Energy performance analysis of a forced circulation solar water heating system equipped with a heat pipe evacuated tube collector under the Mediterranean climate conditions

Altin MARAJ*
Department of Energy, Faculty of Mechanical Engineering, Polytechnic University of Tirana, Albania, amaraj@fim.edu.al

Andonaq LONDO
Department of Energy, Faculty of Mechanical Engineering, Polytechnic University of Tirana, Albania, alondo@fim.edu.al

Alemayehu GEBREMEDHIN
Department of Manufacturing and Civil Engineering, Norwegian University of Science and Technology, Norway, alemayehu.gebremedhin@ntnu.no

Coskun FIRAT
Energy Institute, Technical University of Istanbul, Turkey, coskun.firat@itu.edu.tr

ABSTRACT

This work represents the energy performance analysis during the annual time period of a forced circulation solar water heating system equipped with a heat pipe evacuated tube collector under the Mediterranean climate conditions. For the purpose, recorded data from a field-trial installation are exploited. The recorded data obtained every min are used to perform the energy analysis during an annual period. The analysis is performed by using mathematical models and by representing the results for each month. Monthly values of useful heat gain from the solar collector, useful heat gain from the storage tank, collector efficiency, system efficiency, and solar fraction offered a clear view regarding the operation of a forced circulation solar water heating system for this climate region. Also, the annual energy balance of the system obtained from the calculation is built.

KEYWORDS

forced circulation, heat pipe, useful energy gain, collector efficiency, system efficiency, solar fraction

1. INTRODUCTION

The usage of solar energy for thermal purposes varies greatly from a region to another. There are huge differences regarding the type of the system, solar collector, and application. For these reasons the energy evaluation of solar water heating systems and solar collectors under different climate conditions is very important. The same configured and designed system equipped with the same solar collector represents different energy performances in different climate regions.

* Corresponding author

Around 74 % of solar thermal systems installed in Europe by the end of 2016 were for domestic hot water usage. Leaning on the system type, it was noticed that the share of forced circulation systems in Europe was 61 %. These systems are more common in Central and North Europe. Referring to the total water collector area in Europe, evacuated tube collectors (ETC) accounted for 13.7 % of the total capacity in operation by the end of 2016. While, for Albania their share was 1.33 %, or $A_{ETC} = 2{,}760$ m^2 [1].
The Evacuated Tube Solar Collector (ETSC) consists of several evacuated tubes. Inside each evacuated tube, a vacuum is created between the absorber and the transparent glass cover. The absorber is connected to a heat pipe. Heat pipes are used to transfer heat by using the phase change of the fluid inside the pipe. It consists of a perfectly insulated (to minimize losses from the fluid to the outside) circular pipe with an annular wick layer. Solar radiation incident at the evaporator end boils the fluid inside the pipe. The vapour migrates to the condensing end, and transfers the heat of vaporization to the fluid loop at the condensing end. The heat created by the fluid loop is used at the end-use point. After thermal energy is released into the heat transfer fluid, the vapour is condensed and is returned to the evaporator end by capillary action through the wicks or by gravitational force [2].
In the field of solar thermal applications, the knowledge about the thermal performance of different solar collectors and solar water heating systems are very important.
The solar collectors are considered a particular kind of heat exchanger, which converts the solar radiant energy into heat. Many researchers have put efforts in evaluating, analysing, and improving the efficiency of different solar collectors utilized in solar thermal applications.
Gill *et al.* studied a heat pipe evacuated tube collector installed in an active system under Northern Maritime climate conditions. The annual efficiency of the considered collector was 0.82. Also, efficiency values were higher in winter months [3].
Ayompe *et al.* compared the performance between a flat plate collector and a heat pipe evacuated tube collector under temperate climate conditions. The annual average collector efficiency was 0.461 and 0.607 for the flat plate collector and the evacuated tube collector, respectively [4].
Sakrieh and Al-Ghandoor investigated the performance of five types of solar collectors experimentally under the climate conditions of Al-Zarqa, Jordan. The average efficiency achieved for the evacuated tube collector was 0.76, while for the flat plate was lower [5].
Hayek *et al.* investigated the overall performance of solar collectors experimentally under weather conditions of the Eastern Mediterranean Sea. They concluded that collector efficiency for heat pipe evacuated tube collectors was (15-20) % higher compared to the water-in-glass evacuated tube ones [6].
Hassanien *et al.* investigated the performance and the viability of using an evacuated tube solar collector to assist a heat pump for greenhouse heating in Kunming, China. The annual thermal efficiency of the collector was 0.49 [7].
Sabiha *et al.* enhanced the performance of a heat pipe evacuated tube collector by using single walled carbon nanotubes nanofluids under climate conditions of Kuala Lumpur, Malaysia. In the case of water as heat transfer fluid the highest efficiency was 0.5437, while for the new fluid it was 0.9343 for the same flow rate of 0.025 kg/s [8].
Depending on whether they require circulation pumps or not to run, solar water heating systems can be grouped into two basic categories: passive circulation systems and active circulation systems (forced circulated systems). The second systems eliminate the restrictions regarding the placement of the collector towards the storage tank. In this system type, a pump is used to circulate the heat transfer fluid through the closed collector loop to a heat exchanger [9].
Many researchers have studied the solar water systems of different types and equipped with different solar collectors.

Ayompe and Duffy analysed the energy performance of a forced circulation solar water heating system with a heat pipe evacuated tube collector situated in a temperate climate (Dublin, Ireland). The annual average daily collector efficiency was 0.63, while the system efficiency was 0.52 [10].
Hazami *et al.* validated the TRNSYS model of a forced circulation solar water heating system equipped with a heat pipe evacuated tube collector in a region with typical North-African climate conditions (Borj Cedria, Tunisia). The study highlighted that the annual system efficiency was 0.76 [11].
Mazarron *et al.* analysed the effect of tank water temperature on the delivered energy for an active solar water heating system with evacuated tube collector. When the required temperature was 50 °C, the annual system efficiency was 0.64 [12].
Chow *et al.* carried out experimental and numerical evaluation of thermosiphon systems with single-phase and two-phase solar collector. It was noticed that the annual thermal performance of the two-phase solar collector was higher [13].
Redpath investigated the performance of two configurations for thermosiphon heat pipe evacuated tube solar water heaters for the northern maritime climate. The study revealed that the efficiency for the system with internal heat pipe condenser was 0.63, while for the other configuration with external heat pipe condenser was 0.475 [14].
Daghigh and Shafieian evaluated theoretically and experimentally the performance of a solar water heating system with evacuated tube heat pipe collector. They presented the effect of several factors on the thermal performance for the studied solar collector [15].
Kaligorou presented optical, thermal and thermodynamic analysis of collectors. Also, a description of methods used to evaluate the collector performance was offered [16].
For the selected region there is a gap regarding papers related to forced circulation solar water heating systems equipped with evacuated tube collectors. A forced circulation solar water heating system equipped with two flat-plate collectors connected in parallel with a total absorber area of 4.41 m^2 placed side by side with the studied system was evaluated by Maraj et al. [17]. The results showed that during the same time period, the annual averaged value of collector efficiency and system efficiency were respectively 0.494 and 0.411.
In general, the research work was focused mainly on the performance of different solar collectors under different operation and climate conditions. Several studies were performed on thermosiphon and forced circulation systems installed in locations with climate conditions (Northern Maritime, North Africa, Eastern Mediterranean, etc.) different from the Mediterranean climate. Also, the length of measurement period is very important to perform the energy analysis and evaluation of a solar water heating system. The considered long-term system performance was based on a 12-months period.
In this study, the energy performance analysis and evaluation of a forced circulation solar water heating system equipped with a 1.476 m^2 heat pipe evacuated tube collector was performed for the Mediterranean climate conditions. Their analysis and evaluation were based on parameters obtained from measurements and quantities calculated through the mathematical model. The studied trial system is a single family one and its collector is with heat pipe evacuated tubes. It was above mention that this collector type is very rare in the selected region, because of the massive diffusion of flat-plate solar collectors. Consequently, this study provides detailed information regarding the annual and monthly values of the useful gain from the solar collector, collector efficiency, useful energy delivered by the solar circuit to the storage tank, delivered energy to the thermal consumer, system efficiency, solar fraction, losses, etc.

2. EXPERIMENTAL SETUP

Figure 1 shows the external and the internal part of the studied Solar Water Heating (SWH) system, which is installed in the premises of the Department of Energy, Faculty of Mechanical Engineering, Polytechnic University of Tirana – Albania. Tirana is the capital of Albania and is situated in the central part of the country. The average altitude of the city is 110 m above the sea level and the geographical coordinates are 41.33 °N and 19.82 °E. The selected town has a typical Mediterranean climate and it falls at "Cs" group according to Köppen climate classification. It is characterized as hot and dry summers and mild and rainy winters [18]. Average annual sunshine hours is $\bar{n}_v = 2500$ h/year [19].

Figure 1. View of the external and the internal part of the solar water heating system

The SWH system utilized in this study is with forced circulation. Its main components include the solar collector, pipes, storage tank, circulation pump, controls, etc.

The system was equipped with a heat pipe evacuated tube collector. The collector slope was 45° and the surface azimuthal angle was -10°. Figure 1 also shows the view of the AS 100 HP8 collector produced by Augusta Solar GmbH. The solar collector consists of a row with 8 heat pipe evacuated tubes. Each of the heat pipe tubes are connected to the heating circuit through a dry coupler. At Table 1 the main technical specifications of the utilized solar collector are shown [20].

Table 1. Main technical specifications of the utilized solar thermal collector

	Evacuated tube collector
Gross area (m^2)	2.1
Aperture area (m^2)	1.476
Zero-loss efficiency (-)	0.735
First-order coefficient ($W/(m^2 \cdot K)$)	1.16
Second-order coefficient ($W/(m^2 \cdot K^2)$)	0.0053

The storage tank has a volume of 0.160 m^3 and is located in the laboratory. It is insulated by rigid polyurethane mould injected with a thickness of 0.045 m. It has an internal spiral tube and no any immersed heater is placed within it.

The solar circuit consists of copper pipes coated with external industrial insulation of crosslinked polyethylene (PE-X) foam, structured in closed type microcells. Also, they have an ultraviolet resistant protective film. The diameter of the copper pipes is 18 mm. The pipe length from the collector to the store is 12.5 m and vice versa is 13.5 m. An aqueous solution of higher boiling glycol (Antifrogen SOL HT) is used as the heat transfer fluid. It has a high saturation temperature and low freezing temperature. This mixture prevents problems like freezing of the heat transfer fluid in low temperatures and the corrosion in system components [21].

The circulation of the heat transfer fluid is achieved by Resol FlowCon B pump station. The solar pump, turns on when the appointed temperature difference is 5°C. Also, it turns off when the temperature difference is 3°C. The temperature difference is monitored through the system controller Resol DeltaSol MX.

The studied solar water heating system layout, the main components, and the sensor placement are shown in Figure 2. The measurement of heat transfer fluid temperatures is achieved by using the thermocouples $t_{c,i}$, $t_{c,o}$, $t_{s,i}$, and $t_{s,o}$. While, the domestic water temperatures are obtained by using the thermocouples t_{supply}, t_{del}, and $t_{m,h}$. The flow rates for the heat transfer fluid and domestic water are provided by using two Resol V40-6 flowmeters signed by FRS in the layout. The ambient air temperature near the solar collector was achieved by using the thermocouple ATS, which is a Resol FAP30.

The measurement of global solar irradiance on the tilted solar collector area is realised using the sensor SRS, which is a Resol CS10 solar cell [22].

The collected data during the daily operation are transferred from the controller to the DL2 Datalogger and later to a personal computer (PC). Later, they are elaborated by the help of appropriate software.

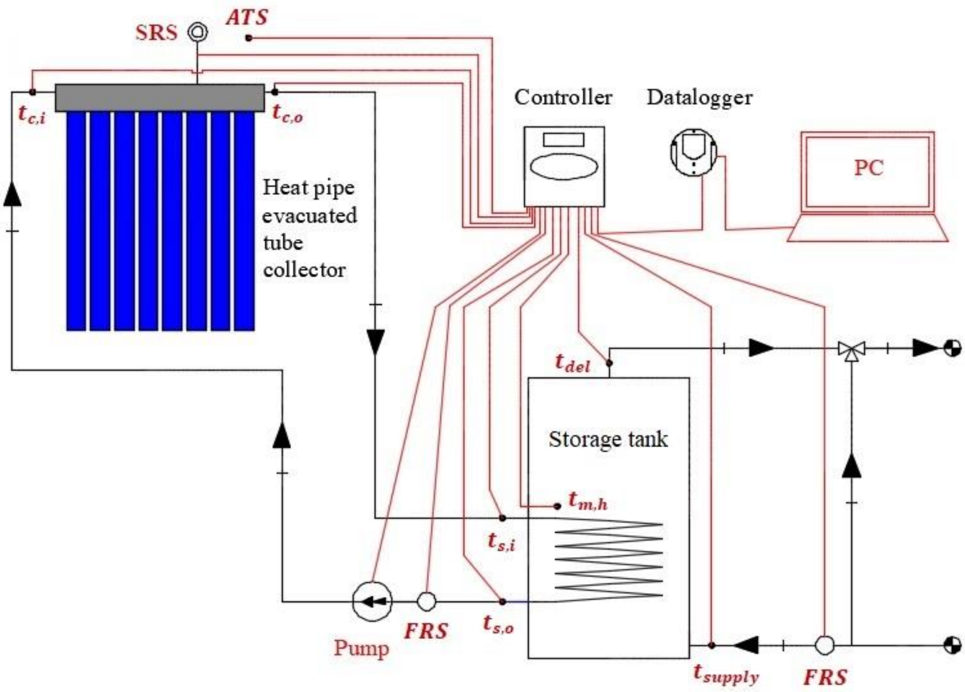

Figure 2. Main components and utilized sensors in the solar water heating system

3. ENERGY PERFORMANCE ANALYSIS

SWH system refers to the complete arrangement of many components that together collect, store, and deliver useful heat to the thermal consumer. It includes the solar collector, pipes, storage tank, circulation pump, controls, etc. Each component has its effect on the energy performance of the SWH system.

The performance and energy evaluation of the considered system are performed leaning on the following mathematical model.

The required rate of addition of sensible heat is given as [23]:

$$\dot{L} = \dot{m}_w \cdot c_{pw} \cdot \left(T_{set} - T_{supply}\right) \tag{1}$$

The rate of delivered energy to the thermal consumer can be written as:

$$\dot{L}_S = \dot{m}_w \cdot c_{pw} \cdot \left(T_{del} - T_{supply}\right) \tag{2}$$

The rate of useful gain from the solar collector is defined as [23]:

$$\dot{Q}_u = \dot{m}_p \cdot c_{ph} \cdot \left(T_{c,o} - T_{c,i}\right) \tag{3}$$

The rate of useful energy delivered by the solar circuit to the storage tank can be written as:

$$\dot{Q}_{sc} = \dot{m}_p \cdot c_{ph} \cdot \left(T_{s,i} - T_{s,o}\right) \tag{4}$$

This way, the instantaneous collector efficiency is given as [23]:

$$\eta_{coll} = \frac{\dot{Q}_u}{A_c \cdot G_t} \tag{5}$$

The instantaneous system efficiency of solar energy conversion to useful thermal energy at the storage tank outlet is obtained as [24]:

$$\eta_{sys} = \frac{\dot{L}_S}{A_c \cdot G_t} \tag{6}$$

The trial solar water heating system is a small one. For this reason, the solar fraction is a useful concept for its evaluation. For month *i* the fractional reduction of purchased energy when a solar energy system is used, called the solar fraction, is given by the ratio [23]:

$$f_i = \frac{L_{S,i}}{L_i} \tag{7}$$

The same concept applied on an annual basis, with quantities integrated over the year [23]:

$$F = \frac{\sum_{i=1}^{12} f_i \cdot L_i}{\sum_{i=1}^{12} L_i} \tag{8}$$

The losses in the solar collector, solar circuit pipes, and storage tank were defined indirectly by the following expressions:

$$\dot{Q}_{loss}^{coll} = \dot{E}_{sun} - \dot{Q}_u \tag{9}$$

$$\dot{Q}_{loss}^{pipe} = \dot{Q}_u - \dot{Q}_{sc} \tag{10}$$

$$\dot{Q}_{loss}^{st} = \dot{Q}_{sc} - \dot{L}_S \tag{11}$$

4. RESULTS AND DISCUSSIONS

In this study, the annual energy evaluation and analysis of a forced circulation SWH system equipped with a heat pipe evacuated tube collector installed in a region with typical Mediterranean climate conditions belonging to the “Cs” group were performed.

For this purpose, the database of measured parameters of the considered SWH system for a 12-months period was utilized. Their description is performed leaning on their placement in the subsystems of collection, circulation, and storage.

The environmental parameters included were the tilted global solar irradiance, ambient air temperature near the solar collector, ambient air temperature near the storage tank. Referring to the heat transfer fluid circuit the measured parameters included were the volume flow rate, the inlet and outlet temperature from the solar collector and the storage tank. Measured parameters regarding the domestic water included were the volume flow rate, the temperatures in the middle height of the storage tank, supply cold water, and delivered water to the thermal consumer.

The energy evaluation and performance analysis were carried out based on the mathematical model which refers to the solar collector and the SWH system. Finally, the annual energy balance was built accordingly.

The monthly values of irradiation on solar collector plane are given in Figure 3. For the selected region, the values of this parameter during the summer period were higher when compared to those in the winter period. The magnitude of insolation values depends mainly from the latitude, season and local climatic conditions. The minimum value of irradiation on solar collector plane for the considered period was recorded in the month of December ($H_T^{min} = 105$ kWh/month), while the maximum in July ($H_T^{max} = 274.1$ kWh/month). The annual irradiation on solar collector plane for the considered time period was $H_T^{year} = 2{,}212$ kWh/year.

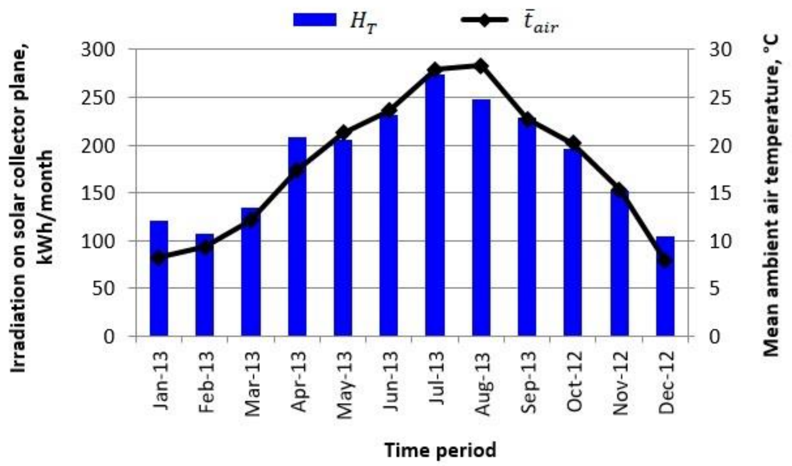

Figure 3. Monthly values of irradiation on solar collector plane and ambient air temperature

Also, the mean monthly values of ambient air temperature near the studied solar collector are shown at Figure 3. Referring to the curve of ambient air temperature, there is an increase of its values during the summer months. This was attributed to the fact that during these months the insolation was higher. Ambient air temperature varied in the interval between $\bar{t}_{air} = (7.9 - 28.3)$ °C, where the minimum value refers to the month of December and the maximum to that of July. Averaged annual ambient air temperature for the considered period was $\bar{t}_{air} = 17.9$ °C.

Figure 4 shows monthly values of the required energy $(\dot{L})$, the delivered energy to the thermal consumer $(\dot{L}_s)$, the useful heat gain from the solar collector $(\dot{Q}_u)$, and the useful energy delivered by the solar circuit to the storage tank $(\dot{Q}_{sc})$. heir values were obtained by the expressions 1, 2, 3, and 4 respectively.

From the graph of useful heat gain from the solar collector it was noticed that this quantity was higher in the months with higher values of insolation. It varied between 62.5 kWh/month in December till 168.3 kWh/month in July. The annual useful heat gain from the heat pipe evacuated tube solar collector was 1,345 kWh/year.

Also, even the useful energy delivered by the solar circuit to the storage tank showed the same tendency. Because of the presence of thermal losses in the insulated copper pipes of the primary circuit its values were slightly lower. The minimum and the maximum value occurred in December (60.3 kWh/month) and in July (164.7 kWh/month), respectively. The annual useful energy delivered by the solar circuit to the storage tank was 1,311 kWh/year.

The tendency is similar even for the delivered energy to the thermal consumer. Thermal losses in the storage tank indicated their negative effect in the magnitude of this quantity. Monthly values of delivered energy to the thermal consumer ranged between $(36.7 - 141.3)$ kWh/month, where the minimum was noticed in December and the maximum in July. The annual delivered energy to the thermal consumer was 1,009 kWh/year.

Regarding the graph of the required energy (load) in Figure 4, it was noticed that its values were higher in the months with lower ambient air temperature and vice versa. It was attributed to the fact that during these months the supply cold water temperature was lower. Consequently, the values represented their effect in increasing the required energy. Even the effect of the month representative day number can be seen in the results, particularly in the month of February through a slight reduction in the colder period. The minimum value of the required energy for the considered period was observed in September where $L_{min} = 153.5$ kWh/month, while the maximum in March where $L_{max} = 203.1$ kWh/month. The annual required energy was 2,129 kWh/year.

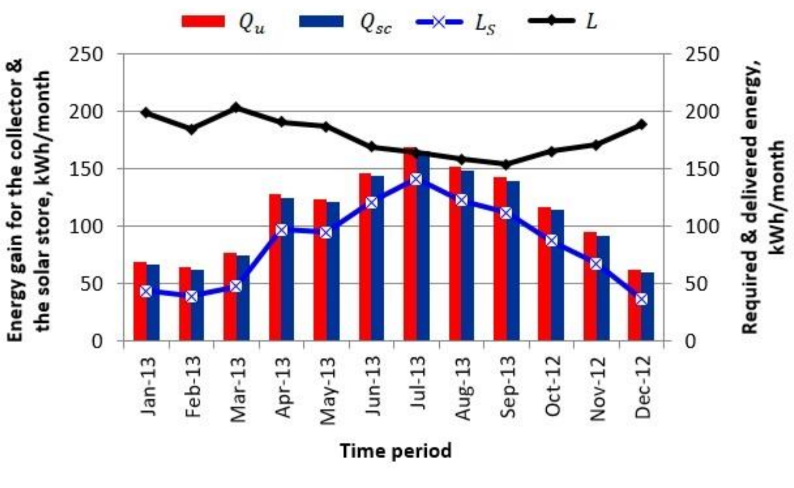

Figure 4. Useful energy gains for the collector, the storage tank, the delivered energy, and the load

Monthly values referring the losses in the heat pipe evacuated solar tube collector, the solar circuit, and the storage tank are shown at Figure 5.

The losses in the heat pipe evacuated solar tube collector were higher in the months with higher insolation and ambient air temperature than those in the other months. It was mainly related with the insolation values. Also, the effect of the month's day number was distinguished in the month of February through a slight reduction in its magnitude. The minimum value occurred in December (42.5 kWh/month), while the maximum in July (105.8kWh/month). The annual losses in the heat pipe evacuated solar tube collector for the selected time period were 867 kWh/year.

In Figure 5, from the curve of the losses in the solar circuit it was noticed that this quantity fluctuated between 2.2 kWh/month in December till 3.6 kWh/month in July. These losses took place in the insulated copper pipes of the solar circuit situated externally and internally of the building. The annual thermal losses in the solar circuit were 34 kWh/year.

Thermal losses in the storage tank ranged between $(21.8 - 29)$ kWh/month, where the minimum occurred in December and the maximum in July. The higher values were attributed to the fact that during the summer months the temperatures in the storage tank were higher. The annual thermal losses in the storage tank were 302 kWh/year.

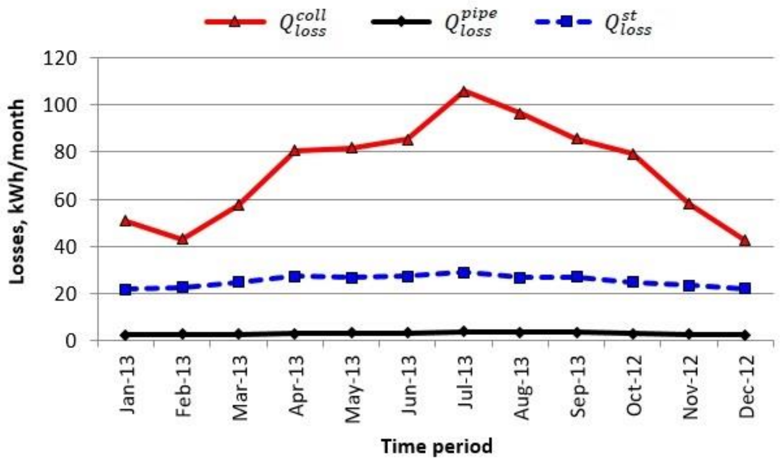

Figure 5. Losses in the solar collector, primary circuit, and storage tank

In Figure 6 the energy balance for the forced circulation SWH system equipped with a heat pipe evacuated tube collector related to the studied period is shown.

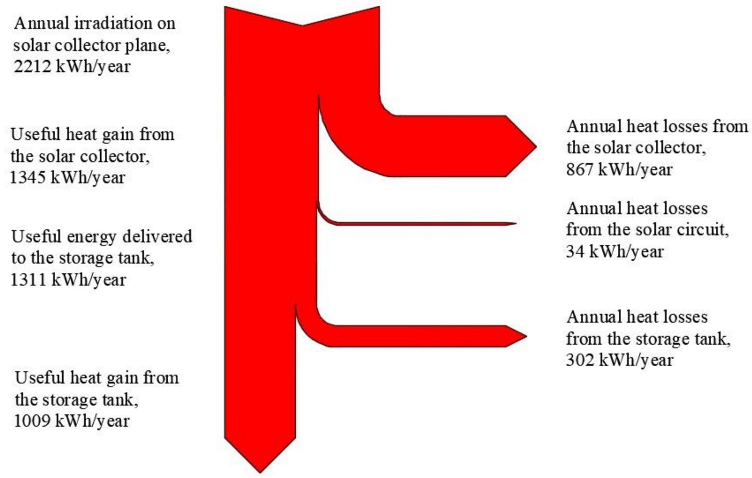

Figure 6. Annual energy balance for the studied solar water heating system

Figure 7 shows monthly values of thermal efficiency for the heat pipe evacuated tube collector. It was observed that monthly values of efficiency for the heat pipe evacuated solar tube collector were associated with low fluctuations varying between $\eta_{coll} = (0.602 - 0.636)$. These fluctuations were noticed to be ≤ 3.4 % and were strongly associated with the vacuum presence in this solar collector type, which reduces further the unavoidable thermal losses. The minimum value for the monthly collector efficiency was noticed during February, while the maximum during July. During months with lower values of insolation, even the ambient air temperature was lower and vice versa. Their combined effect was followed by higher thermal losses during these months. For these reasons, during this time period the monthly efficiency values for the evacuated tube collector were slightly lower than in the warmer months.

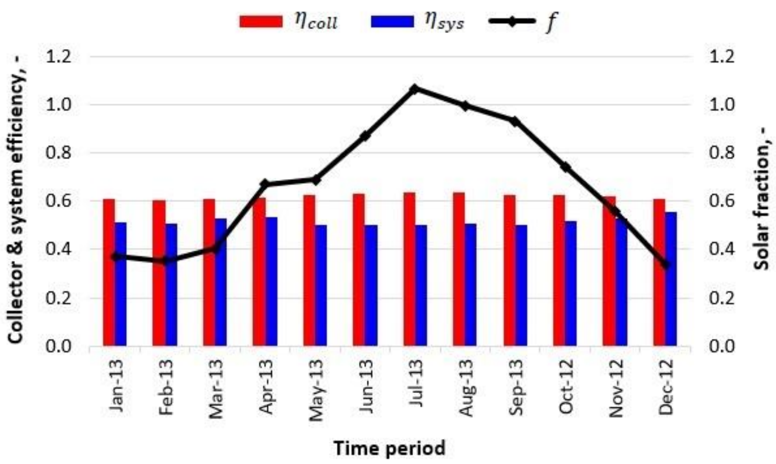

Figure 7. Collector efficiency, system efficiency, and solar fraction

Also, in Figure 7 even monthly values of thermal efficiency for the studied forced circulation SWH system equipped with a heat pipe evacuated collector are shown. Minimum monthly value of the system efficiency was noticed in September where $\eta_{sys}^{min} = 0.499$, while the maximum was achieved in December where $\eta_{sys}^{max} = 0.553$. It was observed a slight increase of system efficiency values during the months in which the insolation had lower values and vice versa. During these months, even the ambient air temperature was lower. The lower temperature difference between the heat transfer fluid flowing inside the solar circuit and the ambient air temperature near the solar collector represented its effect in increasing slightly the system efficiency. Also, the system controller had its impact in optimizing the system efficiency by controlling the temperature difference between the outlet of the evacuated tube collector and the middle height of the storage tank. Through the solar circulation pump, even the flow rate in the heat transfer fluid loop was optimized by the system controller. During the annual period the fluctuations of monthly values for the system efficiency were ≤ 5.4 %.

The black line included in the Figure 7 represents the monthly values of solar fraction obtained by the expression (7). It is a figure of merit commonly used for evaluating the SWH systems. The solar fraction for the field-trial forced circulation solar water heating system ranged between $(0.339 - 1.064)$, where the minimum occurred in December and the maximum in July. Referring to this graph, there is an increase of solar fraction during the summer months. This implies that its values are highly affected by the insolation. The annual solar fraction for the studied trial system during the selected time period was 0.665.

Based on the obtained results for the considered time period, it was concluded that the annual efficiency for the heat pipe evacuated solar tube collector was $\eta_{coll}^{annual} = 0.62$, while its value for the forced circulation solar water heating system was $\eta_{sys}^{annual} = 0.516$. For regions with a typical Mediterranean climate conditions falling at "Cs" group, it can be said that monthly values of system efficiency for a forced circulation solar water heating system equipped with a heat pipe evacuated tube collector fluctuated ≤ 5.4 %.

5. CONCLUSIONS

The annual energy performance of a forced circulation solar water heating system equipped with a heat pipe evacuated solar tube collector installed in a particular region with typical Mediterranean climate conditions of "Cs" group was carried out. Recorded data obtained from this trial installation during a 12-months period were used. The conclusions are obtained as follows:

- In the selected region the annual irradiation on solar collector plane for the considered time period was $H_T^{year} = 2{,}212$ kWh/year, while the mean annual ambient air temperature was $\bar{t}_{air} = 17.9$ °C.
- The annual useful heat gain for the heat pipe evacuated solar tube collector, the useful energy delivered by the solar circuit to the storage tank, and the delivered energy to the thermal consumer were $Q_u = 1{,}345$ kWh/year, $Q_{sc} = 1{,}311$ kWh/year, and $L_S = 1{,}009$ kWh/year, respectively.
- During the considered time period, the annual losses in the heat pipe evacuated tube collector were 867 kWh/year, while the annual thermal losses in the solar circuit and in the storage tank were 34 kWh/year and 302 kWh/year, respectively.
- Monthly values of efficiency for the heat pipe evacuated solar tube collector fluctuated between $\eta_{coll} = (0.602 - 0.636)$, while for the system they varied between $\eta_{sys} = (0.499 \div 0.553)$.
- The annual efficiency for the heat pipe evacuated solar tube collector was $\eta_{coll}^{annual} = 0.62$, while for the forced circulated solar water heating system was $\eta_{sys}^{annual} = 0.516$.
- The annual value of solar fraction during the selected time period was $F = 0.665$.

A comparison of results from this study towards those carried out in the premises of the Department [25] revealed that the annual collector efficiency for the heat pipe evacuated tube collector was 0.62, while for the flat-plate solar collector was 0.494. Also, the annual system efficiency for the forced circulation SWHS equipped with flat-plate solar collector was 0.411 [17]. These results highlight the higher thermal performance of the heat pipe evacuated tube collector compared to the flat-plate solar collector.

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NOMENCLATURE

A_c - collector area, m^2
A_{ETC} - collector area for evacuated tube collectors, m^2
c_{ph} - heat transfer fluid specific heat, kJ/(kg·K)
c_{pw} - water specific heat, kJ/(kg·K)
f - monthly solar fraction, -
F - annual solar fraction, -
$\dot{E}_{sun}$ - incident solar energy, W
G_t - total solar irradiance, W/m^2
H_T^{max} - maximum monthly value of irradiation on solar collector plane, kWh/(m^2·month)
H_T^{min} - minimum monthly value of irradiation on solar collector plane, kWh/(m^2·month)
H_T^{year} - annual irradiation on solar collector plane, kWh/(m^2·year)
$\dot{L}$ - required rate of addition of sensible heat, or load, W
L_{min}- minimum monthly value of the load, kWh/month
L_{max} - maximum monthly value of the load, kWh/month
$\dot{L}_S$ - rate of delivered energy to the thermal consumer, W
$\dot{m}_p$ - mass flow rate of heat transfer fluid, kg/s
$\dot{m}_w$ - mass flow rate of water, kg/s
$\bar{n}_v$ - annual averaged number of sunny hours, h/year
$\dot{Q}_{loss}^{coll}$ - solar collector losses, W
$\dot{Q}_{loss}^{pipe}$ - solar circuit pipe losses, W
$\dot{Q}_{loss}^{st}$ - storage tank losses, W
$\dot{Q}_{sc}$ - rate of useful energy delivered by the solar circuit to the storage tank, W
$\dot{Q}_u$ - rate of useful energy gain from the solar collector, W
$\bar{t}_{air}$ - mean ambient air temperature, °C
$T_{c,i}$ - inlet collector temperature, K
$T_{c,o}$ - outlet collector temperature, K
T_{del} - delivered temperature, K
T_{set} - setpoint temperature, K
$T_{s,i}$ - inlet storage tank temperature, K
$T_{s,o}$ - outlet storage tank temperature, K
T_{supply} - supply cold water temperature, K
η_{coll} - collector efficiency, -
η_{sys} - system efficiency, -
η_{coll}^{annual} - annual value for the collector efficiency, -
η_{sys}^{annual} - annual value for the system efficiency, -
η_{sys}^{max} - maximum value for the system efficiency, -
η_{sys}^{min} - minimum value for the system efficiency, -

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