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HYBRID SOLAR COLLECTOR FOR WATER AND AIR HEATING: EFFECTS OF STORAGE TANK VOLUME AND AIR CHANNEL SHAPE ON EFFICIENCY

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This paper presents a mathematical model that has been developed to study the effect of the water storage tank volume and working fluids mass flow rate on the efficiency of a Hybrid Solar Collector (HSC) system for different Romania climates. The thermal storage system consists of three separate fully mixed tanks. It means that the temperature in the tank is uniform. The simulation results show that the system performance increases about 2.1% for a 500L volume of the storage tank with constant air flow rate 0.06 kg/s compared to the system with 300L volume of storage tank. Moreover, the HSC system performance is significantly affected by the air channel shape. The efficiency of the HSC system can be improved through the use a large thermal storage system.

Keywords: hybrid solar collector, solar thermal analysis, storage tank

1. Introduction

Solar energy is an economical alternative to today's energy demand and can be utilized as a form of heat like solar water and air heating. The solar water heating system requires a heat storage tank, because it is dependent on the sun. In all case the tank needs to hold the heat when the sun doesn't shine and provide backup heat from another water heating resource.

Many studies have been conducted on the storage tank comprised in solar water collector systems. Among these, one analysis focused on the performance of solar thermosiphon water heaters with heat exchangers in storage tanks [1]. Ref. [2] presented the performance analysis of variable volume tank systems applied to the solar heating and cooling (SHC) system configuration, as a function of the climate. The results show that the SHC system configurations may be useful for all weather locations if a sufficiently high solar fraction is reached. Ref. [3] investigated the effect of the hot water storage tank volume and configuration

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on efficiency in a thermosyphon solar water heater (SWH). The conclusion was that the efficiency of SWH system can be increased by using a smaller collector area or larger hot water storage tank. Ref. [4] studied the effect of various design factors on the stratification performance of a rectangular storage tank. One of the successful and possible applications of solar energy is water heating and air heating together by solar energy, with usage in diverse areas like building air and water heating and also process heating applications, resulting in optimum usage of energy and space. The efficiency of dual purpose solar water and air heating system was studied and compared with the single purpose solar water heating system [5]. The efficiency achieved by using the dual purpose (DPS) solar heating system is about 3 to 5 % higher compared to that of a single purpose solar water system. This clearly indicates the advantage of using a dual purpose solar collector in terms of enhanced heat delivery and thermal efficiency. Therefore, in this paper a theoretical study was conducted to investigate the performance of a Hybrid Solar Collector (HSC) that is working with water and air simultaneously with the help of a numerical model.

We analyze the performance of a hybrid solar collector for water and air heating with different mass flow rates, for different shapes of the air channel and three volumes of the storage tank which is used to accumulate the thermal energy gained from the sun by the collectors. To achieve this aim, a program was developed and solved numerically in MATLAB, with weather data characteristic to the climatic conditions of Romania.

2. Thermal storage

To overcome the disadvantage of the intermittent nature of solar energy we used a thermal storage which is a very important part of any solar thermal system. Several studies had been carried out on Sensible Heat Storage (SHS) systems. Ref. [6] referred to the best operational strategies in order to get higher energy gain by using closed loop flat plate solar collector systems. The effect of multi-tank thermal storage (MTS) in a solar water system was investigated by [7]. The size of the storage tank is relevant in the solar system performance as storage volume has impact on the accumulated energy, the collector and heat exchanger efficiency [8]. In this work, in order to get the maximum amount of thermal energy supplied the storage tank, the sensible heat storage technique was adopted. Multiple configurations of the HSC system were implemented and studied, resulting in different volumes of the fully mixed storage tank (the water within the tank is at uniform temperature) and two types of air channel: without fins and with triangular fins. In this system the thermal storage consist of three separate tanks connected in parallel. The volume of the first storage tank was 300L, the second and the third storage tank each had a capacity of 100L. The tanks are connected by insulated pipes, that can be easily separated from one another by valves in order to change the size of the storage. The first law of thermodynamics applied to the water in the storage tank is:

$$M_w C_{p,w} \frac{dT_{w,s}}{dt} = Q_{in,w} - Q_{loss} - Q_{out} \tag{1}$$

where: M_w $C_{p,w}$ is the product between mass and specific heat of water in the storage tank, t is the time, $T_{w,s}$ is the water temperature in the fully mixed water storage tank, $Q_{in.,w}$ is the energy transferred from the solar collector to the storage tank, Q_{loss} is the energy loss from the storage tank and Q_{out} is the energy delivered to the load.

For simplification, heat losses from the connection pipes between the collector and storage tank were neglected. As a result, the water temperature at the solar collector inlet equals the water temperature at the exit of the fully mixed storage tank. The initial value of the water temperature in the storage tank is 30^o C and the air inlet temperature is equal to ambient air temperature. The inlet water temperature in the solar collectors is equal to the water temperature in the fully mixed water storage tank.

3. System layout

The layout of the proposed HSC system is schematically shown in Fig. 1. The studied installation is a Hybrid Solar Collector (HSC) system for water and air heating with a flat-plate solar collector and water storage tank. The main components of the thermal HSC heating system are:

1- The Hybrid solar collector.

2- Three insulated fully mixed storage, i.e. uniform temperature of the water in the tanks.

3- Pump between storage tanks and collector.

The model of hybrid solar collector mainly is inspired by [9] with some changes that will be specified in this paper. The HSC considered in this study is south facing and inclined at 30°, depending on the local latitude of the location (Timisoara, Romania). The length of collector is 1.94 m and width 0.94 m. The transparent cover is the upper part of the collector, it is made from glass. The surface of the absorber plate is equal to the full aperture area of the collector; it’s fixed below 30 mm of the glass cover. It collects the solar energy and gives the heat both to the water passing through 10 copper tubes (0.007 m diameter) welded on top of it, and to the air that flows through the channel at the bottom side. There are two shapes of air channel used in this study: air channel without fins and air channel with triangular fins. There are 10 fins arranged regularly inside the air channel. The rear and the side of the collector are insulated by a polystyrene sheet, in order to minimize heat loss. The pump connected between the Hybrid solar collector and the storage tank, operates almost continuously in clear sunny days. During cloudy or colder days, the pump often is stopped. The control on the pump is regulated by the difference between the collector temperature and the water storage tank temperature. The control activates the flow when this value is higher then 3 K; when it falls below 1 K the pump is turned off

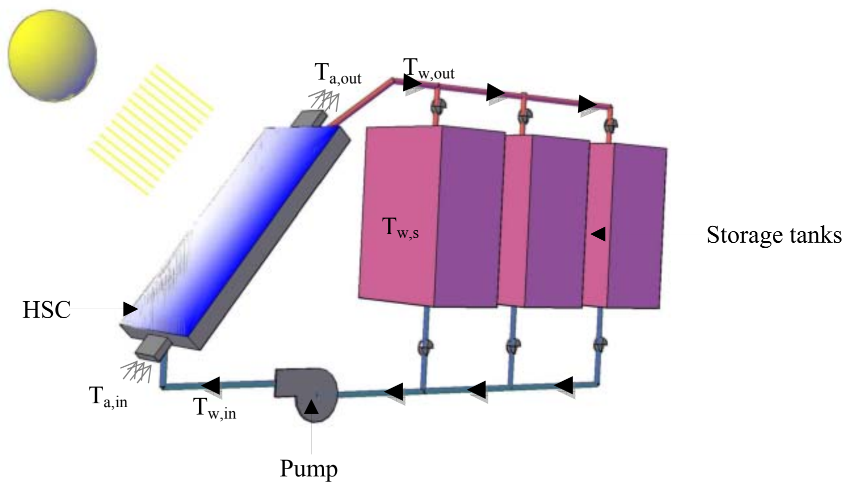

Fig.1. Forced circulation HSC system with three different storage tanks volume

With the assumption that all the losses are based on the mean plate temperature T_{pm} the overall heat loss from the collector can be represented as:

$$Q_l = U_L A_c (T_{pm} - T_{amb}) \tag{2}$$

where : Q_l is the overall heat loss from the collector [W], A_c gross collector area [m^2], T_{pm} mean plate temperature [K], T_{amb} ambient temperature [K] and U_L the collector overall heat loss coefficient, which is equal to the sum of the top U_t, back U_b and edge U_e losses [W/m^2 K]:

$$U_L = U_t + U_b + U_e \tag{3}$$

The convection heat transfer coefficients h_f between the hot fluids (water or air) and walls of water tube or air channel [W/m^2 K], were calculated from the relationship:

$$h_f = \frac{Nu_f k_f}{D_h} \tag{4}$$

where the Nusselt number for water is given by a new formula, different from the Nusselt formula that was used in [9]:

- For the water laminar flow case, the Nusselt number depends on the Prandtl and Graetz numbers [10]:

$$Nu_w = \frac{\dfrac{3.66}{\tanh[2.264 Gz_D^{-1/3} + 1.7 Gz_D^{-2/3}]} + 0.0499 Gz_D \tanh(Gz_D^{-1})}{\tanh(2.432 \Pr^{1/6} Gz_D^{-1/6})} \tag{5}$$

- For the turbulent flow of water:

$$Nu_w = 0.023 \mathrm{Re}_D^{4/5} \Pr^{0.4} \tag{6}$$

- For the air flow inside the channel without fins the Nusselt number is estimated by the equation [11]:

$$Nu_a = 0.0158 \mathrm{Re}_D^{0.8} \tag{7}$$

- For the air flow inside the channel with triangular fins the following equation was used [12]:

$$Nu_a = Nu_o + \beta \frac{b}{L_1} n, \left\{ \begin{array}{lll} Nu_o = 2.821 & \beta = 0.126 \mathrm{Re}_D & \mathrm{Re}_D < 2800 \\ Nu_o = 1.9 * 10^{-6} \mathrm{Re}_D^{1.79} & \beta = 225 & 2800 < \mathrm{Re}_D < 10^4 \\ Nu_o = 0.0302 \mathrm{Re}_D^{0.74} & \beta = 0.242 \mathrm{Re}_D^{0.74} & 10^4 < \mathrm{Re}_D < 10^5 \end{array} \right\} \tag{8}$$

The useful energy gain of a solar collector is given by [13]:

$$Q_u = A_c \left[(\tau\alpha) I_T - U_L \left(T_{pm} - T_{amb} \right) \right] \tag{9}$$

where: Q_u useful energy gain [W], I_T is the incident solar global irradiance [W/m^2] and $\tau\alpha$ is the fraction of the solar radiation accumulated by absorber plate.

The heat flux transferred from the solar collector to the storage tank is given by a common method for on-off pump control in forced-circulation solar hot-water systems:

$$Q_{in,w} = \left\{ \begin{array}{ll} \dot{m}_w C_{p,w} \left(T_{w,out} - T_{w,in} \right) & if\ Q_u > 0 \\ 0 & if\ Q_u \le 0 \end{array} \right\} \tag{10}$$

When the pump is operating, the heat flux transferred to the storage tank equals the useful heat flux provided by the solar collectors without thermal losses in the connecting pipes.

The useful heat gain for air can be expressed as a function of the air flow rate through the collector as:

$$Q_{u,a} = \dot{m}_a C_{p,a} (T_{a,out} - T_{a,in}) \tag{11}$$

where : $Q_{u,a}$ is the useful heat gain for air [W], m_a air mass flow rate [kg/s], $C_{p,a}$ specific heat of air [J/kg K] and $T_{a,out}$, $T_{a,in}$ the outlet and inlet air temperatures respectively [K].

The thermal efficiency (η) of the HSC is defined as the ratio between the useful absorbed energy by the fluids and the solar energy received by the collector surface.

$$\eta = \frac{Q_u}{A_c I_T} \tag{12}$$

4. Meteorological database

Measurements performed in the Romanian town of Timisoara (latitude 45°46′N, longitude 21°25′E and 85m altitude above mean sea level) are used in this study. The climate of Timisoara is temperate continental with an Ivanov index of continentality 130.9 % [14]. The multi-year averages of monthly minimum, mean and maximum ambient temperatures range between -5.2°C, -1.5°C and 2.7°C, respectively (in January) and 15.1°C, 21.5°C and 28.2°C (in July), respectively [15].

Air temperature and global and diffuse solar irradiance (G and G_d, respectively) is recorded on a horizontal surface at the Solar Radiation Monitoring Station of the West University of Timisoara [16]. Measurements are performed all day long at equidistant time intervals of $\Delta\tau$ =15s. DeltaOHM LP PYRA 02 first class pyranometers which fully comply with ISO 9060 standards and meet the requirements defined by the World Meteorological Organization are employed. The sensors are integrated into an acquisition data system based on National Instruments PXI Platform including a PXI-6259 data acquisition board optimized for high accuracy.

4. Results and discussions

The performance of HSC systems depends on the system design parameters as well as on weather conditions, such as solar irradiance and ambient temperature. In this case study, the weather conditions for three days with different radiative characteristics in Timisoara, Romania: a day with clear sky and higher solar radiation intensity 27 July-2009, a cold day with cloudy sky in winter 28 January-2009 and a day with partly cloudy sky 25 February-2009 were taken into account to study the effect of the incident solar global irradiance and ambient air temperature on the HSC system, as shown in Fig. 2. The figure indicates that the maximum water temperature in storage tank was obtained on the clear day at a constant mass flow rate (0.02 kg/s) and inlet water temperature at the beginning of 293 K. It also shows the temperature variation of water in the storage tank at different hours of the day. At the end of the day, the final temperature of water in the storage tank on 26 July and 25 February reached 319 and 300 K respectively. Also, it can be seen that the pump did not operate on 28 January- 2009 due to the lower incident solar global irradiance and lower ambient air temperature registered during that day.

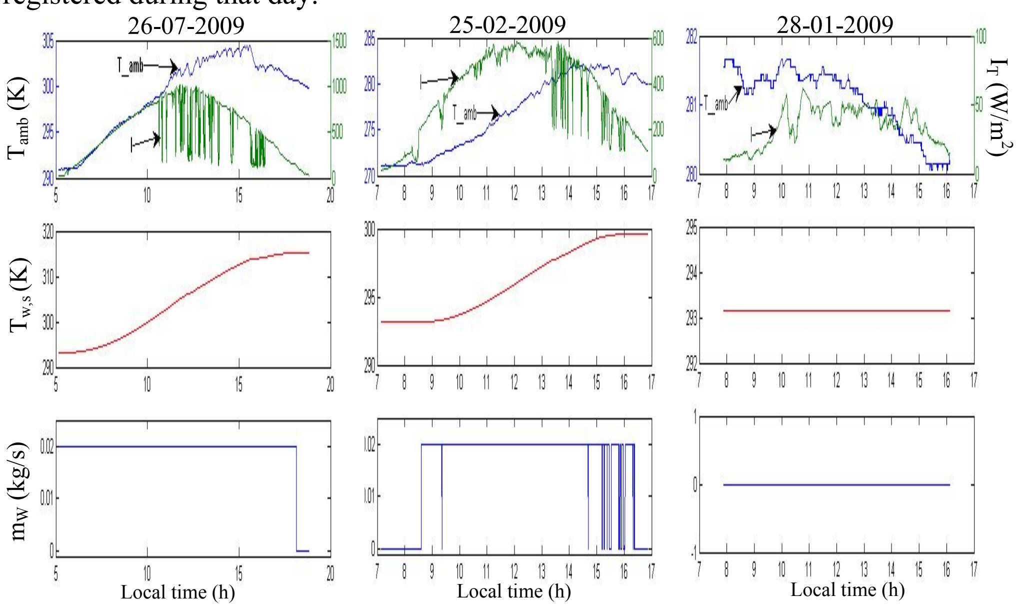

Fig.2. Effect of incident solar global irradiance and air ambient temperature in the collector loop during the day at constant water flow rate.

The total daily average efficiency (water and air) at different flow rates of the working fluids in the HSC system without fins is given in Fig. 3. The performance of the HSC system was studied on three different days: normal sunny day, cloudy day and cold day.

Three different capacities of the water storage tank were considered, namely 300,400 and 500 L. This is the order of values used in practice every day. It can be seen from this figure that the efficiency increases when the volume of storage tank increases. The maximum daily efficiency of the HSC system was obtained for the configuration with 400 L of water in the storage tank associated with 1.82 m^2 surface area of the solar energy collection system. For example, values between 0 and 0.14 kg/s were adopted in a study dealing with modeling variable mass flow rate of water and air. For almost all the mass flow rate values chosen, the highest efficiency was reached with the 400L configuration, on 26 July.

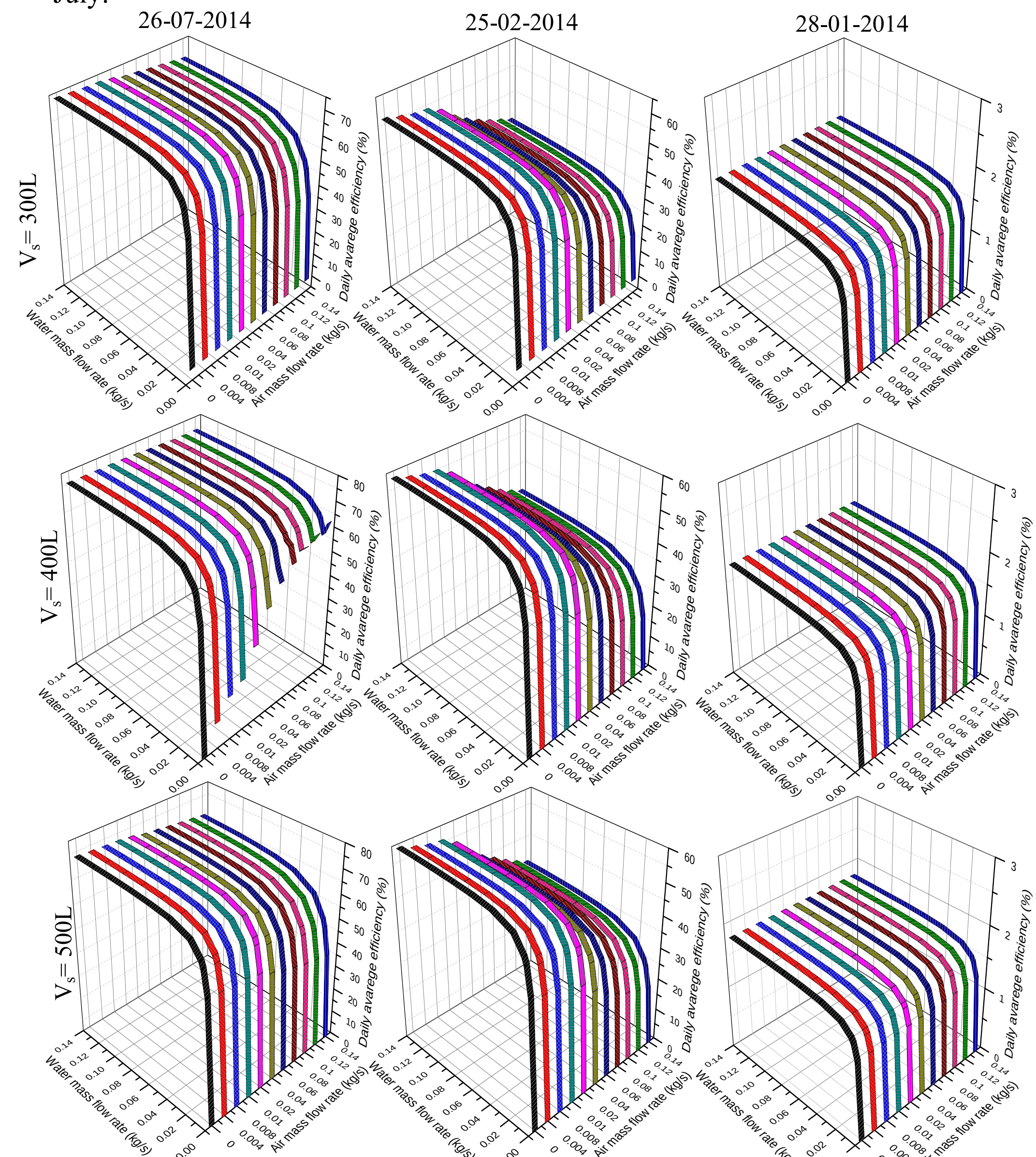

Fig. 3. Total daily efficiency at different storage tank volumes, dependence on three different days and various flow rates of the working fluids.

In Fig. 4, total daily efficiency patterns on 26 July- 2009 are shown for different mass flow rates such as; 0, 0.02, 0.04, 0.06, 0.8, 0.1, 0.12 and 0.14 kg/s of the HSC system with triangular fins and 400L hot water storage tank. The efficiency curve is irregular at a higher mass flow rate of air compared with the HSC system without fins in fig. 3 at the same days and volume of the storage tank.

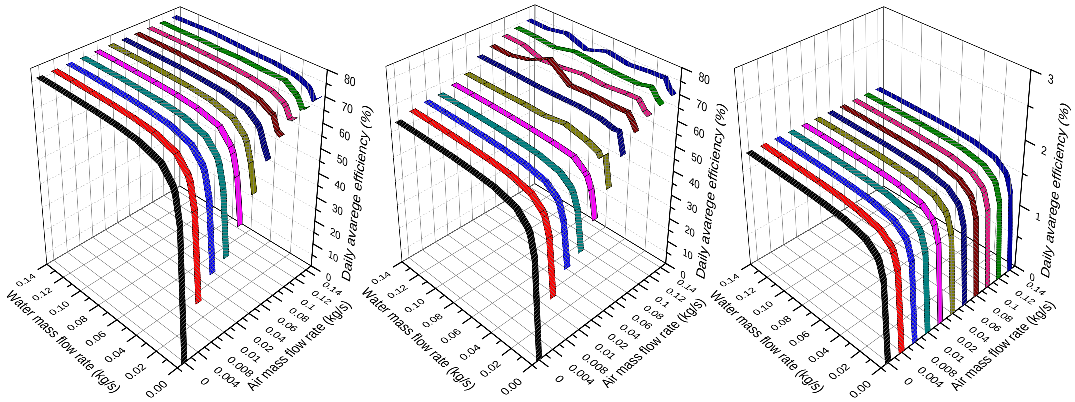

Fig. 4. Total daily efficiency of HSC system with triangular fins and 400L volume of storage tank

Fig. 5. shows the daily thermal energy that was accumulated in the full mixed 400L water storage tank for different mass flow rates of water and air. As seen in the figure, the total daily heat accumulated in the water storage tank increases while the mass flow rate increases. The maximum value obtaind was at a high water flow rate and low air flow rate, which events on the day with clear sky 26 July-2009.

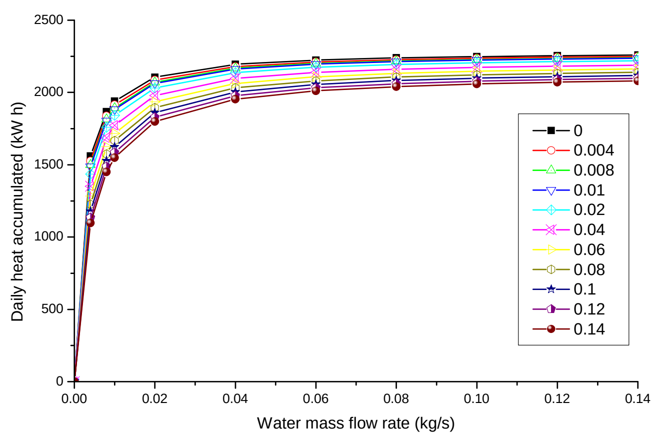

Fig. 5. Effect of water flow rate on a daily heat flux accumulated in storage tank during the day for a different air flow

Fig. 6 shows the daily accumulated heat by the HSC system with 400 L water storage tank, on 26 July, at a constant air flow rate of 0.12 kg/s. We can see a very little difference that could be detected between the accumulated heat by the HSC with fins and without fins that is caused by the fact that the process of heating the air is dependent mainly on the heat losses from the collector.

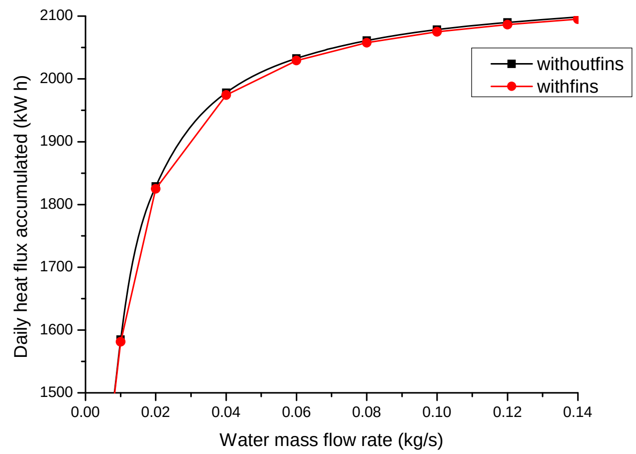

Fig. 6. Comparison of daily heat accumulated in the water storage tank on 26 July 2009

Fig. 7 shows the efficiency of the HSC system increases when the volume of the storage tank increases at constant air mass flow rate (0.06 kg/s). Also, when the storage tank volume is 500L, the efficiency of the collector becomes highest, while it becomes lowest when the storage tank volume is 300 L, according to [2, 3]. The maximum and minimum average daily efficiency obtained from the HSC were 45.8% and 43.7% for storage tank volume 500L and 300L respectively.

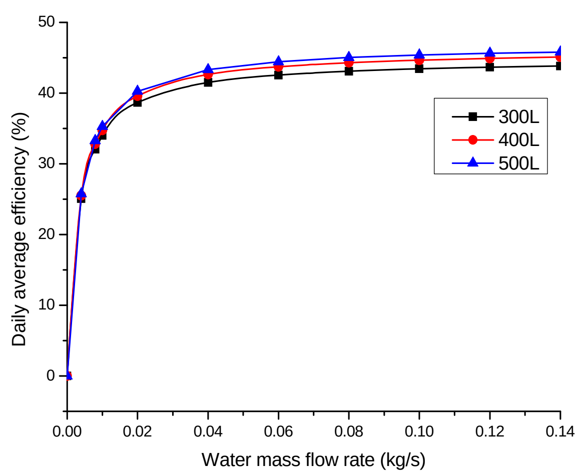

Fig.7 . Daily efficiency variation with water mass flow rate for different storage tank volumes, on 25 February 2009.

Fig. 8 shows the relation between the final value of the storage tank water temperature and tank volume at constant air mass flow rate (0.06 kg/s). According to the figure, the temperature of the storage tank decreases when the volume of the tank increases. The highest temperature of the water was in the tank at 300 L of volume tank [2].

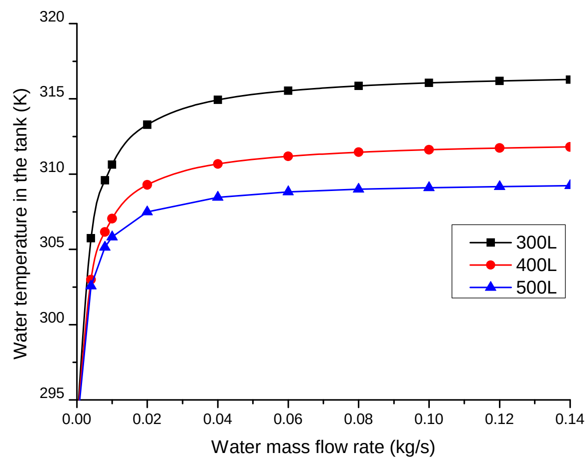

Fig. 8. Tank water temperature variation with mass flow rate for different storage tank volumes on 26 July 2009.

5. Conclusions

In this paper a hybrid solar collector system for water and air heating is investigated under different weather conditions (cloudy and clear days), for various mass flow rate values of the working fluids and three volumes of the thermal storage tank. The mathematical model was implemented and solved numerically in Matlab. The following useful conclusions can be drawn after analyzing the simulations results:

1. The HSC system can raise the water temperature inside the storage tank to 30° C on 26 July 2009.
2. The efficiency of an HSC system can be increased by increasing the volume of the water storage tank.
3. Better performance is achieved for the air channel configuration with triangular fins, compared to the one without fins.
4. Comparing the results for the three considered values of the storage tank volume (300, 400 and 500 L), it was observed that the highest efficiency is obtained for the system with a volume of 400 liters and 1.82 m^2 collector surface.

5. Thermal energy accumulated in the tank, was very small or nonexistent during the cold day compared with the warm day.
6. The HSC system permits to store the maximum of thermal energy in the storage during the day than to return it at night.

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