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Title: Design Framework for the Development of Dual Heat Recovery System in Photo-Voltaic Powered Air Conditioning Systems

Koketso MADITSI[1], Opeyeolu LASEINDE[2]

[1] University of Johannesburg, Johannesburg, 201446621@student.uj.ac.za

[2] University of Johannesburg, Johannesburg,otlaseinde@uj.ac.za

Abstract: Energy regeneration through heat recovery is practically possible for maximizing energy obtained from the sun, by recovering and reusing the heat that is typically lost within energy dependent electrical equipment's. The study is aimed at developing an efficient and cost effective heat recovery system, which is an improvement to existing variants. Solar thermal systems utilize flat plates or evacuated tube collectors which absorb the heat from the sun. Similarly, Photo-Voltaic (PV) systems absorb solar irradiation to generate electricity. A combination of both technologies results in Solar Photo-Voltaic Thermal (PV/T) systems wherein thermal plates or liquid contained tubes cool PV collectors resulting in increased efficiency. The PV cooling mechanism is important because excessive heat in PV panels generates high resistance, which impedes the performance of the solar cell and in the process, results in lower efficiency. PV/T systems are currently sold at relatively high cost and their availability is limited. The study focuses on the development of a dual heat recovery system for harnessing both the heat build-up on the PV plates and the heat generated from the heat exchanger exhaust outlet of a solar air-conditioning system, by incorporating electro-thermal generators and Peltier devices for the optimization process. The research is sectioned into design, prototype development, and a testing phase. The focus of this paper is to share the design phase of the project. The design highlighted herein is a cost effective and highly efficient PV/T model with a different heat absorption approach in comparison to conventional PV/T systems. The heat recovery system design is complete and is currently undergoing extensive tests to complete the testing and optimization phase.

1. INTRODUCTION

The energy sector is globally going through a transition because of increasing demand for cleaner energy. Renewable sources of energy are widely being promoted, which calls for more research on how best to maximize the energy potential of these greener sources (Da Rosa, 2005). The energy emitted by the sun is about 3.8 x 1023 kW whereas only about a third of this is received on the earth surface, which is estimated at about 1.2 x 1014 kW (Ramos, et al., 2017). Notwithstanding, the fraction received on earth is not fully harnessed due to a lot of system inefficiencies through heat losses. This unlimited amount of energy during sunny days may be collected using various collection methods of the irradiance. Solar energy can play important role in the Heating Ventilation and Air Conditioning (HVAC) systems of buildings, by the application of solar absorption systems in combination with heat recovery systems, which can generate both heat and electricity for heating and cooling of residential buildings, shipping vessels, commercial facilities and industries (Martinez, et al., 2018).

Energy regeneration through heat recovery is also practically possible for maximising energy obtained from the sun, by recovering and reusing the heat that is typically lost within solar energy dependent electrical equipment's. Hybrid Photovoltaic Thermal (PV/T) collectors generate heat and electricity simultaneously in one module as presented in figure 1. The basic idea behind the PV/T concept is to utilize more of the solar radiation by also harvesting the waste heat that is generated in Photo Voltaic (PV) modules. In a PV/T collector, a thermal absorber and the photovoltaic cells are integrated into a single module (Kalogirou & Tripanagnostopoulos, 2007). The solar radiation that is not absorbed by the cells for electricity production and not lost to the surroundings is transferred to the thermal absorber positioned at the back (rear) of the module. Working fluid such as air and liquids transports the heat away from the PV cells, and the heat lost by the PV module is the heat gained by the cooling medium. As a result, both heat and electricity are generated from the same panel. Hybrid PV/T technologies may be implemented within local energy systems to cover a large fraction of the corresponding heat demands at high efficiency, low cost and with low associated emissions therefore, enabling the emergence of such distributed systems (Ramos, et al., 2017). The proposed solar technology is motivated by the need to utilize both electrical and thermal output from the combined technology and since solar air conditioning system uses both of these outputs, there may be a huge demand for this technology based on economic considerations and factors associated with environmental impacts of this clean energy system (Hormazabal, et al., 2016).

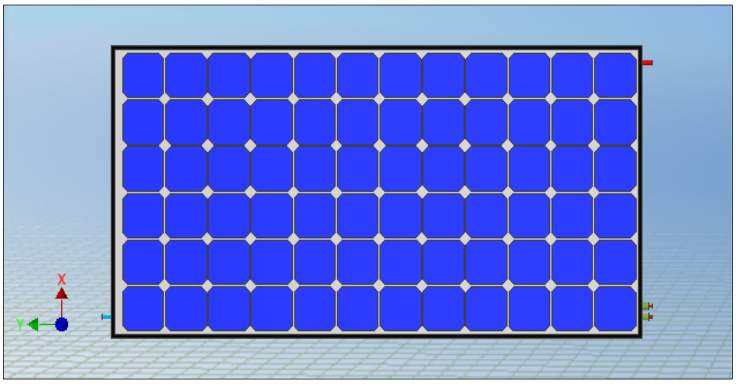

Figure 1: Solar PV/T module

There is a significant drop in efficiency of solar PV panels due to high surface temperature, which impedes the performance of the cells, and in the process, lowers the thermal and electrical output of the electricity and heat produced from PV systems (Sorensen, 2007). Current cooling methods of the solar cells are effective for electricity production for low temperature application but ineffective and less efficient for heat generation (Thorpe, 2011). The exhaust air leaving the air conditioning system outlet escapes at a temperature significant enough for re-utilization processes. Some methods applied for energy reutilization have proven to be highly efficient (Sorensesn & Katic, 2003). In this research, the improvement in efficiency of PV output and the re-utilization of the exhaust air temperature is desirable, to develop a more efficient and cost effective heat recovery system for capturing the excessive heat loss from both the exhaust airflows of an air conditioning system and from the panel of the PV system. The combined heat may be fed back into a system that will convert the captured heat into a source of energy that will be useful to the solar air conditioning unit. The study followed an exploratory method, which involved an extensive and intensive literature review followed by the design phase. The Non-Destructive Testing (NDT) of materials and generation of simulations using TRNSYS computer software for simulations are beyond the scope of this research and this approach focuses more on the complete system design including the energy efficiency within the air conditioning system. However, the study presented focused more on the design of a PV/T system with different heat absorption to conventional PV/T systems and ANSYS was adopted in the research in place of TRNSYS.

2. LITERATURE REVIEW

Literature on air-cooled PV/T technologies suggest that hybrid solar electric-thermal systems produce both electricity and heated air, which has the potential of generating two to three times more energy than a standalone PV system without a cooling medium (Donwell, 2016). In some cases, air-cooling may achieve more electricity with an estimated 25% more cost efficiency, based on some PV/T manufactures (ART solar (Pty) Ltd). The two solar technologies in one footprint offset both heating and electricity costs, while also increasing the PV performance by up to 10% by cooling the panels. Other technologies available for PV cooling are the separate solar thermal systems using water as the cooling medium, and the solar electric concentrated systems using oil and other highly concentrated chemical mix (Jager, et al., 2014).

PV/T systems are usually designed to meet 30% of the heating load because they operate at lower temperatures and have lower thermal efficiencies than traditional flat-plate or evacuated-tube collectors (Moss, et al., 2018). PV module generally achieve between 6 to 20% efficiency if not optimized in terms of installation. The inclination to face the direction of the sun, shading based on positioning, cooling of the panel as the surface temperature rises, and the type of panel design greatly contribute to the efficiency obtained. Higher efficiencies are a function of rightly putting measures in place to optimize the system in terms of the aforementioned factors. These measures may include rightly inkling the panels to face South and installing a solar tracking positioning system that rotates the panel in the direction of the sun as the sun moves from the East to the West in a normal day. The application of a cooling medium as proposed in this research also improves the efficiency of the panels (Cozzini, 2012). The lost energy, estimated to be between 80 to 94% of incident solar radiation, is mostly converted to heat and a greater portion of this energy can be used to satisfy thermal heating loads (Sorensesn & Katic, 2003). Another measure for improving efficiency of the PV modules is the installation of this array away from obstructions such as buildings, trees, and high structures, which cast shadows and reduces the irradiance absorption (Lynn, 2010).

According to the Imperial report in London (Ramos, et al., 2017), solar cells in PV collectors suffer lower temperature stresses, which are known causes that increases the possibilities of major PV system failure due to cell breakage, encapsulation, discolouration and delamination. Figure 2 illustrates this relationship where the module efficiency decreases in warm environment and increases in cool environment based on an experiment carried out on the selected panels for the research. This emphasises the need to keep the module as cool as possible.

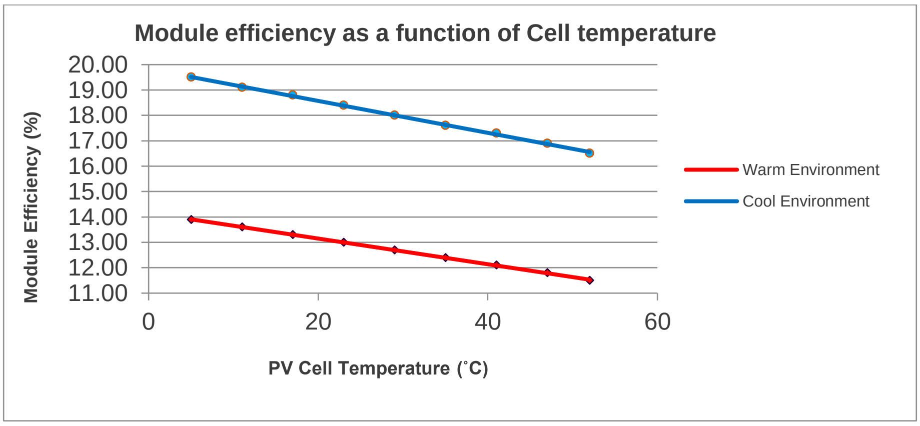

Figure 2: Comparative Cell Temperature over Module Efficiency

High surface temperature on the PV panel induces the solar cell to overheat and in the process, the efficiency of electrical output decreases and this is because of the vibrations caused by solar radiations, which further impedes the electrons already freed during sunlight to electricity conversion (Dean, et al., 2015). The research carried by Dean and McNutt suggests that weather has special effects on the performance of PV cells. The photons from the sun radiation sometimes do not have sufficient energy to free electrons from the material surface of the absorber depending on the weather. The location/position of the sun gives rise to temperature difference on the panel surface thus the panel must be positioned in a way that will direct the radiations towards the transparent screen and to the absorber. Alternative solutions are the parabolic concentrators, which concentrates the sun radiation towards the receiver (Jager, et al., 2014).

The Peltier fans are special kind of fans, which uses a heat sink in between the extracting and exhausting surfaces. The smaller fan draws heat from a conditioned space and transfers the heat to the bigger fan underneath which exhaust the heated air on the other side of the conditioned space. This “Peltier Effect'' results in cooling on one side and heating on the other side. They typically consume around 30 – 90 Watts of the electrical output depending on the size (Tahakkar, 2016).

Thermoelectric generators are devices, which generates electrical current directly from the heat source. They use the temperature of the thermoelectric materials of the hot and cold side. As the heat from the hot site piles up, the electrons and poles from the PN junction gets excitations, this effect induces electrical field for the flow of charge with the circuit connected at the cold side of the generator. For better conversion of heat to electricity, it is significant for thermoelectric materials to have low thermal conductivity and high electrical conductivity as to accommodate the temperature rise to the cool side, which increases the electrical resistance hence, lowering the output produced (Jensen, et al., 2010). It is mandatory for the cool side to be maintained for a considerable temperature difference of the thermoelectric materials. Typical conversion efficiency for these devices are approximated to be around 5 -8%, with this mentioned, these devices are suitable for low power applications (BCS, 2008). These devices may be integrated in the proposed PV/T model in this study, to power the low energy consumption Peltier fans for maximum optimisation of the electrical output produced by the PV alone.

3. METHODOLOGY

The study followed an exploratory method, which involved holistic review of past works from literature, followed by the design of a model using Autodesk Inventor Professional. The design was developed based on lapses of current systems identified in literature. There were numerous options to consider, however; the approach selected was partially based on simulation results carried out driven by software, and partly based on physical evaluation of different components and designs of existing heat recovery systems. The testing involved the use of predictive simulations carried out by ANSYS and solid works. Currently, the research is in the final testing phase wherein physical tests to validate the simulation results of the design phase of the project being presented in this paper. The results obtained will be further validated using Comsol Multiphysics algorithms, which is a virtual experimentation application. The model will also undergo material alteration to determine the most efficient heat recovery material that will be recommended for final prototype development.

Data sources

Required information were sourced from local manufactures of Photovoltaic (PV) panels, which involved sites visits to study the full geometry of the PV modules and their operations. Numerous manufactures confirmed the conclusive literature that PV modules remains inefficient with increasing panel temperature, especially in South Africa where the ambient temperature can reach as high as 50ºC. The study on optimization process then began where the use of the Peltier fans were studied in detail. The modified Peltier fan is used in this study to recover the heat from the PV module. Conference proceedings, journal articles and books were major sources of information that contributed to the model developed in the research.

Waste heat recovery in the presented PV/T system

The PV module alone is a heat liberating system and without proper system design, this heat may be lost to the surrounding environment. The design presented recovers some of this heat to a maximum by cooling off the panel while extracting and exhausting this heat from the panel surface and the surrounding. Energy from the sun may come in different forms of rays and some of this are absorbed by the PV cells while others builds up heat to the panel surface. The heat or rays not absorbed by the PV module are absorbed by the thermal absorber positioned at the rear of the PV module. The absorber transfers this heat by conduction to the liquid-contained tubes underneath which in turn, partly cools the module. The design presented accommodates a modified Peltier fans which is held by a transparent glass below the PV layer. A small fan extracts excess heat from the PV layer and exhaust it to the absorber in the second compartment, this cools the first compartment to the maximum and provides the second compartment with excess heat which is concentrated more on the center of the absorber. The liquid-contained tubes are then designed in such a way that more of these tubes are concentrated on the center for maximum heat collection. The result is a PV/T system with an improved electrical efficiency and higher liquid temperature outlet.

ANSYS simulations

ANSYS software was used to predict the cooling effect of the panel. The software requires having all numerical and operational boundary conditions of the proposed model. The 3 Dimensional model from Inventor was imported into ANSYS simulation environment where thermal properties such as thermal conductivity, convective heat coefficient, heat flux, rotational speed, ambient and surface temperature were defined after meshing the geometry. This cooling effect helped in generating the graphs of module efficiency as a function of cell temperature. The last step was used together with the PV efficiency equation defined later under numerical interpretations.

SolidWorks simulations

Thermal and flow analysis was performed using the above-mentioned software which followed an approach similar to the procedure taken using ANSYS. The flow analysis carried out on the Peltier fan served the purpose of generating information that showed the nature of the extraction process from the proposed geometry. This helped identifying regions exposed to high thermal conduct with the surface. Thermal analysis was also used to predict the areas where high thermal exposure exists by entering the necessary boundary conditions as mentioned in ANSYS simulation above. The predictive simulations explained in this section are further elaborated under the result section.

4. RESULTS AND DISCUSSIONS

This section provides an overview of the whole design where drawings, tables, simulations and graphs, provide a clear design of the proposed PV/T model.

4.1. 3-Dimensional Model

The design was carried out using Autodesk Inventor Professional. Figure 3 shows different layers of the PV/T system of which the design specifications are presented in Table 1. The frontal layer (upper portion) shown in figure 3 is the glazing of the PV module. The Peltier fan is positioned at the centre of the module where its light weight is held by the hard transparent glass which also accommodates the radiation not absorbed by the PV cells. The liquid transporting tubes underneath the thermal absorber are designed in such a way that they accommodate excess heat produced by the fan.

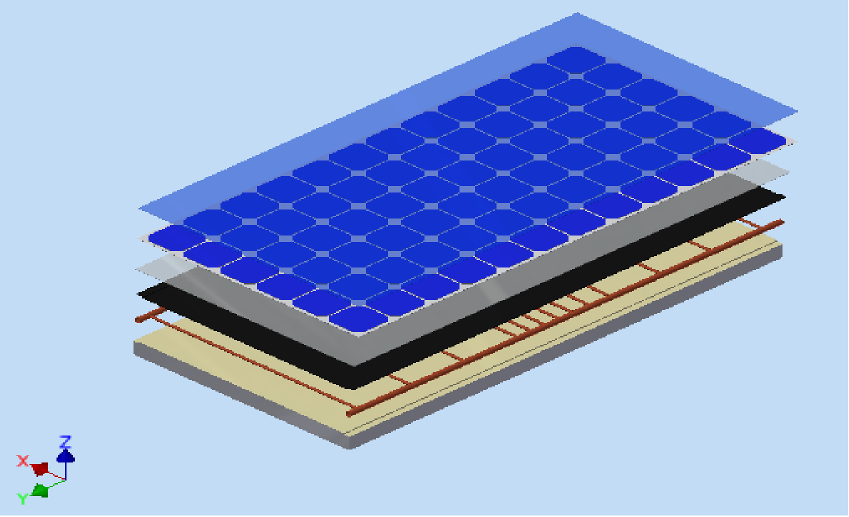

Figure 3: PV/T layers

Table 1: Design specifications

Component	Material	Dimensions (mm)	Thermal Conductivity (W/m.K)
PV outer cover	Glass	1586 x 800 x 2	0.96
PV module	Mono-Silicon	1586 x 800 x 2	148
Cell	Mono-Silicon	125 x 125 x 2	148
Frame	Aluminium	1606 x 820 x 10	237
Peltier fan	Thermoplastic	D100 and D180 x 30	-
Anti-reflective cover	Glass	1566 x 780 x 2	0.96
Insulation	Styrofoam	1566 x 780 x 60	0.003
Tubes	Copper	D20 and D10 x 2	401
Case	Aluminium	1606 x820 x 220	237
Absorber	Copper coated	1566 x 780 x 60	401

Table 2: Operational conditions

Maximum Operating Temperature	150 ºC
Maximum Operating Pressure	22 bar
Water Flow Rate	80 litres/hour
Nominal Power	200W

Figure 4 and 5 illustrates the inside design of the PV/T module and shows the positioning of the Peltier unit. There is an allowance between the Peltier fans and the PV glass. Similarly, underneath the bigger fan, the same allowance exists to allow heat distribution to the absorber.

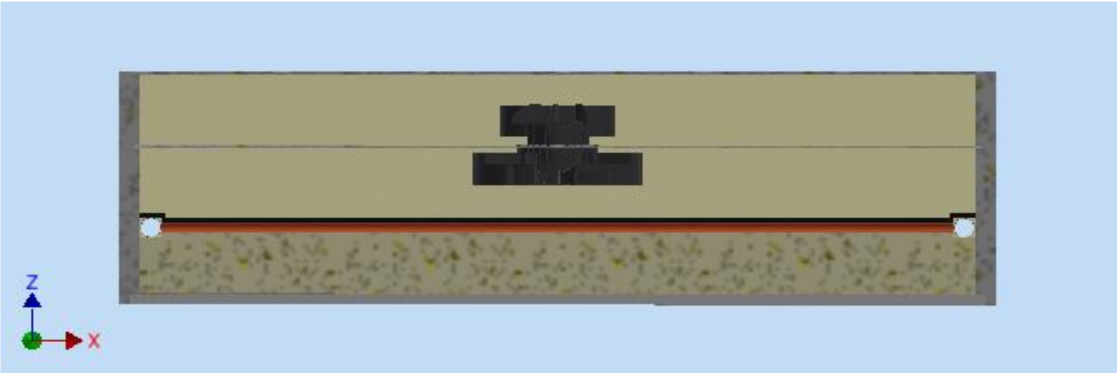

Figure 4: Sectioned wide view

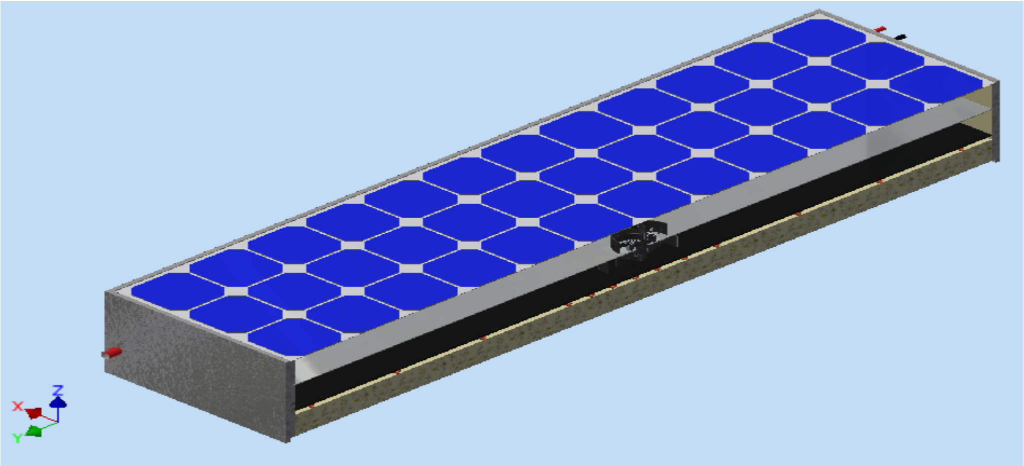

Figure 5: Angled sectioned view

Figure 6 illustrates the Peltier fan developed for cooling the surface cells and drawing the heat absorbed downwards towards the absorber area and the tubes, positioned directly under the absorber layer. Figure 7 shows the section view AA of the PV/T model for better illustration of the components making out the whole unit.

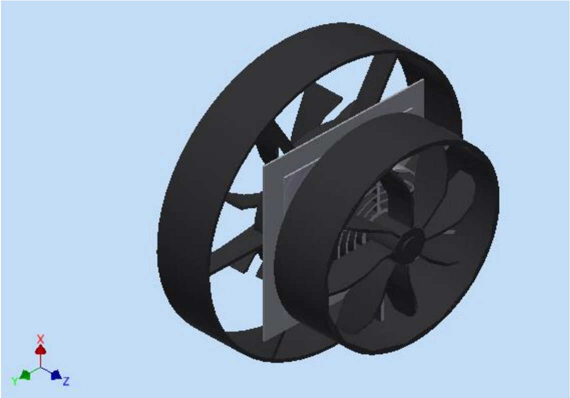

Figure 6: The modified Peltier fans

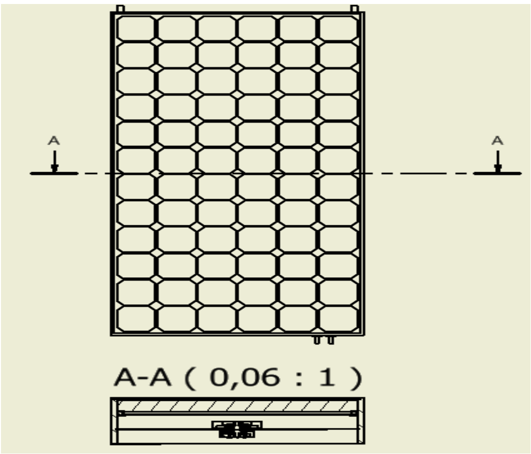

Figure 7: Model section view

4.2. Flow and Thermal Analysis

Flow analysis

The fan extracts heat from the PV module, in the process cooing it and transferring the heat using the Peltier effect to the absorber which in turn transfer the heat to the liquid contained tubes underneath. Figure 8 illustrates this effect where the maximum temperature lines are shown over the panel surface and the absorber area.

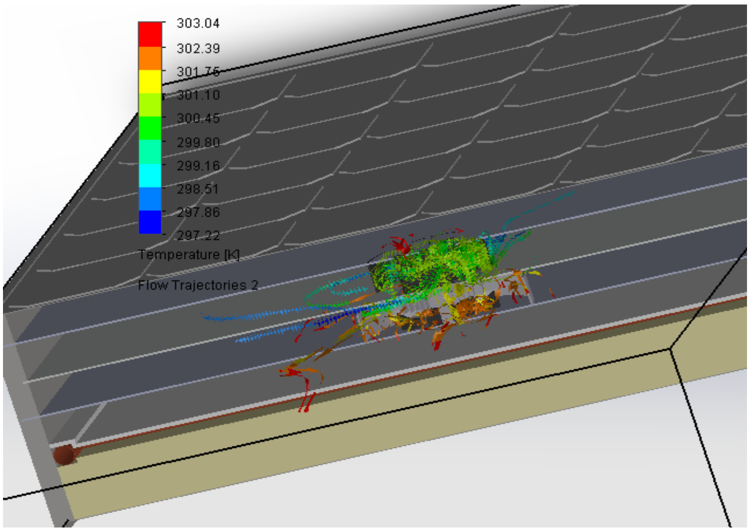

Figure 8: Flow Analysis in SolidWorks

Thermal Analysis

The analysis in Figure 9 on the thermal absorber compartment shows that heat is concentrated more around the centre than the sides. Hence, more heat is transferred to the centre due to the positioning of the Peltier fan. Both of the designs incorporate the tubing system with more tubes concentrated on the centre for maximum thermal collection. As such, the centre of the tubes is ideal for positioning the thermal generator for maximum efficiency. This is important because the Peltier fan shall be powered by the electric energy generated by the thermoelectric generator.

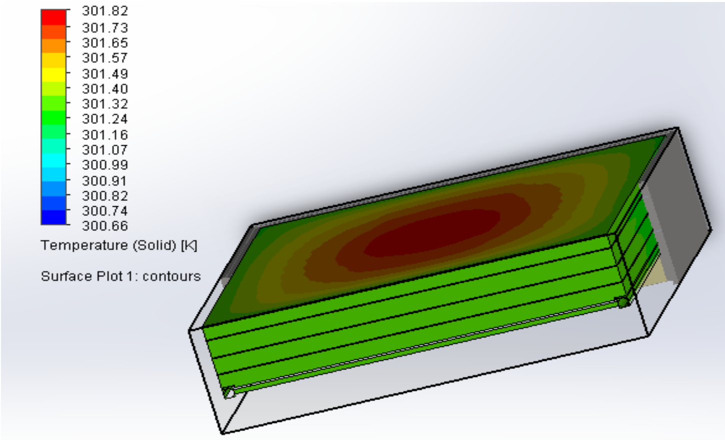

Figure 9: Thermal Analysis in SolidWorks

4.3. Graphical and Numerical Interpretation

Design 1

The design shown in figure 8 uses a timer where the Peltier is to extract heat from the PV module and cool the cells within a certain time range and after that time, the fan automatically draws heat until the time expires. The graph below showed that as the module is cooled after every 3 minutes of fan shutoff, the efficiency of the module fluctuates by a small percentage. The proposed design ensures that the module operates at a higher efficiency as compared to conventional PV or PV/T operating at the same temperature.

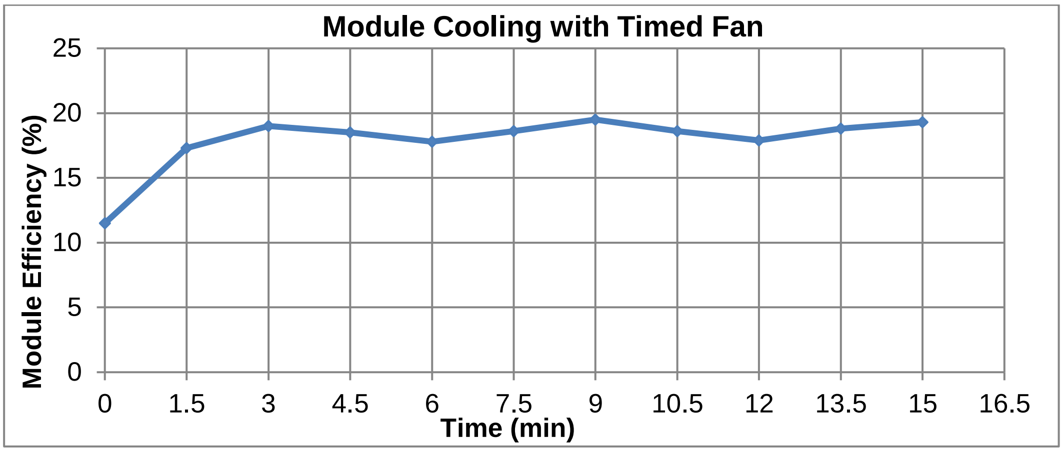

Figure 10: PV timed cooling

Design 2

The design for Figure 11 below uses a continuous cooling process where the Peltier extracts heat from a module without using a timer. The fan rotates at a certain speed to maintain the efficient cell operating temperature within the PV compartment. The graph in figure 11 shows that by using this design, the efficiency of the module in terms of electricity generated is almost constant. The slight fluctuations witnessed in design 1 as shown in figure 10 is eliminated by this design. The efficiency remained high irrespective of the time range as shown. The challenge of design 2 is how to effectively maintain the rotational speed of the fan to avoid overcooling or undercooling. The incorporation of a thermostat is currently being considered, however; because the temperature is different across layers and within each layer, this may not be ideal. Furthermore, as efficient as this option is in design 2, the possibility of early failure (damage) of the Peltier fan is eminent due to constant operation.

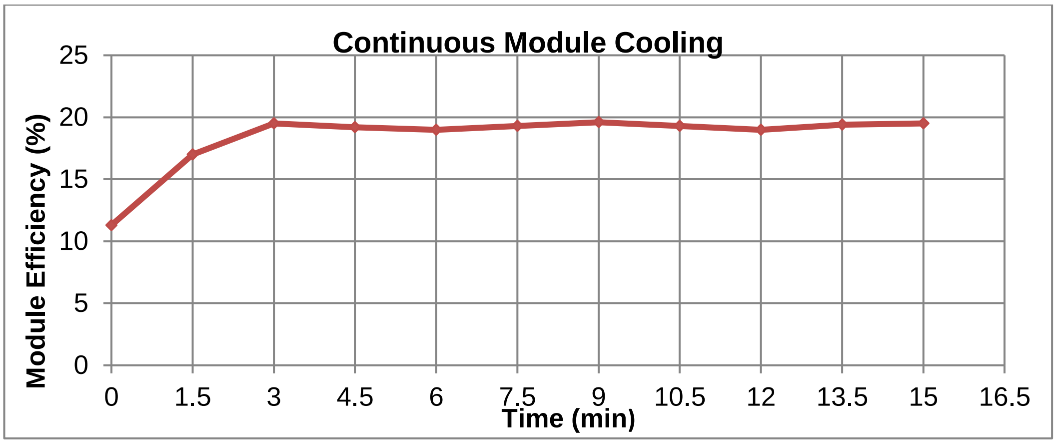

Figure 11: Continuous module cooling

Equation 1 below was used together with the predictions from ANSYS to generate the graphs above. Equation 2 may be used to calculate the thermal output of the PV/T system with known quantities of the fluid inlet and outlet. The proposed model is an efficient electrical and thermal output. Depending on the panel and ambient temperature of the environment, the thermal output may be so high such that the system integrates the thermal storage tank for domestic heating (Eastop & McConkey, 1993).

$$\eta_{module} = \frac{(PV/T)\ power\ output\ in\ kW}{A_{module}}$$

Equation 1: The electrical efficiency of the PV/T module

$$\eta_{thermal} = \frac{m \times C_p \times (t_{outlet} - t_{inlet)}}{A_{PV/T\ module}}$$

Equation 2: The thermal efficiency of the PV/T module

Where:

- η = Electrical and thermal efficiency (%)
- m = mass flow rate of air (kg/s)
- C_p = specific heat capacity of air (1.012 kJ/kgK)
- t = outlet and inlet tube temperatures (ºC)
- A = Area of the module (m^2)

5. CONCLUSIONS

The model presented has a high thermal and electrical output. It uses the Peltier effect to cool the PV panel and exhaust that heat into the absorber. Design 1 uses a timer to control the cooling fans of the Peltier connected to the PV module while design 2 uses continuous cooling without a timer. Design 2 yielded maximum desirable results as it maintained the efficiency of the module, but this was factor dependent which is to be avoided by using Design 1 as it is controlled by the timer and also yielded maximum results with small fluctuations. The initial electrical efficiency for both of these designs from the numerical analysis is approximately 11%, at time 0 second before the integration of the cooling systems. Design 1 after 15 minutes of predictive testing resulted in a range of electrical efficiency between 11.5% and 19.5% and for design 2, the range was between 11.3% and 19.5%.This emphasises the need to implement Design 1 with less implications as opposed to Design 2, as both of these designs can reach an electrical efficiency as high as 19.5%. The testing phase of the physical prototype is currently on for further validating the model designs illustrated in this paper. The prototype is currently being tested using different environmental temperature conditions across South Africa, different solar irradiation variants, and different materials. Since reliability is a major component considered in engineering design, the longevity of the two designs will be considered using a lifecycle assessment approach. As a recommendation, researchers can consider testing this system in summer and comparing the obtained results with winter conditions, which is currently beyond the scope of this research.

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