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# Challenges in hybrid nanofluids behavior in turbulent flow: Recent research and numerical comparison

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ABSTRACT

Numerical and experimental researches on nanofluids have increased rapidly over the last few years. In spite of some inconsistent reports—mainly due to the deficient understanding of the involved mechanisms—nanofluids have developed as a favorable heat transfer fluid. Recently, hybrid nanofluids were defined as a new class of nanofluids with possible applications in almost all the fields of heat transfer. This is mainly because of the synergistic effect through which they provide promising properties of all of its constituents. The augmented thermal conductivity of nanofluids over the basic heat transfer fluids (e.g. water) is considered one of the driving factors for enhanced performance in heat transfer. Nevertheless, most of the studies are discussing the thermal conductivity and only few are about viscosity variation, while other properties are neglected.

The idea of using hybrid nanofluids is to further improve the heat transfer characteristics of individual nanofluids and to beneficially combine different properties from oxides, carbon nanotubes, metals, composites etc. This review summarizes most of the recent research on the preparation, thermophysical properties, correlations and heat transfer characteristics of hybrid nanofluids and compares some fully and partially described hybrids.

Review showed that proper characterization may make hybrid nanofluids a very promising new heat transfer fluid. However, a lot of research work is still needed in the field of preparation and stability, characterization, and applications to overcome the barriers in implementing these new fluids in real-life applications.

## 1. Introduction

Choi [1] defined nanofluids as engineered colloids made up of a base fluid and different nanoparticles. These nanoparticles exhibit thermal conductivities higher than those of the base fluids and have sizes smaller than 100 nm. The introduction of nanoparticles significantly improves the heat transfer performance of regular, common heat transfer fluids. These fluids may be water, organic liquids (e.g., ethylene, triethylene-glycols, refrigerants, etc.), oils, biofluids, polymeric solutions, as well as other liquids. Nanoparticle materials include metals (e.g., gold, copper), metal oxides (e.g., alumina, silica, zirconia, titania), oxide ceramics (e.g. $Al_2O_3$, CuO), metal carbides (e.g., SiC), metal nitrides (e.g., AIN, SiN), carbon in various forms (e.g., graphite, carbon nanotubes) [2] and most of the studies are concentrated on water and ethylene glycol-based nanofluids [3–16]. Further, a few recent reviews on nanofluids and their applications [25] will be discussed in terms of the latest findings.

Hussein et al. [17] reviewed some nanofluids computational simulations and found that most of the numerical results are in agreement with identified experimental work. They emphasized that the reported heat transfer coefficient augmentation is dependent on the increase in the solid nanoparticles concentration. Also, research with a smaller particle size showed an increase in heat transfer enhancement when compared to larger size nanoparticles.

Another review of published literature [18] summarized some of the experimental, numerical, and analytical studies on nanofluids. One of the main conclusions of this review is that more research is needed for nanofluids heat transfer and fluid flow behavior in curved tubes.

An interesting discussion on numerical techniques was performed by Vanaki et al. [19]. Their intention was to give a comprehensive review on different numerical approaches employed in nanofluid flow simulation, to report the advantages and disadvantages of each approach, and to find a suitable technique which gives more credible results as compared to experimental results. So, they adopted the single-phase model for numerical implementation and their conclusion is that the single-phase model can give similar results to the two-phase model.

A quick reference guide on nanofluid behavior on heat transfer—considering conduction, convection, and radiation—was accomplished by Lomascolo et al. [20]. Their overall finding was that research in this

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## Nomenclature

| | |
|---|---|
| c | specific heat |
| D | hydraulic diameter |
| G | generation of turbulent kinetic energy due to mean velocity gradients |
| h | heat transfer coefficient |
| k | thermal conductivity |
| L | channel length |
| Nu | Nusselt number |
| $\overline{P}$ | time averaged flow variable |
| Pr | Prandtl number |
| q | wall heat flux |
| r | ray |
| R | ray, R=D/2 |
| Re | Reynolds number |
| T | temperature |
| $\overline{t'}$ | fluctuations in temperature |
| $\overline{T}$ | time averaged temperature |
| $\overline{u'}$ | fluctuations in velocity |
| v | axial velocity |
| $\overline{v}$ | time averaged velocity |
| V | volume fraction of nanocomponent |

*Greek symbols*

| | |
|---|---|
| ε | rate of dissipation |
| φ | volume fraction of particles |
| κ | turbulent kinetic energy |
| ρ | density |
| σ | effective Prandtl numbers |
| μ | fluid dynamic viscosity |

*Subscripts*

| | |
|---|---|
| bf | refers to base-fluid |
| n | refers to nanoparticle |
| nano | refers to nanocomposite |
| nf | refers to nanofluid property |
| m | refers to a mean value |
| mexit | refers to a mean value on exit |
| r | refers to “nanofluid/base-fluid” ratio |
| w | wall |
| ε | refers to rate of dissipation |
| κ | refers to turbulent kinetic energy |

field is relatively new and the results are unsatisfying at this moment, even though it has been given considerable focus.

Devendiran and Amirthan [21] reviewed the preparation of metal and metal oxide nanofluids and hybrid nanofluids as well as various techniques used to study the physical and chemical characteristics of nanofluids. The nanofluids thermophysical and heat transfer properties along with specific heat models for nanofluids, were overviewed. Finally, various areas of application of nanofluids, such as transportation, electronic cooling, energy storage, and mechanical applications, etc., are discussed.

Raja et al. [22] published a recent review that considers different parameters that govern nanofluid characteristics, heat transfer performance, and their applications. The intention of Raja's review was to provide an overview of the most recent studies on nanofluid found in the literature and can be seen as a useful update of current state of the art of nanofluids. The conclusion is that convective heat transfer behavior of nanofluids is superior to conventional fluids. Both numerical and experimental studies reveal and identify nanofluids as a new possible coolant that will reduce the heat exchanger overall size, improving also the heat transfer. Plus, it was shown that very few scientists found two-phase models to give better results than the single-phase model, when numerical studies are involved.

A review by Muhammad et al. [23] outlines the importance and benefits of implementing nanofluids in solar collectors. In order to do this, there is a need to restructure the design of solar collectors so as to achieve practical utilization for both domestic and industrial water heating systems.

Another review [24] discusses the literature on the enhancements in thermophysical and rheological properties resulting from experimental works conducted on molten salt nanofluids used in solar thermal energy systems and reveals their importance.

A review by Bigdeli et al. [25] presents several theoretical and empirical models describing nanofluid thermophysical properties. Specifically, a strong sensitivity of nanofluid properties to their design

**Table 1**
A review on few hybrid nanofluids method of preparation and main findings.

| Authors | Hybrid nanofluid type | Method of preparation | Main findings |
|---|---|---|---|
| Han and Rhi [37] | Ag-$Al_2O_3$/water | two mixed nanofluids | hybrid nanofluids were not effective in comparison with the nanofluids with Ag or alumina |
| Suresh et al. [38] | $Al_2O_3$–Cu/water | hybrid nanocomposite | enhancement of 13.56% in Nusselt number at Re=1730 |
| Madhesh and Kalaiselvam [39] | Cu-$TiO_2$/water | hybrid nanocomposite | the convective heat transfer coefficient increases with 52% and the overall heat transfer coefficient has a 68% enhancement |
| Jana et al. [41] | CNT-Au/water CNT-Cu/water | Au added to CNT water based nanofluid | for both studied hybrid nanofluids, the claimed synergistic effect of the hybrid nanofluid did not appear to create a higher thermal conductivity [41] |
| Abbasi et al. [42] | γ-$Al_2O_3$ – MWNT/water | hybrid nanocomposite | maximum 14.75% enhancement in thermal conductivity |
| Munkhbayar et al. [43] | Ag - MWNT/water | hybrid nanocomposite | 14.5% higher thermal conductivity for the hybrid in comparison with the nanofluid containing only MWNTs. |
| Nine et al. [44] | Cu/$Cu_2O$ – water | hybrid nanocomposite | thermal conductivity for non-ground MWCNTs is higher than that of the nanofluid with ground MWCNTs |
| Chen et al. [45] | MWCNT – $Fe_2O_3$/water | two kinds of particles mixed in water | 28% enhancement for thermal conductivity of hybrid nanofluid |
| Sundar et al. [46] | MWCNT–$Fe_3O_4$/water | hybrid nanocomposite | enhancement in Nusselt number of maximum 31.10% at Re=22,000 |
| Baby and Ramaprabhu [47] | $Fe_3O_4$+$SiO_2$ – MWNT/water | hybrid nanocomposite | thermal conductivity is increasing by 24.5% for nanofluids with 0.03% volume fraction |
| Nimmagadda and Venkatasubbaiah [48] | $Al_2O_3$+Ag/Water | two kinds of particles mixed in water | the hybrid nanofluid had the heat transfer coefficient enhanced by maximum 148% in comparison with the base fluid. |
| Esfe et al. [49] | Ag+MgO/water | hybrid nanocomposite | thermal conductivity and viscosity of the hybrid nanofluid increases by adding nanocomposites particles in the base fluid |

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