Performance Evaluation of a Photovoltaic Thermal (PVT) System Using Nanofluids

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Abstract: In this study, a performance evaluation of a photovoltaic thermal (PVT) system using nanofluids was carried out through an efficiency comparison study using water, CuO-water, and Al₂O₃-water nanofluids as the heat medium of the PVT system. In addition, a model for computational fluid dynamics (CFD) analysis was established, and the validity of the model was verified by comparing it with the experimental results of the PVT system. Through this, it was confirmed that the outlet temperature of the PVT system using nanofluids can be predicted by applying various conditions. Based on the results, the use of nanofluid as heating medium for the PVT system is proposed to improve the efficiency sufficiently compared to the conventional heating media.

Keywords: nanofluid; photovoltaic thermal system; greenhouse gases; heat medium; Al₂O₃

1. Introduction

Solar energy is an eco-friendly renewable energy source that can produce energy in two forms, i.e., heat and electricity, and is commonly used in photovoltaic (PV) and solar thermal system individually [1]. However, a PV system has a low energy conversion efficiency, and it therefore faces problems such as the decrease in efficiency and aging of the cell due to the rise in temperature of the solar cell [2]. Thus, it is important to release heat of the solar cell in a PV system. A photovoltaic thermal (PVT) system is a combination of the PV and solar thermal systems that not only produces heat and electric energy at the same time but also prevents the reduction of PV efficiency through heat absorption of the heat medium [3]. The performance of the PVT system is influenced by various design parameters, such as mass flow rate, number of glass covers, diameter and thickness of absorbing tube, and thermal conductivity of heat medium [4].

In order to improve the performance of the PVT system, several studies on the flow change of the heat medium and structural improvement of the collector have been conducted. Sopian et al. [5] conducted a steady-state analysis of the performance of single-pass and double-pass combined PVT collectors. The simulation results show that the performance of the double-pass collector is excellent and that the double-pass collector produces more thermal energy and has a higher cooling effect on the solar cell than the single-pass collector. Bambrook and Sproul [6] confirmed the thermal and electrical efficiencies of varying air mass flow rates using a PVT air system. Their results showed that the mass flow rate of air tends to increase thermal efficiency as the flow rate increases in the range of 0.013 to 0.115 kg/s.m² of mass flow rate. In addition, high flow rates, even though cooling of the PVT models was greatly enhanced, the electrical efficiency was not increased significantly. Similarly, Chow et al. [7] evaluated a PVT collector with the presence of a glass cover from the thermodynamic perspective. They observed that the glazed PVT system was suitable for maximizing the total energy output, and the unglazed system had excellent electrical efficiency because the glass cover is disadvantageous in terms of electricity. In addition, Ibrahim et al. [8] designed various absorbers of PVT systems...
and studied the efficiency of each type through simulation. Values of 50.12% for thermal efficiency of the spiral flow design and 11.98% for cell efficiency were obtained.

However, most of the heat mediums used in many studies were conventional fluids such as water and air. These common fluids have lower thermal conductivity than solid metals, which limits the maximum efficiency of the existing system. Therefore, it is necessary to enhance efficiency by improving the heat transfer characteristics of the heat medium [9]. This problem can be improved by manufacturing nanofluids using nano-powder material that can be produced relatively easily through recent advances in nanotechnology [10].

A nanofluid is formed by the dispersion of nanosized powder particles with high thermal conductivity in a conventional fluid. It has a large transfer area, high dispersion stability and high thermal conductivity coefficient [11]. In addition, even if a small quantity of nanoparticles is added at a volume ratio of less than 1%, the thermal conductivity increases by about 10%, and the convective heat transfer characteristics increase by up to 30% [12]. Therefore, several studies using nanofluids in PVT systems have recently been reported. Ghadiri et al. [13] conducted an experimental study comparing the efficiency of the PVT systems using Fe₃O₄-water in concentrations of 1 wt%, 3 wt%, and distilled water and found that the overall efficiency of the 3 wt% Fe₃O₄-water fluid improved by approximately 76%. Mahammad et al. [14] confirmed the effects on thermal and electrical efficiency of the PVT systems using SiO₂-water nanofluids and pure water as coolants. Their study showed that the overall energy efficiency of PVT systems using SiO₂-water nanofluids in 1 and 3 wt% concentrations was increased by 3.6% and 7.9%, respectively, compared to pure water. Karami and Rahimi [15] showed that when the concentration of nanoparticles was 0.1 wt%, Boehmite nanofluids had better cooling performance than water and that the electrical efficiency was 20.57% and 37.67% in linear and spiral channels, respectively.

Various studies on the heat transfer properties of nanofluids have confirmed their availability as a thermal medium for heat transfer, but due to the difference in size and concentration of nanofluids, more research is needed to achieve efficiency using nanofluids as a thermal medium in solar energy systems [16].

A sun trackable PVT system was constructed in this study. In order to evaluate the efficiency of the PVT system, the comparative experiments were conducted using water and nanofluids (CuO-water and Al₂O₃-water) as heating medium. Thermal and electrical efficiencies of the PVT system were investigated on comparison with heating medium. Outlet temperature of heating medium and surface temperature of the PVT system were predicted with computational fluid dynamics (CFD) simulation analysis and compared with measured values.

2. Materials and Methods

2.1. Experimental Study of PVT System

The experimental work in the current study has the same experimental composition and method as that of a previous study [17]. The PVT collector used in this study was flat and composed of a PV module, a heat-absorbing pipe, a heat-absorbing plate, and insulation. The heat-absorbing pipe, heat-absorbing plate, and insulation were made of copper, aluminum, and expanded polystyrene (EPS), respectively. The diameter and thickness of the heat-absorbing pipe were 1 and 0.1 cm, respectively, and the thickness of the insulation was 4.3 cm (Figure 1). The rest of specifications are listed in Table 1.
Figure 1. Shows the schematic diagram of the photovoltaic thermal (PVT) system in whole, where sub-figure (a) shows different parts of the PVT collector; sub-figure (b) is cross section diagram of the PVT collector, and sub-figure (c) gives details on the dimensions of the collector.

Table 1. Specifications of photovoltaic (PV) module.

| Item                                      | Specification |
|-------------------------------------------|---------------|
| Cell type                                 | Mono crystalline |
| Cell dimensions (mm²)                     | 155 × 155     |
| No. of cell                               | 10            |
| Typical module efficiency (%)             | 15–20         |
| Normal operation cell temperature (°C)    | 45 ± 2        |
| The temperature coefficient of $I_{sc}$ (%/°C) | 0.024       |
| The temperature coefficient of $V_{oc}$ (%/°C) | −0.245       |
| The temperature coefficient of $P_{max}$ (%/°C) | −0.359       |

Two PVT systems were configured identically and labeled A and B. System A used nanofluid as a heat transfer medium, while system B was selected as a control to use water. The nanofluids (CuO and Al₂O₃ nanoparticles) were dispersed in primary distilled water at a concentration of 0.5 wt%. In order to increase the dispersion stability, cetyltrimethyl ammonium bromide (CTAB) and gum arabic (GA) were added at different concentrations. The produced nanofluids were measured 10 times in total through a thermal characteristic analyzer, and the nanofluid with the highest thermal conductivity was used in the experiment. In the case of CuO-water nanofluid, when the dispersion stabilizer GA was added at 1/2 times the concentration of the nanofluid, the thermal conductivity was highest at 0.901 W/m °C. Similarly, for Al₂O₃-water nanofluid, when the dispersion stabilizer CTAB was added at 1/10 times the critical micelle concentration, the thermal conductivity was highest at 0.829 W/m °C. Therefore, two nanofluids and water were applied as the heat transfer medium for the experiment. The comparative experiment was conducted for 240 min between 09:00 and 15:00 h. Unlike the previous research [17], the collection form of solar energy consisted of a two-axis tracking method in which solar energy was vertically collected. The flow rate of the heating transfer medium was fixed at 3 L/min.
For the performance analysis of the PVT system, thermal efficiency, electrical efficiency, overall efficiency, and energy saving efficiency were calculated as follows based on the experimental data. Equations (1)–(3) were used to calculate the heat collection efficiency ($\eta_{th}$).

$$Q_{th} = \dot{m}C_p(T_o - T_i)$$

$$\eta_{th} = \frac{Q_{th}}{A_{PVT}G}$$

$$\eta_{th} = \eta_0 - \alpha \left( \frac{T_i - T_a}{G} \right)$$

where $Q_{th}$ is collected heat, $\dot{m}$ is mass flow rate, $C_p$ is specific heat, $T_o$ is outlet temperature, $T_i$ is inlet temperature, $A_{PVT}$ is area of the PVT collector, $G$ is solar radiation, $\eta_0$ is thermal efficiency when the difference between the inlet and ambient temperature is zero, $\alpha$ is heat loss coefficient, and $T_a$ is ambient temperature. Equations (4) and (5) were used to calculate the electrical efficiency ($\eta_e$).

$$\eta_{th} = \frac{Q_{th}}{A_{PVT}G}$$

$$\eta_{th} = \eta_0 - \alpha \left( \frac{T_i - T_a}{G} \right)$$

where $P_{max}$ is maximum electrical power, $V_{max}$ is maximum voltage, $I_{max}$ is maximum current, and $\eta_e$ is electrical efficiency.

There are two ways to represent total efficiency: overall efficiency and energy saving efficiency. Total efficiency ($\eta_o$) is a method that simply shows the overall efficiency by summing the heat collection efficiency and the electrical efficiency, so it is same as Equation (6) [18]. The energy accumulation efficiency ($\eta_f$) is also a method to show the overall efficiency by converting heat and electric energy, which are different types of energy, into one energy type. In order to display this method in the form of thermal energy before it is converted in a power plant, the electrical efficiency is divided by the conversion efficiency of 0.38, which is the conversion efficiency of a typical electric power plant, and added to the collection efficiency, as shown in the following Equation (7) [19].

$$\eta_o = \eta_{th} + \eta_e$$

$$\eta_f = \eta_{th} + \frac{\eta_e}{0.38}$$

2.2. Simulation Analysis of the PVT System
2.2.1. Shape Modeling and Mesh

Shape modeling was done by assuming and simplifying the shape of the PVT collector for quick analysis of the PVT system, as follows (Figure 2). The total of 10 PV cells is not distinguished but is simplified to 1 body. Since the thickness of ethylene-vinyl acetate (EVA) for adhesion to the cell is very thin, it is left out on the assumption that all heat is completely transferred. Except for the glass cover, where sunlight enters, the heat-absorbing tube, heat-absorbing plate, and PV cell on all sides were completely sealed with insulation except for the parts that contact each other. Thus, only the glass cover was affected by the outdoor environment. The frame of the PVT collector was omitted on the assumption that heat cannot be received from the heat insulating material inside because it is located on the outermost side of the PVT collector.
The equations for analysis were calculated at the cells or center of the nodes of the generated grid. Therefore, it is important to create a dense grid of shapes for high gradient analysis. In addition, when generating a grid, if the quality of the grid is poor, the accuracy of the analysis results may decrease. Therefore, it is necessary to generate a good quality grid. In our study, the model of the PVT collector used was selective mesh that sequentially creates a lattice by constructing six bodies of one part with the heat medium, heat-absorbing tube, heat-absorbing plate, PV cell, glass cover, and heat insulating material. Lattices were created in the order of: heat medium, heat sink, PV cell, glass cover, insulation. In order to create a high-quality grid, the element size was set to $1.003 \times 10^{-3}$ m in consideration of the curvature occurring at the contact surface between the heat-absorbing plate and the insulating material. In addition, the patch forming method was used for the grid generation method of the heat-absorbing plate body, and the auto mesh was used for the rest. A total of 3,729,144 and 157,036 nodes and elements of the resulting grid were created, respectively. Orthogonal quality was 0.76596, and skewness quality was 0.23447.

2.2.2. Property Values and Boundary Conditions

The properties and boundary conditions applied for CFD analysis are shown in Tables 2 and 3. The nanofluid used as a heat medium has a small change in volume and mass because very small amounts of nanoparticles and surfactant were added as compared to the base fluid. Therefore, the density applied to the property values was assumed to be 1000 kg/m$^3$ of the commonly used water, and nanofluid was assumed to be a single-phase fluid. In addition, specific heat ($C_p$) was applied by calculating the density ($\rho$), thermal conductivity ($k$), and thermal diffusivity ($\alpha$) measured by a thermal property analyzer through Equation (8).

$$C_p = \frac{k}{\rho \alpha} \quad (8)$$

| Zone Name | Type   | Boundary Condition         | Value         |
|-----------|--------|----------------------------|---------------|
| Inlet     | Mass-flow-inlet | Mass flow rate (kg/s) | 0.05          |
| Outlet    | Pressure-outlet | Gauge pressure (pascal) | 0             |
| Glass     | Wall   | Heat transfer coefficient (W/m$^2$K) | 5 measured |
| Glass     | Wall   | Free stream temperature (°C) | measured |
| Glass     | Wall   | External emissivity       | 0.84 [22]    |
| Glass     | Wall   | External radiation temperature (°C) | measured |
| Insulation| Wall   | Heat flux (W/m$^2$)       | 0             |
Table 3. Cell zone conditions.

| Body        | Material          | Density (kg/m$^3$) | Specific Heat (J/kgK) | Thermal Conductivity (W/mK) | Remark     |
|-------------|-------------------|-------------------|-----------------------|-----------------------------|------------|
| Working fluid | Water             | 998.2             | 4182                  | 0.6                         | default    |
|             | Al$_2$O$_3$/water nanofluid | 1000 | 3872                  | 0.829                      | measured   |
|             | CuO/water nanofluid | 1000             | 3754                  | 0.901                       | measured   |
| Absorbing tube | Copper            | 8978             | 381                   | 387.6                       | default    |
| Absorbing plate | Aluminum          | 2719             | 871                   | 202.4                       | default    |
| PV module   | PV cell           | 2330             | 677                   | 148                         | [22]       |
| Glass       | Glass             | 1.8              | 500                   | 3000                        | [22]       |
| Insulation  | Insulation        | 80               | 1120                  | 0.04                        | [21]       |

The inlet boundary condition was set by converting the volume flow rate of 3 L/min used in the experiment into the mass flow rate. The outer wall of insulation was set to 0 under the assumption that there is no heat transfer phenomenon as a result of external ventilation under the condition of complete insulation. Glass applied the convective heat transfer coefficient and the outside temperature using a mixed thermal condition that can simultaneously apply the outside conditions and solar radiation energy. The measured total solar radiation ($G$) was set by calculating the radiation temperature ($T$).

$$G = \sigma T^4$$  \hspace{1cm} (9)

where $\sigma$ is the Stefan–Boltzmann constant, so it has the value of $5.67 \times 10^{-8}$ W/m$^2$k$^4$.

2.2.3. Model and Validation for Simulation Analysis

For CFD analysis of the PVT system, the CFD simulation was performed with the continuous equation, energy equation, standard $k$-$\varepsilon$ turbulence model, and for the discrete ordinates radiation model, we used ANSYS FLUENT software (19.1, ANSYS Inc., Kanonsberg, PA, USA) for simulation [22]. Simulation analysis was analyzed as a steady state by applying experimental conditions when the difference between the PVT inlet temperature and the outside temperature was 0, 3, 6, 9, 12, and 15 °C. Through this, the RMSE was calculated to check the error between the calculated predicted value and the actual experimental value. The model fit is shown using the coefficient of determination $R^2$. Table 4 shows the values applied for the analysis.

Table 4. Input values used for simulation.

| Working Fluid | Temperature of Difference (°C) | Inlet Temperature (°C) | Ambient Temperature (°C) | Radiation Temperature (°C) |
|---------------|--------------------------------|------------------------|---------------------------|---------------------------|
| water         | 0                              | 24.363                 | 23.812                    | 86.959                    |
|               | 3                              | 27.288                 | 24.423                    | 87.923                    |
|               | 6                              | 31.675                 | 25.938                    | 88.367                    |
|               | 9                              | 35.513                 | 26.223                    | 88.647                    |
|               | 12                             | 39.613                 | 27.150                    | 88.134                    |
|               | 15                             | 43.225                 | 28.260                    | 78.853                    |
| CuO-water     | 0                              | 14.388                 | 14.063                    | 86.154                    |
|               | 3                              | 17.663                 | 14.657                    | 87.970                    |
|               | 6                              | 22.200                 | 16.167                    | 89.736                    |
|               | 9                              | 25.450                 | 16.440                    | 89.828                    |
|               | 12                             | 28.313                 | 16.328                    | 90.173                    |
|               | 15                             | 31.925                 | 16.932                    | 90.357                    |
| Al$_2$O$_3$-water | 0                              | 24.413                 | 23.815                    | 86.912                    |
|               | 3                              | 23.363                 | 23.850                    | 87.572                    |
|               | 6                              | 29.563                 | 23.610                    | 88.670                    |
|               | 9                              | 34.913                 | 25.936                    | 88.810                    |
|               | 12                             | 38.025                 | 26.348                    | 88.078                    |
|               | 15                             | 42.913                 | 27.77                     | 84.936                    |
3. Results and Discussions

3.1. Experimental Environments

To compare the efficiency of the PVT system using nanofluids, preliminary experiments were conducted under the same conditions using water from systems A and B as working fluids. As a result, the power value of system B was always higher than that of system A. On average, the electrical efficiency of system B was 0.2% higher, which was considered in the final experiment results. All experiments were started in the range where the difference between the inlet temperature and the outside temperature of the initial endothermic pipe was ±3 °C. Table 5 shows the environmental conditions for each experiment.

Table 5. The experimental environmental conditions.

| Nanofluid      | Inlet Temperature (°C) | Solar Radiation (W/m²) | Ambient Temperature (°C) | Wind Speed (m/s) |
|----------------|------------------------|------------------------|--------------------------|------------------|
| CuO-water A    | 16.13~36.58            | 921~990.3              | 13.94~18.81              | 0~1.3            |
| CuO-water B    | 16.08~37.88            |                        |                          |                  |
| Al₂O₃-water A  | 24.81~43.29            | 865.33~974.9           | 23.52~28.42              | 0~0.9            |
| Al₂O₃-water B  | 25.09~45.04            |                        |                          |                  |

3.2. Experimental Results

Figure 3 and Table 6 are experimental results of a trackable PVT system using CuO-water nanofluids, showing the changes in heat collection efficiency, electrical efficiency, and solar radiation and average values. The heat collection efficiency of the PVT system using CuO-water nanofluid was increased by 11.75% compared to the system using water. When considering the results of the preliminary experiment, the electrical efficiency increased by 0.11%. In addition, the total efficiency and energy accumulation efficiency were improved by 11.86% and 12.04% compared to the system using water.

![Figure 3](image)

(a) The thermal efficiency
(b) The electrical efficiency

Figure 3. Shows the efficiency and radiation of the PVT system using water and CuO-water nanofluid over time, where (a) shows the thermal efficiency over time while (b) shows the electrical efficiency over time.

Table 6. The average efficiency of the PVT system using water and CuO-water nanofluid.

| Heat Medium        | ηₖh(%) | ηₑ(%) | ηₒ(%) | η₇(%) |
|--------------------|--------|-------|-------|-------|
| CuO-water nanofluid| 38.13  | 13.09 | 51.22 | 72.58 |
| Water              | 26.38  | 12.98 | 39.36 | 60.54 |

In addition, the heat collection and electrical efficiency according to the value of (Tᵢ – Tₐ)/G are shown in Figure 4. The equations of heat collection efficiency of the PVT system using CuO-water nanofluid and water were ηₖh = 46.802 – 682.97x and
\[ \eta_{th} = 43.174 - 1315.8x, \] respectively. In the equation of heat collection efficiency, \( x \) means \( (T_i - T_a)/G \). Here, when \( (T_i - T_a)/G \) was 0, the maximum heat collection efficiency was 46.81\% when CuO-water nanofluid was used and 44.74\% when not applied. It is judged that heat loss occurred as the temperature difference between the outside air and the temperature increased as the inlet temperature of the heat-absorbing pipe increased. In the case of electrical efficiency, the equations are respectively \( \eta_e = 14.232 - 94.698x \) and \( \eta_e = 14.176 - 81.695x \), when \( (T_i - T_a)/G \) was 0, the highest electrical efficiency was 14.61\% and 14.37\%. In the case of electrical efficiency, the temperature of the heat medium and the temperature of the solar cell rose together, so it is judged that the electrical efficiency tends to decrease due to the temperature characteristic of the solar cell.

Figure 4. The efficiency of the PVT system using water and CuO-water nanofluid according to \((T_i - T_a)/G\), where (a) shows the thermal efficiency while (b) shows the electrical efficiency.

Figure 5 and Table 7 show the changes and average values of heat and electrical efficiency of a traceable PVT system using water and Al\(_2\)O\(_3\)-water nanofluid over time. The heat collection efficiency was increased by 8.19\% compared to water, and electrical efficiency shows an increase of 0.08\% \( p \). In addition, the total efficiency of the PVT system using Al\(_2\)O\(_3\)-water nanofluid was 8.27\% \( p \), and the energy accumulation efficiency was found to be 8.4\% \( p \) higher than the case of used water.

Figure 5. The efficiency and radiation of the PVT system using water and Al\(_2\)O\(_3\)-water nanofluid over time, where (a) shows the thermal efficiency, while (b) shows the electrical efficiency.

Table 7. The average efficiency of the PVT system using water and Al\(_2\)O\(_3\)-water nanofluid.

| Heat Medium               | \( \eta_{th}(\%) \) | \( \eta_e(\%) \) | \( \eta_o(\%) \) | \( \eta_f(\%) \) |
|---------------------------|----------------------|-------------------|-------------------|-------------------|
| Al\(_2\)O\(_3\)-water nanofluid | 35.96                | 12.49             | 48.45             | 68.83             |
| Water                     | 27.77                | 12.41             | 40.18             | 60.43             |
Figure 6 shows the heat collection efficiency and electrical efficiency according to \((T_i - T_a)/G\). The heat collection efficiency of the PVT system using Al\(_2\)O\(_3\)-water nanofluid and water is \(\eta_{th} = 16.011 - 918.62x\) and \(\eta_{th} = 44.212 - 1572.6x\), respectively. The equations of electrical efficiency were \(\eta_e = 13.203 - 61.653x\) and \(\eta_e = 13.159 - 45.621x\), respectively. In addition, the highest heat collection efficiency of Al\(_2\)O\(_3\)-water nanofluid is 46.10%, while that of water was 41.45%, and in the case of electrical efficiency, the value was 13.19% for Al\(_2\)O\(_3\)-water nanofluid and 13.25% for water.

Mohammad et al. [9] investigated the effects of Al\(_2\)O\(_3\)-water nanofluid in the PVT system from the energy viewpoint. They reported results of 36.66% and 13.44% for electric and thermal energy efficiency, which is slightly higher than 35.96% and 12.49% in our results. As a neglected aspect of this study, energy is required for pumping fluid into the PVT system.

3.3. Simulation Verification

Table 8 shows the experimental values for each heat medium and the predicted values through simulation. In addition, Figure 7 is a graph of 1:1 correspondence between experimental and predicted values for verification of the analytical model. Table 9 shows the calculated values of the determination coefficients \(R^2\) and root mean square error (RMSE), which indicate the good fitness of the model. Outlet temperature of the PVT system was well predicted with simulation analysis because the \(R^2\) is higher than 0.9 and the RMSE is lower than 0.09 for all heating mediums (water, CuO-water, and Al\(_2\)O\(_3\)-water). The difference of outlet temperature for the PVT system was less than 0.5 °C between predicted and measured values. In comparison with outlet temperature, surface temperature of the PVT system could not be accurately predicted with simulation analysis, with a lower value of \(R^2\) (<0.9) and higher value of RMSE (>2.0) for all heating mediums. Simulation results for the surface temperature of the PVT system showed a temperature difference in the range of 0.03 to 5.85 °C between predicted and measured values.
Table 8. Predicted values through CFD and measured values through experiment.

| Heat Medium | Difference of Temperature (°C) | Exp. Outlet (°C) | Exp. Surface (°C) | CFD Outlet (°C) | CFD Surface (°C) |
|-------------|--------------------------------|-----------------|-----------------|----------------|-----------------|
| water       | 0                              | 24.90           | 30.02           | 24.92          | 26.16           |
|             | 3                              | 27.84           | 31.28           | 27.82          | 29.01           |
|             | 6                              | 32.40           | 39.26           | 32.36          | 33.44           |
|             | 9                              | 35.95           | 39.41           | 35.95          | 36.93           |
|             | 12                             | 39.86           | 40.15           | 40.00          | 40.85           |
|             | 15                             | 43.46           | 43.63           | 43.46          | 43.98           |
| CuO-water   | 0                              | 15.08           | 18.07           | 15.07          | 16.34           |
|             | 3                              | 18.36           | 20.93           | 18.33          | 19.56           |
|             | 6                              | 22.85           | 27.88           | 22.83          | 24.01           |
|             | 9                              | 26.08           | 28.29           | 26.04          | 27.13           |
|             | 12                             | 28.90           | 27.20           | 28.86          | 29.88           |
|             | 15                             | 32.53           | 29.58           | 32.43          | 33.36           |
| Al2O3-water | 0                              | 25.00           | 28.86           | 25.01          | 26.17           |
|             | 3                              | 27.00           | 27.13           | 26.94          | 28.07           |
|             | 6                              | 30.20           | 33.35           | 30.11          | 31.17           |
|             | 9                              | 35.50           | 38.59           | 35.40          | 36.34           |
|             | 12                             | 38.58           | 39.33           | 38.46          | 39.30           |
|             | 15                             | 43.30           | 40.11           | 43.24          | 43.88           |

Figure 7. Predicted and measured values of outlet and surface temperature. Lines are 1:1. Where (a) indicates the Outlet temperature (water), (b) Surface temperature (water), (c) Outlet temperature (CuO-water), (d) Surface temperature (CuO-water), (e) Outlet temperature (Al2O3-water), and (f) Surface temperature (Al2O3-water).
Table 9. Validation of simulation by comparison of predicted and measured temperature.

|                     | Water | CuO-Water | Al₂O₃-Water |
|---------------------|-------|-----------|-------------|
|                     | Outlet Surface | Outlet Surface | Outlet Surface |
| R²                  | 0.99994 | 0.89392 | 0.99999    |
| RMSE                | 0.05764 | 3.17968 | 0.04801    |

4. Conclusions

In order to evaluate the efficiency of a PVT system, a comparative experiment was conducted using nanofluid. Among the tested media, the total efficiency and energy accumulation efficiency of the PVT system using CuO-water nanofluid as a heating medium were 51.22% and 72.58%, respectively, which were higher than those using Al₂O₃-water nanofluid. However, in the case of electrical efficiency, the efficiency tended to decrease due to rise in temperature in all heat mediums; hence, the difference in efficiency was not significant. The surface temperature difference in the case of using water and nanofluid was 0.6 °C to a maximum of 2 °C; thus, the difference in the amount of electricity produced was not high. However, the PVT system had a higher overall energy efficiency than the solar system. This is a positive result because the improvement of the thermal energy alone can sufficiently increase the overall performance of the system. Therefore, using a nanofluid as a heating medium of the PVT system is expected to improve the efficiency sufficiently compared to the existing heating medium.

Additionally, the proposed PVT model for simulation analysis was confirmed by comparing the experimental and predicted values. The actual measured surface temperature was influenced by the outside air of the collector, which may have led to the difference between the predicted and actual values. The outlet temperature of the heating medium was predicted more accurately than the surface temperature.

Since it is suggested that the flow rate affects the efficiency of the PVT system, the critical flow rate of each nanofluid will be investigated in future study. Moreover, the surface temperature of the PVT system would be more exactly predicted by considering additional outside wind speed with air temperature and radiation in the CFD simulation.

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