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Performance enhancement of flat plate solar collector using nanofluids

PhD Thesis

by

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CONTENTS

1. INTRODUCTION, OBJECTIVES

The flat plate solar collector (FPSC) generates heat energy by absorbing solar energy from the sun utilising the high absorbing black plate which help to maximize energy absorption. This plate heats the working fluid by passing the absorbed energy to the fluid. There is now significant interest in solar thermal systems in the engineering field. Many factors affect the performance and energy generation ability of FPSCs. The traditional working fluids' low thermal conductivity is the most important of these factors, as it has a significant impact on the solar collector's performance. Today, the efficiency of such solar systems can be improved via optimisation techniques along with state-of-the-art technologies and materials.

Recently, scientists have laid great emphasis on the significance of nanoparticles. The nanoparticles when added to fluids resulted in an improvement in fluid properties. The nanofluid is said to be mono nanofluid when it is produced by adding a single nanoparticle to the base fluid whereas the nanofluid is said to be hybrid nanofluid when it is produced by adding numerous nanoparticles to the base fluid. Nanofluids have gained a lot of popularity because of their extraordinary properties with several studies being performed globally to identify the contribution rendered by nanofluids in enhancing the FPSC performance. This study renders main objectives listed below:

- To quantify the rheological behaviour of mono and hybrid nanofluids based on nanoparticle concentration in the nanofluid and temperature.
- To experimentally evaluate the dynamic viscosity of SiC/DW, ZrO_2/DW, and ZrO_2-SiC (50–50%)/DW nanofluids based various temperatures and solid volume fraction.
- To experimentally determine the thermal conductivity of SiC/DW, ZrO_2/DW, and ZrO_2-SiC (50–50%)/DW nanofluids at different concentrations and temperatures.
- To study the effect of various concentrations and flow rate of nanofluids on the thermal performance of the FPSC system.
- To explore the new correlations for estimate the Nusselt number of mono and hybrid nanofluids.
- To assessment the effect of nanofluids as working fluids on the exergy destruction, entropy generation, and exergy efficiency of the FPSC system.
- To validate the ANSYS simulation models with experimental results that estimation of the performance of the FPSC with mono and hybrid nanofluid.

2. MATERIALS AND METHODS

This chapter covers the description of the materials, techniques, and equipment used, as well as the scientific methodologies employed in the experimental measurements to accomplish the research goals.

2.1. Preparation and thermophysical properties of nanofluids

A two-step approach was used to obtain samples of ZrO_2/DW, SiC/DW, and ZrO_2-SiC (50:50%)/DW nanofluids. Subsequent to weighting, nanoparticles of ZrO_2 and SiC at the intended solid volume fraction (0.025, 0.05, 0.075, and 0.1%) were added to purified water. It was necessary to firstly calculate the necessary mass amounts before the various nanofluid fractions could be prepared. A digital scale with high sensitivity was used for measuring the materials' weight. Subsequent to the addition of nanoparticles to the water, the mixture was stirred using a magnetic stirrer for approximately 1.5 h. Afterward, suspensions were entered into an ultrasonic processor for the process of breaking down the agglomeration among the particles as well as preventing sedimentation; this process lasted approximately 3–4 h. Finally, a zeta potential test is performed to check the stability of the prepared samples of nanofluids.

In the current study, the transient hot wire method is used to measure thermal conductivity in this research. A KD2-Pro device from Decagon Devices Inc was used for measuring the thermal conductivity of the three nanofluids; ZrO_2/DW, SiC/DW, and ZrO_2-SiC/DW in this study at volume concentrations of 0.025%, 0.05%, 0.075%, and 0.1% for 20 °C to 60 °C temperatures. The sensors, KD2-Pro KS-1, 60 mm long with a diameter of 1.27 mm, were inserted in the nanofluids' vials. A sensor is put in the sample fluid, and the temperature response time is recorded. The thermal properties of a material, such as thermal conductivity, determine the temperature response time. Thermal conductivity was recorded after every 60 s.

Additionally, a Brookfield DV2TRVTBG rotational viscometer was used for measuring the ZrO_2/DW, SiC/DW, and ZrO_2-SiC/DW nanofluids' viscosity as well as for identifying their rheological characterization when influenced by varying parameters. The parameters of the experiment were fixed such that the temperature ranged between 20 and 60 °C to measure the nanofluids' dynamic viscosity at different solid volume fractions. Such viscometers function by taking measurements of fluid's resistance caused by the torque from the spindle placed into the fluid. Hence, this facilitated the process of conducting analysis of the nanofluids' rheological properties and viscosity according to the effects of shear rate and temperature at varying concentrations.

2.2. Experimental setup description

The tests were performed on the FPSC in the laboratory of solar energy under the Hungarian weather conditions. The SKV-3 collector type is used that has been provided by Fiorentini Hungary Kft., a solar systems supplier in Hungary. Pictures of the FPSC and main parts of the system, and a schematic of the experimental arrangement is demonstrated in Fig. 1 and Fig. 2.

Fig. 1. Major components of solar system for the experimental setup

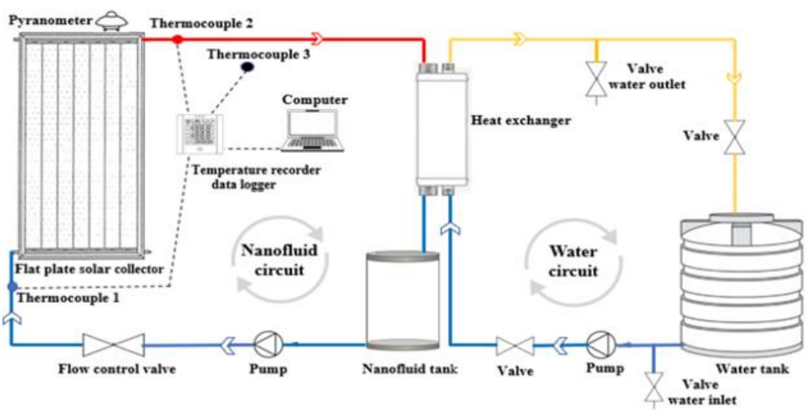

Fig. 2. Schematic view of the experimental system

The FPSC is the supreme important part of the tested system. There are two loops in the FPSC, in which the first loop comprised the working nanofluid. The nanofluid extract heat from the FPSC while circulating by a pump. This nanofluid is circulated using a pump and subsequently heating of the nanofluid is performed by the solar collector. After being heated by the collector, the nanofluid exits via the collector and passes to the heat exchanger to transmit heat to the water that passed in second loop. The hot fluid is kept continuously in the tank in the second loop. The tank has a capacity of around 50 liters. In the first loop, the nanofluids is storage in the tank around 5 liters. Various devices are used to obtain the measurements, such as calibrated thermocouples (K-type) to determine the inlet/outlet flow temperature, and a flow sensor to identify the fluid flow rate, which is regulated with a simple valve. A KIPP-CM11 pyranometer was used to quantify solar radiation. In addition, a thermocouple was used to measure the ambient air temperature. Before the electric pump, a flow sensor was attached to the water pipe. A simple valve was attached to the water pipe after the electric pump to regulate the mass flow rate of working fluid within the solar system. The fluid temperatures in the inlet and outlet of the FPSC were measured using four K-type thermocouples. In addition, the air temperature was measured using one thermocouple. The sensors were linked to a 12-channel digital temperature recorder with a data logger (Lutron BTM-4208SD). In addition, Interfaces can be used to connect each measuring instrument (KIPP-CM11 pyranometer and temperature data logger) to the computer.

2.3. Experimental method

The thermal performance of the FPSC was examined using the ASHRAE Standard 93–2003. This standard has the objective of presenting test methods that could be applied to determine the thermal performance of solar collectors. For this, experimental measurements are required for the incident solar radiation rate, and the rate of energy added to the working fluid when it circulates into the collector, under steady-state or quasi-steady-state conditions. According to ASHRAE Standard, the tests should be accomplished in different inlet temperatures. In addition, they should be carried out symmetric to the solar noon and should fulfil certain conditions, such as the least solar radiation of 790 W/m^2. As it is mandatory to meet the steady state conditions, the mass flow rate should be kept within ± 1%, the outdoor ambient air temperature should not change by over ± 1.5 °C, irradiation should remain constant within ± 32 W/m^2, and the inlet temperature should remain within ± 1 °C for the whole test duration. The experiments were carried out from 10 a.m. to 3 p.m. (local time) on sunny days. The FPSC efficiency was determined at different mass flow rates of 0.025, 0.033 and 0.041 kg/s. Graphs were formulated to present the experimental results, which demonstrated the FPSC efficiency for a decreased temperature parameter [(Ti-Ta)/GT].

2.4. Mathematical relations for efficiency of solar collector

Based on the first law of thermodynamics, the useful heat gain, Q_u, under steady-state conditions expressed as:

$$Q_u = \dot{m}\, C_p (T_{fo} - T_{fi})\, U_o A_o\, (T_s - T_b).$$

It follows that the efficiency (η) of FPSC can be reformulated an according to ASHRAE is:

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{(T_{fi} - T_a)}{G_t}.$$

The efficiency according to the second law (or exergy (η_{ex})) is represented by

$$= 1 - \frac{T_a \dot{S}_{gen}}{\left(1 - \frac{T_a}{T_{sur}}\right) \dot{Q}_s}.$$

The equations used to calculate the Reynolds number (Re), Prandtl number (Pr) and Nusselt number (Nu) have been listed as follows:

$$Re = \frac{4\,\dot{m}}{\pi\, D_i \mu}, \quad Pr = \frac{\mu\, c_p}{k}, \quad Nu = \frac{h_i D_i}{k}$$

where D_i is the inside diameter of the tube, μ is the viscosity of working fluid, k is the thermal conductivity of working fluid, c_p is the heat capacity of working fluid and h_i convective heat transfer coefficient.

2.5. Numerical simulation of flat plate solar collector

This study involves using ANSYS-Fluent 2022 for the numerical simulation of FPSC with a nanofluids-based collector. ANSYS (pre-processing, solution, and post-processing) were the primary solution processes used to analyse each model during this investigation. Using a CFD code (such as Fluent), the flow-governing equations for a single-phase problem have been numerically solved. Using the finite volume method to discretize the fluid domain, which enables the transformation of partial differential equations (PDEs) into streamlined algebraic equations, the whole set of governing equations was solved. A pressure-based solver and the segregated iterative approach were used to solve the flow-governing equations within the given boundary conditions. For spatial discretization, the least-squares cellbased gradient method was taken into consideration. Through the combined solution of the pressure-velocity coupling of the SIMPLE algorithm, the continuity equation, momentum equations, and energy equation have all been determined.

3. RESULTS

This chapter presents the most important results obtained from the experimentation and their discussions.

3.1. Nanofluids rheological behaviour

It is a critical thermophysical characteristic and has a considerable effect on lubrication and pumping power, which in turn affects convective heat transfer. Hence, for the purpose of evaluating the rheological properties of ZrO_2/DW, SiC/DW and ZrO_2-SiC/DW nanofluids, measurements of the nanofluids' viscosity were taken at varying shear rates to get insight into the rheological behaviour of the given nanofluid. A fluid is defined as being Newtonian in cases where the shear stress is a linear function of the shear rate. Moreover, Fig. 3 demonstrates the changes in dynamic viscosity according to the shear rate at various temperatures and volume fraction of 0.1% for the given nanofluids. As the dynamic viscosity remains constant with regard to the shear rate, this suggests that the nanofluids of ZrO_2/DW, SiC/DW and ZrO_2-SiC/DW behave in a Newtonian manner.

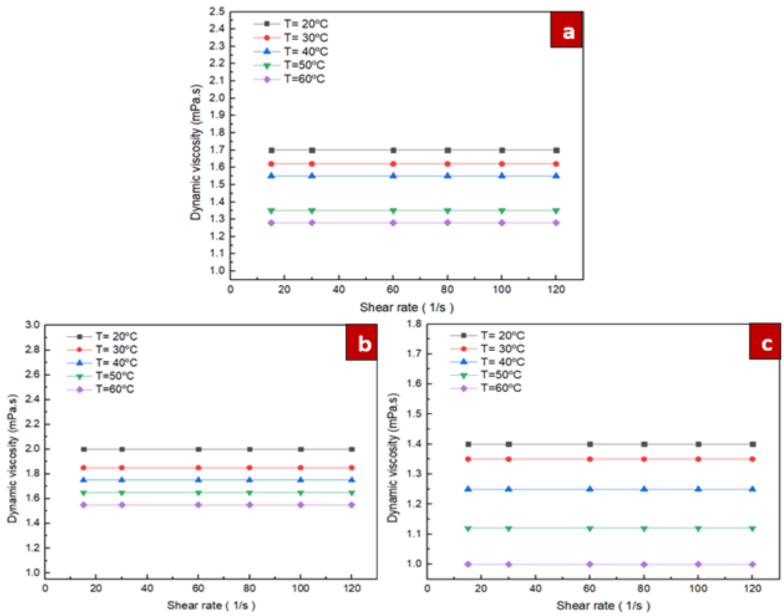

Fig. 3. Dynamic viscosity vs. shear rate at solid volume fraction of 0.1% for different temperatures, (a) ZrO_2-SiC/DW, (b) ZrO_2/DW and (c) SiC/DW nanofluid

3.2. Dynamic viscosity of nanofluids

According to the measurements, the definition of the "relative viscosity" is based on the ratio between the dynamic viscosity of nanofluids and the viscosity of distilled water. In Fig. 4, the relative dynamic viscosity in relation to temperature and solid volume fraction for the nanofluids of ZrO_2-SiC, ZrO_2/DW, and SiC/DW is shown. Fig. 4 shows that a rise in temperature causes a slight rise in the viscosity with the viscosity rising more evidently at higher concentrations of nanoparticles. Hence, it can be inferred that temperature changes do not have a significant effect on relative viscosity specifically at lower solid volume fractions. In short, at low nanoparticle concentrations, relative viscosity is independent of temperature. This pattern was also supported in past studies. The fluid showed higher relative dynamic viscosity as the volume fraction was increased with a more prominent rise at higher nanoparticle concentration because of the particle aggregation of nanoparticles leading to sedimentation and clustering of nanoparticles. When nanofluids applied in engineering applications, it is frequently to demonstrate usually call for mathematically expressing nanofluid's thermo-physical properties in equation form since equations allow experts to accurately predict values of dynamic viscosity of fluids based on the given values of temperature (T) and solid volume fraction (φ).

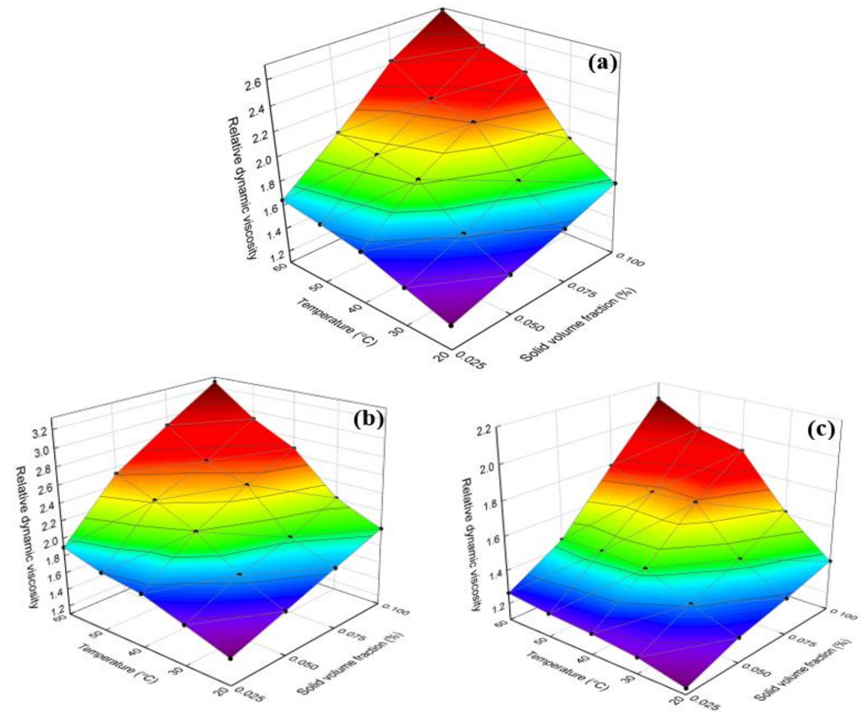

Fig. 4. 3D surface of relative dynamic viscosity at various volume concentrations and temperatures for (a) ZrO_2-SiC/DW, (b) ZrO_2/DW, and (c) SiC/DW nanofluids

3.3. Thermal conductivity of nanofluids

The comprehension of thermal conductivity enhancement needs to understand the meaning of thermal conductivity ratio, which is the thermal conductivity of a nanofluid divided by the thermal conductivity of the base fluid provided the temperature remains the same. Thermal conductivity ratio allows comparison of the rise in thermal conductivity coefficient of the nanofluid and base fluid at various temperatures which enables the experts to gain valuable insight into how increasing volume fraction affects the thermal conductivity. Relative thermal conductivity is also explained with the help of a diagram that shows changes in thermal conductivity because of changes in volumetric fraction. The relative thermal conductivity of ZrO_2-SiC, ZrO_2/DW, and SiC/DW nanofluid is recorded at different temperatures and solid volume fraction shown in Fig. 5. It is evident from the figure that relative thermal conductivity increases with a rise in volume fraction and temperature. Increasing the nanoparticle volume fraction leads to the clustering of particles whereby the particles bind to each other. The clustering of nanoparticles causes a rapid transfer of heat from one particle to another compared to the transfer of heat in a basic fluid such as water.

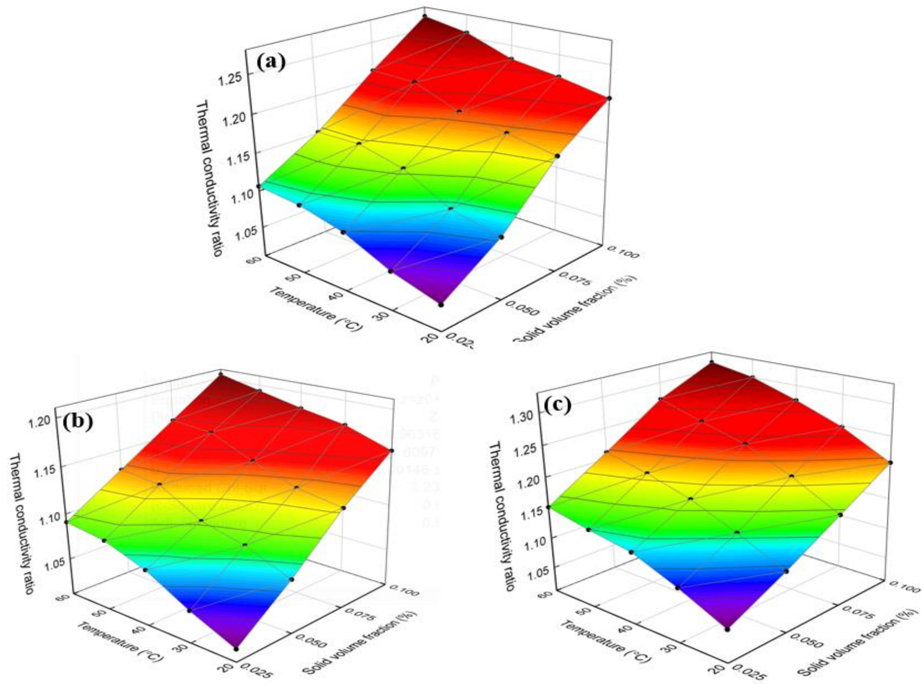

Fig. 5. 3D surface of thermal conductivity ratio at various volume concentrations and temperatures for (a) ZrO_2-SiC/DW, (b) ZrO_2/DW, and (c) SiC/DW nanofluids

3.4. Thermal performance of flat plate solar collector

In this section, an extensive discussion was carried out to demonstrate the thermal impact on the FPSC thermal system efficiency due to the dispersion of adding ZrO_2, SiC and ZrO_2-SiC nanoparticles to distilled water. The collector's thermal efficiency as a function of the lowered temperature parameter [(Ti-Ta)/GT] is investigated as the independent variable for each of the scenarios researched. As stipulated by the ASHRAE Standard, a linear curve is fitted between thermal efficiency and reduced temperature [(Ti-Ta)/GT].

3.4.1. Test case 1 silicon carbide nanofluid

This study investigates four distinct nanoparticle volume fractions of 0.025%, 0.05%, 0.075, and 0.1% SiC nanofluid. As shown in Fig. 6, thermal efficiency is plotted against the reduced temperature parameter [(Ti-Ta)/GT] for water and the respective nanofluids at mass flow rates of 0.025, 0.033 and 0.041 kg/s, respectively. The value of the reduced temperature parameter [(Ti-Ta)/GT] is significant in terms of explaining how this factor alters the solar collector's efficiency.

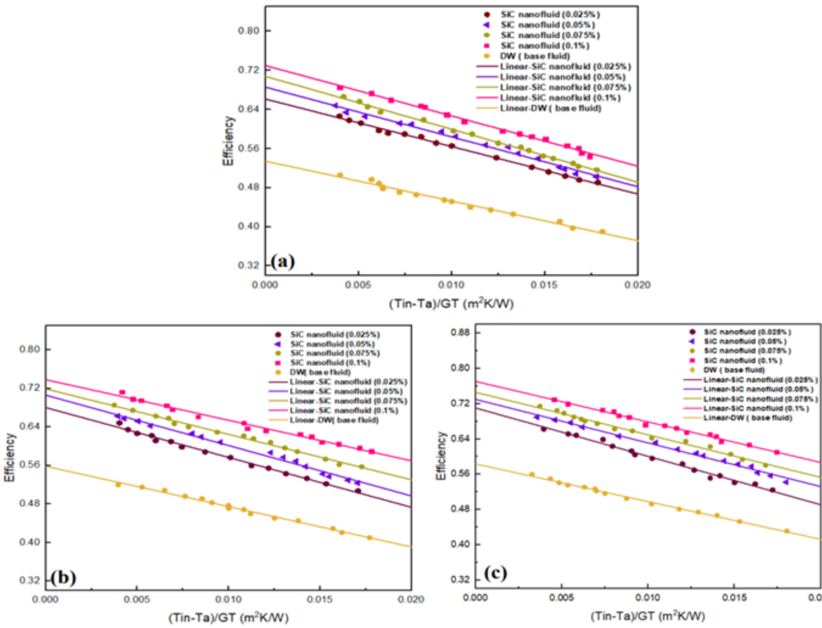

Fig. 6. The thermal efficiency of FPSC for SiC/DW nanofluid: (a) 0.025kg/s, (b) 0.033 kg/s, and (c) 0.041 kg/s

As illustrated in Fig. 6, when nanofluids are used, the solar collector's efficiency is increased in comparison to water, while the addition of an increased volume of nanoparticles also causes it to rise.

Additionally, increased mass flow rates cause the collector's efficiency to increase. Resultantly, from all the investigated scenarios, the collector's efficiency was maximized enhancement at 35% when the volume fraction and mass flow rate were 0.1% and 0.041 kg/s, respectively. The conclusion can be drawn that the collector's efficiency and heat removed energy parameter are both increased when the mass flow rate rises. This can be explained by the fact an increase in the Reynold's number of the max flow rate causes the heat transfer to be increased as a result of turbulence and the layers of fluid becoming mixed. This is fundamentally a result of Brownian motion, which is regarded as being the primary factor causing nanofluids to have increased thermal conductivity in comparison to water.

3.4.2. Test case 2 *zirconium oxide nanofluid*

This part discusses in depth the effect of ZrO_2 nanoparticles concentration fraction on the thermal efficiency performance of the FPSC. Four different volume fractions were analyzed in this experiment, employing distilled water as a working liquid. The chosen volume fraction concentrations which are 0.025%, 0.05%, 0.075%, and 0.1% have great stability and effective thermal performance. Various flow, namely 0.025 kg/s, 0.033 kg/s and 0.041 kg/s were used to conduct this experiment. Fig. 7 shows the results of these experiments for the respective flows of 0.025 kg/s - 0.041 kg/s.

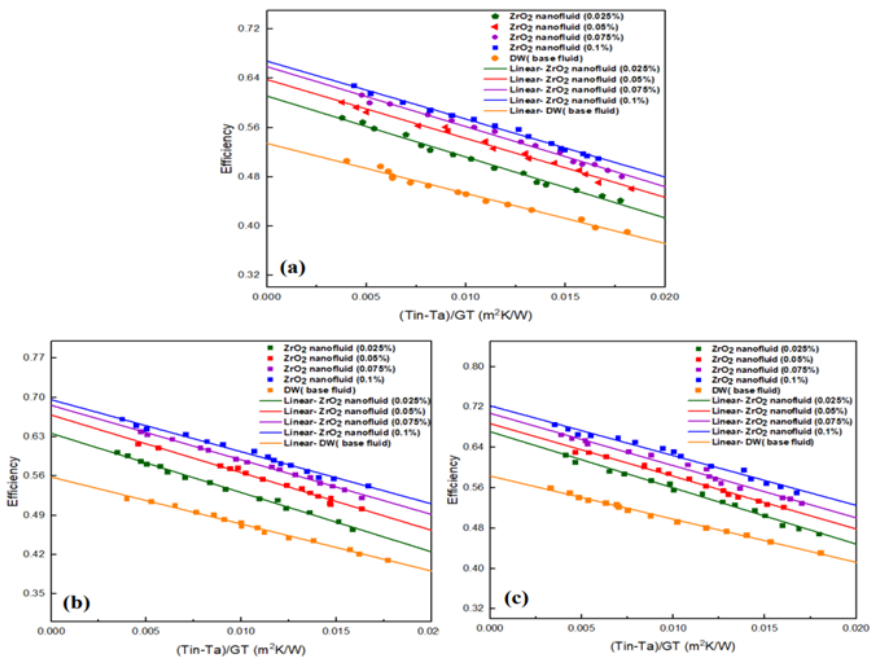

Fig. 7. The thermal efficiency of FPSC for ZrO_2/DW nanofluid:
(a) 0.025kg/s, (b) 0.033 kg/s, and (c) 0.041 kg/s

The efficiency values versus the reduced temperature parameter, [(Ti-Ta)/GT] are indicated in this figure along with a linear fitted curve to represent the studied case. It can be seen that a higher value is attained for the FPSC thermal efficiency when ZrO_2 was added in contrast to DW, the more the nanoparticles added the increase the thermal efficiency. When 0.1% concentration of ZrO_2 is added at the flow of 0.041 kg/s, the thermal efficiency of the FPSC increased by 25.43% in comparison to DW.

3.4.3. Test case 3 zirconium oxide - silicon carbide hybrid nanofluid

Table 1 shows F_R (τα) and F_RU_L reported for FPSCs filled with ZrO_2-SiC/DW hybrid nanofluid.

Table 1. F_RU_L, F_R (τα) and R^2 at various mass flow rates and concentrations

Solid volume fraction φ%	Mass flow rate (kg/s)	F_R (τα)	F_RU_L	R^2
0.025%	0.025	0.6329	8.306	0.9914
	0.033	0.6522	8.482	0.9932
	0.041	0.6719	8.613	0.9920
0.05%	0.025	0.6553	9.858	0.9936
	0.033	0.6786	10.105	0.9868
	0.041	0.6966	10.204	0.9909
0.075%	0.025	0.6784	10.064	0.9937
	0.033	0.6993	10.231	0.9869
	0.041	0.7281	10.322	0.9924
0.1%	0.025	0.6992	10.24	0.9925
	0.033	0.7258	10.548	0.9924
	0.041	0.7521	10.647	0.994
Distilled water	0.025	0.5441	8.232	0.9863
	0.033	0.5581	8.2875	0.9914
	0.041	0.5713	8.353	0.9954

The values are arranged for similar mass flow rates. The reduced temperature parameter [(Ti-Ta)/GT] is evaluated for the given hybrid nanofluid to determine the thermal efficiency of the FPSC. Fig. 8 and Table 1 indicate significant changes in FPSC's efficiency with changes in the volume fraction of ZrO_2-SiC/DW hybrid nanofluid.

The experiment revealed that nanofluid depicted higher heat removable factor as compared to water. The value for heat removable factor rises at a higher nanofluid mass flow rate and higher volume fraction.

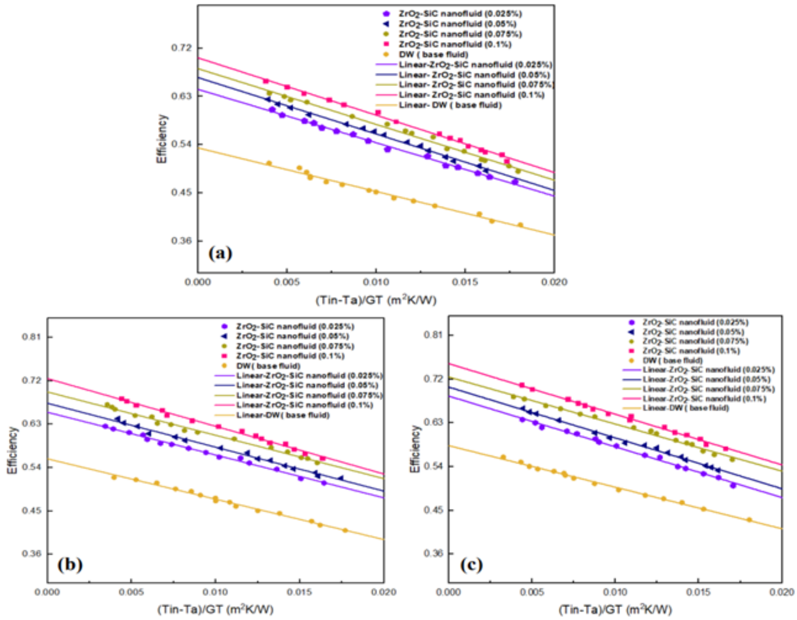

Fig. 8. The thermal efficiency of FPSC for ZrO_2-SiC/DW hybrid nanofluid with different Solid volume fraction: (a) 0.025 kg/s, (b) 0.033 kg/s, and (c) 0.041 kg/s

The outcomes also revealed that the nanofluids showed higher convective heat transfer coefficient than the water. The ZrO_2- SiC/DW hybrid nanofluid also showed a rise in the F_R (τα) and F_RU_L. Hence, the ZrO_2-SiC/DW hybrid nanofluid has improved the FPSC efficiency noticeably. The efficiency of FPSC was found to be associated with the nanoparticle concentration or volume fraction in the nanofluid. The nanoparticle concentration is increased, the rise in the number of nanoparticles leads to a greater heat convection effect between base fluid and nanoparticles resulting in higher values of heat transfer and Nusselt number.

The current part also shows that FPSC shows a rise in efficiency with increasing concentration of nanoparticles until the concentration reaches a certain level. The FPSC considered in this study depicted high efficiency at a volume fraction of 0.1%. Moreover, the FPSC efficiency was evaluated at different concentrations or volume fractions (φ) of ZrO_2-SiC/DW hybrid nanofluid (0.025%, 0.05%, 0.075%, and 0.1%) and mass flow rates (0.025, 0.033 and 0.041 kg/s). The rise in the value of F_R (τα) energy absorbance is observed with increasing mass flow rate for each volume fraction of hybrid nanofluid.

3.5. Nusselt number of nanofluids

The Nusselt number is applied widely in fluid dynamics and heat transfer. This number quantifies the ratio of convective heat transfer to conductive heat transfer at the surface of a fluid. The volume concentrations and Reynolds number evaluated for the fluid help determine its average Nusselt number. It was observed that nanofluids depicted a higher value of the Nusselt number indicating a higher rate of heat transfer than water. The addition of nanoparticles to the base fluid and increasing the fluid flow rate led to a greater value of Reynolds number. The rise in the Reynolds number and the temperature gradient leads to changes in the Nusselt number since these parameters raise the heat transfer coefficient. It is evident from Fig. 9 that using nanofluids instead of base fluid led to a rise in the Nusselt number besides improving the heat transfer properties of the collector. It is noticed that the Nusselt number of nanofluids increases with increase of particle volume concentrations and Reynolds number.

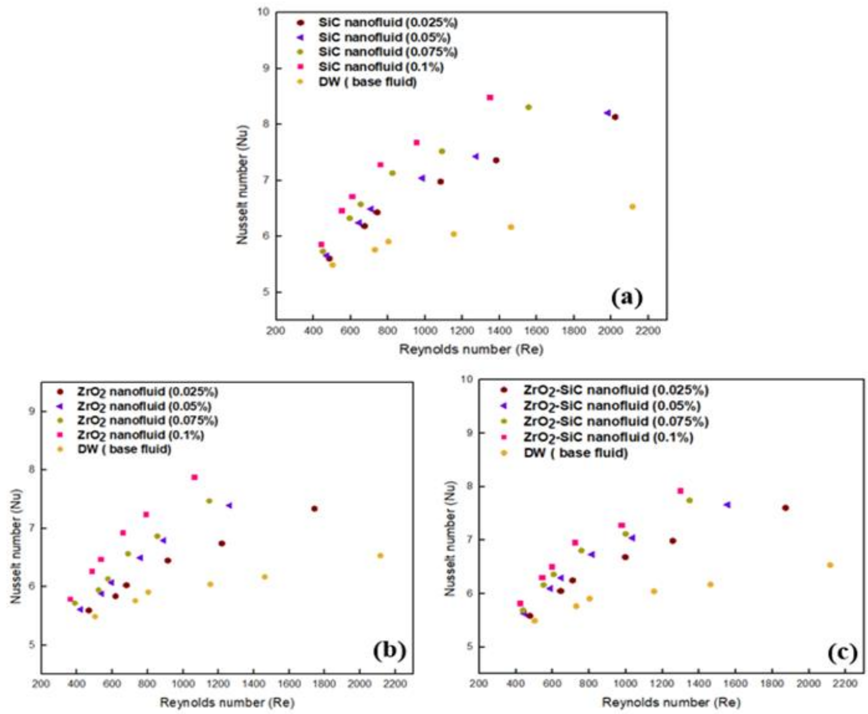

Fig. 9. Nusselt number of nanofluids at variation values of solid volume fraction and Reynolds numbers for (a) SiC/DW, (b) ZrO_2/DW, and (c) ZrO_2-SiC/DW nanofluids

3.6. Exergy analysis of flat plate solar collector

The value of entropy generation and exergy destruction determine the solar collector's exergetic performance using SiC/DW, ZrO_2/DW, and ZrO_2-SiC/DW nanofluids as working fluid. The decline in entropy generation and exergy destruction leads to higher exergetic efficiency of thermal systems. Hence, these two parameters need to be carefully considered to ensure higher system efficiency. The values of entropy generation and exergy destruction were obtained at different nanoparticles concentrations in the fluid and mass flow rates have been presented in Figs. 10-12. These figures clearly show that as the volume fraction nanoparticle concentration increases and mass flow rate of the working fluid is decreased; there is a decline in entropy generation and exergy destruction.

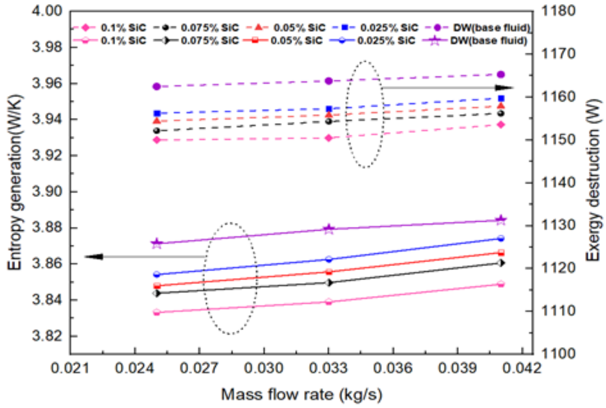

Fig. 10. Entropy generation and exergy destruction of FPSC for SiC/DW nanofluid and distilled water at various mass flow rates

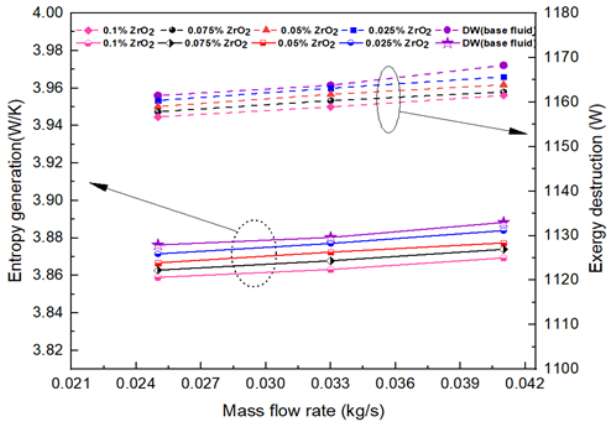

Fig. 11. Entropy generation and exergy destruction of FPSC for ZrO_2/DW nanofluid and distilled water at various mass flow rates

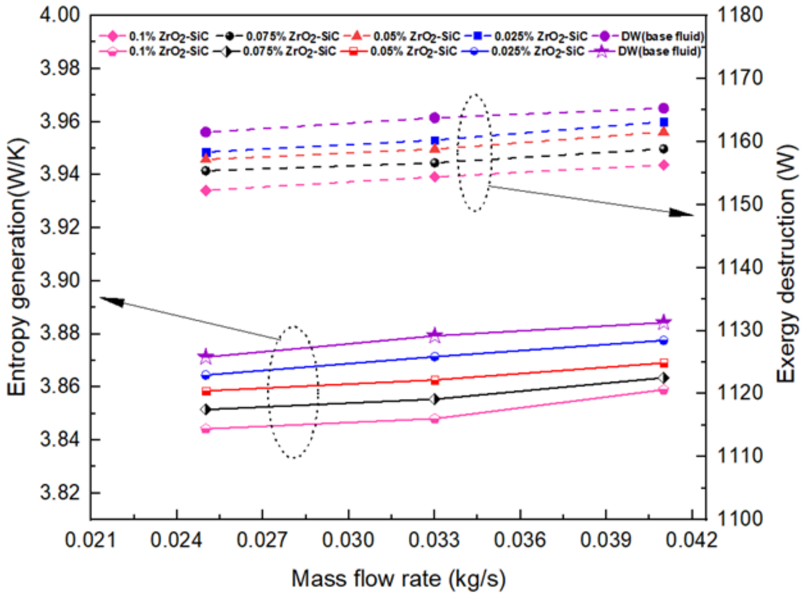

Fig. 12. Entropy generation and exergy destruction of FPSC for ZrO_2-SiC/DW nanofluid and distilled water at various mass flow rates

In the current study, the experiments revealed that the concentration of nanoparticles has a direct effect on the exergy efficiency which increases as bigger nanoparticles are used in a nanofluid. The exergy efficiency is inversely related to the mass flow rate. The exergy efficiency increase value of 16.05% was attained for a volume fraction of 0.1% ZrO_2 particles dispersed in water. The use of ZrO_2-SiC/DW hybrid nanofluid comprised of particles with 0.1 % concentration yields higher exergy efficiency than the water base fluid. Moreover, the high exergy efficiency of hybrid nanofluids compared to water makes it a better absorbing medium.

It was also discovered that there is a 28.31% rise in exergy efficiency when a nanoparticle's concentration of 0.1% is introduced into the working fluid. In addition, the highest value of nearly 37.42% was obtained for 0.1% volume fraction of SiC particles dispersed in water. Moreover, the exergy efficiency showed a positive association with solar radiation. The solar collector containing water showed the lowest exergy efficiency while that filled with 0.1% nanofluid showed the most exergy efficiency.

4. NEW SCIENTIFIC RESULTS

This section presents the new scientific findings from the research as follows:

1. Rheological behavior of mono and hybrid nanofluid

I have examined and evaluated the rheological properties of three types new nanofluids (zirconium oxide, silicon carbide and their hybrid (50:50%) by solid volume fraction) based distilled water. In order for nanofluids' rheological behaviour to be researched, it is firstly necessary to determine their viscous behaviour from Newtonian and non-Newtonian perspectives. Besides, for the purpose of evaluating the rheological properties of ZrO_2/DW, SiC/DW and ZrO_2-SiC/DW nanofluids, measurements of the nanofluids' viscosity and shear stress were taken at varying shear rates across the range of temperatures to get insight into the rheological behaviour of the given nanofluid.

Based on the experimental results, I found that the changes in shear stress as result of the shear rate show a linear pattern, it can be deduced that the given nanofluids exhibit Newtonian behaviour characteristics. I have also observed that the changes in dynamic viscosity of the given nanofluids according to the shear rate at various temperatures remains constant, this indicated that the nanofluids of ZrO_2/DW, SiC/DW and ZrO_2-SiC/DW behave in a Newtonian manner.

2. Experimental correlation between the relative dynamic viscosity and volume fraction, and temperature nanofluid

According to results obtained from the experiments, I have put forward a novel correlation capable of predicting the investigated nanofluids' viscosity in relation to solid volume fraction and temperature. This correlation is valid for volume fraction (φ) ranging from 0.025% to 0.1% and temperatures (T) ranging from 20 °C to 60 °C.

For ZrO_2/DW nanofluid:

$$\frac{\mu_{nf}}{\mu_{bf}} = 0.7986 + 9.72\,\varphi + 0.013\,T - 62.174\,\varphi^2 - 0.00006\,T^2 + 0.261\,\varphi\,T$$

For SiC/DW nanofluid:

$$\frac{\mu_{nf}}{\mu_{bf}} = 0.8814 - 1.6\,\varphi + 0.013\,T + 10.465\,\varphi^2 - 0.0002\,T^2 + 0.204\,\varphi\,T$$

For ZrO_2-SiC/DW hybrid nanofluid:

$$\frac{\mu_{nf}}{\mu_{bf}} = 0.7096 + 3.84\,\varphi + 0.022\,T - 24.284\,\varphi^2 - 0.0002\,T^2 + 0.228\,\varphi\,T$$

I have observed that the comparison of the laboratory data with the outcomes from the proposed correlation showed a 5.31% margin of deviation and R^2 value of 98.52% for ZrO_2/DW, by 5.27% and 99.11% for SiC/DW, and by 3.51% and 98.92% for ZrO_2-SiC/DW nanofluids, respectively.

3. *Effect of volume fraction and temperature on thermal conductivity of nanofluid*

I have pointed out that the volume fraction of nanoparticles and temperature strongly influences thermal conductivity of zirconium oxide, silicon carbide, and hybrid nanofluid. I noticed that a positive association of the thermal conductivity of nanofluid with parameters like temperature and solid volume fraction. Besides, I proved experimentally that the thermal conductivity of the given nanofluid increased with rising temperature and higher solid volume fraction. I have also discovered that the effect of higher volume fraction on thermal conductivity of the given nanofluids outshines the effects of temperature.

Through the experimental findings, I have observed that the thermal conductivity enhancement for ZrO_2/DW was 20.45%, 30.3% for SiC/DW and that of ZrO_2-SiC/DW was 25.75% at maximum solid volume fraction and temperature.

Based on experimental results, I have explored a novel proposed correlation for ZrO_2/DW, SiC/DW and ZrO_2-SiC/DW nanofluids thermal conductivity enhancement ratios as a function of volume fraction and temperature. It is accurate and valid for temperatures (T) between 20 and 60 °C and fraction volumes (φ) of 0.025% to 0.1%.

For ZrO_2/DW nanofluid:

$$\frac{k_{nf}}{k_{bf}} = 0.9606 + 1.609\,\varphi + 0.0014\,T, R^2 = 0.9889$$

For SiC/DW nanofluid:

$$\frac{k_{nf}}{k_{bf}} = 0.9631 + 2.134\,\varphi + 0.0025\,T, R^2 = 0.9906$$

For ZrO_2-SiC/DW hybrid nanofluid:

$$\frac{k_{nf}}{k_{bf}} = 0.9619 + 2.076\,\varphi + 0.0015\,T, R^2 = 0.986$$

I found that the comparison between experimental results and correlations outputs showed a good agreement which signifies that the results were accurate. Moreover, I noticed that the proposed correlations gave an acceptable value of the maximum margin of deviation equal to 1.49% for ZrO_2/DW nanofluid, by 1.2% for SiC/DW nanofluid and by 1.15% for ZrO_2-SiC/DW hybrid nanofluid.

4. Effect of nanofluids on the thermal efficiency of FPSC

I have unfolded and improved the experimental thermal efficiency of FPSC by using new nanofluids as a working fluid in solar collector. I experimentally investigated the four solid volume fractions (0.025%, 0.05%, 0.075% and 0.1%) of ZrO_2/DW, SiC/DW, ZrO_2-SiC/DW nanofluids as well as the impact of three different mass flow rates (0.025, 0.033 and 0.041 kg/s). I found that increasing thermal efficiency of FPSC and greater heat transfer in solar system when replace the base fluid (water) inside the solar collectors with the given nanofluids.

Besides, I proved experimentally that a rise in mass flow rate with the increase in nanofluid concentration led to a rise in thermal efficiency of FPSC. Based on experimental results, I have identified that in the case of 0.041 kg/s flow rate, 0.1% volume fraction of SiC/DW, ZrO_2/DW and ZrO_2-SiC/DW nanofluids showed a 35.53%, 26.2% and 31.46%, respectively, in the maximum enhancement of thermal efficiency of FPSC in comparison to water.

According to results obtained from the experiments, I have developed novel correlation for FPSC thermal efficiency as a function of the reduced temperature factor [(Ti-Ta)/GT] and solid volume fraction (φ). Besides, I have estimated all the coefficients of the developed thermal efficiency correlation for the FPSC based nanofluids:

$$\eta_c = a + b\left(\frac{T_i - T_a}{GT}\right) + c\,\varphi + d\left(\frac{T_i - T_a}{GT}\right)^2 + e\,\varphi^2$$

5. Empirical correlation of the Nusselt number for nanofluid in solar collector

Based on experimental results, I have established a new empirical correlation for estimating the Nusselt number for nanofluids in solar collector as a function of volume concentration, Reynold’s number, and Prandtl’s number.

For ZrO_2/DW nanofluid:

$$Nu = 0.10158\, Re^{0.4742} Pr^{0.5173} (1 + \varphi)^{1.712}$$

For SiC/DW nanofluid:

$$Nu = 0.07495\, Re^{0.5251} Pr^{0.506} (1 + \varphi)^{3.683}$$

For ZrO_2-SiC/DW nanofluid:

$$Nu = 0.04677\, Re^{0.5596} Pr^{0.6468} (1 + \varphi)^{2.7573}$$

The above correlations are valid for volume concentrations ranging from 0% to 0.1% and Reynolds numbers between 361.07 and 2115.1 while Prandtl's number between 2.57 and 6.98.

6. *Impact of nanofluids on the entropy generation and exergy destruction, and exergy efficiency of FPSC*

I have evaluated and justified the effect of entropy generation and exergy destruction that took place inside the FPSC filled with new ZrO_2/DW, SiC/DW and ZrO_2-SiC/DW nanofluids on the solar collector's exergetic performance. Hence, these two parameters need to be carefully considered to ensure higher system efficiency. Besides, I experimentally investigated the entropy generation and exergy destruction based on different solid volume fractions of nanofluids and its impact on FPSC performance.

According to experimental results, I have observed that the decline in entropy generation and exergy destruction leads to higher exergetic efficiency of FPSC. I have discovered that using nanofluids as working fluids yields lower values of entropy generation and exergy destruction. This is because a more concentrated nanofluid is characterized by higher thermal conductivity.

Based on the experimental results, I observed that the nanoparticles are good conductors of heat and hence enhance the fluid's thermal conductivity when combined with the fluid. Consequently, the exergy efficiency experiences a rise. I have also discovered that there are 37.42%, 16.05% and 28.31% rise in exergy efficiency when a nanoparticles concentration of 0.1% of SiC/DW, ZrO_2/DW, ZrO_2-SiC/DW nanofluids, respectively.

7. *Numerical analysis of FPSC performance*

I have developed a new CFD model for flat plate solar collector filled by new nanofluids of silicon carbide, zirconium oxide, and their hybrid nanofluids. This model is like the experiment model in dimensions in order to investigate the performance of FPSC using mono and hybrid nanofluids. To achieve that purpose, I have observed that using ANSYS Fluent software through the adoption of the finite volume method for calculating the output temperature, absorber plate temperature and efficiency of FPSC. I have validated calculated results by comparing experimental data and theoretical results that accounted for Nusselt correlations. Besides, I have found that the results of the experimental and simulation work with DW and both the SiC/DW, ZrO_2/DW, and ZrO_2- SiC/DW nanofluids in FPSC had efficiencies that were close to each other.

5. CONCLUSION AND SUGGESTIONS

The efficiency of FPSC filled with ZrO_2/DW, SiC/DW and ZrO_2-SiC/DW nanofluids was examined in this work. The use of the new nanofluids as a state-of-the-art heat transfer liquid remains in solar collectors and definitely merits further scientific investigation. For this study, nanofluids were prepared with different concentrations, namely 0.025%, 0.05%, 0.075% and 0.1%. Each of the nanofluids was filled inside the solar collector to see the changes it caused in the collector's efficiency. Moreover, following the ASHRAE standard, the study considered different mass flow rates of 0.025, 0.033 and 0.041 kg/s to study the impact of mass flow rates on solar collector efficiency. Based on the findings of the current study, it is possible to make the following inferences:

- The Newtonian behaviour of the given nanofluids was observed at each temperature setting.
- The results indicate that dynamic viscosity increased to the maximum level at a solid concentration of 0.1% and temperature of 60 °C, where the increase was around 226.3% for the nanofluid of ZrO_2/DW, 110.5% for the nanofluid of SiC/DW, and 169.47% for the hybrid nanofluid of ZrO_2-SiC/DW.
- The thermal conductivity enhancement for ZrO_2/DW was 20.45%, 30.3% for SiC/DW, and 25.75% for ZrO_2-SiC hybrid nanofluid at maximum solid volume fraction and temperature.
- The FPSC thermal efficiency was increased as 33.57%, 26.2% and 31.46% for 0.1% SiC/DW, ZrO_2/DW and ZrO_2-SiC/DW nanofluids at flow rate of 0.041 kg/s, respectively, in comparison to water.
- It was revealed during the experiment that the exergy efficiency of the solar collector increases when the distilled water is replaced with nanofluids. The FPSC exergy efficiency increased by 37.42% ,16.05% and 28.31% when SiC/DW, ZrO_2/DW, ZrO_2-SiC/DW nanofluids, respectively, were used.
- The results obtained from the numerical and experimental work were in good agreement, so the outcomes of the experiments served to validate the numerical model.

It has been proposed that research needs to focus on more factors that affect nanofluid properties. The factors recommended for future studies include nanoparticle aggregation, shape, size, sonication time and base fluid. The study also emphasizes more research in future on nanoparticles can also be used in solar selective absorber nano coatings to find out they increase efficiency of FPSC. Studies on using nanoparticles in anti-reflective nanocoating on glass cover and their effects on thermal efficiency of FPSC are recommended.

6. SUMMARY

PERFORMANCE ENHANCEMENT OF FLAT PLATE SOLAR COLLECTOR USING NANOFLUIDS

In this work, comprehensive experimental and numerical investigations were carried out to evaluate the flat plate solar collector's thermal and exergy enhancement using nanofluid were undertaken. The nanofluids of SiC/DW, ZrO_2/DW and ZrO_2-SiC/DW were prepared using a two-steps method by dispersing the given nanoparticles in distilled water (DW) by the ultrasonic processor and a magnetic stirrer. Solid volume fractions (φ) of the given nanofluids of 0.025%, 0.05%, 0.075% and 0.1% were used. Stability of nanofluids were examined by zeta potential test. After that, thermal conductivity and viscosity were measured using the using a KD2-Pro thermal analyser and a Brookfield viscometer, respectively, at temperatures ranging from 20 to 60 °C. In the next step, the nanofluids are employed into a flat plate solar collector (FPSC) to identify the performance change of the collector. Besides, thermal and exergy efficiencies tests were conducted on the solar collector. The investigation of the solar collector's performance was based on ASHRAE Standard 93-2003. All experimental investigations on the flat plate solar collector were conducted at the Hungarian University of Agriculture and Life Sciences (MATE) in Gödöllő, Hungary. Ultimately, a CFD model was created to assess the thermal performance of the given nanofluids at FPSC in the experiment indicated above.

The results showed that the thermal conductivity of the nanofluid was enhanced with increased volume fractions and temperature. The thermal conductivity enhancement for ZrO_2/DW at the volume fraction of 0.1% was 20.45%, that of ZrO_2-SiC/DW was 25.75%, and that of SiC/DW was 30.3%. Additionally, according to the results of the experiments, new correlations capable of predicting for both the investigated nanofluids' viscosity and thermal conductivity in relation to solid concentration and temperature have been suggested.

The collector's thermal efficiency was enhanced by 35.53%, 26.2% and 31.64% for a volume fraction of 0.1% of SiC/DW, ZrO_2/DW and ZrO_2-SiC/DW nanofluids, respectively, when the value of [(Ti – Ta)/GT] was zero and mass flow rate of 0.041 kg/s. Additionally, an increase of 37.4%, 16.05% and 28.31% were recorded for the exergy efficiency at volume fraction of 0.1% SiC/DW, ZrO_2/DW and ZrO_2-SiC/DW nanofluids than its value in distilled water. The experiments also discovered new correlations for determining the Nusselt number of the given nanofluids and thermal efficiency of FPSC. Moreover, this study is significant as it presents a new nanofluids that can be used in renewable energy applications.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Refereed papers in foreign languages:

1. **Ajeena, Ahmed M.**, Farkas, I., Víg, P. (2024): Energy and exergy assessment of a flat plate solar thermal collector by examine silicon carbide nanofluid: An experimental study for sustainable energy. Applied Thermal Engineering, Vol. 236, Paper No121844.https://doi.org/10.1016/j.applthermaleng.2023.121844 (Scopus: D1, IF: 6.4)
2. **Ajeena, Ahmed M.**, Farkas, I., Víg, P. (2024): Characterization, rheological behaviour, and dynamic viscosity of ZrO_2-SiC (50–50)/DW hybrid nanofluid under different temperatures and solid volume fractions: An experimental study and proposing a new correlation. Powder Technology, Vol. 431, Paper No 119069. https://doi.org/10.1016/j.powtec.2023.119069 (Scopus: Q1, IF: 5.2)
3. **Ajeena, Ahmed M.**, Farkas, I., Víg, P. (2023): Performance enhancement of flat plate solar collector using ZrO_2-SiC/DW hybrid nanofluid: A comprehensive experimental study. Energy Conversion Management X, Vol. 20, Paper No 100458. https://doi.org/10.1016/j.ecmx.2023.100458 (Scopus: Q1, IF: 6.3)
4. **Ajeena, Ahmed M.**, Farkas, I., Víg, P. (2023): A comprehensive experimental study on thermal conductivity of ZrO_2-SiC /DW hybrid nanofluid for practical applications: Characterization, preparation, stability, and developing a new correlation. Arabian Journal of Chemistry, Vol. 16, Paper No 105346. https://doi.org/10.1016/j.arabjc.2023.105346 (Scopus: Q1, IF: 6)
5. **Ajeena, Ahmed M.**, Farkas, I., Víg, P. (2023): A comparative experimental study on thermal conductivity of distilled water-based mono nanofluids with zirconium oxide and silicon carbide for thermal industrial applications: Proposing a new correlation. International Journal of Thermofluids, Vol. 20, Paper No 100424. https://doi.org/10.1016/j.ijft.2023.100424 (Scopus: Q1)
6. **Ajeena, Ahmed M.**, Farkas, I., Víg, P. (2023): A comparative experimental investigation of dynamic viscosity of ZrO_2/DW and SiC/DW nanofluids: Characterization, rheological behavior, and development of new correlation. Heliyon, Vol. 9, Paper No e21113. https://doi.org/10.1016/j.heliyon.2023.e21113 (Scopus: Q1, IF: 4)
7. **Ajeena, Ahmed M.**, Víg, P., Farkas, I. (2022): A comprehensive analysis of nanofluids and their practical applications for flat plate solar collectors: Fundamentals, thermophysical properties, stability, and difficulties. Energy Reports Vol. 8, pp. 4461–4490. https://doi.org/10.1016/j.egyr.2022.03.088 (Scopus: Q1, IF: 5.2)
8. **Ajeena, Ahmed M.**, Farkas, I., Víg, P. (2023): Experimental approach on the effect of ZrO_2/DW nanofluid on flat plate solar collector thermal and exergy efficiencies. Energy Reports, Vol. 10, pp. 4733–4750. https://doi.org/10.1016/j.egyr.2023.11.036 (Scopus: Q1, IF: 5.2)