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Performance comparison of four passive types of photovoltaic–thermal systems

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ABSTRACT

In this paper, concept of a passive photovoltaic–thermal system (PVT) means the combination of a photovoltaic (PV) panel and an integrated collector-storage solar water heater (ICSSWH) for co-generation of heat and electricity. In this work, the four different absorber types of passive PVT systems have been simulated and compared. To compare, the aluminum with fin, the aluminum without fin, the Tedlar and the black painted glazing absorbers were selected. In the case of finned absorber, it is assumed that parallel fins have been installed longitudinally back of the absorber plate in the direction of the natural flow of the water to enhance the heat transfer rate and efficiency. Both the height (L_{fin}) and the numbers effects of fins on the collector performance have been studied. The simulation results show that the aluminum with fin absorber has the highest both the electrical and the thermal efficiencies from other absorber types. Fins reduce the cell temperature and increase the total efficiency (η_{pvt}) about 12%.

1. Introduction

Solar energy, directly or indirectly is the major source of renewable energy available to humankind. In solar engineering of thermal processes, a set of enhancement techniques is widely used to improve the performance of heat exchangers.

The mind of PVT module was produced many years ago. In 1975, Wolf [1] analyzed the performance of a combined solar photovoltaic and heating system for a single family residence over a full year. The results of that analysis clearly indicated that the operation of combination solar heating and photovoltaic system was technically feasible and was also cost-effective. Also, the value of the combined energy output was significantly greater than that of single purpose system's output alone.

The operating temperature plays a key role in the photovoltaic conversion process. The surplus incident solar radiation is changed into heat, which increases the temperature of the PV module and reduces its efficiency. Both the electrical efficiency and the power output of a PV module depend linearly on the operating temperature [2]. Recently, there has been growing interest in the PVT systems technology, which can achieve lower operating cell temperatures. Although hybrid systems are not yet a fully mature technology and their commercialization is still in its early stages [3], the majority designs of PVT systems are hybrid which may use a photovoltaic driven fluid pump to maintain a flow of fluid inside the collector [4–8]. Some hybrid systems use water as a heat transfer fluid while others use air. Many modifications have been proposed in the design of the hybrid systems including the use of finned, corrugated absorbers and multiple-pass air flow configurations [9–13].

There are many different designs of solar thermal collectors, such as tube-and-sheet, parallel plates, double flow, etc. Lower unit cost and the acceptable efficiency are two important factors for choosing a domestic solar collector [14]. The efficiencies of many solar thermal systems, such as solar water heaters, air heaters and distillation systems are in the range of about 40–60% for low and medium temperature applications [15]. The use of the storage collector, such as an ICSSWH system, allows the simplification of the current system and the use of a heat exchanger having a great heat transferring surface with a high effectiveness. It also permits the reduction of costs of installation and operation of the solar heating water system [16]. Khalifa and Jabbar [17] studied an experimental comparative performance between a storage solar domestic hot water system and conventional one that showed the superiority of the storage system. Muneer et al. [18] constructed two different designs of the ICSSWH system (plain and finned types) for Pakistani textile industry. There, three months of experimental data were collected for the two heaters types. The monetary and embodied energy payback periods for the two heaters plain and finned types were, respectively, found to be 6.7 and 6.1 years, and 185 and 169 days.

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Nomenclature

A_c	collector area as: $A_c = L \times W$, (m^2)
A_{fin}	fins area as: $A_{fin} = 2(L \times L_{fin})$, ($m^2$)
A_{ins}	lateral area of the collector insulation, (m^2)
C_f	specific heat of the water of tank, (J/(Kg K))
C_p	specific heat of the absorber plate, (J/(Kg K))
I	total solar intensity radiation on the collector, ($W/(m^2)$)
Gr	dimensionless Grashoff number
h_f	convective heat transfer coefficient between the absorber and the tank water, ($W/(m^2 K)$)
$h_{g\text{-}amb}$	convective heat transfer coefficient between the glass and ambient, ($W/(m^2 K)$)
$h_{rg\text{-}sky}$	radiation heat coefficient between cover glass and sky, ($W/(m^2 K)$)
K_{abs}	thermal conductivity of absorber surface, (W/(m K))
K_f	thermal conductivity of tank water, (W/(m K))
K_{fin}	thermal conductivity of fin material, (W/(m K))
K_g	thermal conductivity of cover glass, (W/(m K))
K_{ins}	thermal conductivity of insulation, (W/(m K))
K_{sc}	thermal conductivity of solar cell, (W/(m K))
L	collector length, (m)
L_{abs}	absorber surface thickness, (m)
L_{fin}	height of fin, (m)
L_g	cover glass thickness, (m)
L_{ins}	insulation thickness, (m)
L_{sc}	solar cell thickness, (m)
M_f	water mass inside the storage tank, (Kg)
N_{fin}	numbers of fins
Nu	dimensionless Nusselt number
Pr	dimensionless Prandtl number
t	time, (s)
T_{amb}	ambient temperature, (°C)
T_{bs}	absorber back surface temperature, (°C)
T_{sc}	solar cell temperature, (°C)
T_{sky}	sky temperature, (°C)
T_f	tank water temperature, (°C)
T_f^t	tank water temperature at time of $\tau = t$, (°C)
T_f^0	initial value of the tank water temperature at time of $\tau = 0$ (°C)
U_{loss}	heat loss through the storage tank insulation, ($W/(m^2 K)$)
$U_{tc,a}$	an overall heat transfer coefficient from solar cell to ambient through glass cover, ($W/(m^2 K)$)
U_T	an overall heat transfer coefficient from solar cell to absorber back surface, ($W/(m^2 K)$)
u_{win}	wind velocity, (m/s)
V_A	top section volume of the storage unit, (m^3)
V_B	bottom section volume of the storage unit, (m^3)
W	width of PV module, (m)
W_{fin}	fin thickness, (m)

Greek symbols

α_{sc}	solar cell absorbance
α_{abs}	absorber front surface absorbance, black oil color absorbance
$(\tau\alpha)_{eff}$	product of effective absorptivity and transmittivity
β_0	temperature coefficient of solar cell efficiency, (1/K)
β_{sc}	solar cell packing factor
θ	tilt angle of the ICSSWH system, (°)
η_0	efficiency at standard test condition ($I(t) = 1000 W/m^2$ and $T_{sc} = 25$ °C
η	fin effectiveness
η_{fin}	fin efficiency
η_{th}	temperature dependent thermal overall efficiency
η_{sc}	temperature dependent electrical overall efficiency
η_{sci}	temperature dependent electrical instantaneous efficiency of solar cell
η_{pvt}	total efficiency of PVT system
ρ_f	water density, (Kg/m^3)
τ_g	transmittance of the cover glass
ν	kinematics viscosity, (m^2/s)
σ	Stefan–Boltzman constant, ($W/(m^2 K^4)$)

The primary ICSSWH systems suffered substantial heat losses to ambient, especially at non collection times. During this time (e.g. night-time), the water circulation is reversed; and then the heat losses by conduction from the water in the tank to ambient noticeably increases. Recently, to reduce these energy losses, the improved designs of the ICSSWH systems have been introduced. One of these enhanced designs was suggested by Ziapor and Aghamiri [19].

The concept of a passive PVT system was proposed in our previous work [20]. It was a combination of a PV panel and an ICSSWH system for co-generation of heat and electricity. It did not use any photovoltaic driven water pump to maintain a flow of water inside the collector. In fact, it acted passively. From that work, the some important simulation results are as follows: (1) The high solar cell packing factor is resulted to the high solar cell temperature, the high tank water temperature, the high thermal system efficiency and the low solar cell efficiency. (2) Although, with increasing of the tank water mass, the system efficiencies increase; but reversely, the water tank temperature decreases. (3) The optimized values for tank water mass (M_f) and the collector area (A_c), can be chosen from the domestic need warm water temperature. For an example, with selection as $M_f = 120$ Kg, $A_c = 1.5\ m^2$, then the final characteristics of the present PVT system obtains as: $T_f = 45.9$ °C, $\eta_{sc} = 12.55\%$, $\eta_{th} = 36.15\%$ and $\eta_{pvt} = 48.70\%$.

The aim of this paper is to improve the mentioned above proposed passive PVT system. One of the promising applications of this PVT system is building. The energy consumption in buildings has recently increased and in some countries, it reaches almost 40% of the total energy use. The proposed PVT system can provide the needs of building to electricity, warm water, space heating and lighting. Because of the simple in structure and operation, an ICSSWH combined with PV module is cheaper than the other solar devices. In such system, no additional land area is required. In order to enhance the heat transfer rate and efficiency of this passive PVT system, parallel fins are longitudinally installed back of the absorber plate in the direction of the natural flow of the water inside the water storage section of the passive PVT system.

In order to evaluate the performance characteristics of the storage tank, there are two categories as follows [19]: (1) – The water within the tank takes the uniform temperature (i.e. fully mixed or unstratified tank model). (2) – The water tank may operate with the significant degrees of stratification, that is, with the top of the tank hotter than the bottom (i.e. stratified tank model). In this study unstratified tank model has been used [20].

2. Formulation of the finned passive PVT system

Fig. 1 schematically shows the cross section of the present finned passive PVT system. It consists of the one cover glazing, the solar cell, the absorber plate (From aluminum material with the thermal conductivity of 250 (W/(m K)) and the plate thickness