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Prototype Design of Solar Collector Hybrid Heating System and Testing of Triethylene Glycol Nanofluid

Muhammed BABALIOGLU[1], Hakan BUYUKPATPAT[2], Abdullah GENC[1*]

[1]Isparta University of Applied Sciences, Faculty of Technology, Department of Mechatronics Engineering, Isparta, Türkiye
[2]Bartin University, Faculty of Engineering, Architecture and Design, Department of Computer Engineering, Bartın, Türkiye
Muhammed BABALIOGLU ORCID No: 0000-0002-3852-5932
Hakan BUYUKPATPAT ORCID No: 0000-0003-3277-8653
Abdullah GENC ORCID No: 0000-0002-7699-2822

**Corresponding author: abdullahgenc@isparta.edu.tr*

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Keywords
Solar energy, Solar collector, Hybrid heating system, Triethylene glycol, Nano fluid, Heat transfer fluid

Abstract: The inclusion of solar energy, which is a renewable energy source, in heating systems in buildings provides significant advantages. To make heating with solar energy sufficient and efficient, nanofluids are used in solar collectors. In this study, a hybrid heating prototype is produced, a control mechanism controlling the operation of the hybrid system is established and tests are carried out by including monoethylene glycol, propylene glycol, aluminum oxide, copper oxide, titanium dioxide, especially triethylene glycol-based nanofluids in the system. Finally, a new nanofluid is obtained by mixing triethylene glycol with aluminum oxide and is tested on the prototype. With the tests carried out under the same conditions, the temperature differences of the nanofluids in a certain time period are observed and recorded. In the experiments, the mixtures are examined for heating in the solar collector in the range of 0-90 minutes, and the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, and 8th mixtures show 12.5°C, 13.4°C, 18.4°C, 8.6°C, 21°C, 15.4°C, 18.0°C, and 16.4°C temperature changes, respectively. According to the results, it is observed that the 5th mixture, the pure water, and aluminum oxide mixture, is the fastest heating liquid with a temperature change of 21°C. The 4th mixture containing water, and triethylene glycol is the mixture that heats up the slowest with a temperature change of 8.6°C. Although the water and triethylene glycol mixture performs more inefficiently than other mixtures, it is thought that it can be used for heat storage since it heats up for a long time and cools down for a long time.

Güneş Kollektörlü Hibrit Isıtma Sisteminin Prototip Tasarımı ve Trietilen Glikollü Isı Transfer Sıvısının Test Edilmesi

Anahtar Kelimeler
Güneş enerjisi, Güneş kollektörü, Hibrit ısıtma sistemi, Trietilen glikol, Nanoakışkan, Isı transfer sıvısı

Öz: Yenilenebilir enerji kaynağı olan güneş enerjisinin, binalardaki ısıtma sistemlerine dâhil edilmesi önemli avantajlar sağlamaktadır. Güneş enerjisi ile ısıtmanın yeterli ve verimli hale gelebilmesi için güneş kollektörlerinin içerisinde ısı transfer sıvıları kullanılmaktadır. Bu çalışmada hibrit bir ısıtma prototipi üretilerek, hibrit sistemin çalışmasını denetleyen kontrol mekanizması oluşturulmuş ve trietilen glikol esaslı ısı transfer sıvısı başta olmak üzere mono etilen glikol, propilen glikol, alüminyum oksit, bakır oksit, titanyum dioksit sisteme dahil edilerek testler yapılmıştır. Son olarak trietilen glikol ile alüminyum oksit birbirine karıştırılarak yeni bir ısı transfer sıvısı elde edilmiş ve prototip üzerinde test edilmiştir. Aynı şartlar altında gerçekleştirilen testler ile ısı transfer sıvılarının belirli zaman diliminde sıcaklık farkları gözlemlenerek kaydedilmiştir. Yapılan deneylerde 0-90 dakika aralığında karışımlar güneş kollektöründe ısıtılmak üzere denenmiş ve karışımlar sırasıyla; 1. karışım 12.5°C, 2. karışım 13.4 °C, 3. karışım 18.4°C, 4. karışım 8.6°C, 5. karışım 21°C, 6. karışım 15.4°C, 7. karışım 18.0°C, 8. karışım 16.4°C sıcaklık değişimi göstermiştir. Sonuçlara göre 5. karışım olan saf su ve alüminyum oksit karışımı 21°C derece sıcaklık değişimi ile en hızlı ısınan sıvı olduğu gözlemlenmiştir. 4. karışım olan su ve trietilen glikol karışımı ise 8.6°C sıcaklık değişimi ile en yavaş ısınan karışım olduğu gözlemlenmiştir. Su ve trietilen glikol karışımı diğer karışımlara göre daha verimsiz bir performans sergilese de uzun sürede ısınıp uzun sürede soğuduğu için ısının depolanması amacıyla kullanılabileceği düşünülmektedir.

1. INTRODUCTION

Most of the energy sources used to supply the heat needs of buildings in Turkey and in the world consists of fossil fuels. The problem of global warming and air pollution, which is significantly affected by fossil energy sources, reveals the common problem of all humanity. With the use of fossil fuels, the amount of greenhouse gases released into the atmosphere increases considerably. Global warming is increasing with the accumulation of greenhouse gases in the atmosphere, and therefore, the glaciers are melting, and climate changes occur. Air pollution, which negatively affects humans and all other living things, reduces the quality of life, and causes various diseases [1].

Many meteorological and hydrological differences have been identified, especially in the last century, with the completion of the industrial revolution and the increase in the use of fossil fuels. In Figure 1, the increase in the amount of carbon dioxide (CO_2) gas in the atmosphere, which is one of these differences, is given according to the years.

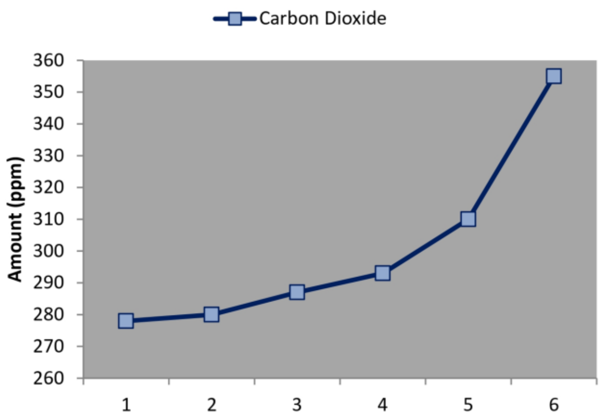

Figure 1. Graph of carbon dioxide increase according to years [2]

The accumulation of carbon dioxide gas, which is one of the greenhouse gases, in the atmosphere and its increase since the beginning of the 2000s brings along global problems. The accumulation of carbon dioxide gas and other greenhouse gases in the atmosphere causes the problem of global warming. The global average temperature increase is given in Figure 2.

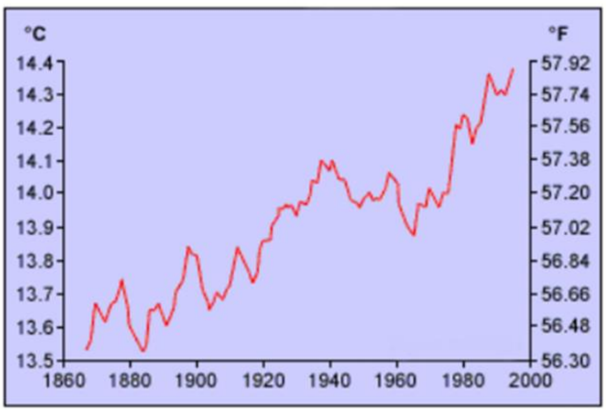

Figure 2. Global average temperature increase [2]

It is seen that the graph of the increase in carbon dioxide and other greenhouse gases accumulating in the atmosphere and the graph of the global average temperature increase depend on the cause-effect relationship. Greenhouse gases that cause global warming trigger global warming at the rate they accumulate in the atmosphere. One of the most common renewable energy methods that can be used as an alternative to fossil fuel use is solar energy [3]. There are studies on the evaluation of the energy from the sun in many areas [4]. Figure 3 shows the atlas of Turkey's solar energy potential. Considering the location of Turkey and the amount of solar radiation, it should be noted that it has an ideal level of sunshine.

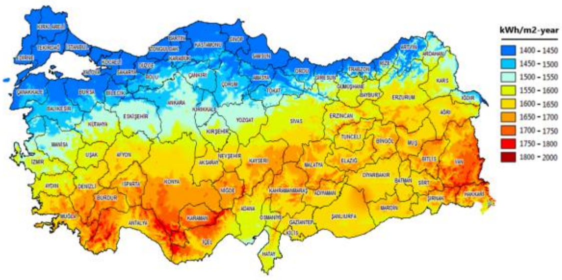

Figure 3. Turkey's solar energy potential atlas [5]

Turkey has a total annual sunshine duration of 2,737 hours and an average of 7.5 hours of sunshine per day [6]. Especially Turkey's Mediterranean, Eastern Anatolia, Southeastern Anatolia, as well as Central Anatolia, and southern parts of the Aegean have high levels of sunshine. Supplying the heating needs by utilizing solar energy according to Turkey's sunshine potential has a positive impact on problems such as global warming, air pollution, and the current account deficit arising from energy imports by reducing the use of fossil fuels [6]. Solar collector water heating systems, which are widely used to supply hot water need, are also used to supply the heat needs of the buildings in the hot regions of Turkey. Systems with solar collectors, which cannot perform water heating in rainy and cloudy weather in winter, operate as a hybrid with fossil fuels, which are the existing heat source [7-8].

The properties of the heat transfer fluid used in circulation and heating in solar energy systems working with heat transfer fluid are very important. There are many studies on nanofluids in collectors and heat transfer systems. Bohne et al. [9] are carried out to determine parameters such as thermal conductivity and density because of the mixture (mix.) of ethylene glycol, which is widely used among heat transfer fluids, with water.

Ogut and Dilki [10] in their study performed the process of adding nanoparticle SiO_2 (Silicon dioxide) to the water fluid and increasing the volume ratio of the nanoparticle. As a result of the test, they observed that it improved the heat transfer and increased the average Nusselt number. They have stated that an improvement of around 18% is achieved in the average Nusselt number compared to the base fluid. As a result of their study, Akcay and Akdag obtained velocity and temperature distributions in the pipe for continuous and pulsatile flow conditions. As a result of the analysis, it has been seen that the best heat transfer performance is obtained for SiO_2-water nanofluid for $R_e = 500$ and $\varphi = 3\%$. In another study, a heat transfer fluid consisting of TiO_2 (titanium dioxide) nanofluid and pure water is obtained. It is observed that the metal oxide particles in this heat transfer fluid increase the conductivity of the working fluid, resulting in an increase of approximately 11.76% in the efficiency of the heat pipe [11]. In their study, Dagdevir and Ozceyhan [12] revealed that the modeling of nanofluid with a single-phase model in numerical analysis is in great agreement with the literature in terms of both heat transfer and hydraulic performance.

Morever, Kilic et al. [13] carried out an experiment with TiO_2/water nanofluid mix. in a flat plate solar collector in a pulsed ultrasonic bath for a certain time. The results they obtained were found to be 48.67% more efficient for TiO_2/water and 36.20% more efficient for pure water compared to water. Verma et al. [14] performed the performance analysis of water-based MWCNTs with CuO and MgO nanofluids in a flat plate solar collector in their study. In the study, the exergetic and energetic efficiency of the solar collector was obtained with different efficiency values of CuO and MgO in certain parameters compared to water. In another study [15], solar collector performance was investigated by using water, Al_2O_3, and CuO nanofluids. The results obtained in the study showed that Al_2O_3 and CuO nanofluids increased the thermal efficiency compared to water.

Michael Joseph Stalin et al. [16] used water and CeO_2/water nanofluid in their study and compared them according to Energy, economic and environmental factors. In the experiment with CeO_2/water nanofluid, approximately 28% more efficient system was obtained compared to water, while it was stated that a 24.52% reduction could be achieved in the size of flat plate solar collectors using the same capacity water with CeO_2/water nanofluid. In addition, it has been observed that approximately 300 MJ energy savings, 175 kg less CO_2 emission, and approximately 2.1 years earlier payback time can be achieved with CeO_2/water nanofluid. Akram et al. [17] on the other hand, used carbon and metal oxides-based nanofluids. Density, viscosity, and specific heat capacity of nanofluids were evaluated in the study. The results obtained from the experiment were compared with f-GNPs, ZnO, and SiO_2 in the collector compared to water, and an increase in efficiency of 17.45%, 13.05%, and 12.36% was observed, respectively. In a study [18], the exergy and energy efficiency of DWCNTs-TiO_2/water nanofluid with an innovative geometric structure were evaluated. It was observed that the energy and exergy efficiency increased by 22.19% and 23.26%, respectively, under the most ideal conditions, according to the Re, PR, and Nuave values. Also, Özbaş [19], carried out a study on the use of waste vegetable oils in solar heating systems. This study is aimed to evaluate waste vegetable oils and increase the efficiency of solar heating systems. In another study [20], the heat transfer and flow behavior of ionic-based nanofluids under magnetic influence is investigated. Unlike the literature, it is carried out by simulating with the ANSYS Fluent program.

The control mechanisms of solar collector heating systems with hybrid systems have of great importance. Positive effects on efficiency can be achieved with the algorithmic structure used in the design of the control mechanism. The correct determination of the heating conditions reduces the use of fossil fuels and increases the efficiency of the system. The heat transfer fluid in the solar collector and the installation can increase the amount of energy gain to be obtained from the sun per unit of time and can provide it to the heating installation with minimum loss.

In this study, a hybrid heating prototype is produced and a control mechanism controlling the operation of the hybrid system is established. In the prototype system, monoethylene glycol, propylene glycol, aluminum oxide, copper oxide, and titanium dioxide, especially triethylene glycol-based nanofluid, are included in the system and their efficiency on the system has been tested. As a novelty, a new nanofluid is obtained by mixing triethylene glycol with aluminum oxide and tested on the produced prototype. As a result of the tests carried out under the same conditions, the temperature differences of the nanofluids over time are observed and recorded. This study is organized in three parts. Section 1 includes the introduction, Section 2 includes the designed systems and methods, Section 3 includes the findings of the study, and the last includes evaluation and results.

2. MATERIAL AND METHOD

2.1. Solar Collectors

Solar collectors are used to absorb the heat energy from the sun and transfer the absorbed heat energy to the nanofluid. Solar collectors are positioned to make the best use of the angle of incidence of the sun's rays [21]. Planar solar collectors consist of glass, absorber plate, liquid pipes, and an insulated zone to prevent heat loss. Planar solar collectors are positioned with an inclination between 30°-45° and absorb the heat energy from the sun [22]. The expression of the heat energy absorbed by the absorber plate is given in Equation 1 [23].

$$\dot{Q}_{abs} = \tau a A G \quad (1)$$

where τ, a, A (m^2), and G (W/m^2) is indicated the transmittance property of the glass, absorptivity of the absorber plate, the area of the collector surface, and the solar radiation incident per unit surface area, respectively. Some of the heat energy obtained from the sun is emitted to the air around the collector by convection, and some to the atmosphere by radiation. The heat energy lost through convection and radiation is given in Equation 2 [23].

$$\dot{Q}_{loss} = UA(T_c - T_a) \quad (2)$$

where U (W/m^2.°C), T_c (°C), and T_a (°C) indicate heat loss coefficient, average collector temperature, and air temperature, respectively. The part of the heat energy from the sun transmitted to the heat transfer fluid in the solar collector is expressed as useful heat energy. Useful heat energy is equal to the difference between the total heat energy absorbed and the heat energy lost. In Equation 3, the expressions used in calculating the amount of useful heat are given [23].

$$\dot{Q}_{useful} = \dot{Q}_{abs} - \dot{Q}_{loss} = \tau aAG - UA(T_c - T_a) = A[(\tau aG - U(T_c - T_a)] \quad (3)$$

where $\dot{Q}_{abs}$ is the total absorbed heat energy and $\dot{Q}_{loss}$ is the lost heat energy. In addition, the amount of useful heat energy can be obtained with the mass flow rate of the heat transfer fluid used in the solar collector with Equation 4 [23].

$$\dot{Q}_{useful} = \dot{m}c_p\left(T_{w,out} - T_{w,in}\right) \quad (4)$$

where $\dot{m}$, c_p (J/kg.°C), $T_{w,out}$ and $T_{w,in}$ indicate the mass flow rate, the specific heat of water, the inlet water temperature, and the outlet water temperature, respectively. The efficiency of a solar collector is obtained by the ratio of the useful heat energy to the total radiation energy coming to the solar collector. The efficiency of the solar collector is expressed in Equation 5 [23].

$$Q\eta_c = \frac{\dot{Q}_{useful}}{\dot{Q}_{incident}} = \frac{\tau aAG - UA(T_c - T_a)}{AG} \quad (5)$$

$$= \tau a - U\frac{(T_c - T_a)}{G}$$

where $\dot{Q}_{useful}$ is the useful heat energy and $\dot{Q}_{incident}$ is the total radiation energy.

2.2. Prototype Design of Solar Collector Hybrid Heating System

The prototype of the hybrid heating system with a solar collector is given in Figure 4. In the creation of the prototype planar solar collector, tank, radiator, pump, resistance, and control panel are used. Outdoor temperatures are recorded with LM35 temperature sensors, tank liquid temperature is recorded with a NTC temperature sensor. Arduino Mega 2560 is used as a microcontroller in the control of the hybrid heating system. The Arduino Mega 2560 is an open-source Atmega2560 based microprocessor board built on the foundations of the development environment that implements a simple I/O board and processing language. It has 54 digital input/output pins (14 of which can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connector, a power jack, an ICSP connector, and it consists of a reset button.

With the planar solar collector, the heat energy taken from the sun is transferred to the nanofluids and stored. When the stored liquid reaches the set value according to the air temperature value, it is sent to the radiator. When the nanofluid cannot reach the desired temperature level, it is heated with the help of a resistance. The efficiency of the results relative to each other is tested by considering only the solar energy of the nanofluids and the temperature changes in the tank.

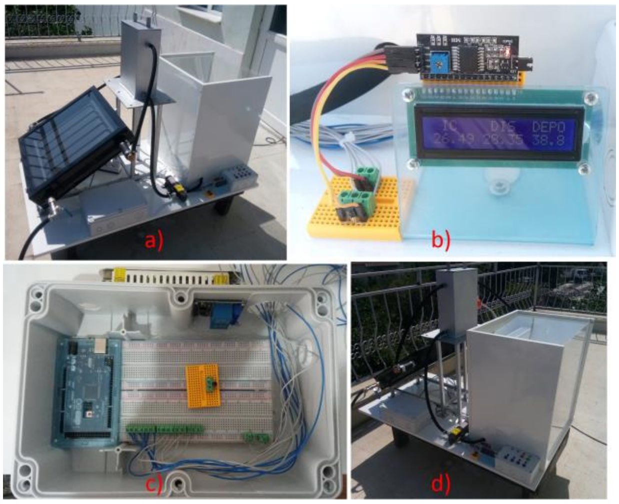

Figure 4. (a) Front view of the hybrid heating system prototype, (b) panel control, (c) electronic design, and (d) back view of the hybrid heating system prototype

The flow diagram of the hybrid working algorithm of the produced prototype is given in Figure 5. The flow chart is the presentation of the algorithm that makes the system work in algorithmic order and rule using visual elements.

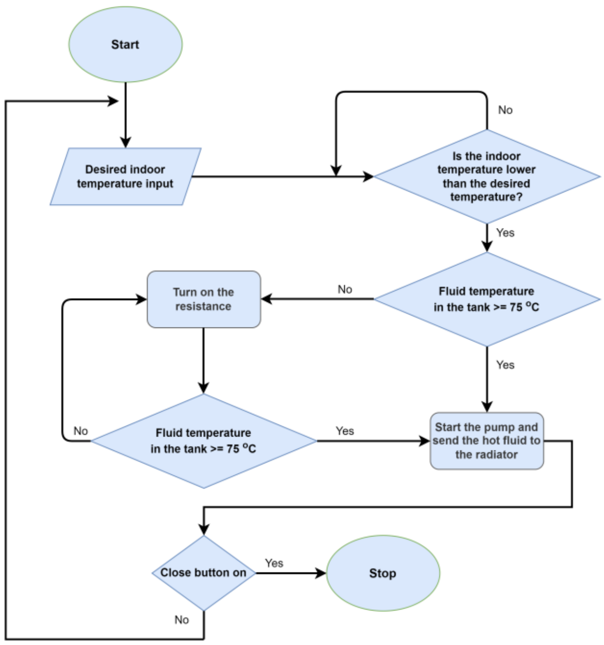

Figure 5. Flow chart of the hybrid heating model

2.3. Preparation of Nanofluids

Nanofluids are prepared at the rates determined to be tested and kept in 5-liter bottles. nanofluids, each prepared as 10 liters, are put into the fluid tank for testing on the prototype. The contents and ratios of the prepared mixes are given in Table 1. The bottles in which the nanofluid mix. are prepared are given in Appendix A.

Table 1. Mixing ratios and contents of nanofluids

Mixture	Chemical component	Volume ratio (%)
1	Water Benzotriazole	99.8% 0.2%
2	Water Monoethylene glycol Benzotriazole	49.9% 49.9% 0.2%
3	Water Propylene glycol Benzotriazole	49.9% 49.9% 0.2%
4	Water Triethylene glycol Benzotriazole	49.9% 49.9% 0.2%
5	Pure Water Aluminum Oxide Benzotriazole	99.0% 0.8% 0.2%
6	Pure Water Copper Oxide Benzotriazole	99.0% 0.8% 0.2%
7	Pure Water Titanium Dioxide Benzotriazole	99.0% 0.8% 0.2%
8	Water Triethylene Glycol Pure Water Aluminum Oxide Benzotriazole	49.5% 24.95% 24.95% 0.4% 0.2%

3. RESULTS

The findings obtained with the experimental studies are given in this section. The performance of nanofluids mixed at certain ratios according to time is investigated.

3.1. Test Results of Nanofluid Mixtures (1st-8th mix.)

Temperature changes till ninety minutes are recorded as a result of the tests performed with water, and benzotriazole (1st mix.), water, monoethylene glycol, and benzotriazole (2nd mix.), water, propylene glycol, and benzotriazole (3rd mix.) water, triethylene glycol, and benzotriazole (4th mix.) mixtures. The results obtained are shown in Figure 6.

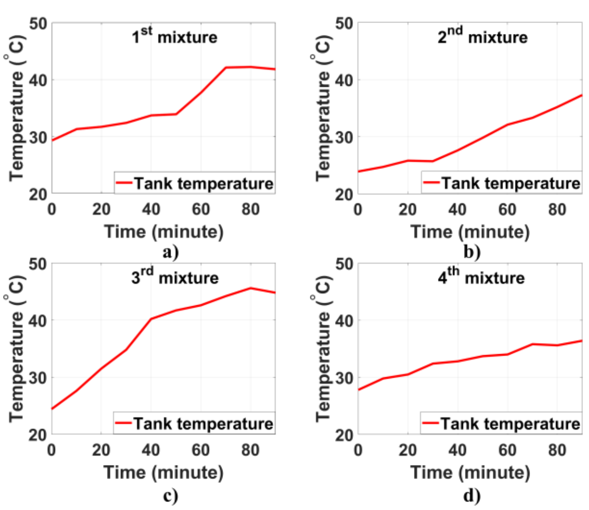

Figure 6. The variations of tank temperatures for (a) 1st mix., (b) 2nd mix., (c) 3rd mix., and (d) 4th mix.

Temperature changes are recorded with the tests performed with pure water, aluminum oxide, and benzotriazole (5th mix.), pure water, copper oxide, and benzotriazole (6th mix.), pure water, titanium dioxide, and benzotriazole (7th mix.), water, triethylene glycol, pure water, and aluminum oxide (8th mix.) mixtures. The results obtained are shown in Figure 7.

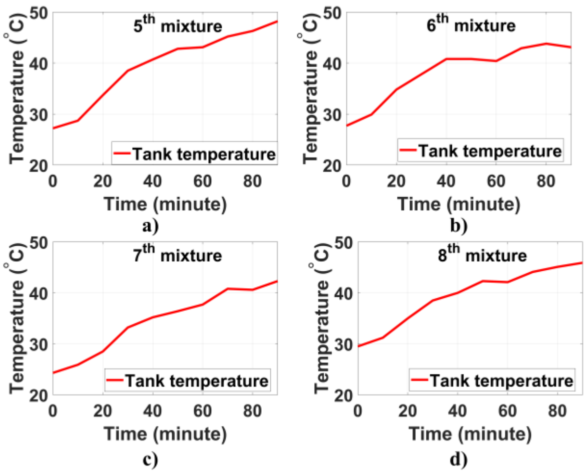

Figure 7. The variations of tank temperatures for (a) 5th mix., (b) 6th mix., (c) 7th mix., and (d) 8th mix.

In this work, all measurements are carried out between 1 and 10 July 2022 in Mihalgazi district of Eskişehir province in Turkey. As aforementioned before, the efficiency of the solar collector value is found by dividing Q_{useful} value by the $Q_{incident}$ value as expressed in Equation 5. The symbols in this equation can be expressed as follows. τ is heat transmittance of glass, α is the absorptivity of the absorber plate, A is the surface area of the collector, U is the heat loss coefficient and G is the solar radiation incident per unit surface area. G value has nearly calculated the values given in Figure 8 for Eskişehir province. Since temperature change of the 5th mix. is maximum, the efficiency is calculated for only 5th mix., and the efficiency depending on collector temperature change is given in Figure 8d. According to the measurement setup in this study, $\tau = 0.89$, $\alpha = 0.92$, U=10.1 W.°C^{-1}m^{-2} for 3 mm single glazed aluminum frame material, A= 0.5×0.5 m^2 and T_a=27.2 ºC. T_c for 5th mix. varies from 24 ºC to 48.2 ºC. We can calculate G value by dividing the value in July in Figure 8a (6.01 KWh.m^{-2}.day) by the value in July in Figure 8b (10.52 hours). It should be noted that according to the efficiency value obtained in Figure 8d, the designed system provides sufficient requirements.

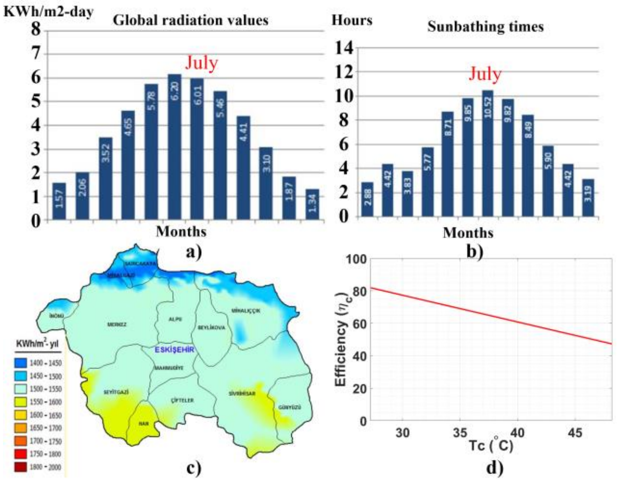

Figure 8. a) Global radiation values, b) sunbathing times in Eskişehir province, c) total solar radiation of Eskişehir province and d) efficiency of collector for the 5th mix.

3.2. The Comparison of Mixtures Made with Nanofluids

As a result of the tests, the temperature is increased by 12.5°C in the 1st mix., 13.4°C in the 2nd mix., 18.4°C in the 3rd mix. and 8.6°C in the 4th mix. in the range of 0-90 minutes. In similar tests, the temperature increases by 21°C in the 5th mix., 15.4°C in the 6th mix., 18.0°C in the 7th mix., and 16.4°C in the 8th mix. In Figure 9, the heating performances of the mixtures are given together.

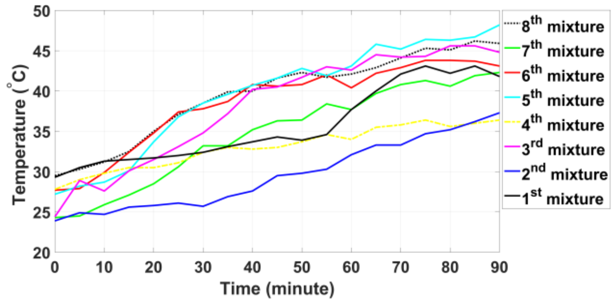

Figure 9. The comparison of tank temperatures

➢ It is observed that the mix. showing the lowest heating rate with a temperature increase of 8.6°C has water, triethylene glycol mix., and the mix. showing the highest heating rate with a temperature increase of 21°C has pure water and aluminum oxide mix.

➢ Water, propylene glycol mix., and pure water, titanium dioxide mix., which are the mixtures that heat up the most after pure water, aluminum oxide mix., provided positive results when used in solar collectors.

➢ In the 8th mix., water, pure water, triethylene glycol and aluminum oxide mix. is made and tested. As a result of the tests, a temperature increase of 16.4 degrees is observed in the range of 0-90 minutes.

➢ With the test results obtained, it is observed that triethylene glycol performs negatively only when mixed with water, and it heats up 2 times more when mixed with aluminum oxide.

➢ It is seen that it has not appropriate to use a water, triethylene glycol mix. as a heating fluid in solar collectors, but it has appropriated to use pure water, aluminum oxide mix. in solar collectors.

➢ When the studies in the literature are examined, the heat transfer rates of nanofluids and ethylene glycol groups in solar collectors are investigated. Unlike the studies in the literature, the heat transfer rates of triethylene glycol and triethylene glycol + aluminum oxide mixtures are experimentally investigated in this study. Moreover, the temperature of the pure water + aluminum oxide mix. increased from 27.2 ºC to 48.2 ºC within 90 minutes, resulting in a 21 ºC temperature increase. In the experiment, which is carried out with only water without mixing, the temperature of the water increased from 29.3 ºC to 41.8 ºC within 90 minutes, resulting in a temperature increase of 12.5 ºC. According to the results obtained, it is determined that the pure water + aluminum oxide mixture heated 59.52% more than the normal unmixed water. In another study, it is observed that the pure water + aluminum oxide mixture is 61.1% more efficient than the normal unmixed water in the yield value calculated according to the ASHRAE 93-2003 standard [24].

4. DISCUSSION AND CONCLUSION

In this study, a prototype of a hybrid heating system with a solar collector is produced and eight different nanofluids are tested on the prototype. Nanofluid containing triethylene glycol is compared with other nanofluids and its effects on solar collector are investigated. Eight different nanofluids are tested under the same conditions and their thermal performance is evaluated according to each other. As a result of the tests, it has been seen that triethylene glycol had the lowest heating rate. It has been shown that triethylene glycol, which does not transfer heat quickly, can be efficient if it is used as a storage of heat energy obtained as a result of stable performance. It is also observed that the highest temperature increase is achieved with the 21°C temperature increase of the pure water, aluminum oxide mix. In future studies, it is aimed to be used in cases where a low heating rate is desired in accordance with the characteristic features of triethylene glycol.

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Appendices

Appendix A. Photos of Eight Different Mixtures

1.

(Water + Benzotriazole)

2.

(Water + Monoethylene glycol + Benzotriazole)

3.

(Water + Propylene Glycol + Benzotriazole)

4.

(Water + Triethylene glycol + Benzotriazole)

5.

(Pure water + Aluminum oxide + Benzotriazole)

6.

(Pure water + Copper oxide + Benzotriazol)

7.

(Pure water + Titanium dioxide + Benzotriazole)

8.

(Water + Triethylene glycol + Pure water + Aluminum oxide + Benzotriazole)