Recent Patents on Nanofluids (Nanoparticles in Liquids) Heat Transfer

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Abstract: Advances in high power technology are demanding size reduction of thermal systems resulting in constrained spaces for increased heat transfer. This has led to thermal management problems in emerging systems which have defied solution by conventional cooling methods. Due to recent developments in nanotechnology, a new class of heat transfer fluids called nanofluids was discovered. A nanofluid is a solid-liquid mixture produced by dispersing metallic nanoparticles in a liquid to enhance the heat transfer performance. Experiments have shown that nanofluids have substantial higher thermal conductivities compared to the base fluids. This application of nanometer-sized particles in liquids holds huge prospects for confronting cooling problems in thermal systems. This paper summarizes the explanations that have been presented for the enhanced thermal conductivity of nanofluids, the methods of preparation as well as recent and important patents on nanofluids heat transfer. It also identifies areas for further research. This review indicates that exploitation of nanofluids could lead to development of coolants that can be applied in thermal systems leading to remarkable impact in many sectors especially energy and transportation. Also, the principles of nanoparticles in biofluids can be applied to drug delivery in body tissues thus providing new medical treatment methods.

Keywords: Nanofluids, nanoparticle, heat transfer, thermal energy transfer, thermal conductivity.

1. INTRODUCTION

One of the technological applications of nanoparticles that hold enormous promise is the use of heat transfer fluids containing suspensions of nanoparticles to confront cooling problems in thermal systems. The term “nanofluid” refers to a solid-liquid mixture or suspension produced by dispersing tiny metallic or nonmetallic solid particles in liquids. The size of nanoparticles (usually less than 50 nm) in liquid mixtures gives them the ability to interact with liquids at the molecular level and so, conduct heat better than today’s heat transfer fluids. Nanofluids can display enhanced heat transfer because of the combination of convection and conduction and additional energy transfer by particle dynamics and collision. Suspensions of millimeter and micron-sized solid particles in liquids have been investigated for cooling and other applications but because of the relatively large sizes of the particles, they tend to cause abrasive action, which erodes system components. Also, they clog small flow channels and have the propensity to settle under gravity resulting in undesired pressure drops. In contrast, nanoparticles in fluids have extremely low momentum, which greatly reduces abrasive wear if any. Nanofluids can be described as colloids since a colloid is a substance made up of a system of particles that is insoluble yet remains in solution and dispersed in another fluid medium.

The concept of enhancing the thermal conductivity of fluids by suspending solid particles in them started from the theoretical work by Maxwell [1]. Since this work was published, a number of studies on the use of suspensions of solid particles (millimeter and micron-sized) in liquids for cooling and other applications have been performed. Ahuja [2] experimentally investigated the effect of heat transport and laminar fluid flow in polystyrene suspensions. Choi *et al*. [3] produced nanotube-in-oil suspension and measured the effective thermal conductivity. When compared to nanostructured materials dispersed in fluids, the study found that nanotubes provided the highest thermal conductivity enhancement thus opening the door to a wide range of applications of nanofluids.

Das *et al*. [4] investigated the temperature dependence of thermal conductivity enhancement of nanofluids using water as base fluid and particles of CuO and Al_2O_3 as suspension materials. The results indicated an increase of enhancement characteristics with temperature. Lee *et al*. [5] produced CuO and Al_2O_3 nanofluids and measured their thermal conductivities using the transient hotwire method. The results showed that these nanofluids have substantially higher thermal conductivities than the base liquids without nanoparticles. Studies by Eastman *et al*. [6] found that nanofluids exhibit superior properties relative to conventional heat transfer fluids and fluids containing micrometer-sized metallic particles.

Figure (**1**) shows a comparison of the thermal conductivity of water as base fluid with copper-water nanofluid for various volume fractions. The graph clearly shows that the thermal conductivity of water is enhanced with the addition of nanoparticles. It also shows that the effective thermal conductivity of the nanofluid increases with volume fraction of the solid particles. Other results also show that nanofluid consisting of copper nanoparticles dispersed in ethylene glycol has much higher effective thermal conductivity than either pure ethylene glycol or ethylene glycol containing the same volume fraction of dispersed oxide nanoparticles. Other studies, which have demonstrated that nanofluids exhibit better heat, transfer characteristics than traditional heat transfer fluids include

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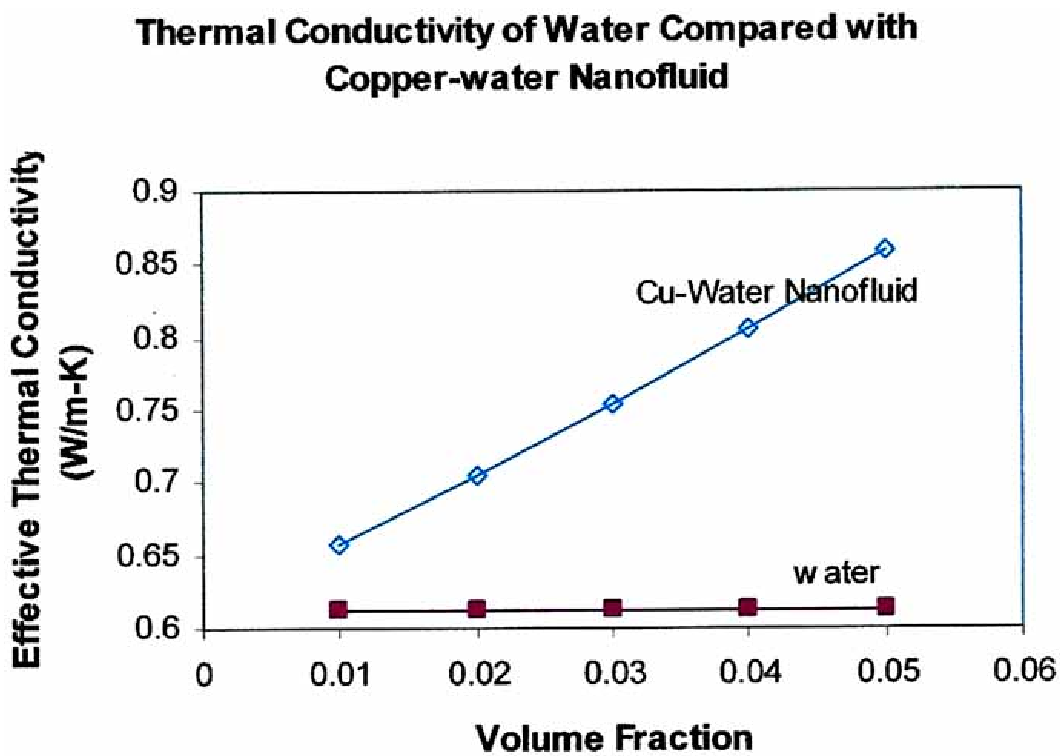


Fig. (1). Thermal conductivity of water compared with copper-water nanofluid.

Xuan and Li [7], Wang *et al*. [8], Hwang *et al.* [9], Murshed *et al.* [10], Xie *et al*. [11], Yu and Choi [12] and Xuan *et al*. [13].

Regarding convection related studies, Wang and Mujumdar [14] summarized recent research on fluid flow and heat transfer characteristics of nanofluids in forced and free convection flows. Polidori *et al.* [15] used integral formalism approach to investigate natural convection heat transfer of Newtonian nanofluids in laminar external boundary layer. The study noted the heat transfer enhancement of nanofluids but found that apart from the thermal conductivity, there are other factors that contribute to the natural convection. Yang *et al.* [16] investigated the convective heat transfer coefficient of graphitic nanoparticles in automatic transmission fluid and synthetic base oils in a horizontal tube. The report indicated that the graphite nanoparticles increased the thermal conductivities of the fluids significantly at low weight fraction loadings.

2. REVIEW OF POSSIBLE EXPLANATIONS FOR THE ENHANCED HEAT TRANSFER

A number of studies have been performed to explain the reasons for the enhanced thermal performance of nanofluids. Early attempts to predict the experimentally measured values of the thermal conductivity of nanofluids were made with existing theories such as those by Maxwell [1] and Hamilton-Crosser [17]. However, these theories predicted lower values for the experimentally measured values because they considered only the thermal conductivities of the liquid and solid phases and used volume fraction and particle shape as variables. Theories such as the nanolayer theory and the average polarization theory were reported later. Xue [18] considered the interface effect between the solid particles and the base fluid and developed a model for the effective thermal conductivity based on Maxwell theory and the average polarization theory. The study by Yu and Choi [12] determined that the solid-liquid interfacial layers in the nanofluid plays an important role in the enhanced thermal conductivity especially when the particle diameter is less than 10 nm. It proposed that the solid-like nanolayer behaves like a thermal bridge between the solid particle and the liquid.

Evans *et al.* [19] used a kinetic theory based analysis for the heat flow in nanofluids to demonstrate that the hydrodynamic effects associated with Brownian motion have only a minor effect on the thermal conductivity of the nanofluid. Wang *et al.* [20] reported on a method for modeling the effective thermal conductivity of the nanofluid based on the effective medium approximation and the fractal theory and Xie *et al.* [21] investigated the impact of the interfacial nanolayer on the effective thermal conductivity of the nanofluid. Bhattacharya *et al*. [22] reported on a technique for computing the effective thermal conductivity of nanofluids using Brownian dynamics simulation and the equilibrium Green-Kubo method. One of the inferences from the study is that Brownian motion of the particles might not have a significant contribution to the effective thermal conductivity for nanofluids with large particles but it becomes significant for nanofluids with smaller particles.

Keblinski *et al*. [23] explored possible explanations for the enhanced thermal performance of nanofluids. These include Brownian motion of the particles, molecular level layering of the liquid at the liquid/particle interface, the nature of heat transport in the nanoparticles and the effects of particle aggregation. Brownian motion implies that the nanoparticles move through the liquid and create solid-solid transfer of heat as the particles collide. The study however concluded that Brownian diffusion contributes less than thermal diffusion in nanofluids heat transfer. On the molecular-layering of the liquid at the liquid/particle interface, the study analyzed the liquid layer at the solid-liquid interface and concluded that the nanolayer plays a role in the heat transfer but it is not the only factor that is responsible for the enhanced thermal conductivity of the nanofluid. On the nature of thermal transport in nano-particles, the study indicated among other factors that assumption of diffusive thermal transport in the nanoparticles is not valid. Thermal energy is transferred in random directions by propagating lattice vibrations in the nanoparticles which justifies microscopic treatment of the heat particles based on ballistic phonon analysis. The study also reported that possible nanoparticle clustering creates paths of lower thermal resistance which results in increasing the effective thermal conductivity of the nanofluid. Thus, with decreasing packing fraction of the cluster, heat will move rapidly within the clusters.

Xuan and Roetzel [24] investigated the mechanism of heat transfer enhancement and stated that the nanoparticles enhance the rate of heat transfer by gaining thermal dispersion in the flow and increasing the thermal conductivity due to the ultrafine particles. It also infers the possibility of particle clustering affecting the heat transfer. Possible reasons for the increased effective thermal conductivity of nanofluids given by Vadasz *et al.* [25] include (a) thermal wave effects through hyperbolic heat conduction, (b) particle driven or thermally driven, natural convection, (c) convection induced by electro-phoresis and (d) hyperbolic thermal natural convection. Molecular dynamics study performed by Xue *et al.* [26] on a simple liquid concluded that molecular-level layering of the liquid at the liquid/particle interface does not affect the thermal transport properties much. However, it adds that this may not be so for complex liquids.

In a review article, Eastman *et al.* [27] observed that thermophoresis which has to do with motion of colloidal nanoparticles in response to temperature can contribute to the enhancement of thermal conductivity in nanofluids. With this, the molecules in the hot area of the liquid impact the nanoparticles with a larger momentum because of their higher energy content. This is as opposed to the molecules from the cold area of the liquid. This phenomenon creates a temperature gradient for further heat transfer because of the movement of the particles. However, Koo and Kleinstreuer [28] studied the effect of thermophoresis on the thermal conductivity of nanofluids using kinetic theory and found that its contribution to the enhanced heat transfer is not significant. The study observed the electric dipole constant to be a very important parameter which influences the inter-particle potential which influences the thermal conductivity dependence. Using an order-of-magnitude analysis, with Brownian-motion-based convective-conductive model, Prasher *et al.* [29, 30] determined that convection due to Brownian movement of the nanoparticles is mainly responsible for the observed enhancement of the thermal conductivity of nanofluids. The studies pointed out that molecular level layering of the liquid at the liquid/particle interface and heat transfer due to translational Brownian motion and interparticle potential do not significantly contribute to the heat transfer enhancement of nanofluids.

It can be seen from this brief review that a number of explanations and theories underlying the heat transfer mechanisms in nanofluids have been given by various published studies. However, these have not been well established as some theories disagree with some others. The lack of agreement between the results and explanations could be due to different research techniques and research basis. One thing which is clear is that more research needs to be performed to arrive at more comprehensive and suitable explanations and theories.

3. PREPARATION OF NANOFLUIDS AND THERMAL CONDUCTIVITY MEASUREMENT METHODS

Nanofluids are produced by dispersing nanoparticles into the base liquid. Well-known base liquids that have been used for this purpose include water, various types of oils and ethylene glycol. The commonly used nanoparticles include carbon nanotubes, copper, CuO, Al_2O_3, TiO_2, gold and silver. Knowledge of the constituents of nanofluid is very important for understanding the heat transfer enhancement and mechanisms. Thus, preparation of nanofluids for experimental studies should be carefully performed. It is essential that there should be no chemical reactions between the particles and the base fluid. There should be insignificant agglomeration of the particles and the nanofluid should be stable.

The two major procedures for preparing nanofluids are (a) the single-step method and (b) the two-step method. In the single-step method, the nanofluid is produced in one step as the name suggests but in the two-step method, nanoparticles are first produced followed by the second step of dispersing the particles in the base fluid. In the single-step method, the nanoparticles are produced and simultaneously dispersed into the base fluid. A number of examples that describe the single-step and the two-step procedure are given in subsequent paragraphs. The one-step method is a better method for preparing metallic nanofluids and it has the advantage of reduced agglomeration in the nanofluid. The two-step method is more efficient for preparing nanofluids containing oxide nanoparticles. In order to achieve stability and suppress agglomeration, some researchers apply techniques during the preparation which include, use of ultrasonic vibration, control of the pH value of the suspension and addition of surface activators and dispersants. The technique applied is usually such that properties of the constituents of the nanofluid are not significantly affected. This is because addition of surface active agents can affect the heat transfer performance of the nanofluid. Surface activators and dispersants that have been used by researchers include oleic acid, thiols, laurate salts and sodium dodecylsulfate.

Zhu *et al.* [31] used a one-step method to prepare copper nanofluids by reducing $CuSO_4.5H_2O$ with $NaH_2PO_2.H_2O$ in ethylene glycol under microwave irradiation. The study reported that nonagglomerated copper nanofluids were obtained. Transmission electron microscopy, infra red analysis and sedimentation measurements were made and it was found that this method is a fast and efficient method for preparing copper nanofluids. Kim *et al*. [32] presented a one-step electrochemical method for producing and characterizing water-based stable carbon nano colloid without adding surfactants at room temperature. The study reported that analysis showed that the carbon nano colloid produced in the study was considerably stable for over a period of 600 hours. Hwang *et al*. [33] applying a one-stoop method prepared nanofluid with relatively small nanoparticles of the order of 3 nm by employing a modified magnetron sputtering system. Sputtered nanoparticles were directly mixed with running surfactant-added to silicon oil thin film formed on a rolling drum. It was observed that silver nanoparticles produced by this method were dispersed homogeneously in the silicon oil-based fluid and the nanofluid was stable. Eastman *et al*. [6] used a one-step method to produce nanofluids with nanocrystalline copper particles dispersed into ethylene glycol. The technique which was originally developed by Akoh *et al*. [34] is called the VEROS (Vacuum Evaporation onto a Running Oil Substrate) technique. The method involves direct condensation of metallic vapor into nanoparticles by contact with a flowing low vapor pressure liquid.

Using a two-step method, Lee *et al*. [5] produced oxide nanofluids for their thermal conductivity measurement experiments. CuO, and Al_2O_3, nanoparticles were first produced by gas condensation processing that involves vaporizing metallic or nonmetallic precursor species in the presence of controlled gas pressure. This first step was followed by a second step in which the nanoparticles were dispersed into the base liquids (water and ethylene glycol) in a mixing chamber of polyethylene container. Characterization of the nanoparticles was performed using transmission electron microscopy. Liu *et al*. [35] used a two-step method to prepare nanofluids of multi-walled carbon nanotubes in ethylene glycol and synthetic engine oil. Hwang *et al*. [33] reported on various production and dispersion techniques based on two-step method and concluded that the high-pressure homogenizer was the most effective method for breaking down agglomerated nanoparticles suspended in base fluids.

Xuan and Li [7] used a two-step method to prepare transformer oil-copper nanoparticles nanofluid. Oleic acid was used as the dispersant to stabilize the suspension. The suspension was vibrated in ultrasonic vibrator for 10 hours. Distribution and cluster of the nanoparticles were investigated using an electron microscope. The study also used a two-step method to prepare water-copper nano-particles nanofluid. Laurate salt was used to improve the stability of the suspension. The suspension was vibrated in ultrasonic vibrator. It was found that the stable suspension formed could last for more that 30 hours when left stationary. The study compared the dispersion and stability behavior of the transformer oil-copper nanoparticles nanofluid and the water-copper nanoparticles nanofluid and reported that the transformer oil-copper nanoparticles nanofluid has superior characteristics. It deduced that viscosity of the liquid may be crucial for the dispersions and stability of nanofluids.

Regarding the thermal conductivity, experiments have shown that it is the property largely responsible for the enhanced heat transfer of nanofluids. A wide range of studies have been reported on the measurement of this property. The transient hot wire technique developed by Nagasaka and Nagashima [36] has widely been used for the measurement of thermal conductivity of nanofluids. The method uses metallic wire coated with thin electrical insulation instead of bare hot wire as the heating element and resistance thermometer. Other methods have been developed and used for the measurement. Wang *et al*. [37] developed a 3ω technique in which a conductive wire was used as both sensor and heater for simultaneous measurements of the thermal conductivity and thermal diffusivity of the nanofluid. Murshed *et al*. [38] developed a transient double hot-wire technique for simultaneous precise measurements of the effective thermal conductivity and effective thermal diffusivity of the nanofluid. Optical method, steady-state parallel plate method and the temperature oscillation method have also been used for the measurement of thermal conductivity of nanofluids. Rusconi *et al*. [39] used a non-invasive optical method to measure the thermal conductivity and thermal diffusivity of colloidal particle dispersions. The study indicated that this method is rapid and highly accurate. Wang *et al*. [8] measured the effective thermal conductivity of mixtures of fluids and CuO and Al_2O_3 nanoparticles using the steady-state parallel-plate technique. Das *et al*. [4] used temperature oscillation technique to measure the thermal conductivity of nanofluids.

4. RECENT AND IMPORTANT PATENTS ON NANOFLUIDS HEAT TRANSFER

Since the discovery of heat transfer enhancement of nanofluids less than two decades ago, a number of patents related to nanofluids heat transfer have been filed. One of the first related patents was that by Choi and Eastman [40] who invented an apparatus and method for enhancing the heat transfer in liquids namely, deionized water, ethylene glycol and oil. The method involves dispersing nanocrystalline particles such as copper, copper oxide and aluminum oxide in the liquids. The particles produced are heated in a vacuum while passing a thin film of low vapor pressure liquid near the substance. A thioglycolic acid is added to the nanofluid as a stabilizing agent. Figure (**2**) [40] is a schematic diagram of the apparatus for the practice of the invention. In this figure, a cylinder 20 with a crucible 22 that can be heated while containing the substance 24 to be vaporized is subjected to a vacuum. The cylinder 20 can be rotated to transport a thin layer 28 of the liquid 26 on the surface. To prevent the liquid from increasing the vapor pressure inside the cylinder 20, it is cooled by a cooling system 32. The technique described is used for liquids that have enough low vapor pressure to prevent vaporization of the liquid and consequent gas condensation and agglomeration of the particles. The patent also includes a technique for dispersing nanoparticles into high vapor pressure fluids.

One of the most recent related patents is that by Davidson and Bradshaw [41] who invented compositions with nano-particle size conductive material powder and methods for using them to transfer heat in a transformer or basically between a heat source and a heat sink. Another recent patent is that by Zhang and Lockwood [42] and is on enhancing the thermal conductivity of fluids using high

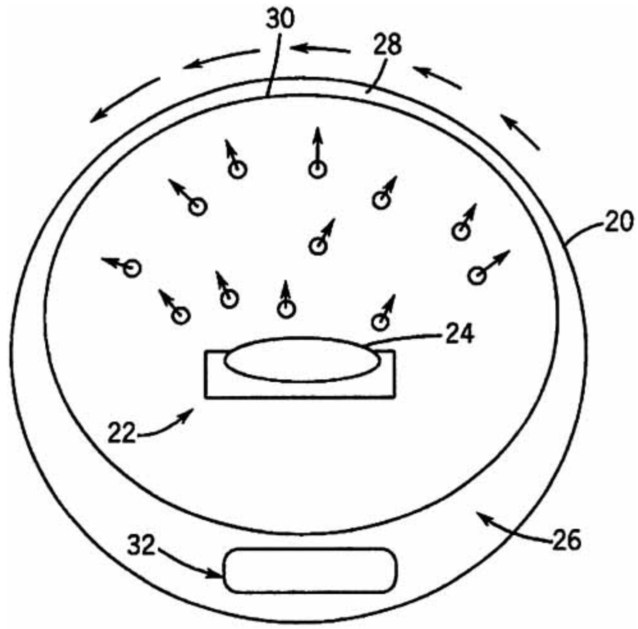


Fig. (2). Schematic diagram of an apparatus for the invention [40].

thermal conductivity graphite nanoparticles and carbon nanotubes. The graphite is dispersed in the fluid either by ultrasonication, milling or chemical dispersion. Chemical dispersants are added in the nanofluid for long term stability.

Hajikata *et al.* [43] invented a heat transport nanofluid, structure and method that results in a high heat transfer coefficient. This is important for heat exchanger thermal energy transfer. This nanofluid includes a solvent, surface-coated particles together with organic components dispersed in the solvent. The phase of the nanofluid changes in response to temperature in order to achieve high heat transfer coefficients. Figures (**3a**) and (**3b**) [43] respectively are schematic diagrams illustrating the structured state and unstructured state of this nanofluid. In these figures, the heat transport fluid 19 includes solvent, nanoparticles 1 with coating agents 7 and organic components 3. When the temperature of the fluid 19 is lower than a predetermined value, the organic components 3 are structured but when the temperature is equal to or higher than a predetermined value (which is higher than the first temperature), the organic components 3 are unstructured. This makes the nanofluid to change from a structured state to an unstructured state in response to temperature changes. This patent is based on JP241582 filed on September 6, 2006.

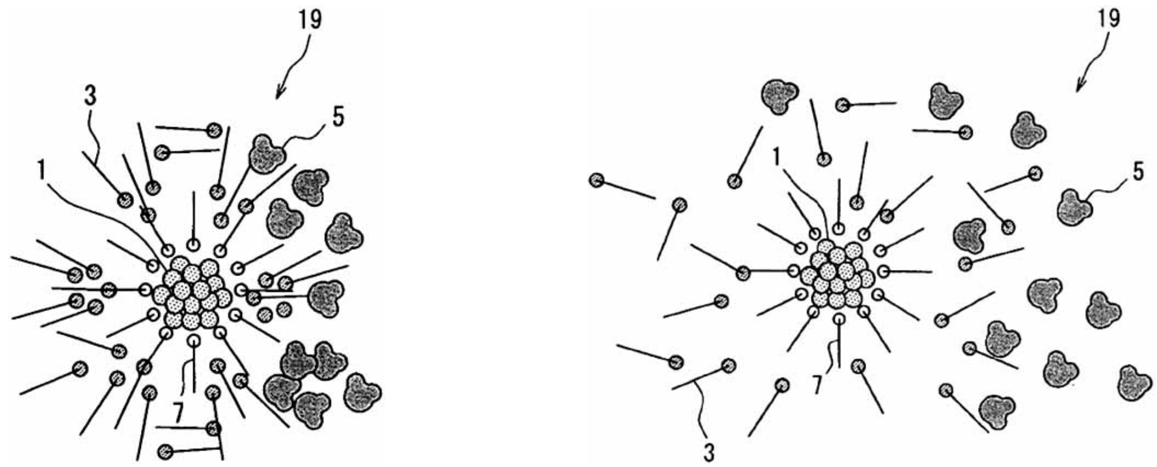
Hong and Marquis [44] invented a method for the preparation of stable nanofluids. This process involves suspension of carbon nanoparticles in a hydrophilic heat transfer fluid to enhance the heat transfer characteristics such as thermal conductivity and freezing point. Carbon nanoparticles are dispersed directly into a mixture of heat transfer fluid and other additives including surfactants (to increase stability of the nanofluid) with intermittent ultrasonication. Another invention is that by Hong *et al*. [45] which relates to three processes for preparing stable suspension of carbon nanoparticles in a heat transfer fluid to enhance thermal conductive, lubrication and viscous properties. The first process disperses carbon nanoparticles directly into the fluid and other additives in the presence of surfactants with occasional ultrasonication. In the second process, carbon nanoparticles are first dispersed into a volatile solvent after which the heat transfer fluid, surfactants and other additives are added and thoroughly mixed. Finally, the volatile solvent is removed leaving behind nanofluid that is uniformly dispersed. The third process involves using physical agitation to disperse carbon nanoparticles into a mixture of surfactants and other additives in the heat transfer fluid at an elevated temperature.

Li *et al.* [46] invented a one-step method for preparing nanofluids consisting of metal oxide nanoparticles dispersed in oily fluids such as lubricant oils. An alkaline aqueous solution and an organic acid metal salt are introduced into a rotating packed bed. The two solutions flow radially through a packing of the bed away from the axis under a centrifugal force making adequate contact with each other. Metal oxide nanoparticles are consequently formed due to relevant reactions at the interface. Figure (**4**) Illustrates a rotating packed reactor that is suitable for the invention [46]. The diagram shows the rotating packed bed which has an annular pack region 12. It is set up on a housing 11. Alkaline aqueous solution which is stored in a tank 1 is pumped by means of a pump 14 into the rotating bed through the inlet at 9. At the same time, an organic solution of an acid metal salt is pumped using 15 from a liquid tank 2 into the bed via another inlet 6. A liquid distributor 4 sprays the organic solution uniformly onto the annular pack region 12. Centrifugal force generated by a variable motor 13 causes the two solutions to rapidly move outwards causing very tiny liquid droplets to be created when the two solutions pass through the packing of the annular pack region 12. As the minute liquid droplets make contact with each other, metal oxide nanoparticles are formed because a base in the aqueous solution and the organic acid metal salt in the organic solution undergo reactions at the interface of the two phases. The products of reaction are collected at the bottom of the housing 11 and discharged through liquid outlet 7 to collection tank 8. A similar invention was patented as a United Kingdom patent [47].

Lockwood *et al.* [48] invented a method for gear oil composition containing nanoparticles. Carbon nanomaterials with graphite structure such as carbon nanotubes and other nanoparticles of carbon are used to improve the viscosity, shear stability, friction properties and thermal conductivity of the gear oil. A surfactant or dispersing agent is used to stabilize the nanoparticles. The gear oil contains other additives such as severe pressure and anti-wear formulations and corrosion inhibitors necessary for gear oil formulation. In the method, processed bulk graphite of high thermal conductivity is ground, milled and dispersed in the base oil by ultrasonication or chemical dispersion.

5. CURRENT & FUTURE DEVELOPMENTS

A variety of aspects related to nanofluids heat transfer phenomena are currently being studied and some arising inventions are being patented. There are currently a wide range of ongoing studies related to nanofluid preparation methods, and the understanding of thermal conductivity and



(3a) **(3b)**

Fig. (3a,b). respectively are schematic diagrams illustrating the structured state and unstructured state of this nanofluid [43].

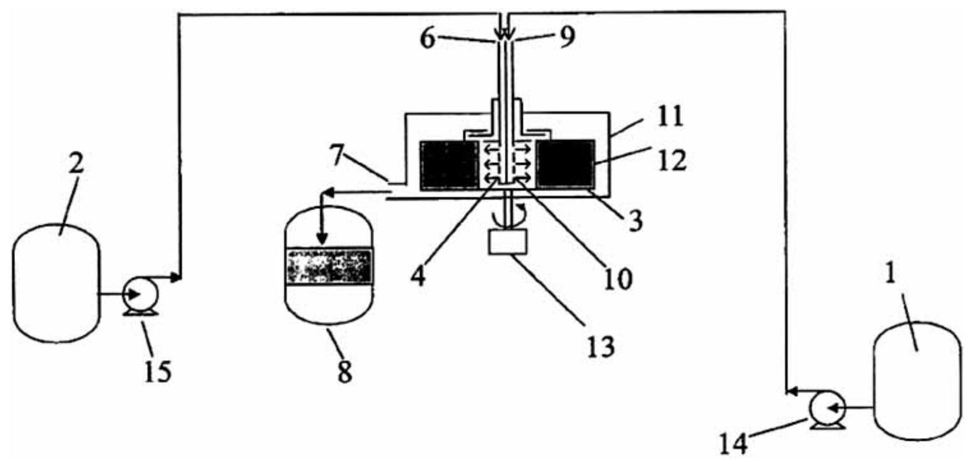


Fig. (4). Rotating packed bed reactor [46].

heat transfer characteristics. Future challenges in this area include (a) the need to create accurate models of the thermal behavior of nanofluids to improve understanding on the underlying heat transfer mechanisms in nanofluids, (b) identifying further innovative applications of nanofluids especially in the area of fluid dynamics and heat exchangers where the application is most needed and (c) the need for more improved modeling and experimental studies on the thermal interactions at the nanoscale to help settle the disagreement between some results on the heat transfer mechanisms in nanofluids. It is clear that traditional macroscopic theories for solid/liquid suspensions are limited for explaining nanofluid theory. Emerging areas of investigation include the application of (a) magnetic field and (b) aggregation of nanoparticles into clusters to enhance the thermal conductivity of nanofluids.

Wright *et al*. [49] reported on a new concept of integrating magnetically sensitive metal or metal oxide nanoparticles in a fluid containing carbon-nanotubes in order to enhance the thermal conductivity of the fluid. The study found that the thermal conductivity of nanofluids containing Ni coated single wall carbon nanotube was significantly enhanced in the presence of applied magnetic field. The surfactant used in the nanofluid was sodium dodecylbenzene sulfonate. The explanation given for the enhanced thermal conductivity is that under the applied magnetic field the Ni coated nanotubes form aligned chains that help to connect the nanotubes resulting in improved contacts. In another study, Wensel *et al*. [50] reported a 10% increase in the thermal conductivity of nanofluids containing metal oxide nanoparticles and carbon nanotubes with applied magnetic field. The report on the study added that the resulting nanofluid can be used for coolant applications since the viscosity was similar to that of water. The enhanced thermal conductivity was attributed to the possible aggregation of metal oxide particles on the surface of nanotubes by electrostatic attraction thus forming the aggregation chain along the nanotube. Lo *et al*. [51] prepared Ni nano-magnetic fluid using submerged arc nanoparticle synthesis system (SANSS). Ni nanoparticles of average diameter 10 nm were fabricated and used for preparing the nanofluid. It was found that the molecules of the surfactant PVP-K30 used for the nanofluid adhered to the surface of the nanoparticles resulting in good dispersion, steady suspension and satisfactory flow of the nanofluid.

Prasher *et al*. [52] used effective medium theory to demonstrate that the thermal conductivity of nanofluids can be enhanced substantially by the aggregation of nanoparticles into clusters thus showing the importance of cluster morphology on the improvement of the thermal conductivity of nanofluids. Evans *et al.* [53] studied the effects of aggregation and interfacial thermal resistance on the effective thermal conductivity of nanofluids and nano-composites. The study found that the thermal conductivity of nanofluids can be enhanced significantly by the aggregation of nanoparticles into clusters depending on the filler conductivity, cluster morphology and the interfacial thermal resistance. Another study that supports the enhancement of thermal conductivity of nanofluids under aggregation phenomena is that by Philip *et al*. [54]. This study reports a dramatic enhancement of the thermal conductivity of Fe_3O_4 based nanofluid under the influence of an applied magnetic field. The explanation given for the enhanced thermal conductivity is that under the influence of the magnetic field, chainlike structures form causing the dipolar interaction energy to become greater than the thermal energy thus resulting in effective conduction of heat through the structures.

An overview of recent developments and patents on nanofluids heat transfer has been presented in this paper. Current research developments have shown that nanofluids have substantial thermal conductivities compared to the base fluids. However, existing theories underlying the heat transfer mechanisms in nanofluids have not been well established and some published theories even disagree with some others. It is clear that the field of nanofluids presents a new field of research and innovative applications that look promising. Exploitation of nanofluids could lead to development of coolants that can be applied in thermal systems leading to remarkable impact in many sectors especially energy and transportation. Designers will be able to reduce the size of cooling components leading to smaller and lighter thermal systems, and possible lower costs. Also, the principles of nanoparticles in biofluids can be applied to drug delivery in body tissues thus providing new medical treatment methods.

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