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Modeling a flat solar panel equipped with PCM for an organic ranking cycle

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Abstract

In this study, the performance of phase change materials (PCM) in solar panels and its combination with the organic Rankine cycle, has been investigated. After thermal modelling of the flat plate collector (FPC) and obtaining the amount of collector output energy, different parts of the system are comprehensively examined. Thermodynamic analysis of the solar collector (equipped with PCM) and the organic Rankine cycle is carried out using EES. The parameters affecting the system performance are also investigated, including the amount of solar radiation, the minimum evaporator temperature difference, and the relationship between exergy efficiency and the amount of surface radiative flux. The results reveal that the system performance in the presence of PCM is significantly superior compared to the case without PCM.

Keywords: Thermodynamic analysis; Solar energy; Flat plate collector; Phase change materials; Organic Rankine Cycle; Energy and exergy analysis

1. Introduction

Since environmental pollution and the shortage of fossil energy have significant impacts on daily life, the optimal use of new energy sources is important [1-2]. Given climate change and increasing demand for energy worldwide, researchers are seeking to continuously investigate and optimize tools and scenarios for exploiting alternative energy sources [3]. Also, the main concern for using solar energy is that the peak energy demand during the day, which is from evening to night, has no compatibility with the intensity of solar radiation at this time. In other words, it can be said that the need for energy increases precisely when the sun has the lowest radiation intensity [4-5].

The best solution for using a large energy source like the sun is to use systems that can store solar energy during the day to use it during the hours of the night when energy is needed [6].

This motivation led to the design of thermal energy storage systems. The operating principles of these systems are based on the latent heat of materials [7-8]. In order to understand the physics of phase change materials, it's important to consider the mathematical aspect of the melting and freezing process [9-15]. The energy storage potential of a material is determined by its latent heat [10]. Whether full energy storage potential of a material is utilized or how quickly it stores energy depends on the rate of heat transfer into and out of the PCM [11]. In order that material to undergo a phase change within a suitable temperature range, the phase change must be accompanied by a latent heat effect in order to store useful energy [12]. and be reversible over many cycles without significant degradation [13]. In this paper, the use of solar energy whit phase change materials PCM and its combination with an organic Rankine cycle has been investigated to improve the performance of solar energy at times when solar energy reaches its minimum. The system experiences two processes during a day: day and night operation. For PCM modules, there are two processes: energy storage (charging process) and energy release (discharging process). The charging process during day is based on the absorption of solar radiation and the heat transferred to the PCM layer. The charging process causes the PCM to melt and store thermal energy as latent heat. The discharging process during the night causes the PCM to solidify and release the latent heat to the pipes through conduction.

In this paper, first, the analysis and presentation of equations related to the modeling of a flat solar panel are examined, and then its combination with the organic Rankine cycle and the energy and exergy analysis of the cycle are examined. In the next step, the equations related to phase change materials are presented, and its analysis is performed in the solar panel, and the desired cycle is analyzed again with phase change materials, the results obtained in two sections are compared together. And the

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effect of phase change materials on the cycle is interpreted.

2. Problem Statement

Figure1 shows the schematic diagram of a system based on flat solar panels with phase change materials and the organic Rankine cycle.

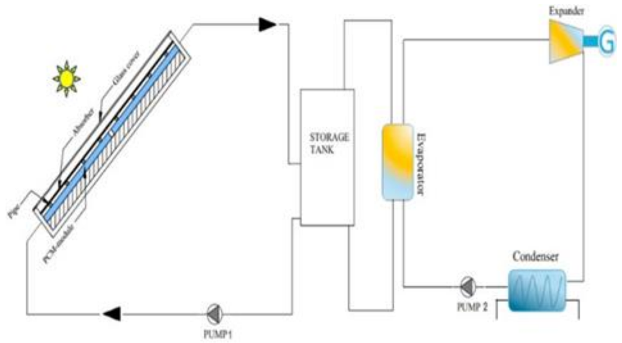

Fig 1. Overview of the cycle studied in this paper

Table 1 presents the parameters related to modeling the flat plate collector and organic Rankine cycle, as well as the phase change materials.

Table 1
Modeling parameters

Collector	
Size [m]	3×2
Plate-to-cover spacing [m]	0.025
Ambient air and sky temp [K]	298
Inlet temperature [K]	305
Pressure atm [Kpa]	101
Wind heat transfer coefficient [w/m^2-C]	30
Collector tilt [deg]	45
Insulation conductivity [W/m-C]	0.04
Back-insulation thickness [m]	0.05
Collector thickness [m]	0.075
Edge insulation thickness [m]	0.025
Tube spacing [m]	0.075
Tube diameter (inside) [m]	0.013
Heat transfer coefficient inside [W/m^2-C]	300
flow rate [kg/s]	0.04
ORC	
T_0 [C]	25
P_0 [Kpa]	100
Condenser Temperature [C]	30
eta_Pump [%]	90
eta_Turbine [%]	80
Mass Flow Rate of Heat Transfer **[**kg/s**]**	1
Mass Flow Rate ORC [kg/s]	5
Turbine Pressure [Kpa]	1300
PCM-modules	
Melting Temperature (◦C)	41-46
Density[sol] (kg/m3)	880
Density[liq] (kg/m3)	770
Specific heat capacity (j/kg-K)	2000
Latent heat (kj/kg)	160
Thermal Conductivity (W/m-K)	0.2

3. Methodology

In the steady state, the efficiency of a solar collector is described by an energy balance that represents the distribution of incident solar energy into useful energy received, thermal losses, and optical losses. The solar radiation absorbed by a collector per unit area of the absorber plate is equal to the difference between the incident solar radiation and the optical losses, which is defined by the following equation [12].

$$s = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g I (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right) \tag{1}$$

The heat energy loss from the collector to the surrounding environment through conduction, convection, and infrared radiation can be expressed as the product of the heat transfer coefficient and the difference between the average temperature of the absorber plate and the ambient temperature [26][27].

$$Q_u = A_c[S - U_L(T_{pm} - T_a)] \tag{2}$$

The loss from the upper surface per unit area is equal to the heat transfer through the absorber plate to the first coating:

$$q_{loss,top} = \square_{c,p-1c}\left(T_p - T_{1c}\right) + \frac{\sigma\left(T_p^4 - T_{1c}^4\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{1c}} - 1} \tag{3}$$

Now the energy directed to the tube area per length in the flow direction can be calculated by applying the instantaneous law to the unit fin base [27].

$$q'_{fin} = -k\delta \frac{dt}{dx}\Big| x = \frac{W-D}{2} = \frac{k\delta m}{U_L}[S - U_L(T_b - T_a)] \tanh\left(m\frac{W-D}{2}\right) \tag{4}$$

If it is assumed that all losses occur at a constant sink temperature T_a, then the overall collector loss coefficient U_L is the sum of the loss coefficients from the top, bottom, and corners.

$$U_L = U_t + U_b + U_e \tag{5}$$

For a double-coated system, the high loss coefficient from the collector plate to the environment is equal.

$$U_t = \frac{1}{R_1 + R_2 + R_3} \tag{6}$$

In this section, the equations used to determine the efficiency of the organic cycle are presented. Thermodynamic model conditions:

- The fluid used in the organic Rankine cycle is R123.
- Steady-state conditions have been investigated.
- No pressure drop in the condenser, evaporator, pipes
- The pressure is assumed to be the same throughout the cycle.
- The heat source used in the evaporator is from a solar collector under the plate.

Figure 2 shows the components of a basic ORC for converting heat into useful electrical power. As can be seen in the figure, the ORC cycle consists of four different processes:

- Process 1-2 (pump process)
- Process 2-3 (constant- pressure heat gain process)
- Process 3-4 (expansion process)
- Process 4-1 (constant-pressure heat dissipation)

For each component, the first and second laws of thermodynamics are used to find the work output, heat gain and heat rejection, and the irreversibility of the components and the system.
The equilibrium equation is as follows [27].

$$\sum_i E_i + \dot{Q} = \sum_o E_o + \dot{W} \qquad (7)$$

E_i and E_o are the input and output energy rates.

As shown Equation 8, the dimensionless Stefan number is the ratio of the specific heat to the latent heat of fusion, where ΔT is the temperature difference between the heat source and the melting point of the material.

$$St = \frac{cp\Delta T}{L_f} \qquad (8)$$

The storage capacity of a phase change material heated from T_1 to T_2, if the material undergoes a phase transformation at T*, is the sum of the change in the sensible heat of the solid (lower phase temperature) from T_1 to T*, the latent heat at T*, and the sensible heat of the liquid (higher melting or phase) from T* to T_2:

$$Q_S = m[C_s(T^* - T_1) + \lambda + C_1(T_2 - T^*)] \qquad (9)$$

m is the mass of the substance, C_S and C_1 are the heat capacities of the solid and liquid, respectively, and λ is the latent heat of phase transformation.

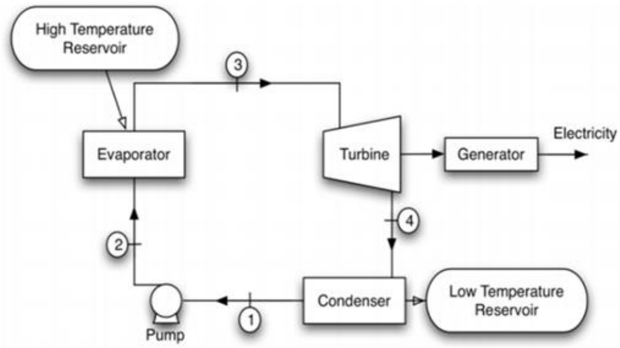

Fig 1. Schematic representation of the ORC cycle

4. Results and Discussion

In this section, the results obtained from modeling the combined FPC and ORC systems are presented, and then the results obtained from modeling the flat plate collector with phase change materials and the organic Rankine cycle and examining the effect of phase change materials on the efficiency of the system are presented.
Table 2 presents the output results of the combined FPC and ORC systems separately.
Table 3 shows the output results of the combined organic Rankine system and solar collector for different points in the cycle. It compares the effects of solar radiation on system performance, including energy and exergy efficiency, as well as the network of the system.
Figure 2 illustrates parametric study of solar radiation on system performance, in which solar radiation is changed from 400-900 W/m^2.

Table 2
Output result of the combined FPC and ORC system

Collector	
Q_U	997 W For One collector
η	23% For a collector
ORC	
Electrical_net (w)	62 kJ/s
η_{ex}	1.1
η_{El}	9.547
$\dot{W}_{turbine}$	75 kw
W_{pump}	4.55 kj/s
$\dot{W}_{net}$	70 kw

Table 3
ORC Modeling output results

State no	Fluid	Temperature T(C)	Pressur P(kpa)	Entropy s (kj/kg K)	Enthalpy h (kj/kg)	Mass flow rate, (kg/s)	Exergy
1	R123	30	109.7	1.109	231.4	5	0.3479
2	R123	30.51	1300	1.109	232.3	5	4.464
3	R123	123	1300	1. 406	336.5	5	83.1
4	R123	59	109.7	1.416	324.5	5	8.292
5	-	135.9	100	7.546	2748	1	504
6	-	99.63	100	7.359	2227	1	38.55

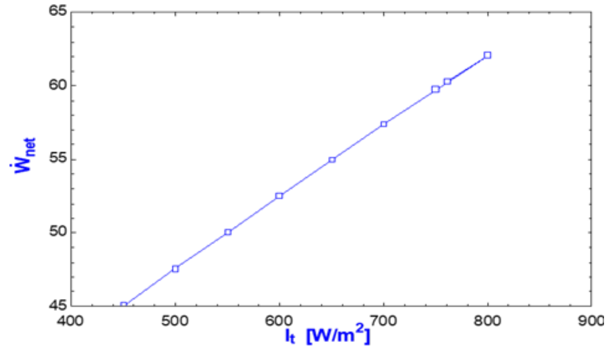

Fig 2. Diagram of the relationship between turbine work and the amount of radiation on the surface

With the increase in net output power relative to solar radiation, and as shown in Figure 2, the net output power has increased from 40 to 55. This indicates that with the increase in solar radiation, the amount of energy input to the organic Rankine cycle finds its application, which, while increasing the amount of energy input to the ORC cycle, increases the amount of turbine output work, which also increases the net output power.

Figure 3 shows that with increasing exergy efficiency, it decreases. According to the exergy efficiency equation, with increasing radiation on the surface, the amount of energy entering the organic Rankine cycle increases, and as a result, the electrical work increases. It also increases with increasing collector energy. According to the exergy efficiency equation, which is the fraction of electrical work over collector exergy, both the numerator and denominator increase, but because the increase in collector exergy is greater than the increase in electrical work, the exergy efficiency decreases.

Figure 4 shows that increasing the minimum evaporator temperature difference of the ORC cycle reduces the turbine output work.

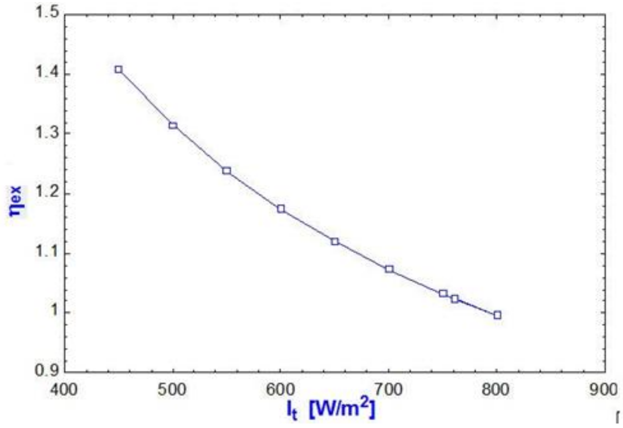

Fig 3. Relationship between turbine work and the amount of radiation on the surface

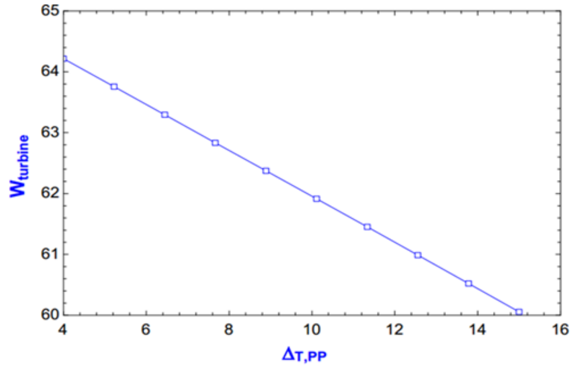

Fig 4. Relationship between turbine work and the amount of radiation on the surface

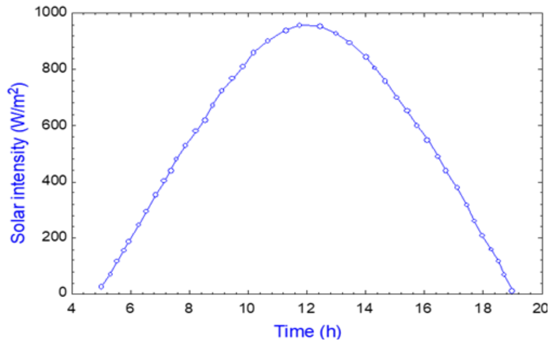

Fig 5. Hourly changes in solar radiation observed in June

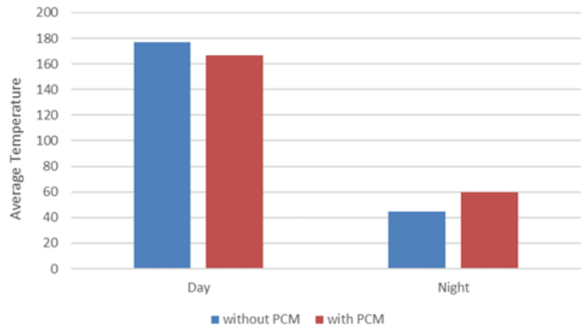

Fig 6. Average outlet water temperature for PCM on and off mode during night and day

Figure 5 shows the hourly variations of solar radiation investigated using the Perrin de Brichambaut model on a horizontal surface.

Figure 6 shows that the PCM setting causes a decrease in temperature during the day and an increase in temperature at night.

5. Conclusions

In this study, the performance of the solar collector and the organic Rankine cycle in two cases with and without PCM phase change materials have been comparatively analyzed.

According to the modeling and research conducted, the results showed that the inclusion of phase change materials creates a significant effect in the system. The useful heat of the collector with PCM produced lower amounts of energy during the day and higher amounts during the night, compared to the collector without PCM.

The results showed that the storage system stores thermal energy during the day to release it at night. In fact, the useful heat without PCM reaches zero at 6 PM in all cases, while the useful heat with PCM provides positive values and the temperature difference is more stable during the night.

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