Comparative Economic Analysis of Single- and Dual-fluid Based Photovoltaic Thermal Systems for Building Energy Needs

M. Imtiaz Hussain[1] and Jun-Tae Kim[2]

[1] Green Energy Technology Research Center, Kongju National University, Cheonan, Korea

[2] Department of Architectural Engineering, Kongju National University, Cheonan, Korea

Abstract

This study presents a comparative economic analysis of single- and dual-fluid based photovoltaic/thermal (PV/T) systems for energy supply of an apartment with varied demands. Nanofluid (CuO/water) and Conventional heat transfer fluids were operated both separately and simultaneously under the same-sized PV/T system. The performance of single- and dual-fluid PV/T systems for apartment energy needs was investigated for winter from November to February. The apartment heat load and the PV/T system performance were predicted via EnergyPLus® and Matlab® simulation software, respectively. Based on recent inflation rate, interest rate, and utilities unit prices in South Korea, economic viability of both single- and dual-fluid PV/T systems was assessed to supply energy to a top floor apartment of a 4-storey residential building. It is found that dual-fluid PV/T systems powered by nanofluids yield the best life cycle savings and discounted payback period than that of single-fluid PV/T systems. Net savings earned from mitigation of CO_2 over the lifetime of dual-fluid PV/T systems are surprisingly higher than the solar collectors associated with single-fluid systems.

Keywords: Dual-fluid PV/T system, Transient model, Economic analysis, Building energy needs

1. Introduction

Photovoltaic/thermal (PV/T) collector, which integrates photovoltaic (PV) cells and thermal collector into single unit, can reach high yields per unit area (Chow, 2003). The conversion of solar energy into thermal and electrical energy allows the cooling of PV cells and hence exploitation of heat energy from its surface. Myriad of studies have been carried out on performance enhancement of hybrid PV/T systems using different heat transfer fluids such air, water, synthetic oils, and nanofluids (Hussain et al., 2018; Tian and Zhao, 2013). In above-mentioned list of fluids, air is not much effective compared to liquid type coolants because of lower heat capacity. To have high useful energy from PV/T system several techniques such as new coolant materials and optimization of absorber are possible. In this study we are interested in both aforementioned techniques including application of different fluids and modification of absorber design.

Over the years, the utilization of colloidal solutions or nanofluids in solar collecting systems has increased substantially. By adding nanoparticles into conventional fluids can change the thermo-physical properties of the resultant mixture (Hussain and Kim, 2018). The most importantly increasing their thermal conductivity compared to conventional fluids. The heat transfer and electrical efficiency of the PV/T system depends mainly on the thermo-physical properties of the coolants (Al-Waeli et al., 2017). Therefore, use of nanofluid as a coolant has proven to be effective at increasing overall efficiency of the PV/T systems.

The simultaneous application of two heat transfer fluids for cooling of PV cells offer a wide range of options, where either fluid can be operated depending on energy demands. In situation where space matters such as high-rise or apartment buildings, dual-fluid PV/T system seems more appealing and an attractive option. Abu Bakar et al., (2014) proposed an improved design of a bi-fluid PV/T system which comprised of copper pipes for carrying water and a single pass air channel. The dual-fluid heat exchanger was designed in such a way that both fluids flow perpendicular to one another and thus creating transverse flow effect. Because of cross flow condition, energy balance equations for each PV/T component were solved using 2D steady state model. Following the 2D

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mathematical model developed by Abu Bakar et al., (2014), Jarimi et al., (2016) added slight modification to this model considering finned air channel configuration. Besides, the developed 2D steady state model was validated using indoor experimental results.

The presented study aims to compare the economic viability of single- and dual-fluid PV/T systems for apartment energy needs, and also address the challenges and opportunities of the nanofluid heat exchanger in comparison to conventional fluids. A mathematical model of a dual-fluid PV/T system is developed and validated using experimental results from published study.

2. Mathematical Model

A MATLAB computer program is used to perform the simulation. A thermo-electric model based on interdependent energy balance equations is analyzed using ordinary differential equations (ODE) solver. During simulation real time calculation of heat transfer coefficients has been done and material properties were taken as constant. A generic mathematical model of a PV/T system is developed, which could be applied to both single- and dual-fluid heat exchangers.

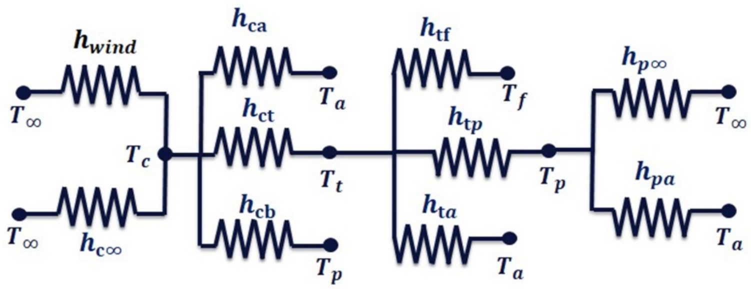

Fig. 1: The dual-fluid PV/T thermal resistance circuit.

In the PV/T system, the temperature change across the interface between layers of different materials is attributed to the thermal resistance, as shown in Fig. 1. Dynamic interdependence temperature responses for different collector components (PV laminate, pipe absorber, nanofluid, inside air, and back panel) were predicted using energy balance equations (Chow, 2003). The energy balance for each collector component is presented as follows:

$$M_c C_c (dT_c/dt) = G\alpha_c - E - h_{wind} A_{c\infty}(T_c - T_\infty) - h_{c\infty} A_{c\infty}(T_c - T_\infty) - h_{ct} A_{ct}(T_c - T_t) - A_{ca} h_{ca}(T_c - T_a) - h_{cp} A_{cp}(T_c - T_p) \quad \text{(eq. 1)}$$

M_c, C_c and T_c are the mass, specific heat and temperature of the PV cells, respectively. G is the solar radiation and α_c is the absorptivity of the PV cells. The electrical energy output from the PV module can be calculated using following correlation:

$$E = GP\eta_e \quad \text{(eq. 2)}$$

The electrical efficiency (η_e) is estimated as a function of PV cells temperature as recommended by (Florschuetz, 1979) as follows:

$$\eta_e = \eta_r[1 - \beta_r(T_c - T_r)] \quad \text{(eq. 3)}$$

β_r and η_r are the temperature coefficient and electrical efficiency at reference solar cells temperature, respectively. The energy balance equations for the pipe carrying fluid can be written as:

$$M_t C_t (dT_t/dt) = h_{ct} A_{ct}(T_c - T_t) - A_{tf} h_{tf}(T_t - T_f) - A_{ta} h_{ta}(T_t - T_a) - h_{tp} A_{tp}(T_t - T_p) \quad \text{(eq. 4)}$$

$$h_{tf} = Nu_f k_f / D_i \quad \text{(eq. 5)}$$

M_t, C_t and T_t are the mass, specific heat and temperature of the pipes, respectively. Nu_f is the Nusselt number. k_f and D_i are the thermal conductivity of the circulating fluid and inner diameter of the tube, respectively. In case of nanofluid, the Nusselt number can be calculated using following correlation (Zerradi et al., 2014):

$$Nu_{nf} = Pr^{0.1039}(1.0257\phi + 1.1397Re^{0.205} + 0.788\phi Re^{0.205} + 1.2069) \quad \text{(eq. 6)}$$

ϕ is the concentration of nanoparticles in the base fluid. Pr and Re are the Prandtl and Reynolds numbers, respectively. The heat transfer equation for the temperature node for the fluid flow can be expressed as:

$$M_f C_f (dT_f/dt) = \dot{m}_f C_f\,(T_{f,o} - T_{f,in}) + A_{tf}\,h_{tf}(T_t - T_f) \quad \text{(eq. 7)}$$

$\dot{m}_f$ and C_f are the mass flow rate and specific heat of the circulating fluid, respectively. $T_{f,in}$ and $T_{f,o}$ are the fluid inlet and outlet temperatures, respectively. The heat transfer equation for the air node is then written as:

$$M_a C_a (dT_a/dt) = \dot{m}_a C_a\,(T_{a,o} - T_{a,in}) + A_{pa}\,h_{pa}(T_p - T_a) + A_{ta}\,h_{ta}(T_t - T_a) + A_{ca}\,h_{ca}(T_c - T_a) \quad \text{(eq. 8)}$$

M_a, C_a and $\dot{m}_a$ are the mass, specific heat and mass flow rate of the circulating fluid, respectively. Finally, the energy balance for the back panel can be obtained as:

$$M_p C_p (dT_p/dt) = h_{tp}A_{tp}(T_t - T_p) + h_{cp}A_{cp}(T_c - T_p) + h_{ap}A_{ap}(T_a - T_p) - h_{p\infty}A_{p\infty}(T_p - T_\infty) \quad \text{(eq. 9)}$$

M_p, C_p and T_p are the mass, specific heat and temperature of the back panel, respectively. The total useful energy produced and thermal efficiency of the solar collector is given by summation of outcomes from air and liquid fluids heating components as follows:

$$Q_{th} = \dot{m}_f C_f\,(T_{f,o} - T_{f,in}) + \dot{m}_a C_a\,(T_{a,o} - T_{a,in}) \quad \text{(eq. 10)}$$

$$\eta_{th} = \frac{\dot{m}_f C_f\,(T_{f,o} - T_{f,in}) + \dot{m}_a C_a\,(T_{a,o} - T_{a,in})}{A_{cl} G} \quad \text{(eq. 11)}$$

Q_{th} and η_{th} are the total useful energy and thermal efficiency of the dual-fluid PV/T system. Net CO_2 mitigation and carbon credit earned over the collector life can be calculated as (Barnwal and Tiwari, 2008):

$$\text{Net } CO_2 \text{ mitigation} = (Q_{th} * \text{lifetime} - \text{embodied energy}) * 0.98 * 10^{-3} \quad \text{(eq. 12)}$$

Embodied energy is the amount of energy required during manufacturing of PV module from raw materials to final product use. In this study the value of embodied energy is taken as 1380 kWh/m^2 (Tiwari et al., 2007). If the CO_2 mitigation is being traded at rate of 20 euro/ton then the earned carbon credit over the collector lifetime can be expressed as:

$$\text{Net } CO_2 \text{ credit} = \text{Net } CO_2 \text{ mitigation} * 20 \quad \text{(eq. 13)}$$

3. Research Design

To assess the PV/T performance under extreme weather conditions, heating load for a top floor apartment of a 4-storey residential building was calculated using EnergyPLus® simulation software. The apartment with facing south-east directions has dimensions of 8m x 4m x 3.5m. During load calculation, a basic heating, ventilation and air conditioning (HVAC) is used instead of a full HVAC system. A basic HVAC system is also called Ideal Loads Air System.

For PV/T system, a mono-crystalline PV cells with exposed surface area of 1.62 m^2 is considered for simulation (Fig.2). The dual-fluid heat exchanger comprised of a parallel tube thermal absorber and a single pass air heater. In order to minimize thermal resistance, the copper tube exchanger is attached directly onto the rear surface of the PV module with help of thermally conductive glue or thermal adhesive. While in conventional finned-tube concept, the absorber sheet is used between tube and PV module. To enhance the turbulence within the air channel, a set of baffles is arranged transverse to air flow. This promotes convection heat transfer to circulating air and hence minimizes the thermal resistance between air and channel walls. In order to enhance emissivity, matt black surfaces for copper tube, PV rear and air channel were considered. Copper oxide (CuO) nanoparticles with fixed volume concentration (0.70 %) in pure water are used for nanofluid preparation.

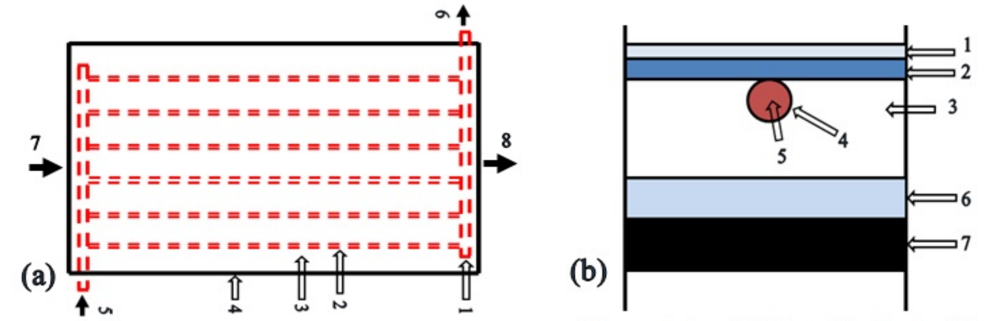

Fig. 2: Dual-fluid PV/T system (a) assembly and flow pattern (b) cross-section view

4. Results and discussions

Since we do not have experimental results for the dual-fluid PV/T system, therefore, the validation of the mathematical model was performed using test data from the published article. For this purpose, a simple case of air type PV/T collector published by Joshi et al., (2009) was selected. Using identical geometrical configurations and operating conditions as given in selected published article, the experimental results from the published study were compared with the results from the mathematical model. The root mean square percentage differences for the average PV module and outlet air temperatures between the simulation and test data were no more than 4.4% and 5.0%, respectively. Therefore, we are now in a position to say that the developed model could be used to predict the PV/T performance under a wide range of climatic conditions.

The overall efficiency of the PV/T system mainly depends on the fluid type used for heat removal from the PV module. Considering independent and simultaneous modes of fluid operation, total four modes were taken into consideration such as nanofluid plus air, water plus air, nanofluid and water. The overall efficiency of the PV/T system was plotted against different flow rates of the fluid as presented in Fig. 3. In case of simultaneous modes, nanofluid or water flow rate was varied at fixed air flow rate. Compared to independent fluid modes, the PV/T system associated with simultaneous modes showed greater efficiencies. However, the efficiency of the PV/T system with CuO nanofluid/air was relatively high compared to other heat transfer fluids. The additional energy produced was due to superior thermo-physical properties of the nanofluid as a coolant which increases total system efficiency per unit area.

The effectiveness of the nanofluids over the conventional heat transfer fluids can be described in terms of heat transfer coefficient. Table 1 shows the variations of convection heat transfer coefficients in function of fluid flow rate, when CuO nanofluid and water are used as the coolants for the PV/T system. As expected, the convection heat transfer coefficient increases with an increasing concentration of nanoparticles and the mass flow rate. However, compared to water, the nanofluid for all given concentrations has produced higher convection heat transfer coefficients between the absorber surface and the circulating fluid. This may have caused by low specific heat and high thermal conductivity of the nanofluid, which ultimately results in an increase of surface area of the heat exchanger.

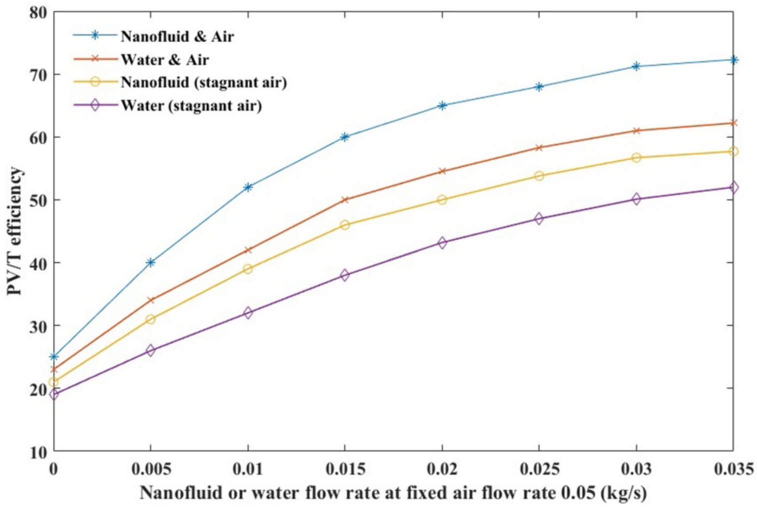

Fig. 3: Variations of PV/T efficiency against variable of nanofluid or water flow at fixed air flow rate

Tab. 1: variations of the convection heat transfer coefficient against flow rate using water and nanofluid

Mass flow rate (kg/s)	h_{tf} using water	h_{tf} using nanofluid (0.3%)	h_{tf} using nanofluid (0.5%)	h_{tf} using nanofluid (0.7%)
0.005	390.21	430.07	445.99	465.30
0.01	435.02	482.30	505.05	530.39
0.015	470.31	520.22	548.69	575.41
0.02	495.44	548.93	570.76	605.02
0.025	507.26	563.54	582.52	620.27
0.03	506.95	574.18	593.72	635.95

Under similar working conditions, daily PV cells temperature is predicted using different modes of fluid operation (Fig. 4). Hourly solar radiation and ambient temperature data is used to estimate PV module temperature against variable fluid ranges. During simultaneous mode, both nanofluid or water and air were operated at specific sets of fixed flow rates. At a fixed nanofluid or water flow rate of 0.025 kg/s and air flow rate of 0.05 kg/s, the maximum PV module temperature were 48.7 °C and 43.5 °C for water/air and nanofluid/air, respectively. Whereas using nanofluid and water individually the PV module temperature is 55.1 °C and 52.1 °C, respectively. It is observed that utilization of dual-fluid as a coolant removes extra accumulated solar heat from the PV module and hence improves its overall energy production performance. Furthermore, a rise in the temperature for each fluid is calculated as a difference between outlet and inlet fluid temperatures. This is the best way to find the thermal contribution of each fluid when nanofluid or water and air are being operated simultaneously. As shown in Fig. 5, during simultaneous mode both nanofluid and water have the lower temperature rises than that of air. However, due to higher thermal conductivity, the nanofluid in combination with air has the highest thermal output. Lower specific heat causes air to achieve higher temperature in shorter time than that of nanofluid or water.

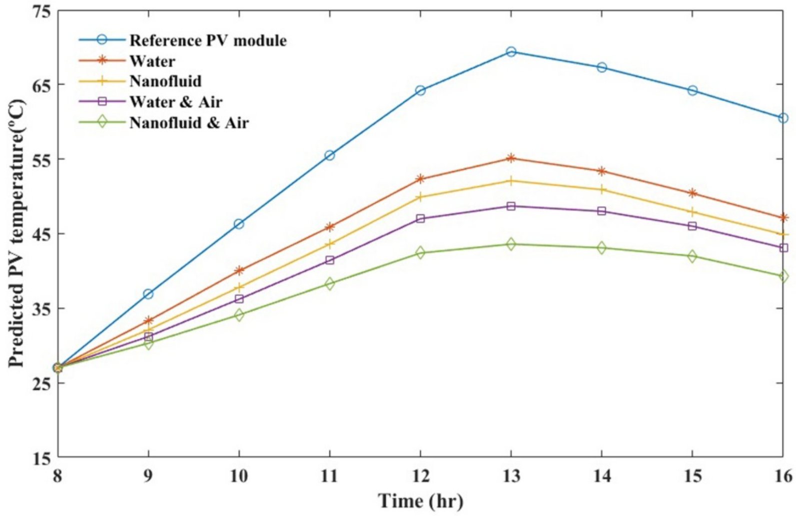

Fig. 4: Variations of PV/T temperature against different modes of fluid operation

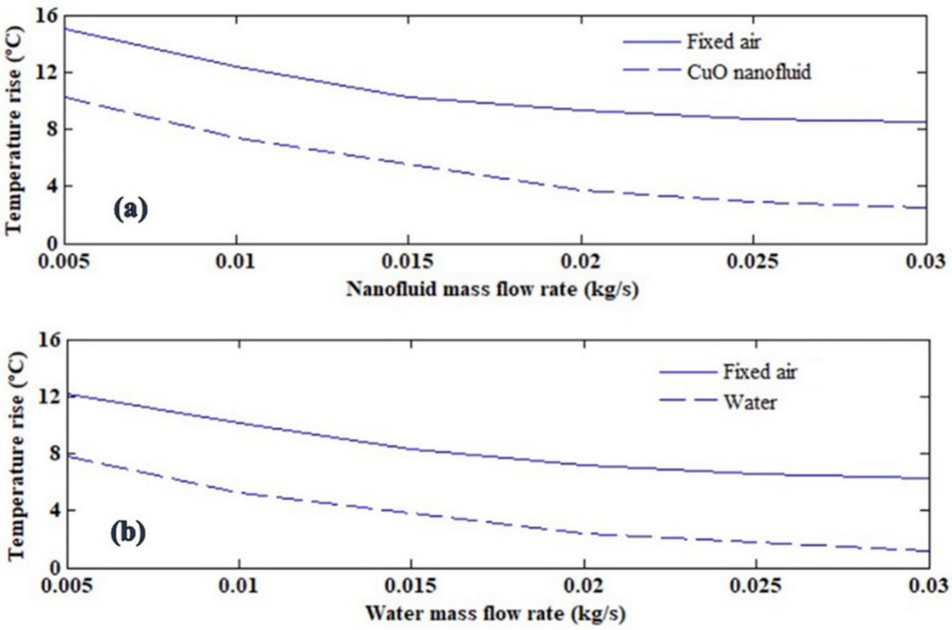

Fig. 5: Temperature rise against variable (a) nanofluid flow rate (b) water flow rate at fixed air flow of 0.05 kg/s

Economic feasibility and compatibility-prosperity of single- and dual-fluid PV/T systems for apartment energy needs was evaluated as the replacement of commonly used energy sources such as electricity and natural gas. Based on local unit cost of utilities (KEPCO) and load supplied and required by the apartment, the life cycle savings (LCS) and discounted payback period (DPP) of the PV/T systems were estimated (Imtiaz Hussain et al., 2016). When single fluid is used, the LCS based on electricity and natural gas is 1558.7 and 1260.2, and 1418.9 and 1147.2 for PV/T with nanofluid and PV/T with water, respectively. For nanofluid based dual-fluid PV/T system, the DPP relative to electricity and natural gas were found to be 8 and 10 years, respectively and LCSs as the replacement of electricity and gas were found to be 1998.6 and 1615.9 USD, respectively (Table 2). The LCS relative to electricity was found to be higher because of high price per unit for electricity compared to natural gas. It is worth to note that LCS based on electricity and natural gas is almost 2 times the present cost of the dual-fluid PV/T with nanofluid, which is promising.

Tab. 2: Life cycle savings and discounted payback period of the PV/T system based on electricity and natural gas

PV/T System using	Life Cycle Savings (USD) Based on		DPP (years) Based on		Parameters for Economic Analysis (expected useful life of 25 years)
	Electricity	Natural Gas	Electricity	Natural Gas	
Nanofluid plus air	1998.6	1615.9	8	10	Present PV/T system cost = 940 USD; Electricity = 0.094 USD/kWh; Gas = 0.076 USD/kWh; Inflation rate = 1.8%; Interest rate = 2%
Water plus air	1765.5	1432.4	10	11	
Nanofluid only	1558.7	1260.2	13	14	
Water only	1418.9	1147.2	15	16	

Relevant to electricity and natural gas monthly costs, the energy cost for an apartment with PV/T system is presented in Fig. 6. Due to the high energy demands, the monthly cost for January is notably higher than December and February. These higher values can be explained by the fact that freezing ambient temperature condition during that part of the year. It is important to note that the nanofluid based dual-fluid PV/T system totally eliminates the electricity and natural gas consumption for apartment heating for February. Furthermore, in coldest month of the year (January), the dual-fluid PV/T has proved to be the best option which reduces apartment heating cost to 11.91 USD relevant to use of electricity (44.03 USD) and natural gas (36.69 USD). Whereas for February reduce the auxiliary energy consumption to zero, which means that complete energy demand is solely fulfilled by the dual-fluid PV/T.

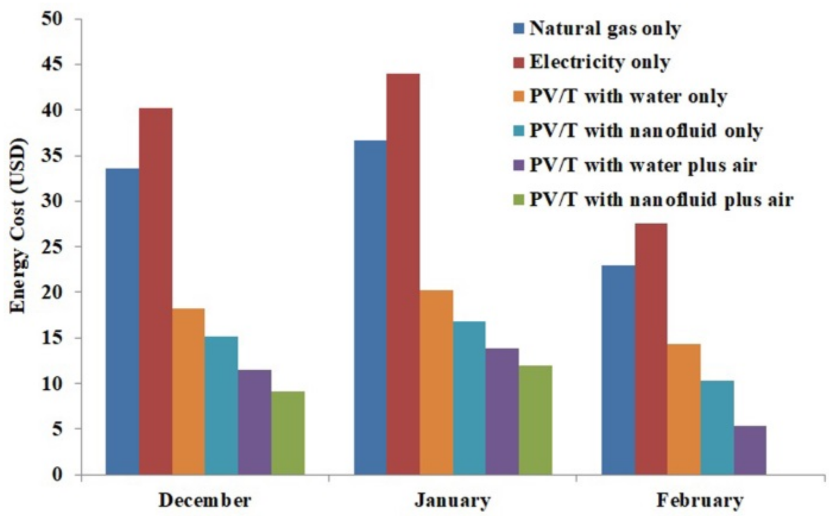

Fig. 6: Energy cost for apartment needs using utilities and PV/T system with different heat exchangers

Based on application of different heat transfer fluids in PV/T system the potential CO_2 mitigation and carbon credit are presented in Fig. 7. The results show that net savings from emission reduction are higher using dual-fluid powered PV/T systems in comparison with single fluid based systems. However, a combination of nanofluid and air as a dual-fluid provides significant improvement in the PV/T energy efficiency with negligible economic penalty. It was found that using nanofluid plus air, water plus air, nanofluid, and water the CO_2 mitigation over the lifetime of PV/T was about 10.2, 8.7, 7.5, and 6.4 tonnes, respectively. It is observed that the value of earned carbon credit (USD) using nanofluid plus air as a dual-fluid is 262 USD which is almost 40% higher than that of single fluid case. Higher CO_2 mitigation and carbon credit with nanofluid powered dual-fluid PV/T can be interpreted as being too favorable disposed to superior thermo-physical properties.

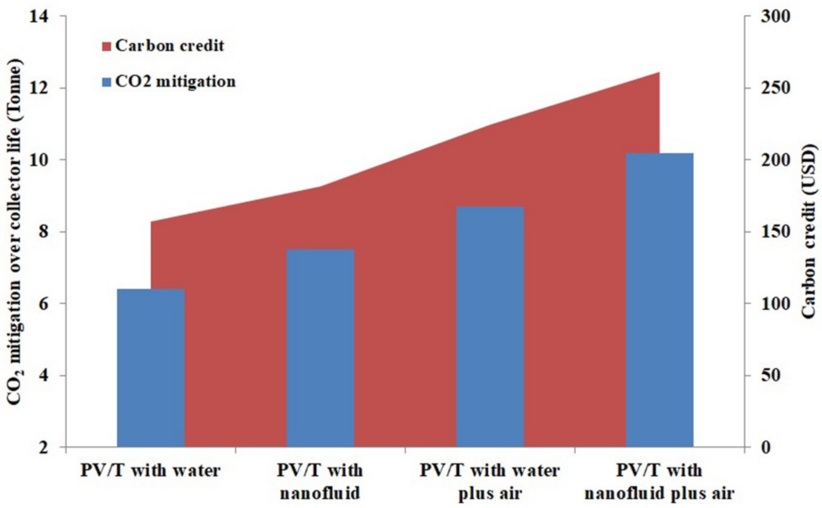

Fig. 7: CO2 mitigation and carbon credit over collector life using different modes of fluid operation

Due to large amounts of thermal losses, top floor apartment of a residential building under normal and severe weather conditions always exhibit high energy needs. To better understand the energy supplied by the PV/T system, a Top floor apartment is considered for performance assessment. Table 3 depicts the monthly variations (November to February) of energy demand load for apartment and total load supplied by the PV/T based on different heat transfer fluids. It was observed that the utilization of nanofluid based PV/T system eliminates the dependency on auxiliary energy for daily energy requirements for a building. According to results, in context of energy supplying the nanofluid based PV/T system dominates over the air and water based systems for above-mentioned five months. Furthermore, application of dual-fluid as a coolant has significant impact on the PV/T performance which results in elimination of auxiliary energy needs for some months e.g. November and February.

Tab. 3: Energy demand load for apartment and total load supplied by the PV/T

Months	Apartment heating load (kWh)	Load supplied by PV/T system using (kWh)			
		Water	Nanofluid	Water plus air	Nanofluid plus air
November	115.4	92.3	110.1	131.3	152.5
December	352.1	83.9	101.3	120.8	133.4
January	358.3	75.5	93.2	114.9	129.1
February	180.9	97.9	123.1	153.9	185.4

5. Conclusion

Economic and energy analyses of single- and dual-fluid type PV/T systems were performed for apartment energy needs. It has been shown that the thermal and electrical energy per unit area yield by dual-fluid PV/T system is almost 30% higher than that of single-fluid PV/T system. It was found that application of dual-fluid PV/T system eliminates the dependency on auxiliary energy for building heating even in cold winter of Korea. Relevant to electricity and natural gas energy costs, using nano-engineered dual-fluid PV/T system the average heating cost for the January, as the coldest month of the year, was reduced by 68 - 73%. Furthermore, nanofluid based single- and dual-fluid PV/T systems have shown the best life cycle savings as the replacement of auxiliary energy and also shorter payback periods compared to conventional fluids based PV/T systems.

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7. References

Abu Bakar, M.N., Othman, M., Hj Din, M., Manaf, N.A., Jarimi, H., 2014. Design concept and mathematical model of a bi-fluid photovoltaic/thermal (PV/T) solar collector. Renewable Energy 67, 153-164.

Al-Waeli, A.H., Chaichan, M.T., Kazem, H.A., Sopian, K., 2017. Comparative study to use nano-(Al2O3, CuO, and SiC) with water to enhance photovoltaic thermal PV/T collectors. Energy Conversion and Management 148, 963-973.

Barnwal, P., Tiwari, G., 2008. Life cycle energy metrics and CO2 credit analysis of a hybrid photovoltaic/thermal greenhouse dryer. International Journal of Low-Carbon Technologies 3(3), 203-220.

Chow, T., 2003. Performance analysis of photovoltaic-thermal collector by explicit dynamic model. Solar Energy 75(2), 143-152.

Florschuetz, L., 1979. Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. Solar Energy 22(4), 361-366.

Hussain, M.I., Kim, J.-T., 2018. Performance Optimization of Unglazed Nanofluid Photovoltaic/Thermal System: Energy and Exergy Analyses. International Journal of Photoenergy 2018.

Hussain, M.I., Ménézo, C., Kim, J.-T., 2018. Advances in solar thermal harvesting technology based on surface solar absorption collectors: A review. Solar Energy Materials and Solar Cells 187, 123-139.

Imtiaz Hussain, M., Ali, A., Lee, G.H., 2016. Multi-module concentrated photovoltaic thermal system feasibility for greenhouse heating: Model validation and techno-economic analysis. Solar Energy 135, 719-730.

Jarimi, H., Bakar, M.N.A., Othman, M., Din, M.H., 2016. Bi-fluid photovoltaic/thermal (PV/T) solar collector: Experimental validation of a 2-D theoretical model. Renewable Energy 85, 1052-1067.

Joshi, A., Tiwari, A., Tiwari, G., Dincer, I., Reddy, B., 2009. Performance evaluation of a hybrid photovoltaic thermal (PV/T)(glass-to-glass) system. International Journal of Thermal Sciences 48(1), 154-164.

KEPCO, KEPCO. https://home.kepco.co.kr/kepco/EN/F/htmlView/ENFBHP00103.do?menuCd=EN060201. (Accessed March, 20 2017).

Tian, Y., Zhao, C.Y., 2013. A review of solar collectors and thermal energy storage in solar thermal applications. Applied Energy 104, 538-553.

Tiwari, A., Raman, V., Tiwari, G., 2007. Embodied energy analysis of hybrid photovoltaic thermal (PV/T) water collector. International Journal of Ambient Energy 28(4), 181-188.

Zerradi, H.; Ouaskit, S.; Dezairi, A.; Loulijat, H.; Mizani, S., 2014. New Nusselt number correlations to predict the thermal conductivity of nanofluids. Adv. Powder Technol 25 (3), 1124-1131.

8. Nomenclature and Symbols

M	mass (kg)
C	specific heat (J/kg ºC)
T	temperature (ºC)
A	surface area (m^2)

h_{wind}	convection heat transfer coefficient due to wind (W/m^2 ºC)
$h_{c\infty}$	radiation heat transfer coefficient between PV & ambient (W/m^2 ºC)
h_{ct}	conduction heat transfer coefficient between PV & tube (W/m^2 ºC)
h_{ca}	convection heat transfer coefficient between PV & inside air (W/m^2 ºC)
h_{cp}	radiation heat transfer coefficient between PV & back panel (W/m^2 ºC)
h_{tf}	convection heat transfer coefficient between tube & fluid (W/m^2 ºC)
h_{ta}	convection heat transfer coefficient between tube & inside air (W/m^2 ºC)
h_{tp}	radiation heat transfer coefficient between tube & back panel (W/m^2 ºC)
h_{pa}	convection heat transfer coefficient between back panel & inside air (W/m^2 ºC)
$h_{p\infty}$	convection heat transfer coefficient between PV & ambient (W/m^2 ºC)
E	electrical energy (W)
P	packing factor
G	solar radiation (W/m^2)

Greek

α	absorptivity
ŋ	efficiency
β_r	solar cell temperature coefficient (l/K)

Subscripts

c	PV plate
t	absorber tube
f	nanofluid
a	inside air
p	back panel
∞	ambient air
e	electrical
r	reference
f,o & f,in	fluid outlet & inlet
a,o & a,in	air outlet & inlet
th	thermal
cl	collector