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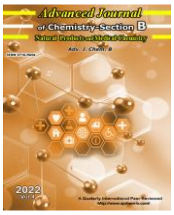

Original Research Article

Investigating the Effect of Nanofluids in Improving the Performance of Heat Exchangers

Alireza Bozorgian [1]*, Amin ahmadpour [2]

[1]*Department of Chemical Engineering, Mahshahr Branch, Islamic Azad University, Mahshahr, Iran*
[2]*National Petrochemical Company, Research and Technology Company, Iran*

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K E Y W O R D S

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Heat Transfer
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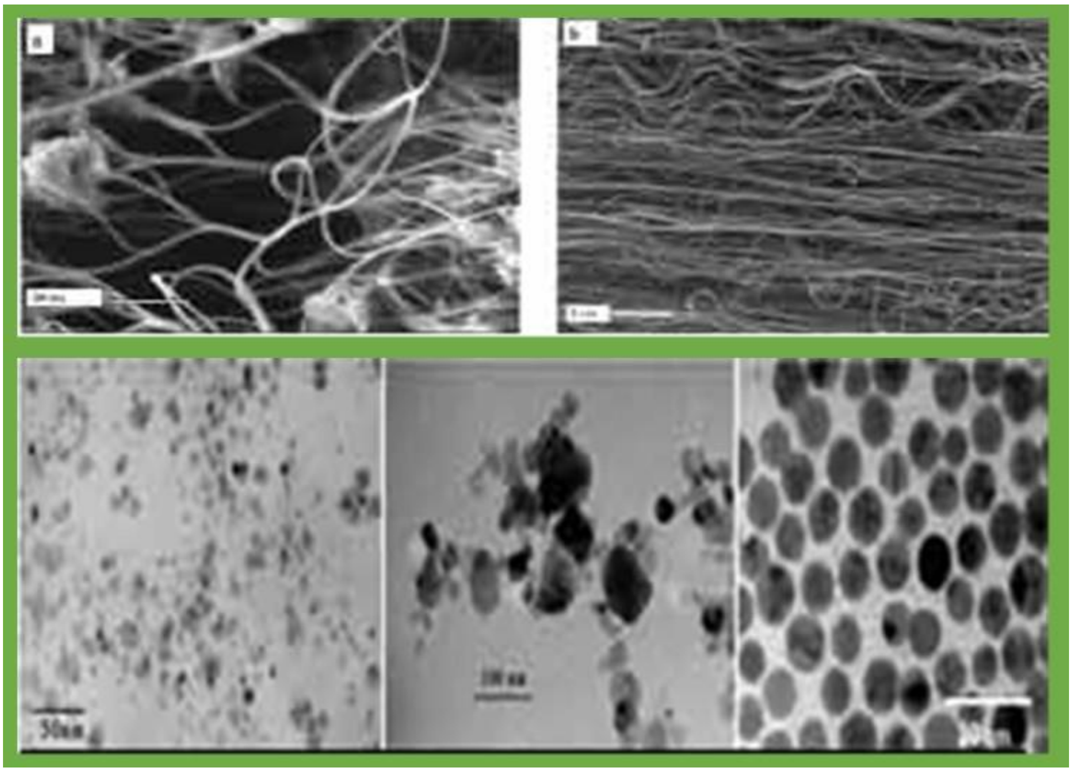
A B S T R A C T

Heat exchangers are used in various industries such as power plants, air conditioning and oil and gas industries. The main role in converters is the responsibility of the fluid flowing in them. Optimizing the heat transfer properties of these fluids can be an important step towards optimizing the performance of the heat exchanger and ultimately increasing productivity in industries. The use of advanced and optimized cooling systems is inevitable. Nowadays, the issue of reducing or optimizing energy consumption is very important due to the depletion of fossil fuel resources. For this purpose, the designers of heat exchangers believe that it is possible to significantly reduce the energy consumption of this equipment by making small changes. The optimization of the existing heat transfer systems is usually done by increasing their surface, which always increases the volume and size of these devices. Therefore, to overcome this problem, new and effective coolants are needed, and nanofluids have been proposed as a new solution in this field. Due to the significant increase in thermal properties, nanofluids have attracted the attention of many scientists in recent years. In this article, the properties of nanofluids have been investigated as one of the most suitable and strongest choices in the field of cooling fluids, which the investigations showed, the exceptional properties of nanofluids include more thermal conductivity than normal suspensions, non-linear relationship between conductivity and concentration of solid materials and There is a strong dependence of conductivity on temperature and a strong increase in heat flux in the boiling zone.

* Corresponding author: Alireza Bozorgian
✉ E-mail: E-Mail: alireza.bozorgian@iau.ac.ir

GRAPHICAL ABSTRACT



Introduction

A new group of fluids, that are able to transfer heat, is called nanofluids. Nanofluids are made by dispersing nanometer-sized particles in common heat exchanger fluids to increase thermal conductivity and improve heat transfer performance [1-3]. Nanofluid is a new type of heat transfer medium that shows a great ability to transfer heat. These fluids are produced by adding metallic and non-metallic particles in the nano scale to the base fluid under special techniques. These particles remain in suspension and do not cause wear problems in equipment and transmission lines [4]. Nanofluids have many applications in heat exchangers, air-space industries, power plants, etc. and in all cases, they reduce the energy consumption of the system and by improving the design, they create the possibility of producing compact systems. The use of nanofluids can significantly reduce industrial water consumption due to their high heat transfer intensity [5-7]. In some researches, the thermal conductivity of nanofluids is several times higher than predicted by theories. Another very interesting result is the strong dependence of thermal conductivity of nanofluids on temperature and the increase of almost three times of their critical heat flux compared to normal fluids [8-10]. These changes in thermal properties of nanofluids are not only of interest to academics, and in the case of successful preparation and confirmation of their stability, they can create a promising future in thermal management of the industry [11-13]. Of course, the suspension of metal nanoparticles has been used in other fields, including the pharmaceutical industry and cancer treatment. Anyway, the research in the field of nanoparticles has a very wide future [14].

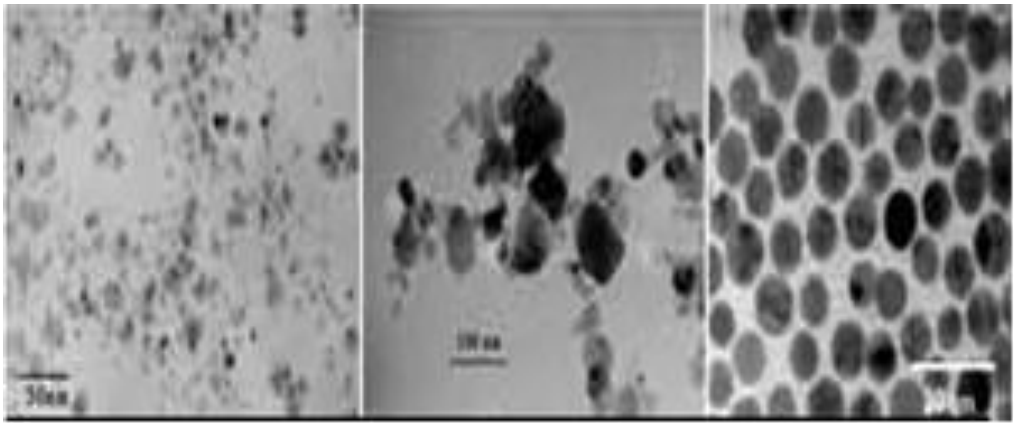


Fig. 1. TEM images of copper nanofluid (left), copper oxide nanoparticles (middle), and gold-lead colloidal particles (right) used in interface resistance studies. Copper oxide particles are clustered and gold-lead colloids have proper distribution and uniform size.

A review on the effects of metal nanoparticles on heat transfer of nanofluids

The impact of nanotechnology on particles and materials produced with this technology is such that it is possible to distinguish such materials from similar materials in macromolecular size and define new properties for them [15-17]. Among the properties affected by nanotechnology, we can mention the physical chemical properties of nanometer particles and the fluid containing them, which have many differences compared to macromolecular materials. The conduction mechanism in fluids at the macromolecular scale is very low, because the conductive heat transfer coefficient of fluids (K) is very low compared to solids [18-20]. On the other hand, microcrystalline particles and solids have a conductivity coefficient of about 31 times that of liquids. In this way, the conductivity coefficient of fluids can be increased to a large extent using particles suspended in them. These metal oxide particles can be Al_2O_3, Cu, CuO, or carbon nanotubes suspended in the fluid can be used instead. The use of nanoparticles in fluids increases heat transfer coefficient and consequently increases heat transfer, and also reduces production and operational costs. In addition, increasing heat transfer enhances the efficiency. Therefore, the required power of pump and the level of heat transfer are reduced, which in turn reduces the fixed costs (F.C.I). Furthermore, the increase in efficiency leads to better control of the transferred heat, which reduces the negative effects of energy on the environment [21-23].

Solid particles in single-phase flow

Adding solid particles suspended in the base fluid is one of the methods of heat transfer. Increasing thermal conductivity coefficient is the main idea in improving heat transfer characteristics of fluids. Since the thermal conductivity coefficient of solid particles is usually much larger than that of fluids, it is expected that addition of these solid particles will increase thermal conductivity coefficient of the base fluid. Increasing the coefficient of thermal conductivity of liquids as a result of adding particles with millimeter and micrometer size has been known for more than a hundred years, but the use of these particles is due to practical problems such as rapid sedimentation of particles, severe wear, pressure drop, and it is not possible to use them in very small channels [24-26]. Recent advances in materials technology have provided the production of nanometer-sized particles that can overcome these problems. By spreading these nano materials in the fluid, a new type of fluid is created, which is called nanofluid. Suspended nanomaterials strongly affect the kinetic and thermal properties of the base fluid [27].

Extensive research has been done on the thermal characteristics of nanofluids, and almost all of them confirm the significant improvement of these properties. In this regard, the addition of gas bubbles and other liquids to the base fluid does not show improvement as much as the addition of nanoparticles [28].

The exceptional properties of nanofluids include higher thermal conductivity than normal suspensions, non-linear relationship between conductivity and concentration of solids, strong dependence of conductivity on temperature, and a strong increase in heat flux in the boiling zone. These exceptional properties, along with the stability of relatively easy preparation method and acceptable viscosity, have made these fluids to be considered as one of the most suitable and strongest choices in the field of cooling fluids [29-31]. The results of one of the studies published in the field of changing thermal conductivity of nanofluid as a function of concentration are shown in Figure (2).

Heat transfer in static fluids

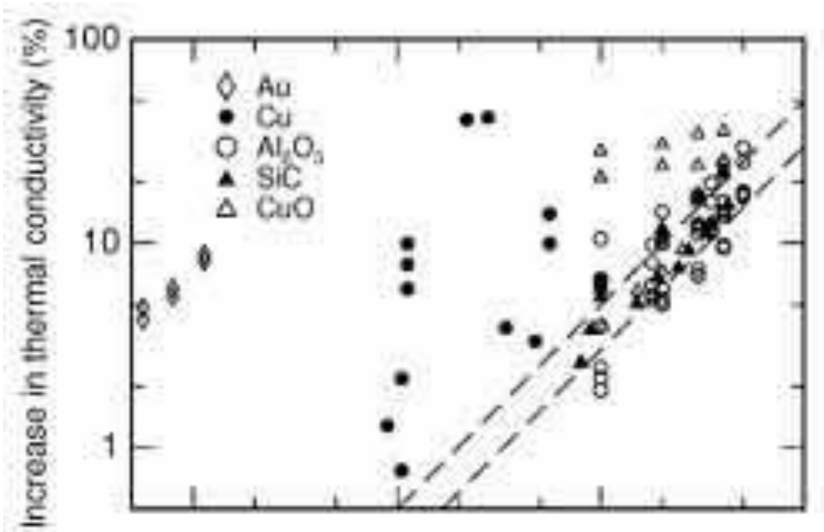


Fig. 2. The relationship between electrical conductivity and volume component of nanoparticles based on the average mean theory for highly conductive nanoparticles (bottom dashed line) and dense clumps model.

Most researches on thermal conductivity of nanofluids have been done in the field of fluids containing metal oxide nanoparticles. Masuda has reported a 30% increase in thermal conductivity by adding 4.3% by volume of alumina to water, but he has reported a 15% increase for the same type of nanofluid with the same volume percentage. The difference in these results is due to the difference in the size of nanoparticles. He knows the work done in these two researches. The average diameter of the alumina particles used in the first experiment was 13 nm and in the second experiment, it was 33 nm. Zai *et al.* have reported a 20% increase for 50% volume of these nanoparticles [32-34]. A similar group reached similar results for silicon carbide nanoparticles, but observed relatively less improvement in the thermal conductivity of nanofluids containing copper oxide nanoparticles compared to aluminum nanoparticles. While Wang reported a 17% increase in thermal conductivity for only 0.4% volume of copper oxide nanoparticles in water. For nanofluid based on ethylene glycol, an increase of more than 0.4% has been reported for 0.3% by copper volume with an average diameter of ten nanometers. Patel observed a high increase of 21% for the 11% volume suspension of gold and silver nanoparticles dispersed in water and toluene, respectively. In some cases, no significant increase in conductivity has been observed. Recently, another research on the conductivity dependence on temperature is being carried out for high concentrations of metal oxide nanoparticles and low concentrations of metal nanoparticles. In both cases, a two- to four-fold increase in conductivity has been observed in the temperature range of 20 to 50 °C, and if confirmed these properties can be used in heating systems for higher temperatures. The highest increase in conductivity has been reported in the suspension of carbon nanotubes, which, in addition to high thermal conductivity, have a high ratio of length to diameter (Figure 3) [35].

Since carbon nanotubes form a fiber network, their suspension acts more like polymer composites. Bircock reported a 125% increase in conductivity in polymer-nanotube epoxy containing 1% single-walled nanotubes. He also observed that thermal conductivity increases with increasing temperature. Choi has reported a 16% increase in thermal conductivity for a 1% suspension of multi-walled nanotubes in oil (Figure 3b). Various reports and researches have been presented in the field of increasing thermal conductivity of carbon nanotube suspension. He has reported a ten to 20% increase in thermal conductivity in a suspension of one volume percent with water fluid. Wen and Ding also reported a 25% increase in conductivity in a suspension of 0.8% by volume in water. Asil has reported the highest increase of 38% for a suspension of 6% by volume in water. Wen and Ding reported a rapid increase in conductivity at concentrations of about 0.2% by volume and showed that this increase remains almost constant thereafter. In all reports, an increase in conductivity with temperature was observed (Figure 4), although this increase almost stops for temperatures higher than 30 °C [36-38].

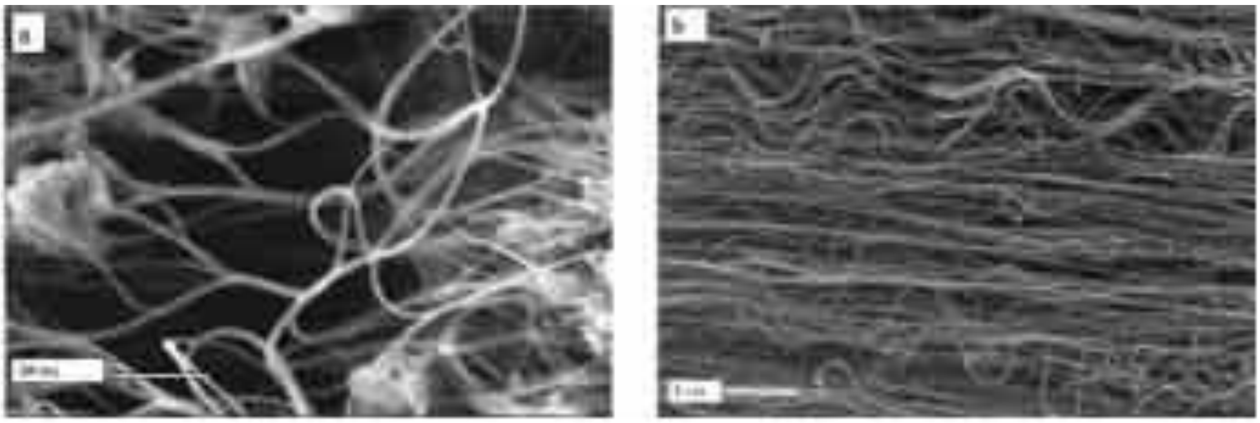


Fig. 3. SEM images of single-walled (a) and multi-walled and (b) carbon nanotubes used in suspensions and composites

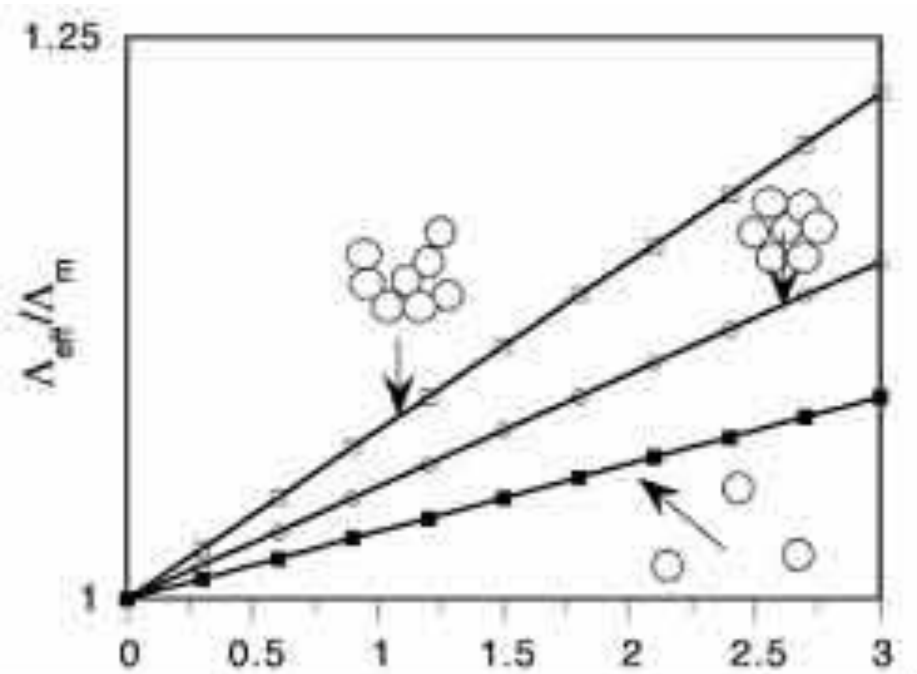


Fig. 4. Prediction of thermal conductivity of composites as a function of filler volume component Solid square: particles with proper distribution

●*Circle: clusters of dense particles with 60 percent by volume.*

●*Square: clusters with lower density with 40 percent of nanoparticles by volume.*

Thermal conductivity of nanofluid

Thermal conductivity of nanofluid has been studied the most. This article also deals with thermal conduction in static fluid. Since nanofluid is considered as a composite material, its thermal conductivity is obtained by the effective medium theory, which was obtained by Musotti, Clausius, Maxwell, and Loranza in the 9th century. As shown in Figure (2), many researches are in good agreement with this prediction. Among others, the following researches can be mentioned: silicon carbide nanofluid with a size of 26 nm and alumina-water and alumina-ethylene glycol nanofluids. The interface resistance between the nanocorn and the fluid around it reduces the prediction of this theory. Of course, the finer the particles, the lower this resistance. At high concentrations of nanoparticles (Figure 1), if the nanoparticle masses are small, the effective average theory works well. Because the mass of nanoparticles occupies more space than single nanoparticles, and therefore the volume component of the mass is more than that of single nanoparticles. In dense masses of nanoparticles, the relative density is approximately 60%, and in cases where the masses are more open in terms of structural condition, we see a greater increase, which the experimental results also show. Of course, thermal conductivity of bulk nanoparticles is smaller than individual particles. Of course, it is not an important factor against high thermal conductivity of nanoparticles [39].

Flow, displacement and boiling

Recently, nanofluid heat transfer coefficients have been measured in free and forced displacement. Das started experiments to determine boiling thermal properties for nanofluids. U measured the critical heat flux of boiling alumina-water nanofluids and reported a threefold increase in critical heat flux (CHF) compared to pure water. In this context, Vassallo prepared silica-water nanofluid and reported the same three-fold increase in CHF. In addition to be dependent on thermal conductivity, the free displacement heat transfer coefficient is dependent on other properties such as specific heat, density, and dynamic viscosity, although in these low volume percentages, as expected and observed, specific heat and density are very Base fluid is close. Wang measured the alumina-water viscosity and showed that better and more dispersed the particles, the lower the viscosity [40-42]. He reported a 30% increase in viscosity for a suspension of 3% by volume, which seems to be three times more compared to the result of Packercho, which indicates the viscosity dependence on the nanofluid preparation method. Xuan and Li obtained the friction coefficient for nanofluid containing one to two percent of copper particles and showed that this coefficient is almost similar to water-based fluid. Eastman showed that forced displacement heat transfer coefficient of a suspension of 0.9% by volume of copper oxide nanoparticles is 15% higher than the base fluid. Zhuang and Lee also measured the forced displacement heat transfer coefficient in turbulent flow and showed that a small amount of copper nanoparticles in deionized water increases heat transfer coefficient significantly. For example, adding two volume percent of copper nanoparticles to water increases its heat transfer by about 39%. Whereas, compared to the above results, Pequecho observed a 12% decrease in heat transfer coefficient in the suspension containing 3% by volume of alumina and titana under the same conditions. By working on free displacement as opposed to forced displacement, Putra observed a decrease in heat transfer. By conducting boiling tests on alumina-water, Das showed that with increasing volume percentage of nanoparticles, the boiling efficiency decreases compared to the base fluid [43].

He attributed this reduction to the change in surface properties of the boiler due to the deposition of nanoparticles on its uneven surface, not to the change in fluid properties. By measuring the critical heat flux for boiling on flat and square copper surfaces immersed in water-alumina nanofluid, Yu showed that heat flux of these fluids is three times that of water, and the average bubble size, increase and frequency of their production decreases, which confirms these results. Vassalo also worked on water-silica nanofluid and reported the increase of critical heat flux for concentrations less than one thousandth volume percent. There is still no model to predict these increases and factors affecting it [44].

Smart cooling and heating by nanofluids

Nanofluids can act as smart materials and switch between a state of high and effective heat dissipation (on) and a state of low heat dissipation (off). Heating and cooling are very important to achieve optimal performance in any technological device. Convection is a fundamental process for heat transfer in fluids. This process plays an essential role in a large number of natural phenomena such as air circulation in the atmosphere and water circulation in the oceans, and it is very important in countless technological applications in which cooling and thermal insulation are important. Adding some nanoparticles in the form of a suspension to a fluid and creating a so-called nanofluid greatly increases heat transfer power of the fluid, although the reason for this increase is still not completely clear. In the past, the attention of scientists and engineers was more focused on loss of large amounts of heat because they believed that high heat loss prevents the device from overheating, and thus increases its efficiency. In recent years, due to the lack of abundant sources of clean energy and the wide spread of devices such as mobile phones and laptops that use batteries, the need for intelligent management of resources and prevention of energy waste has become more apparent. Now Robert Sergino and Albert Vailanti, physicists at the University of Milan, have shown that a special class of nanofluids can act as a smart material and be used like a heat valve to control the heat flow. These nanofluids can be easily adjusted either in "low" or "high" mode [45].

Metal nanofluids and cooling engines

The characteristics of diesel engines are rapidly changing in terms of limitations in reactions and work efficiency. Cooling systems should be able to work under higher temperatures and transfer more heat to the surrounding environment. The size of radiators should also be reduced so that the additional equipment of trucks is removed and transportation with them becomes easier. Realistically, it will be possible to enclose more cooling power in less space only by using new technologies such as nanofluids. Another application of these modelings is to predict the thermal conductivity of a nanofluid based on the concentration, operating temperature, and size of nanoparticles dispersed in the fluid. After all, it is possible that the properties of nanolayers formed on the surface of suspended nanoparticles are a factor for further increasing the thermal conductivity of nanofluids. The two key mechanisms of Brownian motion and nanolayers are the most important factors in increasing thermal conductivity of heat transfer fluids. Argon laboratory researchers are investigating the potential dangers of nanofluids for radiator systems. They managed to build a device that is able to measure and test the effect of different cooling currents on the performance of a radiator. Future research will focus more on the type of nanoparticles used in the manufacture of nanofluids, including aluminum particles and coated metal oxide nanoparticles.

Diffusion model for heat transfer modeling of nanofluid flow inside the tube

Nanofluids provide a very high and unpredictable improvement in the properties and amount of heat transfer. In the field of heat transfer of nanofluids, it seems that the use of diffusion pattern in the analysis of nanofluid flows brings encouraging results compared to the results of homogeneous flow. In the conducted researches, a relation for diffusion conductivity coefficient was initially introduced and an attempt was made to numerically solve the nanofluid flow using the diffusion pattern inside a tube. The efficiency of the presented model has been investigated in the case of nanofluid containing aluminum oxide particles in water. Forced displacement heat transfer of nanofluid in slow flow inside a tube with constant temperature. Nowadays, one of the issues raised in heat transfer processes is the need to significantly increase heat flux and miniaturize heat transfer equipment. The conventional fluids for heat transfer; including water, ethylene glycol, and motor oil have very low thermal conductivity coefficients compared to metals and even metal oxides. The process of producing nanometer particles should be considered as a revolution in increasing heat transfer. Fluids containing very fine suspended particles of nanometer size, which are called nanofluids, show great potential for increasing heat transfer. Special attention should always be paid to this group of fluids as heat transfer media.

Examples of nanofluid applications include

1- Application in heat exchangers, which leads to a significant reduction in the flow rate of the working fluid, and finally heat exchangers with smaller size and weight are designed.

2- Nanofluid is used in the production of cooling systems for silicon mirrors and advanced monochromators producing x-rays and photons.

3- In engine oil cooling systems, a study has been carried out that shows a further reduction of the friction coefficient by means of engine oil at high speeds by adding nano-copper powder to engine oil.

4- It is possible to reduce the radiator dimensions of vehicles using nanofluid. Direct and indirect use of nanofluid reduces the amount of energy consumed by making the car's radiator smaller.

5- If nanofluid is used in supercomputer chips, high-speed computing systems, electronic equipment, microwave tubes, high-power lasers, and heat pipes, the produced heat will be exchanged more effectively.

In this article, forced displacement heat transfer of nanofluid Al_2O_3 and water, water and CuO, as well as water and Cu in slow flow inside the pipe with constant wall temperature, in a designed and built experimental system, has been experimentally investigated and the changes in the number Nusselt and average heat transfer coefficient in terms of Pequet number in different concentrations of nanoparticles have been investigated. The results of the studies show an extraordinary increase in the heat transfer coefficient and Nusselt number by adding nanoparticles to water, and this increase increases with the volume fraction of nanoparticles and Peclet number. In addition, the research results show an increase in the displacement heat transfer coefficient by means of Cu metal particles, which is more compared to metal oxide particles. In these investigations, the percentage of increase in the heat transfer coefficient of nanofluid compared to water has been determined experimentally and the reasons for the discrepancy between the experimental results and theoretical values have been discussed.

Preparation of nanofluids

Improving the thermal properties of nanofluid requires choosing the appropriate preparation method of these suspensions to prevent their settling and instability. According to the application, there are many types of nanofluids, such as metal oxide nanofluids, nitrites, metal carbides, and nonmetals, which have been created with or without the use of surfactants in fluids such as water, ethylene glycol, and oil. Many studies have been done on how to prepare nanoparticles and their dispersion methods in base fluid, and here we briefly mention some common methods for preparing nanofluids. One of the common methods of nanofluid preparation is the two-step method. In this method, first, the nanoparticle or nanotube is usually prepared as dry powders by chemical vapor deposition (CVD) in an inert gas atmosphere, and in the next step, the nanoparticle or nanotube is dispersed inside the fluid. For this purpose, some methods such as ultrasonic vibrators or surfactants are used to minimize nanoparticle masses and improve dispersion behavior. The two-step method is very suitable for some cases, such as metal oxides in deionized water, and it has been less successful for nanofluids containing heavy metal nanoparticles. The two-step method has potential economic advantages because many companies have the ability to produce nano-powders on an industrial scale. The one-step method has progressed parallel to the two-step method. For example, nanofluids containing metal nanoparticles are prepared using the direct evaporation method, and in this method, the metal source is evaporated under vacuum conditions (Figure 1, left). In this method, the mass concentration of nanoparticles reaches its minimum, but the low vapor pressure of the fluid is considered as one of the disadvantages of this process, but despite this, various single-step chemical methods have been created for the nanofluid preparation, one of which is the salt recovery method and the preparation of its suspension in different solvents for the preparation of metal nanofluids (Figure 1, right). The main advantage of the one-step method is very good control over the size and distribution of particles.

Conclusion

In the last ten years, interesting properties have been reported for nanofluids, among which thermal conductivity has attracted the most attention, but recently other thermal properties have been further researched. Nanofluids can be used in various fields, but this work faces obstacles, including the fact that several points should be paid more attention to nanofluids:

- ✓ Inconsistency of experimental results in different laboratories.
- ✓ Weakness in determining the characteristics of nanoparticle suspension.
- ✓ Lack of suitable models and theories to investigate the change of nanofluid properties.

The exceptional properties of nanofluids include higher thermal conductivity compared to the normal suspensions, non-linear relationship between conductivity and concentration of solids, strong dependence of conductivity on temperature, and a strong increase in heat flux in the boiling zone. Exceptional properties along with stability, relatively easy preparation method, and acceptable viscosity have caused nanofluids to be considered as one of the most suitable and the strongest choices in the field of cooling fluids. A small amount (about one percent by volume) of copper nanoparticles or carbon nanotubes in ethylene glycol or oil increases the thermal conductivity of these fluids by 40 and 150 percent, respectively.

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