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CRITICAL ISSUES AND APPLICATION POTENTIALS IN NANOFLUIDS RESEARCH

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ABSTRACT

Development of many industrial and new technologies is limited by existing thermal management, and need for high-performance cooling. Nanofluids, stable colloidal mixtures of nanoparticles (including nanofibers and functional nanocomposites) in common fluids, have a potential to meet these and many other challenges. Colloidal nano-mixtures with functionally-stable and active-like nanostructures that may self-adjust to the process conditions, require systematic surface-chemistry study and enhancements (coatings with functional layers, surfactants, etc), in addition to investigation of thermo-physical characteristics and phenomena.

A comprehensive, systematic and interdisciplinary experimental research program is necessary to study, understand and resolve critical issues in nanofluids research to date. The research must focus on both synthesis and a careful exploration of thermo-physical characteristics. Development of new-hybrid, drag-reducing nanofluids may lead to enhanced flow and heat transfer characteristics. The nanoparticles in these fluids yield increased heat-transfer while the long-chain polymers are expected to enhance flow properties, including active and functional interactions with nanoparticles, thus providing potential for many applications yet to be developed and optimized.

INTRODUCTION

Nanofluids are stable colloidal suspensions of nanoparticles, nanofibers, or nanocomposites in common, base fluids, such as water, oil, ethylene-glycol mixtures (antifreeze), polymer solutions, etc. Nanoparticles are very small, nanometer-sized particles with dimensions usually less than 100 nm (nanometers). The smallest nanoparticles, only a few nanometers in diameter, contain only a few thousand atoms. These nanoparticles can possess properties that are substantially different from their parent materials. Similarly, nanofluids may have properties that are substantially different from their base fluids, like much higher thermal conductivity, among others.

Argonne National Laboratory (ANL) is recognized for pioneering scientific achievements in nanofluids research, including innovative production methods, thermal characterization, and theoretical studies that correlate enhanced thermal conductivity with dynamic mechanism between nanoparticles and base-fluid molecular layers. The Northern Illinois University in collaboration with ANL, are initiating a new systematic and comprehensive, interdisciplinary research: (1) to resolve the critical issues in nanofluids research to date, and (2) to develop new-hybrid, drag-reducing polymer-nanofluids with enhanced thermo-physical and tribological characteristics.

There has been a vast interest and even ‘hype’ about using nanofluids to meet new challenges in cooling and thermal management due to a number of experimental studies which demonstrated ‘anomalous’ enhancement of thermal conductivity when small amount of nanoparticles or nanofibers are suspended in common fluids. However, much of the current literature is either incomplete or inconsistent. Theoretical work, developing in the absence of a reliable experimental framework, has resulted in the awkward situation of having a larger number of competing theoretical hypotheses than systematic experimental results to prove, apparently anomalous phenomena. Regardless of a number of research studies in this area, the basic research remains in the initial stage, the promising results are still to be experimentally re-confirmed and established, and possibly enhanced.

It has been demonstrated, by Choi and others, that nanofluids with ‘harder-to-make’5-25 nm metallic-nanoparticles or carbon-nanotubes, have superior thermal-conductivity to nanofluids produced by direct mixing of 25-100 nm metal or metal-oxide nanoparticles in common, base fluids. Nano-materials are intrinsically unstable, since they possess a large

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fraction of surface atoms and thus tend to oxidize and/or stick together, driven by the reduction of surface energy and other inter-particle forces. In general, functional nanoparticle coatings are required to prevent oxidation, while electrostatic stabilization, steric stabilization, or both may need to be employed to prevent flocculation. Colloidal nano-mixtures, with metastable, nanostructures that actively self-adjust to the process conditions (e.g. electro-magnetic, flow-shearing or temperature fields, similar to the drag-reducing, polymer solutions, see next Section) could yield even greater benefits than just improved thermal conductivity. An extensive investigation of the thermo-physical characteristics of such materials will be required, in order to deduce the appropriate surface-chemistry enhancements (coatings with functional layers, surfactants, etc) that will yield enhanced properties.

A comprehensive, systematic and interdisciplinary experimental research program is necessary to study, understand and resolve critical issues in nanofluids research to date. The research must focus on both synthesis and a careful exploration of surface-chemistry and thermo-physical characteristics. Development of new-hybrid, drag-reducing nanofluids may lead to enhanced both flow and heat transfer characteristics. The nanoparticles in these fluids yield increased heat-transfer while the long-chain polymers are expected to enhance flow properties, including active interactions with nanoparticles, thus providing potential for many applications yet to be developed and optimized. It is known that some polymer additives are friction drug-reducers in turbulent flow, but also heat-enhancers in laminar flow. Furthermore, nanofluids may be used in micro scale devices, where the flow is usually laminar, but also in large scale devices (common heat exchangers), where both laminar and turbulent flows are encountered.

The ultimate goal is to understand the underlying physical phenomena of diffusion, momentum and energy transport in these novel nanofluids, by correlating and modeling measured nano- and macro-characteristics, thus making possible development and production-optimization of tailor-made nanofluids with significantly enhanced thermo-physical properties, critical for existing and emerging flow and heat transfer applications.

POLYMER NANOFLUIDS:
Functional and Active Complex Fluids

Since Choi (1995) [1] coined the term “nanofluids” for carbon and metal-based nanoparticles in common heat-transfer fluids, research has intensified, due to the substantially increased thermal conductivity of those nanofluids, and the tremendous potential for many applications. Biologists [2] and physicists [3] have used the term nanofluids to describe bio-nanoparticles, like DNA and other protein molecules in aqueous solutions, or for fluids confined in slit nano-pores or other nano-meter sized enclosures. In the advanced electronics and new emerging industries there is a great need for efficient thermal management and cooling. In many other industries such as energy production and utilization, manufacturing and transportation, thermal management is critical and nanofluids could yield tremendous benefits. Excellent and up-to-date reviews on nanofluid research are provided by Choi *et. al.* [4] and Eastman *et. al.* [5].

Another class of fluids, known as “drag-reducing” fluids, has intrigued many investigators, ever since Toms’ discovery

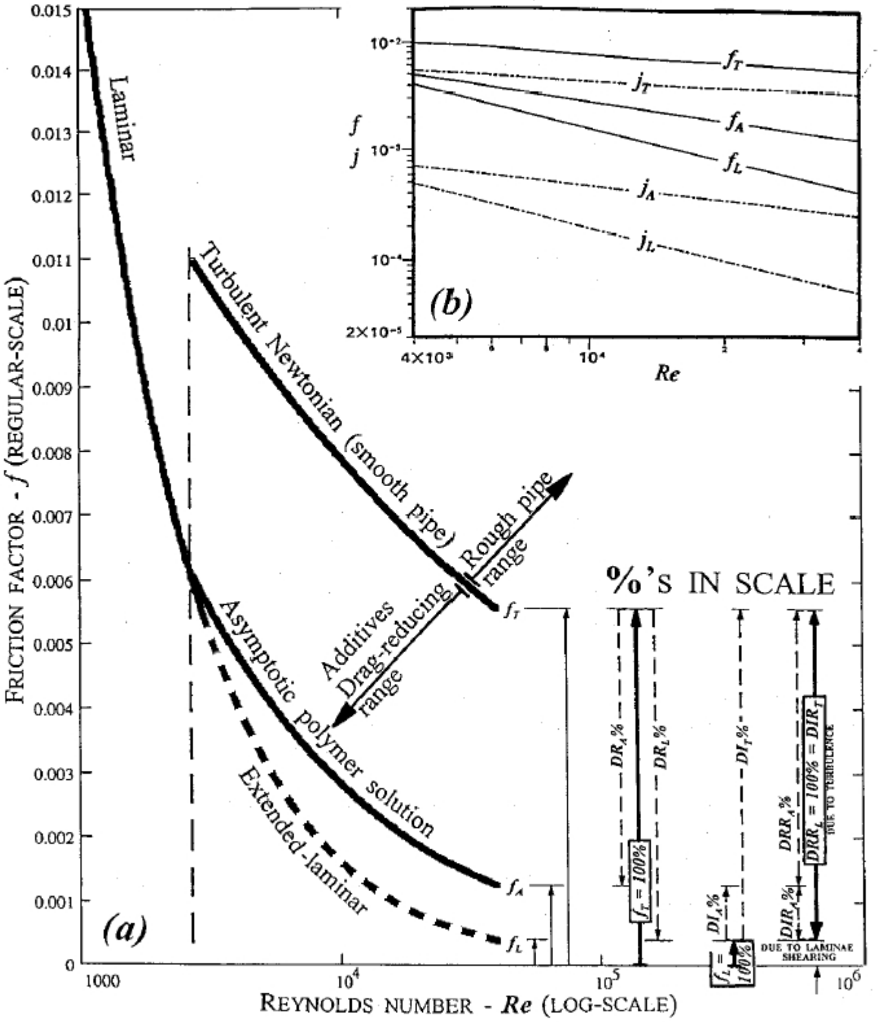

FIG. 1: Friction-factor vs. Reynolds-number curves for laminar, turbulent, and polymer drag-reducing asymptotic flows
(in semi-log scale as opposed to usual log-log scale) [11].

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(1949) [6] that the friction drag of some solutions under turbulent flow conditions is considerably smaller (several times) than the expected values. Drag-reducing fluids are also nanofluids, i.e. solutions of minute concentrations of certain nano-size (somtimes micro-size) additives, like high-polymers, soap and surfactant aggregates, or fibers, in common fluids, like water or oil. The pressure drop in turbulent pipe flows containing drag-reducing non-Newtonian fluids is several times lower than for the corresponding Newtonian fluids as discussed in an extensive review by Metzner [7]. These phenomena can be characterized by the so-called Virk's minimum asymptotic friction value [8]. Unfortunately, heat-transfer is also reduced. Kostic has been studying the drag-reducing fluids in laminar non-circular duct flows and discovered enhanced heat transfer [9]. Hartnett and Kostic [10] reviewed the flow and heat transfer phenomena of Newtonian and non-Newtonian fluids in rectangular ducts, and Kostic [11] presented an overview on turbulent drag and heat transfer reduction and laminar heat transfer enhancement of certain non-Newtonian fluids in non-circular duct flows, see Figure 1. More recently Escudier and Smith [12] conducted an experimental study of turbulent flow of non-Newtonian liquids through a square duct.

Complex fluids, like polymer solutions have functional, process-adjusting, active molecular-structures, and exhibit well-known shear-rate dependent viscosity, see Fig. 2. Randomly-oriented, long-chain macro-molecules increase substantially the zero-shear-rate (zero velocity) solution viscosity, but under shearing stresses, they self-align with the flow and viscosity is substantially reduced with the shear-rate increase. This is more dramatically demonstrated in turbulent flow, where a minute concentration (50 *ppm*) of long-chain macromolecules may reduce turbulent friction fivefold by suppressing transverse turbulence fluctuations, and in turn substantially reduce turbulence dissipation and over-all friction, see Fig. 1 [11].

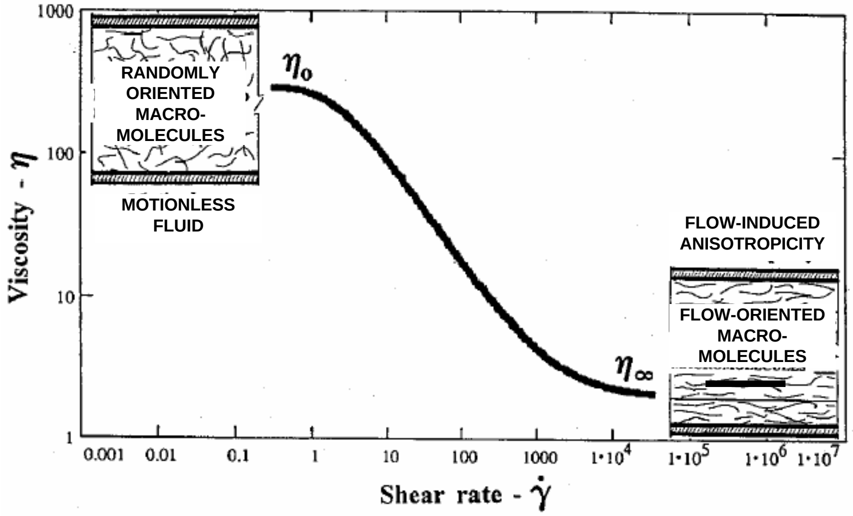

FIG. 2: Shear-rate dependent viscosity due to process-adjusting active structure of an aqueous polymer solution [11]

The polymer-nanofluids, could be developed, and are expected to be even more complex and active fluid mixtures, and thus have more degrees-of-freedom to 'self-adjust' under different process- and field-conditions. To develop, study, understand, and optimize polymer-nanofluid functionalities, by reducing instabilities while promoting those fluid structural activities that enhance flow and heat transfer characteristics as well as other characteristics, will be a research challenge and potential for many applications.

Another research challenge could be to combine the nanoparticles and drag-reducing additives, and thus develop a Drag-Reducing nanofluid (dubbed DR-nanofluid). The expectation is to obtain a hybrid nanofluid with improved flow and heat transfer characteristics. Furthermore, developing nanofluids with polymer additives or "POLY-nanofluids" may have other applications for creating more functional nanostructures, since polymer molecules may provide an enhanced web-like structure for nanoparticles in base fluids. Development of nanofluids, with enhanced or entirely different properties from their base fluids, is a new challenge and opportunity, and may have unprecedented application potentials.

IMPROVEMENT OF PHYSICAL ONE-STEP PRODUCTION METHOD AND DEVELOPMENT OF POLYMER-NANOFLUIDS

Most of the nanofluids used in research so far are produced by a two-step process. First, nanoparticles are produced as a dry powder, typically by inert gas condensation [13]. The second step involves dispersion of dry nanoparticle powder into a base fluid, like water, oil or ethylene-glycol. An advantage of the two-step process is that the inert-gas condensation technique has been scaled up to commercial nano-powder production [14]. A deficiency of this method is the tendency of nano-powders to agglomerate during storage and dispersion in the base fluids, particularly with heavier metallic nanoparticles. Surfactants and other surface-stabilization additives can be used to achieve more homogeneous and more stable suspensions. In addition to mechanical mixing, ultra-sonic mixers can be used to break up agglomerates and give more uniform dispersions. In general, however, although the process works well for some oxides, it has not been able to yield metallic nanofluids with substantially enhanced thermal conductivity.

By contrast, the one-step, or direct-evaporation process, involves nanoparticle source evaporation and direct condensation and dispersion onto the base fluid in a single step. This method has been developed by Yatsuya and coworkers [15] and improved by Wagner *et. al.* [16]. The one-step method has been employed by Choi and Eastman [17] in Argonne National Laboratory (ANL) and successfully used to produce nanofluids with very

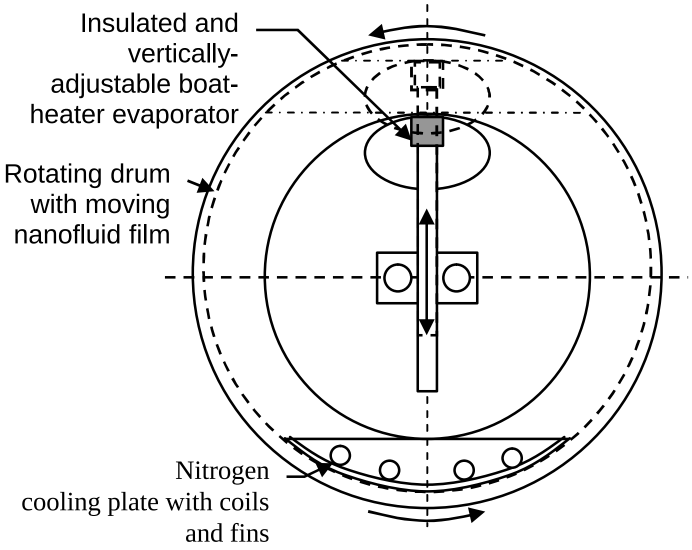

FIG. 3: Improved new-design for the one-step, direct-evaporation nanofluid production apparatus

small copper nanoparticles (about 10 nm) and exceptionally high thermal conductivity [18]. However, the one-step process is intrinsically more difficult to reproduce, since particles cannot be characterized and pre-sorted before addition to the fluid. Consequently, the ANL method, although an excellent idea, needs to be substantially improved in order to yield controlled particle sizes and sustained nanofluid production.

Proposed substantial improvement of the ANL one-step method [19], to produce stable nanofluids with well characterized and consistent properties, and development of complementary methods of chemical synthesis of nanofluids (see next Section), are exceptionally critical, since lack of consistent nanofluid production and characterization limits the progress of the future research in this and related areas.

Further research is required to develop an advanced, hybrid polymer-nanofluid, with not only the observed heat transfer enhancement, but also reduced flow friction. To develop enhanced drag-reducing heat-transfer nanofluids, it is important that very small-size metallic nanoparticles be used. This presently requires the use of the one-step, direct evaporation method since it has yielded higher thermal conductivities than those reported with other methods [18]. Kostic spent the last two summers working with Choi and Hull at ANL to improve the one-step nanofluid production method and a patent application is pending relating to this work [19]. To resolve critical production difficulties, we propose the following improvements in the concept and design of the existing one-step nanofluid apparatus shown in Figure 3. They are: (i) strategic positioning of metal boat-heater evaporator much closer to the moving fluid film in axial instead of transverse direction to the rotating drum, (ii) adjustment of the heater vertical position to make possible production of optimal size of nanoparticles, the latter being dependent, among other parameters, on the heater proximity to the moving fluid film, (iii) insulation of the heater with foam and a covering of reflective foil to minimize radiation loss and protect the foam insulation, (iv) improved control of the drum rotation velocity in order to optimize fluid heating and evaporation and increase the fluid mixing and cooling; (v) improved cooling using a finned plate heat exchanger with brazed tubing coils; and (vi) improved instrumentation and control of the vacuum pressure and temperature, among others.

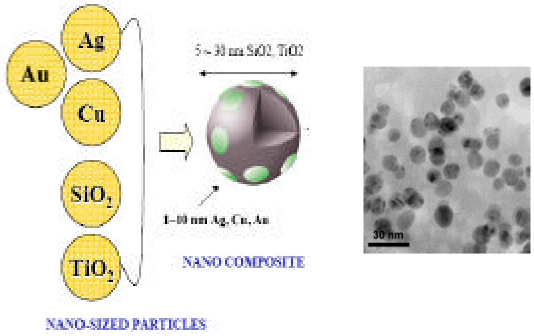

FIG. 4: A typical synthesis of nanoparticles, nanocomposites, and functionalized carbon nanotubes (not shown).

CHEMICAL SYNTHESIS OF NANOCOMPOSITES, PROCESSING AND STABILIZATION OF NANOFLUIDS

Electro-chemical surface interactions are very important,

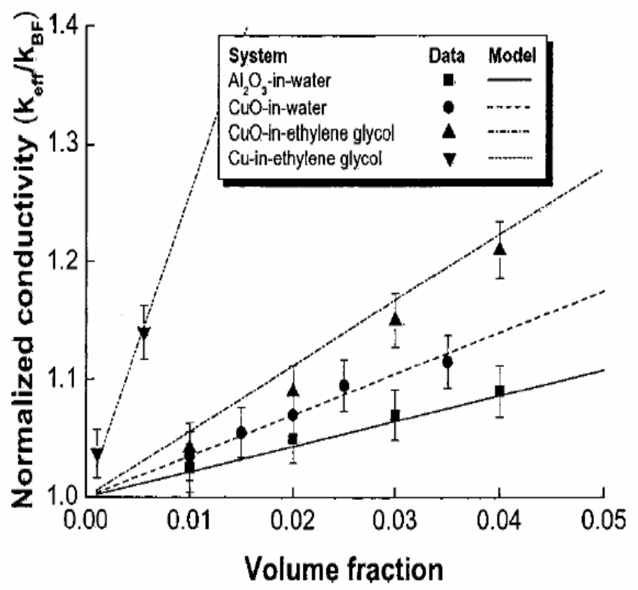

FIG. 5: Thermal conductivities of nanofluids, normalized to thermal conductivity of the corresponding base fluid, as function of volume fraction for different types of nanoparticles. Model predictions (straight lines) and experimental data (symbols) show very good agreements [35].

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particularly for small nanostructures, since they in turn will influence physical interactions and macroscopic thermo-physical properties, important for engineering applications. An important complement to the physical one-step nanofluid production method described above is a chemical one-step production method [20]. Another important research activity is in area of chemical surface-stabilization, to minimize nanoparticle agglomeration and oxidation. Chemical synthesis of (core-shell) nanoparticles also provides an alternate route to nanofluid production [21-27]. The chemical synthesis of functional nanocomposites and the processing of nanofluids could be divided into two tasks: (1) synthesis and stabilization of nanomaterials (shown in Fig. 4) and (2) dispersion and stabilization of nanomaterials in base fluids (including drag-reducing fluids) to form nanofluids. The nanoparticles of Cu, Ag, and Au could be synthesized by chemical reduction [28] and photoreduction [29], while the functionalized carbon nanotubes are commercially available. The stabilization of nanomaterials may be investigated by two techniques: (1) encapsulation of particles within a matrix of mercaptosilanes, thioglycolic acid, or other metal chelating agents, and (2) formation of nanocomposites and nanoparticle cores via a sol-gel chemical synthesis method [29]. The effect of different surface coatings on the transport phenomena between the particle and the fluid are an important area of investigation [30-34].

The drag-reducing fluids may contain water, different co-solvents, lubricants, co-polymer emulsions, dispersants and surfactants, rheological agents, surface energy controlled agents, and pH and ionic strength adjusting agents. The formulation principle and techniques for drag-reducing fluids and nanofluids should be similar to those formulations of water-based organic-inorganic hybrid emulsions. Different techniques could be developed and employed to synthesize and formulate the nanofluids with polymer additives.

NANOFLUID THERMAL CONDUCTIVITY AND VISCOSITY, AND FLOW AND HEAT-TRANSFER CHARACTERIZATION

Many experimental results of nanofluids' thermal conductivity have been reported and summarized [4,5]. The main characteristics are: (1) thermal conductivities are far above those of the base fluids and above the traditional solid-liquid suspensions, (2) a strong temperature dependence of the thermal conductivity and (3) a strong thermal conductivity to nanoparticle-concentration dependence. Carbon nanotubes (about 1% *vol* of 25-nm particles) produced the highest increase of 150% in thermal conductivity, while copper nanoparticles (about 0.5% *vol* of 10-nm size) increased the base fluid thermal conductivity by 40%. In comparison, the thermal conductivity increase for oxide nanoparticles is an order of magnitude smaller. The substantial increase in thermal conductivity is not yet fully understood. Recently, Jang and Choi hypothesize that Brownian-like motion of nanoparticles drag the base fluid and thus induce micro-scale convective heat transfer. They were able to successfully model their measured data [35], as shown in Figure 5. It is necessary to carry systematic nano-structural characterization of nanofluids to confirm the above hypothesis and to provide experimental data for new ones.

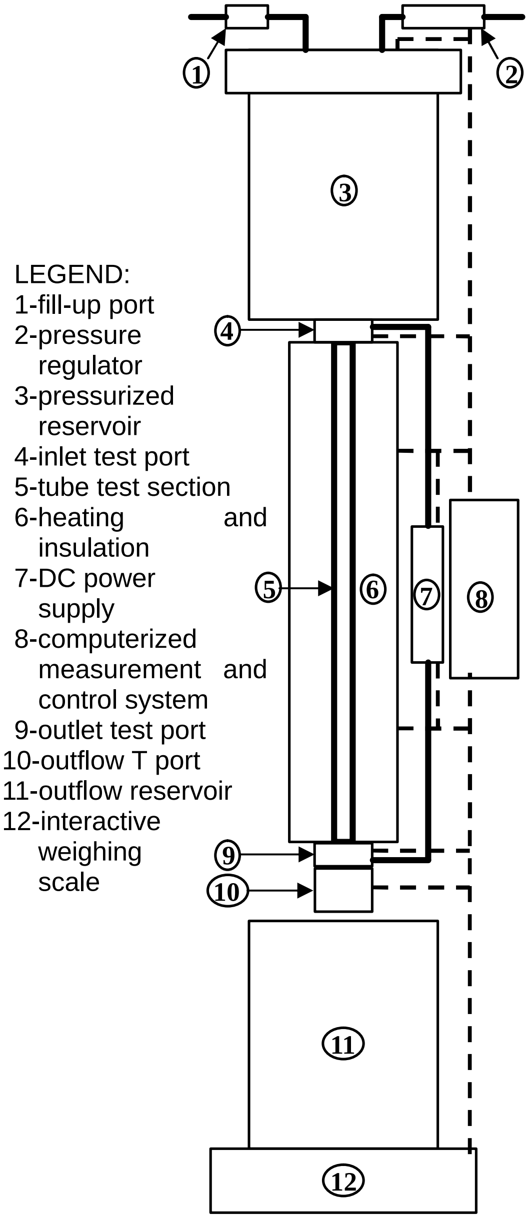

FIG. 6: A nanofluid flow and heat-transfer apparatus

A coated-platinum, hot-wire thermal conductivity apparatus is usually used for measurement of thermal conductivity, as function of nanoparticle size distribution, concentration and temperature. The transient hot wire method is well-established and reliable [36, 37, 38], however, due to electrical conductance of metallic nanofluids the platinum wire is epoxy- or silica-coated, and special care needs to be taken to minimize adverse temperature gradients and resolve some stability issues experienced at higher temperature levels [39].

Measurements of viscosity as function of shearing rate and temperature, and viscoelastic properties are required for development of new non-Newtonian polymer solution. Due to complexity of polymer-nanofluids, new methods may need to be developed for non-isotropic thermal conductivity, including dependence of thermal conductivity on flow shearing [40, 41, 42]. Nanoparticle, polymer, and base fluid interactions may be significant, particularly at higher concentrations, and other additives, including surfactants, may have profound

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influence on rheology, thermal conductivity, and other thermo-physical properties.

Thermal conductivity studies have been the focus of nanofluid research so far, but ultimately, their flow and heat transfer characteristics in real, practical applications will determine their usefulness as advanced flow and heat-transfer fluids. Initial heat transfer studies with nanofluids in boiling, free and forced convection are promising [43, 44, 45]. A simple flow and heat transfer apparatus is depicted on Fig. 6. To avoid problems with pumping new nanofluids, fluid flow could be provided using a pressurized tank, and mass flow rate measurements of unknown fluid rheology (even unknown viscosity), may be achieved using a simple digital weighing scale with computerized data acquisition system. This will be a batch flow testing, thus not having advantages of a continuous steady state operation. However, if instrumentation and interactive, computerized data acquisition are used [46], more useful data may be obtained faster than in a slow steady-state operation, thus making the batch testing mode very efficient. Furthermore, polymer-nanofluid degradation will be minimized by not using a pump. Extensive and systematic investigation in wide flow range and for different flow configurations is required for correlation of complex-nanofluids' flow and heat transfer characteristics.

CHARACTERIZATION OF NANOFLUID MICRO-STRUCTURE AND DIFFUSION

A valuable characterization tool for the structure of suspensions at nanoscale is the small angle x-ray scattering (SAXS) and small angle neutron scattering (SANS) [47]. In these techniques a nanofluid is illuminated by a collimated x-ray or neutron beam and the intensity of scattering is measured as a function of angle. Experimental results are typically expressed as wave-vector dependent cross sections. Under the approximation of a relatively monodisperse suspension, the scattering cross section can be related to the product of the particle form factor, which is determined by the shape of the particle, and the structure factor for correlations between different particles. These data, in principle, may contain a wealth of information about the nanofluids. A number of properties of the suspensions can be obtained fairly easily, such as average particle size, gross characteristics of shape (e.g. are they round, or oblong, what is their ratio of surface area to volume, how thick are the core and the shells of the particles), the polydispersity and the extent to which particles remain isolated or have agglomerated. More detailed information can only be obtained through comparison with detailed theoretical studies, such as have been done for polydisperse suspensions of interacting particles [48, 49, 50].

The mechanism by which the addition of polymers reduces the friction drag in a fluid is expected to be related to an orientation of the polymer along the flow direction. Similarly, in a polymer-nanofluid it is expected that polymer-nanoparticle interactions should act to orient both the polymers and the particles along the flow direction. In order to understand interactions between polymers and nanoparticles under flow conditions it will be crucial to study the nano-scale structure under flow. Since the direction of shear will induce an asymmetry into the system, this will align the nano-particles and polymers. In order to detect and analyze such asymmetries, scattering is measured using an area detector that can resolve the angle of scattering relative to the flow direction. In principle, if flow allows particles to align, then this can permit more detailed information about the shape and interactions to be recovered from the scattering patterns.

Equilibrium dynamics can be measured using a relatively recent x-ray scattering technique called x-ray photon correlation spectroscopy (XPCS), which is based on the traditional laser based photon correlation spectroscopy (PCS). In the XPCS technique a sample is illuminated with a fully coherent x-ray beam, instead of the more typical situation in which the incident x-rays consist of a large number of incoherent regions. The effect of coherent illumination is to obtain a speckle pattern superimposed on the usual SAXS pattern. Measurements of the time-correlation function of the speckle pattern at different wavevectors gives information on the dynamics within the fluid as a function of length scale. In the limit, XPCS patterns yield the macroscopic particle diffusion coefficient. For concentrated solutions the particles interact with each other and their motions become correlated. There are detailed theoretical predictions for the dynamics structure factor under such circumstances, and these have been partly confirmed by experiment [51]. The XPCS could be measured for a series of polymer nanofluids in order to extract diffusion coefficients and relate them to macroscopic flow and heat transfer properties. It has recently been suggested that nanoparticles drag with them a shell of neighboring solvent particles (molecular clusters) as they diffuse, and that the properties of this solvent shell are critical to their heat transfer properties [35]. This hypothesis could be checked by comparing the hydrodynamic radius of nanoparticles, measured from their diffusion rate with the average particle radius measured from SAXS or SANS. It will also be possible to examine correlations between the flow of different particles mediated by hydrodynamic coupling through the fluid [52], as well as the entrapment of particles due to direct interactions. Critical to understanding POLY-nanofluids will be to compare the diffusive dynamics of nanofluids with and without the presence of polymer additives.

The Preliminary XPCS and SAXS experiments were carried out at the ANL's Advanced Photon Source in order to evaluate the potential for using these techniques to understand the properties of the nanofluid [53]. Figure 7 displays the measured SAXS from nominally 51 nm Al_2O_3 nanoparticles in ethylene glycol. The calculated scattering from monodisperse spherical particles is shown superposed as the dot-dash line. The characteristic minimum due to destructive interference from the front and back surfaces of the sphere are missing in the measured data. This may be an indication that the manufactured particles have a broad size distribution. The other line shows the calculated scattering from particles with a

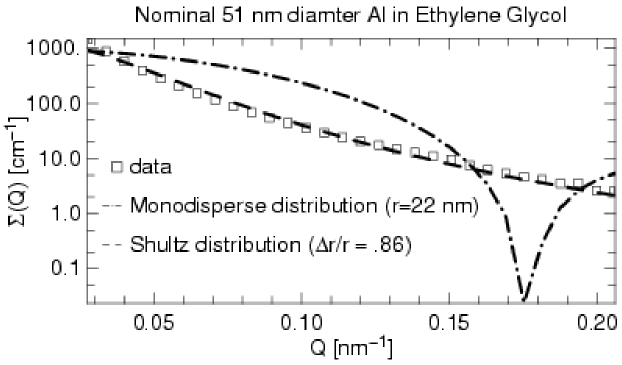

FIG. 7: SAXS measured from a dilute nominally 51 nm diameter Al_2O_3 nanoparticles in ethylene glycol [53].

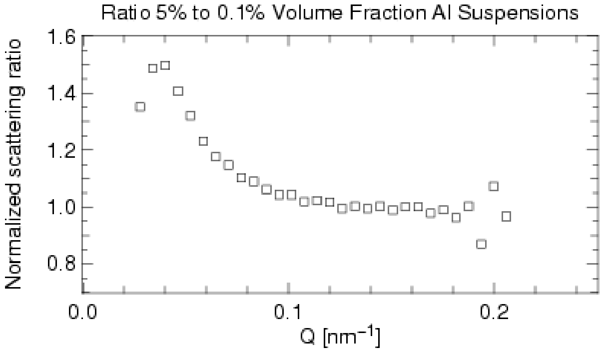

FIG. 8: Inter-particle structure factor for a nominally 5% volume fraction solution of nominally 52 *nm* diameter Al_2O_3 nanoparticles [53].

86% variation in size and a number averaged diameter of 22 nm [54]. Figure 8 displays the scattering from a more concentrated dispersion (nominally 5% volume fraction of Al_2O_3) normalized by the scattering from the dilute suspension. The resulting ratio is a measure of inter-particle correlations. The data show a clear peak, corresponding to liquid like correlations between the particles. Such a strong peak indicates the presence of attractive forces between the nanoparticles.

The above experimental results indicate the kind of measurements that can be done on a nanofluid system. It will be of obvious interest to see how the addition of polymers affects the nanoparticle dynamics. Our research teams intend to carry out systematic studies with newly to-be developed nanofluids, by varying nanoparticle size, polydispersity and polymer size in order to study and resolve related issues.

CONCLUSION

There are many challenges in nanofluids research, including development of improved and new methods for production and characterization of diverse, complex nanofluids with polymer additives. These polymer-nanofluids are expected to possess exceptionally high thermal conductivity while at the same time having improved flow characteristics. Application potentials are unforeseeable and may revolutionize the field of heat transfer. They range from cooling densely packed integrated circuits at the small scale to heat transfer in nuclear reactors at the large scale. Critical innovation improvements of the ANL one-step, evaporation-direct-deposition method will lead to an improved understanding and optimization of the method, including systematic investigation of nanofluid properties as function of the process parameters. This is very important since nanofluids produced by the one-step, direct evaporation method, have demonstrated much higher thermal conductivity than metal- or metal-oxide-based nanofluids produced by the common two-step mixing method. Exploration of various combinations of different polymers and nanofluids will lead to an improved understanding of the stability criteria for these suspensions and crucial data regarding which combinations of polymers and nanofluids lead to optimal flow and heat transfer characteristics. Furthermore, the chemical and physical interactions between the drag-reducing polymer additives and metal-based nanoparticles remain to be tested, and may result in more complex, but potentially very useful functional and active nanostructures and phenomena.

In addition to the physical one-step method, the development of new chemical synthesis and stabilization methods for nanofluid production with very-small size, metal nanoparticles, is a critical undertaking. Study of the nano-scale surface chemistry, and physical structure and dynamics, will yield improved understanding of the momentum and energy transport-mechanisms and thus contribute to the general understanding of the physics of complex fluids. Finally, even with the use of the state-of-the-art instrumentation, the nano-scale characterization of surface-chemistry, physical structure and dynamics of nanoparticles and polymer macro-molecules in base fluids, will present a major challenge, particularly under flow-shearing and heat-transfer conditions. Comprehensive and systematic experimental measurements will characterize heat transfer and flow friction properties on the macroscale, as well as chemistry, structure and dynamics on the nanoscale. These experimental investigations should be integrated with theoretical analysis and computational modeling in order to correlate the nanoscale structure and properties with the flow and heat transfer characteristics. This should lead to new insight into the mechanisms of drag reduction and thermal diffusion in composite fluids. The theoretical modeling will provide feedback on how to further develop and optimize the complex nanofluid production processes.

Improved fundamental understanding of complex nanofluids and active processes in nanofluids will have an even broader impact. Nature is full of nanofluids, like blood, a complex biological nanofluid where different nanoparticles (at molecular level) accomplish different functions, and where nanofluid functional components actively respond to their local environment. Many mining and manufacturing processes involve waste products that consist of mixtures of nanoscale particles with fluids. A wide range of active self-assembly mechanisms for nanoscale structures start from a suspension of nanoparticles in fluid. The future research should lead to development of new experimental methods for characterizing (and understanding) nanofluids in the lab and in nature, as well as to development of computer based models of nanofluids and functional, active nanofluid phenomena.

The future research in nanofluids area may have much broader impact and open the road for development of diverse, complex nanofluids with polymer additives, including biological nanofluids, dubbed POLY-nanofluids, with unprecedented potential in existing, new emerging, and critical applications, including energy production and conversion, transportation, environmental control and cleanup, bio-medical applications, and directed self-assembly of nanostructures, and related fundamental nanoscale phenomena and processes in functional and active nanostructures.

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