

Challenges for nanofluid applications in heat transfer technology

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Abstract. Nanofluid has a potential to become a promising coolant in many diverse industrial processes. However, that opportunity faces several challenges that need to be solved through a long road of nanofluid research programs. Three kinds of the challenges that will be studied in this paper are: 1) determination of nanofluid thermophysical properties, 2) heat transfer characteristics of nanofluid, and 3) the stability factor of nanofluid. This paper also assesses the issue that must be addressed when nanofluid is utilized in nuclear technology applications. The radiation safety aspect of nanofluid utilization in nuclear reactor technology must be taken into account. The comprehensive and multidisciplinary research and assessment are crucial to be carried out in order to ensure the practical applications of nanofluid as new and potential heat transfer fluid.

1. Introduction

The term of 'nanofluid' is firstly proposed by Choi and Eastman in 1995 while presenting the new way to enhance the thermal conductivity of heat transfer fluid (HTF) [1]. In the past, the effort to increase the thermal conductivity of fluid has been done by dispersing the solid particles in millimeter or micrometer-sizes into conventional HTF (water, ethylene glycol, oil, etc.) as base fluids. However, the inclusion of solid particles in millimeter or micrometer sizes brings several problems, such as sedimentation, channel clogging, and abrasion. Then, those problems are solved by reducing the size of suspended solid particles into nanometer sizes, about 1-100 nm, producing nanofluid. The kinds of nanoparticles used are usually metals (Cu, Au), oxide metals (Al_2O_3 , TiO_2 , CuO, Fe_3O_4), and non-metallic element (carbon).

There are two methods of nanofluid preparation namely single-step method and two-step method [2]. The single-step method is also known as bottom-up process since the nanoparticles are created from the atomic or molecular components that grow up in size becoming nanometer-sized particles. In this process, base fluids are prepared simultaneously with the nanoparticles preparation. This kind of method is typically applied in laboratory scale. In the two-step method, nanoparticles are made from a bulk material that is disintegrated into smaller parts (top-down process). At the second step, the resulted nanoparticles are suspended in their base fluid. The typical method used in practical applications is the two-step method due to the easiness factor.

The inclusion of nanoparticles aims to increase the thermal conductivity of nanofluid since the added nanoparticles have higher thermal conductivity than base fluids. Figure 1 shows us that water and other conventional HTF have much lower thermal conductivity than common metallic and non-metallic solid.



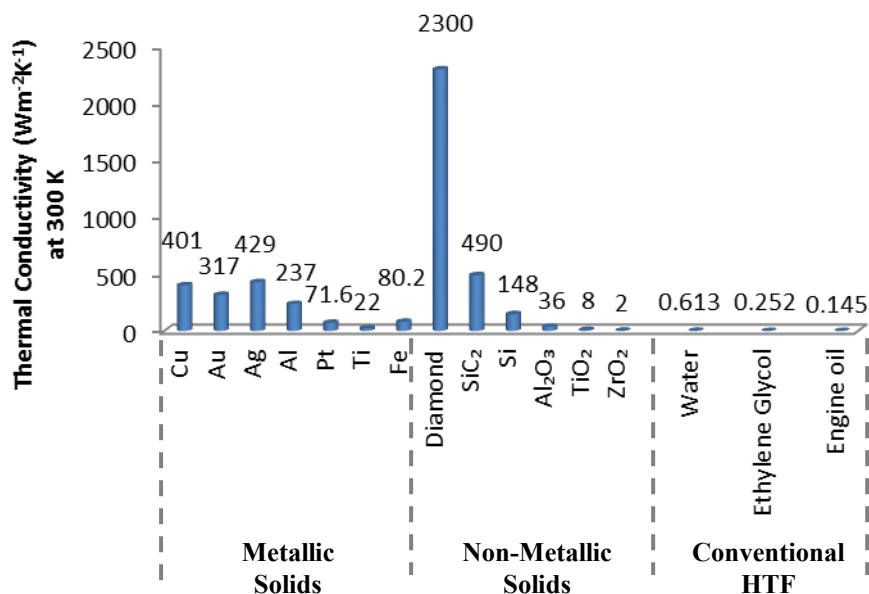


Figure 1. Thermal conductivity values of materials [3]

The higher the thermal conductivity of nanoparticles, the higher the expected heat transfer performance of nanofluid. According to the purpose of nanofluid creation, the major topic that is firstly explored is the thermal conductivity of nanofluid. The existing researches have reached the unified conclusion that thermal conductivity of nanofluid is higher than that of base fluid. The increase of thermal conductivity varies depending on many parameters, such as nanofluid concentration, nanoparticle type, temperature, and nanoparticle shape. The prediction of nanofluid thermal conductivity is performed through the experimental research and theoretical modelling. Due to the increase of thermal conductivity and promising heat transfer performance, nanofluid is potential to be applied in many various fields, e.g.:

- As the coolant in microchips cooling and other electronics
- As the mixture of diesel fuel to increase the total combustion heat and to decrease the pollution of exhaust emission
- As the coolant in the various industrial cooling process
- As the coolant in nuclear reactor technology, as both primary coolant and emergency coolant at the reactor safety features
- As the drug delivery for medical application. The size of nanoparticle makes the delivery to be more effective.

However, the research on nanofluid has given the insight that the application of nanofluid as heat transfer fluid still meets a lot of challenges. The purpose of this paper is to assess several challenges on the application of nanofluid as the alternative coolant, i.e.:

- determination of nanofluid thermophysical properties
- analysis of heat transfer characteristics of nanofluid
- stability factor of nanofluid.

As complement, this paper will also assess the challenge of nanofluid application in nuclear technology.

2. Determination of Nanofluid Thermophysical Properties

Thermophysical properties data are crucial in analyzing the heat transfer performance of nanofluid. Determination of nanofluid properties becomes an important issue because the measurement results of

several properties are dispersed in the wide range. Although there are a number of theoretical models proposed by researchers to predict the values of nanofluid properties, there is no an accurate model that is generally accepted.

Some of the thermophysical properties that have the effects on the heat transfer performance of nanofluid are:

2.1. Thermal conductivity

The results of nanofluid thermal conductivity measurements found in literature have a certain range. A benchmark study was done by Buongiorno et al. [4] proved that the different measurement methods tend to produce the systematic difference in the measurement results. The measurement of the thermal conductivity of nanofluid has been done by researchers using various techniques. The most popular technique used is the transient hot wire (THW) method. Other measurement techniques are temperature oscillation method [5] and cut-bar apparatus method [6].

Researchers also try to predict the thermal conductivity of nanofluid theoretically. The classical models [7], such as Maxwell model, Bruggeman model, Jeffrey model, and Rayleigh model, used for predicting the thermal conductivity of liquid suspension containing mm or μm sized solid particles tend to underpredict the thermal conductivity of nanofluid. Therefore, a lot of new models appear by taking into account several factors that are not accounted in the classical model. Various possible heat transport mechanisms responsible for the thermal conductivity of nanofluid are considered in the new models, such as conduction through nanolayer, nanoparticle Brownian motion, nanoparticle vibration, and thermophoresis mechanism. The summary of classical and theoretical models of nanofluid thermal conductivity can be found in Zhang's book [2]. The proposed theoretical models combine the static models and the dynamic models. The static model likes classical model, assumes that nanoparticles and base fluid molecules are in static positions. Oppositely, the dynamic models consider the effects of nanoparticles movement due to Brownian motion to the thermal conductivity of nanofluid. However, a general model for predicting nanofluid thermal conductivity has not been available yet. It means that the real heat transport mechanisms prevail in the nanofluid system that contribute to the thermal conductivity of nanofluid are still not known clearly.

2.2. Viscosity

The number of theoretical models for predicting nanofluid viscosity is not as much as that for predicting nanofluid thermal conductivity. The conventional models are usually used to predict the dynamic viscosity of nanofluid, such as Einstein equation [8], Brinkman equation [9], and Batchelor equation [9]. The empirical correlations come from the measurement activities are also not found much.

Viscosity is the important factor in considering the reliability of nanofluid in practical applications. The inclusion of nanoparticles must increase the viscosity of nanofluid compared to that of base fluid. Hence, it will bring the impact to the pumping power increment. The benefits of nanofluid as heat transfer fluid are determined based on the consideration between the increase of heat transfer performance and the increase of pumping power. The properties comparative method [10] showed that viscosity has the important role in natural convective heat transfer. It becomes a factor that is responsible for the decrease of natural convective heat transfer of nanofluids.

2.3. Density

Density (ρ) of nanofluid is typically determined using the mixture rule as below:

$$\rho_{eff} = (1 - \phi)\rho_f + \phi\rho_p \quad (1)$$

The subscripts of p and f represent nanoparticle and base fluid, respectively.

2.4. Specific heat

Specific heat (c_p) of nanofluid could be determined using mixing rule (Eq. (2)) and thermal equilibrium principle (Eq. (3)).

$$c_{p,eff} = (1-\phi)c_{p,f} + \phi c_{p,p} \quad (2)$$

$$\rho_{eff} c_{p,eff} = (1-\phi)\rho_f c_{p,f} + \phi \rho_p c_{p,p} \quad (3)$$

2.5. Expansion thermal coefficient

Similar to specific heat, expansion thermal coefficient (β) of nanofluid is determined either using Eq. (4) and Eq. (5).

$$\beta_{eff} = (1-\phi)\beta_f + \phi\beta_p \quad (4)$$

$$\rho_{eff} \beta_{eff} = (1-\phi)\rho_f \beta_f + \phi \rho_p \beta_p \quad (5)$$

The determination of nanofluid properties needs to be explored further, especially through experimental measurements. The measurement data obtained are important to build and validate the accurate theoretical models.

3. Heat Transfer Characteristics of Nanofluid

Research on heat transfer using nanofluid aims to compare the heat transfer performance of nanofluid and that of base fluid. Unfortunately, researchers gave the different results, primarily in natural convective heat transfer. Putra et al. [11] conducted an experiment of natural convective heat transfer using Al_2O_3 -water nanofluid and CuO-water nanofluid in a horizontal tube. The result showed that the heat transfer performances of both nanofluids are lower than those of water. The numerical researches performed by Khanafer et al. [12] and Mahmoudi et al. [13] give the contradictive results. Several researches performed numerically [14], theoretically [15], and experimentally [16] showed the existence of nanoparticles optimum concentration. At that optimum concentration, the heat transfer performance of nanofluid changes from higher than the heat transfer performance of base fluid to lower than that of base fluid. The viscosity is assumed to be the most important factor that is responsible for the degradation of the nanofluid heat transfer.

In forced convective heat transfer using nanofluids, generally the results showed the increase of heat transfer performance. The increase of heat transfer performance varies depending on many factors. One of the contributing factors for the increase of nanofluid heat transfer is the thermal conductivity of nanofluid. Further research is needed to assess other influential factors of heat transfer performance of nanofluid. The characteristics of mixed convective heat transfer of nanofluid are also need to be studied further due to its complexity. Both the experimental and numerical studies of mixed convective heat transfer using nanofluid are still rarely found.

The heat transfer performance of nanofluid compared to that of base fluid could be qualitatively predicted using the properties comparative method. In the previous paper [10], we have shown that the natural convective heat transfer of Al_2O_3 -water nanofluid and ZrO_2 -water nanofluid tend to be lower than that of water. In this paper, we will use the properties comparative method to analyze the forced convective heat transfer of nanofluid. The ratio between the heat transfer coefficient (h) of nanofluid to that of water in forced convection mode based on their thermophysical properties, is given by Eq. (6) and (7).

$$Nu = \frac{hd}{k} = Re^m Pr^n \quad (6)$$

$$\frac{h_{eff}}{h_f} \approx \left(\frac{k_{eff}}{k_f} \right)^{1-n} \left(\frac{\rho_{eff}}{\rho_f} \right)^m \left(\frac{c_{p,eff}}{c_{p,f}} \right)^n \left(\frac{\mu_{eff}}{\mu_f} \right)^{n-m} \quad (7)$$

where Nu is Nusselt number, Re is Reynolds number, Pr is Prandtl number, k is thermal conductivity, d is diameter or characteristic length, and μ is dynamic viscosity. The typical values of m (0.5 or 0.8) are higher than those of n (0.3). Hence, the contributions of properties effects within Eq. (7) in consecutively decreasing order are k , ρ , c_p , and μ . The enhancement of the forced convective heat transfer coefficient of nanofluid is proportional to the increase of thermal conductivity, density, and specific heat. The forced convective heat transfer coefficient of nanofluid is deteriorated by the enhancement of dynamic viscosity. It is clear that for types of nanofluids which have low increase of viscosity compared to water, their forced convective heat transfer performances should be higher than those of water.

Here, we can see that the valid values of nanofluid thermal properties are important in analyzing the heat transfer performance of nanofluids accurately. In addition, more experimental researches are needed to reach the conclusive results.

4. Stability Factor

The ability of nanoparticles to agglomerate is a critical problem faced in the practical application of nanofluid. The agglomeration brings the effects to the properties of nanofluid and hence impacts on the heat transfer performance of nanofluid. The agglomerates formed could have various sizes and configurations depending on many factors, primarily elapsed time. Koblinski [17] showed that the nanoparticles configuration in an agglomerate affects the thermal conductivity of nanofluid. The different time duration between nanofluid preparation and the experimental study as well as the different time duration of experimental study performed also determine the agglomerates characteristics. The number, size, and configuration of agglomerates can change every time. That is why it becomes to be difficult to control the agglomeration effects to the thermal conductivity of nanofluid.

Different nanofluid preparations, such as dispersion method, the time duration for ultrasonic vibration process, etc. affect the stability level of nanofluid. Fedele et al. [18] showed that the selection of dispersant type and dispersion technique could improve the nanofluid stability. In their study, the high-pressure homogenization was found to be the best method of dispersion technique. They also found that the *n*-dodecyl sulphate and polyethylene glycol are the best dispersants to improve the stability of SWCNHs-water and TiO_2 -water nanofluids. Other ways to increase the stability of nanofluid are the using of surfactant and the arrangement of nanofluid acidity. However, the stability that is reached in low pH condition makes nanofluid to be difficult to be applied in many application systems.

Finally, it can be analyzed that the dispersed measurement data of nanofluid properties, especially thermal conductivity and viscosity, may be caused by the unknown number, sizes, and configurations of formed nanoparticles agglomerates.

5. Nuclear Application Aspect

The application of nanofluid in nuclear reactor system must be assessed from the safety aspect, especially radiation safety aspect. Nanoparticles could be activated by neutrons through neutron capture reaction producing the nucleus at the excited states. The unstable activation products reach their stable states by emitting gamma rays, beta particles, alpha particles, fission products or neutrons (in nuclear fission). The higher the energy of emission, the more hazardous the impact received. Another considerable aspect is the amount of neutron population in the reactor core. Every type of nanoparticle has certain neutron absorption cross sections. The type of nanoparticle used should have low neutron absorption cross section to maintain the population number of neutron in the core. However, the existence of nanoparticles in the reactor core is prohibited if it increases the criticality

value (neutron multiplication number) deviating from the limiting operational condition. The increase of criticality can cause the uncontrolled thermal power increase. Several kinds of metallic substances that have low neutron absorption cross section are Al, Mg, Zr, Si, and Bi [19]. Those substances can be considered to be used as nanoparticles.

Finally, it is clearly seen that the development of nanofluid application in many fields needs a comprehensive research program that covers the basic research and the applied research. The nanofluid research is a multidisciplinary research that collaborates various fields of sciences, such as chemistry, physics, engineering, and mathematics. One of the main topics of basic research needed is research on molecular physics to investigate the real mechanisms of momentum and energy transport within the nanofluid system from a molecular point of view. Based on that knowledge, we can know all factors which affect the nanofluid thermophysical properties and hence we can develop ways to improve the heat transfer performance of nanofluid. There are also a lot of applied research topics needed to be explored, for example, the heat transfer characteristics of nanofluid, the increase of pressure drop, the feasibility of nanofluid applications in various technical equipments, etc.

6. Conclusion

The limitation of knowledge and scientific literature on nanofluid hydrodynamics and thermal characteristics brings several challenges in nanofluid applications. More comprehensive studies and multidisciplinary research are absolutely needed to perform for solving those challenges. A lot of research topics related to nanofluid have existed to be implemented in the future. The research should combine and collaborate the experimental research, the numerical research, and the theoretical research.

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