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A survey on experimental and numerical studies of convection heat transfer of nanofluids inside closed conduits

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Abstract
Application of nanofluids in heat transfer enhancement is prospective. They are solid/liquid suspensions of higher thermal conductivity and viscosity compared to common working fluids. A number of studies have been performed on the effect of nanofluids in heat transfer to determine the enhancement of properties in addition to rearrangement of flow passage configurations. The principal objective of this study is to elaborate this research based on natural, forced, and the mixed heat transfer characteristics of nanofluids exclusively via convection for single- and two-phase mixture models. In this study, the convection heat transfer to nanofluids has been reviewed in various closed conduits both numerically and experimentally.

Keywords
Nanofluid, convection heat transfer, closed conduits flow, experimental study, turbulence

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Introduction

With the wide spread application of heat transfer in industry, the demand for enhancement of efficiency has been raised significantly, which resulted in development of recent inventive methods. Improving the efficiency of heat treatment devices has enhanced the energy consumption on one hand and has reduced the size of such devices on the other, resulting in the reduction of material and production costs. Such enhancements were possible through increasing the surface area in contact per unit volume which causes enhancement of pressure drops and requires more powerful pumps. In addition to that, the price of heat transfer equipment escalates. Advancement of nanotechnology in general along with application of nanofluids as heat transfer medium is breakthrough in the past two decades.

Choi and Eastman,[1] in 1995, were the first to present the concept of nanofluids. Nanofluids are basically

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heat-conducting fluids which consist of a base fluid and suspended particles in the range of 1–100 nm. Solid particles have better thermal conductivity compared to the conventional base fluids; as a result, the addition of solid nanoparticles is expected to increase the thermal conductivity of the nanofluids.[2–4] For example, thermal conductivity of solid particles of Cu (copper) is 700 and 3000 times greater than the thermal conductivity of water and engine oil, respectively, in liquid forms.[5] The addition of micro-sized solid particles to the base fluids was proposed decades ago. It was established that the micro-particles had the tendency to settle from suspension, which resulted in blockage of channels, pipes, and heat exchangers. Moreover, accumulation of such abrasive solid particles causes erosion corrosion in pipes, damaged pumps, and other devices. Application of nanofluids where the suspended nano-sized particles remain suspended in the base fluids would lessen the effect of erosion corrosion, fouling, and the pipe blockages.[6]

The application of nanofluids in forced convection heat transfer

Experimental studies in tubes and ducts

Pak and Cho[7] were the first who presented data on studies of nanofluid convection heat transfer and fluid flow through a tube of 10.66-mm diameter, namely, “dispersed fluid with submicron particles.” They used nanoparticles of about 13 and 27 nm sizes and named the fluids as nanofluids. Considerable rise in heat transfer coefficient was observed in turbulent regime with suspended particles. In addition, it was observed that the Dittus–Boelter formulation for pure water as well as for the water/nanoparticles fluid flow could be applicable in this experiment. The increase in the heat transfer coefficient was 45% and 75% with 1.34% and 2.78% Al_2O_3 nanoparticles, respectively. It is apparent that this phenomenon is not dependent on the increase in conductivity solely and the resulting enhancement in the heat transfer through convection cannot be attributed to the rise in the nanofluid conductivity only. However, their overall depiction is gloomy. It is identified that the friction factor of Darcy is following the Kays correlation. Therefore, because of rise in viscosity, considerable frictional pressure drop would occur. Meaning that, even though nanofluid’s heat transfer coefficient rises, substantial pressure drop occurs consequently. Applications of convection heat transfer always involve the challenge of heat transfer enhancement versus undesired resulting pressure drop. Boundary layer interruption, more complete turbulent flow creation, or other similar heat transfer enhancement methods have relative pressure penalty, which results in requirement of a higher pumping power that may counterbalance heat transfer enhancement effects. Better picture can be obtained by comparing enhancements of heat transfer at the pumping power identical to the prior case. Pak and Cho[7] stated that, γ-Al_2O_3/water and TiO_2/water nanofluids decrement heat transfer coefficient about 3% to 12% at constant average velocity in comparison to pure water. The work of Li et al.[8] changed this depiction substantially. Pure slightly bigger (≈ 100 nm) copper particles and carefully designed test loops were used in this experiment. The graph of heat transfer coefficient measurement versus the velocity depicts a great increment in convection heat transfer using nanofluids. On one hand, this result opposes interpretation from Pak and Cho[7] that for fluid flows constantly at an average velocity, the heat transfer coefficient would decline as low as 12% when containing nanofluids. Conversely, Li et al.[8] showed a 40% rise in heat transfer coefficient for the same velocity. These researchers explained this conflict between their work and Pak and Cho[7] study in the way that the high increase in viscosity could have suppressed the turbulence which results in reduction of heat transfer. Therefore, they specified that the volume fraction, the dimension of the particle, as well as characteristics of material are significant. Moreover, having designed the experimental system appropriately, a considerable increase in coefficient of heat transfer is obtainable.

Further essential investigations on convection heat transfer in nanofluids were conducted by Wen and Ding[9] which is important in different aspects. Predominantly, it appeared as the primary research to observe the effect of the entry length. Longer hydrodynamic and thermal entering sections are often found in the laminar flows. In these sections of the flow, the heat transfer coefficient is higher because the boundary layer is thinner. The local heat transfer coefficient through the tube during laminar flow was measured by Wen and Ding.[9] Different water/γ-Al_2O_3 nanofluids were used to flow through a 4.5 mm internal diameter and 970 mm length copper tube in their study. Considerable increase in convective heat transfer coefficient was noticed all the way. This enhancement was highest at the entry-length section, and it was further enhanced with the concentration of the particle. This confirms that both the steady entrance section and the other heat transfer enhancement systems like boundary layer interruptions as well as creation of artificial entrance can be used as “smart” choice to augment heat transfer. Investigations in a test rig similar to the previous experimental setups were conducted by Yang et al.[10] Tubes with 4.57 mm inner diameter and 457 mm (i.e. 100 diameters) length were used. A significant feature of the used test loop was the small holdup fluid volume and application of water at high temperature for heating instead of electrical heating. The second characteristic is rather more significant because of the fact that Kabelac and Kuhnke's[11] work demonstrated that heating by electricity can affect the nanofluids' particle motion and also there is possibility of particles to carry electrical charge.

Four dissimilar experimental fluids with diverse combinations of two base fluids and graphite nanoparticles, ranging between 2% and 2.5% concentration, were tested by Yang et al.[10] Disk-shaped particles of 20–40 nm diameter and 1–2 nm thickness were used in the investigation. Yang et al.[10] concluded that loading of particles, source of nanoparticles, temperature, and base fluid have influence on the results of heat transfer. However, multiple data deviations in different papers are obtained compared with the works of Yang et al.[10] This may happen due to the particles' shape (disk shape) and their major dimension, the diameter which is rather large. This disqualifies them to be named as nanoparticles. This creates the uncertainty whether this work can be categorized as nanofluid at all.

Work of Zeinali Heris et al.[12] has resulted in similar conclusions as Li et al.[8] The experiment was performed using a copper tube of 6 mm diameter and for water/Al_2O_3 as well as water/CuO nanofluids. The higher enhancement in convective heat transfer was reported for Al_2O_3-based nanofluid compared to water/CuO nanofluid. Two major observations in this effort were that heat transfer enhances considerably with particle volume fraction augmentation. Also, enhancements are more at greater Peclet numbers.

Thus, in general, it seems that distribution of size, particle source, preparation method, dispersion technique, value of pH, and many other factors are accountable for the divergent trends in data collected experimentally between Li et al.,[8] Wen and Ding,[9] and Zeinali Heris et al.[12] on one hand and Pak and Cho[7] and Yang et al.[10] on the other hand.

Another experiment on convection which contains carbon nanotubes (CNTs) as nanoparticles was conducted by Ding et al.[13] Multi-walled carbon nanotubes (MWCNTs) were used in a setup consisting of a 4.5 mm inner diameter tube. The tube was electrically heated. Rotors with high speed (at about 24,000 r/min) were used in order to disperse the nanomaterials in base fluid and avoid CNTs agglomeration. Measuring the thermal conductivity of the nanofluids showed 50% thermal conductivity enhancement by adding 0.7% CNT to the base fluid. It appeared that temperature had tremendously influenced conductivity, with just 10% increase in suspension temperature. Their work also showed great improvement with respect to convective heat transfer. The enhancements were tested corresponding to the factors such as concentration of particles, Reynolds number, axial distance, and pH value. At $Re = 800$, about 350% enhancement was observed for convective heat transfer coefficient. Furthermore, the enhancement was found increasing abruptly, above a certain Reynolds number which was related to shear-thinning behavior of the working fluid.

Turbulent convective heat transfer of dilute Al_2O_3/water nanofluid through a circular pipe was studied experimentally by Fotukian and Nasr Esfahany.[14] The tests were performed on Al_2O_3/water nanofluid with 0.03%, 0.054%, and 0.135% loading. The range of Reynolds number was from 6000 to 31,000. Data obtained from experiments illustrated that adding minor quantity of nanoparticles to base fluid considerably enhances the heat transfer. At $Re = 10{,}000$ and 0.054 vol% of nanoparticles, 48% rise in the heat transfer coefficient was observed compared to pure water. Addition of further nanoparticles did not enhance heat transfer in turbulent regime. The relative heat transfer coefficient enhanced with increasing the Reynolds number. It was noted that at $Re = 2000$ and nanofluid volume concentration of 0.135%, there was a rise of 30% in pressure drop in comparison to pure water.

The heat transfer enhancement at low volume concentration of Al_2O_3 nanofluid with longitudinal strip inserts in a circular tube was experimentally investigated by Sundar and Sharma.[15] The main objective of the study was to investigate convection heat transfer to Al_2O_3/water nanofluid and its friction factor at various aspect ratios (ARs). Experiments were performed for water and nanofluid Reynolds number in the range of 3000–22,000, alumina volume concentration (φ) of $0\% \leq \varphi \leq 0.5\%$, and longitudinal strip AR in the range of 1–18. The friction factor of 0.5 vol% nanofluid with longitudinal strip insert and at the AR of 1 is 5.5 and 3.6 times greater at $Re = 3000$ and $Re = 22{,}000$, respectively, compared with pure water or nanofluid flowing through a normal tube. The heat transfer coefficient of 0.5 vol% Al_2O_3 nanofluid with longitudinal strip insert with $AR = 1$ was 50.12% and 55.73% higher at Reynolds number of 3000 and 22,000, respectively, when compared to the same nanofluid. These enhancements were 76.20% and 80.19% in comparison with pure water flowing in a normal tube.

Nanofluid's heat transfer was tested in annular duct by Nasiri et al.[16] The selected nanofluids were Al_2O_3 and TiO_2 using water as the base fluid. Reynolds number for the two nanofluids ranged from 4000 to 13,000. The volume concentrations of two types of nanofluids were selected equal to 0.1%, 0.5%, 1.0%, and 1.5%. The Nusselt numbers of the two nanofluids were greater than those of the base fluid and more enhancements were obtained with the augmentation of nanoparticle concentration. At Peclet number of about 24,400, the enhancements of Nusselt number for Al_2O_3/water nanofluid at concentrations of 0.1%, 0.5%, 1.0%, and 1.5% were 2.2%, 9%, 17%, and 23.8%, respectively. At Peclet number of 53,200, the Nusselt number enhancement for TiO_2/water nanofluid at particle concentrations of 0.1%, 0.5%, 1.0%, and

1.5% were 1%, 2%, 5.1%, and 10.1%, respectively. Relative heat transfer coefficient was enhanced by augmentation of nanoparticle concentration for both nanofluids. This enhancement is due to the presence of the Brownian motion, nanofluid thermal conductivity, thinner boundary layer thickness, nanoparticle migration in nanofluid, and probable slip velocity at the adjacent walls. Comparison between the two nanofluids also showed similar properties for both working fluids at the equal particle concentration. This result is obtained from the greater thermal conductivity and smaller Al_2O_3 particle size in Al_2O_3/water nanofluid.

Numerical studies in tubes and ducts

Namburu et al.[17] simulated turbulent flow and heat transfer enhancement for three types of nanoparticles added to both water as well as ethylene glycol (EG) and water mixture flowing through a circular pipe. In this study, k-ε turbulent model proposed by Launder and Spalding[18] was adopted. The conclusions illustrated that an increase in concentration of nanofluid is led to rise of the average Nusselt number.

The thermal characteristics and pressure drop of Al_2O_3/Water-EG (60:40) nanofluid in turbulent forced convection flow were investigated numerically by Bayat and Nikseresht.[19] The flow was axisymmetric, steady, and turbulent through a circular tube which had 1 cm diameter and 1 m length. The finite volume technique was used to discretize a set of coupled non-linear Navier–Stokes differential equations. A broad range of Reynolds number of $10^4 < \mathrm{Re} < 10^5$ was proposed for modeling. The obtained results indicated that the amount of dispersed nanoparticles in base fluid has a significant influence on heat transfer, Prandtl number, pressure drop, and the pumping power. Utilization of the nanofluid and the base fluid (water) at the equal pumping power has resulted in a great difference in pressure drop. It means that although nanofluids afford more thermal augmentation at higher Reynolds number, they are inadvisable for use in the real turbulent systems due to the considerably high pumping power.

Ghaffari et al.[20] numerically studied the turbulent mixed convection heat transfer to Al_2O_3/water nanofluid flowing through a horizontal curved pipe with the particle size of about 28 nm. The effects of the buoyancy force, centrifugal force, and nanoparticle concentration are assessed in this study. The result illustrated that increases in the nanoparticle volume fraction enhanced the Nusselt number even though its impact on the skin friction coefficient was not remarkable.

Yarmand et al.[21] numerically studied the heat transfer to four different nanoparticles in a rectangular heated pipe at turbulent flow and at constant heat flux boundary conditions. The authors found that the effect of Reynolds number is more important than concentration effect of nanoparticles on heat transfer to nanofluid.

The effects of simulation strategy on turbulent flow were investigated by Behzadmehr et al.[22] This study involved two concepts for modeling which were the multiphase mixture model and the single-phase model. Continuum theories for multiphase mixtures were developed by Truesdell and Toupin,[23] Ingram and Cemal Eringen,[24] and more recently by Drumheller and Bedford[25] and Ahmadi.[26,27] Thermodynamic formulation of mixture flows in turbulent regime was developed by Ahmadi and Ma,[28] Abu-Zaid and Ahmadi,[29] and Ahmadi et al.[30] and has been used by Garoosi et al.,[31] Goodarzi et al.,[32] and Garoosi et al.[33] Fluid in mixture model is considered as a single fluid having two phases where their linkage is deliberated to be strong. Nevertheless, each phase has its distinguished velocity vectors, and within any specific volume fraction, there is a definite volume fraction of each phase.[34] The achievements obtained by Behzadmehr et al.[22] strongly support the superiority of the mixture model over the single-phase model for recalculating the Nusselt number data generated by Li et al.[8] for water/Cu nanofluids. The results emphasized that the uniform particle distribution assumption is invalid for great values of Re/φ. The obtained results confirmed the observation of Li et al.[8] in which the nanoparticles do not have a major influence on fluid frictional behavior.

Lotfi et al.[35] reported the effect of different models of nanoparticle simulation on forced convection turbulent flow in a circular tube. They made comparisons among three different single-phase, two-phase mixture, and Eulerian models. Comparison of the experimental values showed that the mixture model is the most accurate one.

Bianco et al.[36] examined the turbulent forced convection heat transfer to water/Al_2O_3 nanofluids inside a 1-m-long tube of diameter 0.01 m and used the two-phase mixture model in FLUENT software. The aluminum oxide particles had 38 nm diameter. As expected, the highest heat transfer rate for a given concentration was achieved at the largest Reynolds number while the increase in particle volume fraction amplified the heat transfer.

Haghshenas Fard et al.[37] studied heat transfer efficiency of laminar convection heat transfer to nanofluids numerically using single-flow as well as two-phase flow models. They found that the heat transfer coefficient of nanofluids increases with the rise of volume fraction of nanofluids and Peclet number.

Allahyari et al.[38] studied the laminar mixed convection of Al_2O_3–water nanofluid in a horizontal tube under heating at the top half surface of a copper tube using two-phase mixture model. They observed that increase in the nanoparticle concentration had remarkably enhanced the heat transfer coefficient, whereas the skin friction coefficient was not considerably influenced.

Inside heat exchangers

A variety of heat exchangers have been widely employed in different engineering applications. Examples are double pipe or plate heat exchangers (PHEs) used in power production and recovery, food processing, chemical industry, and mechanical appliances such as air conditions, refrigerators, and ventilators.[39,40] In recent years, efforts have been made to enhance heat transfer performance of heat exchangers. The applied methods mostly include creation of turbulent flow,[41,42] use of fins, twisters, and baffles.[43–45] An obstacle in heat transfer improvement of heat exchangers is the limited thermal properties of conventional coolants. Nevertheless, improvement in the thermal efficiency of a PHE would require an augmentation in the thermal capability of the working fluid,[46] which was taken into account by Choi and Eastman[1] who introduced nanofluids for the first time. Nanofluids enhance the hate transfer because (a) nanoparticles increase the thermal conductivity of the operating fluid, which eventually enhances the heat transfer efficiency of the system,[47] and (b) as the temperature increases, the Brownian motion of nanoparticles increases, which improves the convective heat transfer of the fluid.[48]

Many attempts have been made in the field of nanofluids by different researches in recent years.[49–51] Some of these works concentrated on nanofluid usages in various classes of heat exchangers.[52–54] Pantzali et al.[55] numerically and experimentally studied the influence of 4 vol% CuO/water nanofluids on the efficiency of a miniature PHE with modulated surface. Their study reveals that increase in heat transfer is higher at lower flow rates. Results reveal that for a certain heat load, the desired volumetric flow rate for nanofluid is less than that for water, which leads to less pressure drop and therefore lower pumping power.

Kwon et al.[56] evaluated the heat transfer coefficient and pressure drop through a PHE using two different water-based nanofluids containing Al_2O_3 and ZnO nanoparticles. The experimental results were presented for pure water at concentrations of 1%, 3%, and 6% of Al_2O_3 nanofluids while the concentration of ZnO nanofluids was 1%. Their findings for Al_2O_3/water nanofluids elucidated that using the volume fraction of 6%, the overall heat transfer coefficient is maximized, whereas the overall heat transfer coefficient associated with the concentration of 3% is lower than the results at concentration of 1%. In addition, they reported that there was no significant difference between the overall heat transfer coefficient of ZnO and Al_2O_3 nanofluids at the same concentration where the Reynolds number was approximately between 150 and 350. The authors observed that the pressure drop increases by particle loading. They recorded a linear increase in pressure drop with respect to volumetric flow rate.

Turbulent convective heat transfer of nanofluids in a corrugated PHE has been studied by Pandey and Nema.[57] The nanofluids comprised aluminum oxides nanoparticles in water as base fluid at various concentrations. At a given heat duty, the results indicated that the required flow rate for nanofluid is lower than that for water, while pressure drop is higher for nanofluid.

Kabeel et al.[58] tested Al_2O_3 nanofluids in a corrugated PHE. It was found that increasing the nanomaterial concentration dramatically increased the heat transfer coefficient and transmitted power. At a given Reynolds number, the maximum rise in heat transfer coefficient was 13% with 9.8% uncertainty. This increment was even lower when constant flow rates were considered. Hence, there was doubt about the influence of nanofluids on improving the heat transfer in the heat exchangers being investigated.

Taws et al.[59] experimentally tested CuO/water nanofluid in a chevron-type two-channel PHE. Through the experiments, they determined the forced convective heat transfer of the nanofluid and hydraulic characteristics of the heat exchanger. Nanofluid was applied in volume concentrations of 2% and 4.65% at different Reynolds numbers with a maximum value of 1000. It was noted that at a certain Reynolds number, the friction factor appeared higher for nanofluids than water. Calculating the Nusselt number for 2% nanofluid concentration revealed no noticeable increase in heat transfer. Nanofluid at 4.65% concentration actually decreased the heat transfer. These findings were incongruent with the results of Elias et al.[60] who found a significant rise in heat transfer coefficient and heat transfer rate using 0%–1% Al_2O_3 and SiO_2 nanofluid concentrations. Khairul et al.[61] obtained the same results as Elias et al.[60] using CuO nanofluid up to 1.5% in a corrugated PHE.

Influence of TiO_2/water nanofluid on pressure drop and heat transfer was investigated by Abbasian Arani and Amani.[62] The size of the particles chosen was 30 nm. The volume fraction of 0.002 and 0.02 and the Reynolds number ranging from 8000 to 51,000 were selected to conduct the experiments. The test section was a horizontal double tube counter-flow heat exchanger. From their results, it can be obtained that increase in volume fraction of nanoparticles or Reynolds number would result in increase in Nusselt number. Meantime, all nanofluids obtain greater Nusselt number in comparison to distilled water. It has been established that for using the nanofluid at high Reynolds number, more power is required compared to that at lower Reynolds number. Thus, it is required to encounter the pressure drop of nanofluid against enhancements in the Nusselt number at all the Reynolds numbers. It was observed that using nanofluids at the higher Reynolds numbers is less beneficial than using nanofluids at the lower Reynolds numbers. It was obtained that optimum thermal performance factor equal to 1.8 is gained with the application of the water/TiO_2 nanofluid having 0.02% volume fraction and at Reynolds number equal to 47,000.

Duangthongsuk and Wongwises[63] used TiO_2/water nanofluid in a horizontal counter-flow double tube heat exchanger to test the hydrothermal properties of the nanofluid. Their conclusion was that increase in mass flow rate of either hot fluid or nanofluid gives rise to the heat transfer coefficient of the nanofluid. This coefficient also increases with the reduction in nanofluid temperature. Convective heat transfer coefficient of two nanofluids was experimentally investigated in two types of heat exchangers by Zamzamian et al.[64] The nanofluids were synthesized from Al_2O_3 and CuO nanoparticles in EG as base fluid and examined in double pipe and PHEs. It was found that convective heat transfer coefficient of nanofluids increases with the rise in nanofluids temperature. This result conformed with the results of Akhtari et al.,[65] while differed from what was concluded by Duangthongsuk and Wongwises.[63] Heat transfer properties of CuO/water and TiO_2/water nanofluids were numerically examined in a double tube helical heat exchanger by Huminic and Huminic.[66] The result shows that the use of nanofluids in laminar condition considerably improves the convective heat transfer; the increment is higher when particle concentration increases. This was similar to the findings of Chandra Sekhara Reddy and Vasudeva Rao.[67] However, Wu et al.[68] found different results when examined laminar and turbulent flow of nanofluids in a double-pipe helically coiled heat exchanger. They used Al_2O_3/water nanofluid with weight concentration percentage from 0.78 to 7.04 at a fixed flow velocity. Enhancement percentage of heat transfer was insignificant in both flow conditions, ranging between 0.37% and 3.43%.

Backward- and forward-facing steps

The separation and reattachment flow occurs due to sudden changes in flow passage which could be found in a variety of applications such as power plants, combustion furnaces, nuclear reactors, heat exchangers, and cooling electronic devices. Attempts to enhance heat transfer rate in thermal systems are adopted in many studies in the past decades by introducing separation flow over forward- or backward-facing steps, sudden expansion, ribs channels, etc. The separation and recirculation flow results from a sudden contraction in the passage as a forward- or backward-facing step can be consider as a good example. This pattern of separation flow is not only developed in practical applications but is also showed in nature such as lakes and rivers. The pioneer investigators, Boelter et al.,[69] Ede et al.,[70] Seban et al.,[71] Abbott and Kline,[72] Seban,[73] Filetti and Kays,[74] Goldstein et al.,[75] Durst and Be Whitelaw,[76] and De Brederode and Bradshaw,[77] developed experimental and theoretical methods of studying separation flow that takes place due to changes in the cross section of the passage. With advances in measurement devices and CFD software, the researchers have identified detailed information regarding the structure of separation flow and recirculation zone.

Backward-facing steps. Armaly et al.[78] employed a laser Doppler anemometer to measure the velocity distribution and reattachment length for air flow over a backward-facing step. They investigated the laminar, transition, and turbulent range domains, and the obtained results were in good agreement with the experimental and numerical findings. The study of the fluid flow of two non-Newtonian liquids in sudden expansion with viscoelastic polyacrylamide (PAA) solutions and a purely viscous shear-thinning liquid was performed by Pak et al.[79] The Reynolds number was varied from 10 to 35,000 with an expansion ratio of 2–2.667; according to the results from the laminar range, the reattachment length of non-Newtonian fluid was shorter compared to the Newtonian fluid and two to three times shorter for the turbulent range than water. The effects of step height on heat transfer and turbulent flow characteristics were presented numerically by Jianhu and Armaly.[80] Uniform heat flux was maintained at the downstream region of the passage and the Reynolds number was fixed at Re = 28,000. It was found that an increase in step height caused the primary and secondary recirculation zones to enlarge. Khanafer et al.[81] carried out a numerical study on the heat transfer and laminar mixed convection of pulsatile flow over a backward-facing step with the help of the finite element method. Based on the results, by increasing the Reynolds number, the heat transfer rate amplified while the thickness of the thermal boundary layer reduced. In contrast, Chen et al.[82] numerically studied heat transfer and turbulent forced convection flow over a backward-facing step. The results revealed enhanced heat transfer in response to an increase in step height.

Tinney and Ukeiley[83] investigated turbulent oil flow over double backward-facing step using particle image velocimetry (PIV). They observed large turbulences at the central region of the backward step.

Abu-Nada[84]—who can be considered as a pioneer in numerical study of heat transfer to nanofluid over steps—studied the effect of different types of nanofluids over a backward-facing step using finite volume method. The types of studied nanoparticles in this investigation were Cu, Ag, Al_2O_3, CuO, and TiO_2 with the volume fraction from 0.05 to 0.2 at the range of Reynolds number from 200 to 600 (laminar regime). His results indicated a noticeable enhancement of Nusselt number at the top and bottom of the backward-facing step. More recently, Togun et al.[85] presented a numerical investigation of laminar as well as turbulent heat transfer and nanofluid flow through backward-facing step. The Reynolds numbers ranged from 50 to 200 for the laminar range and 5000 to 20,000 for turbulent regime, an expansion ratio equal to 2 and constant heat flux of $4000\,W/m^2$. Their results showed that increasing Reynolds number and volume fraction of nanoparticles lead to an increase in Nusselt number; the highest Nusselt number value was obtained for laminar flow.

Forward-facing steps. Shakouchi and Kajino[86] presented experimental study of heat transfer and fluid flow over single and double forward-facing step using laser Doppler velocimetry (LDV). Effects of step height on heat transfer and flow characteristics have shown more enhancement of heat transfer with the double forward step compared to the single step. Yilmaz and Öztop[87] have numerically studied turbulent convection air flow and heat transfer over double forward-facing step using standard k-ε turbulence model. They had insulated the top wall and steps while the bottom wall before the step was heated. The obtained results have shown that the second step could be used as a control device for heating and fluid flow. Laminar flow and turbulent convection flow over vertical forward-facing step were numerically and experimentally studied by Abu-Mulaweh et al.[88] and Abu-Mulaweh[89] where they found that increase in step height leads to increase in turbulence and temperature variations. In contrast, Wilhelm and Kleiser[90] and Marino and Luchini[91] conducted numerical study of laminar fluid flow over horizontal forward-facing step. They found that with the increase in separation and reattachment length, the Reynolds number increases. Effects of forward-facing step on turbulent forced convection heat transfer of functionalized multi-walled carbon nanotube (FMWCNT) nanofluids were studied numerically by Safaei et al.[92] Their study demonstrated that volume fraction of nanoparticles and Reynolds number affects the heat transfer considerably. For more enhancement in heat transfer, Oztop et al.[93] presented numerical study of turbulent heat transfer and air flow over a double forward-facing step with obstacles. The results indicated improvement of heat transfer with increase in AR of obstacle, step height, and Reynolds number.

From the literature, it is clear that the nanofluid flow and heat transfer (laminar as well as turbulent) over backward or forward-facing step require more investigations.

The application of nanofluid in natural and mixed convection heat transfer

Inside cavities and enclosures

The heat transfer phenomenon in which both forced convection and free convection exists simultaneously is known as mixed convection. Mixed convection heat transfer is observed when the influence of forced flow is important on a buoyant fluid flow or when the effect of buoyancy matters on a forced flow.[94,95]

The practical application of mixed convection heat transfer in various areas, such as solar collectors, double-layer glass, building insulation, electronic cooling, food drying, and sterilization among others, has been reported in the literature. Mixed convection heat transfer occurs in several ways. One way is to move the walls within an enclosure in the presence of hot or cold fluid. Shear stresses are thus produced, forming hydrodynamic and thermal boundary layers in the enclosed fluid flow, eventually leading to a forced convection condition. Numerous studies have been conducted in this area. Among the notable works are those by Khanafer and Vafai,[96] Oztop and Dagtekin,[97] Sharif,[98] Basak et al.,[99] Chung and Vafai,[100] Basak et al.,[101] Grosan and Pop,[102] Karimipour et al.,[103] Rahman et al.,[104] Ramakrishna et al.,[105,106] Selimefendigil and Oztop,[107] and Alipanah et al.[108] Another technique is to introduce hot or cold fluid from one side through the isothermal walls and have the fluid exit from the other side. A number of researchers have imposed a constant heat flux on the wall as the fluid passes through the channel and subsequently analyzed the heat transfer effect.[109–114]

Experimental studies on enclosures. Heat transfer and fluid flow of nanofluid in cavities and enclosures has become attractive field of research in the recent years. The majority of studies focus on the laminar flow regime. Putra et al.[115] were the pioneer to study on this area. They studied free convection in a horizontal cylindrical cavity which was filled with water (as base fluid) containing 131.2 nm Al_2O_3 particles as well as 87.3 nm CuO particles. The experimental setup is represented in Figure 1. It was observed that the free convection heat transfer in nanofluids is less than that of pure water with a rise in particle concentration. This reduction was greater for CuO nanofluid compared to Al_2O_3 nanofluid. It was observed by Putra et al.[115] that the nature

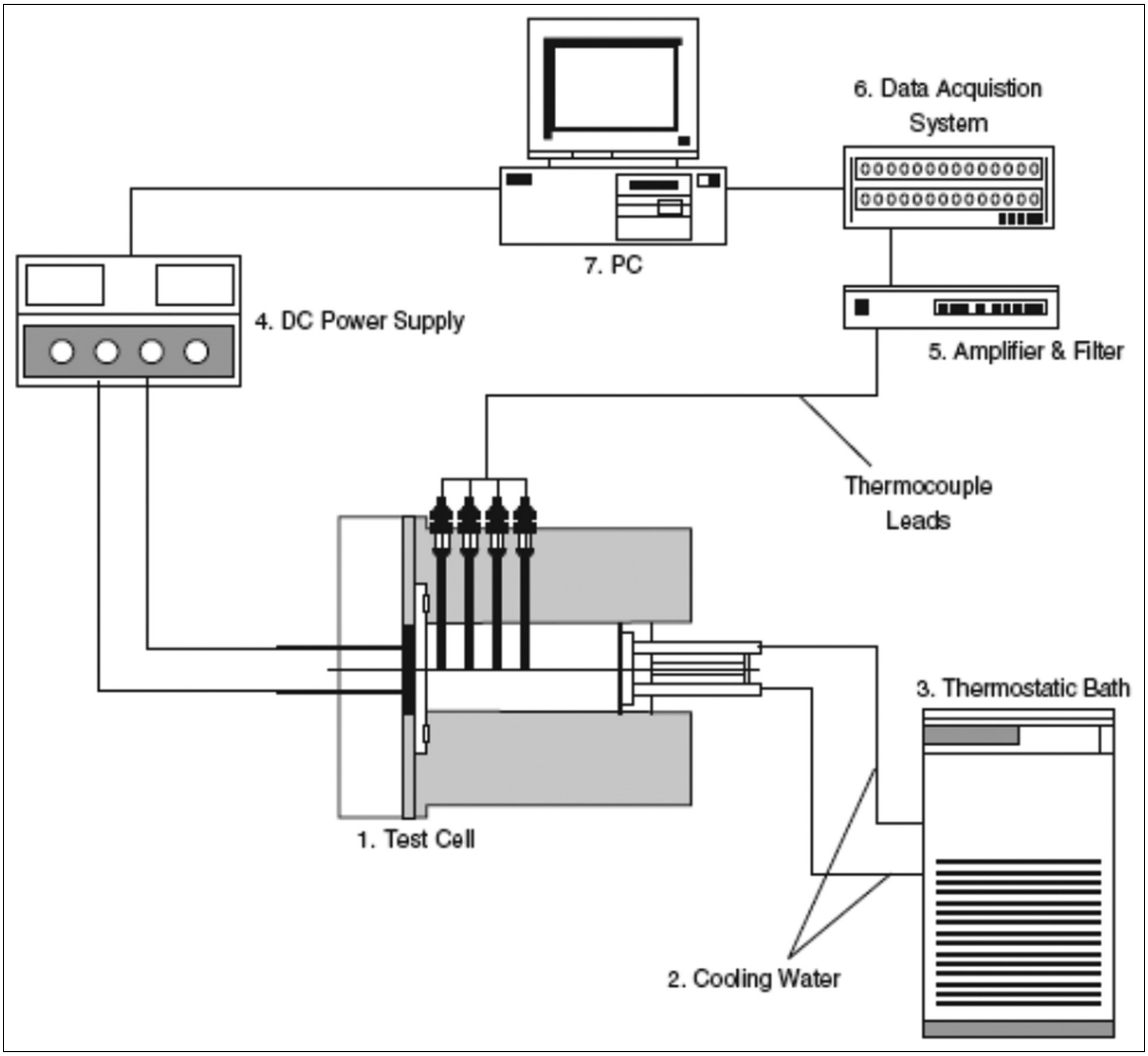

Figure 1. Experimental setup for study of free convection.[115]

of this reduction is different in comparison to that of normal slurries and is not a double diffusive feature. Actually, they announced this phenomenon to the slip among the fluid and the nanoparticles since the denser CuO nanoparticles demonstrated more reduction.

Further investigations on the characteristics of free convection in nanofluids were done by Wen and Ding.[116] First, the zeta potential of the nanofluid was measured for the purpose of pH value determination at which the TiO_2 nanoparticles would be stable in a solution of water/acid. The experimental apparatus is illustrated in Figure 2. The resulting configurations reassure the heat transfer reduction in free convection through nanofluids. Such reduction was attributed to convection driven by modification of dispersion properties, particle–particle and particle–surface interaction as well as concentration gradient.

Ho et al.[117] experimentally studied the free convection heat transfer of alumina nanofluid (0.1–4 vol%) in vertical square enclosures of different sizes. Their results demonstrated that concluding the effect of using nanofluid for free convection heat transfer enhancement inside an enclosure is generally impossible, as different items and forces are engaged in the phenomenon.

A comparative experimental study is conducted by Zeinali Heris et al.[118] to examine the effects of metal oxide nanopowders including TiO_2, CuO, and Al_2O_3 suspended in turbine oil on the natural convection flow inside a titled cube cavity. Three inclination angles of 0°, 45°, and 90° and three weight fractions of 0.2%, 0.5%, and 0.8% were investigated in their works. Their results showed that for any inclination angle and Rayleigh number, the Nusselt number is higher for turbine oil compared to the nanofluids. For TiO_2 nanofluid, with

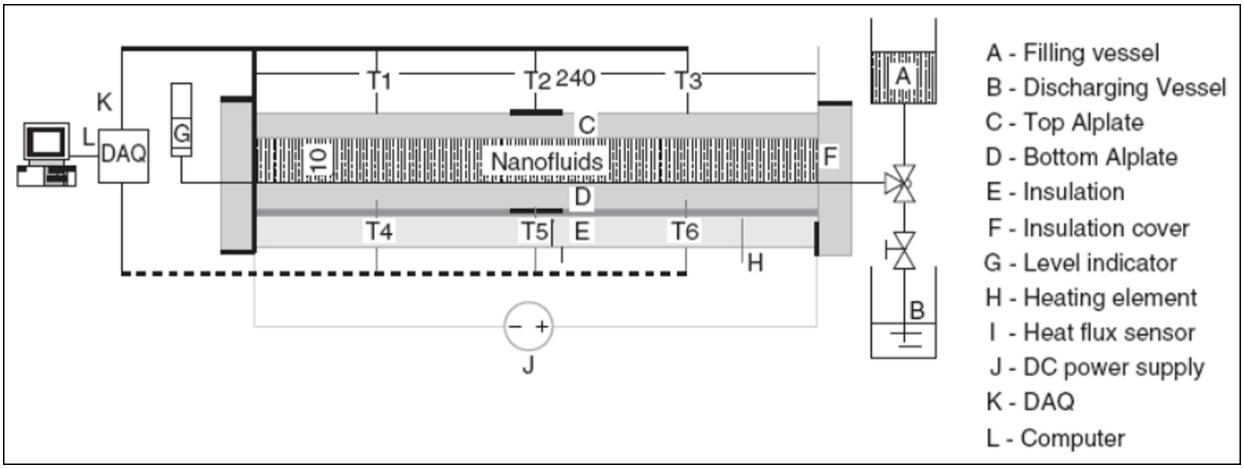

Figure 2. Experimental apparatus for the study of free convection.[116]

increasing the inclination angle from 0° to 90°, the Nusselt number increased. In other words, the optimum inclination angle for TiO_2 nanofluid was 90°. However, the tests on the two other nanofluids indicated that at the low concentration (i.e. 0.2 wt%), the maximum heat transfer occurs at the inclination angle of 45°. As a conclusion, they claimed that "besides some factors such as shape, size, heat absorption, Brownian motion, and physical and chemical properties of the nanoparticles, future experimental studies are needed to know the possible reasons behind the changes in the Nusselt number for different nano materials."[118]

Numerical studies on enclosures. Khanafer et al.[119] were the first researchers who analyzed numerically the natural convection of nanofluids inside a differentially heated cavity. The cavity consisted of two horizontal adiabatic wall and hot and cold vertical walls. The famous stream function–vorticity formulation was used to implement an easier algorithm for incompressible flow analysis. The finite difference method with the use of alternating direction implicit (ADI) algorithm together with a power law scheme was utilized to explain the transient formulations. This was corroborated by the results obtained from FIDAP software and also with the experimental data from plain fluids. Successively, research on free convection in a gradually heated cavity with water/Cu nanofluids at solid volume fraction of $0\% \leq \varphi \leq 20\%$ was carried out. Consequently, substantial growth in nanofluids heat transfer and natural convection were obtained. It must be noted that the experimental observations of Putra et al.[115] contradicted with the results of this study which needs to be clarified in future studies.

Jou and Tzeng[120] carried out similar study through a differentially heated cavity. The stream function–vorticity formulation was also used in this study, in exact manner to that used in a prior investigation by Khanafer et al.[119] The effects of Grashof number and cavity AR (width/height) on thermal characteristics of the cavity were studied. Corresponding results demonstrated that the growth of volume fraction of nanofluids and buoyancy parameter result in an intensification in the average heat transfer coefficient. However, use of these results in real systems is very difficult since synthesis of a fully stable nanofluid at 20% volume fraction of nanoparticle by the present methods (e.g. sonication and pH control) is almost impossible. The natural convection in an isosceles triangular enclosure was simulated by Aminossadati and Ghasemi.[121] A heat transfer enhancement was observed by them when the solid volume fraction and Rayleigh numbers were increased.

Mahmoudi et al.[122] simulated a cooling system which had been working in natural convection, and they have concluded with a statement that the average Nusselt number increases linearly with the increase in solid volume fraction of nanoparticles.

Mansour et al.[123] numerically studied a mixed convection flow in a square lid-driven cavity partially heated from below and filled with different nanofluids to observe the effect of particles type and concentration on heat transfer. They reported that increase of solid volume fraction in the suspension raises the corresponding average Nusselt number.

Abu-Nada and Chamkha[124] studied steady free convection of the CuO-EG-water nanofluid inside a rectangular enclosure using the finite volume method. The corresponding Rayleigh number was in the range of 10^3–10^5, the volume fraction of nanoparticles was in range of 0%–6%, and the AR was from 0.5 to 2. They concluded that at low values of AR and Ra, the average Nusselt number is increased with the increase of volume fraction of nanoparticles.

While there has been tremendous progress in computing techniques and experimental techniques, the analysis of turbulent flows inside enclosure is still a challenging topic in fluid mechanics. It is also rather difficult to measure flow velocities at low speeds in enclosure boundary layers using the presently available sensors and probes. Although there has been much progress in numerical methods such as detached eddy simulation (DES), large eddy simulation (LES), and direct numerical simulation (DNS), it is still hardly possible to predict the stratification in the core of the enclosure. Non-linearity and coupling of the governing equations have made the computing time consuming. In particular, for large enclosures, the Rayleigh number is quite large, and the flow is in the turbulent regime.

The review of the related literature indicates that no comprehensive study of turbulent mixed convection heat transfer of nanofluids inside enclosures has been conducted. Most of the studies corresponded with the turbulent forced convection or the natural convection heat transfer inside tubes which have been discussed in sections "Experimental studies in tubes and ducts" and "Numerical studies in tubes and ducts."

Nguyen et al.[125] experimentally studied heat transfer and erosion/corrosion of the water/Al_2O_3 nanofluid at $\Phi = 5\%$ for an impinging jet system. Their study indicated that the surface heat transfer coefficient improves significantly, but their erosion tests demonstrated that nanofluids have the potential to cause premature wear of mechanical systems.

The presented background study predominantly indicates that the knowledge on nanofluid as an effective coolant[126–129] as well as an erosive material[125] is still at its early stages. In other words, the phenomenon of natural and mixed convection heat transfer of nanofluids in turbulent flow regime is not well understood.

Conclusion

This literature review has presented an assessment on the published studies about enhancement of heat transfer in natural, forced, and mixed convection with the aid of nanofluids. This article has assessed experimental as well as numerical publications of the research output in the literature. The numerical study comprised both single-phase and two-phase models.

The reviewed study depicts that enhancement of heat transfer via convection with the application of nanofluid is still open to further discussion and there is ongoing debate on the aspect of nanoparticles in the enhancement of heat transfer since the topic is dramatically knowledge extensive and the current investigations are apparently not sufficient. Most results obtained from numerical analysis indicate that characteristics of nanofluids significantly enhance the heat transfer in the fluid via convection. However, data obtained from experiments represented that sometimes existence of nanoparticles worsens heat transfer. It could be noticed that in the experiments often two types of nanofluids were utilized which were Al_2O_3/water and TiO_2/water. As a result, benchmark experiments are not very desirable to ensure whether the numerical results are valid. It could be noted that the numerical data represent inconsistency in heat transfer enhancements, which is vital to approach single-phase model as well as the two-phase model, and recognize which one appears to be the more desirable model to characterize the nanofluids flow. This is due to the fact that slip velocity between the particle and base fluid plays an undeniable role on the heat transfer performance of nanofluids. Thus, the results of nanofluid studies may find various fields of applications such as coolant fluids in heating and cooling systems,[130,131] solar collectors,[132] heat exchangers,[133] water purification systems,[134] fuel cells,[135] and electronic devices.[136]

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