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# Nanofluids for Heat Transfer – Potential and Engineering Strategies

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## 1. Introduction

In an age of increasing heat fluxes and power loads in applications as diverse as power electronics, renewable energy, transportation, and medical equipment, liquid cooling systems are necessary to enhance heat dissipation, improve energy efficiency, and lengthen device lifetime. To satisfy these increasing thermal management needs, the heat transfer efficiency of conventional fluids must be improved.

Nanofluids are nanotechnology-based heat transfer fluids that are engineered by stably dispersing nanometer-sized solid particles (such as ceramics, metals, alloys, semiconductors, nanotubes, and composite particles) in conventional heat transfer fluids (such as water, ethylene glycol, oil, and mixtures) at relatively low particle volume concentrations. Nanofluids have been considered for applications as advanced heat transfer fluids for almost two decades, since they have better suspension stability compared to micron-sized solid particles, can flow smoothly without clogging the system, and provide enhanced thermal and physical properties.

Nanofluids are in essence nanocomposite materials, with adjustable parameters including, but not limited to nanoparticle material, size, and shape, base fluid, surfactants and other additives. The thermal conductivity of heat transfer fluid is widely recognized as a main factor influencing the heat transfer efficiency. Low thermal conductivity of conventional fluids (i.e. 0.1-0.6 W/mK at 25°C) improves when solid particles with significantly higher thermal conductivity values (i.e. 10-430 W/mK for pure elements) are added. Therefore addition of small solid particles to liquids improves thermal conductivity of suspension, while still allowing for convection heat transfer mechanism of the fluid. The magnitudes of the effects reported in the literature are scattered from few percent (as predicted by effective medium theory (EMT) [1-3]) to hundred percents per nanoparticle volume concentration (i.e. abnormal enhancements [4-6]).

## 2. Diversity of nanofluids

Theoretical efforts and modeling of the thermal conductivity enhancement mechanisms in nanofluids [7, 8] have not come up with a universal theoretical model that carefully predicts the thermal conductivity for a variety of nanofluid compositions. The macroscopic effective medium theory (EMT) introduced by Maxwell [1] and further developed for non-spherical particle shapes by Hamilton and Crosser [2] predicts that thermal conductivity of two

component heterogeneous mixtures is a function of the conductivity of pure materials, the composition of the mixture and the manner in which pure materials distributed throughout the mixture. Hamilton-Crosser model allows calculation of the effective thermal conductivity ( $k_{eff}$ ) of two component heterogeneous mixtures and includes empirical shape factor,  $n$  given by  $n = 3/\psi$  ( $\psi$  is the sphericity defined as ratio between the surface area of the sphere and the surface area of the real particle with equal volumes):

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

where  $k_p$  and  $k_0$  are the conductivities of the particle material and the base fluid and  $\phi$  is volume fraction of nanoparticles. Thus, according to this model [2], suspensions of particles with high shape factor (elongated and thin) should have higher thermal conductivities.

Despite the large database supporting EMT, there are many experimental results showing significantly higher or lower thermal conductivity enhancements [4-6] indicating that basic EMT doesn't account for all contributing factors. A number of mechanisms for enhanced thermal conductivity were suggested to explain the experimental data, and include the interaction between nanoparticles and liquids in form of interfacial thermal resistance [9-11], formation of condensed nano-layers around the particles [12-14], the particle size effects [15], agglomeration of nanoparticles [16-18], the microconvection mechanism due to Brownian motion of nanoparticles in the liquid [19-21], surface plasmon resonance [22-24], and near field radiation [25, 26]. None of these mechanisms alone seems to have the capacity of explaining the variety of experimental thermal conductivity enhancements in nanofluids, but it appears that different combinations of suggested mechanisms could explain the majority of experimental results. This is possible when different nanofluid parameters engage additional to EMT thermal conductivity enhancing mechanisms.

Large volume of studies has been devoted to characterization of individual thermo-physical properties of nanofluids, such as thermal conductivity, viscosity, and agglomeration of nanoparticles [5, 8, 27-33]. However no agreement has been achieved on the magnitude of potential benefits of using nanofluids for heat transfer applications because of diversity and complexity of the nanofluid systems.

By the type of nanoparticle material the nanofluid systems can be roughly classified into (1) ceramic (oxides, carbides, nitrides) nanofluids; (2) metallic nanofluids; (3) carbonaceous (graphite, graphene, carbon nanotubes, etc.) nanofluids; and (4) nanodroplet/nanoemulsions. Each class of nanofluids draws a unique set of thermal conductivity enhancement mechanisms that contribute to the heat transfer efficiency of these nanofluids.

Ceramic nanofluids are the most investigated class of nanofluids, because of the low cost, wide availability and chemical stability of ceramic nanomaterials. Most reports on ceramic nanofluids agree that the increases in thermal conductivity fall on or slightly above the prediction of EMT corrected for contribution of interfacial thermal resistance and/or elongated nanoparticle shape [3, 9, 18, 34, 35], with the thermal conductivity of solid-liquid suspensions linearly increasing with the volume fraction of the solid particles (black dashed line, Fig. 1).

Metallic nanofluids are less investigated than ceramic nanofluids because of the limited oxidative stability of many affordable metals and high cost of chemically stable precious metal nanoparticles. However many experimental results for metallic nanofluids report

thermal conductivity increases well above the effective medium theory prediction [36-44] as summarized in Figure 1. Data from different research groups are quite scattered, possibly because of the difference in the preparation techniques, particle size, material, base fluids, surfactants, and also uncertainties in measurements of particle concentration and thermal conductivity [3]. It was suggested [23] that metallic nanoparticles possess geometry-dependent localized plasmon resonances (collective oscillations of the metals free electrons upon optical or other excitation), which could be responsible for abnormal thermal conductivity increases in metallic nanofluids. The significant enhancement in thermal conductivity, shown by the majority of metal containing nanofluids, indicates a great potential for revolutionizing industries that are dependent on the performance of heat transfer fluids. Production of metal containing nanofluids faces some major challenges, such as stability towards agglomeration and surface oxidation, availability, cost of materials and manufacturing issues. Use of dry metal nanopowders fabricated in gas phase is limited to precious metals (Au, Pt) resistant to surface oxidation. Generation of nanoparticles directly in the base fluid is recognized to produce more homogeneous nanofluids with fewer agglomerates and also provides better control over the surface state [38].

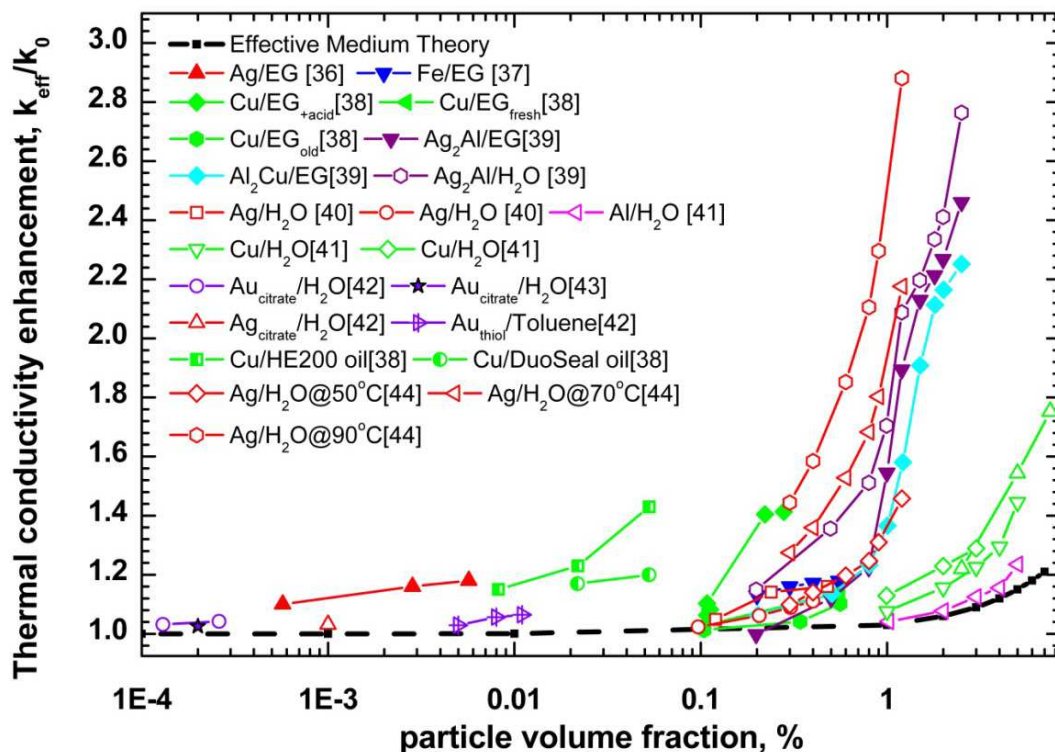


Fig. 1. Summary of published data on the thermal conductivities of metal containing nanofluids in ethylene glycol –EG (solid markers), water (empty markers) and other solvents (semi-empty). Nanoparticle material indicated by color: Ag – red, Fe – blue, Cu – green, Al – magenta, Au – violet

Carbonaceous nanofluids show a wide range of thermal conductivity increases, from very insignificant increase in amorphous carbon black to a 2-3 fold increase in thermal conductivity in some suspensions with carbon nanotubes [45-48] and graphene oxides [49, 50]. A unique nature of anisotropic carbonaceous nanomaterials is most likely responsible

for such a dramatic thermal conductivity increase by engaging additional heat transfer mechanism in suspensions.

Nanoemulsions (liquid/liquid dispersions) [51, 52] are attractive due to their long-term stability, although the potential of nanodroplets in enhancing thermal conductivity is limited, the development of nanoemulsions may open a new direction for thermal fluid studies [53].

### 3. Factors affecting the fluids cooling efficiency

Attention to nanofluids as advanced heat transfer fluids was initially based on the increased thermal conductivity of nanoparticle suspensions. It is not always realized that the thermal conductivity is not the only property that determines the efficiency of heat transfer fluid in practical applications [54]. In the forced flow systems the coolant is pumped through the pipes of a heat exchanger, introducing convective heat transfer mechanisms and pumping power penalties. Therefore the convective heat transfer coefficient becomes more important than the thermal conductivity value. 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 [55] in assumption of a single phase flow.

In the case of hydrodynamically and thermally fully developed laminar flow, the heat transfer coefficient ( $h$ ) is proportional to the thermal conductivity ( $k$ ), and within the acceptable range of inlet/outlet temperature difference is independent of the flow velocity [56]:

$$h \propto k \quad (2).$$

High viscosity of nanofluids compared to base fluid increases the power required to pump the fluid through the system. When the benefit of the increased heat transfer is larger than the penalty of the increased pumping power, the nanofluid has the potential for commercial viability. Experimental studies have demonstrated good agreement between experimentally measured pressure drops in nanofluid flow and values calculated in assumption of single phase fluid flow with viscosity of the nanofluid [58-60].

An alternative merit criterion for laminar flow [57] was suggested to account for pumping power penalties, for situation, when the tube diameter can be increased for the nanofluid to result in the same heat transfer coefficient:

$$\frac{\mu_{eff}}{\mu_0} \approx 1 + C_\mu \phi; \quad \frac{k_{eff}}{k_0} \approx 1 + C_k \phi; \quad C_\mu / C_k < 4; \quad (3),$$

where  $\phi$  is the particle volume concentration,  $\mu$  is the dynamic viscosity of the nanofluid ( $eff$ ) and the base fluid ( $0$ ), and  $C_\mu$  and  $C_k$  are viscosity and thermal conductivity enhancement coefficients, determined from experimental viscosity and thermal conductivity ratios. However this merit criterion is not very practical when efficiencies of two fluids are compared in the same system geometry (i.e. tube diameter).

In turbulent flow regime the heat transfer rate (based on the Dittus-Boelter equation for heating applications) is dependent not only upon the thermal conductivity ( $k$ ), but also on the density ( $\rho$ ), specific heat ( $c_p$ ), viscosity ( $\mu$ ) and flow velocity ( $V$ ) [55]:

$$h \propto \rho^{4/5} c_p^{2/5} \mu^{-2/5} k^{3/5} V^{4/5} \quad (4).$$



Introduction of nanoparticles to the fluid affects all of thermo-physical properties and should be accounted for in the nanofluid evaluations [61]. Density and specific heat are proportional to the volume ratio of solid and liquid in the system, generally with density increasing and specific heat decreasing with addition of solid nanoparticles to the fluid. According to equation (4) the increase in density, specific heat and thermal conductivity of nanofluids favors the heat transfer coefficient; however the well described increase in the viscosity of nanoparticle suspensions is not beneficial for heat transfer. The velocity term in the equation (4) also represents the pumping power penalties resulting from the increased viscosity of nanofluids [55, 58].

The comparison of two liquid coolants flowing in fully developed turbulent flow regime over or through a given geometry at a fixed velocity reduces to the ratio of changes in the thermo-physical properties:

$$\frac{h_{eff}}{h_0} \approx \left( \frac{\rho_{eff}}{\rho_0} \right)^{4/5} \left( \frac{c_{peff}}{c_{p0}} \right)^{2/5} \left( \frac{\mu_{eff}}{\mu_0} \right)^{-2/5} \left( \frac{k_{eff}}{k_0} \right)^{3/5} \quad (5).$$

The nanofluid is beneficial when  $h_{eff}/h_0$  ratio is above one and not beneficial when it is below one. Similar figure of merit the ratio of Mouromtseff values (Mo) was also suggested for cooling applications [62, 63]. The fluid with the highest Mo value will provide the highest heat transfer rate over the same cooling system geometry.

It is obvious that nanofluids are multivariable systems, with each thermo-physical property dependent on several parameters including nanoparticle material, concentration, size, and shape, properties of the base fluid, and presence of additives, surfactants, electrolyte strength, and pH. Thus, the challenge in the development of nanofluids for heat transfer applications is in understanding of how micro- and macro-scale interactions between the nanoparticles and the fluid affect the properties of the suspensions. Below we discuss how each of the above parameters affects individual nanofluids properties.

#### 4. General trends in nanofluid properties

The controversy of nanofluids is possibly related to the underestimated system complexity and the presence of solid/liquid interface. Because of huge surface area of nanoparticles the boundary layers between nanoparticles and the liquid contribute significantly to the fluid properties, resulting in a three-phase system. The approach to nanofluids as three-phase systems (solid, liquid and interface) (instead of traditional consideration of nanofluids as two-phase systems of solid and liquid) allows for deeper understanding of correlations between the nanofluid parameters, properties, and cooling performance. In this section general experimentally observed trends in nanofluid properties are correlated to nanoparticle and base fluid characteristics with the perspective of interface contributions (Fig. 2).

##### a. Nanoparticles

Great varieties of nanoparticles are commercially available and can be used for preparation of nanofluids. Nanoparticle material, concentration, size and shape are engineering parameters that can be adjusted to manipulate the nanofluid properties.

Nanoparticle material defines density, specific heat and thermal conductivity of the solid phase contributing to nanofluids properties (subscripts  $p$ ,  $0$ , and  $eff$  refer to nanoparticle, base fluid and nanofluid respectively) in proportion to the volume concentration of particles ( $\phi$ ):

$$\rho_{eff} = (1 - \phi)\rho_0 + \phi\rho_p \quad (6);$$

$$(c_p)_{eff} = \frac{(1 - \phi)(\rho c_p)_0 + \phi(\rho c_p)_p}{(1 - \phi)\rho_0 + \phi\rho_p} \quad (7);$$

$$k_{eff} = k_0 \left( \frac{k_p + 2k_0 + 2(k_p - k_0)\phi}{k_p + 2k_0 - (k_p - k_0)\phi} \right), \text{ (for spherical particles by EMT)} \quad (8).$$

As it was mentioned previously materials with higher thermal conductivity, specific heat, and density are beneficial for heat transfer. Besides the bulk material properties some specific to nanomaterials phenomena such as surface plasmon resonance effect [23], increased specific heat [64], and heat absorption [65, 66] of nanoparticles can be translated to the advanced nanofluid properties in well-dispersed systems.

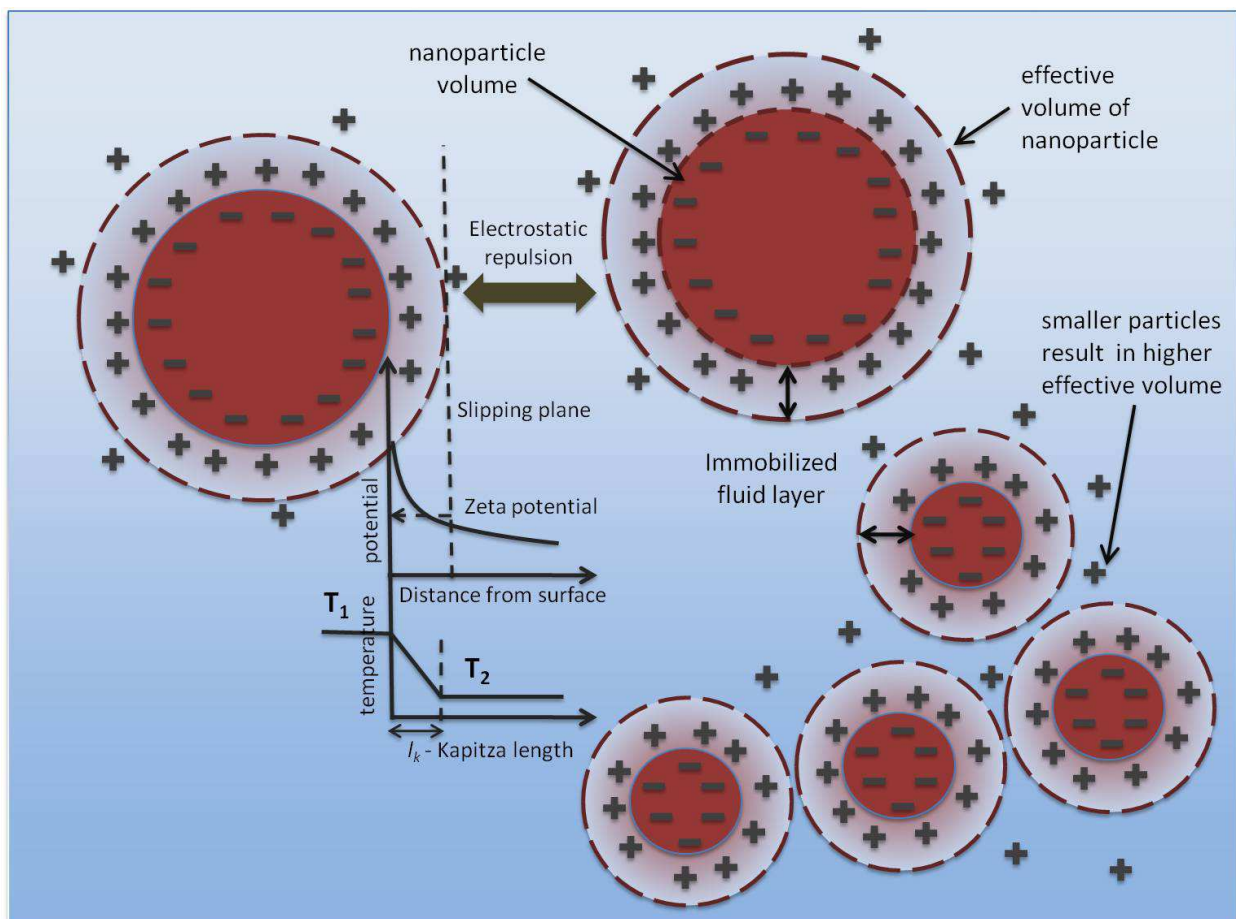


Fig. 2. Interfacial effects in nanoparticle suspensions

The size of nanoparticles defines the surface-to-volume ratio and for the same volume concentrations suspension of smaller particles have a higher area of the solid/liquid interface (Fig. 2). Therefore the contribution of interfacial effects is stronger in such a suspension [15, 34, 35, 67]. Interactions between the nanoparticles and the fluid are manifested through the interfacial thermal resistance, also known as Kapitza resistance ( $R_k$ ),

that rises because interfaces act as an obstacle to heat flow and diminish the overall thermal conductivity of the system [11]. A more transparent definition can be obtained by defining the Kapitza length:

$$l_k = R_k k_0 \quad (9),$$

where  $k_0$  is the thermal conductivity of the matrix,  $l_k$  is simply the thickness of base fluid equivalent to the interface from a thermal point of view (i.e. excluded from thermal transport, Fig. 2) [11]. The values of Kapitza resistance are constant for the particular solid/liquid interface and defined by the strength of solid-liquid interaction and can be correlated to the wetting properties of the interface [11]. When the interactions between the nanoparticle surfaces and the fluid are weak (non-wetting case) the rates of energy transfer are small resulting in relatively large values of  $R_k$ . The overall contribution of the solid/liquid interface to the macroscopic thermal conductivity of nanofluids is typically negative and was found proportional to the total area of the interface, increasing with decreasing particle sizes [34, 67].

The size of nanoparticles also affects the viscosity of nanofluids. Generally the viscosity increases as the volume concentration of particles increases. Studies of suspensions with the same volume concentration and material of nanoparticles but different sizes [67, 68] showed that the viscosity of suspension increases as the particle size decreases. This behavior is related to formation of immobilized layers of the fluid along the nanoparticle interfaces that move with the particles in the flow (Fig. 2) [69]. The thicknesses of those fluid layers depend on the strength of particle-fluid interactions while the volume of immobilized fluid increases in proportion to the total area of the solid/liquid interface (Fig. 2). At the same volume concentration of nanoparticles the “effective volume concentration” (immobilized fluid and nanoparticles) is higher in suspensions of smaller nanoparticles resulting in higher viscosity. Therefore contributions of interfacial effects, to both, thermal conductivity and viscosity may be negligible at micron particle sizes, but become very important for nanoparticle suspensions. Increased viscosity is highly undesirable for a coolant, since any gain in heat transfer and hence reduction in radiator size and weight could be compensated by increased pumping power penalties. To achieve benefit for heat transfer, the suspensions of larger nanoparticles with higher thermal conductivity and lower viscosity should be used.

A drawback of using larger nanoparticles is the potential instability of nanofluids. Rough estimation of the settling velocity of nanoparticles ( $V_s$ ) can be calculated from Stokes law (only accounts for gravitational and buoyant forces):

$$V_s = \frac{2}{9} \left( \frac{\rho_p - \rho_0}{\mu} \right) r^2 g \quad (10),$$

where  $g$  is the gravitational acceleration. As one can see from the equation (10), the stability of a suspension (defined by lower settling rates) improves if: (a) the density of the solid material ( $\rho_p$ ) is close to that of the fluid ( $\rho_0$ ); (b) the viscosity of the suspension ( $\mu$ ) is high, and (c) the particle radius ( $r$ ) is small.

Effects of the nanoparticles shapes on the thermal conductivity and viscosity of alumina-EG/H<sub>2</sub>O suspensions [34] are also strongly related to the total area of the solid/liquid interface. In nanofluids with non-spherical particles the thermal conductivity enhancements predicted by the Hamilton-Crosser equation [2, 70] (randomly arranged elongated particles



provide higher thermal conductivities than spheres [71]) are diminished by the negative contribution of the interfacial thermal resistance as the sphericity of nanoparticles decreases [34].

In systems like carbon nanotube [45-48], graphite [72, 73] and graphene oxide [49, 50, 74] nanofluids the nanoparticle percolation networks can be formed, which along with high anisotropic thermal conductivity of those materials result in abnormally increased thermal conductivities. However aggregation and clustering of nanoparticles does not always result in increased thermal conductivity: there are many studies that report thermal conductivity just within EMT prediction in highly agglomerated suspension [71, 75-77].

Elongated particles and agglomerates also result in higher viscosity than spheres at the same volume concentration, which is due to structural limitation of rotational and transitional motion in the flow [77, 78]. Therefore spherical particles or low aspect ratio spheroids are more practical for achieving low viscosities in nanofluids – the property that is highly desirable for minimizing the pumping power penalties in cooling system applications.

#### **b. Base fluid**

The influence of base fluids on the thermo-physical properties of suspensions is not very well studied and understood. However there are few publications indicating some general trends in the base fluid effects.

Suspensions of the same  $\text{Al}_2\text{O}_3$  nanoparticles in water, ethylene glycol (EG), glycerol, and pump oil showed increase in relative thermal conductivity ( $k_{eff}/k_0$ ) with decrease in thermal conductivity of the base fluid [15, 79, 80]. On the other hand the alteration of the base fluid viscosity [81] (from 4.2 cP to 5500 cP, by mixing two fluids with approximately the same thermal conductivity) resulted in decrease in the thermal conductivity of the  $\text{Fe}_2\text{O}_3$  suspension as the viscosity of the base fluid increased. Comparative studies of 4 vol% SiC suspensions in water and 50/50 ethylene glycol/water mixture with controlled particle sizes, concentration, and pH showed that relative change in thermal conductivity due to the introduction of nanoparticles is ~5% higher in EG/ $\text{H}_2\text{O}$  than in  $\text{H}_2\text{O}$  at all other parameters being the same [68]. This effect cannot be explained simply by the lower thermal conductivity of the EG/ $\text{H}_2\text{O}$  base fluid since the difference in enhancement values expected from EMT is less than 0.1% [7]. Therefore the “base fluid effect” observed in different nanofluid systems is most likely related to the lower value of the interfacial thermal resistance (better wettability) in the EG/ $\text{H}_2\text{O}$  than in the  $\text{H}_2\text{O}$ -based nanofluids.

Both, thermal conductivity and viscosity are strongly related to the nanofluid microstructure. The nanoparticles suspended in a base fluid are in random motion under the influence of several acting forces such as Brownian motion (Langevin force, that is random function of time and reflects the atomic structure of medium), viscous resistance (Stokes drag force), intermolecular Van-der-Waals interaction (repulsion, polarization and dispersion forces) and electrostatic (Coulomb) interactions between ions and dipoles. Nanoparticles in suspension can be well-dispersed (particles move independently) or agglomerated (ensembles of particles move together). Depending on the particle concentration and the magnitude of particle-particle interaction that are affected by pH, surfactant additives and particle size and shape [82] a dispersion/agglomeration equilibrium establishes in nanoparticle suspension. It should be noted here, that two types of agglomerates are possible in nanofluids. First type of agglomerates occurs when nanoparticles are agglomerated through solid/solid interface and can potentially provide increased thermal conductivity as described by Prasher [17]. When loose single crystalline

nanoparticles are suspended each particle acquires diffuse layer of fluid intermediating particle-particle interactions in nanofluid. Due to weak repulsion such nanoparticles can form aggregate-like ensembles moving together, but in this case the interfacial resistance at solid/liquid/solid interface is likely to prevent proposed agglomeration induced enhancement in thermal conductivity.

Relative viscosity was shown to decrease with the increase of the average particle size in both EG/H<sub>2</sub>O and H<sub>2</sub>O-based suspensions. However at the same volume concentration of nanoparticles relative viscosity increase is smaller in the EG/H<sub>2</sub>O than in H<sub>2</sub>O-based nanofluids, especially in suspensions of smaller nanoparticles [68]. According to the classic Einstein-Bachelor equation for hard non-interacting spheres [83], the percentage viscosity increase should be independent of the viscosity of the base fluid and only proportional to the particle volume concentration. Therefore the experimentally observed variations in viscosity increase upon addition of nanoparticles to different base fluids increase with base fluids can be related to the difference in structure and thickness of immobilized fluid layers around the nanoparticles, affecting the effective volume concentration and ultimately the viscosity of the suspensions [34, 67, 68].

Viscosity increase in nanofluids was shown to depend not only on the type of the base fluid, but also on the pH value (in protonic fluids) that establishes zeta potential (charge at the particle's slipping plane, Fig. 2). Particles of the same charge repel each other minimizing the particle-particle interactions that strongly affect the viscosity [34, 67, 84]. It was demonstrated that the viscosity of the alumina-based nanofluids can be decreased by 31% by only adjusting the pH of the suspension without significantly affecting the thermal conductivity [34]. Depending on the particle concentration and the magnitude of particle-particle interactions (affected by pH, surfactant additives and particle size and shape) dispersion/agglomeration equilibrium establishes in nanoparticle suspension. Extended agglomerates can provide increased thermal conductivity as described in the literature [17, 85], but agglomeration and clustering of nanoparticles result in undesirable viscosity increase and/or settling of suspensions [75].

Introduction of other additives (salts and surfactants) may also affect the zeta potential at the particle surfaces. Non-ionic surfactants provide steric insulation of nanoparticles preventing Van-der-Waals interactions, while ionic surfactants may serve as both electrostatic and steric stabilization. The thermal conductivity of surfactants is significantly lower than water and ethylene glycol. Therefore addition of such additives, while improving viscosity, typically reduces the thermal conductivity of suspension.

It should be mentioned here that all thermo-physical properties have some temperature dependence. The thermal conductivity of fluids may increase or decrease with temperature, however it was shown that the relative enhancement in the thermal conductivity due to addition of nanoparticles remains constant [71, 86]. The viscosity of most fluids strongly depends on the temperature, typically decreasing with increasing temperature. It was noted in couple of nanofluid systems that the relative increase in viscosity is also reduced as temperature rises [67, 68]. The constant thermal conductivity increase and viscosity decrease with temperature makes nanofluids technology very promising for high-temperature application. The density and specific heat of nanomaterials change insignificantly within the practical range of liquid cooling applications. Stability of nanofluids could be improved with temperature increase due to increase in kinetic energy of particles, but heating also may disable the suspension stability provided by electrostatic or/and steric methods, causing the temperature-induced agglomeration [76]. Further studies are needed in this area.

## 5. Efficient nanofluid by design

In light of all the mentioned nanofluid property trends, development of a heat transfer nanofluid requires a complex approach that accounts for changes in all important thermo-physical properties caused by introduction of nanomaterials to the fluid. Understanding the correlations between nanofluid composition and thermo-physical properties is the key for engineering nanofluids with desired properties. The complexity of correlations between nanofluid parameters and properties described in the previous section and schematically presented on Figure 3, indicates that manipulation of the system performance requires prioritizing and identification of critical parameters and properties of nanofluids.

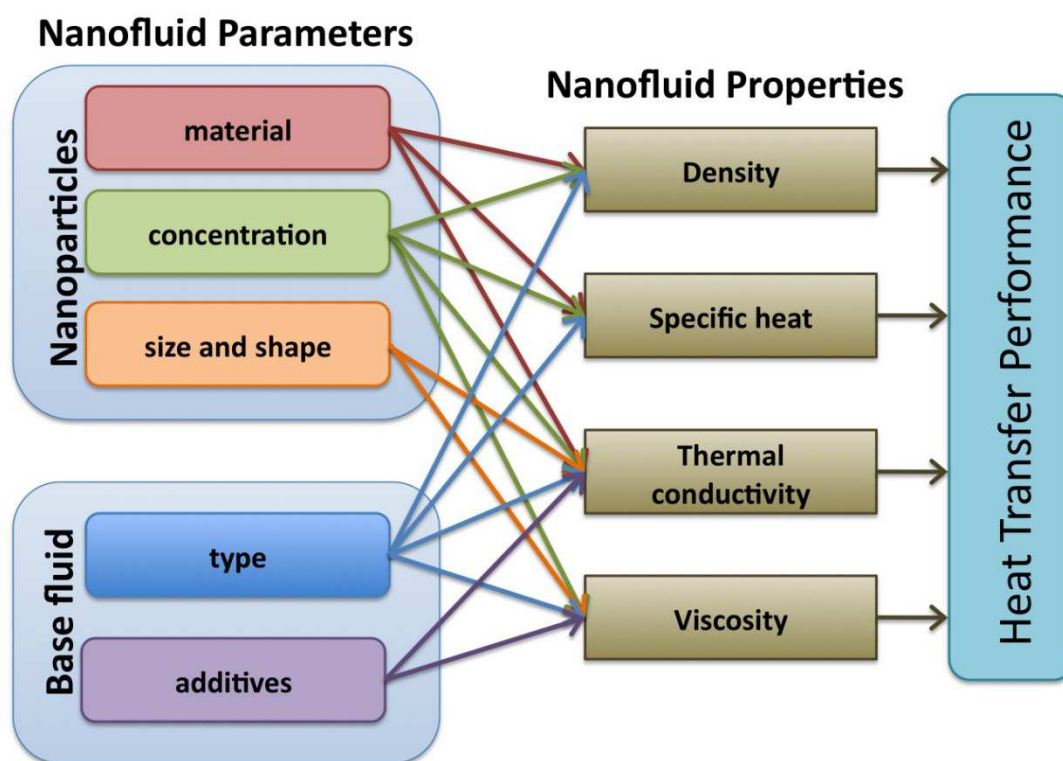


Fig. 3. Complexity and multi-variability of nanoparticle suspensions

Systems engineering is an interdisciplinary field widely used for designing and managing complex engineering projects, where the properties of a system as a whole, may greatly differ from the sum of the parts' properties [87]. Therefore systems engineering can be used to prioritize nanofluid parameters and their contributions to the cooling performance.

The decision matrix is one of the systems engineering approaches, used here as a semi-quantitative technique that allows ranking multi-dimensional nanofluid engineering options [88]. It also offers an alternative way to look at the inner workings of a nanofluid system and allows for design choices addressing the heat transfer demands of a given industrial application. The general trends in nanoparticle suspensions reported in the literature and summarized in previous sections are arranged in a basic decision matrix (Table 1) with each engineering parameter in a separate column and the nanofluid properties listed in rows. Each cell in the table represents the trend and the strength of the contribution of a particular parameter to the nanofluid property.

	NANOFLUID PARAMETERS	Nanoparticle material	Nanoparticle concentration	Nanoparticle shape	Nanoparticle size	Base fluid	Zeta potential/fluid pH	Kapitza resistance	Additives	Temperature
NANOFLUID PROPERTIES										
Stability	↑↑	▲	▲	▲	▣↓	○	▣	x	▣	?
Density	↑↑	▣	▣↑	x	x	▣	x	x	x	x
Specific Heat	↑↑	▣	▣↓	x	x	▣	x	x	x	▲
Thermal Conductivity	↑↑	○	▣↑	○	▣↑	▲	○	▣↓	▲	○
Viscosity	↓↓	▲	▣↓	▣	▣↓	▣↑	▣	x	○	▣
Heat Transfer Coefficient	↑↑	▣	▣↑*	▣	▣↑	▣	▣	▣↓	○	▣
Pumping Power Penalty	↓↓	x	▣	▣	▣↑	▣	▣	x	○	▣
Relative Importance		4.0	6.25	3.75	5.0	5.25	4.0	2.0	2.75	3.75

Table 1. Systems engineering approach to nanofluid design. Symbols: ▣- strong dependence; ○- medium dependence; ▲- weak dependence; x - no dependence; ? - unknown or varies from system to system; ↑↑ - larger the better;↓↓ - smaller the better; ↑- increase with increase in parameter; ↓- decrease with increase in parameter; \*-within the linear property increase

Symbols “x”, “▲”, “○”, and “▣” indicating no, weak, medium, and strong dependence on nanofluid parameter respectively are also scored as 0.0, 0.25, 0.5 and 1.0 for importance [88]. The relative importance of each nanofluid parameter for heat transfer can be estimated as a sum of the gained scores (Table 1). Based on that the nanofluid engineering parameters can be arranged by the decreasing importance for the heat transfer performance: 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 (Table 1) 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 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. Summary

In general nanofluids show many excellent properties promising for heat transfer applications. Despite many interesting phenomena described and understood there are still several important issues that need to be solved for practical application of nanofluids. The winning composition of nanofluids that meets all engineering requirements (high heat transfer coefficients, long-term stability, and low viscosity) has not been formulated yet because of complexity and multivariability of nanofluid systems. The approach to engineering the nanofluids for heat transfer described here includes several steps. First the thermo-physical properties of nanofluids that are important for heat transfer are identified using the fluid dynamics cooling efficiency criteria for single-phase fluids. 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 and analyzed using the system engineering approach that allows identifying the most influential nanofluid parameters. The relative importance of engineering parameters resulted from such analysis suggests the potential nanofluid design options. The nanoparticle concentration, base fluid, and particle size appear to be the most influential parameters for improving the heat transfer efficiency of nanofluid. Besides the generally observed trends in nanofluids, discussed here, nanomaterials with unique properties should be considered to create a dramatically beneficial nanofluid for heat transfer or other application.

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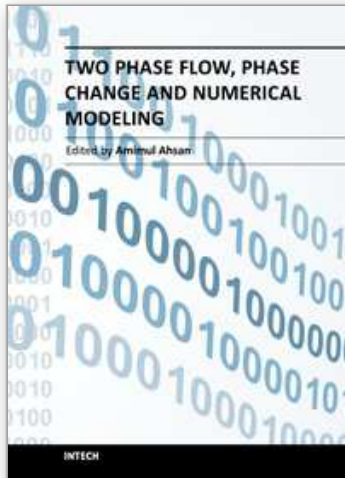
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## **Two Phase Flow, Phase Change and Numerical Modeling**

Edited by Dr. Amimul Ahsan

ISBN 978-953-307-584-6

Hard cover, 584 pages

**Publisher** InTech

**Published online** 26, September, 2011

**Published in print edition** September, 2011

The heat transfer and analysis on laser beam, evaporator coils, shell-and-tube condenser, two phase flow, nanofluids, complex fluids, and on phase change are significant issues in a design of wide range of industrial processes and devices. This book includes 25 advanced and revised contributions, and it covers mainly (1) numerical modeling of heat transfer, (2) two phase flow, (3) nanofluids, and (4) phase change. The first section introduces numerical modeling of heat transfer on particles in binary gas-solid fluidization bed, solidification phenomena, thermal approaches to laser damage, and temperature and velocity distribution. The second section covers density wave instability phenomena, gas and spray-water quenching, spray cooling, wettability effect, liquid film thickness, and thermosyphon loop. The third section includes nanofluids for heat transfer, nanofluids in minichannels, potential and engineering strategies on nanofluids, and heat transfer at nanoscale. The fourth section presents time-dependent melting and deformation processes of phase change material (PCM), thermal energy storage tanks using PCM, phase change in deep CO<sub>2</sub> injector, and thermal storage device of solar hot water system. The advanced idea and information described here will be fruitful for the readers to find a sustainable solution in an industrialized society.

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Elena V. Timofeeva (2011). Nanofluids for Heat Transfer – Potential and Engineering Strategies, Two Phase Flow, Phase Change and Numerical Modeling, Dr. Amimul Ahsan (Ed.), ISBN: 978-953-307-584-6, InTech, Available from: <http://www.intechopen.com/books/two-phase-flow-phase-change-and-numerical-modeling/nanofluids-for-heat-transfer-potential-and-engineering-strategies>

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