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Performance Analysis of a Building Heating System using Underground Source Heat Pump and Photovoltaic Thermal Collector

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ABSTRACT: This study investigates the performance evaluation of a building heating system equipped to underground storage tank heat pump and photovoltaic thermal collector. The system consists of an underground spherical tank, a photovoltaic thermal collector and a heat pump. The performance evaluation of the combined system is carried out from the energy and exergy perspective. Developing energy balance for various components of the system, the analytical relations for water temperature of the auxiliary tank, solar cell temperature, absorber plate temperature and the useful heat gain of photovoltaic thermal collector are obtained. The output electrical power of photovoltaic module is calculated by the four-parameter current-voltage model. By writing the exergy balance for the various components of the system, their irreversibility is specified. The validation of the simulation results is carried. The obtained results indicate that the energy and exergy efficiency is maximum for the collector number of 65 and mass flow rate of 0.25 kg/s. The decrease in storage tank volume causes a decrease in water temperature. The increase of 30% in the collector number causes an increase of 25% in water temperature. The highest and lowest water temperature of the tank is observed on the ground of coarse graveled and granite, respectively.

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1- Introduction

A building heating system by the underground source heat pump and photovoltaic thermal collectors provides the possibility of storing solar energy in warm seasons and using it in cold seasons to supply the thermal energy needed for building heating [1]. Fig. 1 shows the schematic view of the studied system.

Many studies [1-4] have been carried out on the performance evaluation of the building heating system equipped to an underground source heat pump and solar collectors. Yumrutaş and Ünsal [1] investigated the energy analysis and modeling of the solar heating system of a building with the help of a heat pump and an underground energy storage tank. Their proposed model was used to predict the long-term performance of the system. The results of their study showed that the minimum amount of annual water temperature of storage tank is directly related to decreasing tank volume and solar collector area. In previous studies [1-4], the underground heat pump system with the help of conventional solar collectors for building heating has been studied. However, in the present research, photovoltaic thermal collectors have been used instead of conventional solar collectors to heat the building, and the performance analysis of the building heating system equipped to an underground source heat pump and photovoltaic thermal collectors is carried out. In this case, in addition to thermal energy, electricity will be produced at the same time.

2- Governing Equations

The governing equations for water temperature inside the underground storage tank include the transient radial conduction heat transfer [1].

$$\frac{\partial^2 T_w}{\partial r^2} + \frac{2}{r}\frac{\partial T_w}{\partial r} = \frac{\rho_w c_w}{k_w}\frac{\partial T_w}{\partial t} \quad (1)$$

$$T_w(0,t) = finite \quad (2)$$

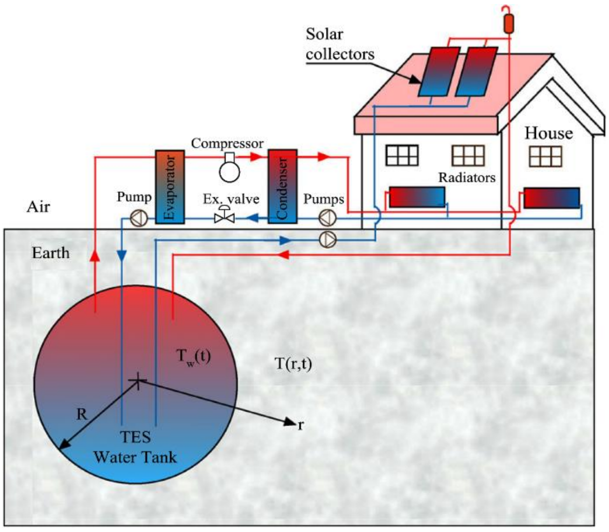

Fig. 1. Heating system by an underground source heat pump and photovoltaic thermal collectors [1]

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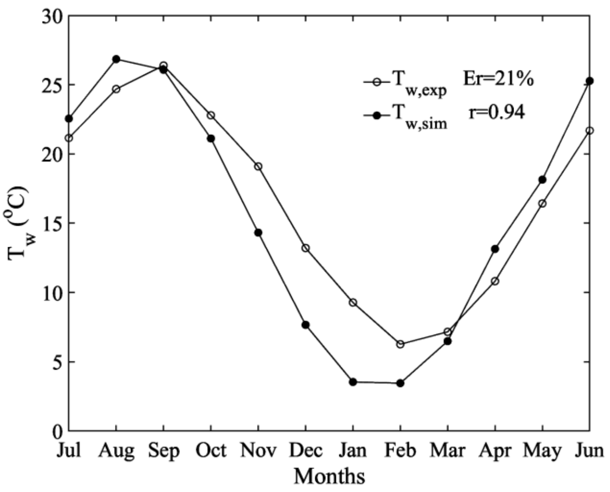

Fig. 2. Simulated and experimental values of the water temperature inside the underground storage tank

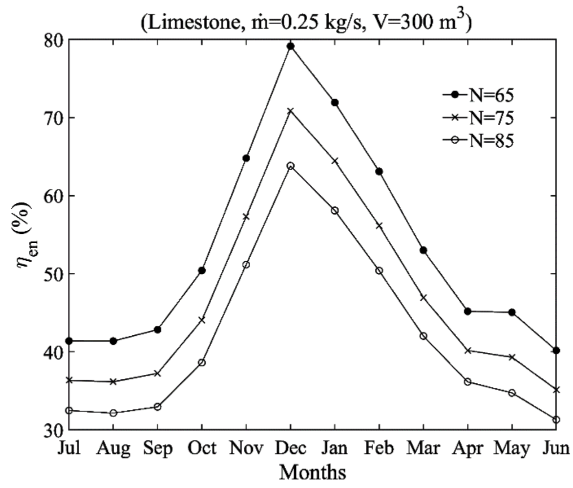

Fig. 4. Effect of changes in the number of photovoltaic thermal collectors on energy efficiency

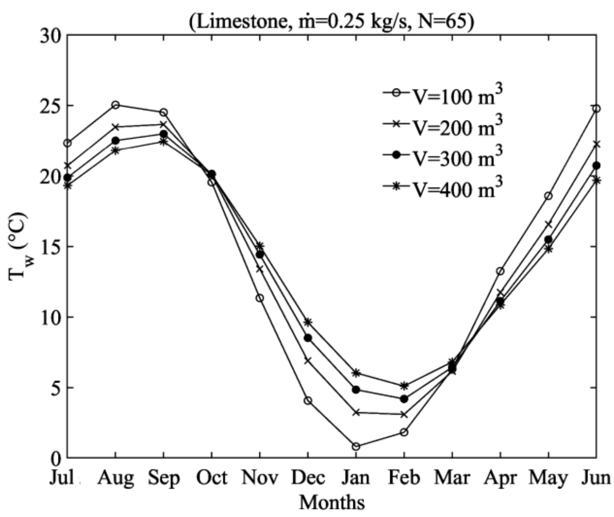

Fig. 3. Effect of changes in the volume of the water tank on the water temperature of the underground water tank

$$T_w(R,t) = T_s \tag{3}$$

$$T(r,0) = T_0 \tag{4}$$

An expression for water temperature inside the underground storage tank can be obtained after the solution of Eq. (1) by the separation of variables method as follows [1].

$$T_w(r,t) = T_s + \sum_{n=1}^{\infty}\left(\frac{2R(T_s - T_0)(-1)^n}{n\pi}\right) \times e^{-\alpha_w\left(\frac{n\pi}{R}\right)^2 t}\frac{1}{r}\sin\left(\frac{n\pi}{R}r\right) \tag{5}$$

where Ts is water temperature on the tank surface in the location of r=R. It can be obtained from the solution of the following equations set.

$$Q_{cond,e} = Q_{cond,w} + Q_u - Q_L \tag{6}$$

$$Q_{cond,e} = 4\pi k(T_s - T_\infty)/(1/R - 1/R_o) \tag{7}$$

$$Q_{cond,w} = -8\pi R k_w (T_s - T_0)\sum_{n=1}^{\infty} e^{-\alpha_w\left(\frac{n\pi}{R}\right)^2 t} \tag{8}$$

$$Q_u = F_R A_c[(\alpha\tau)_{eff} G_c - U_L(T_{f,in} - T_a)] \tag{9}$$

$$Q_L = Q_h - Q_h(T_h - T_w)/(\eta_c T_h) \tag{10}$$

The output electrical power and electrical efficiency of the photovoltaic module can be calculated by the four-parameter model of current-voltage as follows [4]:

$$I = I_L - I_O\left[\exp\left(\frac{V + IR_S}{a}\right) - 1\right] \tag{11}$$

$$\eta_{el} = V_{mp} I_{mp}/(A_c G) \tag{12}$$

The energy efficiency of the hybrid solar heating system can be defined as follows:

$$\eta_{en} = (Q_h + V_{mp} I_{mp}/C_f)/(A_c G + Q_h - Q_L) \tag{13}$$

3- Validation

The present simulation results for the water temperature of the storage tank are validated with the experimental data of Yumrutaş and Ünsal [1] (see Fig. 2).

According to Fig. 2, the simulation results of the present study for water temperature are in good agreement with experimental data of Yumrutaş and Ünsal [1].

4- Results

Fig. 3 shows the effect of changes in the volume of the water tank on the water temperature of the underground tank.

According to Fig. 3, the amplitude of the changes in water temperature decreases with the increase of water tank volume. By increasing the water tank volume, we come close to the thermodynamic meaning of the heat source, so that the temperature fluctuations of the tank water decreases with the entry and exit of the heat. Fig. 4 shows the effect of the number of photovoltaic thermal collectors on the annual energy efficiency. With the increase of 30% in collectors numbers, the energy efficiency decreases about 25%.

5- Conclusions

It is concluded from the results of the present study that the simulation results of this study are in good agreement with the experimental results of previous studies. Also, the increase in the number of collectors increases the electrical power and thermal energy. However, this increase is lower than the increase of absorbed solar energy, therefore the energy efficiency reduces.

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