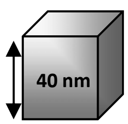
Cylinders



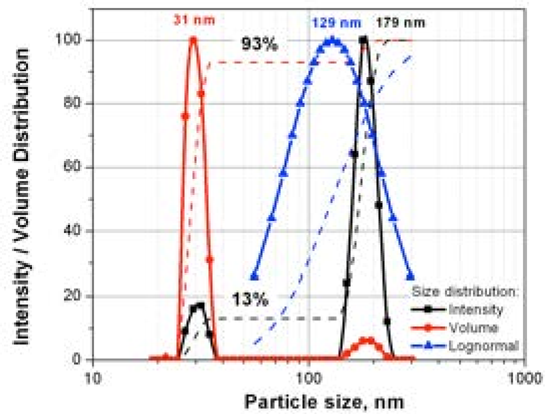


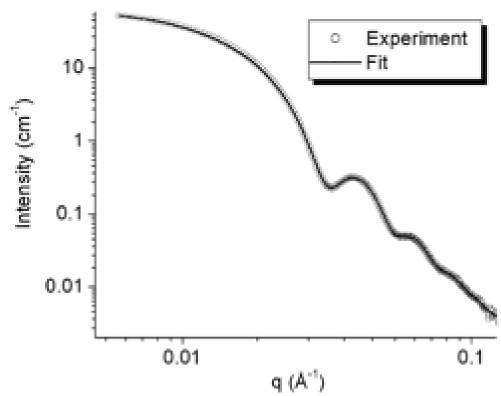
Bricks



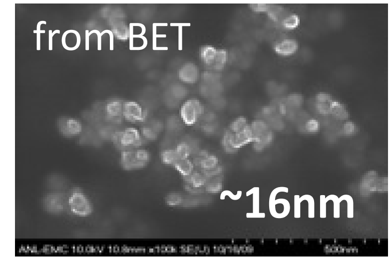


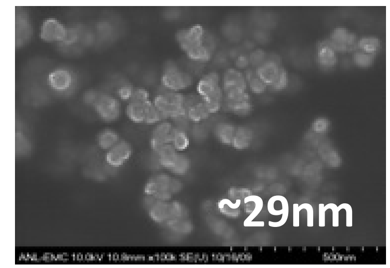
DLS

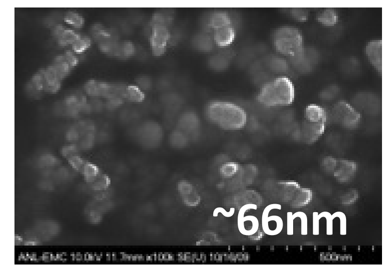


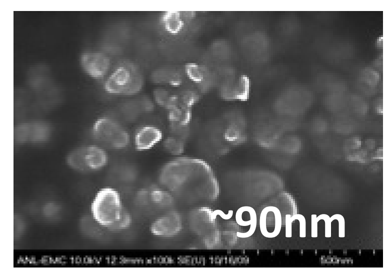


SAXS







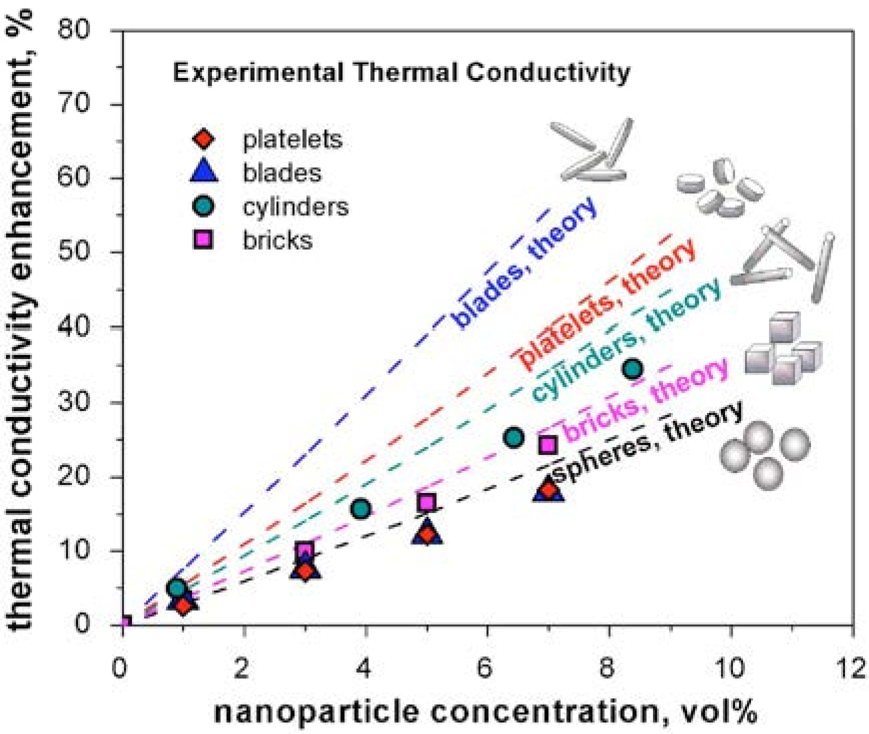


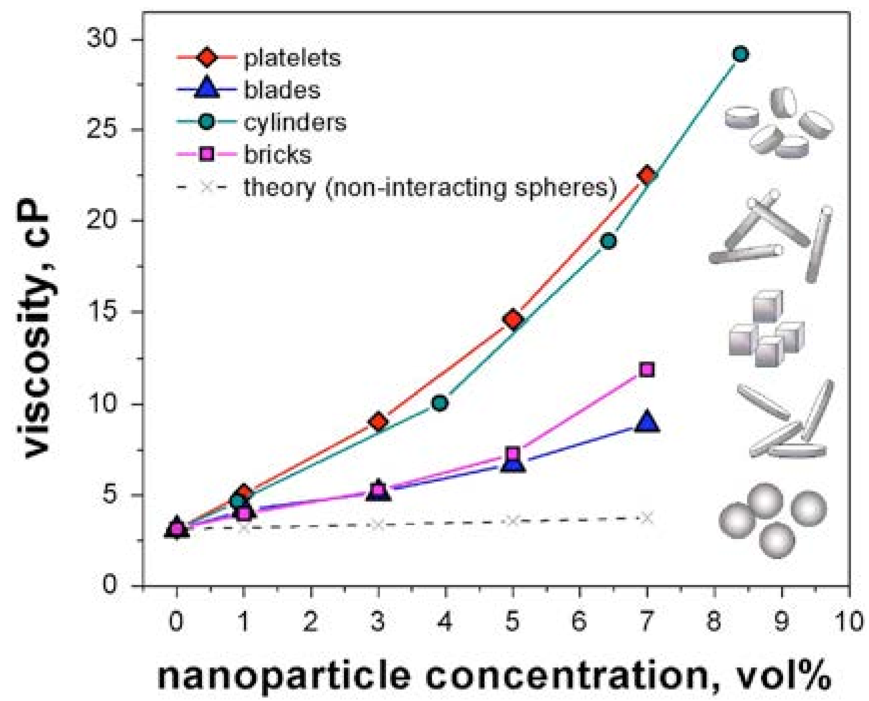
- Nanoparticle phase and crystallite sizes powder XRD
- Particle sizes and agglomeration in solution by DLS, SAXS, BET, TEM, SEM

E. Timofeeva, et al. JAP 106, 014304 2009

D. Singh, et al., JAP 105, 064306 (2009)

Thermal Conductivity and Viscosity of AlOOH in EG/H_2O





Hamilton-Crosser

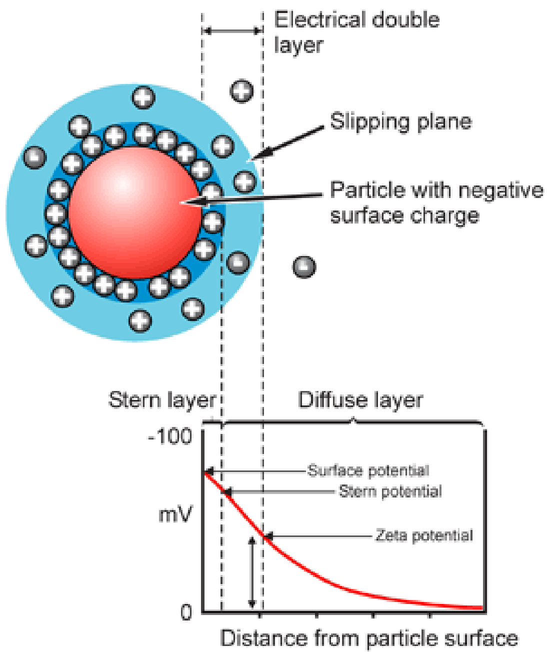
$$\frac{k_{eff}}{k_0} = \frac{k_p + (n-1)k_0 + (n-1)(k_p - k_0)\phi}{k_p + (n-1)k_0 - (k_p - k_0)\phi}$$

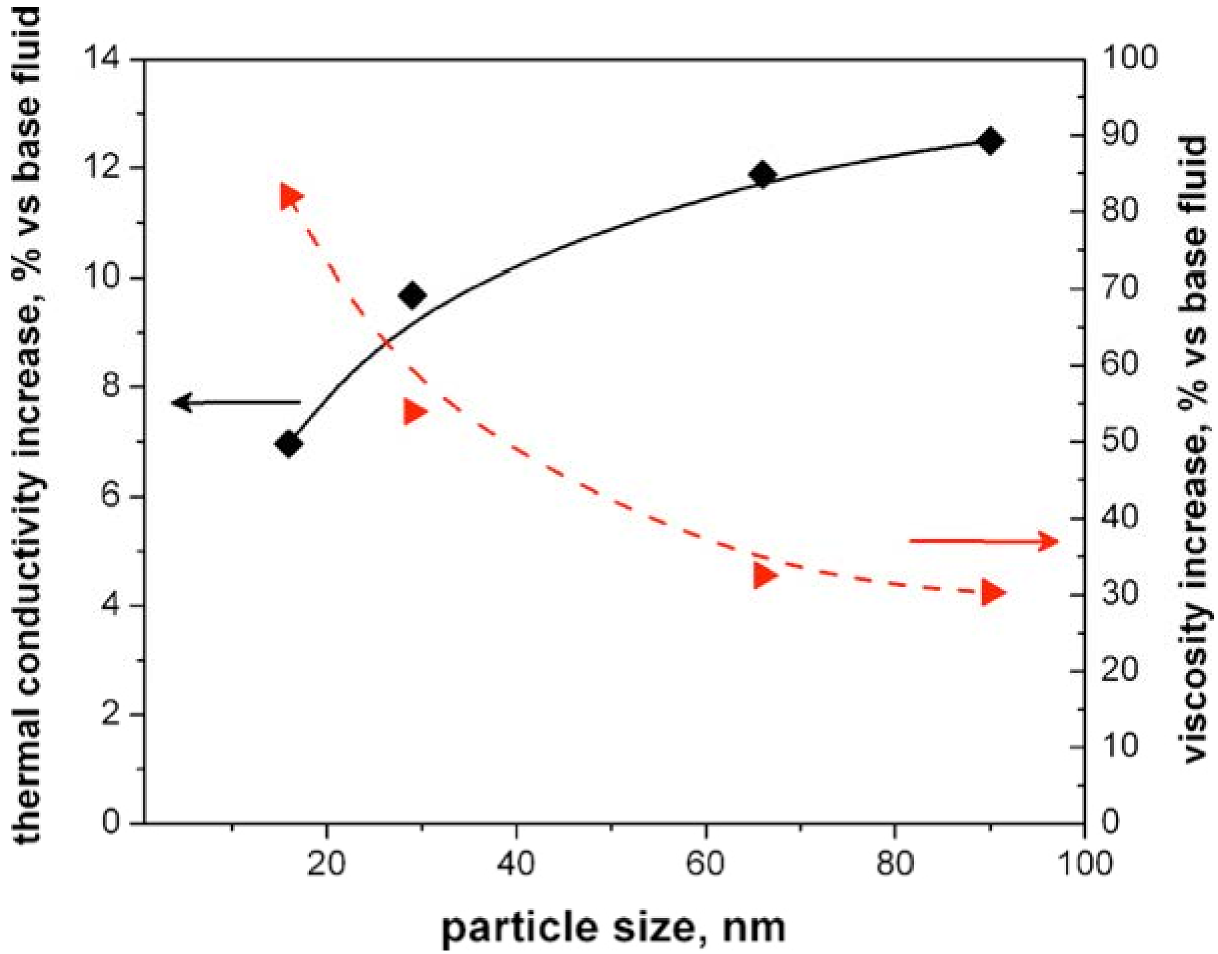
$$n = 3/\psi$$

Einstein-Batchelor

$$\eta_{eff} = \eta_o\left(1 + 2.5\phi + 6.2\phi^2\right)$$

Particle size effect on thermal conductivity & viscosity
4.1 vol.% α-SiC in H_2O

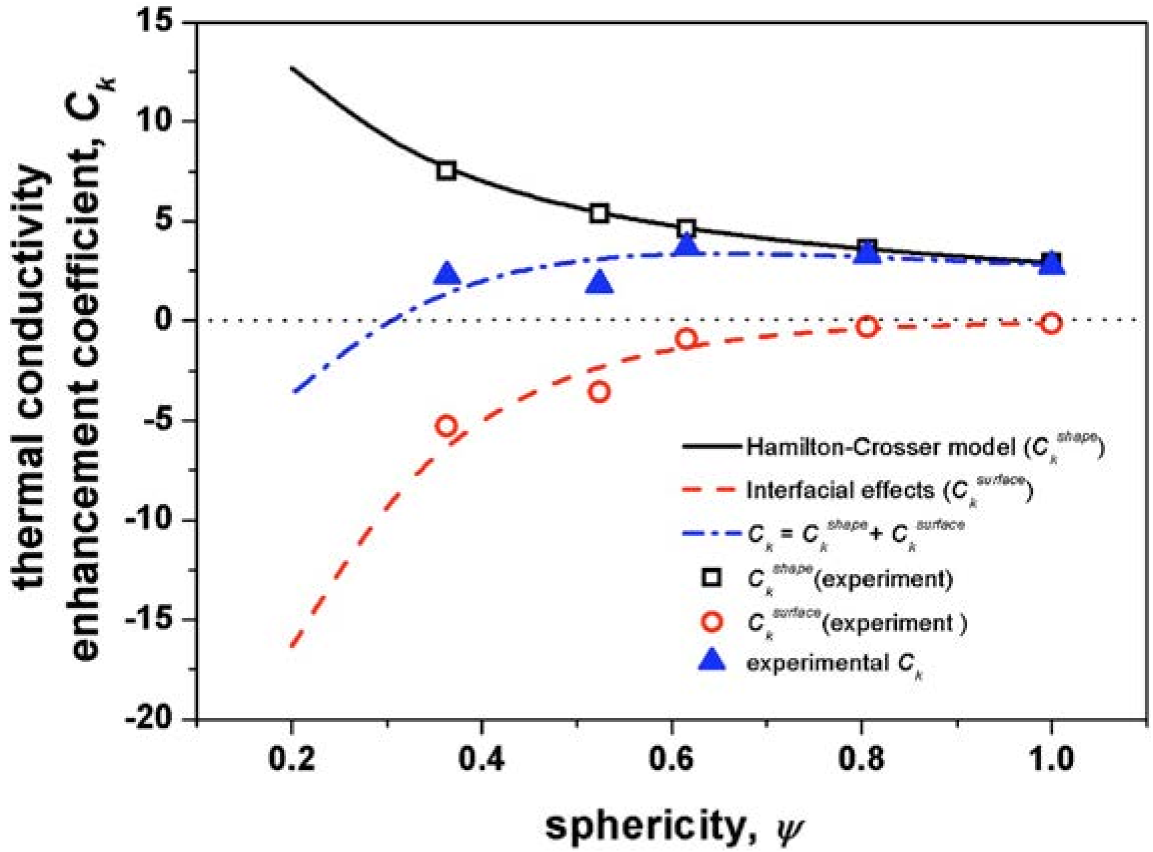




Thermal Conductivity Analysis

$$\frac{k_{nf}}{k_0} = 1 + (C_k^{shape} - C_k^{surface})\phi$$

$$l_k = R_k k_o$$



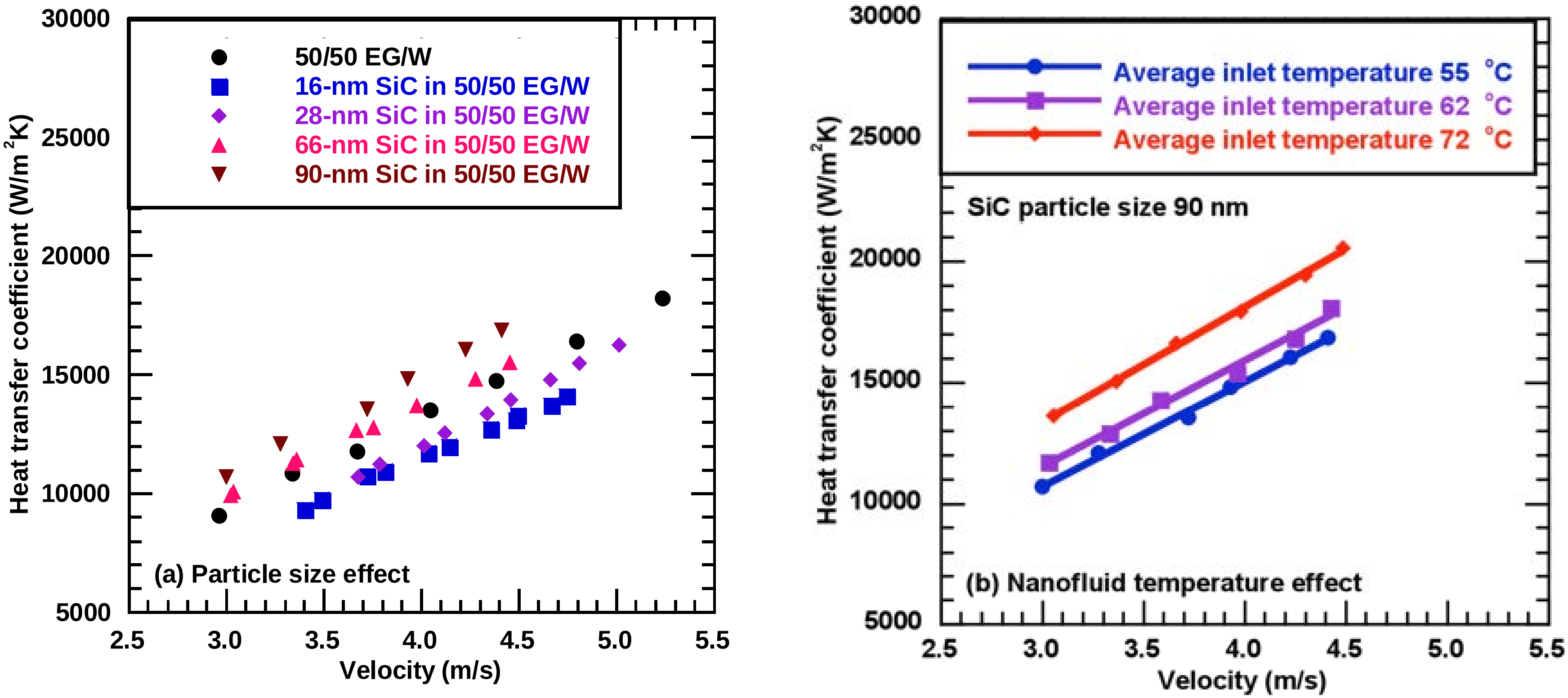
Shape	l_k (nm)
Platelets	1.4
Blades	1.6
Cylinders	1.8
Bricks	1.8

$$\overline{l_k} = 1.6$$

$$\overline{R_k} = 4.4x10^{-9} m^2 K/W$$

Heat transfer α-SiC (4 vol%) in EG/H_2O

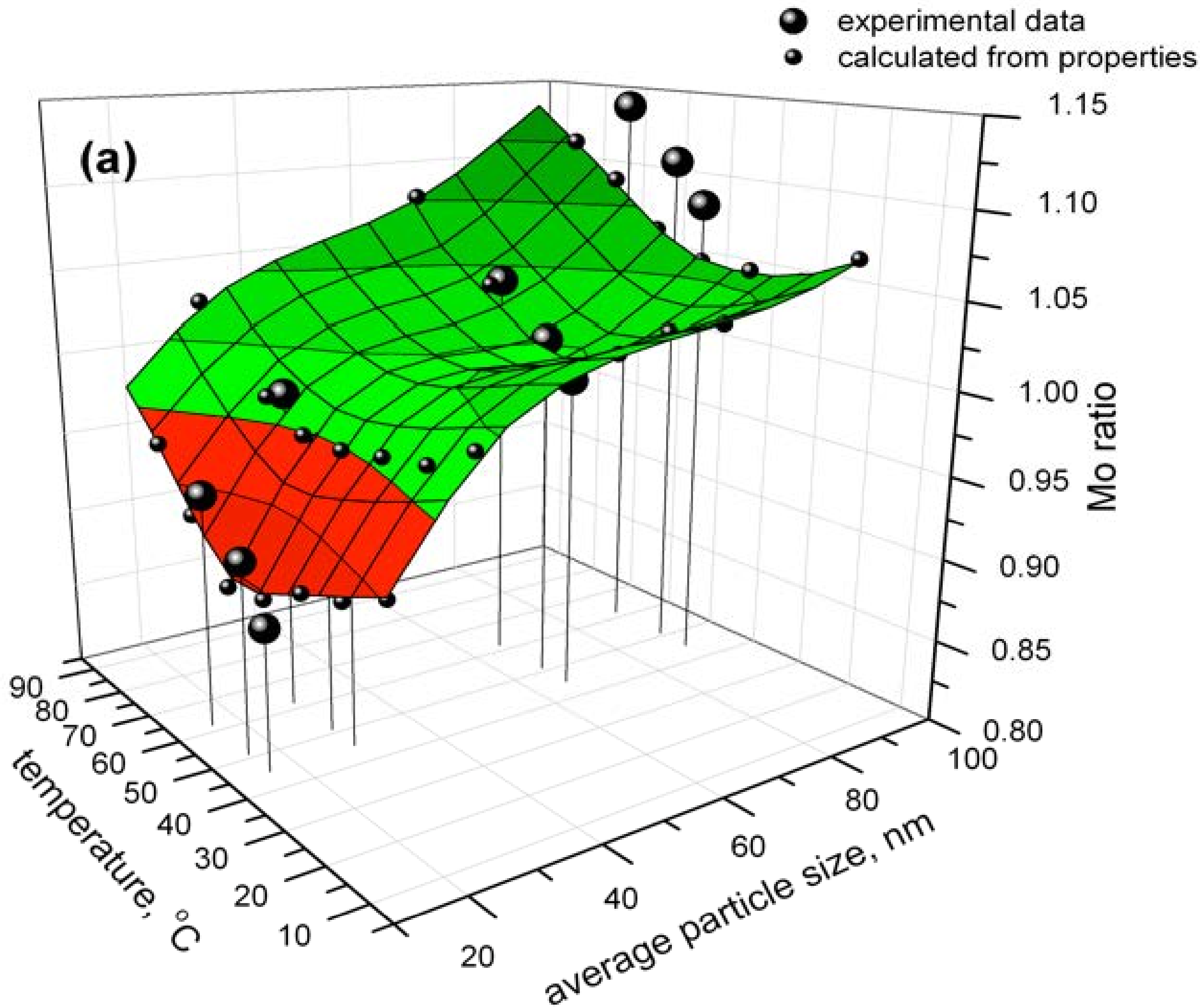
Data from Wen Hu



Inlet T= 55°C

E. Timofeeva, JAP, 109, 014914 (2011)

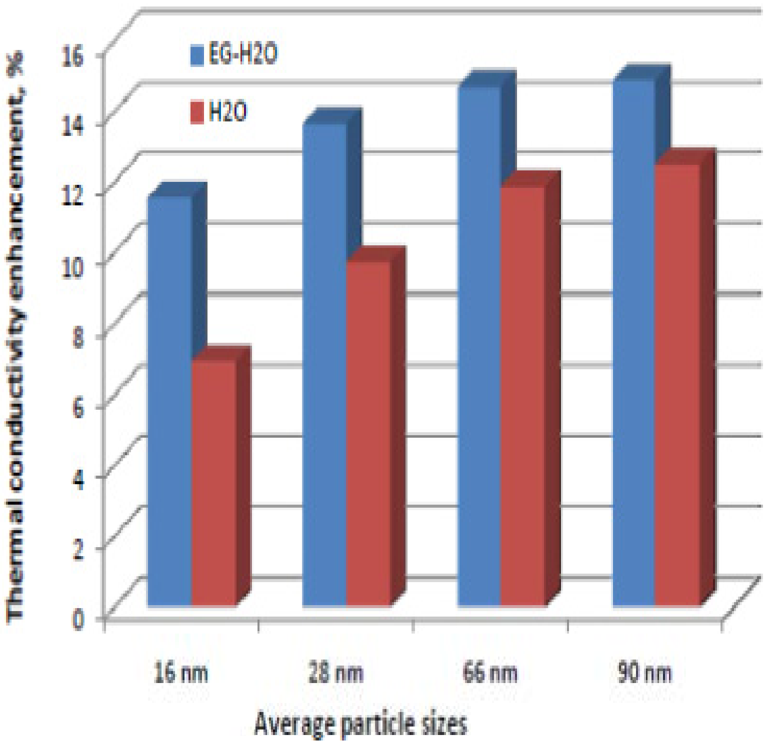
Heat transfer α-SiC (4 vol%) in EG/H_2O turbulent flow Experiment vs. Calculated

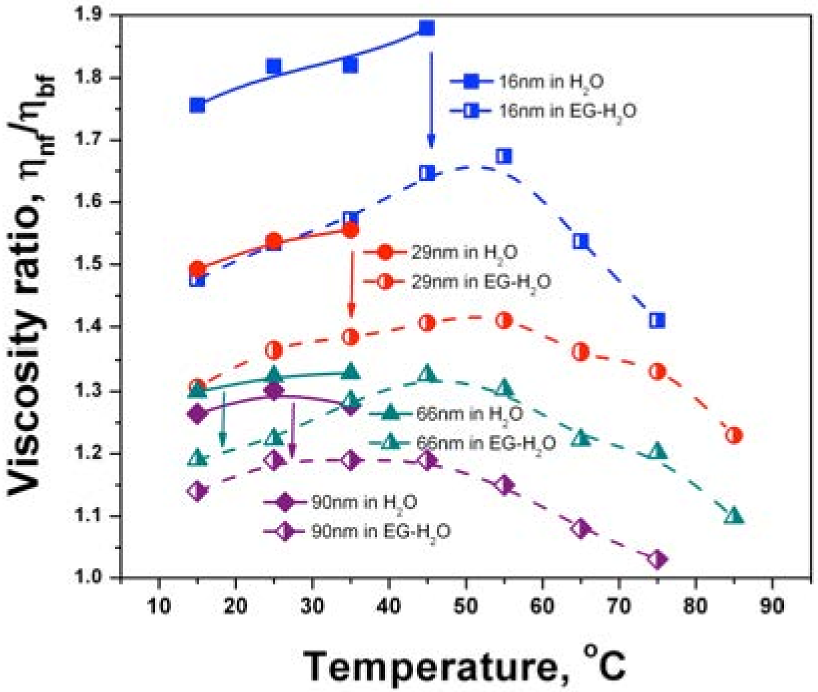


Mo = Efficiency factor

$$M_o = (\rho^{0.8} c_p^{0.4} k^{0.6}) / \eta^{0.4}$$

Comparison of 4 vol % SiC nanoparticles in H_2O and EG/H_2O





– shift of isoelectric point
– higher kinetic energy

NB: Viscosity of 90 nm SiC in EG/H_2O almost equal to that of base fluid for T≥75°C

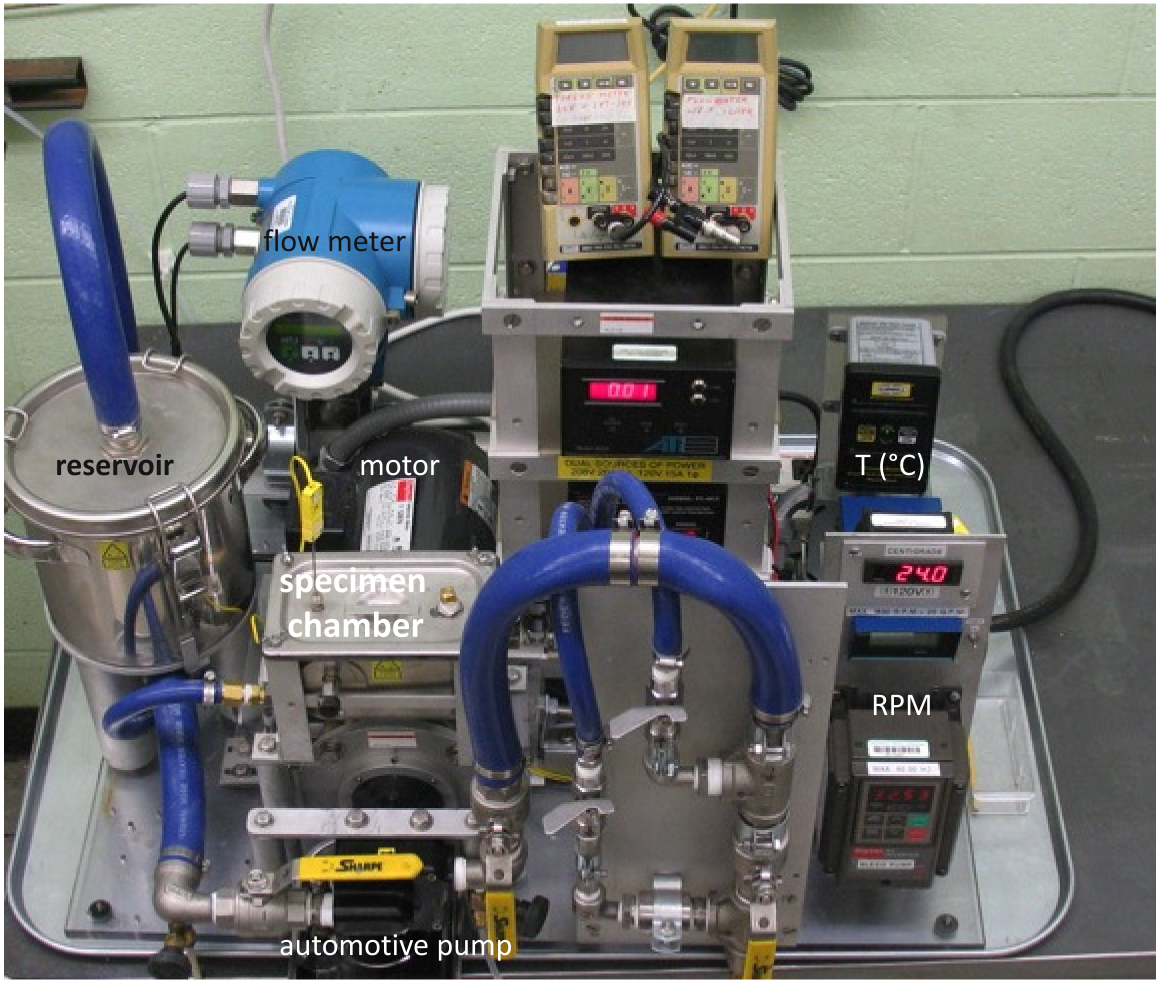
Dependence of Nanofluids on Properties-Systems Engineering Approach

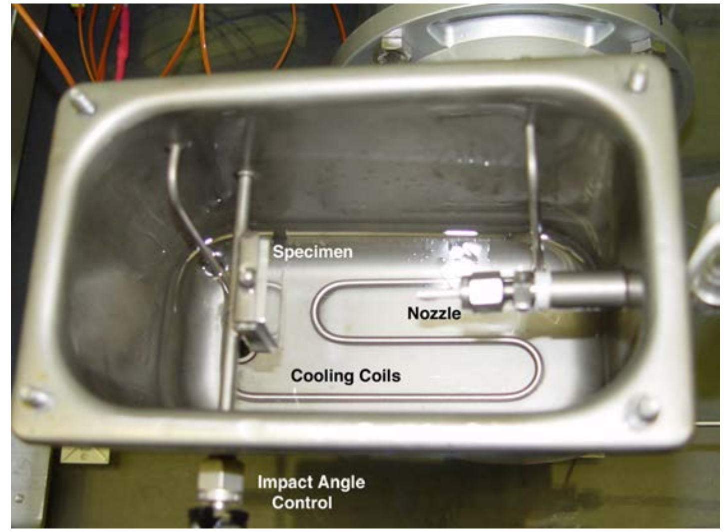
Nanoparticle Properties (Relative Importance)	Viscosity	Thermal Conductivity	Heat Transfer
Material (4.0)	Weak	Strong	Strong
Concentration(6.3)	Strong	Strong	Strong
Shape (3.8)	Strong	Medium	Strong
Size (5.0)	Strong	Strong	Strong

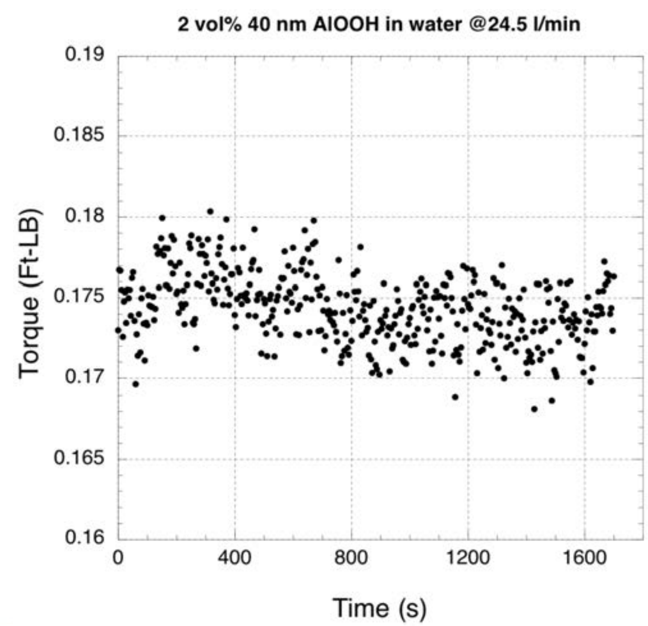
Fluid Properties (Relative Importance)	Viscosity	Thermal Conductivity	Heat Transfer
Base fluid (5.3)	Strong	Weak	Strong
Zeta Potential (4.0)	Strong	Medium	Strong
Additives (2.8)	Medium	Weak	Medium
Temperature (3.8)	Strong	Medium	Strong

E. Timofeeva, et al., Nano Research Letters, 6, 182 (2011)

Pumping Power and Erosion







Torque measurement and
Data logger hidden behind

Pumping Power

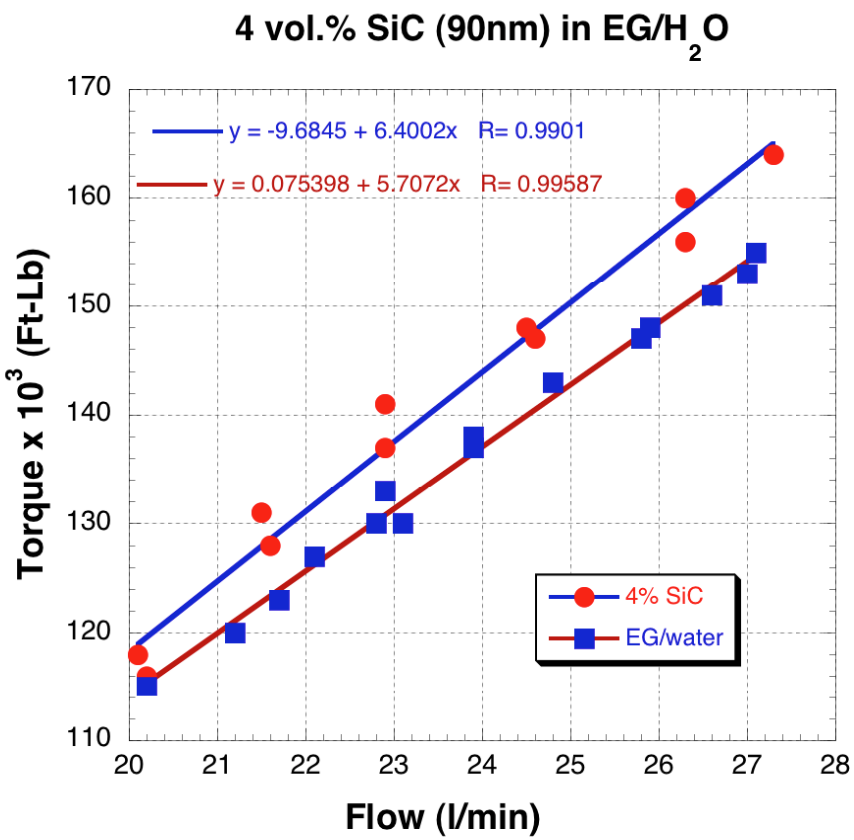
$$P_{shaft} = \tau\omega = P_{pumping}/\eta = Q\Delta p/\eta = \Delta p(\pi d^2/4)V/\eta$$

$$P_{shaft} = \frac{Q\Delta P}{\eta} = \frac{(\pi d^2/4)V[\rho g h + 2\rho V^2 (L/d) f + \sum_i K_i (1/2)\rho V_i^2]}{\eta}$$

Fanning Friction Factor $f = 0.0791\,\mathrm{Re}^{-0.25} = 0.0791(\rho V d/\mu)^{-0.25}$

V = velocity
μ = viscosity
K = friction factor of each component
L – length
d = diameter
ρ = density
η = pump efficiency
R_e = Reynolds number

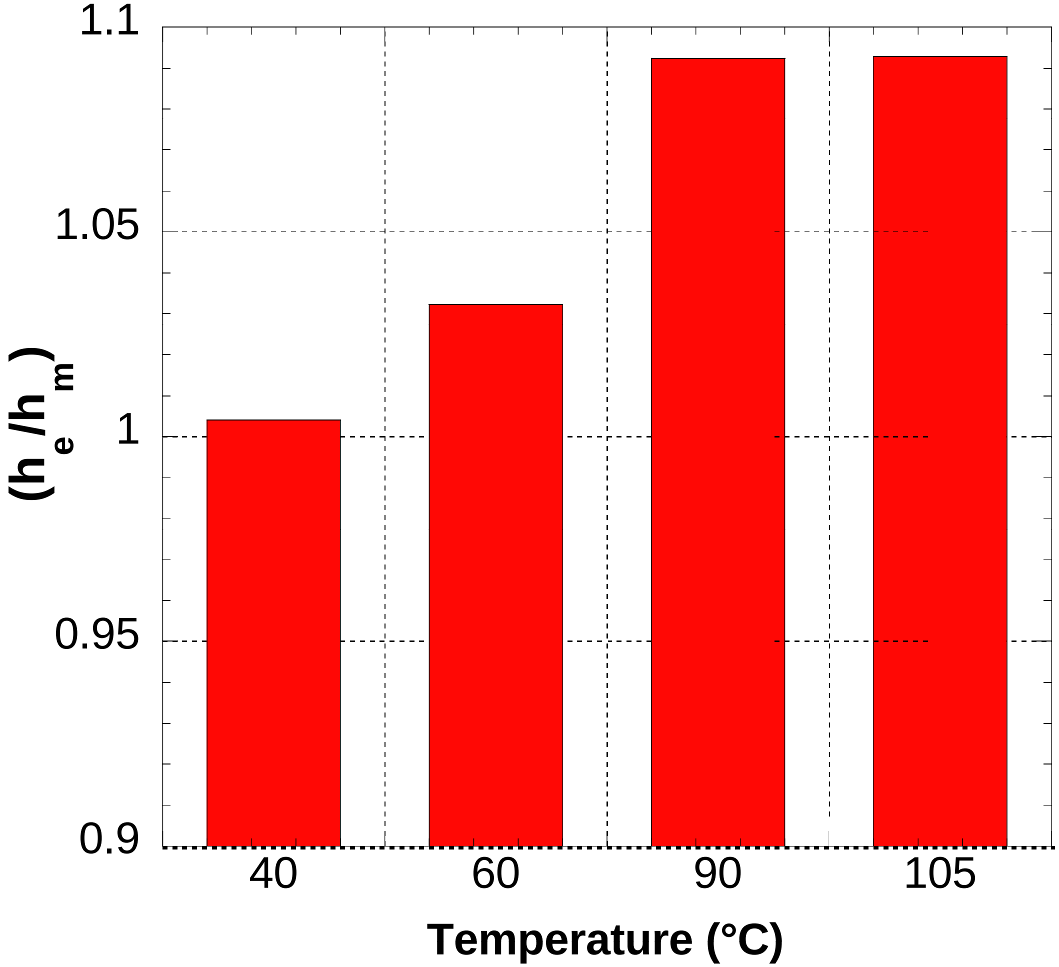
Effect of particle size for SiC



NB: Torque vs R_e gives a false impression

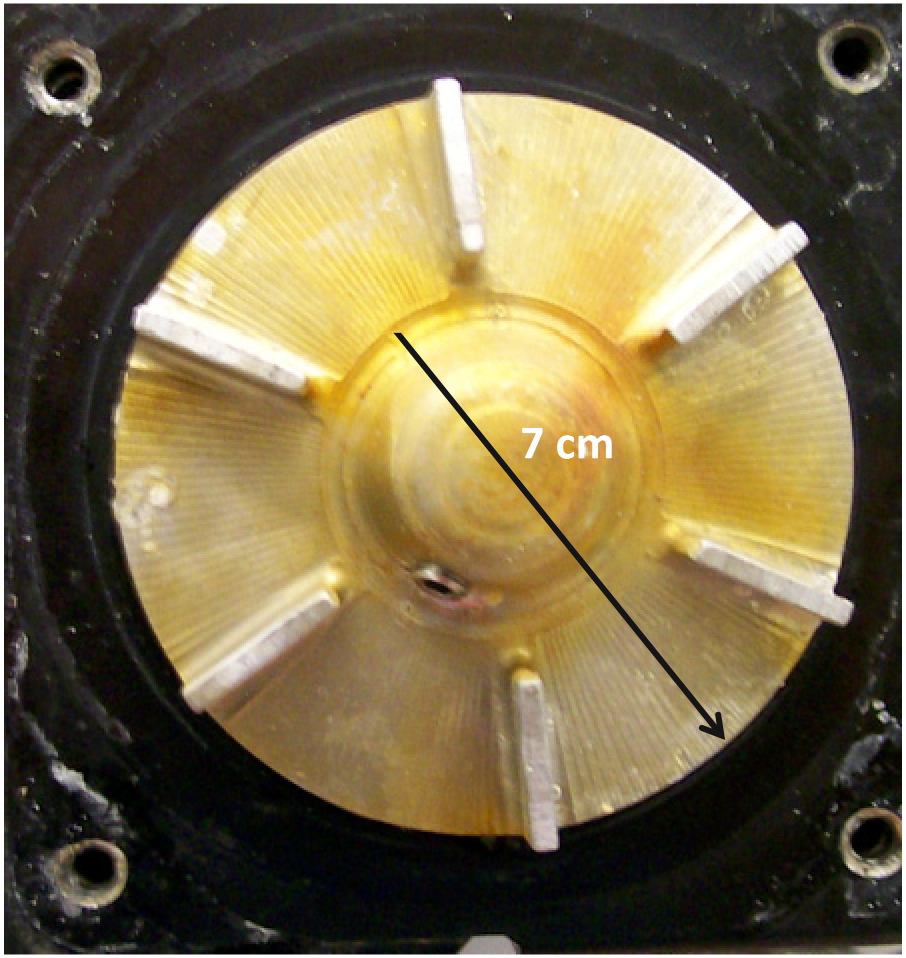
Nanofluid	Relative percent increase in torque — experimental	Relative percent increase in torque—calculated
2.2 vol. % 29 nm SiC in EG/water	9.3	8.7
4.0 vol.% 90 nm SiC in EG/water	5.3	6.5

However, plot vs. constant pumping power is more meaningful – Turbulent Flow



Based on property data, experimental values are slightly higher

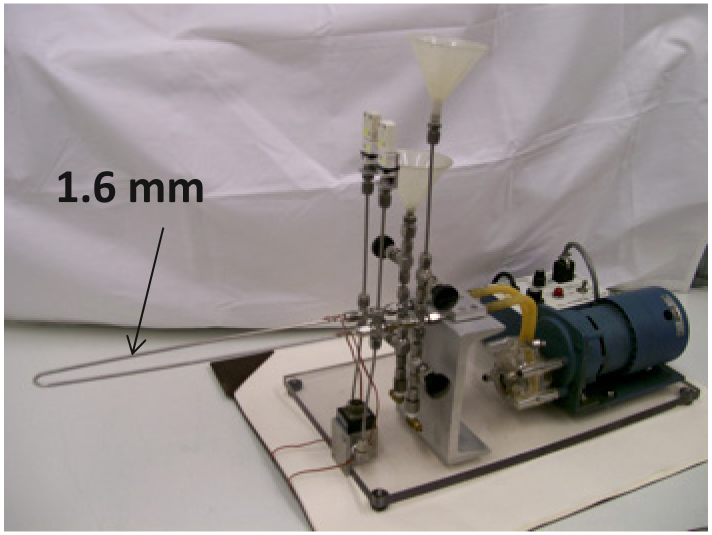
Little erosion (0.65%) for SiC nanofluid after hundreds of hours for 20 l/min≤V≤28 l/min(1400-1900 RPM



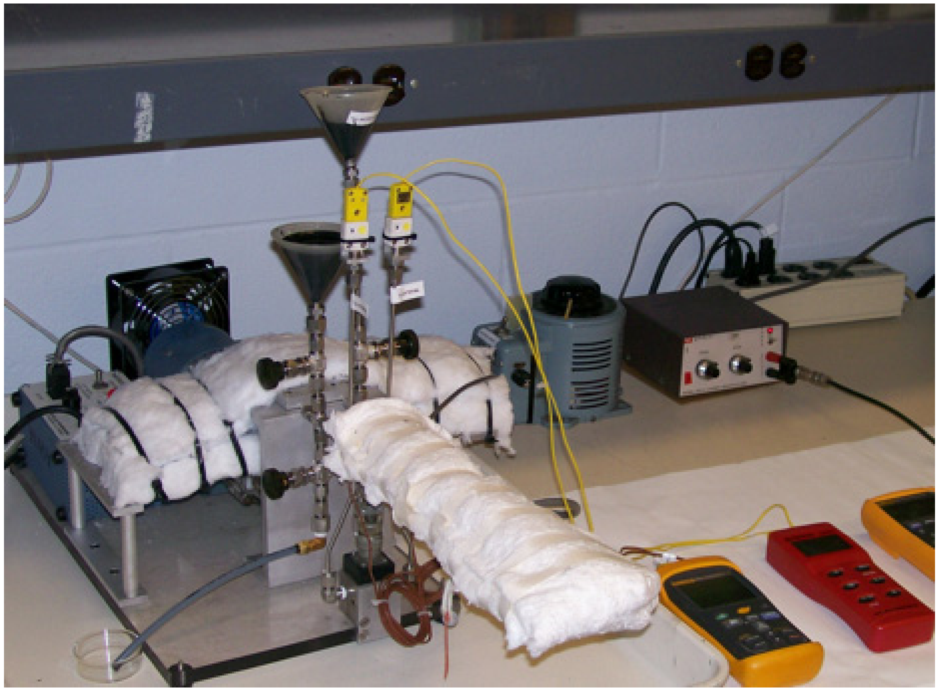
Pump impellor from racing car water pump

Clogging

- **Thus far, no clogging has been observed with graphitic nanofluid**

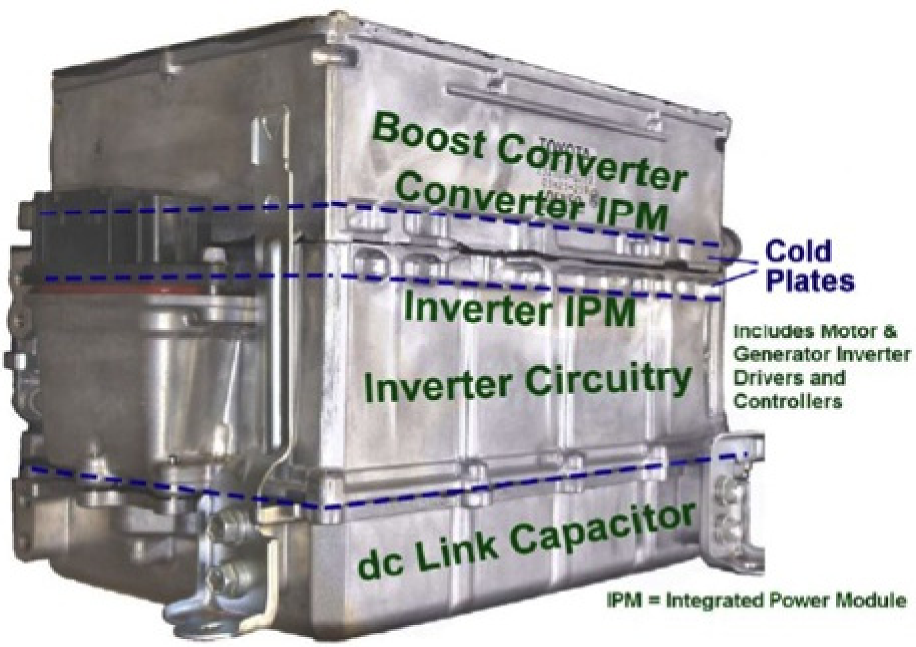


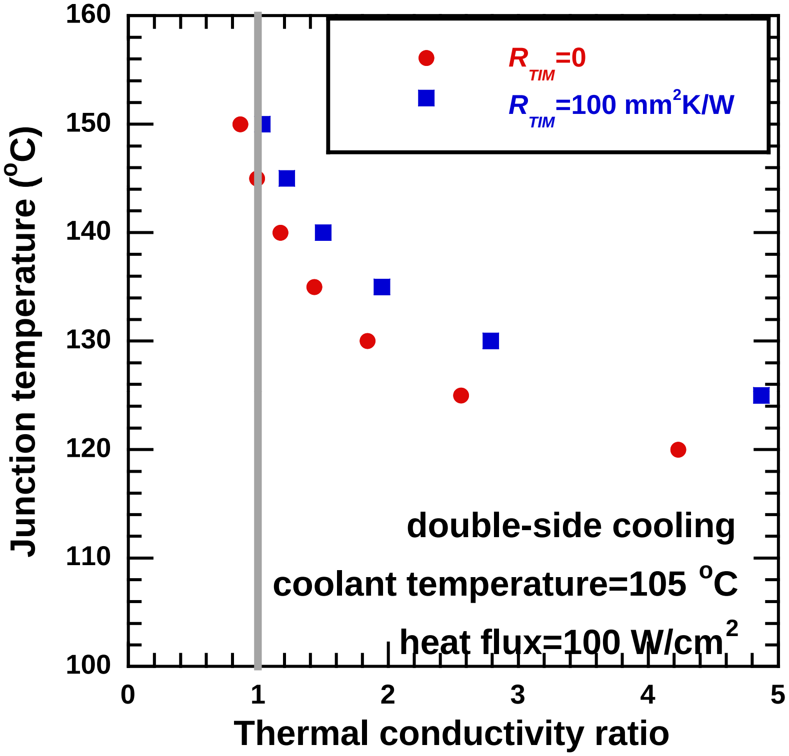
Insulation and heater removed



Application of graphite-based nanofluids

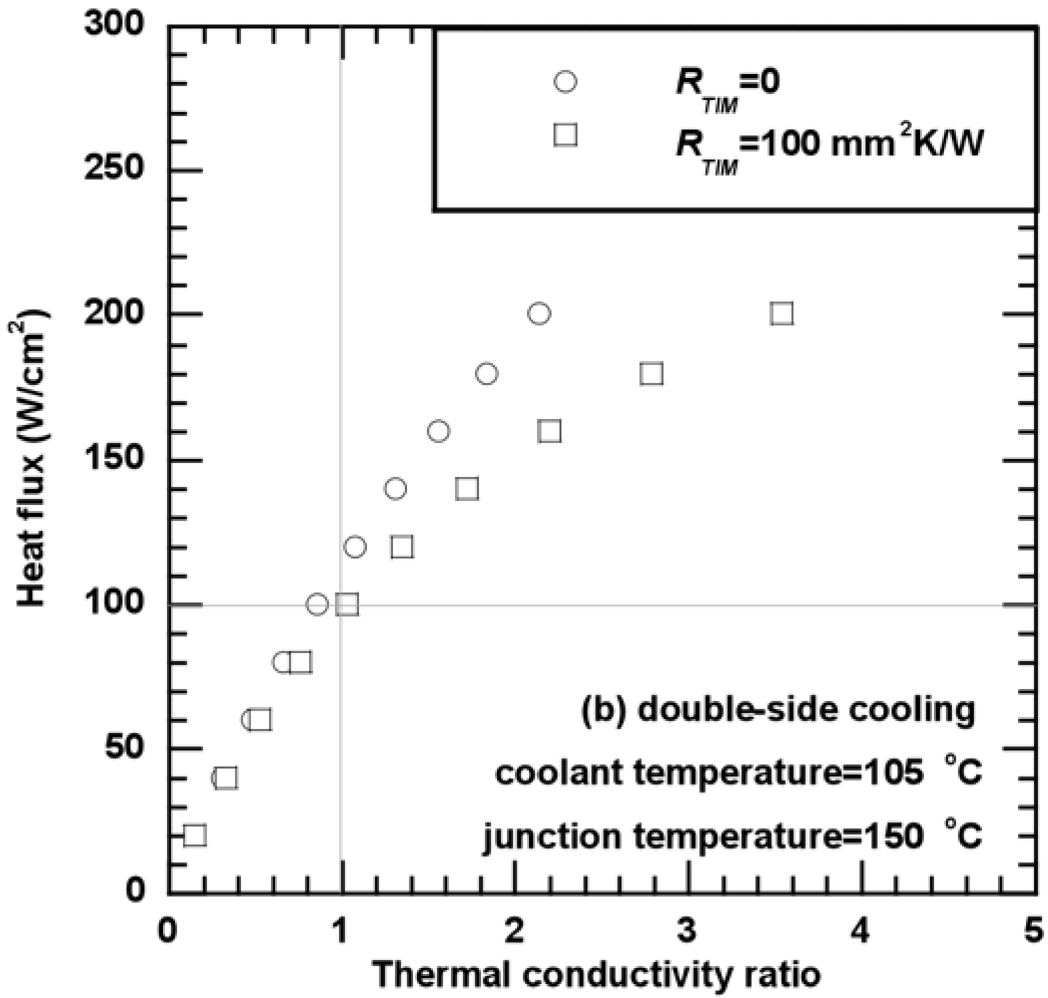
- Cooling power electronics
  - Can nanofluids be used to eliminate the low-temperature heat exchanger?
  - $h_{nf}/h_{base} \geq 1.5$





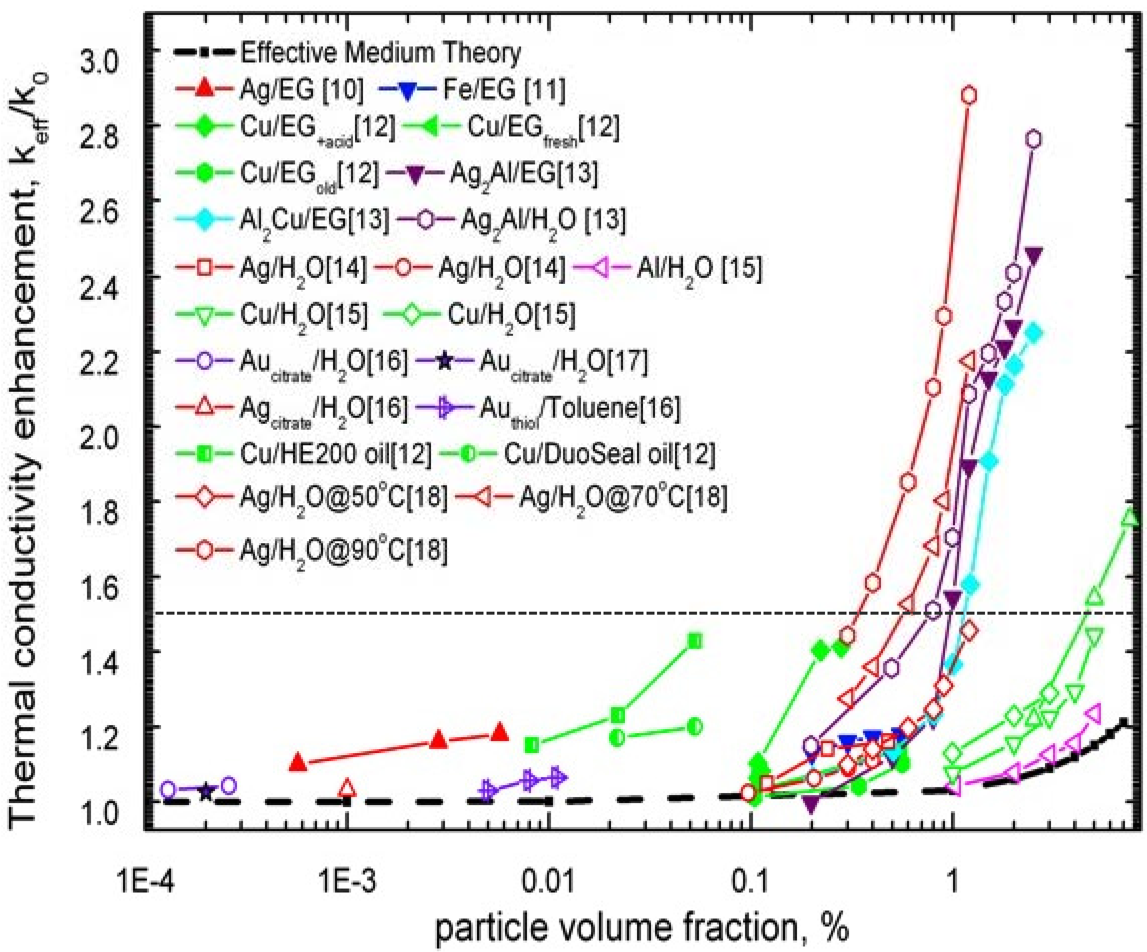
Nanofluid thermal conductivity ratio of 1.5 decreases semi-conductor junction temperature to ≈ 139°C

Heat flux increased by 50% for TC ratio ≈ 1.5

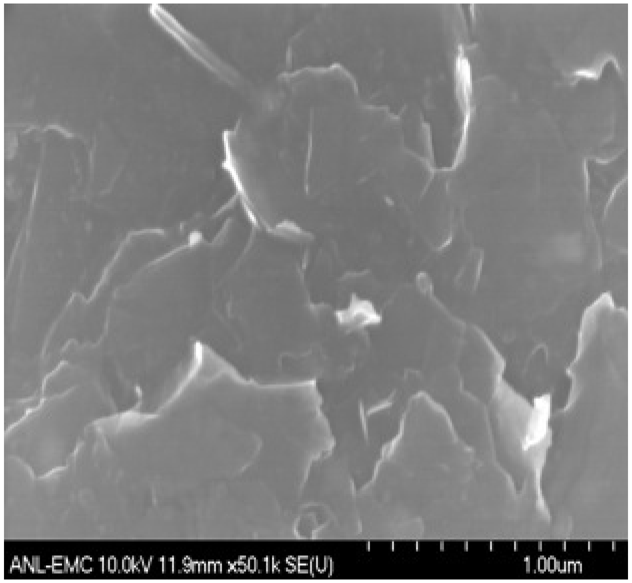


Is such a ratio possible???

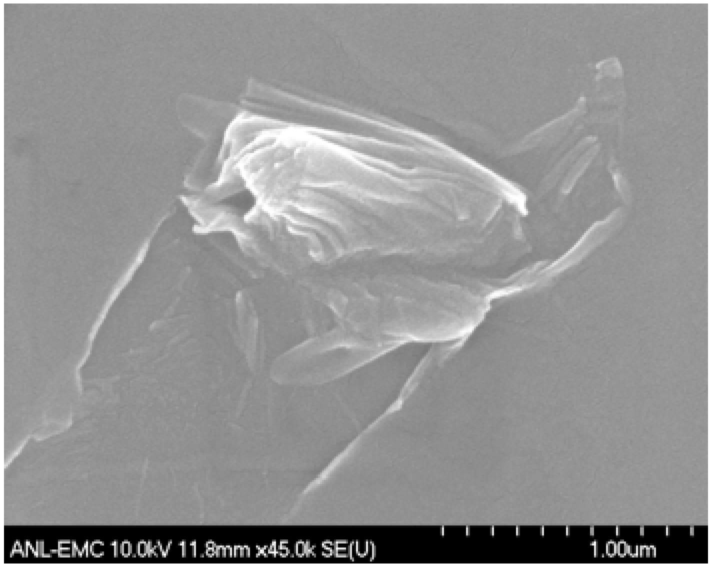
Literature data @ ambient temperature



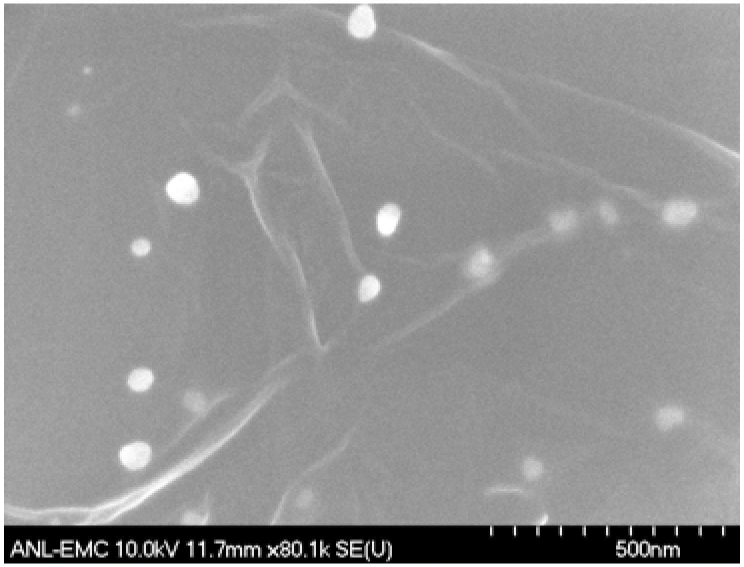
Carbon-based Nanoparticles



Graphite – Valvoline



Graphene oxide – ANL



Graphene oxide with Cu nanoparticles – ANL

Thermal Conductivity - Valvoline Graphite in 50/50 Ethylene Glycol/Water + surfactant

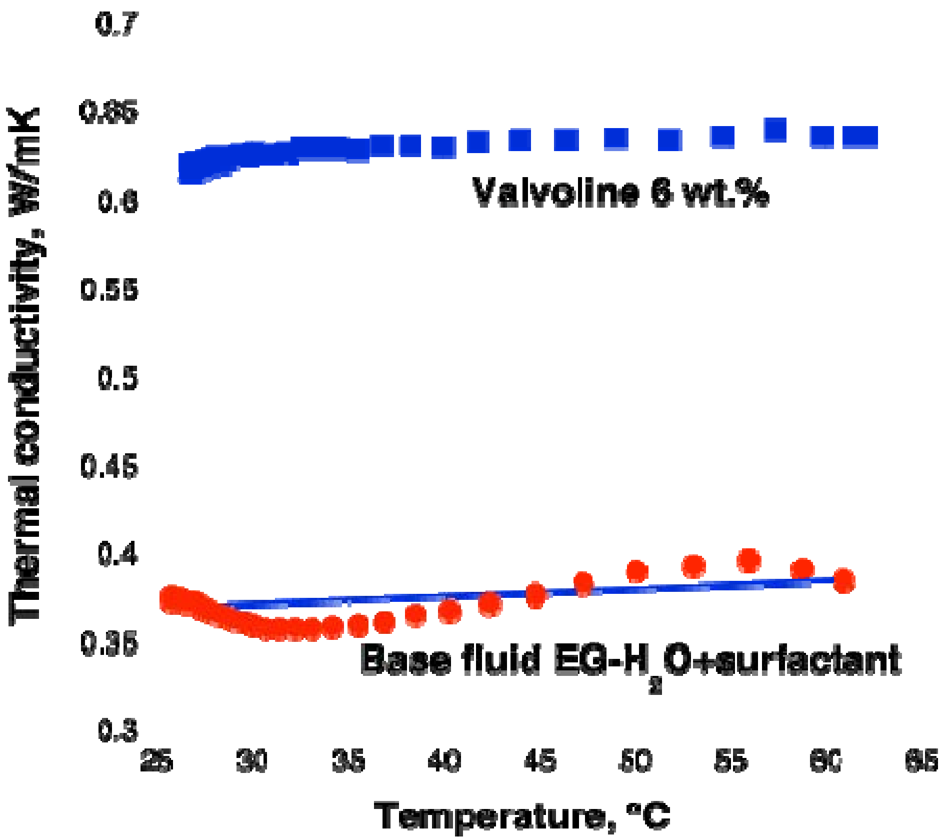
Sample Number	Weight percent (%)	$TC_{nf}/TC_{base\ fluid}$ @ Room Temperature (%)
1	3.5	49.0±2
2	6.0	65.0±5

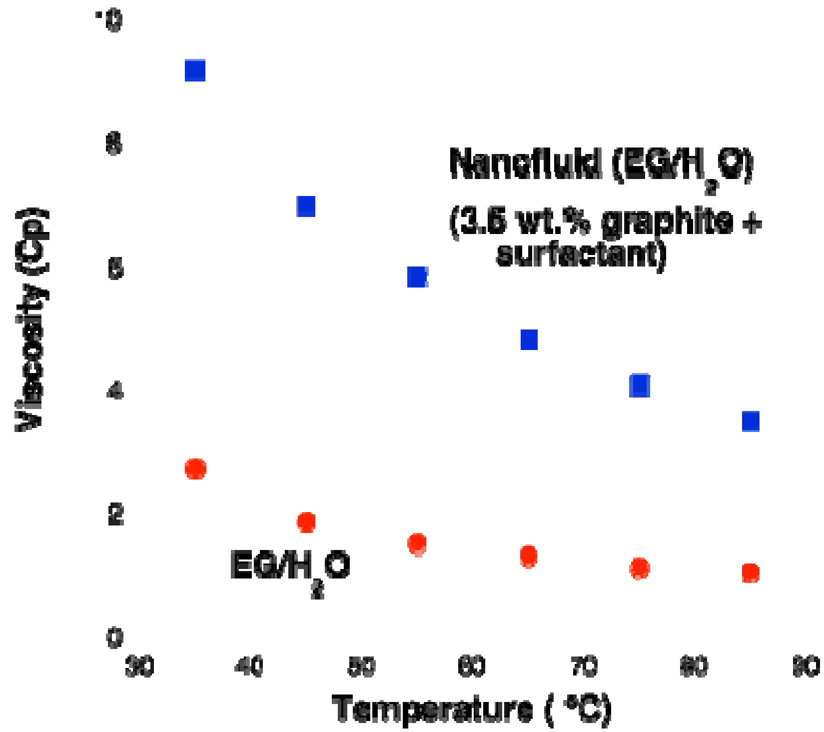
5 wt. % Graphene Oxide Nanosheets

Fluid	TC enhancement (%) 10–60°C	reference
Water	30.2	1
Propyl glycol	62.3	1
Liquid paraffin	76.8	1
Ethylene glycol	61.0	2

[1]*Wei Yu, H. Xie, and W. Chen, JAP 107, 094317 (2010)*
[2]*Wei Yu, H. Xie, and D. Bao, Nanotechnology 21, 055705 (2010)*

Thermal conductivity and Viscosity – Valvoline Graphite





Pumping power of NF/base fluid (@85°C) ≈ 3.5x

hc_{nf}/hc_{base}= 1.49 (laminar), 1.29 (turbulent)

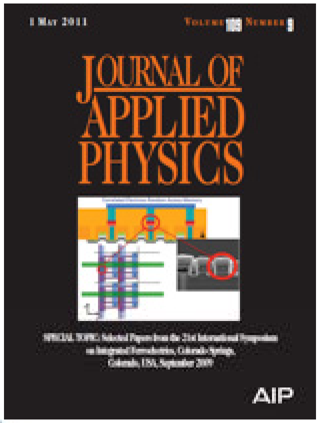
Summary

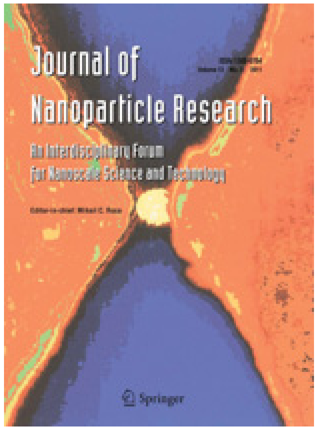
- We have gained considerable knowledge about engineering nanofluids for effective heat transfer
  - Size, Shape & Material
  - Concentration
  - pH
  - Surface resistance (Kapitza resistance)
  - Base fluid

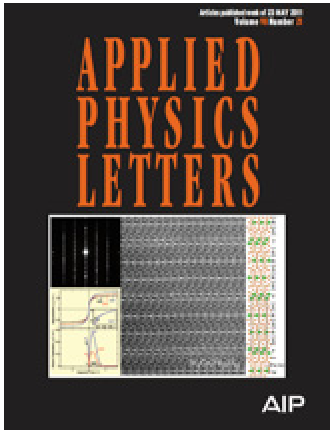
- Applications for graphite-based nanofluids for HEV power electronic cooling using EG/H_2O as base fluid look very promising but need to <u>increase thermal conductivity enhancement</u> and <u>reduce viscosity</u>

Publications
(in refereed journals)

- **An Investigation of Silicon Carbide-Water Nanofluid for Heat Transfer Applications - Mechanical Effects and Thermal Conductivity**, D. Singh, E. Timofeeva, W. Yu, J. Routbort, D. France, D. Smith, and C. Lopez. J. Appl. Physics, **105**, 064306 (2009)
- **Heat transfer to a silicon carbide/water nanofluid**, W. Yu, D. France, D. Smith, D. Singh, E. Timofeeva, and J. Routbort, Intl. J. Heat and Mass Transfer **52**, 3606-3612 (2009)
- **Particle Shape Effects on Thermo-physical Properties of Alumina Nanofluids**, E. V. Timofeeva, J. Routbort, and D. Singh, J. Appl. Physics **106**, 014301 (2009)
- **Mechanisms and Models of Effective Thermal Conductivities of Nanofluids,** W. Yu, D. France, D. Singh, E. Timofeeva, D. S. Smith, and J. L. Routbort, Journal of Nanoscience and Nanotechnology 10, 1-26 (2009).
- **Particle Size and Interfacial Effects on Heat Transfer Characteristics of Water and α-SiC Nanofluids**, E. Timofeeva, D. S. Smith, W. Yu, D. M. France, D. Singh, and J. L. Routbort, Nanotechnology, **21**, 215703 (2010).
- **Thermophysical Property-related Comparison Criteria for Nanofluid Heat Transfer Enhancement in Turbulent Flow**, W. Yu, D. France, E. Timofeeva, D. Singh and J. Routbort, Appl. Phys. Letters **96**, 213109 (2010)
- **Base fluid and temperature effects on the heat transfer characteristics of SiC in ethylene glycol/H_2O and H_2O nanofluids**, E.
- **Pumping Power of a Water-Based Nanofluid Containing Alumina Nanoparticles**, J. Routbort, D. Singh, E. Timofeeva, W Yu, and D. France, J. Nanoparticle Research **13**, 3, 931-937 (2011).
- **Nanofluids for Heat Transfer: An Engineering Approach,** E. Timofeeva, W. Yu, D. France, D. Singh, and J. Routbort, Nanoscale Research Letters, **6** 182 (2011).
- **Heat Transfer Fluids Containing Nanoparticles**, Dileep Singh, Jules Routbort, Wenhu Yu, Elena Timofeeva, David Smith, and David France, Provisional Patent Application 051583.0425 filed July 2, 2009







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Questions ?