Hindawi
International Journal of Photoenergy
Volume 2021, Article ID 5546508, 13 pages
https://doi.org/10.1155/2021/5546508

Research Article

Improvement of Heat Pipe Solar Collector Thermal Efficiency Using Al_2O_3/Water and TiO_2/Water Nanofluids

Sinan Ünvar[1], **Tayfun Menlik**[2], **Adnan Sözen**[2], and **Hafız Muhammad Ali**[3,4]

[1]*Ağrı İbrahim Çeçen University, Vocational School, Ağrı, Turkey*
[2]*Technology Faculty, Energy Systems Engineering, Gazi University, Teknikokullar, Ankara, Turkey*
[3]*Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia*
[4]*Interdisciplinary Research Center for Renewable Energy and Power Systems (IRC-REPS), King Fahd University of Petroleum and Minerals, Dhahran, 31261, Saudi Arabia*

Correspondence should be addressed to Hafız Muhammad Ali; hafiz.ali@kfupm.edu.sa

Received 11 January 2021; Accepted 18 May 2021; Published 8 June 2021

Academic Editor: Mohammad Alghoul

Heat pipe solar collectors (HPSCs) are heat exchangers that carry heat based on the phase change of the heat pipe working fluid. It is aimed to increase the operating temperature range of solar collectors by changing the phase of the working fluid in the heat pipe at low temperature. For this reason, it has become widespread to use nanofluids obtained by mixing nanosized metal oxides with the base fluid in certain proportions in order to increase both the thermal conductivity of the heat pipe working fluids and to increase the specific heat closures. The main purpose of this study, which was conducted to evaluate the performance of HPSCs, is to increase performance, and an experimental study has been conducted in this direction. For this purpose, an HPSC designed and manufactured was used. Al_2O_3-water and TiO_2-water nanofluids containing 2% nanoparticles were used in order to increase performance in the study. HPSC used in the study consists of 8 heat pipes with a length of 100 cm. The experiments were carried out for pure water and nanofluids, and their efficiency and strength were compared. The highest value of instantaneous efficiency was calculated as 48% when pure water was used as the working fluid, 58% for Al_2O_3-water nanofluid, and 64% for TiO_2-water nanofluid. The instantaneous power obtained using pure water was determined as 135.66 W, 167.96 W for Al_2O_3-water nanofluid, and 184.03 W for TiO_2-water nanofluid. The improvement in efficiency was determined as 20.8% for Al_2O_3-water nanofluid and 33.3% for TiO_2-water nanofluid. Improvement in powers was found to be 23.8% for Al_2O_3-water nanofluid and 35.6% for TiO_2-water nanofluid.

1. Introduction

Turkey is a rich country in the diversity of renewable energy sources and its current potential. Particularly, hydro, wind, solar, and geothermal energy has the potential to meet most of the energy needed. However, there are evaluations that this potential is not used effectively enough in the country [1]. The need for energy is increasing day by day in many countries, and the gap between production and consumption tends to open day by day. Among the most important reasons for this situation are as follows: factors such as population growth, technological development, industrialization, and increase in people's life comfort are at the top. For example, between 2002 and 2017, total electrical energy consumption increased from 103 TWh to 296 TWh, an increase of about three times [2]. Due to such an increase in energy use and the widening of the difference between production and consumption, the efficient use of existing energy resources has become a very important issue for every country and has made countries take some precautions. In addition to the precautions taken, the improvement works on the existing systems have become an important issue nowadays, and important steps towards the solution of the energy problem have been taken by accelerating the studies carried out in this direction. Studies are carried out in various countries to develop devices with features such as electricity generation and water heating, especially with the use of solar energy, and researchers working on these issues are also supported.

Particularly, in recent years, studies have been carried out for the use of heat pipes in solar collectors and various working fluids have been used within the scope of improving the efficiency of collectors.

Heat pipes are devices working on the principle of evaporation-condensation of the working fluid. The working fluid, which passes from the liquid phase to the vapor phase under the influence of temperature, rises under the influence of the vacuum environment and natural transport and moves its energies from one region to another [3]. The transport cycle formed in the heat pipe is completed in this way. The temperature of the working fluid, which releases its energy to the region where it rises, drops and therefore passes into the liquid phase. In other words, the heat transfer cycle is completed by making use of the phase change of the working fluid in the heat pipe. Conventional heat transfer fluids have lower thermal conductivity because they have weaker thermal properties than solids, so the use of conventional fluids in thermal systems may be insufficient to improve the performance of engineering devices and improve their compactness [4]. However, there are some ways to increase heat transfer efficiency in heat pipes. One of these ways is the addition of metallic-nonmetallic or polymeric particles to heat transfer fluids. Fluids prepared by suspending nanoparticles of 1-100 nm in size into conventional fluids are called "nanofluid," and their heat transfer properties are better than conventional fluids. The main physical events that cause the heat transfer performance of nanofluids to improve significantly can be summarized as follows [5]:

(i) The increase in the thermal conductivity of the prepared nanofluid, as the thermal conductivity of the solid metal is higher than that of the basic fluid

(ii) The increase in the thermal transfer surface area due to the increase in the thermal conductivity of the fluid

(iii) The increase in the effective thermal capacity of the fluid

(iv) Increased thermal conductivity of the liquid due to high fluid activity and turbulence volume

In recent years, many researches have been conducted on the use of nanofluids in heat pipes. Saffarian et al. conducted a numerical study based on the collector's flow direction to increase the efficiency of the flat plate solar collector. In order to examine their effects on heat transfer efficiency, they specifically examined the parameters of flow direction and the use of nanofluid in the collector and investigated their effects. Accordingly, they analyzed the geometries of structures with U-shaped, wavy, and spiral pipes of the same pipe length on a flat plate solar collector using the k-ε model. As a result of their studies, they determined that the use of wavy and spiral pipes could significantly increase the heat transfer and Nusselt number, and the increase in nanoparticle concentration could also increase the heat transfer coefficient [6]. Mercan and Yurddaş conducted a numerical study to determine the effect of using nanofluids on heat transfer in solar collectors. In this numerical study, they have chosen different fractions, different collector angles, and different mass flow rates as basic parameters for nanofluids. As a result of their studies, they determined that the use of nanofluid improved heat transfer [7]. Dehaj and Mohiabadi used magnesium oxide (MgO) and deionized water nanofluids as working fluids in the heat pipe solar collector. They experimentally examined the effects of these nanofluids on the performance they prepared in different concentrations. As a result of their studies, they found that the performance of the heat pipe solar collector increased as the rate of the refrigerant increased and the concentration of the MgO nanoparticle increased [8]. Kılıç studied the effects of fluids containing nanosized metal oxides in solar collectors on the performance of the system. In his experiments using a flat plate solar collector (FPSC), he used 2% mass alumina-water (Al_2O_3-water) and titanium dioxide (TiO_2) nanofluids. Of the nanofluids used, TiO_2-water nanofluid improved 34.43% in instantaneous efficiency compared to pure water, 32.43% improvement in power output, while Al_2O_3-water nanofluid mixture increased by 9.5% in instantaneous efficiency and 9.06% increased in power output [9]. Sözen et al. conducted a study to examine the effect of nanofluids on system performance in a heat exchanger containing a heat pipe bundle. As a result of their experiments, they determined that the use of nanofluid in the system significantly improved performance. In their tests at 6 kW heater power, they found that the maximum recovery was 37.04% [10]. Kaya et al. conducted an experimental performance assessment in an evacuated tube heat pipe using 50 nm diameter copper oxide- (CuO-) pure methanol nanofluid. Exergy values of different states were calculated, and experimental results were compared. From the data obtained as a result of the study, it was stated that the use of nanofluid provided better performance in heat pipe applications [11]. Daghigh and Zandi conducted an experimental study on the use of nanofluids in heat pipe solar collectors. In their study, they used water as the main fluid and CuO, TiO_2, and MWCNT as nanoparticles. As a result of the experiments, it was determined that the use of nanofluid provided a better thermal performance than the use of water. Compared with water, MWCNT, CuO, and TiO_2 nanofluids have been shown to perform better by 25%, 12%, and 5% in August and 25%, 15%, and 7%, respectively, in October [12]. Gürü et al. studied experimentally the effects of using a nanofluid containing bentonite in heat pipes. The particle ratios of the nanofluids used in the experiments were examined by changing 0.5%, 2%, and 4% by mass. The highest heat pipe efficiency was achieved with an increase of 37% in the parameters of 200 W heating power and 5 g/s cooling water mass flow [13]. Sözen et al. studied using fly ash and alumina nanofluids to evaluate the performance of two-phase closed thermosiphon heat pipe. In their study, they used various metal oxide containing nanoparticles such as SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO obtained from the cyclones of Yatağan Thermal Power Plant. Experiments were carried out at three different heating powers (200 W, 300 W, and 400W) and three different coolant flow rates (5 g/s, 7.5 g/s, and 10 g/s). It has been determined that using nanofluid instead of water at 400 W heating power and 5 g/s cooling water flow provided a 30.1% reduction in heat resistance

Figure 1: Ultrasonic bath setup.

Table 1: Properties of nanoparticles used in the study [35].

	Alumina	Titanium dioxide
Purity	99.5+	99.55+
Particle size (average)	18 nm	38 nm
Surface area	140 m^2/g	35 m^2/g
Density	3900 kg/m^3	4100 kg/m^3

Table 2: Devices and technical features used in preparing nanofluid.

Device name	Technical specifications
Ultrasonic bath (Bandelin DT 255 H)	(i) Voltage: 230 V-50/60 Hz (ii) Ultrasonic power: 160/640 W (ii) Heater power: 280 W (iv) Ultrasonic frequency: 35 kHz (v) Internal volume: 5.5 L
Precision scales (Precisa XB 320M)	(i) Precision: 0.1 mg (ii) Measuring range: 0.02-320 g

[14]. Çiftçi et al. conducted experimental studies to determine the effect of using a nanofluid containing TiO_2 in heat pipes on system improvement. For this purpose, the nanoparticle used in the experiments was mixed with 2% pure water and a nanofluid was prepared by the two-step method. As a result of the experiments conducted at various heating power and mass flow values, they found that the improvement in the highest thermal performance was 16.5% at 200 W power at 5 g/s [15]. Çakır used 2% by volume Al_2O_3 (alumina) nanoparticles in thermosiphon type heat pipe in his study. The researcher used 3 different water flows in the condenser part in his experiments and carried out the experiments at 2 different angles by giving 3 different heat inputs in the evaporator part. As a result of the experiments, it has been determined that the nanofluid used in 500 W heat input at 0.0075 kg/s mass flow and 75° heat pipe slope provided efficiency improvement of 35.7% [16]. Pise et al. investigated the working conditions and performance of a thermosiphon heat pipe with a serpentine-shaped solar collector. In their experimental study, they used 0.05%, 0.025, and 0.05% Al_2O_3 nanofluid and surfactant. They determined the angle of 50° as the optimum value among different slope angles. As a result of their studies, they found that the use of nanofluid provided better performance compared to pure water [17]. Menlik et al. produced 5% volumetric MgO/water nanofluid by direct synthesis using Triton X-100 nonionic surfactant and used it in heat pipes. In the heat pipe experimental setup they prepared, they used flat copper pipes with an inner diameter of 13 mm and wall thickness of 2 mm and 1 mm. As a result of their studies, they found that an improvement of 26% was achieved in heat pipe performance at 200 W heating power and 7.5 g/s flow [18]. Eidan et al. used acetone-based nanofluids to improve the performance of glass tube heat pipes in their study. In their study, they determined different filling rates (40%-50%-60%-70%-80%) and different collector slope angles (30°-45°-60°) as experimental parameters. As a result of their studies and experiments, they determined that the optimum performance values were at a 70% filling rate and at an angle of 45° degrees [19]. Ozturk et al. conducted an experimental study on the heat recovery system in the air recovery unit. They used TiO nanoparticles to increase performance in their studies. In their experimental study, they filled 33% of the evaporator part with working fluid. They carried out their experiments at 5 different cooling flow rates (40, 42, 45, 61, and 84 g/s) and two different heating power (3 kW and 6 kW) and between 25°C and 90°C. As a result, they detected a 50% performance increase at 3 kW heating power, 84 g/s cooling air flow, and a heat recovery system using TiO nanofluid [20]. Sözen et al. used aqueous clinoptilolite as their working fluid and carried out their studies in different working conditions to examine the performance of a heat pipe experimentally and numerically. With the use of aqueous clinoptilolite nanofluid as working fluid, it was determined that the maximum heat transfer increase and the improvement in the heat resistance of the heat pipe were 9.63% and 26.31%, respectively. In addition

Table 3: Thermophysical properties of nanofluids.

Working fluid	Density (kg/m^3)	Specific heat (kJ/kgK)	Thermal conductivity (W/mK)	Viscosity ($kgm^{-1} s^{-1}$)			
				20°C	40°C	60°C	80°C
Pure water	998	4.18	0.607	0.98	0.64	0.45	0.35
Al_2O_3/water	1056	4.32	0.665773	1.02	0.82	0.61	0.42
TiO_2/water	1015	4.26	0.662310	1.01	0.92	0.67	0.54

to the experimental studies conducted by the researchers, the calculations made using computational fluid dynamics have been confirmed, and it has been determined that the experimental and numerical data are in harmony [21]. Tong et al. examined performance using Al_2O_3 and CuO nanofluids as working fluid in flat plate solar collectors. They found that when using Al_2O_3 nanofluid compared to water, 21.9% higher efficiency was achieved. They also evaluated the exergic efficiency of the collector using nanofluids. Accordingly, they determined that when using 1% Al_2O_3 and 0.5% CuO nanofluid, an increase of 56.9% and 49.6% was achieved, respectively [22]. Ozsoy and Corumlu synthesized silver-water nanofluids to determine the thermal efficiency of the evacuated tube solar collector. They determined the definition of this nanofluid, which can maintain its stability for a long time, by X-ray fraction, scanning electron microscope, visible spectroscopy with UV, and thermophysical analysis. As a result of their study, they found that the use of silver-water nanofluid increased the efficiency of the solar collector by 20.7% to 40% compared to pure water [23]. Su et al. conducted a literature study on the use of nanofluid in ETSCs. As a result of their studies, they advocated the view that nanofluids that will be prepared by using boron nanoparticles will have an effect on performance [24]. Zhao et al. synthesized graphene/water nanofluid and conducted an experimental study on the thermal initiation performance of the gravity-supported heat pipe. The concentrations of various graphene nanoplatelets (GNPs) were measured at different temperatures in different analyses, including the thermophysical properties-thermal conductivity and viscosity of the nanofluid. In addition, based on the operational evaluation on the start-up process of a single heat pipe, the performance of solar gravity-assisted heat pipes enriched with nanofluids using different concentrations of GNP was compared using water heating experiments. The results showed that the use of 0.05% by weight graphene/water nanofluid instead of water could lead to 15.1% and 10.7% reduction in start-up time in 30 and 60 W inlet heating conditions, respectively [25].

As can be seen from the literature review, the studies to be evaluated within the scope of passive heat improvement in recent studies for the improvement of heat transfer are directed to the use of nanometal oxides to increase the thermal conductivity of the fluid. In this context, many studies have been carried out such as heat pipes, heat recovery units that use the heat pipe as heat exchanger, cooling and heating applications. The biggest feature that distinguishes this study from others is that the heat pipe is tested not individually but in a solar energy application with experiments. Therefore, the heat gained from solar energy is to reach a temperature sufficient to cause the phase change of the working fluid in the heat pipe evaporator, and even this temperature causes the system to operate at a lower degree. For this, a comparative experimental analysis was carried out using two different nanofluids. In the study, the performances of Al_2O_3-water and TiO_2-water nanofluids were compared with that of pure water.

2. Materials and Methods

2.1. Preparation of Nanofluids. Nanofluids are not a simple solid-liquid suspension. It should also provide the following features [26]:

(i) Prepared suspension should be stable

(ii) Clumping in the particles should be negligible

(iii) The chemical properties of the fluid should not change over time

Two methods are used in nanofluid preparation:

(i) One-step method

The one-step approach is based on combining the production and dispersion processes of nanoparticles in a nanofluid in a single step. For this method, the chemical wetting method, vacuum evaporation method, and submerged nanoparticle synthesis method are widely used. In the one-step method, metal materials with high heat conduction coefficient and rapidly oxidizing are preferred. This is because when metal nanoparticles are synthesized with the fluid, their contact with air is prevented. However, one disadvantage of this method is that only low vapor pressure liquids are compatible with the process, which limits its use [27].

(ii) Two-step method

In this method, the desired nanoparticles are obtained first, and then, the nanoparticles are dispersed into the basic fluid in a way that maintains its stability and homogeneity [28]. Magnetic stirrers, ultrasonic water baths, or homogenizers are used to ensure homogeneous distribution. High surface area and surface activity tend to aggregate in nanoparticles. In the two-step method, surfactants are used to increase stability and prevent agglomeration. The two-step method is the most commonly used method in the preparation of nanofluids due to its low production cost and easy accessibility due to the industrial production of nanoparticles [29]. In addition, this method has a higher commercialization potential, since it is possible to produce large quantities of nanofluids.

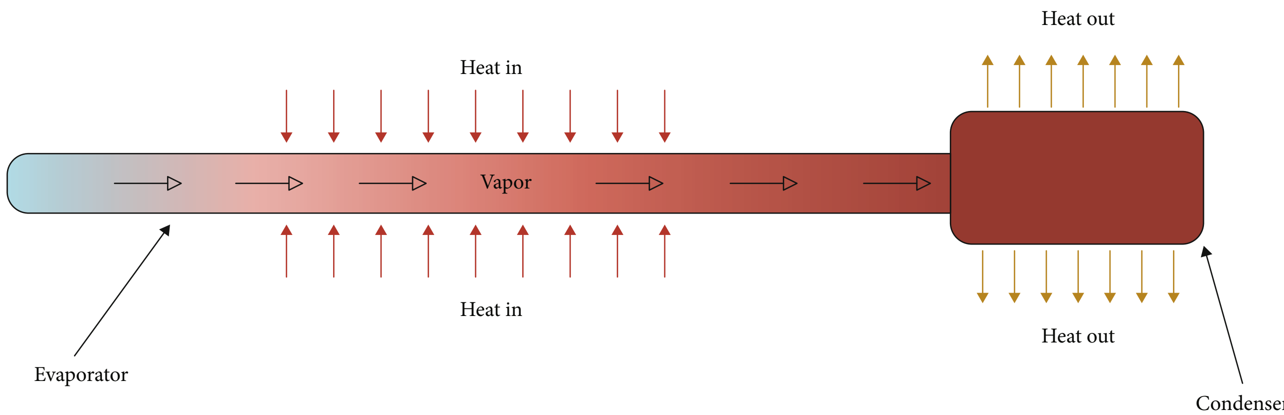

Figure 2: Schematic diagram of a basic heat pipe [37].

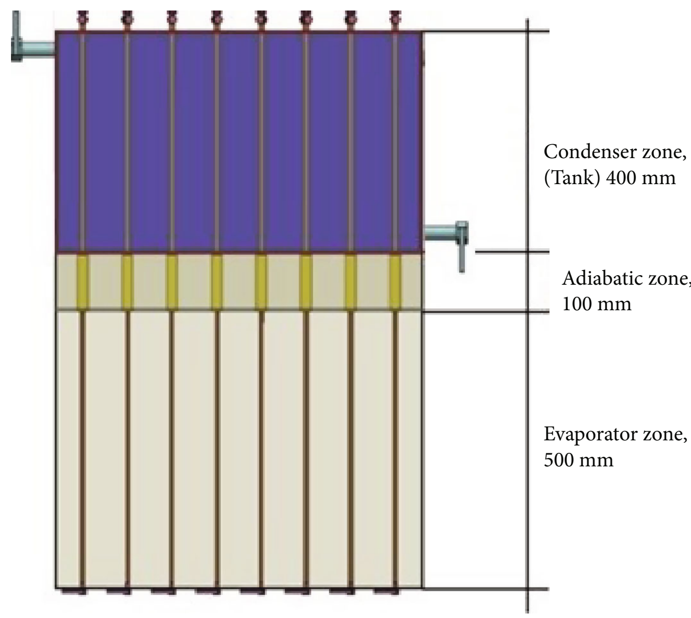

Figure 3: Parts of the heat pipe solar collector.

Table 4: Technical characteristics of the collector.

Tank	Stem	Black sheet, 2 mm
	Insulation	Rock wool, 50 mm
Safe	Stem	Galvanized sheet, 0.45 mm
	Insulation	Rock wool, 60 mm
Absorber		Copper plate, 0.5 mm
Absorber surface		Matte black
Top cover		Glass, 4 mm

The basis of the method is known as the one-step method, nanoparticle production in fluid. The two-step method is the method of suspending the particle into the basic fluid using appropriate methods. Al_2O_3 and TiO_2 nanofluids used in this study were prepared by the two-step method. In the literature, there are 3 methods used to suspend nanoparticles into the basic fluid [30].

2.1.1. Changing the pH of the Suspension. The pH value of nanofluids is related to the surface of nanoparticles, and the pH change can strongly improve the stability of unstable nanoparticles [31]. This is because the stability of the nanofluid is directly related to its electrokinetic properties. Therefore, the zeta potential can be increased or decreased by changing the pH value of the nanofluid. The pH value of a nanofluid can be increased or decreased by adding a suitable nonreactive alkaline or acidic solution [32].

2.1.2. Using Surface Activators or Diluents. The stability of the nanofluid depends on the type of nanoparticles and the basic fluid used. Nanoparticles can be hydrophobic or hydrophilic, and basic fluids can be polar or nonpolar. Hydrophilic nanoparticles such as oxide nanoparticles are easily dispersible in polar basic fluids such as water, and hydrophobic nanoparticles such as carbon nanotubes can be dispersed in nonpolar basic fluids such as oils without requiring a third component. However, surfactants need to be added to stabilize the

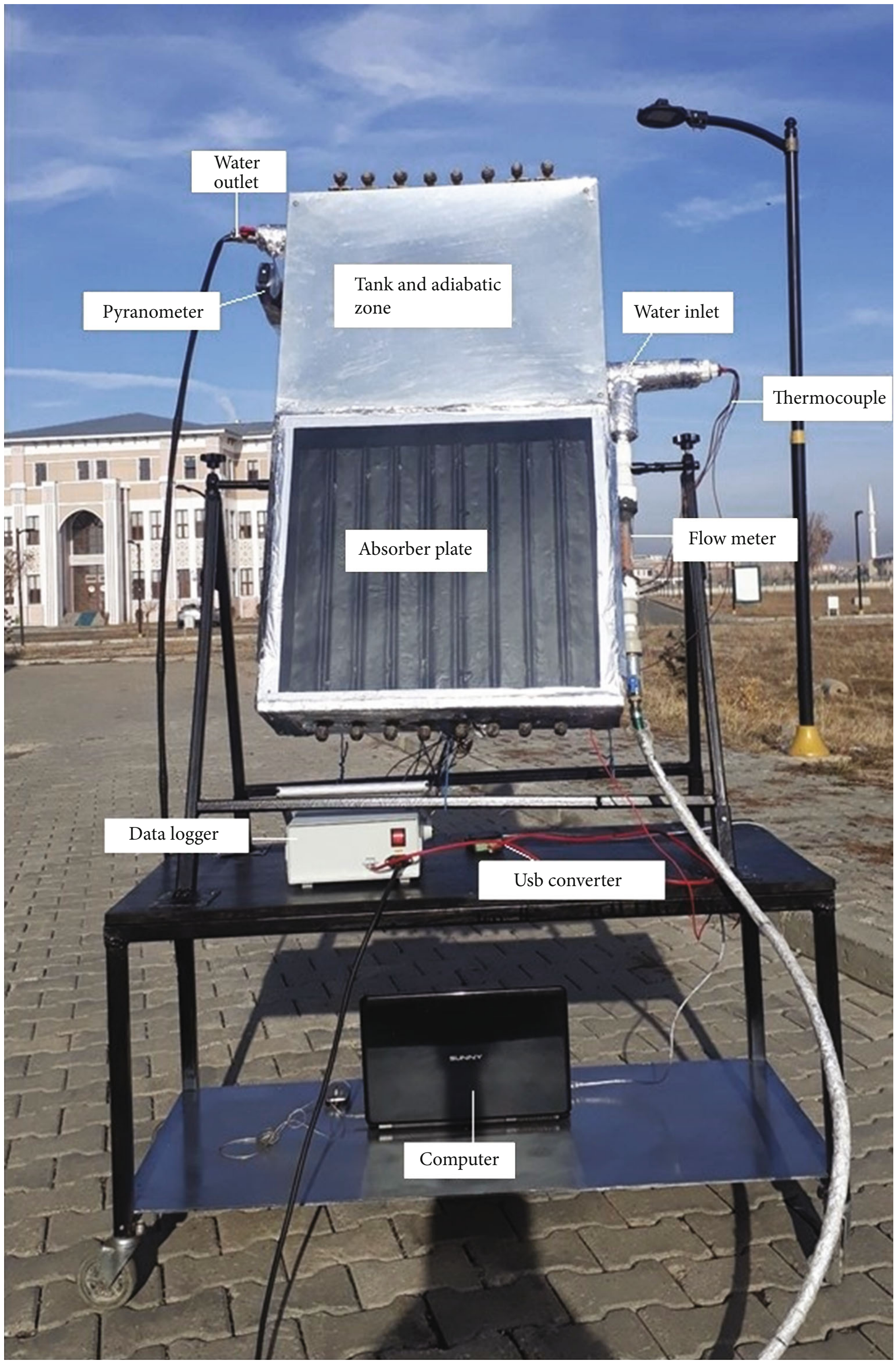

Figure 4: Experimental setup.

nanofluids if hydrophobic nanoparticles are dispersed in polar basic fluids and hydrophilic nanoparticles in nonpolar basic fluids. Surfactants act as a bridge between nanoparticles and elementary fluids and provide continuity [33, 34].

2.1.3. Applying Ultrasonic Vibrations to Particles. Ultrasonic mixing process, which is a physical method based on the use of ultrasonic waves in a fluid, is used to increase the stability of the nanofluid by breaking the gravitational force of the nanoparticles in the precipitate. There are two types of ultrasonicators: probe type and bath type. Sonication time varies according to the study. However, the sonication time should be optimized because an increase in sonication time can reduce the size of the nanoparticles.

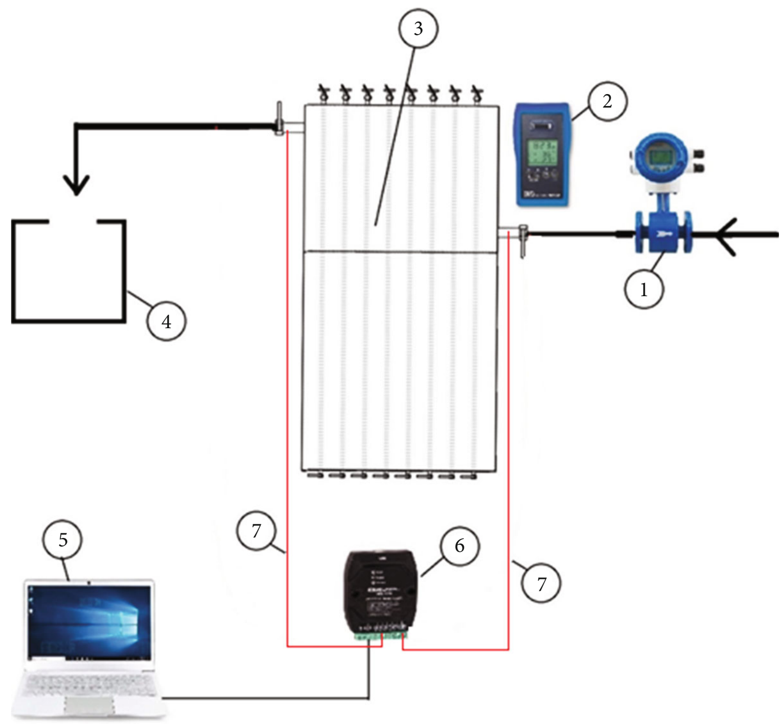

FIGURE 5: Scheme of the experimental setup (1: flow meter; 2: pyranometer; 3: heat pipe solar collector; 4: tanks; 5: computer; 6: data collection card; 7: thermocouple).

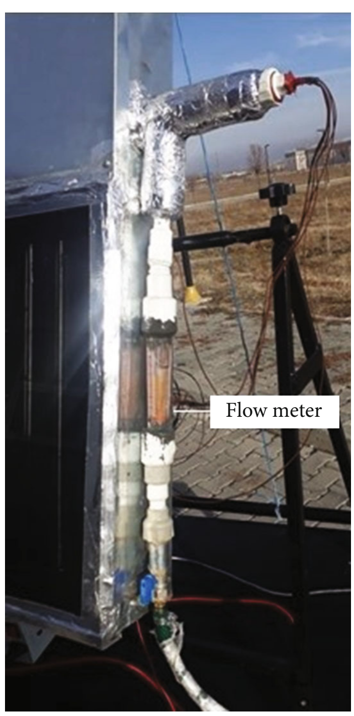

FIGURE 6: Connection of the flow meter to the experimental setup.

Long-term sonication can also damage surfactants found in nanofluids [34].

The Al_2O_3 and TiO_2 nanofluids to be used in the experiments are commercially available (Nanography Nano Technology), and their dimensions are on average 18 nm and 38 nm, respectively. Nanofluids were obtained by mixing Al_2O_3 and TiO_2 nanoparticles with 2% (mass/mass) distilled water. The mixing ratio of 2% was preferred because it is the optimum ratio we have achieved in previous heat pipe works [13–15, 21]. While vacuum is made in each heat pipe with the vacuum pump so that there is no air in it, the heat pipe working fluid is added on the other inlet side. The optimum heat pipe working fluid amount is 1/3 of the evaporator zone volume [13–15]. In order to prevent lumps of nanoparticles from lumpy in the mixture, 0.2% by mass Triton X-100 surfactant was added to the mixture and kept in the ultrasonic bath for 10 hours as a continuous vibration (Figure 1). During this process, the ultrasonic bath was cooled at regular intervals in order to prevent evaporation of the surfactant due to the increase of temperature in the ultrasonic bath. The properties of nanoparticles used in this study are given in Table 1.

The technical properties of the equipment used in the preparation of the nanofluids used in the study are given in Table 2.

The thermophysical properties of pure water and nanofluids used in the experiment are given in Table 3.

2.2. The Experimental Setup. The main purpose of heat pipe solar collectors (HPSCs) is to carry the solar radiation from the evaporator zone to the condenser area with the least loss. A visual including the basic working principle of a basic heat pipe is presented in Figure 2. The heat pipes used in the experiments are made of 1000 mm long, 8 mm inner diameter. and 10 mm outer diameter copper pipes. The lower 500 mm part of the heat pipes is the evaporator region, the

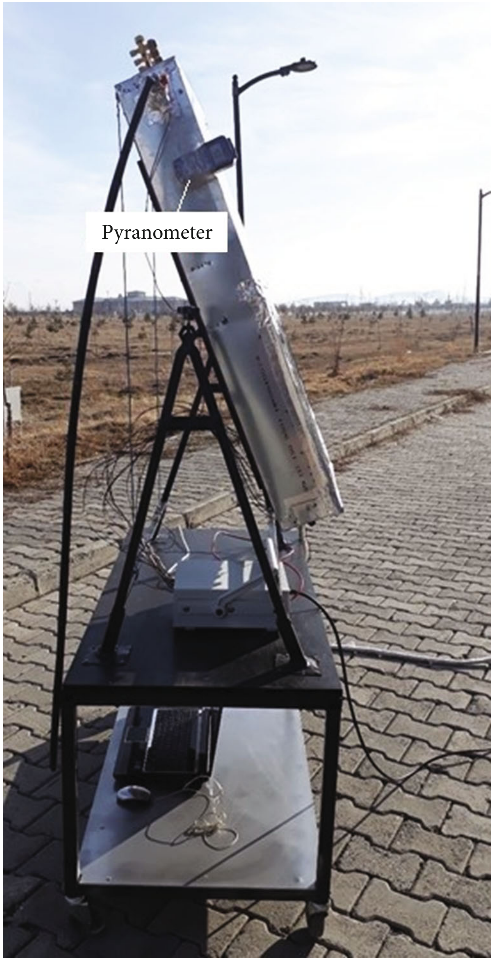

Figure 7: The position of the pyranometer on the collector.

Table 5: Technical features of the pyranometer used in the experiment.

Stability	0.1 W/m^2
Accuracy	±10 W/m^2, ±%5
Deflection	±%3/year
Temperature-induced error	±0.38 W/m^2/°C
Measuring range	1–3999 W/m^2
Sampling rate	0.25 s
Working environment	0°C–50°C, <80%RH

middle 100 mm part is the adiabatic region, and the upper 400 mm part is the condenser region. There are a total of 8 heat pipes in the heat collector solar collector. There is a tank part surrounding the heat pipes passing through the condenser region. Insulation of the adiabatic region was made using glass wool. Evaporator zone is the region where solar radiation is transferred to the heat pipe. The parts of the heat pipe solar collector used in the experiments are shown in Figure 3, and technical specifications are given in Table 4. The experiments were carried out according to the requirements of EN ISO 9806 [36], which is the reference document for determining the performance of thermal solar collectors.

Table 6: Uncertainty calculated parameters and uncertainty values.

Device name	Measuring range	Accuracy	Total uncertainty
Thermocouple T type (LZS-15)	-40/+350°C	±0.5°C	±0.5139
Datalogger UDL200	-200/+400°C	±%0.2	
Pyranometer (SM-206)	1-3999 W/m^2	±%5	
Flow meter (LZS-15)	10-100 kg/h	±%4	

The measurement devices and their properties used in the experiments have been determined according to EN ISO 9806. Radiation from the sun was measured with a handheld pyranometer model SM-206. There are thermocouple connection points at the inlet and outlet of the warehouse to measure temperatures. Thermocouples are T type, and temperatures are read with ORDEL-UDL 200 data logger and transferred to a computer with ORDEL SBA 200 data collection card and analyzed in a computer environment with dali485 software. The LZS-15 flow meter was used to measure the flow rate of the fluid entering the tank. The LZS-15 flow meter (±4%) was used for flow measurements.

Experiments were conducted in two stages to investigate the effect of nanofluids on thermal efficiency in heat pipe solar collectors. The first part experiments were done with pure water, and the second part was done with nanofluids prepared. Experiments were carried out in the month of September (2019), latitude 39°41′31.3″ north and longitude 42°59′22.2″ east coordinates of Ibrahim Chechen University Vocational School (Ağrı, Turkey) in the garden. Experiments were carried out between 09:00 and 17:00, with a collector angle of inclination of 70°, with solar beams perpendicular to the collector surface during the experiment. The experimental setup is given in Figure 4.

A schematic picture of the system is given in Figure 5 for a better understanding of the set of experiments and the connection points of the equipment used.

The flow meter used to control the water circulating in the system to be 0.02 kg/s per unit square meter [29] is mounted as shown in Figure 6.

The pyranometer used to measure global radiation was placed as shown in Figure 7. Before starting any experiment, the pyranometer was mounted in such a way that it was the same as the collector angle of inclination and measurements were made. The technical features of the pyranometer used in the measurements are given in Table 5.

2.3. Uncertainty Analysis. The method proposed by Kline and McClintock was applied to determine the uncertainty of the experimental parameters.

$$= \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2}. \quad (1)$$

$w_1, w_2 \cdots w_n$ are defined as uncertainties of an independent variable. In this case, R is given as in equation (2) to give the total uncertainty of the system. According to this method,

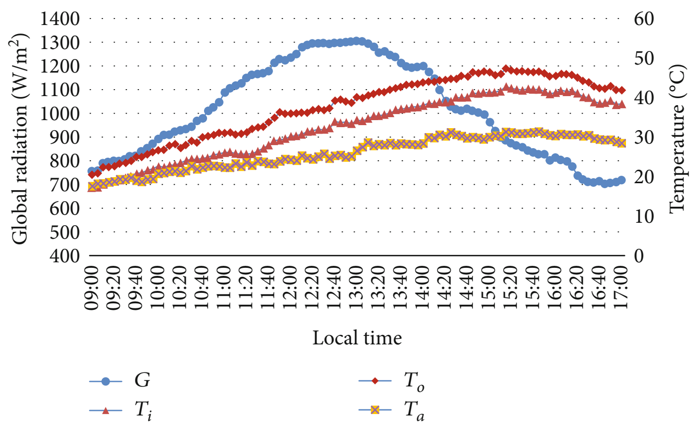

Figure 8: Solar radiation and temperature graphics for pure water.

R is the result function to be measured in the system and x_1, x_2, $x_3 \cdots x_n$ are independent variables affecting the R value [38].

In this case,

$$R = R(x_1, x_2, x_3 \cdots, x_n). \quad (2)$$

The uncertainties of the parameters (temperature, radiation, flow rate, and datalogger) in this study were calculated based on the parameters given in Table 6, indicating that the uncertainty of the experimental data is within the acceptable range.

2.4. Theoretical Analysis. In order to evaluate the thermal performance of the heat pipe solar collector, in the open experimental setup, the energy from the sun was transferred to the collector absorbent plate surface from the sun. The energy transferred to the liquid is expressed as instantaneous power. While performing experimental studies and performance calculations, it was performed in accordance with EN ISO 9806 standards. The main criteria to be followed when conducting experiments according to EN ISO 9806 standards are presented as follows:

(i) It should be an open (cloudless) atmosphere

(ii) Radiation should be more than 700 W/m^2

The heat is transferred from the heat pipes in the condenser area to the moving fluid in the tank, so the cold incoming fluid comes out by heating. The inlet and outlet temperature difference of the heat fluid received by the fluid in the condenser area is equal to the product of the mass flow of the fluid and the average specific heat values of the fluid. This equation is given in equation (3).

$$\dot{Q} = \dot{m}.c.(T_i - T_o). \quad (3)$$

In the equation above, $Q^{\cdot}$ is the heat transferred to the working fluid passing through the tank per unit time, ($m^{\cdot}$) is the flow rate of the water entering the tank (kg/s), c is the mean specific heat of water entering the tank (j/kg·°C), T_i is the temperature of water entering the tank (°C), and T_o out is the temperature of the water leaving the tank (°C).

The flow rate of the water circulating in the tank was calculated according to the following equation according to EN ISO 9806:

$$\dot{m} = 0.02\, A_G. \quad (4)$$

The instantaneous performance (η) of the collector is calculated by the ratio of the heat ($Q^{\cdot}$) transferred to the work fluid passing through the tank to the irradiation value (I) of the collector's openness area [39].

$$\eta = \frac{\dot{Q}}{I}. \quad (5)$$

Arrangement can be made by writing the irradiation value (I) falling in the opening area of the collector in equation (5) in $A_G.G$. Here, $A_G.G$ is the opening area of the collector and G is the radiation intensity.

$$\eta = \frac{\dot{Q}}{A_G.G}. \quad (6)$$

In this study, in evaluating the results, reduced temperature difference, instant performance of collector, and power output per instant temperature difference were used. The reduced temperature difference ($T_m{}^*$) is defined as follows [29]:

$$T_m^* = \frac{T_m - T_a}{G}, \quad (7)$$

$$T_m = T_i + \frac{\Delta T}{2} = T_i + \frac{T_o - T_i}{2}. \quad (8)$$

In equation (7), T_a refers to ambient temperature (°C); in equation (8), T_m refers to the average working fluid temperature (°C).

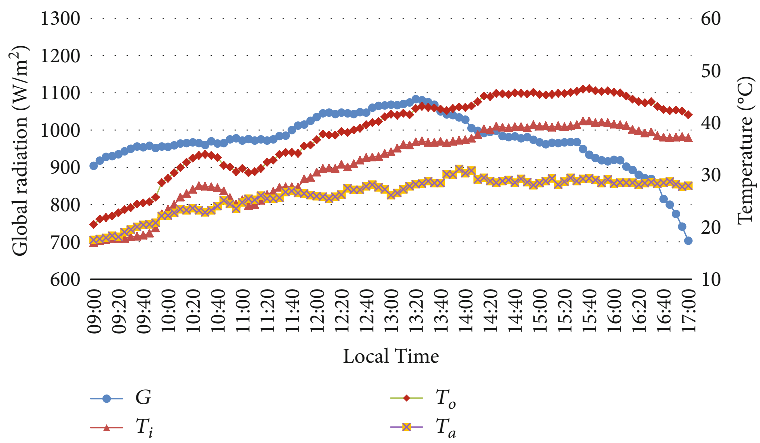

FIGURE 9: Solar radiation and temperature graphs for Al_2O_3-water nanofluid.

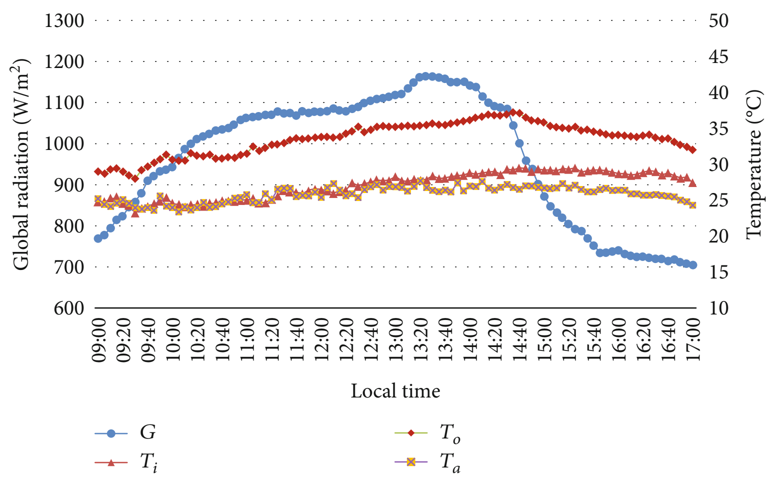

FIGURE 10: Solar radiation and temperature graphs for TiO_2-water nanofluid.

3. Results and Discussions

Measurements in which experimental performances of heat pipe solar collectors were tested using pure water, Al_2O_3-water, and TiO_2-water nanofluid are given in Figures 8, 9, and 10. Data were taken at 5-minute intervals. In Figure 8, the average ambient temperature of the day of the experiment with pure water was measured as 25.98°C. Since our experimental setup is an open system, the tank inlet temperature has changed depending on the temperature of the water coming from the network and the connection distance. It is seen that the storage outlet water temperature (T_o) rises until 15.00 and decreases after this time. It is seen that this decrease is due to the decrease in radiation.

In Figure 9, the average of the ambient temperature of the day on which the experiment was used Al_2O_3-water nanofluid was measured as 26.28°C. It is seen that the storage outlet water temperature (T_o) rises until 16:00 and decreases after this time. Solar irradiance values were measured at the highest values between 12:00 and 14:00. Then, the radiation started to decline. In parallel with this decrease, the water outlet temperature started to decrease.

In Figure 10, the average of the ambient temperature of the day on which the experiment was used TiO_2-water nanofluid was measured as 25.83°C. It is seen that the storage outlet water temperature (T_o) rises up to 14:00 and decreases after this time. Then, the radiation started to decline. In parallel with this decrease, the water outlet temperature started to decrease.

The performance data obtained in the application of EN ISO 9806 [29] standards have been curve fit to the 2nd-degree curves in accordance with the test conditions given that a curve fit should be made to a 2nd-degree curve. As stated here, according to the condition that the coefficient of the term x^2 in the equation is negative, a curve fit is made to a quadratic curve. Here, the x term is the $(T_m - T_a)/G$ value that represents the x-axis of the curve. Figure 11 shows the efficiency graph for pure water, Al_2O_3-water, and TiO_2-water nanofluids. Looking at the graph, the highest instantaneous efficiency is 48% for pure water, 58% for Al_2O_3-water nanofluid, and 64% for TiO_2-water nanofluid. In line with these data, Al_2O_3-water nanofluid mixture provided 20.8% higher performance than pure water; it was observed that TiO_2-water mixture provided 33.3% higher performance than pure water and 9.375% higher performance than

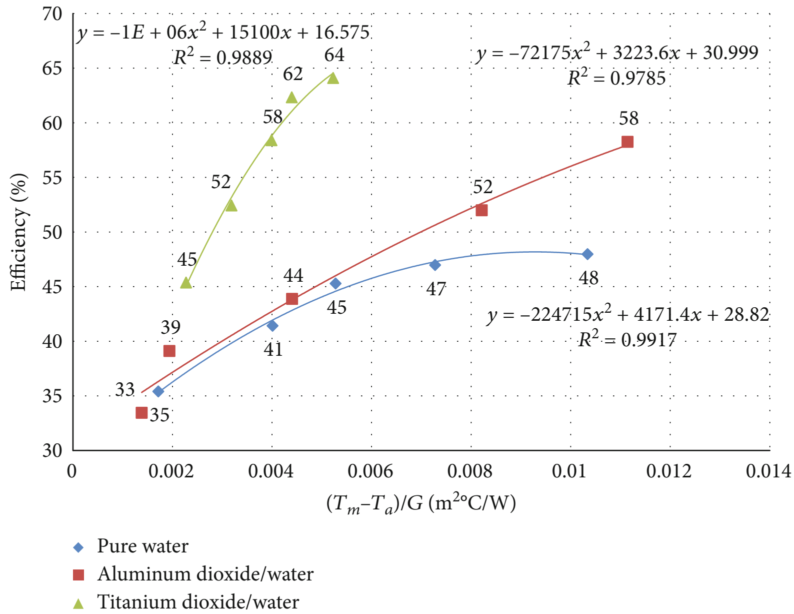

Figure 11: Efficiency chart for pure water, Al_2O_3-water, and TiO_2-water nanofluids.

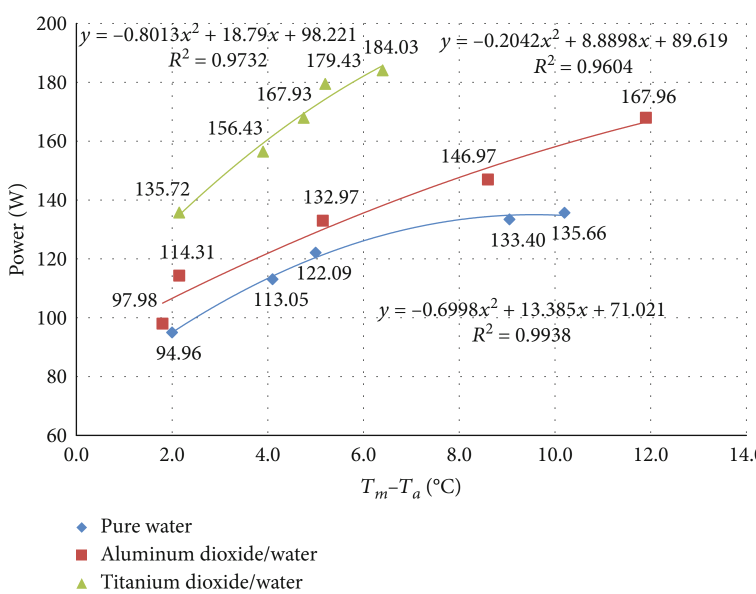

Figure 12: Power output per momentary temperature difference for pure water, Al_2O_3-water, and TiO_2-water nanofluids.

Al_2O_3-water nanofluid mixture. When curve fitting is performed for the data in the graph, the equation obtained for pure water is 48.178% of the maximum efficiency at the reduced temperature of 0.0092815 m^{2}°C/W with accuracy of 0.9917, for Al_2O_3-water nanofluid $R^2 = 0.9785$ with an accuracy of 0.02233 m^{2}°C/W at a reduced temperature of 66.99% of maximum efficiency, and for TiO_2-water nanofluid with $R^2 = 0.9889$ accuracy at a maximum of 0.00755 m^{2}°C/W efficiency was determined as 73.5775%. While TiO_2-water nanofluid reached the maximum efficiency value at lower reduced temperature, Al_2O_3-water nanofluid reached the maximum efficiency value in the wider range.

Figure 12 shows the graph of power output for pure water, Al_2O_3-water, and TiO_2-water nanofluids. Looking at the graph, the highest power outputs were 135.66 W for pure water, 167.96 W for Al_2O_3-water nanofluid, and 184.03 W for TiO_2-water nanofluid. In line with these data, the Al_2O_3-water nanofluid mixture is 23.8% higher than pure water; it has been observed that TiO_2-water mixture provided 35.6% higher performance than pure water and 9.567% higher performance than Al_2O_3-water nanofluid mixture. When curve fitting is performed for the data in the graph, the equation obtained for pure water is $R^2 = 0.9938$ with an accuracy of 9.5634°C instantaneous temperature difference of 135.024 W; for Al_2O_3-water nanofluid,

$R^2 = 0.9604$ accuracy was determined as 21.7918°C instantaneous temperature-aware maximum power 186.590 W; and for TiO_2-water nanofluid, $R^2 = 0.9732$ accuracy was determined as 11.7246°C instantaneous temperature-aware maximum power 208.374 W. While the instantaneous temperature difference of TiO_2-water nanofluid reached the maximum power value at 11.7246°C, it was observed that the instantaneous temperature difference of Al_2O_3-water nanofluid reached the maximum power value of 21.7918°C.

4. Results

In this study, the effect of working fluids on the performance of the heat pipe solar collector has been investigated experimentally. In the study, pure water, Al_2O_3-water nanofluid, and TiO_2-water nanofluid are used as working fluid. The results obtained from the experiments are given follows:

(i) In the comparison of thermal performances based on the data obtained, the maximum performance was obtained from TiO_2-water nanofluid followed by Al_2O_3-water nanofluid and pure water, respectively. While the TiO_2-water nanofluid mixture improved by 33.3% compared to pure water, it was observed that the Al_2O_3-water nanofluid mixture improved by 20.8% compared to pure water. It was determined that the TiO_2-water nanofluid mixture had an improvement of 9.375% thermal performance against Al_2O_3-water nanofluid mixture

(ii) When the power output data per instant temperature difference was examined, it was seen that the results change in direct proportion to the thermal performance values. The change in power output per instant temperature was seen that the TiO_2-water nanofluid mixture improved by 35.6% compared to pure water, while the Al_2O_3-water nanofluid mixture improved by 23.8% compared to pure water. The Al_2O_3-water nanofluid mixture of TiO_2-water nanofluid mixture had an improvement in power output per instant temperature difference of 9.567%

Symbols

$\dot{Q}$: Instantaneous power (W)
$\dot{m}$: Mass flow (kg/h)
c_p: Specific heat capacity (J/kgK)
ΔT: Difference between the fluid's tank outlet and inlet temperature (K)
A_G: Collector gross area (m^2)
η: Instantaneous thermal efficiency
G: Irradiance intensity (W/m^2)
T_m: Average fluid temperature (K)
T^*_m: Reduced temperature difference on the horizontal axis (m^2K/W)
T_i: Tank inlet water temperature (K)
T_o: Tank outlet water temperature (K)
T_a: Outdoor temperature (K)
H_2O: Water
Al_2O_3: Alumina (aluminum oxide)
TiO_2: Titanium dioxide
W: Total uncertainty.

Abbreviations

HPSC: Heat pipe solar collector
TSE: Turkish Standards Institution
ISO: International Organization for Standardization
ETSCs: Evacuated tube solar collectors.

Data Availability

Data will be provided on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] B. Atilgan and A. Azapagic, "An integrated life cycle sustainability assessment of electricity generation in Turkey," *Energy Policy*, vol. 93, pp. 168–186, 2016.

[2] M. D. Toksari, "A hybrid algorithm of ant colony optimization (ACO) and iterated local search (ILS) for estimating electricity domestic consumption: case of Turkey," *International Journal of Electrical Power & Energy Systems*, vol. 78, pp. 776–782, 2016.

[3] E. Çiftçi, A. Sözen, and E. Karaman, "Experimental investigation of nano fluid usage including TiO_2 on the effect of heat pipe performance," *Journal of Polytechnic*, vol. 19, no. 3, pp. 367–376, 2016.

[4] E. F. Akyürek, K. Geliş, B. Şahin, and E. Manay, "Experimental analysis for heat transfer of nanofluid with wire coil turbulators in a concentric tube heat exchanger," *Results in Physics*, vol. 9, pp. 376–389, 2018.

[5] F. Kiliç, T. Menlik, and A. Sözen, "Effect of titanium dioxide/-water nanofluid use on thermal performance of the flat plate solar collector," *Solar Energy*, vol. 164, pp. 101–108, 2018.

[6] M. R. Saffarian, M. Moravej, and M. H. Doranehgard, "Heat transfer enhancement in a flat plate solar collector with different flow path shapes using nanofluid," *Renewable Energy*, vol. 146, pp. 2316–2329, 2020.

[7] M. Mercan and A. Yurddaş, "Numerical analysis of evacuated tube solar collectors using nanofluids," *Solar Energy*, vol. 191, pp. 167–179, 2019.

[8] M. S. Dehaj and M. Z. Mohiabadi, "Experimental investigation of heat pipe solar collector using MgO nanofluids," *Solar Energy Materials and Solar Cells*, vol. 191, pp. 91–99, 2019.

[9] F. Kılıç, "The impacts of fluids on performance containing nanosized metal oxide in solar collectors," *Energy Systems Engineering, [Ph.D. thesis]*, vol. 136, Gazi University, 2017.

[10] A. Sözen, A. Öztürk, M. Özalp, and E. Çiftçi, "Influences of alumina and fly ash nanofluid usage on the performance of recuperator including heat pipe bundle," *International Journal of Environmental Science and Technology*, vol. 16, no. 9, pp. 5095–5100, 2019.

[11] M. Kaya, A. E. Gürel, Ü. Ağbulut et al., "Performance analysis of using CuO-methanol nanofluid in a hybrid system with

concentrated air collector and vacuum tube heat pipe," *Energy Conversion and Management*, vol. 199, article 111936, 2019.

[12] R. Daghigh and P. Zandi, "Improving the performance of heat pipe embedded evacuated tube collector with nanofluids and auxiliary gas system," *Renewable Energy*, vol. 134, pp. 888–901, 2019.

[13] M. Gürü, A. Sözen, U. Karakaya, and E. Çiftçi, "Influences of bentonite-deionized water nanofluid utilization at different concentrations on heat pipe performance: an experimental study," *Applied Thermal Engineering*, vol. 148, pp. 632–640, 2019.

[14] A. Sözen, T. Menlik, M. Gürü et al., "A comparative investigation on the effect of fly-ash and alumina nanofluids on the thermal performance of two-phase closed thermo-syphon heat pipes," *Applied Thermal Engineering*, vol. 96, pp. 330–337, 2016.

[15] E. Çitçi, A. Sözen, and E. Karaman, "Experimental investigation of the effect of using nanofluid containing TiO2 on heat pipe performance," *Politeknik Magazine*, vol. 19, no. 3, pp. 367–376, 2016.

[16] M. Çakır, "Improving the performance of heat pipes by using nanofluid containing alimuna," *Gazi University Journal of Engineering and Architecture Faculty*, vol. 30, 2015.

[17] G. A. Pise, S. S. Salve, A. T. Pise, and A. A. Pise, "Investigation of solar heat pipe collector using nanofluid and surfactant," *Energy Procedia*, vol. 90, pp. 481–491, 2016.

[18] T. Menlik, A. Sözen, M. Gürü, and S. Öztas, "Heat transfer enhancement using MgO/water nanofluid in heat pipe," *Journal of the Energy Institute*, vol. 88, no. 3, pp. 247–257, 2015.

[19] A. A. Eidan, A. AlSahlani, A. Q. Ahmed, M. Al-fahham, and J. M. Jalil, "Improving the performance of heat pipe-evacuated tube solar collector experimentally by using Al_2O_3 and CuO/acetone nanofluids," *Solar Energy*, vol. 173, pp. 780–788, 2018.

[20] A. Ozturk, M. Ozalp, A. Sozen, and M. Guru, "Performance improvement of the heat recovery unit with sequential type heat pipes using TiO_2 nanofluid," *Thermal Science*, vol. 23, 3, Part B, pp. 1755–1764, 2019.

[21] A. Sözen, M. Gürü, A. Khanlari, and E. Çiftçi, "Experimental and numerical study on enhancement of heat transfer characteristics of a heat pipe utilizing aqueous clinoptilolite nanofluid," *Applied Thermal Engineering*, vol. 160, article 114001, 2019.

[22] Y. Tong, H. Lee, W. Kang, and H. Cho, "Energy and exergy comparison of a flat-plate solar collector using water, Al_2O_3 nanofluid, and CuO nanofluid," *Applied Thermal Engineering*, vol. 159, article 113959, 2019.

[23] A. Ozsoy and V. Corumlu, "Thermal performance of a thermosyphon heat pipe evacuated tube solar collector using silver-water nanofluid for commercial applications," *Renewable Energy*, vol. 122, pp. 26–34, 2018.

[24] U. Ö. Su, A. Sözen, and T. Menlik, "Heat pipe evacuated tubular solar collector performance improvement: application of nanofluid," *Journal of Politeknik*, vol. 22, no. 1, pp. 245–257, 2019.

[25] S. Zhao, G. Xu, W. Ning, and Z. Xiaosong, "Experimental study on the thermal start-up performance of the graphane/-water nanofluid-enhanced solar gravity heat pipe," *Nanomaterials*, vol. 8, p. 72, 2018.

[26] K. Geliş, *Investigation of heat transfer and pressure drop of nanofluids in aheat exchanger equipped with tape elements*, Ataturk University, 2013.

[27] Y. Li, J. Zhou, S. Tung, E. Schneider, and S. Xi, "A review on development of nanofluid preparation and characterization," *Powder Technology*, vol. 196, no. 2, pp. 89–101, 2009.

[28] D. K. Devendiran and V. A. Amirtham, "A review on preparation, characterization, properties and applications of nanofluids," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 21–40, 2016.

[29] N. Ali, J. A. Teixeira, and A. Addali, "A review on nanofluids: fabrication, stability, and thermophysical properties," *Journal of Nanomaterials*, vol. 2018, Article ID 6978130, 33 pages, 2018.

[30] Y. Xuan and Q. Li, "Heat transfer enhancement of nanofluids," *International Journal of Heat and Fluid Flow*, vol. 21, no. 1, pp. 58–64, 2000.

[31] R. Choudhary, D. Khurana, A. Kumar, and S. Subudhi, "Stability analysis of Al2O3/water nanofluids," *Journal of Experimental Nanoscience*, vol. 12, no. 1, pp. 140–151, 2017.

[32] R. Azizian, E. Doroodchi, and B. Moghtaderi, "Influence of controlled aggregation on thermal conductivity of nanofluids," *Journal of Heat Transfer*, vol. 138, no. 2, article 021301, 2016.

[33] S. K. S. Babita and S. M. Gupta, "Preparation and evaluation of stable nanofluids for heat transfer application: a review," *Experimantel Thermal and Fluid Science*, vol. 79, pp. 202–212, 2016.

[34] S. Hoseinzadeh, S. A. R. Sahebi, R. Ghasemiasl, and A. R. Majidian, "Experimental analysis to improving thermosyphon thermal efficiency using nanoparticles/based fluids (water)," *European Physical Journal Plus*, vol. 132, no. 197, pp. 1–8, 2017.

[35] "Nanografi Nano Technology," 2019, https://nanografi.com/.

[36] EN ISO 9806, *Solar energy - solar thermal collectors - test methods*, ISO, 2017.

[37] A. Shafieian, M. Khiadani, and A. Nosrati, "Strategies to improve the thermal performance of heat pipe solar collectors in solar systems: a review," *Energy Conversion and Management*, vol. 183, pp. 307–331, 2019.

[38] S. J. Kline and F. A. McClintock, *Describing uncertainties in single-sample experiments*, Mechanical Engineering, 1953.

[39] D. S. Sowmy, P. J. Schiavon Ara, and R. T. A. Prado, "Uncertainties associated with solar collector efficiency test using an artificial solar simulator," *Renewable Energy*, vol. 108, pp. 644–651, 2017.