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Optimization and Evaluation of Monthly and Annual Performance of Flat-Plate Solar Water Heater in Sanandaj City

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ABSTRACT

Solar water heaters are one of the most developed technologies of renewable energy used in the world. The satisfactory and reliable performance of solar water heaters require accurate sizing and designing of the components as well as precise prediction of useful energy intake. This is of greater significance in cold areas due to higher thermal loss and lower solar radiation. Hence, optimization of the system parameters to obtain sufficient efficiency is quite an important matter. This study evaluated the long-term and annual performance of solar water heaters in the cold city of Sanandaj, Iran using TRNSYS software. In the first phase, the general parameters and components of the system were optimized and in the second phase, the performance of the optimized system was assessed. The effects of changing parameters such as storage tank volume, collector area and collector slope on the monthly and yearly performance of the solar water system were analyzed. It was found that 0.35-0.45 m2 was the optimum annual volume of storage tank for the weather conditions of Sanandaj city. Moreover, the optimized values of collector area and its optimized slope were reported to be 8 m2 and 40-60º, respectively. The results showed a direct correlation between environmental conditions and useful energy intake. With regard to time and energy intake, August was found to be more uniform than other months. At the end, the monthly efficiency of the system was evaluated and the findings indicated a proportional efficiency for the system. The maximum monthly efficiency was found to be about 61% in July and minimum level was 42% in January.

1. Introduction

Considering the limited fossil fuel resources and harmful effects caused by unprincipled use of these fuels on environment, conducting research on the application of renewable energies in industrial and scientific communities has been of a great importance. Solar energy, however, is of greater significance owing to being a completely clean energy without any pollution and a completely affordable source of energy. There are many methods proposed for using this clean energy, but heating the water by solar collectors is perhaps the easiest and most economical strategy. With adequate knowledge about solar radiation, solar energy can be easily and effectively used for heating the domestic consumption water or for industrial applications. Scientific advancements in solar water heaters have been dramatically increased in the recent decades. These heaters have been frequently used not only for domestic applications but also for hotels, hospitals, administrative buildings, industries like textile, paper mills and food, and even for heating the water of swimming pools in winter.

In Ian, several economic studies have been carried out on these systems. Satkin performed a socioeconomic analysis of using solar energy to supply the hot water of 4-5-member families in order to economically justify large capital investments on solar collectors in Iran. He determined the energy consumption and the pollution produced by the conventional methods and reported 4.5 years as the initial capital return period for using solar heaters [1]. Eivazi examined the application of solar water heaters for optimized use of solar energy in region 22, Tehran. He also analyzed the emission level of pollutants and percentage of saving in emission of pollutants along with the costs. His results showed a 10.4-year period for initial capital return of using solar collectors [2]. Hasani and Sina evaluated the economical and technical use of solar water heaters and compared the solar collectors with electric, diesel and natural gas water heaters. They reported the capital return periods of 3.3, 3.6 and 16 years for replacement of electric, diesel and natural gas water heaters by solar water heaters, respectively [3].

On the other hand, Hottel and Woertz assessed the performance of flat-plate solar collectors theoretically and experimentally and presented basic quantitative relations among the functional parameters [4]. Bliss obtained a mathematical model for the efficiency factors of different solar collectors [5]. The effect of design specification on the system efficiency has also been assessed by several studies [6-8]. Hahne evaluated the impact of various parameters on the efficiency and heating time of flat-plate collectors [9]. However, a number of these studies have been performed in a short period of time and the operational conditions have been simplified [10].

Various computational instruments have been developed for numerical assessment of the long-term performance and analysis of the effect of solar collector design parameters. TRNSYS software is used for extensive simulation of solar systems under transient conditions, multi-regional buildings with low solar energy intake, renewable energy systems, and fuel cells along with their related facilities. This program has been widely used to study and optimize solar collectors. In addition, numerous studies have utilized TRNSYS to evaluate the effects of design parameters and different operational conditions on the performance of solar heating systems [10].

Buckles and Klein compared the performance of various configurations of forced circulation solar water systems [11]. Also, Michaelides and Wilson optimized the design standards of forced circulation solar collectors [12]. Wongsuwan and Kumar studied the performance of a forced circulation system experimentally and numerically. Numerical simulation was performed by TRNSYS and artificial neural network. The results of both numerical models showed a good agreement with experimanetal results [13]. Nevertheles, most of the studies have been carried out on the systems suitable for the hot regions with moderate winter. In these regions, the thermal loss of the system is low and there are no problems like solifidication [10].

To sum up, the studies conducted have been done over a short time, have frequent simplifications and are appropriate for the hot and moderate regions. Howeevr, the satisfactory and reliable performance of solar water heaters require proper sizing of components and accurate prediction of useful energy intake. On the other hand, the heat loss of solar collectors in the cold areas is high on the one hand, and solar radiation is low on the other hand. This brings about problems such as liquid solifidication within the collector. Therefore, optimization of system arameters is quite important for obtaining a better performance [10]. In this study, the long-term and annual performance of solar water heaters was evaluated in the city of Sanandaj, Iran. In the first phase, the parameters and general components of the system were optimized and in the second phase, the eprformance of the optimized system was evaluated.

2. Materials and Methods

For simulation of solar water heater in the weather conditions of Sanandaj city, the system presented in Figure 1 was analyzed by TRNSYS software. As indicated in the figure, an indirect forced circulation system with indirect thermal convertor is modeled in this study. The working fluid, which is responsible for absorption and transfer of solar energy, is circulating between the hot side of thermal convertor and collector. When the hot water in the storage tank is cooler than the adjusted temperature or the weather is cloudy, the hot water is heated by the auxiliary electric element. Conversely, when the temperature of the produced hot water is higher than the adjusted temperature, cold water is added by a 3-way control valve. The hot water consumption depends on the people’s lifestyle, season, time of the day and geographical parameters. Since there is no accurate and comprehensive study on the water consumption pattern in Sanandaj, an approximate water consumption pattern for a normal family was used. The monthly average temperature of inlet water is dependent upon ambient temperature and urban water temperature. It is evident that this temperature is variant in different seasons and months of the year. These values were obtained from the data of Sanandaj water organization and used in the simulation process. The hot water consumption was defined by a water consumption pattern for the system. Further, the solar cycle pump was turned on and off by a controller through comparison of the temperatures of collector and storage tank. The components considered in this software are presented in Table 1.

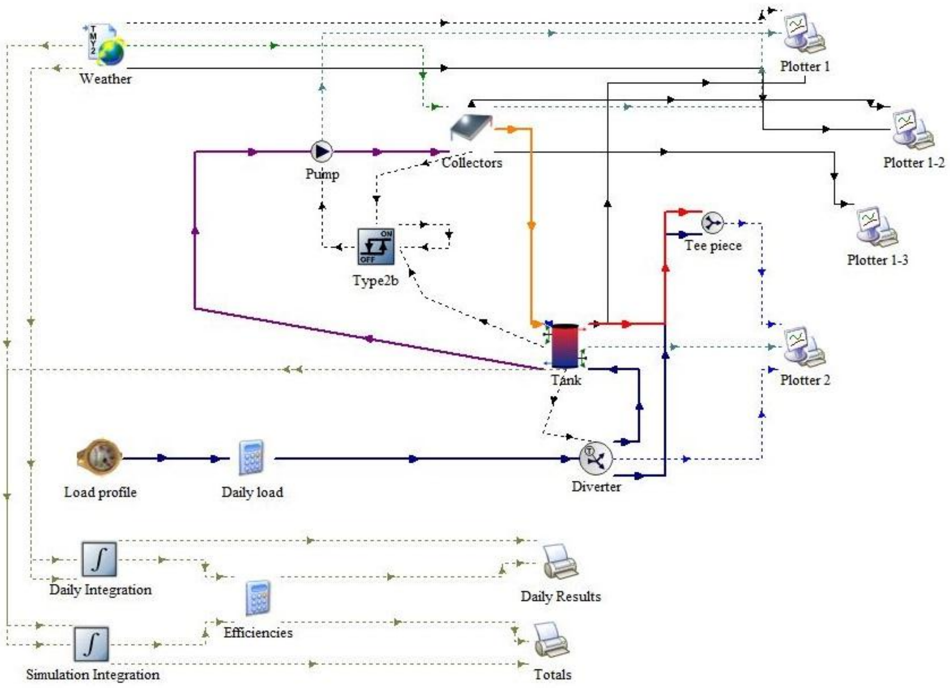


Figure 1. Schematic of the simulated system

Table 1. The components considered for simulation of the system

Model	Part
Solar Collector; Quadratic Efficiency، 2nd Order Incidence Angle Modifiers	Collector
Storage Tank; Variable Inlets، Uniform Losses	Storage tank
Time Dependent Forcing Function: Water Draw	Load profile
Tempering Valve	Diverter
Quantity Integrator	Daily integration
Quantity Integrator	Simulation integration
On/OFF Differential Controller; Old Control Strategy	Controller

As stated, two different simulations were performed in this study. The first phase was aimed to optimize the overall parameters of the system and the second phase was intended to evaluate the performance of the optimized system.

The solar ratio parameter is very much better than other parameters like system efficiency to be used for optimization of the system. This is because the solar ratio represents the overall performance of all system not a specific part of it [10]. The monthly or annual solar ratio, which is a fraction of total energy of hot water supplied by the solar system, is calculated by the following formula:

$$F = \left(Q_{load} - Q_{auxiliary}\right) - Q_{load} \qquad (1)$$

Qload is the total energy exited from the system to supply the required hot water and Qauxiliary is the total auxiliary energy used to supply part of the energy not supplied by the solar energy.

3. Results & Discussion

One of the most important factors for an appropriate designing is complete knowledge of weather conditions during the year. Since this study was designed for Sanandaj city (latitude of 35º and longitude of 45º and a height of about 1580 m above sea level), the required data for designing were collected during one year. Sanandaj is a rather warm region in the summer and very cold in the winter. With a total of 2870 hours solar radiation during the year, it is a rather appropriate region for installing and using solar water heating systems. Figures 2-5 demonstrate the environmental characteristics of this city in January, May, August and November, each representing a season of the year.

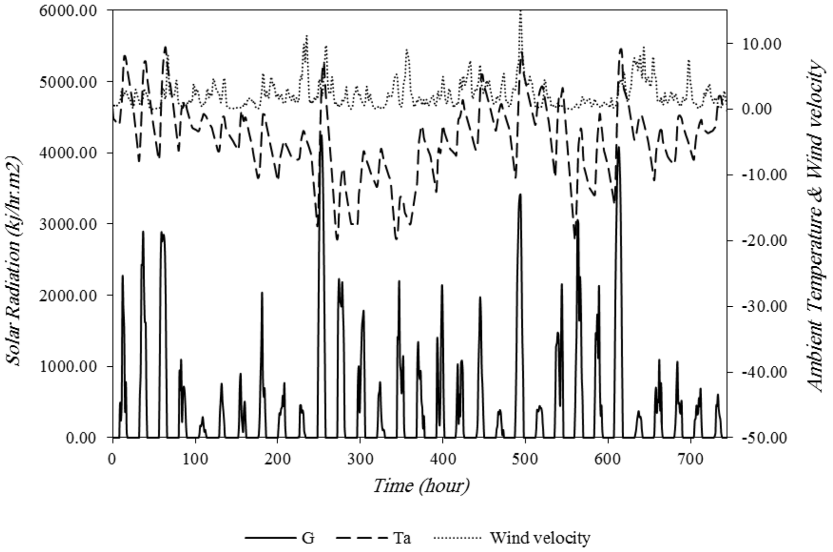


Figure 2. Solar radiation intensity, ambient temperature and wind velocity in January

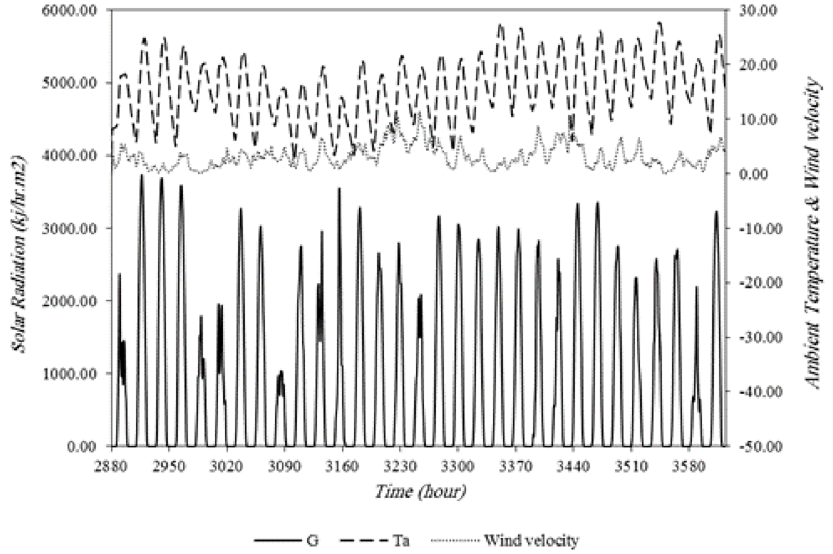


Figure 3. Solar radiation intensity, ambient temperature and wind velocity in May

In designing the collectors, it should be noted that solar radiation intake of the earth is variable and solar radiation is not equal in different days and hours. Therefore, it cannot be claimed that a flat collector is designed for all seasons of the year because its energy intake is quite variable. For example, a system designed for the coldest seasons with least radiation (January or December) is not appropriate and economical for other seasons. Conversely, if it is designed for the seasons with most radiation and hottest temperature, the system will face hot water supply problem in other seasons. Thus, it is necessary to find an optimal level for this parameter during the year. Figure 6 shows the annual solar ratio changes in different areas of collector for the given system. The trend of solar ratio changes is ascending about 8 m2 until reaching the cross-section. After crossing this level, the figure reaches an approximately fixed value. The calculations showed that the optimal area (where there are few solar ratio changes) is about 8 m^2.

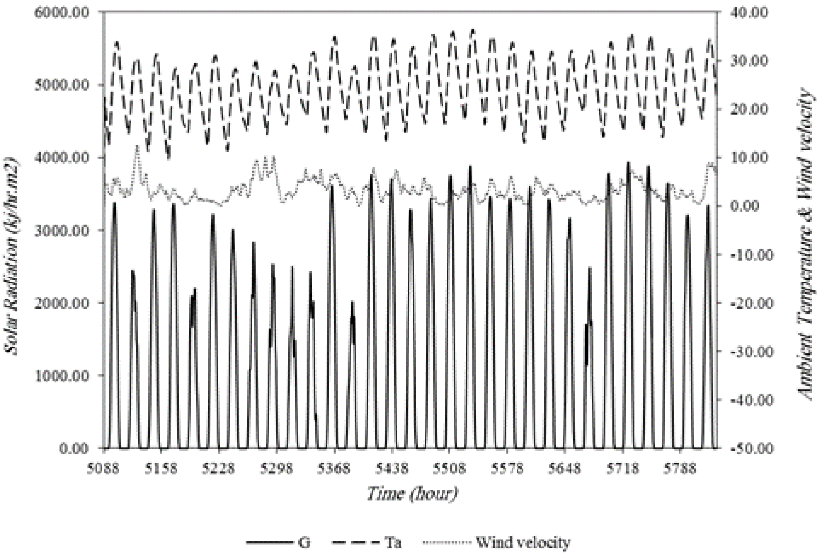


Figure 4. Solar radiation intensity, ambient temperature and wind velocity in August

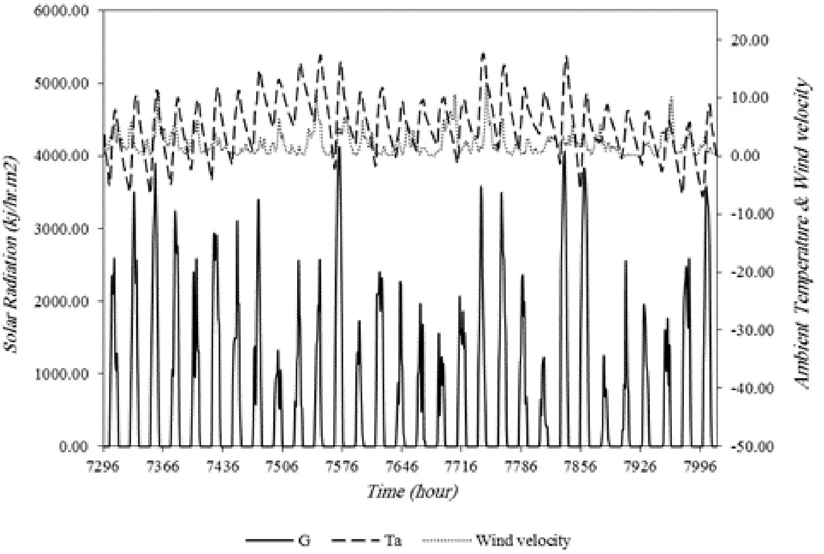


Figure 5. Solar radiation intensity, ambient temperature and wind velocity in November

There are various methods to increase the radiation intake from the sun. One of these methods is increasing the collector surface. To this end, it is necessary to use collectors with larger areas, which consequently increases the cost. Another strategy is changing the collector slope angle due to the changing position of the sun in the sky and solar radiation conditions during different days, months and seasons. Moreover, since the coefficient of absorption of collectors is dependent on the inlet radiation direction, the more appropriate is the collector position, the more is the solar radiation intake of the collector and the more is the absorption rate. The optimum slope angles of collectors depend on the geographical location and climate conditions. Since no study has ever evaluated the impact of collector slope in Sanandaj so far, this parameter was selected as one of the main parameters in this study. The solar ratio changes are proportional to slope changes (Figure 7). Before reaching 50º, the solar ratio has an ascending trend. After crossing this limit, however, this ratio starts to reduce. Thus, the maximum and minimum solar ratio values occur between 40º and 60º.

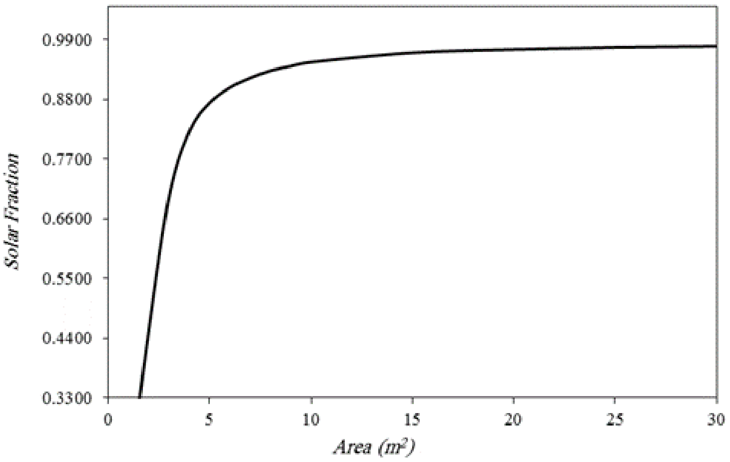


Figure 6. Effect of surface changes on annual solar ratio

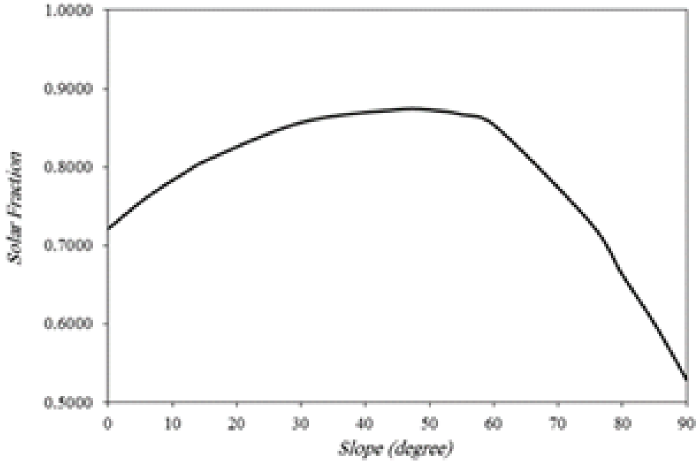


Figure. 7. Effect of collector slope on annual solar ratio

The demand for energy is not usually comparable to its supply by the sun in terms of time. This is because hot water for various purposes is required when the sun has either not risen or has set, or the consumption peak is not compatible with radiation peak. Therefore, a storage tank is needed for an efficient solar system. A storage tank is responsible for balancing the demand and supply as lack of coordination in energy production and consumption is controlled by the storage tank. For example, a sudden and high consumption of energy by the consumer is facilitated by the storage tank without the involvement of the main source of energy consumption in supplying the required energy. It can be argued that a sunny day may be followed by consecutive rainy days. Depending on the regional climate, a short-term storage tank rather than a seasonal storage tank should be used, which includes various types based on their purposive application.

The impact of volume change on annual solar ratio is illustrated in figures 8-11. The optimal volume is obtained when the solar ratio changes are not a lot. In January, the solar ratio is slowly increased with a rise in the storage tank volume. Crossing the volume 0.35 m^2, the solar ratio changes reach about 0.02. Thus, 0.35-0.45 m^2 can be considered an optimal range. In May, after crossing the volume 0.45 m^2, the solar ratio reaches a fixed value. However, the solar ratio changes are very little after 0.4 m^2. In August, the maximum and optimum solar ratio is observed at about 0.4 m^2. The figure of solar ratio changes in November is parabolic. After crossing the volume 0.5 m^2, the solar ratio begins to drop. Nevertheless, the solar ratio changes in 0.35-0.45 ^{m2} volume are trivial.

The effect of volume change on the annual solar ratio is shown in Fig. 12. The analysis of the annual figure shows that the solar ratio changes before reaching 0.35 m^2 are ascending. After crossing this volume, the changes are approximately fixed. The calculations indicated that the annual optimum volume was 0.35-0.4 m^2.

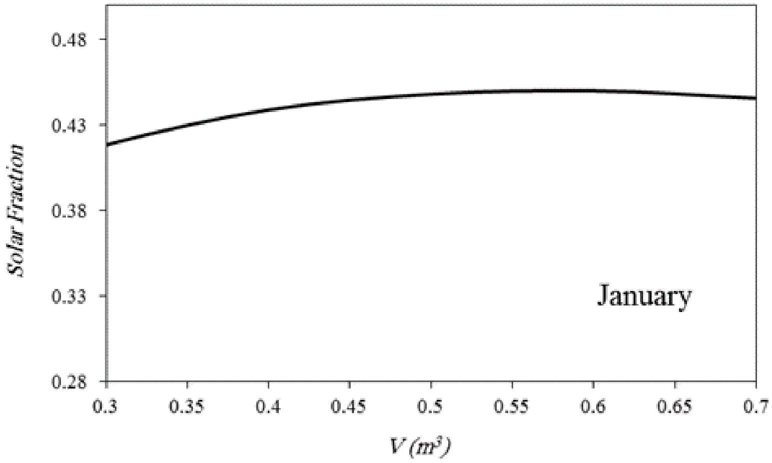


Figure. 8. Effect of volume change on solar ratio in January

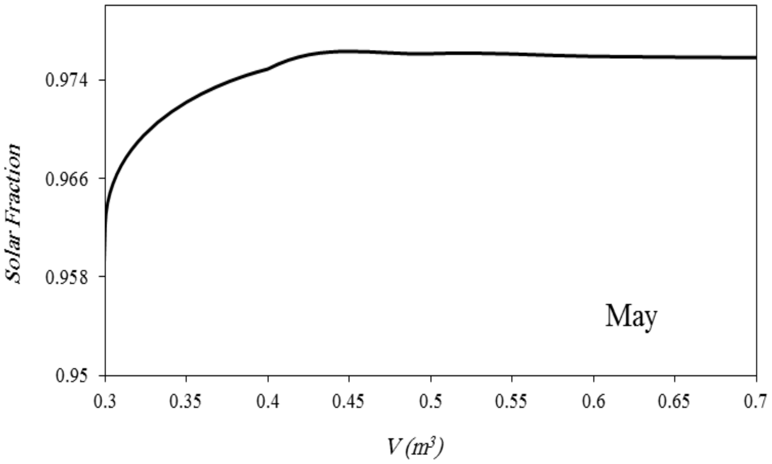


Figure 9. Effect of volume change on solar ratio in May

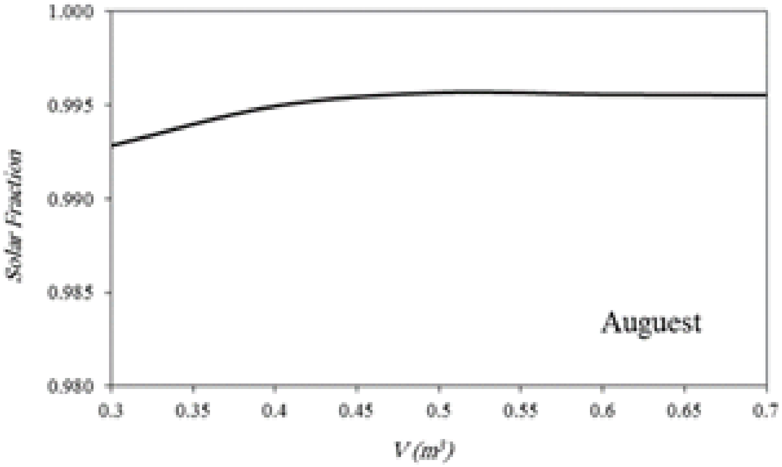


Figure. 10. Effect of volume change on solar ratio in August

Figure 13 presents the useful energy intake in January. The concentration in the transverse direction indicates longer energy intake and in longitudinal direction shows more energy intake. As indicated, the graph has a low congestion and height. Therefore, the useful energy intake in this month is low and irregular. This energy intake reaches zero in some periods. About half of the days in this month, the energy intake reaches less than 2000 Kj/hr. High energy intake in this month is observed in three days. This is because this month is one of the coldest months of the year and most of the days have low radiation and ambient temperature.

Figure 14 depicts the useful energy intake in May. As shown, the useful energy intake in this month is irregular. The energy intake is high in some days of the month and low in some other days. Given the relative increase of radiation and ambient temperature, the useful energy intake is slightly increased. The maximum energy intake in the days with the maximum and minimum energy intake occurs in the second (12041 Kj/hr) and ninth (1902 Kj/hr) days of the month.

Figure 15 shows the useful energy intake in August. As indicated, the useful energy intake is approximately high and regular. The maximum energy intake in the days with maximum and minimum energy intake happens in the twelfth (11615 Kj/hr) and fifth (4415 Kj/hr) days of the month.

Figure 16 demonstrates the useful energy intake in November. As it is shown, the useful energy intake is reduced with increased irregularity because this month is fully located in the autumn. The maximum energy intake in the days with maximum and minimum levels is reported in the twenty third (12887 Kj/hr) and twenty fifth (1908 Kj/hr) days of the month.

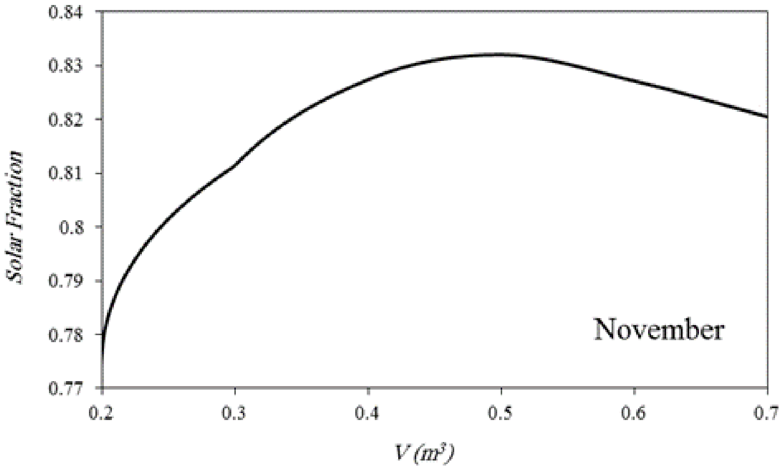


Figure 11. Effect of volume change on solar ratio in November

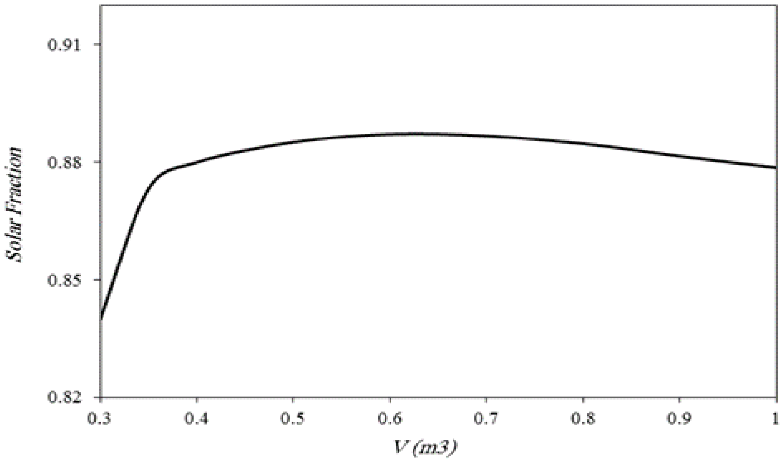


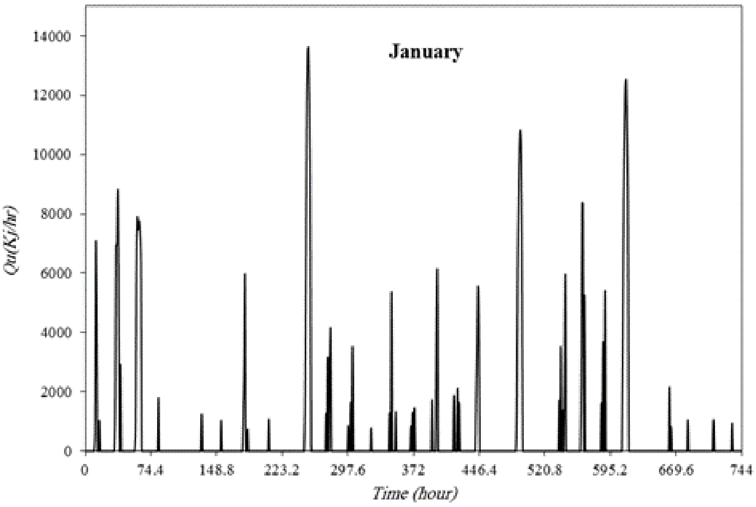
Figure 12. Effect of volume change on annual solar ratio

Figure 17 illustrates the system efficiency in different months of the year. As shown in the figure, efficiency is shown to be parabolic. The system efficiency is promoted with the passage of time. The efficiency reaches its maximum level in July and decreases again. The maximum monthly efficiency (61%) occurs in July and its minimum level happens (42%) in January.

4. Conclusions

The current study performed an optimization and analysis of the performance of solar water heaters in the cold city of Sanandaj, Iran. Four months of the year were chosen for analysis. A summary of the results is presented in the following:

- The solar ratio changes are presented as the storage tank volume and optimal volume. The trend of changes are ascending until 0.45 m^2. After that, no changes are observed and the trend is descending after 0.6 m^2. The annual optimal volume of storage tank is 0.35-0.45 m^2 based on the calculations.
- The solar ratio changes are presented according to the collector cross-section. The solar ratio changes are ascending until reaching the cross-section area of 8 m^2. After crossing this level, the graph reaches almost a fixed value. The optimal area (where the solar ratio changes are low) is about 8 m^2 according to the performed computations.
- The graph of solar ratio changes is parabolic with a change in slope. Before reaching the slope of 50º, the solar ratio is ascending. After passing this level, the solar ratio starts to decline. Therefore, the maximum and optimum solar ratio values occur at 40-60º.



Fiure. 13. Useful energy intake in January

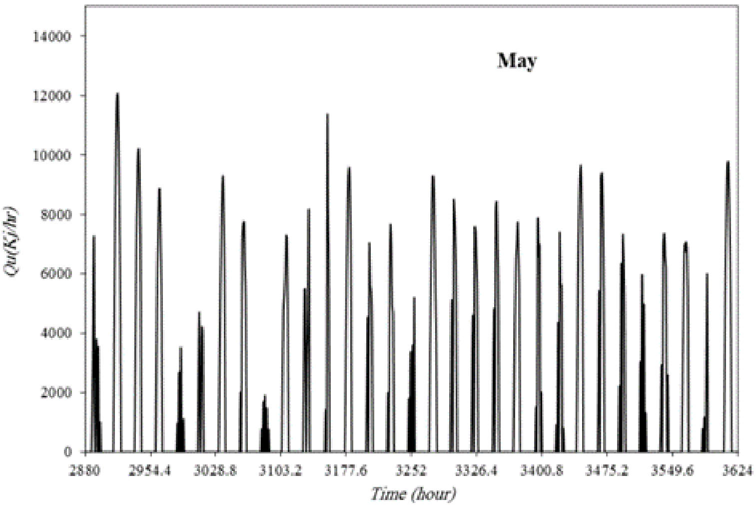


Figure 14. Useful energy intake in May

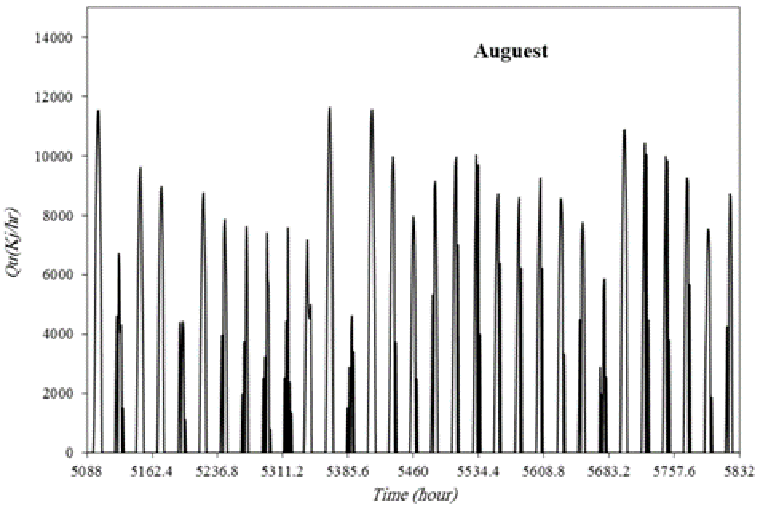


Figure15. Useful energy intake in August

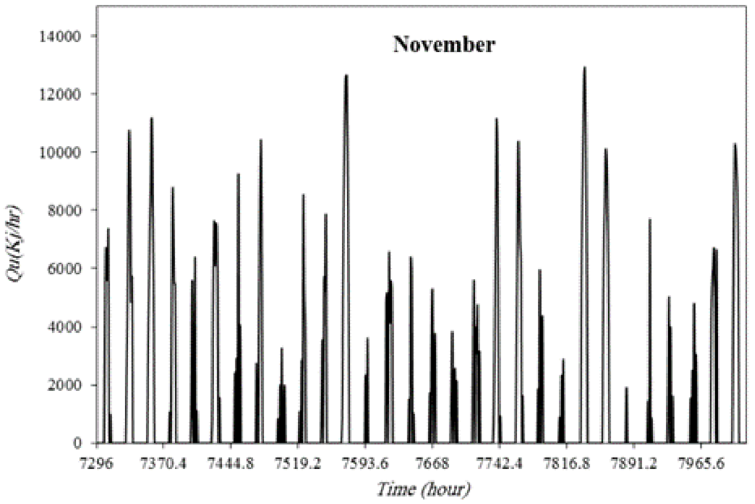
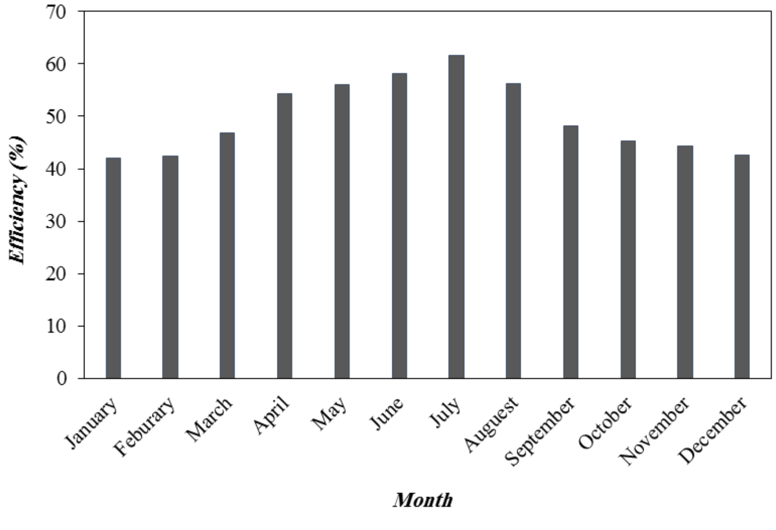


Figure 16. Useful energy intake in November



Figurte 17. Annual efficiency of the system

- The graph of useful energy intake indicates a direct correlation of environmental conditions with this parameter. In terms of time and energy intake, August has a better uniformity than the rest of months.
- The annual efficiency of the system is proportional. The efficiency of the system increases over time. The efficiency reaches its peak and reduces again in July. The maximum annual efficiency is about 61% in July and its minimum level is around 42% in January.

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