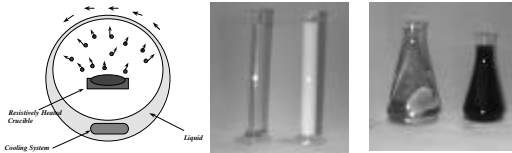


Nanofluids:

Advanced Flow and Heat Transfer Fluids



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Wet-Nanotechnology: nanofluids at NIU in collaboration with ANL

First NIU Nanofluids



Dry- vs. Wet-nanotechnology

- Fluids (gases & liquids) vs. Solids in Nature and (Chemical & Bio) Industry
- More degree of freedoms
– more opportunities...(also more challenges)
- **Nanofluids:** nanoparticles in base fluids
* Understanding nano-scale particle-fluid interactions in physical-, chemical-, and bio-processes, and engineering new/enhanced functional products
- **Directed self-assembly:**
* starts from suspension of nanoparticles in fluids
* ends with advanced sensors and actuators, devices, systems, and processes
- **Synergy** of dry-nanotechnology (solid-state) & wet-nanotechnology (POLY-nanofluids)

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Nanofluids:

Suspensions of nanoparticles in base fluids

Size does matter: unique transport properties, different from conventional suspensions: do not settle under gravity, do not block flow, etc ...

- **Enhancing** functions and properties by combining and controlling interactions
- **Combining** different nanoparticles (structure, size) in different base-fluids with additives
- **Controlling** interactions using different "mixing" methods and thermal-, flow-, catalyst-, and other field-conditions

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Wet-Nanotechnology: nanofluids' applications

Advanced, hybrid nanofluids:

- Heat-transfer nanofluids (ANL & NIU)
- Tribological nanofluids (NIU)
- Surfactant and Coating nanofluids
- Chemical nanofluids
- Process/Extraction nanofluids
- Environmental (pollution cleaning) nanofluids
- Bio- and Pharmaceutical-nanofluids
- Medical nanofluids (drug delivery and functional tissue-cell interaction)

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NIU- nanofluids

Development of advanced hybrid nanofluids:
POLY-nanofluids (Polymer-nanofluids) and
DR-nanofluids (Drag-Reduction-nanofluids)

- Development of **Heat-transfer nanofluids**
 Collaboration with ANL and NSF Proposal
 Related Invention/Patent Application pending
 Coherent X-ray Scattering Dynamic Characterization
- Development of **Tribological nanofluids**
 Center for Tribology and Coating (CTC) Project


More at:

www.kostic.niu.edu/DRnanofluids

Web Search>nanofluids

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NANOFLUIDS FOR ULTRA-HIGH-PERFORMANCE COOLING

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 For
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- Northern Illinois University:
 - M. Kostic, Mechanical Engineering (Flow and Heat Transfer Characterization)
 - L. Lurio, Physics (Structural Characterization)
 - C.T. Lin, Chemistry (Interfacial/Surface Enhancers)
- ANL:
 - Steven U.S. Choi, Energy Technology (Nanofluid Pioneer Researcher)
 - John Hull, TEM Manager, Energy Technology
 - Wenhua Yu, Energy Technology

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Background

- **Need for Advanced Flow and Heat-Transfer Fluids and Other Critical Applications**
- **Concept of Nanofluids**
- **Materials for Nanoparticles and Base Fluids**
- **Methods for Producing Nanoparticles/Nanofluids**
- **Characterization of Nanoparticles and Nanofluids**
- **Thermo-Physical Properties**
- **Flow and Heat-Transfer Characterization**

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Advanced Flow and Heat-Transfer Challenges

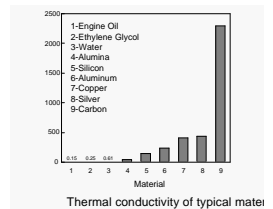
- The heat rejection requirements are continually increasing due to trends toward faster speeds (in the multi-GHz range) and smaller features (to <100 nm) for microelectronic devices, more power output for engines, and brighter beams for optical devices.
- Cooling becomes one of the top technical challenges facing high-tech industries such as microelectronics, transportation, manufacturing, and metrology.
- Conventional method to increase heat flux rates:
 - extended surfaces such as **fins** and **micro-channels**
 - increasing flow rates increases pumping power.
- However, current design solutions already push available technology to its limits.
- NEW Technologies and new, advanced fluids with potential to improve flow & thermal characteristics are of critical importance.
- Nanofluids are promising to meet and enhance the challenges.

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Concept of Nanofluids

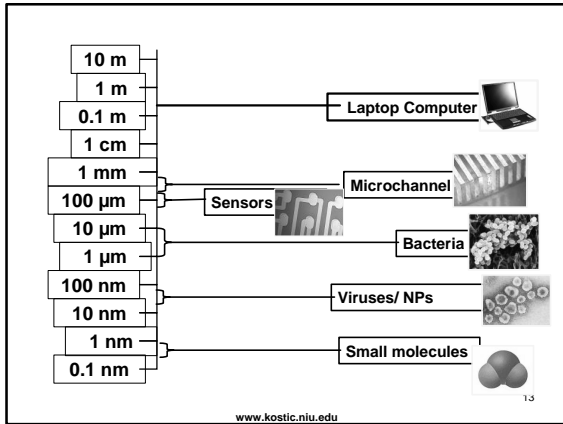
- Conventional heat transfer fluids have inherently poor thermal conductivity compared to solids.
- Conventional fluids that contain mm- or μm -sized particles do not work with the emerging "miniaturized" technologies because they can clog the tiny channels of these devices.
- Modern nanotechnology provides opportunities to produce nanoparticles.
- Argonne National Lab (Dr. Choi's team) developed the novel concept of nanofluids.
- Nanofluids are a new class of advanced heat-transfer fluids engineered by dispersing nanoparticles smaller than 100 nm (nanometer) in diameter in conventional heat transfer fluids.



Solids have thermal conductivities that are orders of magnitude larger than those of conventional heat transfer fluids.

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Why Use Nanoparticles?

- The basic concept of dispersing solid particles in fluids to enhance thermal conductivity can be traced back to Maxwell in the 19th Century.
- Studies of thermal conductivity of suspensions have been confined to mm- or μm-sized particles.
- The major challenge is the rapid settling of these particles in fluids.
- Nanoparticles stay suspended much longer than micro-particles and, if below a threshold level and/or enhanced with surfactants/stabilizers, remain in suspension almost indefinitely.
- Furthermore, the surface area per unit volume of nanoparticles is much larger (million times) than that of microparticles (the number of surface atoms per unit of interior atoms of nanoparticles, is very large).
- These properties can be utilized to develop stable suspensions with enhanced flow, heat-transfer, and other characteristics

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Materials for Nanoparticles and Base Fluids

Materials for nanoparticles and base fluids are diverse:

- Nanoparticle materials include:**
 - Oxide ceramics – Al₂O₃, CuO
 - Metal carbides – SiC
 - Nitrides – AlN, SiN
 - Metals – Al, Cu
 - Nonmetals – Graphite, carbon nanotubes
 - Layered – Al + Al₂O₃, Cu + C
 - PCM – S/S
 - Functionalized nanoparticles
- Base fluids include:**
 - Water
 - Ethylene- or tri-ethylene-glycols and other coolants
 - Oil and other lubricants
 - Bio-fluids
 - Polymer solutions
 - Other common fluids

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Methods for Producing Nanoparticles/Nanofluids

Two nanofluid production methods has been developed in ANL to allow selection of the most appropriate nanoparticle material for a particular application.

- In two-step process for oxide nanoparticles (“Kool-Aid” method), nanoparticles are produced by evaporation and inert-gas condensation processing, and then dispersed (mixed, including mechanical agitation and sonification) in base fluid.
- A patented one-step process (see schematic) simultaneously makes and disperses nanoparticles directly into base fluid; best for metallic nanofluids.

Other methods:
Chem. Vapor Evaporation; Chem. Synthesis; new methods...

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Production of Copper Nanofluids

- Nanofluids with copper nanoparticles have been produced by a one-step method.
- Copper is evaporated and condensed into nanoparticles by direct contact with a flowing and cooled (low-vapor-pressure) fluid.
- ANL produced for the first time stable suspensions of copper nanoparticles in fluids w/o dispersants.
- For some nanofluids, a small amount of thioglycolic acid (<1 vol.%) was added to stabilize nanoparticle suspension and further improve the dispersion, flow and HT characteristics.

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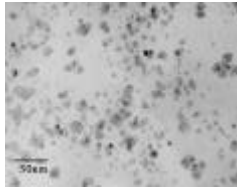
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FIG. 2: Proposed improvements for the one-step direct-evaporation nanofluid production apparatus

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TEM Characterization of Copper Nanoparticles



Bright-field TEM micrograph of Cu nanoparticles produced by direct evaporation into ethylene glycol.

- The one-step nanofluid production method resulted in a very small copper particles (10 nm diameter order of magnitude)
- Very little agglomeration and sedimentation occurs with this new and patented method.

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Dispersion Experiments



Dispersion experiments show that stable suspensions of oxide and metallic nanoparticles can be achieved in common base fluids.

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Multiwalled Carbon Nanotubes (MWNTs) in Oil



CNT nanofluids with and without dispersant: (a) NTs quickly settle without use of a proper dispersant, and (b) NTs are well dispersed and suspended in the oil with succinimide dispersant (5 wt.%).

- Multi-wall nano-tubes (MWNTs) were produced in a chemical vapor deposition reactor, with xylene as the primary carbon source and ferrocene to provide the iron catalyst.
- MWNTs have a mean dia. of ~25 nm and a length of ~50 μm ; contained an average of 30 annular layers.
- Nanotube-in-synthetic oil (PAO) nanofluids were produced by a two-step method.
- Stable nanofluids with carbon-nanotubes and enhanced thermal conductivity are promising for critical heat transfer applications.

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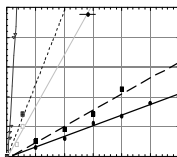
Four Characteristic Features of Nanofluids

- Pioneering nanofluids research in ANL has inspired physicists, chemists, and engineers around the world.
- Promising discoveries and potentials in the emerging field of nanofluids have been reported.
- Nanofluids have an unprecedented combination of the four characteristic features desired in energy systems (fluid and thermal systems):
 - Increased thermal conductivity (TC) at low nanoparticle concentrations
 - Strong temperature-dependent TC
 - Non-linear increase in TC with nanoparticle concentration
 - Increase in boiling critical heat flux (CHF)
- These characteristic features of nanofluids make them suitable for the next generation of flow and heat-transfer fluids.

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Enhanced Nanofluid Thermal Conductivity



Thermal conductivity enhancement of copper, copper oxide, and alumina particles in ethylene glycol.

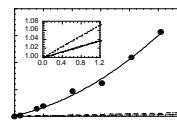
Appl. Phys. Lett. 78, 718, 2001.

- Nanofluids containing <10 nm diameter copper (Cu) nanoparticles show much higher TC enhancements than nanofluids containing metal-oxide nanoparticles of average diameter 35 nm.
- Volume fraction is reduced by one order of magnitude for Cu nanoparticles as compared with oxide nanoparticles for similar TC enhancement.
- The largest increase in conductivity (up to 40% at 0.3 vol.% Cu nanoparticles) was seen for a nanofluid that contained Cu nanoparticles coated with thioglycolic acid.
- A German research group has also used metal nanoparticles (NPs) in fluids, but these NPs settled. The ANL innovation was depositing small and stable metal nanoparticles into base fluids by the one-step direct-evaporation method.

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Nonlinear Increase in Conductivity with Nanotube Loadings



Measured and predicted thermal conductivity enhancement for nanotube-in-oil nanofluids.

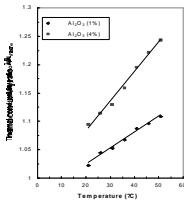
Appl. Phys. Lett. 79, 2252, 2001.

- Nanotubes yield by far the highest thermal conductivity enhancement ever achieved in a liquid: a 150% increase in conductivity of oil at ~1 vol.%.
- Thermal conductivity of nanotube suspensions (solid circles) is much greater than predicted by existing models (dotted lines).
- The measured thermal conductivity is nonlinear with nanotube volume fraction, while all theoretical predictions clearly show a linear relationship (inset).

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Temperature-Dependent Conductivity



Temperature dependence of thermal conductivity enhancement for Al_2O_3 -in-water nanofluids

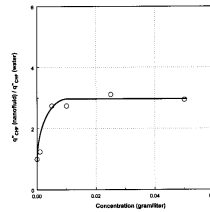
(*) *J. Heat Transfer*, 125, 567, 2003.

- Das et al. (*) explored the temperature dependence of the thermal conductivity of nanofluids containing Al_2O_3 or CuO nanoparticles.
- Their data show a two- to four-fold increase in thermal conductivity enhancement over a small temperature range, 20°C to 50°C.
- The strong temperature dependence of thermal conductivity may be due to the motion of nanoparticles.

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Significant Increase in Critical Heat Flux



CHF enhancement for Al_2O_3 -in-water nanofluids

You et al., *Appl. Phys. Lett.*, in press.

- You et al. measured the critical heat flux (CHF) in pool boiling of Al_2O_3 -in-water nanofluids.
- Their data show unprecedented phenomenon: a three-fold increase in CHF over that of pure water.
- The average size of the departing bubbles increases and the bubble frequency decreases significantly in nanofluids compared to pure water.
- The nanofluid CHF enhancement cannot be explained with any existing models of CHF.

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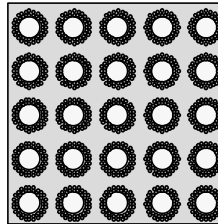
Limitations and Need for TC modeling:

- The discoveries of very-high thermal conductivity and critical heat flux clearly show the fundamental limits of conventional models for solid/liquid suspensions.
- The necessity of developing new physics/models has been recognized by ANL team and others.
- Several mechanisms that could be responsible for thermal transport in nanofluids have been proposed by ANL team and others.

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Nanofluid Structure

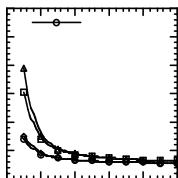


Schematic cross section of nanofluid structure consisting of nanoparticles, bulk liquid, and nanolayers at solid/liquid interface.

- Although liquid molecules close to a solid surface are known to form layered structures, little is known about the interactions between these nanolayers and thermo-physical properties of these solid/liquid nano-suspensions.
- ANL team (*Choi et al.*) proposed that the nanolayer acts as a thermal bridge between a solid nanoparticle and a bulk liquid and so is key to enhancing thermal conductivity.
- From this thermally bridging nanolayer idea, a structural model of nanofluids that consists of solid nanoparticles, a bulk liquid, and solid-like nanolayers is hypothesized.²⁸

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Nanolayer-Dependent Conductivity



Thermal conductivity enhancement ratio as a function of particle radius for copper-in-ethylene-glycol suspension.

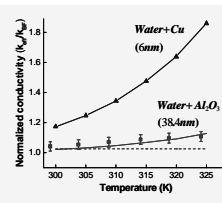
J. Nanoparticle Res., 5, 167, 2003.

- A three- to eight-fold increase in the thermal conductivity of nanofluids compared to the enhancement without considering the nanolayer occurs when nanoparticles are smaller than $r = 5$ nm.
- However, for large particles ($r \gg h$), the nanolayer impact is small.
- This finding suggests that adding smaller (<10 nm diameter) particles could be potentially better than adding more larger-size nanoparticles.

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Brownian motion of nanoparticles



Temperature-dependent thermal conductivities of nanofluids at a fixed concentration of 1 vol.%, normalized to the thermal conductivity of the base fluid.

- A new model that accounts for the Brownian motion of nanoparticles in nanofluids captures the concentration and temperature-dependent conductivity.
- In contrast, conventional theories with motionless nanoparticles fail to predict this behaviour (horizontal dashed line).
- The model predicts that water-based nanofluids containing 6-nm Cu nanoparticles (curve with triangles) are much more temperature sensitive than those containing 38-nm Al_2O_3 particles, with an increase in conductivity of nearly a factor of two at 325 K.

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Summary: New Applications

- Development of methods to manufacture diverse, hybrid nanofluids with polymer additives with exceptionally high thermal conductivity while at the same time having low viscous friction.
- High thermal conductivity and low friction are critical design parameters in almost every technology requiring heat-transfer fluids (cooling or heating). Another goal will be to develop hybrid nanofluids with enhanced lubrication properties.
- Applications range from cooling densely packed integrated circuits at the small scale to heat transfer in nuclear reactors at the large scale.

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Summary: Nature & Self-Assembly

- Nature is full of nanofluids, like blood, a complex biological nanofluid where different nanoparticles (at molecular level) accomplish different functions
- Many natural processes in biosphere and atmosphere include wide spectrum of mixtures of nanoscale particles with different fluids
- Many mining and manufacturing processes leave waste products which consist of mixtures of nanoscale particles with fluids
- A wide range of self-assembly mechanisms for nanoscale structures start from a suspension of nanoparticles in fluid

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Summary: Future Research

- Little is known about the physical and chemical surface interactions between the nanoparticles and base fluid molecules, in order to understand the mechanisms of enhanced flow and thermal behavior of nanofluids.
- Improved theoretical understanding of complex nanofluids will have an even broader impact
- Development of new experimental methods for characterizing (and understanding) nanofluids in the lab and in nature.
- Nanoscale structure and dynamics of the fluids: using a variety of scattering methods: small-angle x-ray scattering (SAXS), small-angle neutron scattering (SANS), x-ray photon correlation spectroscopy (XPCS), laser based photon correlation spectroscopy (PCS) and static light scattering.
- Development of computer based models of nanofluid phenomena including physical and chemical interactions between nanoparticles and base-fluid molecules.

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Summary: Beyond Coolants

- Beyond the primary goal of producing enhanced flow and heat transfer with nanofluids, the research should lead to important developments in bio-medical applications, environmental control and cleanup and directed self-assembly at the nanoscale.
- Possible spectrum of applications include more efficient flow and lubrication, cooling and heating in new and critical applications, like electronics, nuclear and biomedical instrumentation and equipments, transportation and industrial cooling, and heat management in various critical applications, as well as environmental control and cleanup, bio-medical applications, and directed self-assembly of nanostructures, which usually starts from a suspension of nanoparticles in fluid.

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- NIU's ME Department: Chair S. Song

More at: www.kostic.niu.edu/nanofluids

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