Engineered Nanofluids for Heat Transfer and Novel Applications

Elena V. Timofeeva*, Dileep Singh, Wenhua Yu, David M. France
Argonne National Laboratory, 9700 S Cass Ave., Lemont, IL 60439
*email: etimofeeva@anl.gov; phone 630-252-6754

ABSTRACT

An overview of systematic studies that address the complexity of nanofluid systems and advance the understanding of nanoscale contributions to viscosity, thermal conductivity, and cooling efficiency of nanofluids will be presented. The factors and mechanisms contributing to the fluid cooling efficiency will be discussed first, followed by a review of nanofluid engineering parameters and a brief analysis of their contributions to basic thermo-physical properties. The systems engineering approach will be used to describe how various nanofluid parameters contribute to the systems cooling performance. The latter also offers insights into the principles of the efficient nanofluid design for heat transfer and other novel applications.

Keywords: *nanofluids, systems engineering, nanoparticles, suspensions, heat transfer, thermal conductivity, viscosity*

1. INTRODUCTION

Nanomaterial suspensions in liquids (nanofluids) are the new expanding area in nanotechnology, with applications as wide as biomedical, lubrication, thermal management, energy generation, energy conversion, and energy storage. Nanofluids bring out benefits and functionality of both solid and liquid form of matter.

Essentially nanofluids are nanocomposites with liquid matrix and solid nanoparticles dispersed in it. Because of low loadings (<20 vol. %) and nanoscale dimensions of dispersed solid particles nanofluids typically exhibit properties of a fluid, i.e. able to flow under shear, assume the shape of a container, etc. Therefore from the engineering perspective nanofluids follow fluid mechanics and can benefit most applications where conventional fluids are used.

Nanomaterials represent a rapid growing field with overwhelming variety of compositions from pure elements to hybrid and composite nanomaterials. Nanoparticles (one or more dimensions smaller than 100 nm) are of great scientific interest as they are effectively bridge bulk materials and atomic or molecular structures. An important aspect of nanoscale materials is the dramatically increased ratio of surface area to volume, which makes possible new quantum mechanical effects that modify electronic, optical, mechanical and physical properties in nanoparticles. Size-dependent properties are observed such as quantum confinement in semiconductor particles, surface plasmon resonance in some metal particles and superparamagnetism in magnetic materials. Because of unique properties of nanoparticles their integration into the bulk of other materials can result in enhanced properties, i.e. nanocomposites can be engineered to achieve improved functionality.

Therefore nanofluids are functional fluid media that can be engineered to meet the desired characteristics: high thermal conductivity improves the heat transfer; high specific heat advances the thermal energy storage; reduced surface tension improves evaporative/boiled cooling, etc. With nanomaterials one can not only improve the thermo-physical properties of liquids but also introduce additional functionality, such as novel applications of nanofluids in solar collectors, photovoltaic energy generation, and electric energy storage.

2. NANOFLUID STABILITY

Nanofluids also fall under a traditional category of liquid colloidal dispersions, but due to the recent advancements and diversity of nanomaterials they have been instituted into separate sub-category. Nanoparticles suspended in a fluid are in random motion under the influence of several acting forces such as Brownian motion, viscous resistance, intermolecular Van-der-Waals interaction, and electrostatic interactions between ions and dipoles. Stability of nanofluids is determined by the balance of those forces, the size and the shape of nanomaterials, difference in density and interactions between solid and liquid phases. A dispersion/agglomeration equilibrium establishes in nanoparticle suspension reflecting the magnitude of particle-particle interaction on concentration of particles. Nanoparticles in suspension can be well-dispersed (particles move independently) or agglomerated (ensembles of particles move together). Agglomeration can be detrimental to nanofluid stability resulting in sedimentation, but to some degree can be manipulated by pH/zeta potential adjustments (electrostatic stabilization), and/or surfactant additives (steric stabilization).

Because of huge surface area of nanoparticles the boundary layers between nanoparticles and the liquid contribute significantly to the fluid properties, resulting essentially in a three-phase system (liquid, solid, and interface). The contribution and importance of solid/liquid interface in nanofluids is often underestimated. The approach to nanofluids as three-phase systems (instead of traditional consideration of nanofluids as two-phase systems of solid and liquid) allows for deeper understanding the correlations between the nanofluid

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engineering parameters, properties, and estimated performance.

3. ENGINEERING OF NANOFLUIDS

Engineering of nanofluids utilizes scientific knowledge on individual structure-properties correlations to design and formulate nanomaterial/fluid composite with targeted properties. Often times addition of nanoparticles benefits one property while penalizes other fluid properties (i.e. high thermal conductivity and high viscosity nanofluid). In this regard engineering the nanofluid that would be beneficial for a given application is not a trivial task, and should consider a set of critical system parameters. Systems engineering is an interdisciplinary field widely used for designing and managing complex engineering project, where the properties of a system as a whole, may greatly differ from the sum of the parts' properties. The systems engineering approach applied to nanofluid design offers an alternative way to look at the inner workings of a nanofluid system and allows for design choices that address the demands of a given industrial application.

Thermo-physical properties of fluid systems are viscosity, thermal conductivity, specific heat, density, surface tension, heat of vaporization, etc. In nanofluids each of these properties will be dependent on one or more parameters: base fluid properties, nanoparticle material, size, shape, concentration, compatibility of solid and liquid phase (properties of the interface), additives, and temperature. Change in one of those parameters (e.g. particle size) will affect more than just one property (thermal conductivity, viscosity, surface tension). Thus, the challenge in the development of multivariable system such as nanofluids for given application is in understanding of how micro- and macro-scale interactions between the nanoparticles and the fluid affect the nanofluid properties.

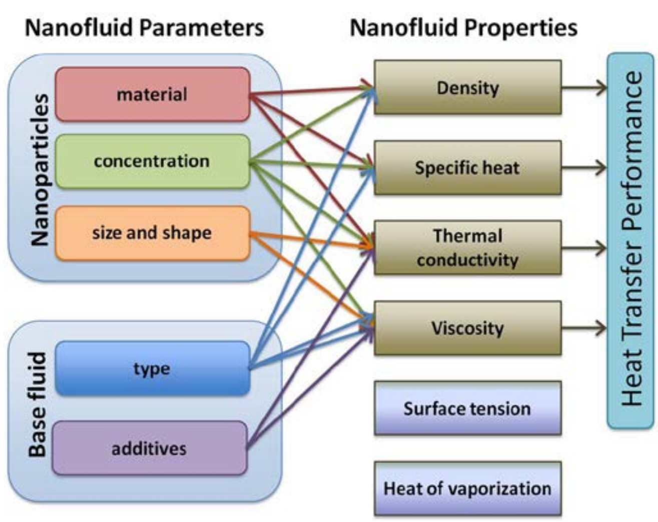

Figure1. Illustration of complexity and multivariability of nanofluid systems.

Nanofluids have been developed for advanced heat transfer applications for almost two decades. Evaluation of cooling efficiency, i.e. ability of the heat transfer fluid to remove heat from the heat source depends on the flow regime and includes assessment of contributions from thermal conductivity, viscosity, specific heat, and density of the fluid and can be estimated from the fluid dynamics equations [1] in assumption of a single phase flow (Fig. 1)

4. TRENDS IN NANOFLUID PROPERTIES

The correlations between the nanofluid parameters and properties are fairly well established in the literature. Thermal conductivity of nanofluids with ceramic nanoparticles follows predictions of effective medium theory providing moderate enhancements of ~3% per each vol% of nanoparticles added [2]. Elongated nanoparticle shapes provide higher thermal conductivity enhancements than spherical particles at the same volume concentrations due to formation of percolative nanoparticle networks [3]. Graphitic nanoparticles with high aspect ratio and anisotropic thermal conductivity (carbon nanotubes [4] and graphene/graphene oxide [5]) were reported to provide 2-3 fold enhancements through percolation. Many experimental results for nanofluids with metallic nanomaterials report thermal conductivity increases well above the effective medium theory prediction. It was suggested [6] that metallic nanoparticles possess geometry-dependent localized plasmon resonances, i.e. collective oscillations of the metals free electrons upon optical or other excitation.

Viscosity of nanofluids increases with particle concentration. For given base fluid, nanomaterial type, and particle concentration viscosity will be higher is suspensions with smaller particles, as well as in suspensions with high aspect ratio nanoparticles [7, 8]. Percolation networks and particle agglomerates result in dramatic increase in viscosity. High viscosity of nanofluids compared to base fluid increases the power required to pump the fluid through the system and in some cases could be detrimental to the efficiency of nanofluid.

Density and specific heat of nanofluids both depend only on volume concentration of nanoparticles and properties of pure solid and liquid.

5. SYSTEMS ENGINEERING APPROACH

The systems engineering approach to nanofluid design includes several steps. First the thermo-physical properties of nanofluids that are important for heat transfer are identified using the fluid dynamics-based cooling efficiency criteria for single-phase fluids (Fig. 1). Then the nanofluid engineering parameters are reviewed in regards to their influence on the thermo-physical properties of nanoparticle suspensions. The individual nanofluid parameter-property correlations are summarized into the decision matrix that allows identifying the most influential nanofluid parameters. Based on such analysis the nanofluid engineering parameters were arranged by the decreasing importance for the heat transfer performance [9]: particle concentration > base fluid > nanoparticle size > nanoparticle material ≈ surface charge > temperature ≈ particle shape > additives > Kapitza resistance. This is an approximate ranking of nanofluid parameters that assumes equal and independent weight of each of the nanofluid property contributing to thermal transport. The advantage of this approach to decision making in nanofluid engineering is that subjective opinions about the importance of one nanofluid parameter versus another can be made more objective.

Applications of the decision matrix are not limited to the design of new nanofluids; it also can be used as guidance for improving the performance of existing nanoparticle suspensions. While the particle material, size, shape, concentration, and the base fluid parameters are fixed in a given nanofluid, the cooling performance still can be improved by remaining adjustable nanofluid parameters in order of their relative importance, i.e. by adjusting the zeta potential and/or by increasing the test/operation temperatures in the above case. Further studies are needed to define the weighted importance and sensitivity of each nanofluid property contributing to the heat transfer. The decision matrix can also be customized and extended for specifics of nanofluids and the mechanisms that are engaged in heat transfer.

6. HEAT TRANSFER NANOFLUID BY DESIGN

Besides the generally observed trends in nanofluids, discussed above, nanomaterials with unique properties are of particular interest to create a dramatically beneficial nanofluid for heat transfer or other application. The overview of thermal conductivity enhancements showed that nanofluids with metallic and anisotropic carbon nanomaterials have the highest potential for heat transfer, however high viscosity of nanofluids with carbon materials and low stability (agglomeration and oxidation) of metallic nanoparticles still represent a challenge.

This challenge inspired a design for new hybrid nanomaterial that would engage both plasmonic and percolation thermal conductivity mechanisms to dramatically boost the cooling efficiency (Fig. 2). The selection of nanomaterials was guided by projected benefits from percolation of graphene sheets, plasmon resonance of metallic nanoparticles, and possibly synergetic effects of combining Cu and graphene. Besides, Cu nanoparticles attached to graphene sheets provide spacial separations and prevent them from agglomeration, which is known to be detrimental for the plasmon resonance mechanism.

A simple, low cost, and up-scalable wet chemical synthesis method was developed for hybrid copper/graphene nanomaterials (Fig. 2). Variations in synthesis procedures and reaction conditions resulted in different morphologies of hybrid nanomaterials, including the purity of Cu phase, particle sizes, nucleation density, and homogeneity of Cu nanoparticle distribution.

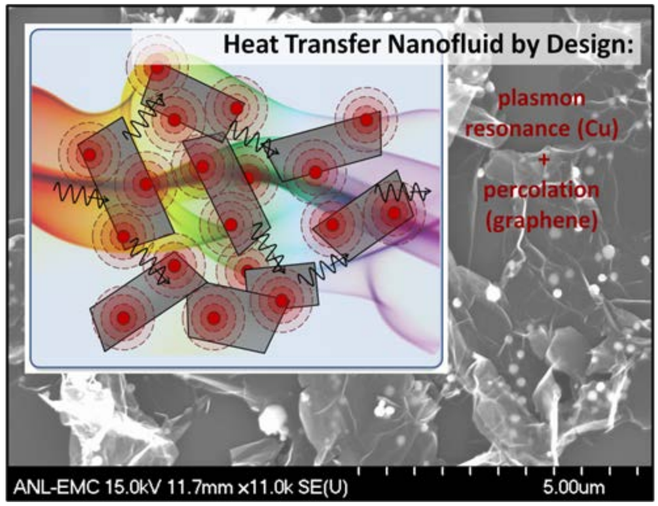

Figure 2. Conceptual design of advanced thermal conductivity mechanism and SEM of hybrid nanoparticles synthesized to meet the design criteria.

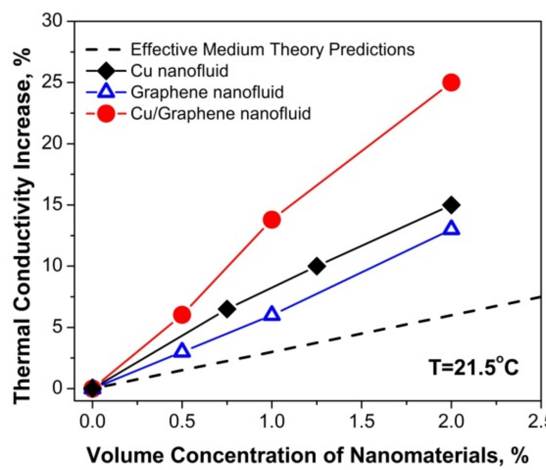

Figure 3. Experimental results confirming advanced thermal conductivity of the engineered Cu/graphene nanofluid.

Hybrid Cu/Graphene nanomaterials were dispersed in synthetic heat transfer fluid Therminol®59 at various volume concentrations. Stable nanofluid dispersions were achieved with combination of surfactants. These engineered Cu/graphene nanofluids have demonstrated advanced thermal conductivity significantly higher than the effective medium theory predictions, and standalone graphene or metallic Cu nanofluids at the same volume concentrations (Fig. 3). This means that same level of enhancement is possible at lower nanomaterial loadings, which will positively reflect on the cost, viscosity and overall commercial viability of nanofluids. Further investigation of the thermal conductivity mechanisms and optimization of hybrid nanomaterial morphology along with suspension stability is in progress.

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