EXPERIMENTAL ANALYSIS DURING THE LONG-TERM PERFORMANCE OF A FORCED CIRCULATION SOLAR WATER HEATING SYSTEM EQUIPPED WITH FLAT PLATE COLLECTORS FOR THE MEDITERRANEAN CLIMATE CONDITIONS

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Abstract- This work represents the performance analysis during the annual time period of a solar water heating system equipped with flat plate solar collectors for the Mediterranean climate conditions. For this purpose, recorded data from a field trial installation are exploited. The recorded data obtained every each 5-min are used to perform the analysis during a yearly 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 field, useful heat gain from the storage, collector field efficiency, system efficiency, and solar fraction offered a clear view regarding the operation of a forced circulation solar water heating systems for this climate region. Also, the annual energy balance of the system obtained from calculation gives a clear view regarding the useful heat gains and the thermal losses in the considered system.

Keywords- Experimental Analysis, Flat Plate Collector, Long Term Performance, Solar Water Heating System.

I. INTRODUCTION

Solar water heating systems are widely used in residential, service and industrial sectors of a country. Because of the required load, forced circulation systems are used mainly in the service and the industrial sectors. Different authors have performed different studies with the aim to analyze the operation of solar water heating plants in real conditions. Ayompe and Duffy (2013) analyzed the thermal performance of a SWH system equipped with flat plate collectors in a temperate climate[1]. Rodriguez-Hidalgo et al. (2012) carried out a study with a building experimental solar facility equipped with flat plate solar collectors [2]. Thür et al. (2006) performed a study regarding the energy savings of solar heating systems [3]. Lee and Sharma (2007) carried out the thermal performance of active and passive water heating systems based on annual operation [4]. Badescu (2005) realized the simulation analysis for a solar water system of a passive house [5]. The present paper investigates the energy performance of a forced circulated solar water heating system for an annual time period. In addition, the energy balance is presented.

II. SYSTEM DESCRIPTION

To perform this work a forced circulation solar water heating system is exploited (Fig. 1). The system is used for research purposes and is installed in the premises of the Department of Energy, Faculty of Mechanical Engineering - Polytechnic University of Tirana – Albania [6]. Tirana is the capital and is situated in the central part of the country. The average altitude is 110 m above the sea level and the geographical coordinates are the latitude 41.33 °N and the longitude 19.82 °E. The selected town has a typical Mediterranean climate and according to Köppen climate classification, it falls at "Cs" group. It is characterized from hot and dry summers and from mild and rainy winters [7]. Annual averaged number of sunny hours are $\bar{n}_v = 2500$ h/year [8].





Fig. 1: External and internal part of the exploited system

The main components of the solar water heating system utilized in this work and the sensor placement are shown in Fig. 2.The system is equipped with two selective solar flat plate collectors connected in parallel. Flat plate solar collectors used in this study are of selective type and manufactured by Isofoton[9]. The total absorber area is $A_c = 4.41$ m^2 and the

storage volume is $V_{st} = 300$ l. The collectors slope is 45°and the azimuthal angle is −10°.

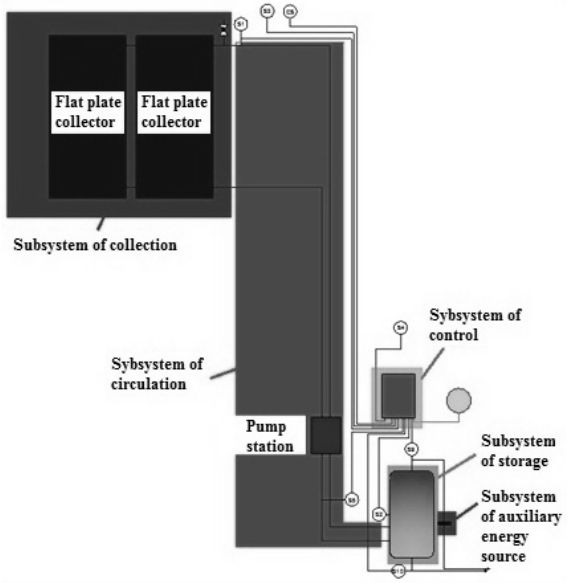


Fig. 2: Main components and utilized sensors of the solar water heating system

The measurement of temperatures is achieved by using thermocouples of PT1000 type. The measurement of global solar radiation on the tilted solar collector area is realized using a solar cell (CS10). Measurement of volume flow rate is obtained through the V40 flow-meter. The collected data during the whole period are transferred from the control system to the data collecting system. Later, they are elaborated by the help of appropriate software [6].

Measured data include global solar radiation on the tilted solar collector area, heat transfer fluid temperature at the inlet and the outlet of the solar collector field, supply cold water temperature, hot water temperature, volume flow rate of the heat transfer fluid and that of the water.

III. ENERGY ANALYSIS

Energy analysis of the field trial installation includes the appropriate mathematical models necessary to define the required energy, energy collected from the collector field, energy delivered to the storage, energy delivered to the thermal consumer, thermal efficiency of the collector field, efficiency of the system and the solar fraction.

The load to be met by a solar water heating system includes three components. First, the sensible heat requirements of the water must be met.

If water flowing at a rate of $\dot{m}$ is to be heated from a supply temperature T_s to a delivery temperature T_d the required rate of the addition of sensible heat is given as [10]:

$$\dot{L}_w = \dot{m} \cdot c_p \cdot (T_d - T_s) = \rho_w \cdot \dot{V}_w \cdot c_{pw} \cdot (T_d - T_s) \quad (1)$$

Second, losses from the distribution system $\dot{L}_d$ must be met. In this case, the thermal consumer is near the storage. Third, losses from the storage tank $\dot{L}_t$ must be met. Taking into consideration the complexity of their calculation, the indirect method is used.

If the heat transfer fluid flowing at a rate of $\dot{m}$ is to be heated from the inlet temperature T_i to the outlet temperature T_o the rate of useful heat gain from the flat plate collector is defined as [10]:

$$\dot{Q}_u = \rho_f \cdot \dot{V}_f \cdot c_{pf} \cdot (T_o - T_i) \quad (2)$$

The solar collector field constitutes the most important component of a solar water heating system. Its main function is to collect the solar radiation, convert it into heat, and further to transfer it to the heat transfer fluid. Collection efficiency is a measure of collector performance. It is defined as the ratio of the useful energy gain over some specified time period to the incident solar energy over the same period and is given as [10]:

$$\eta_{coll} = \frac{\int \dot{Q}_u \cdot dt}{A_c \cdot \int G_t \cdot dt} \quad (3)$$

This way, the instantaneous efficiency of solar energy conversion to useful thermal energy is given as [10]:

$$\eta_{coll-i} = \frac{\dot{m} \cdot C_p \cdot (T_o - T_i)}{A_c \cdot G_t} \quad (4)$$

If water flowing at a rate of $\dot{m}$ is to be heated from a supply temperature T_s to hot water temperature T_{hw} the useful gain from the storage is given as [10]:

$$\dot{L}_{hw} = \rho_w \cdot \dot{V}_w \cdot c_{pw} \cdot (T_{hw} - T_s) \quad (5)$$

System efficiency refers to the amount of solar radiation that is actually utilized to heat up water. It is the ratio of 'useful' solar energy output to the amount of solar radiation that falls on the collector, and is a similar concept to collector efficiency, except that the 'useful' output is measured as it leaves the solar storage unit instead of the collector. Any heat loss occurring in the pipes connecting the collector to the storage, as well as losses in the solar storage tank itself are included in the system efficiency calculation. System efficiency is expressed as [11]:

$$\eta_{sys} = \frac{\int \dot{L}_{hw} \cdot dt}{A_c \cdot \int G_t \cdot dt} \quad (6)$$

This way, the instantaneous efficiency of solar energy conversion to useful thermal energy is given as [11]:

$$\eta_{sys-i} = \frac{\dot{m} \cdot C_p \cdot (T_{hw} - T_s)}{A_c \cdot G_t} \quad (7)$$

One of the indicators necessary for the evaluation and the comparison of solar hot water systems is the solar fraction. This quantity indicates the portion of the required energy covered from the solar energy. It important to emphasize that solar fraction doesn't consider additional parasitic electrical energy (circulation pump, controller, etc.) and the heat losses from the storage. In this case, the field trial installation is a small plant and the additional parasitic electrical energy is small. For this reason, monthly solar fraction becomes important and it can be defined as [10]:

$$f_i = \frac{L_i - L_A}{L_i} = \frac{Q_{u-i}}{L_{w-i}} \quad (8)$$

The annual solar fraction is defined as the ratio of yearly solar contribution to the load divided by the load. It is given as [10]:

$$F = \frac{\sum_{i=1}^{12} f_i \cdot L_{w-i}}{\sum_{i=1}^{12} L_{w-i}} \quad (9)$$

IV. RESULTS AND DISCUSSIONS

In the present work the long term performance of a forced circulation SWH system equipped with flat plate solar collectors is performed. To achieve this goal, the energy analysis of the plant is performed. At first, the recorded data obtained from the acquisition and the storage data system, are exploited. Later, the energy analysis is performed leaning on appropriate mathematical models.

In Fig. 3, the monthly values of global solar radiation on the tilted solar collector area are shown. It is noticed that these values are lower during the winter period and higher during the summer period. Its minimum value happened on December where $H_T^{min} = 291.6$ kWh/month. Whereas, the maximum value was registered on July where $H_T^{max} = 785.4$ kWh/month. The values of solar radiation depends mainly from the local geographical latitude, season, and the climate conditions. Annual value of the global solar radiation on the tilted solar collector area for the considered period was $H_T^y = 6363$ kWh/year.

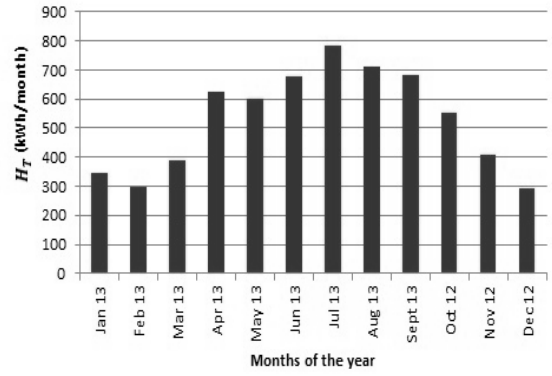


Fig. 3: Monthly values of global solar radiation on the tilted collector area

Monthly average values of the ambient near the solar collector field are shown in the Fig. 4. From the figure, it is noticed that its values are low during January and February. They increase gradually towards the summer months and later, they gradually diminish towards the winter months. Minimum values fluctuate in the interval between $\bar{t}_{air}^{min} = (3 \div 20.3)$ °C and the maximum ones between $\bar{t}_{air}^{max} = (14.3 \div 38)$ °C. The minimum values are noticed on December, whereas the maximum on August.

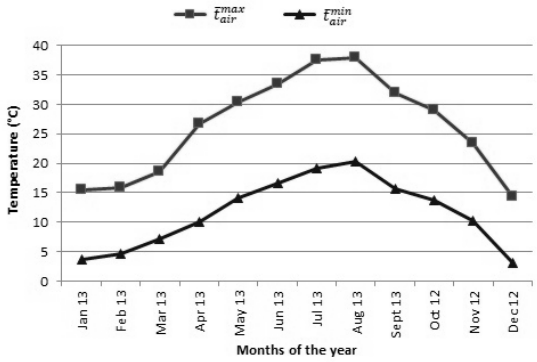


Fig. 4: Monthly average values of ambient near the collector field

The required rate of sensible heat depends from the thermal consumer, cold water supply temperature, and the demand of the hot water. Its values are shown in Fig. 5. During the months with low values of ambient temperature, its values are higher and vice versa. Another effect on its values is represented from the water supply temperature, which is lower during the cold months. This is related with higher values of the required rate of sensible heat. Also, its value is effected even from the day number of the month. The maximum value of this quantity is noticed on March where $L_w^{max} = 380.7$ kWh/month, whereas the minimum is on September where $L_w^{min} = 287.8$ kWh/month. The annual value of required rate of sensible heat is $L_w^{year} = 3993$ kWh/year.

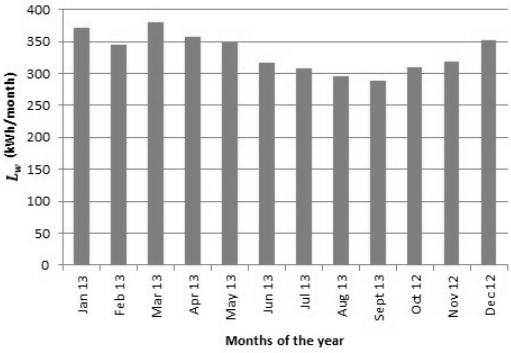


Fig. 5: Required rate of sensible heat

Monthly values of useful heat gain from the solar collector field are shown at Fig. 6. It is noticed that this quantity has higher values in the months where the global solar radiation on the tilted solar collector area

has higher values and vice versa. Also, its values depend even from the ambient temperature near the collector field. So, during the months in which the ambient temperature near the collector field is lower, the losses will be higher. Another factor is the number of the days for each month. The maximum value of useful heat gain from the solar collector field is noticed on July where Q_u^{max} = 347.4kWh/month. The minimum value is noticed on December where Q_u^{min} = 144.7 kWh/month. The annual value of this quantity is Q_u^{year} = 3031 kWh/year.

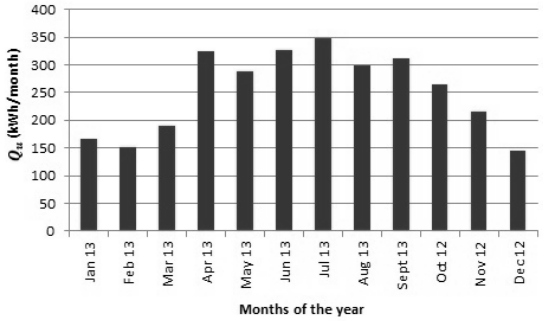


Fig. 6: Monthly values of useful heat gain from the solar collector field

In Fig. 7, the monthly values of useful heat gain from the storage are shown. During the months in which the global solar radiation on the tilted solar collector area has higher values is noticed that this quantity has higher values and vice versa. Also, its values depend even from the water supply temperature and the number of the days for each month. The effect is similar with the case of sensible heat. It is noticed that the maximum value happened on June where L_{hw}^{max} = 316.1kWh/month, whereas the minimum is on December, where L_{hw}^{min} = 113.4 kWh/month. The annual value of this quantity is L_{hw}^{year} = 2574 kWh/year.

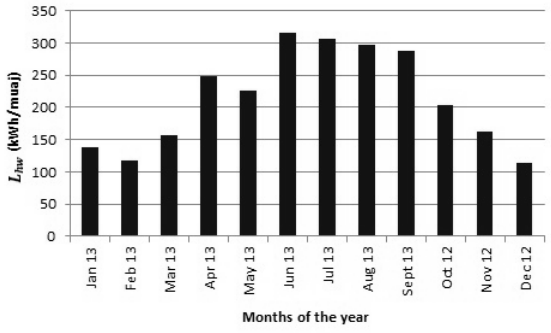


Fig. 7: Monthly values of useful heat gain from the storage

Monthly values of collector field efficiency and system efficiency are shown in Fig. 8. During the months in which the global solar radiation on the tilted solar collector area has lower values is noticed that these quantities have higher values and vice versa. In other words, during these months the efficiency values are higher. Maximum value of the collector efficiency is noticed on November where η_{coll}^{max} = 0.528. On contrary, the minimum value is noticed on August where η_{coll}^{min} = 0.439. Annual averaged value of collector efficiency for the whole study period was η_{coll}^{year} = 0.494.

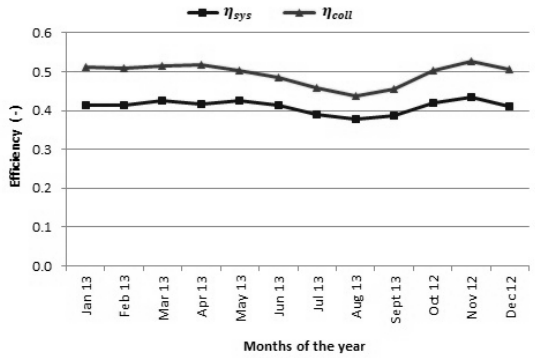


Fig. 8: Monthly values of the collector efficiency and system efficiency

Also, in the Fig. 8 even the monthly values of system efficiency are shown. During the months in which the global solar radiation on the tilted solar collector area has lower values is noticed that these quantities have higher values and vice versa. In other words, during these months the efficiency values are higher. Maximum value of the system efficiency happened on November where η_{sys}^{max} = 0.435, whereas the minimum value is noticed on August where η_{sys}^{min} = 0.378. Annual averaged value of system efficiency for the study period was η_{sys}^{year} = 0.411.

The difference between the solar collector efficiency and the system efficiency equals thermal losses in the system. They include thermal losses in the pipes of the heat transfer closed loop and in the storage. Thermal losses in the plant were higher during April where Q_l^{max} = 10.62 %. Whereas, the minimum value of thermal losses happened during August where Q_l^{min} = 6.111 %.

In Fig. 9 monthly values of solar fraction and those of system efficiency are shown. It is noticed that the values of solar fraction are higher in the months where the global solar radiation on the tilted solar collector area has higher values. Monthly values of solar fraction are higher than the unity during June, July, August and September. While, the minimum value happened on December was f_i^{min} = 0.42. Annual solar fraction for the annual period was F = 0.757. In other words, for the analyzed trial installation the solar energy covered 75.7 % of its sensible load. The difference should be covered from another energy source (electricity, etc.).

Also, the effect of solar fraction on system efficiency is noticed. During the months in whichthe global solar radiation on the tilted solar collector area has higher

values a decrease of system efficiency is noticed. This occurrence is related with the high values of solar radiation and the maximum temperature of hot water inside the storage. For these reason, the controller decreases the flow rate of the heat transfer fluid. The effect of this intervention is accompanied with the decrease of the useful heat gain from the flat plate collector. Also, there are many time periods in which the solar pump stops working.

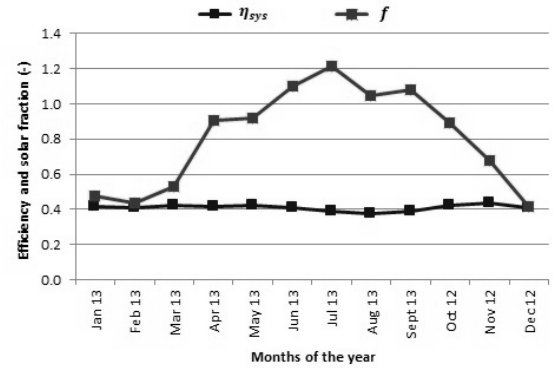


Fig. 9: Monthly values of solar fraction and system efficiency

In Fig. 10 the annual energy balance of the trial field installation is shown. In this case, the considered quantities include annual values of global solar radiation on the collector area $H_T^{year} = 6363$ kWh/year, thermal losses from the flat plate solar collector 3332 kWh/year, useful heat gain from the flat plate solar collector $Q_u^{year} = 3031$ kWh/year, thermal losses from the closed solar loop and the storage 457 kWh/year, and the useful heat gain from the storage $Q_{hw}^{year} = 2574$ kWh/year.

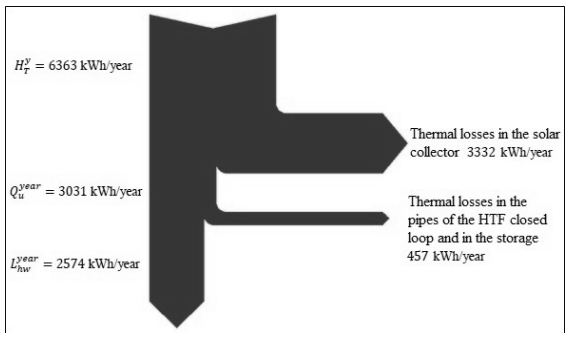


Fig. 10: Annual energy balance

CONCLUSIONS

In this work, a solar water heating system installed in a Mediterranean climate region is analyzed for a 12-months period. From measured and calculated values several results were obtained, as follows:

1) Monthly values of useful heat gain from the solar collector field are proportional with the global solar radiation on the tilted solar collector area. Also, its values depend slightly even from the ambient temperature near the collector field. The annual value of this quantity for the whole study period was $Q_u^{year} = 3031$ kWh/year.

2) Monthly values of useful heat gain from the storage are proportional with the global solar radiation on the tilted solar collector area. The annual value of this quantity was $L_{hw}^{year} = 2574$ kWh/year.

3) Monthly values of collector field efficiency are inverse proportional with the global solar radiation on the tilted solar collector area. The annual averaged value of collector efficiency for the whole study period was $\eta_{coll}^{year} = 0.494$.

4) Monthly values of system efficiency are inverse proportional with the global solar radiation on the tilted solar collector area. The annual averaged value of system efficiency for the whole period was $\eta_{sys}^{year} = 0.411$.

5) Finally, from the annual energy balance of the studied solar water heating system we notice that maximum thermal losses happened in the solar flat plate collector 52.36 %. While, thermal losses from the closed solar loop and the storage were 15.01 %.

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NOMENCLATURE

A_c- collector area, m^2
C_p- fluid specific heat, kJ/(kg·K)
c_{pf}- specific heat rate of heat transfer fluid, kJ/(kg·K)
c_{pw}- specific heat rate of water, kJ/(kg·K)
f_i- monthly solar fraction, -
F- yearly solar fraction, -
G_t- total solar radiation, W/m^2
L_{Ai}- auxiliary energy, kWh
L_i- purchased energy with zero area solar energy system, kWh
L_{Si}- delivered solar energy, kWh
$\dot{L}_w$- sensible heat requirement, kWh
$\dot{m}$- mass flow rate, kg/s
$\dot{Q}_u$- useful energy gain, W
t- time, s
T_d- delivery temperature, K
T_{hw}- hot water temperature, K
T_i- inlet temperature, K
T_s- supply cold water temperature, K
T_o- outlet temperature, K
$\dot{V}_w$– volume flow rate of water, l/min
$\dot{V}_f$– volume flow rate of heat transfer fluid, l/min
V_{st}- storage volume, l
ρ_f – density of heat transfer fluid, kg/m^3
ρ_w – density of water, kg/m^3
η_{coll}- collector efficiency, %
η_{coll-i}- instantaneous collector efficiency, %
η_{sys}- system efficiency, %
η_{sys-i}- instantaneous system efficiency, %

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