Performance Evaluation of Hybrid Photovoltaic and Thermal Solar Collector in Jordan

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ABSTRACT

Jordan has excellent potential for solar energy with 2080 kWh/m² global radiation and more than 300 sunny days a year. An integrated Hybrid Photovoltaic-Thermal (PV/T) solar collector system was constructed and operated at Mutah University in Jordan. The performance of the integrated Hybrid Photovoltaic-solar collector system was evaluated analytically and experimentally. The total sun insolation and various inlet, outlet and tank temperatures were recorded instantaneously every hour of the day for several months in 2010. The discretized temperature distribution of the integrated system and the stratification of the tank were solved numerically. The integrated system was discretized using forward finite difference. The Runge-Kutta fourth order method was used to solve the discretized nodes. Computational Fluid Dynamics (CFD) calculations were used to predict and to evaluate the inlet velocity, temperature, operating pressure of the integrated Hybrid PV/T solar collector system. Good agreement was found to exits between simulated and measured data.

Key words: Hybrid Photovoltaic-Thermal, solar collector, mathematical modeling, solar radiation, CFD, Solid Flow software, Runge-Kutta fourth order, finite difference.

Nomenclature

Letters:

A	area
C	specific heat capacity
[C]	thermal capacity matrix
D	hydraulic diameter
e	thickness
E FR	flow rate factor

F	configuration factor
G	thermal conductance
h	heat transfer coefficient
I	solar irradiance
L	length
[M]	heat exchange coefficients matrix
P	electrical power
Pr	Prandtl number
R	thermal resistance
Re	Reynolds number
T	temperature
T	temperatures vector matrix
UL	collector overall heat loss coefficient
V	wind speed

Subscripts and Superscripts:

22	f inlet fluid in the tank
a	air layer between cover and absorber
abs	absorber
amb	ambient
b	beam radiation
ba	bottom of the absorber
bg	PV module back glass cover (with adhesive)
cd	conductive thermal exchange
co	cover
co1	cover up side
co2	cover down side
cv	convective thermal exchange
d	diffuse radiation
elec	electrical
f	fluid
fg	PV module front glass cover
fk	absorber section numerous
PV	photovoltaic module
r	radiative thermal exchange
s,i	the bottom of the tank
T	overall thermal (thermal equivalent)
T	total system
ta	top of the absorber

INTRODUCTION

Photovoltaic thermal hybrid solar collectors, known as hybrid PV/T systems or PVT, are systems that convert solar radiation into thermal and electrical energy. These systems combine a photovoltaic cell, which converts electromagnetic radiation (photons) into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the PV module. Photovoltaic (PV) cells suffer from a drop in efficiency with the rise in temperature due to increased resistance. Such systems can be engineered to carry heat away from the PV cells thereby cooling the cells and thus improving their efficiency by lowering resistance [1-4].

The basic water-cooled thermal collector design uses conductive-metal piping or plates attached to the back of a PV module. A working fluid, typically water, glycol or mineral oil is then piped through these pipes. The heat from the PV cells is conducted through the metal and absorbed by the working fluid (presuming that the working fluid is cooler than the operating temperature of the cells). In closed-loop systems this heat is either exhausted (to cool it), or transferred at a heat exchanger, where it flows to its application. In open-loop systems, this heat is used, or exhausted before the fluid returns to the PV cells [4-8].

The research work and this article have been organized as follows:

— Hybrid Photovoltaic/Thermal solar collector system was constructed, operated and monitored

— Numerical simulation based on finite difference was obtained.

— Solid Flow CFX was used to simulate and record the hydrodynamic of the PV/T system.

— Experimental and simulation results were compared and evaluated

— Conclusions were drawn

DESCRIPTION OF THE SOLAR PV/T SYSTEM

Hybrid Photovoltaic/Thermal solar collector system was constructed and operated under the climate of Mutah University in Jordan.

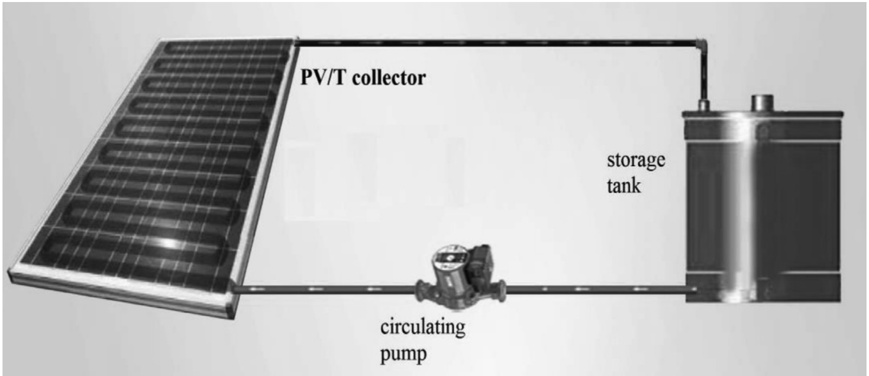

Figure 1: Integrated Hybrid Photovoltaic/Thermal -solar collector system

The systems were composed of PV / T collector, electrical source, storage tank, circulating pump as shown in Figure 1[9-12].

To maximize solar radiation gain the collector was placed at tilt angles 35 to the horizontal surface and facing South (γ=0). The flat-plate collector comprised of a glass cover of 4 mm thickness, a 12 half inch diameter longitudinal pipes 0.9 m long each welded from both ends to two horizontal header pipes, 1.25 inch diameter each. The distance between the centerlines of each two successive pipes is 100 mm. The pipes are welded on top of an absorber steel plate of area 1.2 m x 1.0 m with a thickness of 1.2 mm, and the whole of the inside was painted matt black. Rockwool insulation of 50 mm in thickness was used at the bottom and all sides. The tank is made out of galvanized steel and has a length of 0.5 m and a diameter of 0.3 m.

The total sun insolation and the inlet, outlet, ambient, and tank temperatures were recorded instantaneously every hour over the day for several months. Several instruments were used for measurement and recording: thermocouples, AVO meter, pyranometer, etc. Plots of typical recordings are shown next. Figure 2 presents the daily ambient temperature in May 2010 during 8:00 a m- 5:00 p m. Figure 3 graphs the global radiation for the same hours as in Fig. 2. Figure 4 depicts the measured inlet storage temperature by month. Figure 5 shows the measured inlet temperature, outlet temperature, and storage temperature in a typical May day. Figure 6 presents the measured mass flow rate of water in May. Figure 7 shows the instantaneous efficiency curves averaged versus time in May.

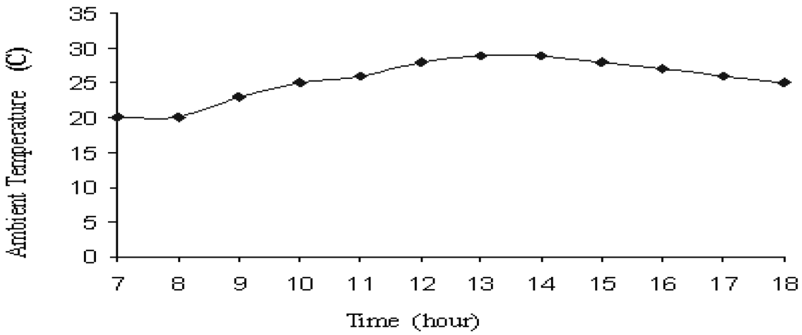

Figure 2: Ambient temperature in May 2010 (C)

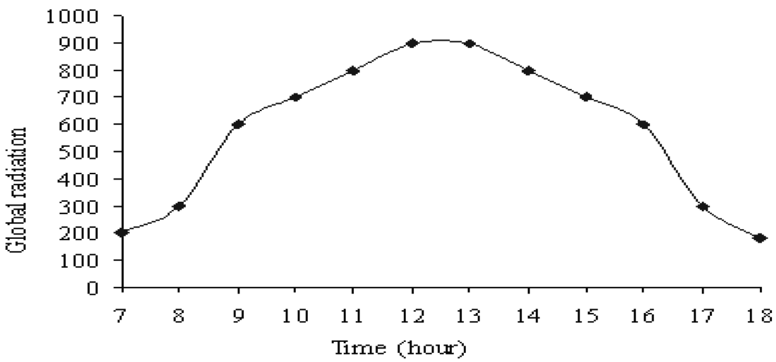

Figure 3: Global radiation in May 2010

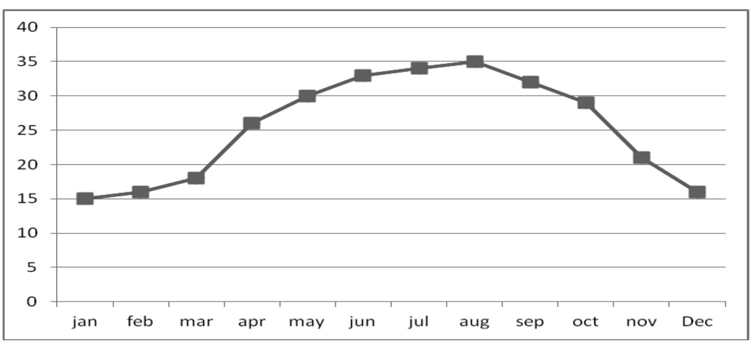

Figure 4: Input storage temperature

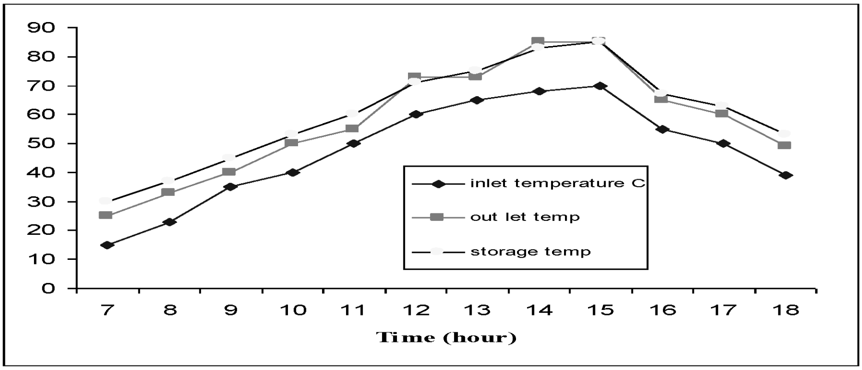

Figure 5: Variation of inlet, outlet and storage temperature in May 2010

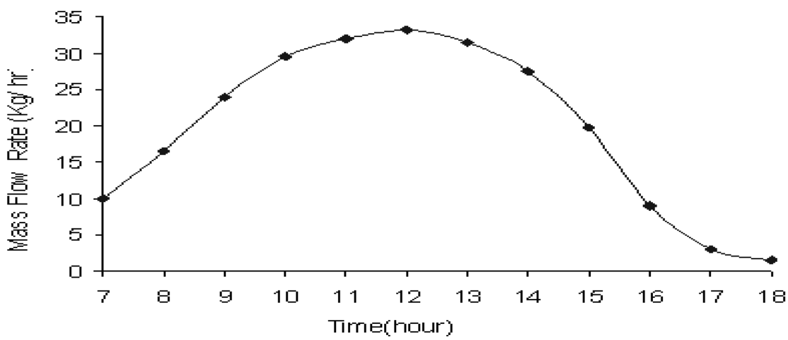

Figure 6: Mass Flow Rate (Kg/hr)

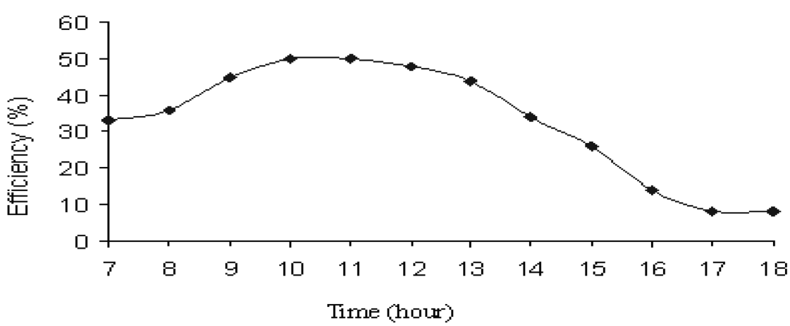

Figure 7: Collector efficiency in May 2010

MATHEMATICAL MODELING [9]

For math modeling of the thermal part of the Integrated Hybrid Photovoltaic/Thermal solar collector, the system was divided into several regions The heat energy balance of each region is written for each section for the system shown in Figure 1[13-18].

For the upper side of the glass cover:

$$\rho_{co1} A_{co1} e_{co1} C_{co1} \frac{dT_{CO1}}{dt} = G^{r}_{co1,sky}(T_{sky} - T_{co1}) + G^{r}_{co1,gro}(T_{gro} - T_{co1})$$
$$+ G^{cv}_{co1,amb}(T_{amb} - T_{co1}) + G^{cd}_{co1,co2}(T_{co1} - T_{co2}) + \phi_1 A_{co1}$$

For the lower side of the glass cover:

$$\rho_{co2} A_{co2} e_{co2} C_{co2} \frac{dT_{CO2}}{dt} = G^{r}_{co2,fg}(T_{fg} - T_{co2}) + G^{cv}_{co2,a}(T_b - T_{co2}) + G^{cd}_{co2,co1}(T_{co2} - T_{co1})$$

For the air layer:

$$\rho_a A_a e_a C_a \frac{dT_a}{dt} = G^{cv}_{co2,a}(T_{co2} - T_a) + G^{cv}_{fg,a}(T_{fg} - T_a)$$

For the front glass of the PV module:

$$\rho_{fg} A_{fg} e_{fg} C_{fg} \frac{dT_{fg}}{dt} = G^{r}_{fg,co2}(T_{co2} - T_{fg}) + G^{cv}_{fg,a}(T_a - T_{fg})$$
$$+ G^{cd}_{fg,pv}(T_{pv} - T_{fg}) + \phi_2 A_{fg}$$

For the photovoltaic cells:

$$\rho_{pv} A_{pv} e_{pv} C_{pv} \frac{dT_{pv}}{dt} = G^{cd}_{pv,bg}(T_{bg} - T_{pv}) + G^{cd}_{pv,fg}(T_{fg} - T_{pv}) + \phi_3 A_{pv}$$

For the back glass of the PV module :

$$\rho_{bg} A_{bg} e_{bg} C_{bg} \frac{dT_{bg}}{dt} = G^{cd}_{bg,ta}(T_{ta} - T_{bg}) + G^{cd}_{bg,pv}(T_{pv} - T_{bg})$$

For the half-top of the absorber:

$$\rho_{ta} A_{ta} e_{ta} C_{ta} \frac{dT_{ta}}{dt} = G^{cd}_{bg,ta}(T_{bg} - T_{ta}) + G^{cv}_{f,ta}(T_f - T_{ta}) + G^{cd}_{ba,ta}(T_{ba} - T_{ta})$$

For the fluid:

$$\rho_f A_f e_f C_f \frac{dT_f}{dt} = G^{cv}_{ta,f}(T_{ta} - T_f) + G^{cv}_{ba,f}(T_{ba} - T_f) + \phi_4 A_f$$

For the insulation:

$$\rho_{ins} A_{ins} e_{ins} C_{ins} \frac{dT_{ins}}{dt} = G^{r}_{gro,ins}(T_{gro} - T_{ins}) + G^{r}_{sky,ins}(T_{sky} - T_{ins})$$
$$+ G^{cv}_{ins,amb}(T_{amb} - T_{ins}) + G^{cd}_{ba,ins}(T_{ba} - T_{ins})$$

Finite Difference

The heat energy balance was formulated for each section of the PV/T solar collector system. The resulting ordinary differential equations were discretized and linearized basing on forward finite difference scheme. Next, the Runge–Kutta fourth order was used to solve the discretized nodes.

A computer program (using Matlab**)** was constructed to solve these ordinary differential equations with time-dependent terms to find the following parameters: Ambient temperature, Glass covers temperature, Average tank temperature, Input solar collector temperature, Output solar collector temperature, PV cell temperature. These numerical solutions have been plotted and are shown in Figures 8-13.

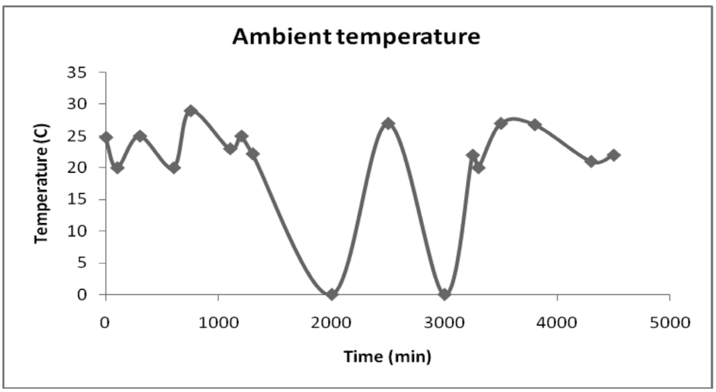

Figure 8: Ambient temperature

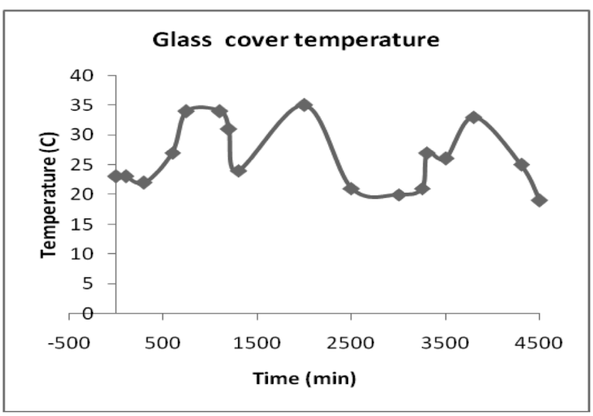

Figure 9: Glass cover temperature

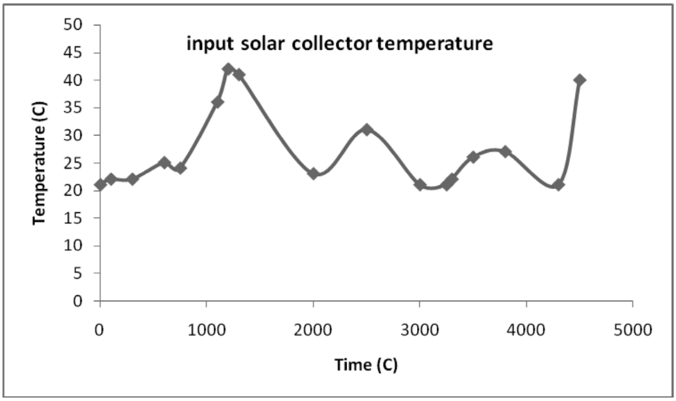

Figure 10: input solar collector temperature

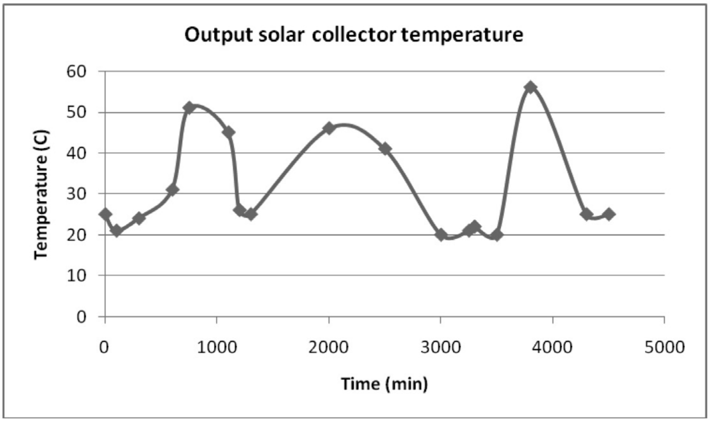

Figure 11: Output solar collector temperature

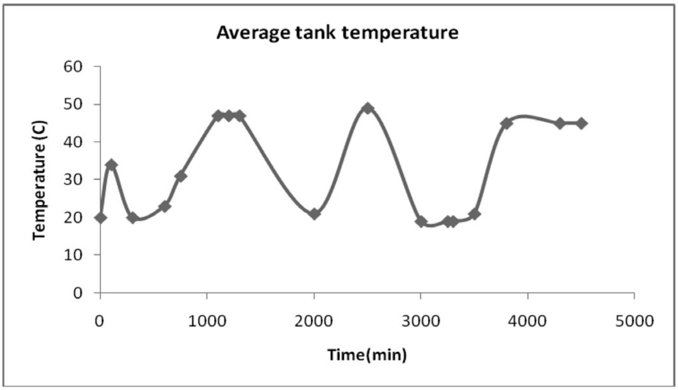

Figure 12: Average tank temperature

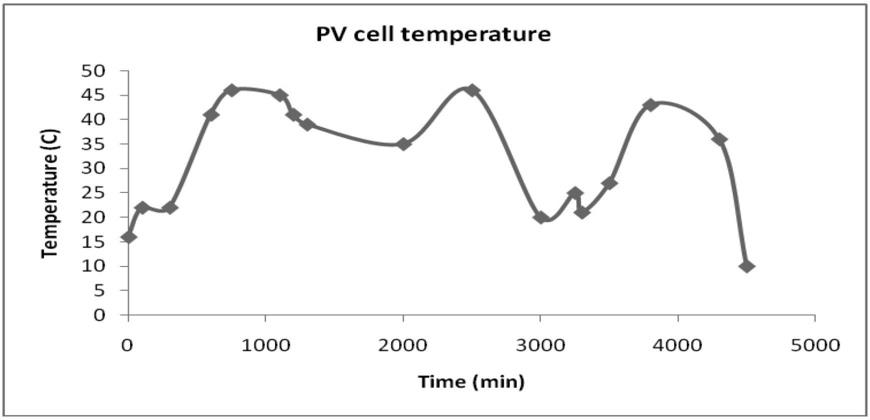

Figure 13: PV cell temperature

SOLID FLOW CFD SIMULATION

The CFX solid software was used to simulate the pressure, velocity, density, and temperature of the storage and the hybrid PV/T –solar collector. Figures 14-21 show the result of using CFX solid software.

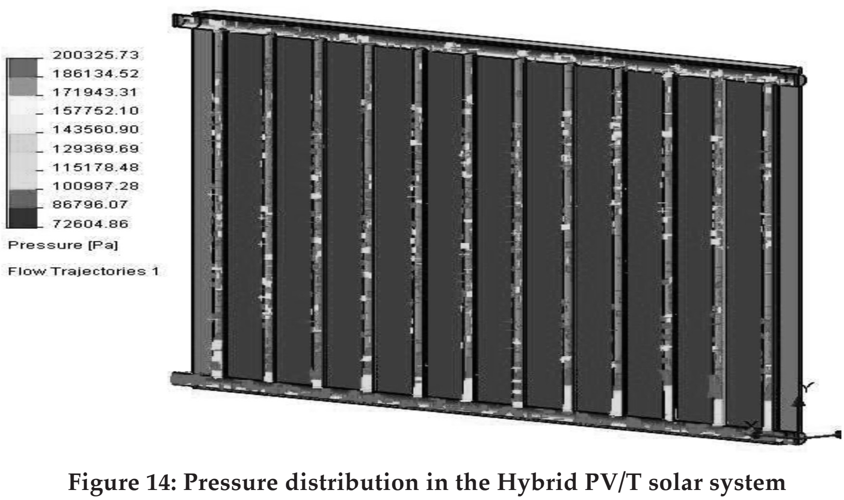

Figure 14: Pressure distribution in the Hybrid PV/T solar system

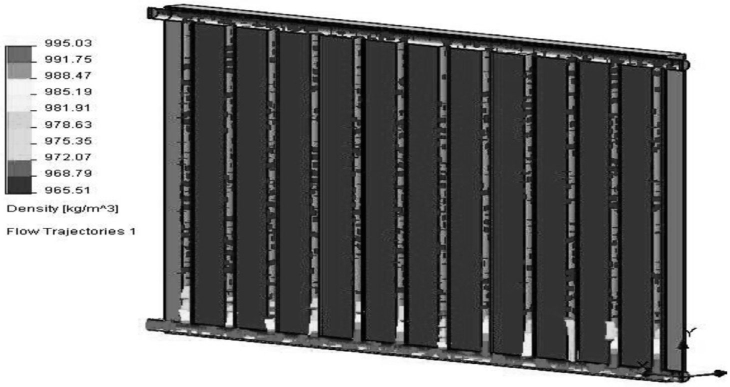

Figure 15: Density distribution in the Hybrid PV/T solar system

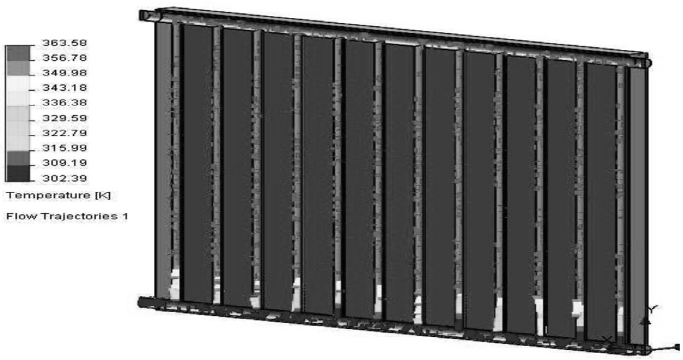

Figure 16: Temperature distribution in the Hybrid PV/T solar system

CONCLUSIONS

A Hybrid Photovoltaic/Thermal (PV/T) solar systems combine a simultaneous conversion of solar radiation in electricity and heat. We developed a nodal model for the solar-thermal part or water heating installation. The following conclusions can be drawn from the underlying work.

1. The PV/T was operated without a problem.
2. Three techniques were used to evaluate the integrated PV/T system: finite difference, finite element, and experimentally.

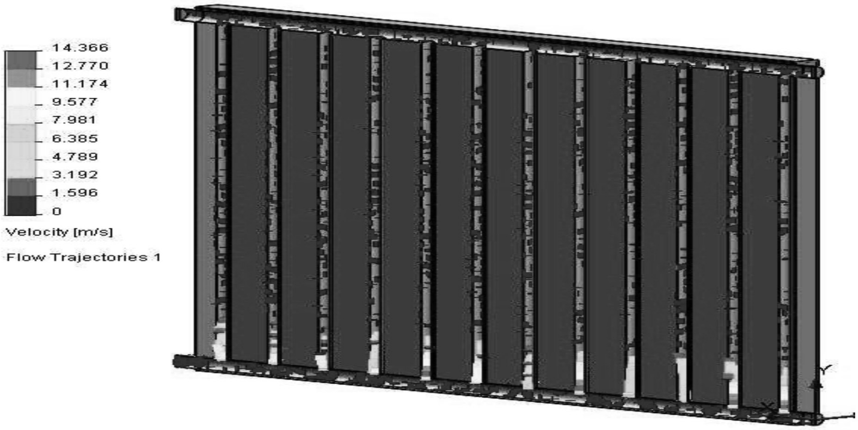

Figure 17: Velocity distribution in the Hybrid PV/T solar system

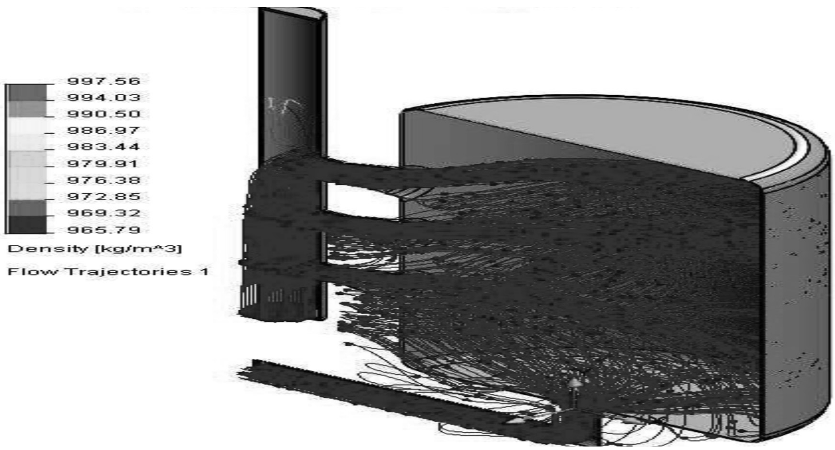

Figure 18: Density distribution in the storage tank

3. The variation of various temperatures in the thermal system (solar collector and storage) have been calculated and analyzed.
4. The weight of the integrated PV/T system was reduced to half.
5. The integrated PV/T system was easily manufactured and assembled.
6. The production cost of the integrated PV/T system was decreased.

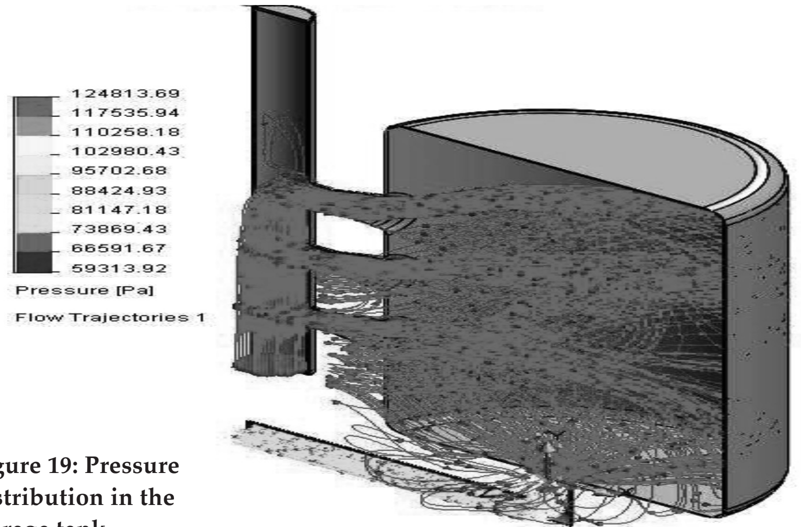

Figure 19: Pressure distribution in the storage tank

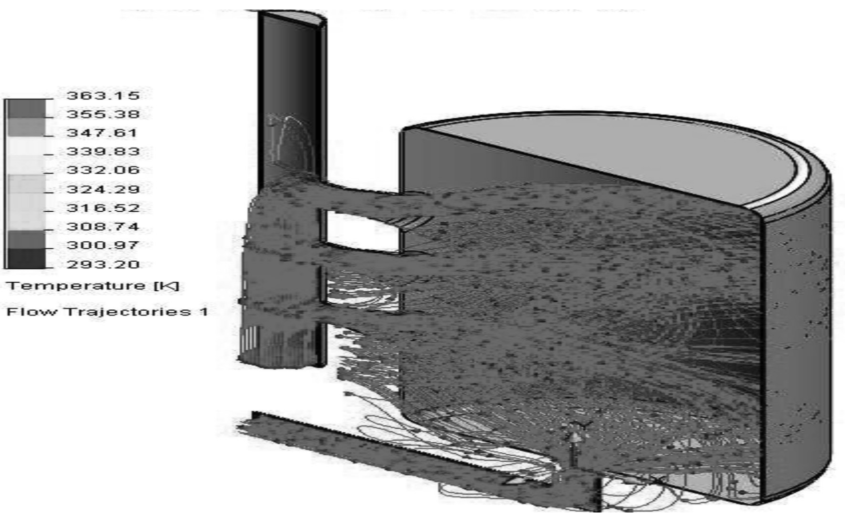

Figure 20: Temperature distribution in the storage tank

7. The PV cell temperature was reduced and stabilized (Fig. 13).

For future research: Evaluate the impact of PV cell temperature reduction and stabilization on the electrical power efficiency of the PV module.

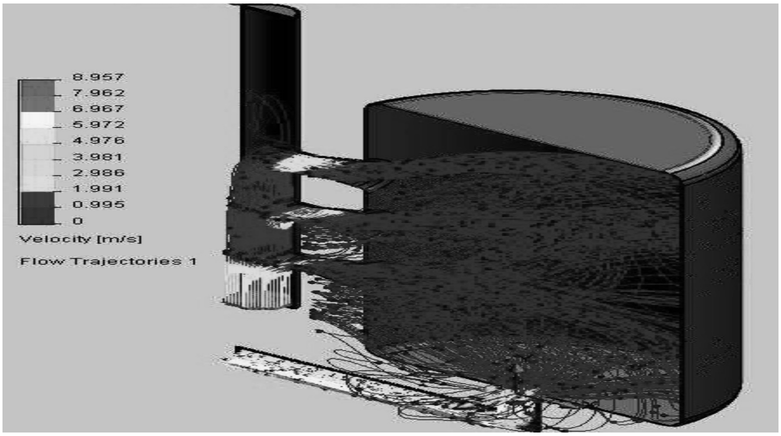

Figure 21: Velocity distribution in the storage tank

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