Enhanced Thermal Conductivity in Nanofluids

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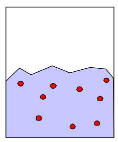
Motivation

- Fluids typically have lower thermal conductivity (*k*) than most solids

Material		Room Temperature Thermal Conductivity (W/m-K)
Metallic Solids:	Silver	429
	Copper	401
	Aluminum	237
Nonmetallic Solids:	Diamond	3300
	Silicon	148
	Alumina (Al_2O_3)	40
Metallic Liquids:	Sodium @ 644K	72.3
Nonmetallic Liquids:	Water	[illegible]



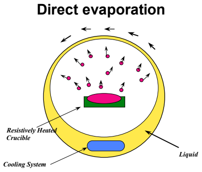
Nanofluids are produced by dispersing nanometer-sized solid particles in liquids

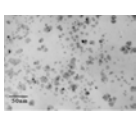
- Goal is to enhance effective fluid thermal conductivity and heat transfer coefficient by suspending solid nanoparticles
- Nanoparticles provide advantages due to better dispersion behavior, less clogging and abrasion, and much larger total surface area

Synthesis Techniques

- We produce nanofluids by 3 techniques:
  - ⇨ direct evaporation
  - ⇨ gas-condensation powder synthesis/dispersion
  - ⇨ chemical vapor condensation
- Materials investigated to-date:
  - ⇨ particles (Cu, Al_2O_3, CuO)
  - ⇨ fluids (water, ethylene glycol, oil)

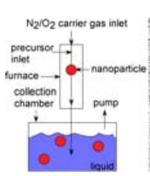
Direct evaporation

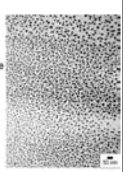




Bright-field TEM image ~10 nm diameter Cu nanoparticles produced by direct evaporation

Chemical vapor condensation





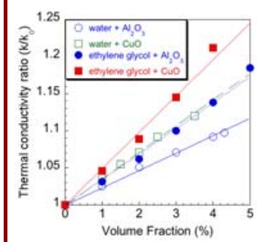
Bright-field TEM image of ~20 nm diameter iron oxide nanoparticles produced by chemical vapor condensation

J. A. Eastman et al., Appl. Phys. Lett., 78, 718 (2001)

Measured Thermal Conductivity Enhancements

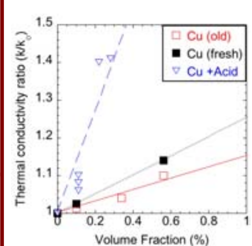
- Nanofluid thermal conductivity is measured by either the transient hot-wire or 3Ω technique

Oxide Nanoparticles



- ~20% increase in *k* seen for 4% CuO in ethylene glycol
- Larger improvement for CuO than Al_2O_3 is surprising

Copper Nanoparticles



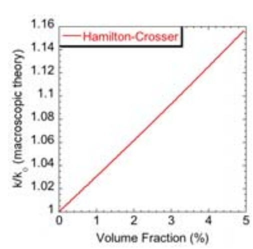
- 10 nm diameter Cu nanoparticles produce much larger increase in *k* than 30 nm diameter oxide nanoparticles
- thioglycolic acid improves dispersion behavior (but adding acid alone does not affect *k*)

Comparison With Theory

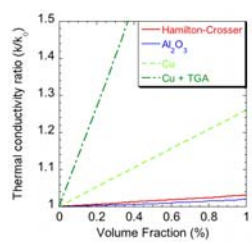
$$\frac{k}{k_o} \approx \frac{1+2V_p}{1-V_p}$$

R. Hamilton and O. Crosser, I&EC Fundamentals, **1**, 187 (1962)

- Hamilton and Crosser's macroscopic theory predicts that the increase in conductivity in nanofluids is independent of particle size and particle conductivity

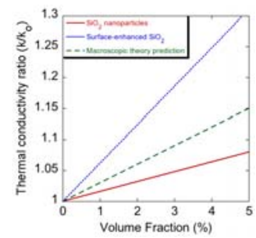


- Our oxide data is in reasonable agreement with Hamilton-Crosser predictions
- However, Cu data shows much larger than expected increase in conductivity (macroscopic theory is not sufficient to explain the behavior of nanofluids)



Importance of Surface Treatment

- Nanofluids containing surface-modified SiO_2 nanoparticles exhibit large increases in thermal conductivity

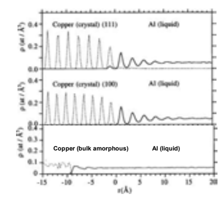


- Similar strong improvements were observed when thioglycolic acid was added to copper nanofluids
- Future work will focus on determining surface treatments of nanoparticles

Possible Mechanisms

- The effects of several possible mechanisms for the improved heat transfer properties of nanofluids are being examined

P. Geysermans *et al.*, Jn. Chem. Phys., **113**, 6382, 2000.



Studies by others have predicted that crystalline surfaces may induce order in liquids

Conclusions / Outlook

- Potential for applications:
  - ⇨ Many industries would benefit from the enhanced heat transfer rates attainable by using nanofluids

U.S. Choi and J.A. Eastman, "Enhanced Heat Transfer Using Nanofluids," U.S. Patent #6,221,275

- Future studies are needed:
  - ⇨ heat transfer mechanism(s) not understood
  - ⇨ optimal nanoparticle/fluid combination may depend on application
  - ⇨ heat transfer depends on more than thermal conductivity (need to determine heat transfer behavior under fluid flow conditions)
  - ⇨ ancillary properties may also be important (*e.g.*, erosion, abrasion, corrosion, stability)

BES - DOE

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MSD - ANL