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Nanofluid technology: Review of current uses in energy field and future research

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Abstract
Nanofluids have superior thermal properties over base fluids such as water, mineral oil, vegetable oil, thermal oil & synthetic oil. This feature makes them very attractive as heat transfer fluids in many energy applications and manufacturing processes. Nanofluids have been defined as suspensions of nanoparticles (1-100 nm) in a base fluid. Nanofluids have other applications in biotechnology applications for drug delivery and advanced sensor technology. Nanoparticles are made of stable metals, metal oxides, or carbon in different forms. However, this paper focuses on a review of the nanoparticle's use, characteristics, and behavior in different fields and enhanced energy, momentum and mass, and heat transfer, and finally presents future research prospects in nanofluid technologies.

Keywords: Nanotechnology, status, research, energy, solar applications of nanobiotechnology

Introduction
Research on nanofluids presented interesting applications and uses for dispersions of nanoparticles mixed or suspended in conventional fluids. Since the term nanofluid was first coined by [1-3]. Nanofluid, is a fluid consisting of solid nanoparticles with a size less than 100nm suspended on it with solid volume fractions. Nanofluids are characterized by suspending nanoparticles of metals and metal oxides [1-7]. Nanoparticles include a wide range of materials including nanocrystalline materials, nanocomposites, carbon nanotubes, and quantum dots. Nanofluid particles exhibit enhanced properties (mechanical, thermal, physical, chemical), phenomena, and processes than conventional materials. There are four types of nanomaterials: Carbon-based nanomaterials, Metal-based nanomaterials metal oxides, Dendrimer, and Composites (nanosized clays) [1-7]. nanoparticles help to improve thermal conductivity and convective heat transfer of liquids when injected with base fluids [1-20]. However, this can be associated with high-pressure drops occurring due to sedimentation, excessive wear, and clogging due to micro-sized particles. Numerous articles have been published in the literature on nanofluids [1-50], and in the following, we will discuss several issues related to nanofluids such as thermodynamic and thermophysical properties, stabilities, and different applications in various fields.

Thermophysical properties of nanofluids
The heat transfer fluid can be significantly enhanced in heating or cooling applications, with suspended nanoparticles increased and in turn the heat capacity of the fluid, the effective thermal conductivity of the fluid is increased with the presence of nanoparticles, and fluid and the flow passage surface are intensified and the interaction and collision among particles, and the mixing fluctuation and turbulence of the fluid are intensified and finally the dispersion of nanoparticles flattens the transverse temperature gradient of the fluid. The thermophysical properties of nanofluids are Viscosity, Specific heat, Thermal Conductivity and Stability. These properties play an important role in the thermal behavior of Nanofluids.

Viscosity
It is important to understand the nature of the nanofluids; Newtonian or shear flow Y. Li, et [1]. They reported that the nanofluids behaved as Newtonian when 13 and 27n nm nanoparticles of Al2O3 and TiO2 were suspended in water and limited to low particle volume fractions. Shear thinning behavior was, however, observed with the increase of particle volume fraction also reported observed with a large increase of viscosity of the behavior of Newtonian or shear nanofluids, and showed that this was not predicted by standard empirical models and in particular, Li *et al*. reported that Newtonian behavior of the nanofluid occurs at 1% to 4% concentrations by volume. It was shown by Lin *et al* [1] that the viscosity and thermal conductivity of nanofluids with carbon nanotubes (CNTs) behave quite differently than other nanofluids. Viscosity is as critical as thermal conductivity in determining and assessing pumping power as well as the heat transfer coefficient in thermal engineering systems. Whereas, higher nanoparticle volume fractions result in more viscous, attenuating the velocity, and reducing convection. In addition, it was shown that a lower reduction of velocity and convection will increase the thickness of the thermal boundary layer thickness; thus, lowering the Nusselt number.

Specific Heat
Literature on experimental measurements of specific heats of nanofluids is very limited as reported by Xiang Q W and Arun S M [2], Similarly, Das [4, 5] reported that a water-alumina nanofluid appeared to have enhanced thermal conductivity, but lower specific heat, compared to the base fluid. Das [4, 5] also studied nanofluids with 2–10% by volume of Al2O3, SiO2, and ZnO nanoparticles in a 60:40 ethylene glycol-water mixture. They also reported that the specific heat of the nanofluids decreases substantially as the volumetric concentration of nanoparticles increases and it increases moderately with temperature and was also reported that theoretically, it was able to predict the nanofluid density and specific heat within a 10% deviation [4, 5]. In addition, it was found by references [6 through 9] that the agglomerated alumina nanoparticles tend to precipitate out of the water solution; consequently,

degrading the thermal properties of the nanofluid. Furthermore, the specific heat is enhanced due to the higher specific surface energy of the surface atoms of the nanoparticles, as compared to the bulk material. The surface energy is higher because of the low vibration frequency and higher amplitudes of the vibrations at the surface of the nanoparticles. However, it has been reported [4, 5] that the enhancement of the specific heat can also be due to additional thermal storage mechanisms due to interfacial interactions between nanoparticles and the liquid molecules.

Thermal Conductivity

Suspended particles remarkably increase the thermal conductivity of nanofluids over the base fluid. It is well known that the thermal conductivity of nanofluids is strongly dependent on the nanoparticle volume fraction as well as the other properties of the nanofluids. Sophisticated theory is used to predict the thermal conductivity of nanofluids, however, there are some semiempirical correlations to calculate the conductivity based upon the two-phase mixture theory. Formulas developed for the two-phase mixtures that contain powders with particle diameters on the order of micrometers or even millimeters can be used. However, these formulas can be applied to obtain a rough estimation of the thermal conductivity of nanofluids. In addition, it must be noted that the effective thermal conductivity of using suspensions can be increased by decreasing the sphericity of the particles under the condition of the same volume fraction. These results clearly show that the increase of the thermal conductivity and the conventional heat transfer depends upon the nanoparticle material [14-23].

Stability of the Nanofluids

Many methods have been developed to assess the stability of nanofluids in the literature [24, 25]. Reference [24] presented the sedimentation method. The sediment weight or known sediment volume of nanoparticles in a nanofluid under an external force field is an indication of the stability of the characterized nanofluid. The variation of concentration or particle size of supernatant particles with sediment time can be obtained by special apparatus [25]. The nanofluids are considered to be stable when the concentration or particle size of supernatant particles remains constant. A sedimentation photograph of nanofluids in test tubes taken by a camera is also a usual method for observing the stability of nanofluids [25]. Zhu *et al*. used a sedimentation balance method to measure the stability of the graphite suspension [29]. Therefore, the centrifugation method is developed to evaluate the stability of nanofluids. Singh *et al*. applied the centrifugation method to observe the stability of silver nanofluids prepared by microwave synthesis in ethanol by reduction of Ag NO3 with PVP as a stabilizing agent [30]. It has been found that the obtained nanofluids are stable for more than 1 month in the stationary state and more than 10 h under centrifugation at 3,000 rpm without sedimentation. The excellent stability of the obtained nanofluid is due to the protective role of PVP, as it retards the growth and agglomeration of nanoparticles by steric effect.

Applications of Nanofluids

Applications of nanofluids include a broad range of engineering applications particularly in the areas of thermal systems; in the following, we will discuss some of these applications in fields related to thermal systems [1-50].

Heat Transfer

Electronic Applications

Nanofluids can be used as coolants in micro-electronic devices where the sizes have been diminishing resulting in high heat generation which needs to be removed efficiently for the optimal functioning of these devices [9] and [10]. In the automobile industry nanofluids can play a very important role in the removal of excess energy that is generated due to the combustion of the fuel. When flowing through the tubes of the radiator nanofluids can lose their heat to the surrounding air through its walls. In all manufacturing processes which require heat transfers, the conventional fluids can be replaced by nanofluids. Understanding the underlying mechanisms that cause the enhancements, it is important to investigate the properties and flow characteristics of nanofluids [4]. Recent research has demonstrated that nanofluids increase the heat transfer coefficient by increasing the thermal conductivity of coolants as pointed out in references [37-38] compared to devices using pure water as a working medium. Nanofluids can increase the thermal resistance and the temperature difference between the heated microchannel wall and the coolant [58-60]. It was found that microchannel heat sinks combined with nanofluids have significant potential as the next-generation cooling devices for removing ultrahigh heat flux. This enhancement is caused by the increase in thermal conductivity of coolant the nanoparticle thermal dispersion effect small pressure drops with the use of the nanoparticles, and low volume fraction [60].

Transportation

Nanofluids can play a significant role in dissipating that thermal waste heat and increasing the efficiency, lowering the weight, and reducing the complexity of thermal management systems. It is, in turn, energy and fuel consumption that is very beneficial to the high performance and high fuel economy of cars and trucks. References [38-41] reported that Ethylene glycol-based nanofluids have attracted much attention in their application as engine coolants because of the low-pressure operation compared with a 50/50 mixture base fluid of ethylene glycol and water, used as automotive coolant. Tzeng *et al*. [41] applied nanofluids to the cooling of automatic transmissions in a four-wheel drive vehicle. The used nanofluids used CuO and Al2O3 nanoparticles were injected into engine transmission oil. Their results showed that CuO nanofluids lowered the transmission temperatures both at high and low rotating speeds.

Industrial Cooling Applications

The use of nanofluids instead of cooling and heating water with nanofluids has the potential to conserve 1 trillion Btu of energy [42]. For the US electric power industry, using nanofluids in closed-loop cooling cycles could save about 10–30 trillion Btu per year (equivalent to the annual energy consumption of about 50,000–150,000 households) [64-65] The associated emissions reductions would be approximately 5.6 million metric tons of carbon dioxide, 8,600 metric tons of nitrogen oxides, and 21,000 metric tons of sulfur dioxide [70]. Experiments were performed [66] to study the performance of polyalphaolefin nanofluids containing exfoliated graphite nanoparticle fibers in cooling showed that the specific heat of nanofluids was found to be 50% higher for nanofluids compared with polyalphaolefin ass base fluid, and also increased with temperature, and enhanced thermal diffusivity and the convective heat transfer.

Heating Building and Reducing Pollution

Sami [44] reported that nanofluids can be used successfully in heating buildings in cold climates compared to base fluid ethylene or propylene glycol mixed with water in different proportions as a heat transfer fluid. The results of his work showed that using nanofluids in heat exchangers reduces volumetric, and mass flow rates and reduces overall pumping power. Moreover, nanofluids when used in heating systems, are capable of delivering equal thermal energy as larger heating systems but at less cost. This also reduces the environmental pollutants and has less liquid and material waste.

Space and Defense

The increases in the critical heat flux in pool boiling with nanofluids compared to the base fluid have been reported by Vassallo *et al.* [45] This study is important since several military devices and systems require high-heat flux cooling to high levels of MW/m2, where cooling of military devices and systems is vital for efficient and reliable operation. Also, it has been reported that other nanofluids with high critical heat fluxes have great potential to supply required cooling in such applications as other military systems, including but not limited to military vehicles, submarines, and high-power laser diodes. Therefore, nanofluids can make a significant improvement in space and defense fields, where power density is very high, and the components' weight is critical.

Mass Transfer Enhancement

Mass transfer enhancement of nanofluids in absorption for NH3/H2O absorption systems has been presented by several studies [39]. The addition of nanoparticles enhanced the absorption performance. These references also studied the effect of nanoparticles and surfactants on the absorption characteristics and their results show that surfactants and nanoparticles improved the absorption performance during the ammonia bubble absorption process numerical investigations of thermodiffusion and diffusion-thermo were also reported.

Energy Applications

Absorption of solar and thermal energy can maximize the size, shape, material, and volume fraction of the nanoparticles, the suspended nanoparticles increase the heat transfer surface area and the heat capacity of the base fluid, suspended Nanoparticles enhance the thermal conductivity which in turn improve the efficiency of heat transfer equipment, they can transfer heat to a small area of base fluid, they can induce mixing fluctuation and turbulence of the base fluid, dispersion of nanoparticles reduces transverse temperature gradient of the base fluid, changing the volume fraction can change the fluid base properties and finally Nanofluids enhance the temperature of solar thermal applications.

Energy Storage

Recently, a significant emphasis has been placed on the storage of thermal energy in energy management and the conservation of waste heat and solar energy in industry and buildings [39]. Latent heat storage is one of the most efficient ways of storing thermal energy [39]. Wu *et al*. Al2O3-H2O nanofluids as a new phase change material (PCM) for the thermal energy storage of cooling systems. The outcome is that the addition of Al2O3 nanoparticles remarkably decreased the supercooling degree of water, advanced the beginning freezing time, and reduced the total freezing time.

Solar Collectors

Recently, references [39] reported that solar absorption by solar collectors can be combined with the emerging technologies of nanofluids and liquid-nanoparticle suspensions can create a new class of nanofluid-based solar collectors. The efficiency improvement was reported by these references up to 5% in solar thermal collectors by utilizing nanofluids as the absorption media. In addition, when compared to the experimental data results showed an increase in efficiency with volume fraction, followed by a leveling off in efficiency as volume fraction continues to increase. Furthermore, it was shown that direct absorption solar collector with the presence of nanoparticles increased the absorption of incident radiation.

Mechanical Applications

Nanoparticles in nanofluids can form a protective film with low hardness and elastic modulus on the worn surface which makes the nanofluids excellent lubricants. Since magnetic fluids are considered as special nanofluids. It is also well known that magnetic liquid rotary seals operate with no maintenance and have extremely low leakage [39].

Friction Reduction

Energy saving and reliability of engineering equipment can be improved with the lubricants integrated nanofluids [37-40]. Nanoparticles have excellent load-carrying capacity, good extreme pressure, and friction-reducing properties. References [39] studied the tribological behavior of Cu nanoparticles in oil on a four-ball machine. Their data showed that Cu nanoparticles as an oil additive had better friction-reduction and anti-wear properties than zinc dithiophosphate, especially at high applied loads. Also, nanofluids can strikingly improve the load-carrying capacity of the base oil [39]. In addition, nanofluids showed the benefits of reducing grinding forces, improving surface roughness, and preventing workpiece burning Compared to dry grinding, MQL grinding could significantly reduce the grinding temperature.

Magnetic Sealing

Ferromagnetic fluids are considered as special nanofluids. They are extremely stable colloidal suspensions of small magnetic particles such as magnetite (Fe3O4). Their properties can be varying their size and adapting their surface coating to meet the requirements of colloidal stability of magnetic nanofluids with nonpolar and polar carrier liquids [39-41]. Mechanical sealing, magnetic sealing is a cost-effective solution to environmental and hazardous gas sealing in different industrial rotation equipment with high-speed capability, low-friction power losses, long life, and high reliability. It was also reported that an iron particle dispersed magnetic fluids can be used in the sealing of a high-rotation pump. The sealing can hold a pressure of 618 kPa to 1800 r/min.

PV-Thermal solar collectors

To improve solar photovoltaic (PV) efficiency, references [41] developed and implemented a novel concept of a combined photovoltaic-thermal solar panel hybrid system using nanofluids where the PV cells of the solar PV panels are cooled by water flows. The excess thermal energy is generated and dissipated due to the intrinsic conversion efficiency limitation of the cell. Consequently, the dissipated and excess thermal energy increases the cell temperature and in turn, reduces the conversion efficiency of the cell. The excess thermal energy absorbed by the cold-water flow through the heat exchanger thermal panel underneath the PV's cells can be used for various domestic or industrial applications. Therefore, the net result is an enhancement of the combined photovoltaic-thermal efficiency of the hybrid system and consequently the PV solar panel. Recently, the performance of nanofluids in a Parabolic Trough Concentrating Solar Collector (CSP)-based power generation plant, an Organic Rankine Cycle (ORC), and a Thermal Energy Storage (TES) system was studied and reported by Sami [41].

Other Applications

The following sections outline the various other applications and uses of nanofluids in another energy-related area;

Biomedical Application

Special nanofluids have been used in antibacterial activities or drug-delivery properties since they have relevant properties and are reported extensively in references [46-48]. Nanofluid technology is useful as a tool for cell-biology research to separate and purify cell populations; tissue repair and hyperthermia for cancer treatment. A few of the pharmaceutical applications include targeted nano-drug delivery systems and antibacterial activity. The future scope is to develop high-performance nanofluids for non-toxic or biodegradable nanoparticles. Commonly used materials include ceramics, polymers, lipids, and metals. Natural and synthetic polymers and lipids are typically used as drug delivery vectors. Particles containing chemotherapeutic agents are engulfed by phagocytes and rapidly cleared by the reticuloendothelial system (RES). Different technologies have developed to sustain the nanoparticles in blood stream one of which includes an alteration of the polymeric composition of the carrier. On the other hand, nanoparticles are coated with hydrophilic polymer to avoid washing out and remain in the bloodstream for a longer period that can sufficiently target cancerous cells. It must be noted that hydrophilic polymer coating on the nanoparticle surface repels plasma proteins and escapes from being opsonized and cleared. This is well known as the "cloud effect". This is commonly used hydrophilic polymers include polyethyleneglycol (PEG) poloxamines, poloxamers, polysaccharides, and so forth.

Antibacterial Activity

The antibacterial behavior of ZnO nanofluids shows that the ZnO nanofluids have bacteriostatic activity against [47-48]. Electrochemical measurements suggest some direct interaction between ZnO nanoparticles and the bacteria membrane at high ZnO concentrations. The antibacterial activity of suspensions of ZnO nanoparticles against Escherichia coli (E. coli) has been evaluated by estimating the reduction ratio of the bacteria treated with ZnO. The survival ratio of bacteria decreases with increasing concentrations of ZnO nanofluids and time. Further investigations have been reported by references that have clearly shown that ZnO nanoparticles have a wide range of antibacterial effects on several other microorganisms. The antibacterial activity of ZnO is dependent on the size and the presence of normal visible light.

The antibacterial behavior of zinc oxide (ZnO) nanofluids shows that the ZnO nanofluids have bacteriostatic activity against Escherichia coli (E. coli). Electrochemical measurements suggest some direct interaction between ZnO nanoparticles and the bacteria membrane at high ZnO concentrations. Jalal *et al*. [47] observed and reported on reduction in the growth of E. coli in antibacterial activity of suspensions of ZnO nanoparticles and the survival ratio of bacteria decreases with increasing concentrations of ZnO nanofluids and time. Further investigations of the subject matter have proved that ZnO nanoparticles have a wide range of antibacterial effects on several other microorganisms. The antibacterial activity of ZnO may be dependent on the size and the presence of normal visible light. Other research reported in the literature showed that the inhibitory activity of ZnO nanoparticles against an important foodborne pathogen, E. coli O157:H7 increases as the concentrations of ZnO nanoparticles increase. ZnO nanoparticles changed the cell membrane components including lipids and proteins. ZnO nanoparticles could deform bacteria cell membranes, leading to the loss of intracellular components, and ultimately the death of cells, considered an effective antibacterial agent for protecting agricultural and food safety. The antibacterial activity research of copper oxide (CuO) nanoparticles showed that they possessed antibacterial activity against four bacterial strains. This can be attributed to the fact that these nanoparticles formed stable complexes with vital enzymes inside cells which hampered cellular functioning resulting in their death.

Metal oxide nanomaterials such as l ZnO and CuO have been used industrially in cosmetics, paints, plastics, and textiles. An important feature that these nanoparticles is that they exhibit antimicrobial behavior against pathogenic bacteria. It was also reported that ZnO, CuO, and iron oxide (Fe2O3) nanoparticles have excellent antimicrobial activity against Gram-positive and Gram-negative bacteria. However, it was shown by reference [47] that the metal oxide nanomaterials, ZnO have the greatest antimicrobial activity against both Gram-positive and Gram-negative bacteria. This study also showed that ZnO nanoparticles have excellent bactericidal potential, while Fe2O3 nanoparticles exhibited the least bactericidal

Nanodrug Delivery

To improve the efficiency and drug action [46]. Over the last few decades, colloidal drug delivery systems have been developed. The small-size, customized surface improves solubility, and the multifunctionality of nanoparticles opens new opportunities for biomedical applications. It was reported in the aforementioned references that gold nanoparticles provide nontoxic carriers for drug- and gene-delivery applications. It has been reported by references [46] that Gold nanoparticles can provide nontoxic carriers for drug and gene delivery applications. The gold core imparts stability to the assembly, while the monolayer allows tuning of surface properties such as charge and hydrophobicity. Another attractive characteristic of gold nanoparticle is their interaction with thiols and providing an effective and selective means of controlled intracellular release. Carbon Nanotubes (CNT) have emerged as a new alternative and efficient tool for the transportation and translocation of therapeutic molecules. It was also found that CNT can work with bioactive peptides, proteins, nucleic acids, and drugs and is used to deliver their cargo to cells and organs. Also, it was reported that CNTs display low toxicity and are not immunogenic, such systems hold great potential in the field of nanobiotechnology and nanomedicine. Reference [48] has developed a novel technique strategy for working of CNTs with two different molecules using the 1, 3- dipolar cycloaddition of azomethineylides. The molecules will target specific receptors on tumor cells will help Cancer treatment options include surgery, chemotherapy, radiation therapy, and hyperthermia. Clinical hyperthermia can treat organs for tumor/cancer therapy is named hyperthermia and can be generated by radio frequency, microwave, and laser wavelengths. Blood vessels are poorly developed within the cancerous tissues and have a lower thermal resistance than healthy tissue [46]. It is well known that Tumor cells are more susceptible to heat than normal cells due to their higher rates of metabolism. That makes hyperthermia a very promising cancer treatment. The cancer cells are damaged at lower temperatures than the healthy tissue. Magnetic nanoparticles have since provided a characteristic for handling and manipulation of the nanofluids by a magnetic force as compared to other metal-type nanoparticles. The nanofluid containing magnetic nanoparticles also acts as a super-paramagnetic fluid that absorbs energy in an alternating electromagnetic field producing a controllable hyperthermia. Nanofluids could also be used for safer surgery by producing effective cooling around the surgical region Magnetic nanoparticles in biofluids can be used as delivery vehicles for drugs or radiation, providing new cancer treatment techniques.

Intensify Microreactors

The enhancement of heat transfer by nanofluids has potential in the area of process intensification of chemical reactors. Reference [39] reported on a nanofluid based on benign TiO2 material dispersed in ethylene glycol in an integrated reactor-heat exchanger. He reported that the overall heat transfer coefficient has been increased up to 35% in the steady state continuous experiments. This resulted in closer temperature control in the reaction of selective reduction of an aromatic aldehyde by molecular hydrogen and a very rapid change in the temperature of the reaction under dynamic reaction control.

Nanofluids as Vehicle Brake Fluids

Reference [45] studied the process of braking and the brake fluid in the hydraulic braking system, and breaking oil. Nanofluids were manufactured using the arc-submerged nanoparticle synthesis system and the plasma charging arc system [41]. It was found that nanofluids have enhanced properties such as a higher boiling point, higher viscosity, and a higher conductivity than that of traditional brake fluid. By yielding a higher boiling point, conductivity, and viscosity, the nanofluid brake oil will reduce the occurrence of vapor lock and offer increased safety while driving.

Microbial Fuel Cell

The literature reported that Microbial fuel cells (MFC) utilize the energy found in carbohydrates, proteins, and other energy-rich natural products to generate electrical power [34]. The performance of MFC depends on electrodes and electron mediators. Wang [34] informed that the new E. coli-based MFC to the previously reported E. coli-based microbial fuel cells with neutral red and methylene blue electron mediators. The performance of the MFC using CNT-based nanofluids and CNT-based electrodes has been compared against plain graphite electrode-based MFC. CNT-based electrodes showed as high as ~6-fold increase in the power density compared to graphite electrodes.

Desalination of Sea Water

Recently magnetized nanofluid Silicon Oxide and Aluminum Oxide have been studied mathematically and numerically in solar desalination multistage flashing chambers using the PV-thermal solar collectors' concept Sami [48-49]. A mathematical formulation was written after mass and energy conservation balances using finite control volume and properties of magnetized SiO2 and A2O3 nanofluids. The flashing process was examined in multiple chambers under various conditions including different solar radiations, brine flows, and concentrations, various magnetic field strengths, different irreversibility, and availabilities as well as flashing chamber conditions. The study concluded that higher solar radiation increases the flash flow produced. It is concluded that higher irreversibility was experienced when water was used as a base fluid. The irreversibility increase depends upon the type of nanofluid and its thermodynamic properties. Furthermore, higher concentration increases the availability at the last flashing chamber depending on the type of nanofluid and its thermodynamic properties. Also, the availability progressively decreased at the last flashing chamber. The higher the magnetic field forces the better the performance of nanofluids in the flashing chambers. The thermal energy accumulated during the thermal storage charging phase was significantly enhanced by using the magnetized nanofluid SiO2. Finally, the model-predicted results compared well with experimental data published in the literature.

ORC with Cooling Capabilities

The performance of nanofluids in a PV Thermal-driven Organic Rankine Cycle (ORC) with cooling capabilities study by Sami [48-49] investigated the enhancement effect and characteristics of nanofluids; Al_2O_3, CuO, Fe_3O_4, and SiO_2 on the performance of the hybrid system composed of PV Thermal, ORC, and cooling coil. The quaternary refrigerant mixture used in the ORC cycle to enhance the ORC efficiency is an environmentally sound refrigerant mixture composed of R152a, R245fa, R125, and R1234fy. It was shown that the enhancement of the efficiency of the hybrid system in question is significantly dependent upon not only the solar radiation but also the nanofluids concentration and the type of nanofluid as well as the fluid temperature driving the ORC. A higher hybrid system efficiency has been overserved with nanofluid CuO. Moreover, it has been also shown that on average, the hybrid system efficiency was higher by 17% with nanofluid CuO compared to water as the heat transfer fluid. In addition, it was also observed that the higher cooling effect produced is significantly increased with the use of the nanofluid CuO compared to the other nanofluids under investigation and water as heat transfer fluid. The results observed in this paper on ORC efficiency and PV solar panel efficiency are comparable to what has been published in the literature.

Phase Change Materials

A numerical model that was established after the energy conservation equations coupled with the heat transfer equations and properties of magnetized nanofluids to predict the behavior of different phase change materials, paraffin under the effect of different operating conditions by Sami [48, 49] It has been observed during the phase charging process that the nanofluid Al2O3 used as heat transfer fluid exhibited the longest time compared to other nanofluids and water as base fluid. Also, the results indicated that the nanofluid Fe304 had the shortest time consumed during the phase charging process under different solar radiations. Besides, it was found the higher the nanofluid concentration the longer the time to reach a liquid fraction compared to water as a base fluid, and less thermal load is needed to reach the threshold of phase change. Finally, the presented numerical model was compared fairly with published experimental data.

Absorption Systems

A numerical model based upon the energy conversion equations and heat transfer mechanisms of magnetized nanofluids taking place during PV-Thermal solar collector and absorption system, PV cell and the heat transfer fluid flowing in thermal tubes welded in the back of the PV panel and heat exchangers of the absorption system, is presented by Sami [48]. This permitted the prediction of the electrical power output of the PV panel, thermal energy generated, and the characteristics of the water-based nanofluids in terms of solar radiation, different nanofluids, and other system geometry parameters. The presented model compared fairly with experimental data with reasonable discrepancy. It was demonstrated that higher solar radiations have a significant impact on heat transfer fluid flow rates, however, low solar radiations increased the nanofluid-based CuO heat transfer flow rates over the water-based ones. Also, it has been shown that the higher the concentration of the magnetized nanofluid CuO the higher the generator thermal energy input compared to the heat transfer fluid-based water and the coefficient of performance of the absorption system. Finally, the results of the model in question are compared fairly with available experimental data.

Heat Pipes

A two-dimensional dynamic heat transfer and fluid flow model was developed by Sami [48,49], to describe the behavior of photovoltaic cells and the performance of a hybrid solar collector photovoltaic–thermal solar panel system. The system was assessed under different magnetic field Gauss forces. Nanofluids were used to drive the heat pipes in a thermal panel under different conditions, such as levels of solar irradiance and different boundary conditions. The model was developed based on the equations of the dynamic conservation of mass and energy, coupled with the heat transfer relationships and thermodynamic properties, in addition to the material properties under different magnetic Gauss forces. Comparisons were made with the literature data to validate the predictive model. The model reliably predicted the key parameters under different nanofluid conditions and magnetic fields, and compared well with the existing data on the subject.

Thermoelectric

A simulation model has been developed by Sami [48] to predict the behavior of a hybrid system composed of PV-Thermal panels and a thermoelectric generator using nanofluids. The model has been established after the energy and mass conservation equations for nanofluids flow the dynamic behavior of the PV-Thermal panels, and the thermoelectric generator has been studied and analyzed under different nanofluid particle concentrations and different solar radiation conditions. The model fairly compared with existing data.

Limitations of Nanofluids

The applications of nanofluid are restricted by many factors where the long-term stability of nanofluid in suspension is a major issue. In the following, we discuss the limitations on the use of nanofluids;

Poor long-term stability of suspension

Reference [46] studied and reported on Physical or chemical methods that have been applied to get stable nanofluids such as (i) an addition of surfactant; (ii) surface modification of the suspended particles; (iii) applying strong force on the clusters of the suspended particles. Lee and Choi [105] found that Al2O3 nanofluids kept after one month exhibit some settlement compared to fresh nanofluids.

Increased pressure drops and pumping power

The efficiency of nanofluid application is determined Pressure drop developed and required pumping power during the flow of coolant as reported by [32-33]. It is known that higher density and viscosity lead to higher pressure drop and pumping power. Different studies have shown a significant increase of nanofluids pressure drop compared to the base fluid.

Lower Specific heat

Several studies have shown that nanofluids exhibit lower specific heat than base fluid.

High cost of nanofluids

Preparing nanofluids requires advanced and sophisticated equipment and is normally associated with higher production costs for nanofluids

Future Research in Nanofluids

Research must be conducted in the area of nanofluids with low viscosity. Studies in this area reported are very limited and also on nanofluids under high-temperature applications. It was found that some nanofluids were prepared without using surfactants or changing pH. This is critical for nanofluids since it may change their thermophysical properties. It is also recommended to study the enhanced thermal conductivity of nanofluids for specific applications. More studies are required on the production of nanofluid and its cost since it has become a barrier to its applications and commercialization. The following summarizes the future developments topics that are needed to enhance further future use of nanomaterials:

1. Nanomaterials and Nanofluids preparation and characterization (nanoparticles, nanoPCM, nanofluids, nanosats, nanofluids),
2. Measurements, and theoretical development of Nanofluid properties,
3. Measurements and theoretical development of Nanofluid heat transfer, Experimental and theoretical analysis on nanofluid transport in porous media,
4. Measurements and theoretical development of Nanoparticle-enhanced phase change materials,
5. Numerical simulations are relevant for potential applications,
6. New numerical models for estimation of nanofluids heat transfer behavior,
7. New innovative areas of nanofluid applications,
8. Critical assessments and
9. Future directions in Nanofluids research.

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