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An Overview of Numerical Investigation of Nanofluids for Enhancement of Heat Transfer in Circular Tubes

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ABSTRACT: Nanofluids tremendously enhances the heat transfer characteristics of the original fluid. It is ideally suited for practical applications due to its marvelous characteristics. The present study not only addresses the unique features of nanofluids but also summarizes the recent research in experimental and theoretical studies on forced and free convective heat transfer in nanofluids. In addition, it numerically investigates the developing laminar forced convection flow of a water – Al_2O_3 nanofluid in a circular tube, submitted to a constant and uniform heat flux at the wall. Discrete particles model is employed with either constant or temperature-dependent properties. Moreover, a comparison with data present in the literature is carried out.

Key words: Nanofluids, Discrete particles model, Convective heat transfer, Thermal conductivity.

I. INTRODUCTION

Ever since the adverse effect of greenhouse gases was discovered, leading to the Kyoto Protocol [1], the search for methods and technological advancement to mitigate the impact of global warming on Planet Earth became a pressing need for the research and industrial communities. The Protocol had exhorted both the developed and developing countries to show intense curiosity with a sense of participation, to find definitive ways to tackle the issue. Subsequent meetings which were held in many countries had called for a gentle decline in the production of greenhouse gases. Even as scientists subscribed to a number of methods to tackle the carbon footprints, the global energy need and inefficient thermal-fluid systems always increased the greenhouse gases.

Convective heat transfer is very important for many industrial heating or cooling equipment. The heat convection can passively be enhanced by changing flow geometry, boundary conditions or by enhancing fluid thermophysical properties. An innovative way of improving the thermal conductivities of fluids is to suspend small solid particles in the fluid. Maxwell [2,3] showed the possibility of increasing thermal conductivity of a mixture by more volume fraction of solid particles. These fluids containing colloidal suspended nanoparticles have been called nanofluids. Several investigations revealed that nanofluid heat transfer coefficient could be increased by more than 20% also in the case of very lownanoparticles concentrations [4,5].

Nowadays there is a fast growth of research activities in this heat transfer area [6-10], because the impact of nanofluid technology is expected to be relevant considering that heat transfer performance of heat exchangers or cooling devices is fundamental in many industries [11]. Recently an industrial application was presented by Kulkarni et al. [12], that proposed aluminum oxide nanofluids as jacket water coolant in a diesel engine for electric generation, showing that the efficiency of waste heat recovery heat exchanger increased due to nanofluid, because of its superior convective heat transfer coefficient. Moreover, Nnanna *et al.* [13] developed a nanofluid heat exchanger for electronic cooling devices. They showed how the system performance improved with respect to conventional equipment. A reduction in energy consumption is possible by enhancing the performance of heat exchange systems. Heat transfer is one of the most important processes in industrial and consumer products and it is worth addressing its influence over carbon footprints. For instance, the present telecommunication demand for enhanced functionality in circuit boards, results in high process density circuit boards.

In such cases, the company spends more than 50% of the total electricity on the thermal management of electronic cooling systems [14]. Further, one of the most influential regulations is the 65 Dba noise limit in a central office environment compared to the 85 Dba in data centers and thus, typical air-cooling methods are unsuitable for these conditions [15]. The dozens of methods such as Fin-Foam Heat Sink, Minichannels, Microchannels, Novel interface materials, Dielectric mist cooling, Forced convective boiling, etc. and their combinations are limited to heat removal of up to 1000 W/cm^2. Some of the electronic systems like ultra-high heat flux optical devices, high-powered X-rays and lasers demand as high as 2000 W/cm^2 of heat removal [16]. Similarly, the growth of Heating Ventilation and Air-Conditioning (HVAC) and chemical processing equipment had adversely increased the carbon footprints. The paradigm shift in their design with respect to heat transfer will both simultaneously reduce the size of the heat exchangers and the energy consumption. In many industrial applications, the conventional heat transfer fluids are refrigerants, water, engine oil, ethylene glycol, etc. Even though an improvement in energy efficiency is possible from the topological and configuration points of view, much more is needed from the perspective of the heat transfer fluid. Further, enhancement in heat transfer is always in demand, as the operational speed of these devices depends on the cooling rate. New technology and advanced fluids with greater potential to improve the flow and thermal characteristics are two options to enhance the heat transfer rate and the present article deals with the latter option. One such latest advancement in heat transfer fluids, is an engineered colloidal mixture of the base fluids and nano-sized metallic particles (1–100 nm). The earlier versions of colloidal fluids such as micro-fluid substances tend to sediment and cause erosion in the moving component. However, nanofluids are claimed to be a non-agglomerated mono-dispersed particles in the base fluids, which proved to be enhancing the heat transfer more than 50% in real time applications even when the volume ratio of the nanoparticle to base fluid is less than 0.3% [17]. As the need for more efficient heat transfer systems increases, researchers have introduced various heat transfer enhancement techniques since the middle of the 1950s. The exponential increase in the number of research articles dedicated to this subject thus far shows a noticeable growth and the importance of heat transfer enhancement technology. Some recent review articles [18–22] have covered a variety of methods for the enhancement of heat transfer. Investigation in convective heat transfer characteristics has been carried out in recent times.

In this study, the various articles related to the mechanism of nanofluid heat transfer, thermo-physical properties and pioneering experiments related to convective and boiling heat transfer of nanofluids are discussed. This article presents the recent research in natural, forced and two-phase convective heat transfer in nanofluids and its applications, and identifies the challenges and opportunities for future research.

II. NANOFLUIDS

This motivated to reduce the size of the material to nano scale, since the small particles have large surface to volume ratio that favors the transport of thermal energy more efficiently. Because of the high thermal conductivity of a solid, a solid reduced to nano scale and then dispersed into the fluid is engineered. Nano fluids are smart fluids based on nano technology in which nano sized material (1nm-100nm) is dispersed into the base fluid. This novel concept was developed in Argonne National Laboratory, (U.S.A) by Dr. Choi. Nano fluid is next generation heat transfer fluid. Properties of fluids changes due to nano particles present in fluids:

i. Nano particles have high surface tovolume ratio.
ii. Better suspension inside the fluid.
iii. Aggregation of nano particle isavoided.
iv. No blocking of the pipe
v. Pressure drop of fluid is less
vi. No erosion of conduits.
vii. Nano particles have 20% of atoms near the surface, allowing them to absorb and transfer heat efficiently

Nano particles used are – Al_2O_3, CuO_2, Ag,Au, SiC, single walled carbon nano tube, multi walled carbon nano tube etc.

Base fluid used are –water, ethyleneglycol, tri-ethylene glycol, oils etc.

III. ENHANCEMENT OF THERMAL CONDUCTIVITY

A substantial increase in liquid thermal conductivity, liquid viscosity, and heat transfer coefficient, are the unique features of nanofluids. It is well known that at room temperature, metals in solid phase have higher thermal conductivities than those of fluids [23]. For example, the thermal conductivity of copper at room temperature is about 700 times greater than that of water and about 3000 times greater than that of engine oil. The thermal conductivity of metallic liquids is much greater than that of nonmetallic liquids. Thus, fluids containing suspended metal particles are expected to manifest enhanced thermal conductivities relative to pure fluids [24]. Masuda et al. [25] dispersed oxide nanoparticles (g-Al with φ = 4.3%) particles in liquid and showed the increase in the thermal conductivity to be 32 and 11%, respectively.

Grimm [26] dispersed aluminum particles (g = 80–1 mm) into a fluid and claimed a 100% increase in the thermal conductivity of the fluid for φ = 0.5–10%. Choi and Eastman [27] showed that the thermal conductivity of Cu–water and CNT– water nanofluids was higher compared to that of their base liquids. Eastmann *et al.* [28] showed that Cu–ethylene glycol (nanoparticles coated with thioglycolicacid) with φ = 0.3% gave a 40%increase in thermal conductivity. Recently, an attempt at the IndiraGandhi Centre for Atomic Research (IGCAR) was made, to align magnetic nanoparticles (Fe_3O_4 coated with Oelic acid) in a basefluid (hexadecane) in a linear chain using a magnetic field, whichwas applied to increase the thermal conductivity by 300% [29]. Further, it was proved that the thermal properties are tunable formagnetically polarizable nanofluids that consist of a colloidalsuspension of magnetite nanoparticles. Moreover, the effective thermal conductivity depends also on other mechanisms of particle motion; the commonly explained physics are as follows.

IV. EXPERIMENTAL INVESTIGATION

Enhancement in heat transfer was tried earlier also, with the help of suspended micro-particles. Ahuja [30,31] conducted experiments on the enhancement of heat transport in the laminar flow of water with micro-sized polystyrene suspension. The results showed a significant enhancement in the Nusselt number and heat exchanger effectiveness compared to that of a single phase liquid. Hetsroni and Rozenblit [32] investigated the thermal interaction between liquid and solid mixtures consisting of water and polystyrene particles in a turbulent flow. Interestingly, polystyrene has very low thermal conductivity close to only 0.08 W/m K. Still, the turbulence intensification and particle rotation effect are to be reasoned for an enhancement of heat transfer. The penalty in pumping power, clogging, agglomeration, sedimentation and erosion are some of the adverse effects of micro-particles. However, this issue has been eliminated with the use of stable nano-sized particulate colloids, and this has paved the way for researchers to further investigate the enhancement of convective heat transfer.

V. MATHEMATICAL MODELLING

Fig. 1a shows the geometrical configuration under consideration. It consists of a tube with a length (L) of 1.0 m and a diameter (D) of 0.01 m. The nanofluid considered is composed of water and Al_2O_3 particles. The fluid enters with uniform temperature and axial velocity profiles at the inlet section. The tube has appropriate length in order to obtain fully developed profiles (velocity and thermal) at the outlet section (L/D = 100). The condition of the axially and circumferentially uniform wall heat flux is considered in this study. Also, the flow and the thermal field are assumed to be symmetrical with respect to the vertical plane passing through the tube main axis so that half of the tube is considered.

The single-phase model, which has been used frequently for nanofluids, is also implemented to compare its predictions with the mixture model. The following equations represent the mathematical formulation of the single-phase model [33] and of the continuous phase of the two-phase model [34]:

Conservation of mass:

$$div(\rho\vec{V}) = 0$$

Momentum equation:

$$div(\rho\vec{V}\vec{V}) = -grad\,P + \nabla \cdot \left(\mu\nabla\vec{V}\right) + S_m$$

Energy equation:

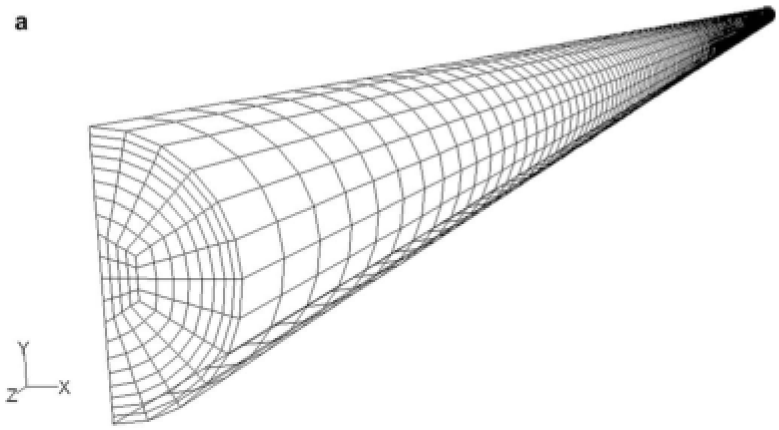
$$div(\rho\vec{V}CpT) = div(kgradT) + S_e$$

The compression work and the viscous dissipation are assumed negligible in the energy equation; the source/sink terms S_m and S_e represent the integrated effects of momentum and energy exchange with base fluid, as shown in the following, and they are equal to zero in the case of single-phase model.

Discrete phase is made of spherical particles following the model given by Ounis et al. [35]. Accordingly, motion equation is expressed in a Lagrangian form, to obtain the following expression [36]:

$$\frac{d\vec{V}_p}{dt} = F_D(\vec{V} - \vec{V}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}$$

where F is an additional term that can eventually include importantadditional forces under determined circumstances (i.e. forces thatarise due to rotation of reference frame, thermophoretic force, Brownian force), $F_D(V-V_p)$ is resistance force per particle massunit. The above Eq. has a general validity, because it is simply the expressionof a force balance on a particle immersed in a fluid. To solve the above Eq., it needs to specify the drag coefficient F_D and it can be doneusing the Stokes' law.



At this point a first limitation is imposed tothe model, because the Stokes' law is valid for Red ≤ 0.1 [39], where Redis defined as:

$$\mathrm{Re_d} = \frac{\rho_{0,\mathrm{bf}} \cdot d \cdot V_{0,\mathrm{av}}}{\mu_{0,\mathrm{bf}}}$$

VI. APPLICATIONS

The micro-channel heat sink (MCHS) has the capability to dissipate large amounts of heat from a small area with a very high heat transfer coefficient and less fluid inventory. Using nanofluids as a coolant in the MCHS could further improve its performance. Chein and Huang [29] analyzed the performance of the MCHS (silicon channel of 100μm × 300 μm dimension) using a Cu–water nanofluid with φ = 0.3-2%. The Nusselt number increased significantly with an increase in Re and φ. The maximum reduction in thermal resistance as compared to pure water was found to be 15% at φ = 2% and power = 3W. The additional reduction in R_{th} is clearly due to thermal dispersion. With regard to pressure drop, no significant differences existed between the nanofluid and water flows.

Ma *et al.* [36] studied the nanofluid (diamond–water; φ = 1%) behavior in an oscillating heat pipe (OHP) and thus developed an ultrahigh performance cooling device, called the nanofluid oscillating heat pipe in which when the input power was increased to the highest value, the temperature difference between theevaporator and the condenser for the nanofluid OHP was less thanthat for the OHP with only pure water.

VII. CONCLUSION

The salient feature that can be drawn from the reviewed literature is that nanofluids are a new class of heat transfer fluids and show greater promise for use in cooling and related technologies. From the observed results it is clearly seen, that nanofluids have greater potential for heat transfer enhancement and are highly suited to application in practical heat transfer processes. This offers an opportunity for engineers to develop highly compact and effective heat transfer equipment. Several published articles show that the heat transfer coefficient of nanofluids is much higher than that of the common-based fluid and gives little or no penalty in pressure drop. The main reason for the heat transfer enhancement of nanofluids is that the suspended nanoparticles increase the thermal conductivity of the fluids, and the chaotic movement of ultrafine particles increases fluctuation and turbulence of the fluids, which accelerates the energy exchange process. Convective heat transfer is enhanced by increasing the particle concentration and the Reynolds number. Besides, the experimental data available for convective heat transfer in laminar, transition and turbulence regions are limited and insufficient to exactly predict the trend for heat transfer enhancement. Furthermore, only very few correlations are available to exactly predict the heat transfer performance of nanofluids, and correlations which include the effect of volume fraction, particle shape and particle size are nil to-date. Therefore, further research on convective heat transfer of nanofluids, and more theoretical and experimental research works are needed in order to clearly understand and accurately predict their hydrodynamic and thermal characteristics.

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