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Effects of Nanofluids in Improving the Efficiency of the Conical Concentrator System

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Abstract: Fossil fuels are being depleted, resulting in increasing environmental pollution due to greenhouse gases and, consequently, emerging detrimental environmental problems. Therefore, renewable energy is becoming more important; hence, significant research is in progress to increase efficient uses of solar energy. In this paper, the thermal performance of a conical concentrating system with different heat transfer fluids at varied flow rates was studied. The conical-shaped concentrator reflects the incoming solar radiation onto the absorber surface, which is located at the focal axis, where the collected heat is transported through heating mediums or heat transfer fluids. Distilled water and nanofluids (Al_2O_3, CuO) were used in this study as the heat transfer fluids and were circulated through the absorber and the heat storage tank in a closed loop by a pump to absorb the solar radiation. The efficiency of the conical concentrating system was measured during solar noon hours under a clear sky. The collector efficiency was analyzed at different flow rates of 2, 4, and 6 L/min. The thermal efficiency, calculated using different heat transfer fluids, were 72.5% for Al_2O_3, 65% for CuO, and 62.8% for distilled water. Comparing the thermal efficiency at different flow rates, Al_2O_3 at 6 L/min, CuO at 6 L/min, and distilled water at 4 L/min showed high efficiencies; these results indicate that the Al_2O_3 nanofluid is the better choice for use as a heating medium for practical applications.

Keywords: nanofluid; conical concentrator system; performance comparison; thermal efficiency

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1. Introduction

Recent progressive development of modern technology continues to increase human energy demand. Referring to the energy consumption for domestic use, the proportion of fossil fuels used, such as oil (44%), coal (29%), natural gas (14%), and nuclear power (11%), being very high, and the contribution of new and renewable energies at only 2% [1]. Accordingly, serious environmental pollution problems are emerging; thus, the need for research and development of new and renewable energy is increasing, leading to increasing investment in this sector worldwide. Moreover, the Korean government has established facilitators for renewable energy and clean technologies, such as the Renewable Energy 3020 Plan [2], the power generation gap support system (Feed-in Tariff—FIT), and the renewable energy portfolio standard (RPS); these are indeed strengthening supports for development and distribution projects.

Among the new and renewable energies, solar energy is considered as a useful energy source in our daily life as it has no environmental pollution and is available in abundance [3]. Available solar energy utilization technologies convert sunlight to direct electricity and heat. In particular, solar heat can be used in various fields and has excellent economic benefits [4,5]. However, due to low energy density, it is difficult to use solar energy continuously depending on the outdoor environment. It is evident that the role of a concentrator is very important in solar thermal systems. Therefore, for the efficient usage of solar energy, various types of solar concentrating systems have been developed, including parabolic trough concentrator (PTC)-type, compound parabolic concentrator (CPC)-type, dish-type, and conical-type systems [6–8]. Among these types, the conical concentrator is easier to manufacture and has lower maintenance costs than the other solar concentrating systems. In addition, conical solar concentrator has the advantage of having a smaller absorbing area compared with the flat plate collectors. Furthermore, compared with flat plate collectors, the conical solar collector has excellent heat collection efficiency, which ranges from 60 to 81% [9]. Therefore, in recent years, an immense amount of research in the development of state-of-the-art solar energy collectors has been carried out in the context of improving heat collection efficiency [10]. For solar concentrating systems, the heat collection performance can also be improved by increasing the light collection rate through applying solar tracking technology.

However, research to improve efficiency through structural improvements in solar thermal systems has recently become minimal and has reached its breaking point. In addition, heat transfer fluids used in solar collectors have been limited to water and air. However, recent developments in nanotechnology have led to the development of nanofluids. Nanofluids refer to fluids (as a base fluid) containing nanoparticles with a size of 100 nm or less. Nanofluids have excellent thermal conductivity [11] and have been applied to various fields, such as air-conditioning systems [12], the cooling of electronic devices, and as the heat medium of heat exchangers [13]. The selection of nanofluids is based purely on their economic viability and excellent thermo–physical properties [14]. Based on reported articles in the literature, it has been concluded that Al_2O_3 and CuO are the most widely used heat transfer fluids in solar heat collecting systems.

Many studies are being conducted to maximize solar energy utilization in concentrating solar collecting systems, but research on the heat medium is limited. Therefore, in the proposed study, the outdoor thermal performance of a conical concentrating system using different nanofluids and conventional fluids was discussed. In this paper, distilled water and nanofluids (Al_2O_3 and CuO) were used as the heating mediums. Due to their excellent thermal stability under high temperature range, nanofluids are considered promising alternative to conventional fluids; moreover, due to high solar flux, concentrating solar collectors are capable of producing high temperatures. A combination of the aforementioned solar collectors and the proposed heating mediums into a single unit could be viewed as a viable solution in the context of maximizing the utilization of solar energy. Therefore, the thermal efficiency of a conical solar concentrator using different nanofluids is analyzed and compared with the most commonly used conventional fluids.

2. Materials and Methods

2.1. Conical Concentrating System Configuration and Method

The proposed conical concentrating system consists of conical concentrator that reflects the sun's light, linearly, onto the absorber, a heat storage tank that stores the solar heat, and a centrifugal pump, which is used for the circulation of the heat transfer fluids or heating mediums. The absorber installed at the focal axis of a conical collector is made of copper. Digital flow meters were used to control the flow rate of the working fluid. The extracted solar heat from the conical concentrating system was stored in the thermal storage tank with the help of the heating medium. A schematic of the conical concentrating system is shown in Figure 1.

The conical concentrating system was mounted on a dual-axis tracking platform, which helps to maximize the available solar energy utilization. The experimental facility was located 37° latitude and 127° longitude.

Distilled water and nanofluids (Al_2O_3, CuO) were used as the heat mediums for the conical concentrating system. During operation, the heating medium, stored in the heat storage tank, passes the flow meter by the circulation pump to absorb heat through the absorber surface. The temperature was measured by installing resistance thermometers (Conax Technologies, New York, NY, USA) in the storage tank and at the inlet and the outlet of the conical concentrating system. The measured temperatures were recorded via data loggers (GL820, GRAPHTEC, Irvine, CA, USA). Insolation and meteorological data were measured using a pyrheliometer (Hukseflux, Delft, The Netherlands) and a weathervane (Wireless Vantage). The flow rate of the heat transfer fluid was controlled by the flow meter (PA-60, KOMETER, Incheon, Korea), and the temperature data was recorded in a unit of 1 min and averaged over 10 min.

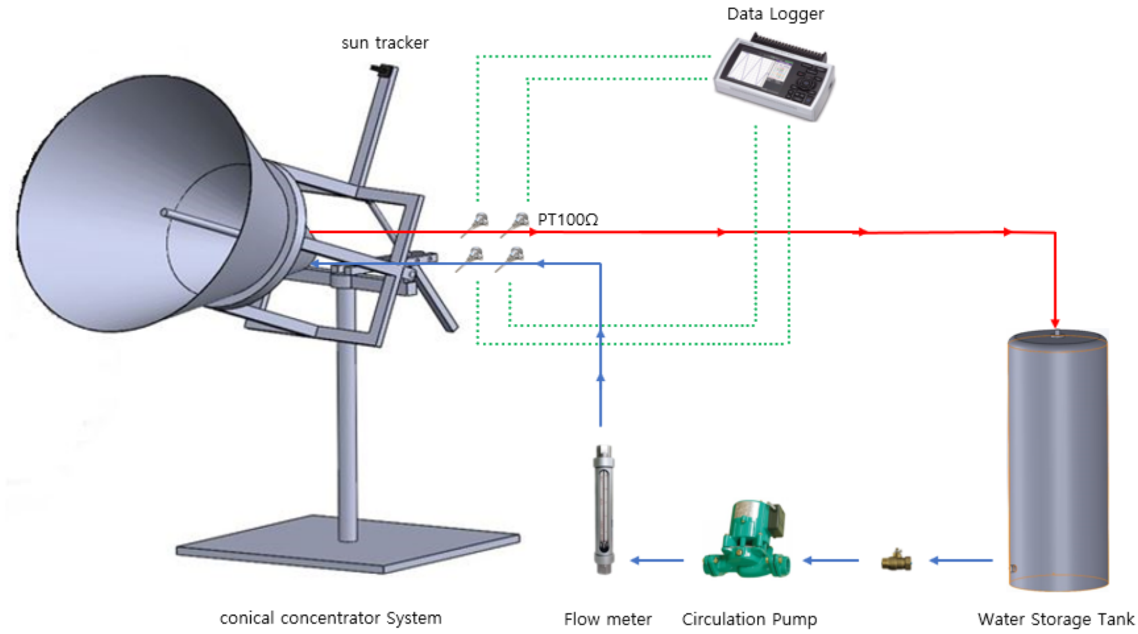


Figure 1. Schematic diagram of the conical concentrator system.

2.2. Nanofluid Manufacturing

In this study, the nanofluid was prepared by a two-step method. Nanofluids were made by dispersing Al_2O_3 and CuO particles, with a size of <50 nm, in distilled water as the base fluid. The nanoparticles used in this study were made by the company AVENTION Co., Ltd. (Incheon, Korea). The thermal conductivity of the nanofluids was analyzed by using different concentrations of surfactant, as suggested by Lee et al. [15]. They used surfactant Cetyltrimethylammonium bromide (CTAB) and Arabic gum (AG) to increase dispersion stability. CTAB was added at 1/10 times, 1 time, and 10 times the critical micelle concentration (CMC), and AG was added at 1/4 times, 1/2 times, and 1 time, based on nanoparticles, because at this point, no CMC concentration was found [15]. Thermal conductivity (W/m °C) was measured by kd2 device. As shown in Table 1, Al_2O_3 and CuO nanofluids had the highest thermal conductivity when 1/10 times of CTAB and 1/2 times of AG, respectively, were added. The nanofluid was prepared by 2 L each; stirring for 30 min using a magnetic stirrer, the prepared mixture is then sonicated for 2 h with an ultrasonic disperser. Besides, stability test for the nanofluids used was conducted at the operating temperature for every 40-day period, and satisfactory stability was found inside the solution with insignificant settling rate. The thermal conductivity of the nanofluids can be calculated by the following correlation [16]:

$$k_{nf} = \frac{\left[\left(k_{np} + 2k_{bf}\right) + 2\phi + \left(k_{np} - k_{bf}\right)\right]}{\left[\left(k_{np} + 2k_{bf}\right) - \phi\left(k_{np} - k_{bf}\right)\right]} \quad (1)$$

where, ϕ is nanoparticles concentration and k_{nf} is the thermal conductivity of the nanofluid. k_{np} and k_{bf} are the thermal conductivities of the nanoparticles and the base fluid, respectively.

Table 1. Thermal conductivity.

Al_2O_3 (0.25%)	Thermal Conductivity (W/m °C)
CTAB 1/10 times	0.851
CTAB 1 time	0.798
CTAB 10 times	0.783
AG 1/4 times	0.805
AG 1/2 times	0.822
AG 1 time	0.826
CuO (0.25%)	Thermal conductivity (W/m °C)
CTAB 1/10 times	0.792
CTAB 1 time	0.784
CTAB 10 times	0.771
AG 1/4 times	0.861
AG 1/2 times	0.949
AG 1 time	0.793

2.3. Efficiency Calculation

In this study, the heat collection efficiency of three identical solar concentrating systems was tested at the similar flow rate and operating conditions across the day, where CuO nanofluid, Al_2O_3 nanofluid, and distilled water were used, separately, for each system. The energy performance of the aforementioned solar collectors was carried out at three flow rates—2 L/min, 4 L/min, 6 L/min.

The amount of heat collected (Q) by the absorber is calculated as follows [17]:

$$Q = mC_p(T_o - T_i) \quad (2)$$

where Q and C_p are the flow rate and specific heat, respectively, of the heat transfer fluid. T_i and T_o are the fluid inlet and outlet temperatures, respectively.

The average temperature T_r of the heating medium was calculated using the following Equation (3):

$$T_r = \frac{T_o + T_i}{2} \quad (3)$$

In order to analyze the efficiency of the conical solar concentrator system, the heat collection efficiency (η) was calculated as presented in Equation (4), as follows:

$$\eta = \frac{Q}{Al} \quad (4)$$

where η and l are the thermal efficiency and beam radiation, respectively, and A is the collector area.

3. Results and Discussion

3.1. Efficiency Analysis according to Flow Rate Heat Medium of Conical Concentrating System

3.1.1. Al_2O_3, CuO, and Distilled Water Efficiency Analysis for Flow Rate of 2 L/min

A series of experiments using Al_2O_3, CuO, and distilled water as the working fluids were performed (on 1 November 2018) at a flow rate of 2 L/min under a clear and cloudless sky. To eliminate the error associated with the mass flow rates and the heating medium, three similar systems were tested and compared under the same operating conditions. The outdoor environmental conditions for the experiment are shown in Table 2.

Table 2. The experimental conditions when the flow rate is 2 L/min.

Flow Rate		2 L/min
Solar Radiation (W/m^2)		636.2–860
Wind Speed (m/s)		0.2–1.9
Ambient Temperature (°C)		8.94–17.51
Inlet Temperature (°C)	Al_2O_3	16.55–66.93
	CuO	16.08–60.95
	distilled water	15.96–54.97

Figure 2 shows the variations of solar radiation and heat collection efficiency over the daily sunshine hours. It was found that the collection efficiency of Al_2O_3 was the highest. More specifically, the average, highest, and minimum efficiencies using the Al_2O_3 nanofluid were 67.8%, 73%, and 54%, respectively; whereas, the average, highest, and minimum efficiencies using the CuO nanofluid were found to be 61.4%, 64%, and 53%, respectively. Furthermore, using distilled water, the average, highest, and minimum efficiencies were 58.7%, 62%, and 50%, respectively. The heat collection efficiency decreased with time, and it was judged that convective heat loss increased as the inlet temperature increased. It is observed that the Al_2O_3 and CuO nanofluids showed better results as heat mediums compared with distilled water due to comparatively higher thermal conductivities.

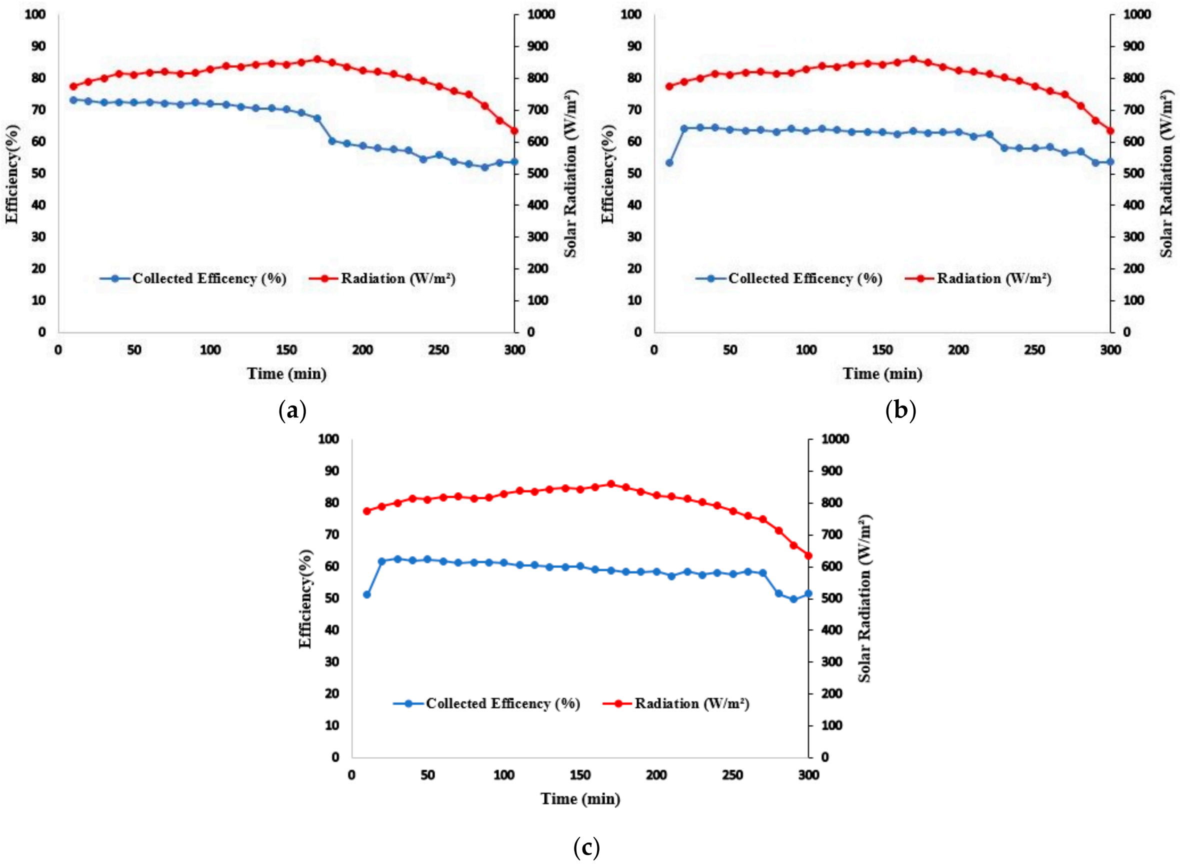


Figure 2. Collected efficiency using (**a**) Al_2O_3, (**b**) CuO, and (**c**) distilled water at 2 L/min.

3.1.2. Al_2O_3, CuO, and Distilled Water Efficiency Analysis for Flow Rate 4 L/min

A series of experiments was also conducted using Al_2O_3, CuO, and distilled water on 2 November 2018, at a flow rate of 4 L/min. The outdoor environmental conditions for the experiment are shown in Table 3.

Table 3. The experimental conditions when the flow rate is 4 L/min.

Flow Rate		4 L/min
Solar Radiation (W/m^2)		740.4–860.2
Wind Speed (m/s)		0–1.9
Ambient Temperature (°C)		10.8–20.7
Inlet Temperature (°C)	Al_2O_3	22.98–74.67
	CuO	22.7–66.68
	distilled water	22.85–60.9

Figure 3 shows the variations of solar radiation and heat collection efficiency over the daily sunshine hours. The average, highest, and minimum efficiencies using the Al_2O_3 nanofluid were 65.6%, 70%, and 61%, respectively; whereas, the average, highest, and minimum efficiencies using the CuO nanofluid were found to be 63.8%, 68%, and 52%, respectively. Furthermore, using distilled water, the average, highest, and minimum efficiencies were lower, at 62.8%, 71%, and 55%, respectively. Here, we can note that the Al_2O_3 and CuO nanofluids showed better results as heat mediums compared with distilled water due to comparatively higher thermal conductivity.

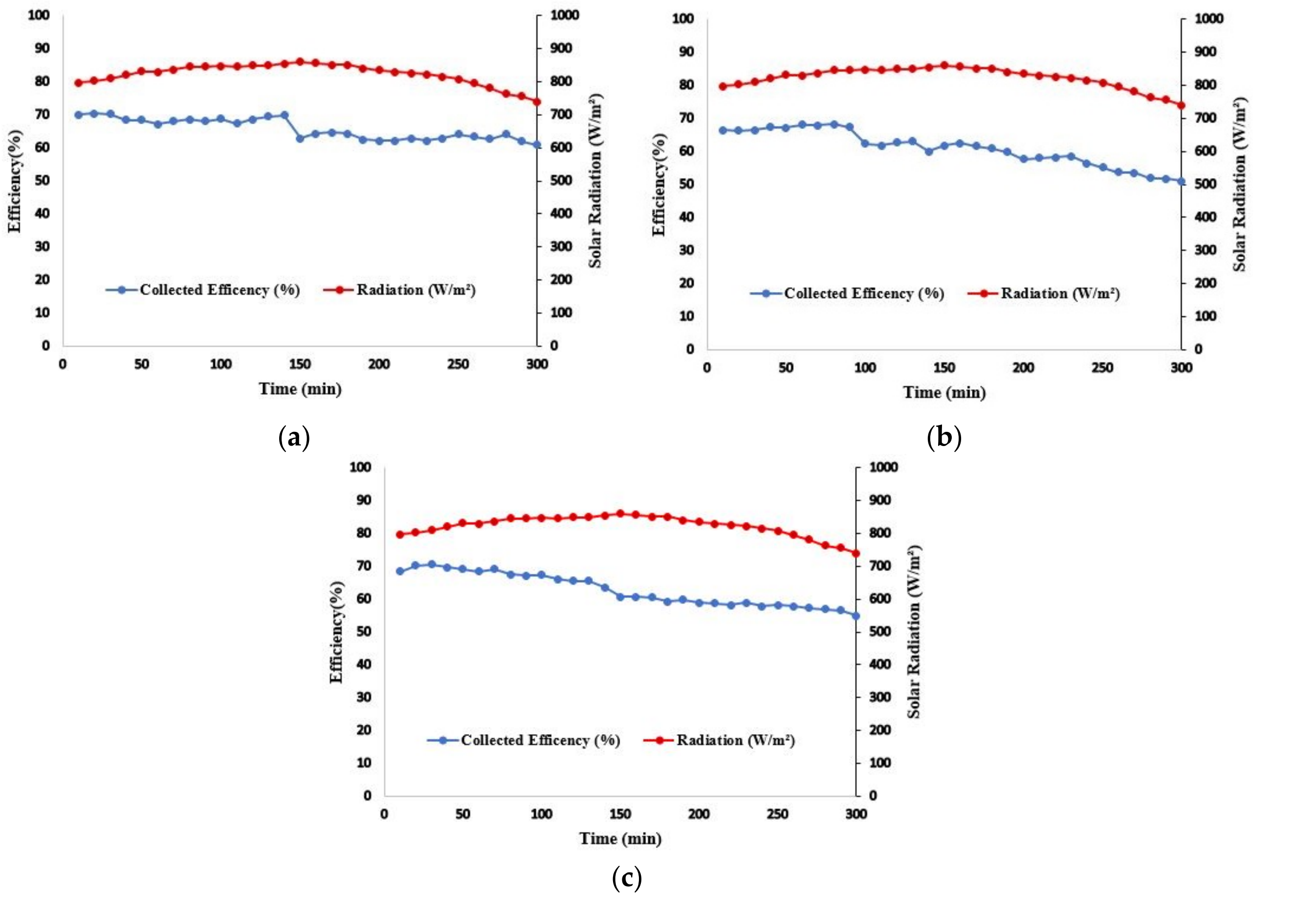


Figure 3. Collected efficiency using (**a**) Al_2O_3, (**b**) CuO, and (**c**) distilled water at 4 L/min.

3.1.3. Al_2O_3, CuO, and Distilled Water Efficiency Analysis for Flow Rate 6 L/min

Following a similar experimental procedure, further experiments were conducted on 4 November 2018, using a different flow rate of 6 L/min. The outdoor environmental conditions for the experiment are depicted in Table 4.

Table 4. The experimental conditions and when the flow rate is 6 L/min.

Flow Rate		6 L/min
Solar Radiation (W/m^2)		696.7–869.3
Wind Speed (m/s)		0–2.1
Ambient Temperature (°C)		10.48–22.28
Inlet Temperature (°C)	Al_2O_3	21.72–79.66
	CuO	21.31–68.8
	Distilled Water	21.62–50.86

Figure 4 shows the variations of solar radiation and heat collection efficiency over the daily sunshine hours. It was found that the collection efficiency of the Al_2O_3 nanofluid was the highest. More specifically, the average, highest, and minimum efficiencies using the Al_2O_3 nanofluid were 72.5%, 87%, and 57%, respectively; whereas the average, highest, and minimum efficiencies using the CuO nanofluid were found to be 65%%, 77%, and 42%, respectively. Furthermore, using distilled water, the average, highest, and minimum efficiencies were lower, at 52.2%, 57%, and 46%, respectively.

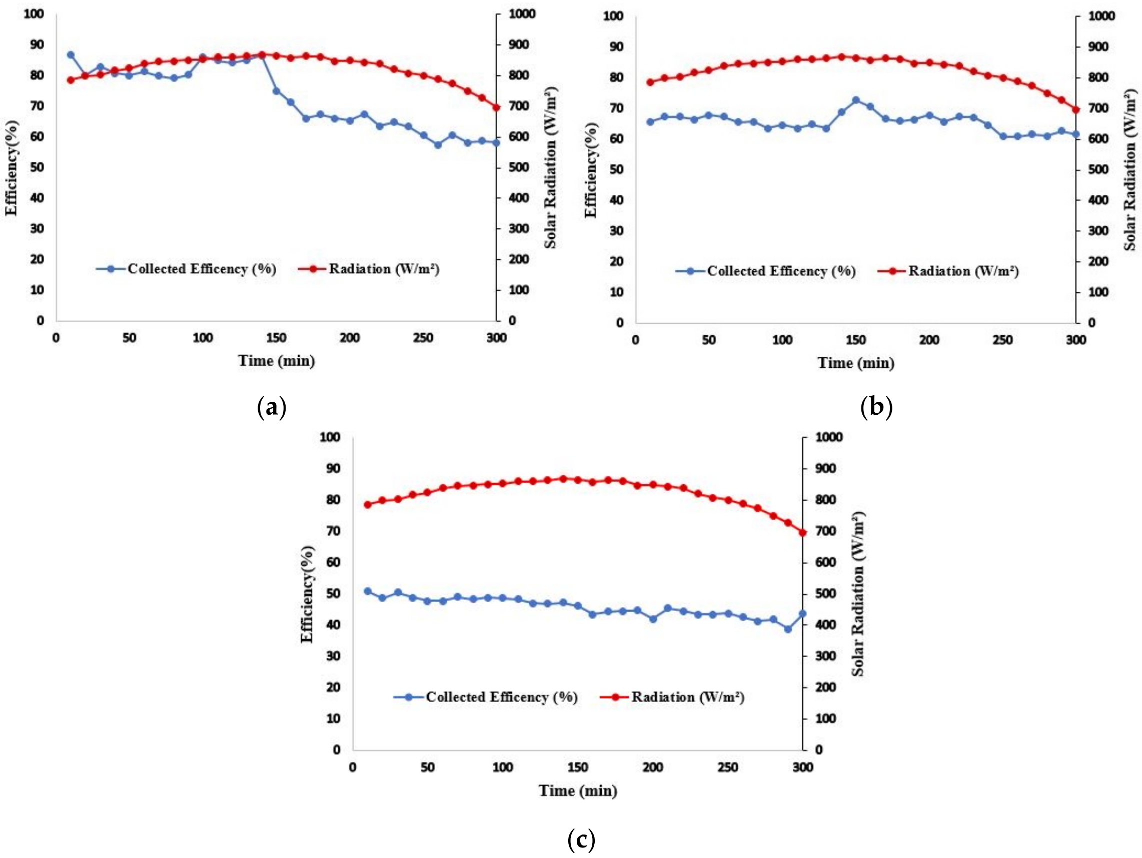
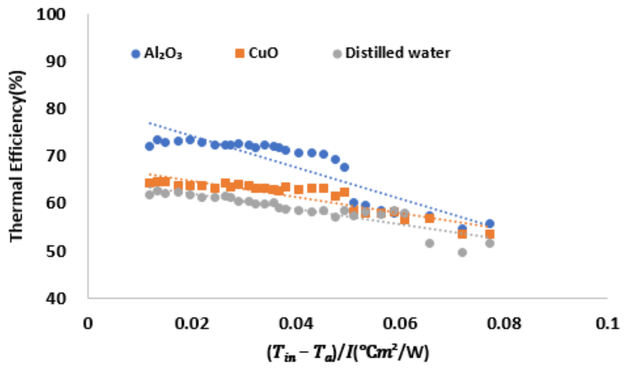


Figure 4. Collected efficiency using (**a**) Al_2O_3, (**b**) CuO, and (**c**) distilled water at 6 L/min.

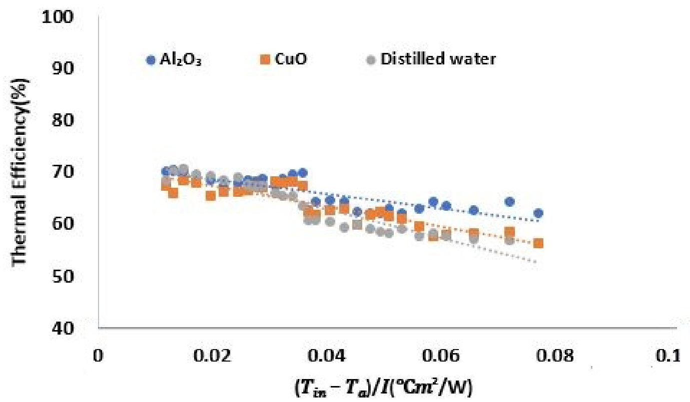
The heat collection efficiency decreased with time, and it was judged that convective heat loss increased as the inlet temperature increased. The heat collection efficiency using the Al_2O_3 nanofluid was the highest. It was observed that the Al_2O_3 nanofluid absorbs a greater amount of heat than water and CuO under similar ambient conditions; therefore, it is concluded that the relatively high thermal conductivity characteristics of the Al_2O_3 nanofluid facilitate heat transfer more successfully, resulting in higher efficiency than water and CuO.

3.1.4. Heat Collection Efficiency according to Change of $(T_i - T_a)/I$

Figure 5 shows the results of analyzing the heat collection efficiency according to the change of $(T_i - T_a)/I$. As the temperature difference between the working fluid and the outside air temperature increases, the collection efficiency decreases. The decrease in efficiency is caused by convection heat losses between the absorber surface and the ambient air temperature. It is concluded that the present system had a higher efficiency in comparison with previously published results; nanofluids have shown better results as heating mediums compared with distilled water. In addition, the Al_2O_3 nanofluid was found to be more efficient than CuO nanofluids due to comparatively higher thermal conductivity.



(**a**)



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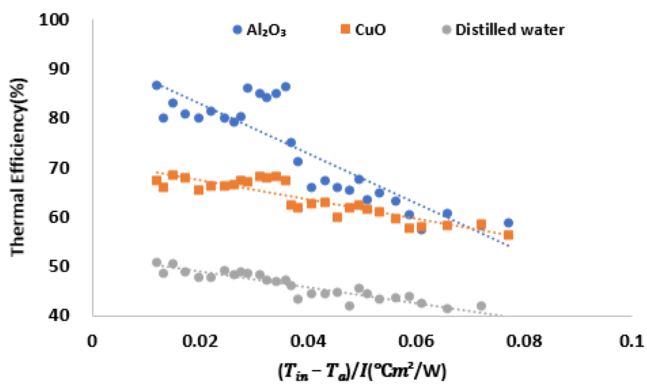

(**c**)

Figure 5. Reduced zero temperature efficiency at (**a**) 2 L/min, (**b**) 4 L/min, and (**c**) 6 L/min.

4. Conclusions

In this study, we analyzed the thermal efficiency of a conical solar collector using nanofluids and conventional fluids. Considering different heat transfer fluids at variable flow rates, the heat collection efficiency for the Al_2O_3 nanofluid at flow rates of 2, 4, and 6 L/min were found to be 65.6%, 67.8%, and 72.5%, respectively; whereas, the CuO nanofluid and the distilled water showed lower efficiencies under similar applied conditions.

Compared with the distilled water, the higher efficiency in the cases of the Al_2O_3 and CuO nanofluids can be explained by their superior thermo–physical properties, which help to extract the extra heat accumulated at the absorber surface. Furthermore, distilled water showed marginal changes in efficiency at all the flow rates from 4 to 6 L/min; therefore, it is clear that the distilled water had the lowest thermal conductivity compared with the nanofluids. Moreover, it was deduced that all the heat accumulated in the absorber was not well recovered by the distilled water, even at high flow rate.

This study was focused on the utilization of nanofluids, especially Al_2O_3 and CuO, as heat mediums for efficient utilization of solar energy in conical solar collector systems. Nanofluids have shown better results as heat mediums as compared with distilled water. In addition, the Al_2O_3 nanofluid was found to be more efficient than CuO due to comparatively higher thermal conductivity. On the basis of the obtained results, the study proposes the practical viability of the nanofluids (especially Al_2O_3) as efficient heat mediums to make maximum use of solar energy as a renewable energy source.

Through this study, it was found that the heat collection efficiency of the conical solar collector was improved using nanofluids as potential heat mediums. However, as the nanofluids circulate continuously through the solar collector, the initial state of dispersion stability is not maintained, and aggregation occurs over time; this may adversely affect the solar collector's performance. Therefore, it is considered necessary to study dispersion stability while circulating nanofluids in the conical concentrating system.

Although nanofluids have higher thermal conductivity than distilled water and their efficiency is high, their heat loss is also high, and it is necessary to study heat loss prevention to improve efficiency.

To increase the absorption rate of available sunlight, painting with Vantablack is recommended, because Vantablack paint is capable of absorbing up to 99.965% of light and might be considered a potential solution. In addition, the addition of a copper coil inside the absorber tube could also help to enlarge the surface area of the absorber, hence maximizing the utilization of the solar energy.

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Nomenclature

Q	concentrated heat (W)
m	mass flow rate (kg/s)
C_p	specific heat (J/kg °C)
T_o	outlet temperature of thermal fluid (°C)
T_i	inlet temperature of thermal fluid (°C)
T_a	ambient temperature (°C)
η	thermal efficiency
I	beam radiation (W/m^2)
A	collector area (m^2)
ϕ	nanoparticles concentration
k_{nf}	the thermal conductivity of the nanofluid (W/m·K)
k_{np}	thermal conductivities of the nanoparticles (W/m·K)
k_{bf}	thermal conductivities of base fluid (W/m·K)

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