International Journal of Thermal Sciences 100 (2016) 75–97

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Review

Single-phase and two-phase treatments of convective heat transfer enhancement with nanofluids – A state-of-the-art review

Sadık Kakaç [a, *], Anchasa Pramuanjaroenkij [b]

[a] TOBB University of Economics and Technology, Ankara, Turkey
[b] Faculty of Science and Engineering, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus, Thailand

ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form
21 September 2015
Accepted 21 September 2015
Available online 11 November 2015

Keywords:
Nanofluids
Effective thermal conductivity
Heat transfer enhancement

ABSTRACT

Nanofluids have shown their advantages and potentials in improving heat transfer rates when the nanofluids are applied as working fluids in thermal systems. Researcher groups concentrating on the nanofluids have increased continuously and focused deeply into various fields; theoretically, experimentally and numerically. This review summarized the important published works on nanofluid preparations, properties, experimental and numerical heat transfer behaviors. In the simulations, two main categories were discussed in detail as the single-phase modeling which the combination of nanoparticle and base fluid is considered as a single-phase mixture with steady properties and the two-phase modeling which the nanoparticle properties and behaviors are considered separately from the base fluid properties and behaviors.

1. Introduction

Enhancing heat transfer rates by utilizing nanofluids has drawn significant attentions from researchers around the world because of heat transfer enhancements caused nanofluids which are different from heat transfer coefficients of base fluids. Nanofluids combine nanoparticles and base fluids which are applied as working fluids in several technologies such as coolants in electronic devices, automotives, power generators and refrigerations. Typical solid nanoparticles, diameter scales of 1–100 nm with high thermal conductivities, are suspended in the base fluids which have low thermal conductivities. The nanofluids have shown that they can enhance effective thermal conductivities and the convective heat transfer coefficients of the original base fluid [1]. The thermal conductivities of the particles; metallic or nonmetallic materials such as Al_2O_3, Ag, CuO, Cu, SiO_2 and TiO_2, are particularly higher than the base fluids even at low concentrations, resulting in significant enhancements in the heat transfer coefficients [1,2]. Nanofluid selection is based on nanofluid properties, sizes, shapes, volume fractions and stabilities of the nanoparticles, as well as, thermophysical properties of nanofluids which play important roles on the heat transfer performances. Generally in nanofluid convective heat transfer modeling, the nanofluid simulations can be considered into two catagories; the single-phase modeling which the combination of nanoparticle and base fluid is considered as a single-phase mixture with steady properties (mixed properties between the nanoparticle and base fluid properties) and the two-phase modeling which the nanoparticle properties and behaviors are considered separately from the base fluid properties and behaviors. These two types of the nanofluid simulations were discussed in detail later in this review.

Sundar and Singh [3] and Li et al. [4] informed that the nanofluid preparation is very important task with the use of nanoparticles to improve the thermal conductivity of base fluids. Two methods were used for producing the nanofluids, (i) single-step method (ii) two-step method. In the single-step method was a process combining the preparation of nanoparticles with the synthesis of nanofluids for which the nanoparticles were directly prepared by physical vapor deposition (PVD) technique or liquid chemical method. In the two-step method, the nanoparticle-preparation step was separated from the nanoparticle-dispersing step. They claimed that the disadvantage of this method was that only low vapor pressure fluids were compatible with the process. They also summarized three interesting works as; preparing copper nanofluids by Zhu et al. [5], Liu et al. [6] and Eastman et al. [7].

* Corresponding author.
E-mail address: sadikkakac@yahoo.com (S. Kakaç).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.09.021
1290-0729/

1.1. Nanofluid density

Wen and Ding [8] introduced the nanofluid density based on nanofluid volume fraction which can be obtained from

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

Sommers and Yerkes [9] measured the density of the Al_2O_3/propanol nanofluid at room temperature and found that the comparison of measured and calculated densities with the use of mixing theory indicated that the differences between them increase with increase in concentration of particles, less than 5% when the weight concentration is up to 5%. Chandrasekar et al. [10] compared Sommers and Yerkes [9] with the mixing theory as shown in Fig. 1.

1.2. Nanofluid specific heat

Pak and Cho [11] and Xuan and Roetzel [12] demonstrated two expressions which were commonly used to determine the specific heat of nanofluids based also on nanofluid volume fraction, ϕ, as

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

$$(\rho c_p)_{nf} = \phi(\rho c_p)_p + (1-\phi)(\rho c_p)_f. \quad (3)$$

Elias et al. [13] concluded in their experimental study that nanofluid specific heat was found to be decreased with the increase of nanoparticle volume concentrations and, by increasing the temperature, the specific heat was observed to be intensified.

2. Nanofluid viscosity

Nanofluid viscosity is one of the important thermophysical parameter for practical applications since it directly affects the pressure drop in forced convection. Generally, increasing the viscosity by adding nanoparticles to base fluids is significant, as the viscosity also depends on particle volume fractions, particle sizes, temperatures, and extents of clustering [14]. Most works reported in the literature are more experimental investigations rather than the numerical investigations.

2.1. Experimental investigation of nanofluid viscosity

Kakaç and Pramuanjaroenkij [1,15] and Sundar et al. [16] summarized empirical viscosity correlations in their review works, where the viscosity correlations were proposed and discussed for different nanoparticles and base fluids. Chandrasekar et al. [10] tabled the experimental relative viscosity of nanofluids as in Table 1 which showed differences between base fluid viscosity and nanofluid viscosity [10,16].

The nanofluid viscosities were observed by several research groups in their experimental investigations. Elias et al. [13] presented new findings on viscosity of Al_2O_3 nanoparticles, 0–1 vol.%, dispersed into water and ethylene glycol based coolant used in car radiator. They prepared nanofluids by using the two-step method. They found that thermal conductivity, viscosity, and density of the nanofluid increased with the increase of volume concentrations, diversely, and with the decrease of the temperature. For the information, if a base fluid is assumed as a Newtonian fluid, the nanofluid with less than 10% volume fraction with water as the base fluid can also be assumed as the Newtonian fluid. In nanofluid application and observation, nanofluid volume fraction is usually less than 10% volume fraction.

Hachey et al. [32] experimentally investigated two surfactant-free nanofluid species, 10 nm γ-Al_2O_3/water and γ-Al_2O_3/ethylene glycol with 1.0, 2.5 and 5.0% particle volume fractions. They found some unexpected results, in some cases, some samples presented exceedingly high dynamic viscosity.

Sundar et al. [33] prepared a magnetic Ni/water nanofluid and experimentally determined thermal conductivity and absolute viscosity of the nanofluid as a function of particle concentration and temperature; they found that an absolute viscosity of Ni nanofluid increased with increase of particle concentrations and decreased with temperature.

Halelfadl et al. [34,35] reported the shear-thinning behavior of nanofluids, the multi-walled carbon nanotubes/water nanofluid viscosity depended on the base fluid type in the Newtonian region; where the relationship between fluid shear rate and fluid shear stress is linear, and the relative viscosity of the stabilized carbon nanotubes nanofluids was affected by both the increase in nanoparticle volume fractions and shear rates.

Saleh et al. [36] measured titanium dioxide nanofluids viscosity and indicated that the relative viscosity increased with increasing nanoparticle volume fraction. However, they concluded that in this case, the nanofluid viscosity was independent of temperature.

Manikandan et al. [37] reported the viscosity of sand–propylene nanofluids decreased with nanoparticle concentration (0–2 vol.%) and temperature (29–140 °C). They suggested that, in the well-dispersed nanofluids, interactions between nanoparticles and propylene glycol through nanoparticles surface led to disturbance of hydrogen bonding network of propylene glycol, this was manifested as reduction in viscosity of dispersion in comparison to pure propylene glycol.

Singh et al. [38] dispersed Cu in two commercial solar heat transfer fluids (TH59 and TH66). They measured dynamic viscosity and perceived that if a good dispersion of nanoparticles was achieved, the composite fluids behaved in a Newtonian manner and the dynamic viscosities increased over the base fluid were minor at temperatures 125 °C and above.

Einstein [39] and Drew and Passman [40] presented the dynamic viscosity expression for dilute suspensions that contain spherical particles with neglecting particles interactions, the well-known Einstein's formula,

$$\mu_{nf} = (1+2.5\phi)\mu_f \quad (4)$$

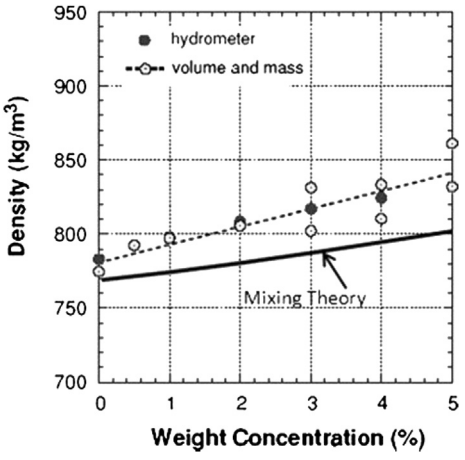

Fig. 1. Density comparison of the numerical results with experimental data of Sommers and Yerkes [9].