Thermo-Hydraulic Performance Analysis of Fe3O4-Water Nanofluid-Based Flat-Plate Solar Collectors

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Abstract: *In this study, we present a detailed thermo-hydraulic analysis of flat-plate solar collectors (FPSCs) with Fe3O4-water nanofluids as the working fluid that is used in the design of these collectors. A wide range of operating parameters were investigated in this study: the temperature and mass flow rate as well as the fraction of nanoparticles in the gas stream (0.1667-0.05 kg/s) are all included in the study. Based on the results of the study, it is shown that increasing the volume fraction of a system up to 2% enhances the energy efficient by 4.28%, whereas the efficiency of the system increases by 8.90%. Although, it also has the effect of increasing friction factor by 13.51 % and pressure drop by 7.93 % as well. There was a significant increase in thermal transfer coefficient, energy efficiency, and power efficiency when Fe3O4 nanoparticles were combined at a volume fraction of 0.5%, which improved thermal transfer coefficient, power efficiency, and energy efficiency by 1290%, 4.33%, and 2.54%, respectively.*

Keywords- Thermo-hydraulic, Flat Plate Solar Collector (FPSC), thermal transfer coefficient, power efficiency, energy efficiency.

I. INTRODUCTION

Solar radiation can be harnessed in various natural and synthetic processes on the earth's surface. Fig. 1. shows that solar energy is transformed into various types of energy such as electrical, chemical, mechanical, and thermal. The solar collector is a heat exchanger specialized in the conversion of sunray into energy kinds such as electrical energy by photovoltaic cells (PV) in the photovoltaic application, thermal energy by solar thermal collectors in solar thermal applications and into both electrical and thermal by PV/T collectors. Solar collectors have two major categories of solar radiation receiving methods, namely, solar collectors concentrate and solar non-concentrated collectors' flat plate solar collector (FPSC). FPSC has been extensively applied in many fields with thermal applications. Solar collectors absorb and convert solar radiation into heat energy for thermal application and move out the heat to a solar liquid passing across them [1].

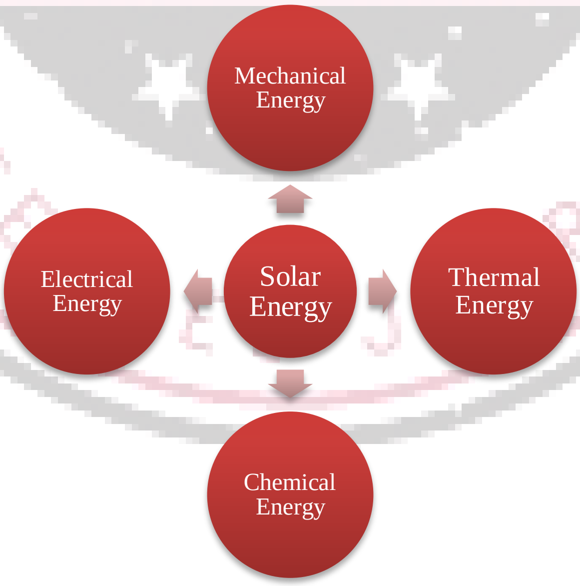

Fig. 1. Conversion of solar energy [1]

The FPSC is a stationary collector and an exchanger system that transforms sunray to thermal energy in solar systems. When solar radiation penetrates the glazing and reaches the absorber plate, the energy is absorbed and transformed into the transferred heat to the fluid that passes through the absorber flow tubes to increase temperature [1].

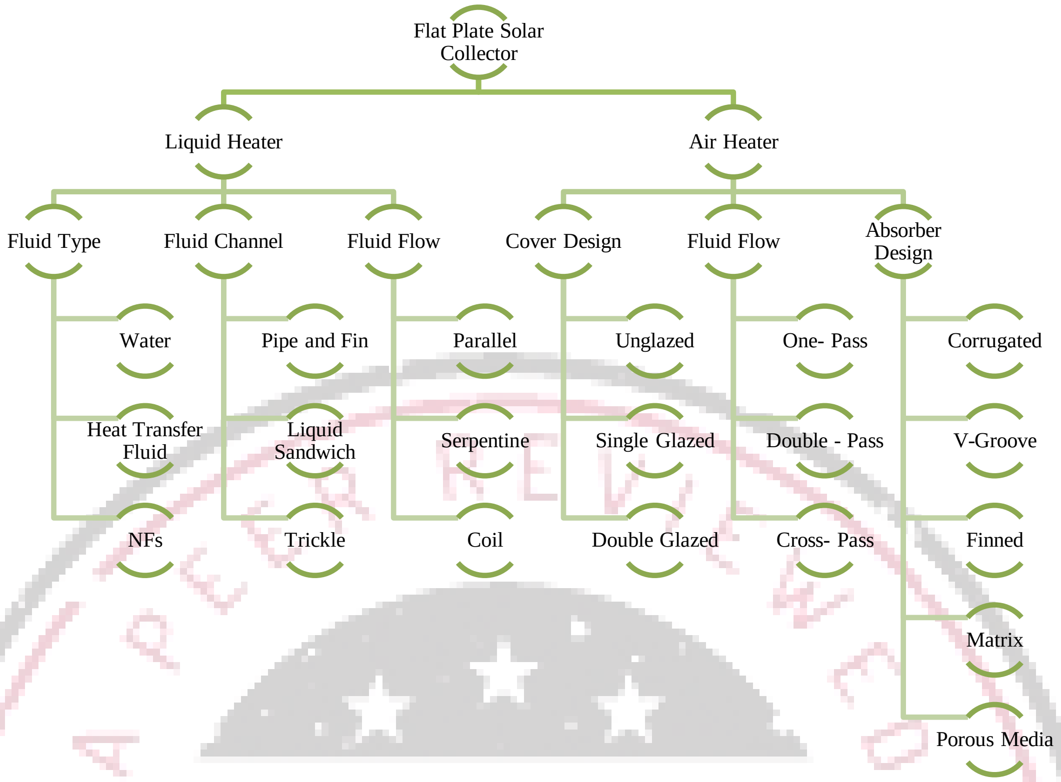

Fig. 2. Classification of FPSC [1]

FPSC is more suitable, easy to design, robust, and requires less maintenance. It is a critical application of solar energy for both domestic and industrial purposes since it absorbed solar energy and converted it to heat, transmitting heat to the household water in the tank by suitable work fluid [2]. The low efficiency of the FPSC energy conversion is a significant drawback due to the coefficient of heat transfer between absorber and operation fluid being low. One of the recent trends towards enhancing the FPSC performance is utilizing nanomaterials in solar fluids (i.e., NFs) as working fluids instead of traditional fluids to achieve enhanced thermal efficiency. Flat-plate solar collector FPSC is the most widely used part of solar heaters, with 20–30 years of working expectation. The environmentally friendly solar heaters require improved heat transfer strategies for better efficiency and performance over a lifetime [3].

Key Components of FPSC

A. Absorber Plate

The most common materials used in making these machines are copper, aluminum, and stainless steel, which are metals with good conductivity. The absorber plate has a special coating that maximizes the absorption of solar radiation, thereby minimizing the heat loss produced by solar radiation. The solar collector captures and then converts the sun's energy into heat by converting it into thermal energy.

B. Transparent Cover

There are a number of materials that could be used to make this, including glass or plastic. It has a dual function, allowing sunlight to enter into the system, and at the same time, reducing heat loss from the absorbing plate due to the transparent cover, also known as glazing. There is a greenhouse effect created by this, which traps the heat within the collector, creating a sense of comfort.

C. Insulation

It is usually made from polyurethane foam, glass fibers, or rock wool, depending on the material you choose. There is an additional insulation that is provided on the back and sides of this collector, which helps to reduce any heat loss into the surroundings of the collector and, as a result, it becomes more efficient.

D. Fluid Tubes

The material used to produce this product is usually copper or aluminum. This tube serves as a heat exchanger between the absorb plate and the fluid carrying the heat, such as water, antifreeze solution, or air, which is attached to or embedded in the absorb plate. Through plastic tubes such as these, heat is allowed to pass through the fluid, and the heat is then conveyed to the storage tank or to the application site.

E. Frame and Casing

In most cases, metals or hard plastics are used as the material for this product. There are several functions of the frame and casing, which provide structural support and protection for the internal component parts that make up the collector.

Working Principles

After passing through the transparent covering, the solar radiation falls onto the absorbing plate, which is normally coated with a selective material to maximize the absorption of solar radiation and to minimize the emissivity in order to reduce thermal radiation losses. A solar absorber plate absorbs energy from this solar radiation, and this energy is then converted to heat as it passes through tubes attached to the absorber plate and then is transferred to the fluid flowing through the tubes. Water, antifreeze, or even air may circulate in the system, depending on its design. It is done by letting the fluid get heated, either by centrifugal pumping or by self-driving, through collector tubes of the system, where by this way it is efficiently absorbing the heat from the absorb plate (due to its design) and distributing it more uniformly throughout the system. When the fluid is now heated, it leaves the collector and is transferred to a storage tank, where it can be stored for later use or directly used for heating. An insulated tank would normally be used to store the collected-heated water, for instance, in water heating systems where the water is stored until required. There are two main ways to reduce the convective and electromagnetic losses of the collector. The transparent cover reduces convective and electromagnetic losses, while conductive heat losses are minimized thanks to the sides and back insulation. Due to these features, the vast majority of the absorbed heat is transferred to the fluid. FPSC systems are generally equipped with great degree of control over the heat transfer process. These control systems include temperature sensors, differential controllers, pumps, in order to maintain the appropriate flow of heat transfer fluid to prevent overheating of the system.

II. LITERATURE REVIEW

Shafiq, M. et al. (2023) [4] The adoption of solar collectors with flat plates is an affordable substitute for reducing greenhouse gases from building heating (FPSCs). Low thermal efficiency, however, poses a serious obstacle to their successful application. Advantageous thermo-physical characteristics of nanofluids may make FPSCs more effective. Accordingly, this work assesses the thermo-hydraulic performance of an FPSC using Fe3O4-water nanofluid. The operating parameters range from 0.1 to 2% for the volume fraction of nanoparticles, 0.0167 to 0.05 kg/s for the mass flow rate, and 303 to 333 K for the collector inlet temperature. The numerical findings demonstrated that under identical operating conditions, increasing the volume fraction up to 2% resulted in an improvement of 4.28% and 8.90% in energy and energy efficiency, respectively. However, a 13.51% and 7.93% rise in the friction factor and pressure drop, respectively, have also been observed. Consequently, the ideal volume fraction (0.5%) of Fe3O4 nanoparticles was found using the performance index (PI) criteria, which improved the convective heat transfer, energy efficiency, and efficiency by 12.90%, 4.33%, and 2.64%, respectively.

Wang, D et al. (2022) [5] Flat-plate solar collectors' (FPSCs') thermal performance is influenced by its size in addition to climatic and operational factors. This study examines the mechanism of FPSC thermal performance enhancement, with a particular emphasis on the influence of collector size. Numerical simulation models for both large-scale flat-plate solar collectors (LSFPSCs), and conventional FPSCs in parallel, are introduced. The relationship between thermal performance and collector dimensions is studied for the LSFPSCs. Furthermore, the effect of the environmental and operational parameters on the thermal performance of the two collector types is investigated. Moreover, the applicability of LSFPSCs in China is analyzed with respect to available operating times, useful energy, and heat loss. The findings show that FPSCs' thermal performance may be successfully increased by expanding the collector size, and that LSFPSCs outperform traditional FPSCs when used in tandem. The collector's effectiveness of the LSFPSCs is better than that of the standard FPSCs, particularly at low solar irradiation, low room temperature, and increased mass-flow rates. Moreover, the LSFPSCs perform best in regions with abundant solar energy. Lhasa has the longest daily operational period of any city under study, at 9.6 hours, and a useable energy percentage of almost 55%.

Geovo, L. et al. (2023) [6] The current study looks at a flat-plate solar collector's theoretical model using nanofluids as a heat-transport medium. Models for the breakdown and transfer of solar irradiation have been used for this purpose. Also, the different models for determining the thermophysical properties of nanofluids were implemented and compared with experimental data on these properties. Using Matlab software, the theoretical model was put into practice, and its validity was checked against experimental data obtained from a flat-plate solar collector that contained MgO water. Results for the validation of the model with data from experiments for MgO-water nanofluid at volume proportions between 0 and 1.5% indicate that the average relative error was 2.02%, the minimal respective error was 0.20%, and the highest relative error was 5.36%. As a result, the theoretical framework was effectively expanded to include MgO-water nanofluid simulation of flat-plate solar collectors. According to a parametric research, pure water did not display the same relative gain in thermal efficiency as the nanofluid with an approximate volume content of 0.75% MgO. Furthermore, by modeling the yearly efficiency of the collector in Porto Alegre, Brazil, while it was run on MgO water, the theoretical framework was applied to a case study. This demonstrated positive results and a wide range of application possibilities.

Jafari S et al. (2022) [7] In many Iranian towns with varying climates, the best spot to put flat-plate solar thermal collection systems for residential structures was found using the analytical hierarchy process (AHP). The payback times of energy and emissions of greenhouse gases (EPBP and GGEPBP), two recently introduced concepts, were also taken into consideration to offer more information from the energy, economic, and environmental (3E) benefits of the system. The payback period of investment (IPBP) was selected as one of the decision criteria. The novelty of this work is proposing a method to find places with the greatest potential to install flat-plate solar collectors. It was performed using AHP as a systematic decision-making tool, and based on energy, environmental, and economic criteria, which are the key aspects of an energy system. To ascertain the values for the several cities under investigation, codes created in the MATLAB program were utilized. The country's center, Yazd, was determined to be the ideal location for the system's installation based on the findings. With EPBP, IPBP, and GGEPBP ratings of 2.47, 3.37, and 0.71 years, respectively, this city is doing well. It was also discovered that this city's collector area measured 109.8 m^2. Yazd had a 26.5 out of 100 rating. Tehran, Bandar Abbas, Rasht, and Tabriz were judged to be the second, third, fourth, and fifth priority for using the system, with ratings of 24.4, 18.6, 15.9, and 14.6 out of 100, respectively.

Seddaoui, A, et al. (2022) [8] This paper presents a new design of vacuum flat plate solar collector (VFPSC). This inspired design is based on a combination of two conventional systems; the flat plate solar collector (FPSC) and the evacuated tube solar collector (ETSC). The new configuration, which is characterised by a curved evacuated cover and rear Rockwool insulation is compared with FPSC and ETSC. Collectors' performance is predicted through a theoretical approach that includes heat transfer and energy balance equations, where thermo-physical and geometrical properties of each collector are considered. The developed computational program is validated against experimental results carried out on FPSC. The optimal number of tubes is identified to perform a comparative study under the best efficiency point for different values of absorber emissivity including collectors' cost. The new VFPSC proves that the combination of front vacuum insulation and back opaque thermal insulation can result in significant heat loss reduction, and thus performance enhancement for the whole emissivity range. As a result, the proposed VFPSC provides more thermal efficiency than FPSC and ETSC by 7.13% and 28.32%, respectively, for an emissivity of 0.95, while for an emissivity of 0.05, it reaches ratios of 22.77% compared to FPSC and almost the same ETSC efficiency levels, with a much lower cost. Moreover, it shows lower heat loss factor compared to other similar VFPSCs. Overall, VFPSC offers a promising solution that has the required ability for producing hot water with a low cost and may take place as heating device in buildings and industrial sectors.

Hussein, O. A et al. (2023) [9] This study focuses on the thermal and rheological properties of a hybrid fluid consisting of Titanium Dioxide/Chemically functionalized Multi-Walled Carbon Nanotubes (TiO2 / CF-MWCNTs) suspended in distilled water (DW) for use in flat plate solar collectors applications. The optimal hybridization ratio of CF-MWCNTs: TiO2 was 40:60. To evaluate thermal efficiency, solar collector tests were conducted using varying flow rates "2LPM, 3LPM, and 4 LPM" according to the ASHRAE'93-2010' principle. The study examined the effects of various weight percentages of TiO2/CF-MWCNTs add up to the DW as working base fluid to determine the optimal concentration for enhancing the performance of the "FPSC" efficiency. The experimental results showed that using TiO2/CF-MWCNTs in the working fluid improved the collector energy efficiency by approximately 9% and 26% at low and high temperature differences, respectively, compared to distilled water (DW). The effectiveness of the composed nanoadditives was valuation through using various morphological analysis techniques, including Ultraviolet–visible spectroscopy (UV–vis), X-ray diffraction, Field emission scanning electron microscopy (FE-SEM), and high-resolution transmission electron microscopy (HR-TEM). The study found that the rating of the performance index "PI" were totally greater than "1" and increased as the weight concentration of TiO2/CF-MWCNTs increased up to 1.10 for 0.1 wt% with a flow rate of 4 LPM, indicating a higher positive effect on energy efficiency than negative effects on pressure drop. The findings revealed that by incorporating only "0.1 wt%" of TiO2/CF-MWCNTs and using a flow rate of 4 LPM, the optimal conditions were achieved, resulted in a remarkable improvement in flat plate solar collector (FPSC) efficiency up to 84%. In comparison to the conventional working fluid employed in FPSC, the results demonstrated a significant improvement.

III. NANOFLUIDS IN SOLAR THERMAL APPLICATIONS

A planned colloidal suspension of nanoparticles in a base fluid is precisely what is meant by a nanofluid. Commonly used as nanoparticles in nanofluids are metals, oxides, carbides, or carbon nanotubes, with water, ethylene glycol, and oil acting as base fluids. Nanofluids may benefit from the distinctive characteristics of nanoparticles, including as low kinetic energy, dimension-dependent physical properties, and a high surface area to volume ratio. The increased surface area also enhances and stabilizes the scattering of nanoparticles in the foundation fluids [10].

Solar thermal collectors convert solar energy into heat by means of a heat transfer medium, which can further be used for heating/cooling purposes. Solar water heating technology using solar radiation is economical choice in both developed and developing countries. Utilizing heat energy obtained from the sun involves a fluid that absorbs the heat so as to directly or indirectly transfer it to another fluid or location. Water is a commonly used fluid. But, it is found that only 13% of incident solar energy is absorbed by water which significantly results in low collector thermal efficiency. The intensity and quality of incoming radiations from the sun are solely controlled by the nature. The only factor that can increase the efficiency of solar-based energy-extraction systems is absorbing maximum radiation from it. A small change in the absorbance of heat by the fluid can cause a great impact on the process of harnessing the sun's energy. Intensification techniques for solar thermal systems thus require an alternative heat transfer fluid as the magnitude of intensification depends on the thermal properties of the fluid used. Many researchers worked on design modification of solar collectors. However, such modifications only result in high economic investments. Hence, an improvement in thermo-physical properties of working fluid is the only feasible route. This type of fluids can thus also be used in solar photovoltaic systems in order to absorb excess heat energy from the PV cells. Similarly, it can act as a filter to prevent excessive unwanted radiations from entering the PV module [11].

The thermal conductivity of nanofluids has improved, according to several researchers investigating them, and this has contributed to the efficiency of many applications. The enhancement in thermal conductivity of nanofluids is temperature-dependent; it rises with rising temperature, making the nanofluids more suitable for high-temperature applications. Another intriguing characteristic of nanofluids was that they dramatically increased the critical heat flux during the process of a pool boiling at extremely low concentrations of smaller nanoparticles. Higher performance in terms of thermal physical parameters was shown by hybrid nanofluids. Hybrid nanoparticles are groups of nanoparticles combined into a single unit with a size of less than 100 nm, and the fluids containing these hybrid nanoparticles are known as hybrid nanofluids [12].

A nanofluid containing Fe3O4 dissolved in water exhibits unique physical and chemical properties due to the dispersion of iron oxide nanoparticles. They interact more effectively with the base fluid because of their high surface area-to-volume ratio. As Fe3O4 has outstanding chemical stability, it ensures that the nanofluid will remain stable and will not degrade over time, thus making it suitable for applications that require long-term heat transfer. Traditional heat transfer fluids are less stable and have a smaller surface area than Fe3O4-water nanofluids.

A major advantage of Fe3O4-water nanofluids that possess enhanced thermal conductivity and heat capacity is the fact that they are efficient heat transferrers. Due to Fe3O4 nanoparticles, the fluid is highly effective in solar collectors and in other heat exchange systems due to its ability to conduct and store heat. Keeping these enhanced thermal properties will require the nanoparticles to be stable and uniformly dispersed, which is crucial to their optimal performance. It has been shown that some methods, such as the use of surfactants or adjusting pH levels, can be used to ensure that the nanoparticles remain well-distributed and stable over time, preventing problems such as agglomeration and sedimentation, and ensuring constant, efficient heat transfer.

IV. CHALLENGES AND FUTURE SCOPE

A. Challenges

Stability of NFs: Long-term stability is the major and important requirement of NFs. Better NF stability results in better thermal conductivity. NFs have very strong van der Waals forces that tend to aggregate, thus preparing homogeneous suspensions is difficult; consequently, maintaining homogeneity in solutions is difficult. The better dispersion and stability of NFs constitutes one of the key requirements of solar thermal systems [13].

2. Behaviour of surfactant usage: One type of blockage is to use a suitable surfactant to prepare NFs for solar collectors. Many studies showed that surfactants have enhanced dispersion in working NFs and minimised particle agglomeration. This study examined the use of different surfactants in various solar collectors to improve suspension and NF stability criteria and see if they opposed damages [14]. Various types of NF surfactants were reported to influence the NF stability and solar thermal adsorption characteristics. [15] tested MWCNTs/water NFs' stability and solar thermal adsorption qualities by adding different surfactant types (SDBS, CTAB, SDS and TX-100). To summarise their research, dispersion stability and absorption properties are strongly influenced by these surfactants used to make NFs. DBS showed the optimum performance among four surfactants and was also recommended for use with DASC and other thermal receptors.

3. NP size and volume concentration: All solar energy systems focus on NP size and mass concentrations regardless of type. [16] studied more research on the NPs' impact in solar systems.

4. Viscosity of NFs: NF viscosity increases according to an increasing NF volume and decreases at the same shear rate in solar energy at an increased temperature. [17] studies on FPSC viscosity of Al2 O3/water and Al2O3/water-ethylene NFs are highly affected by temperature, volume concentrations and base fluid. Increasing NP mass fractions and water-based NFs increase viscosity as non-Newtonian fluid at a higher temperature. Thus, NFs of water-EG show the behaviour of [18]. For example, a higher viscosity increase was found in one of the best solar absorbing fluids as carbon nanotube-based NFs, although the weight of NPs was very small. Therefore, the solar thermal collector needs higher pump power. Increasing the pump capacity to achieve the desired heat efficiency is not preferred since the system increases the operating costs [19].

5. Pumping power and pressure drop: Using of a higher viscosity NF than the base fluid results in pressure drop increment. Therefore, an increase in the pumping power is required. [20] noticed that an increase in the volume fraction of TiO2 /water NF with pressure drop under turbulent flows increases in their tests.

6. Cost of NFs: Higher production of NF suspensions is a major threat in the use of NFs in solar collectors due to difficult processes. NFs are generally produced by either one or two-step methods. However, sophisticated apparatus is necessary to produce NFs using these methods [21] NF costs for solar thermal systems such as heat exchangers. Solar collectors are stressed to reduce their application as a disadvantage.

7. Erosion and corrosion of NFs: The work liquid NPs can cause erosion and corrosion on the surface of thermal equipment for long-lasting use. [22] examined TiO2 , Al2O3, SiC and ZrO2 NFs on the metal surface, erosion and corrosion susceptibility. Results showed that NPs are causing surface damages from chemical corrosion and near negligible mechanical erosion.

B. Future Scope

1. Emerging Trends in Nanofluid Research

The research on nanofluids is never static; new directions are aimed at improving performance and expanding application areas. Developing advanced synthesis methods for nanoparticle production with controlled size, shape, and surface properties is an important trend. There is a possibility that, by doing so, it will improve the thermal conductivity and stability of nanofluids. In the current scientific environment, the focus is currently on the development of eco-friendly and cost-effective base fluids that would allow nanofluids to be more sustainable and economically viable. Furthermore, a growing interest has been shown to study the fundamental mechanisms that govern heat transfer at the nanoscale, which provides a basis for developing more advanced nanofluids, as well as more specialized nanofluids tailored to the missions they may be asked to perform at some point in the future.

2. Hybrid Nanofluids: The Recent Development

It is possible in the future to conduct research in hybrid nanofluids, which can be composed of two or more heterogeneous nanoparticles, as one of the research directions. In the presence of different nanoparticles, hybrid fluids would have synergistic properties that would enhance their thermal properties compared to traditional single-component nanofluids. Nanoparticles made from metallic materials and oxides, for instance, can achieve both a greater uniformity of thermal conductivity and a greater stability simultaneously. An optimized combination and concentration of nanoparticles is the focus of hybrid nano-fluid research, which is focused on balancing performance and stability at an affordable price. There are potentially thousands of applications for these fluids, ranging from cooling systems in electronics to solar collectors which have a very high efficiency, making these fluids ideal for a wide variety of applications. There are a number of important implications concerning renewable energy and industrial processes, which makes it one of the most promising areas of study.

V. CONCLUSION

Using Fe3O4-water nanofluids as a supplemental fluid to flat-plate solar collectors, the study demonstrated that the thermal performance of those collectors is significantly enhanced. The best volume fraction of nanoparticles to implement is a 0.5% volume fraction of nanoparticles, as this offers attractive improvements in both energy and energy efficiency while maintaining manageable increases in friction and pressure drop as a result of the nanoparticles. A number of these findings suggest that Fe3O4-water nanofluids would possess promising properties in enhancing the efficiency of solar thermal systems and in enhancing the sustainability of the systems, as they suggest a viable direction for enhancing both domestic and industrial utilization of solar energy. In the future, new work should be focused on addressing challenges such as the stability of nanofluids and the cost-effective production of this technology so that it can be improved and implemented a much wider range of applications.

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