Evaluation of the Effective Parameters of the Vacuum Tube of Solar Water Heater System

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Abstract
The use of sun's heat to warm up water in the vacuum tube of solar water heater is a new issue considered in the most modern societies. In this regard, the current study aims to evaluate the effective parameters of the vacuum tube of solar water heater system. In addition, regarding the limited reserves of oil and gas, the use of renewable (reversible) and low-cost sources, such as sun, wind, water, and etc. has brought the attention of developed countries. In this field, effective measures have been taken so far to reduce the dependence on gas and oil by utilizing these types of sources. Results show that the annual collectible radiation during each tube solar collector unit is affected by many factors including collector type and the central distance between the adjacent tubes and geometric parameters such as the size of vacuum tubes of solar collector, slope and azimuth angles, the use of diffuse flat reflector (DFR), latitude and weather conditions. The use of DFR can increase the annual collectible radiation of a collector. Among the collectors with the same parameters, T-type collectors gather the more radiation annually rather than the H-type collector.
Keywords:
collector; solar water heater; vacuum tube

1. Introduction

Sun is the most abundant and accessible source of energy for our planet. All other types of energy including the wind, fossil fuel, biomass, etc. originate from the sunlight. Solar energy shines on the earth with the rate of 120 petawatt (per petawatt equivalent to 1015 watt), it means that the energy received from the sun during the day can provide the world's needs for 20 years [1]. The technologies related to the renewable energies supply almost 3.13% of the whole world's needs of energy. As a result, during the years, many scientists have been working on research and development of this type of energy. Among the main reasons for these activities, the global warming, rising energy prices and the reduction of fossil energy can be named. The scientists know the pollution due to the utilization of the fossil energies as the primary cause of global warming [2]. There are various ways of using the solar energy, but heating the air and water using solar water and air heaters may be the simplest and the most economical way; because by having enough knowledge about solar radiation, the solar energy can be applied effectively to warm the water and air of the houses up and even can be used in industrial applications [3]. Today, the goal of many environmental protection organizations in the developed and developing countries is to get sure about the environmental sustainability, in the other words, to consider the principle of sustainable development or to reverse the environment degradation or at least stop this process. To achieve this goal, all governments and humans must replace the fossil fuels and other energy sources with renewable energies, especially the solar eternal and clean energy, in order to decrease the environment pollution [4]. From the economic and environmental perspective, with the finish of exhaustible energy and increases of its price, as well as detrimental effects of these types of energy on environment, the utilization of the renewable energies such as solar energy for supplying the human comfort is increasing all over the world, that one the usage ways is the solar water heater. Therefore, regarding the global high price of energy and its increase in Iran, the most of the people are seeking to use these systems in domestic and industrial scales. Thus, with the technical examination of each of them and compare them on various parameters, different social groups such as professors and engineers can be aware of this field, and at the end it can be said that by applying such system, the hot water and even the space heating can be provided without need for fossil energy,

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which is the purpose of the scientists of recent decades [5]. Undoubtedly, nowadays the use of solar collectors technology as one of the most effective ways of preventing environment degradation by the pollutants resulting from fossil fuels all over the world. Several parameters can change the thermal efficiency of solar water heater including the slope of the collector, the material of the absorber plate, the type of the glass used in the coating, the ambient temperature, the measurement time, and the number of coatings [3]. Solar water heater is most commonly used among other applications of solar energy. The reason can be its simple technology and affordable price. The small solar water heaters have domestic application and larger types have an industrial application [6]. Regarding limited fossil fuel resources and environmental pollution, human concern about the surrounding environment has accelerated and optimized energy consumption has always been one of the most essential topics in Iranian and global energy literature. In order to solve this problem, it is necessary to seek a new, alternative, cheap, and available energy like solar energy. Accordingly, in order to reduce the energy consumption, the current technologies can be replaced with the systems which use renewable energies instead of the fossil fuels as an energy source. The most extensive application of renewable energies is the utilization of them to produce the heat which mainly relates to the solar water heater [7].

2. Review of the Literature

Ghazanfarpour [8] evaluated the solar water heater systems in her thesis and explained that the application of solar energy is the most practical and most affordable method of the utilization of renewable energies to provide hot water of the houses and industrial centers in modern world, and that is why most of the developed and developing countries are investing heavily in this field. At first, the general classification of solar water heaters including two major groups of natural convection (thermosyphon) and forced convection, mentioning the advantages and disadvantages of each are represented. Then the components of the thermosyphon solar water heater system are introduced. The components of these types of water heaters consist of collectors, storage tanks, heat exchangers, controllers, and valves that each of them is described in detail. The collector is the most important part of a water heater whose main task is to absorb sunlight and convert it into the heat and transfer it to the current operating fluid through tubes.

Delfan et al. [9] have represented an experimental study on the impact of the slope angle on the efficiency of solar collectors of vacuum tubes. The experiments were performed in the geographical location of the Kermanshah city on 5 slopes of 22.5, 30, 37.5, 45, and 52.5 degrees. It was tried to present a relation for the efficiency of the vacuum tubes. This relation showed that the efficiency in different slopes obeys two factors of the temperature difference between the environment and the reservoir and the amount of solar radiation on the collector's surface. It also indicated that the collector's efficiency has an inverse relationship with the temperature difference between the environment and the tank and has a direct relationship with the amount of sun radiations on the surface of the collector. Moreover, the results showed that the maximum energy harvest of solar radiation for this kind of collector is 87% and for per unit, the ratio of the ambient temperature difference and reservoir fluid to the radiation will have yield loss of 7.6 percent [9].

Stanciu et al. [10] evaluated the theoretical optimization of the tilt angle for flat plate collectors in different geographic positions and different times during a year. In this study, the density of the solar radiation is estimated on the basis of three analysis models namely Hottel and Woertz model (the simplest), Isotropic diffuse model (Liu & Jordan model) and HDKR model (Hay–Davis–Klucker–Reindl), passing from the simplest to the most complex one. Further, the absorbed solar radiation density is computed and the optimum tilt angle is found for different geographical locations (covering the Globe latitudes). The results indicate that the same angle is obtained when looking for the maximum incident and for maximum absorbed solar radiation.

Dagdougui et al. [11] surveyed the impact of the collector's various type and form of the covers' thermal efficiency. They studied the effect of the types and the number of the covers on the top heat loss of the system. They concluded that the efficiency increases using plexi covers because of decreasing the heat loss but the efficiency does not vary with the increase in collector surface area. Other experimental results suggested that the efficiency decreases with increasing the water temperature. By increasing the fluid mass flux, the efficiency increases and after 0.03 kg almost reaches a constant value.

3. The Application of Solar Thermal Energy

- The power plant applications: the installations using them the absorbed solar thermal energy is converted into the electricity is called the solar thermal power plant. In solar thermal power plants, the main task of solar parts is to produce the required steam to feed the turbines. In the other words, it can be said that these power plants consist of the two solar parts which absorb the solar radiations and produce the steam using the absorbed heat. These solar thermal power plants include the linear parabolic, central receiver, and plate type.

- Solar water heater and solar bath: the thermal energy of the sun can be used to provide the sanitary hot water in homes and public places. In addition, by increasing the capacity of such systems, they can be used in solar baths. Regarding the geographical position of Iran, many solar water heaters and several solar baths have been installed in various parts of the country.

- The heating and cooling of the building and solar optimal ventilation: the first solar house was built in 1993 in which a seasonal heat sink is used for applying it during the year. This new idea which was proposed in the 1930s achieved notable developments in less than a decade. Also, by adding a so-called absorption refrigeration system to the solar systems, these systems can be used in providing the hot water and heating as well as cooling the building in the summer and hot seasons [12].

Advantages and disadvantages of the solar water heater

These systems are very affordable because they can be used even in the cold seasons in the existence of the sun. They also can be an appropriate alternative to the devices working with the electricity and liquid and gas fuels. The users of these devices in some states enjoy good tax rebates. The productivity increases when these water heaters heat the domestic water. Using the solar water heaters in the homes extremely reduces the fuel costs in winter. Moreover, the volume of the air pollution and greenhouse gasses from fossil fuels such as oil, natural gas, and propane highly decrease. One of the disadvantages of the solar water heater is that their most important weak point is their initial installation. The purchased reservoirs must be installed on the roof. Another point which may be undesirable is the space occupied by this system on the roof; especially, it should be installed where absorbs the most sunlight (driveway). Another disadvantage of this system is that the panels are kept on the roof and the sunlight must be there in order to have a suitable efficiency and otherwise the backup system would be needed [13].

Tubular collectors (vacuum tubes) and evacuated-tube collectors

The tubular collectors are perpendicular to the sun at all hours of the day and therefore will absorb the most amount of energy from the sun. Since the use of solar energy is increasing in all industrial, commercial, domestic, and agricultural sectors all over the world, it is used in agriculture to supply the hot water, the light of salons, workshops, and greenhouses, and to provide the electrical energy of the agricultural water extraction pumps [14]. The amount of the energy absorbed by vacuum tubes depends on the various factors such as tilt angle, the dimensional ratio of the tubes, the distance between the parallel tubes, the use or not use of the reflective plate, the distance of this plate to the tubes, geographical conditions of the location, and the surroundings conditions. With the motivation of the optimum design of the vacuum tubes, some experimental and numerical studies are performed on the impact of the vacuum tubes' dimensional ratio on their thermal performance and characteristics of the flow inside the tubes [15]. The operating fluid within the tubes moves in two ways.

A) Normal or passive: due to the thermos siphon phenomenon (gravity)

B) Mandatory or active: a pump is used for the forced circulation of this fluid. The evacuated-tube collector named Collector Glass-Metal, like a double tube heat exchanger consists of two overlapping metal and glass tubes. In this collector, the metal tube named sorbent tube is generally made of copper so that the fluid flows through it and the glass tube is outside and avoids from the displacement losses between the environment and the sorbent tube. In order to minimize the displacement losses, the space between the two tubes is evacuated from the air. The function of this exchanger is as thermos siphon by which the hot fluid flow takes place inside the collector due to the density difference between the hot and cold fluid. Under the influence of the hot fluid flow inside the with-coil storage reservoirs, the water is heated [16]. The thermos siphon type of the vacuum tube collectors is more common than other types of these collectors. This type of water heaters rather than other water heaters which use one manifold to transfer the heat have better thermal performance, simpler structure, and lower initial cost [15].

4. Modeling and Analysis of the Exergy

The modeling of the heat transfer and fluid flow inside real vacuum tube of solar water heater with many tubes requires very strong calculations. Therefore, in order to simplify the problem, just one tube along with the appropriate reservoir is examined numerically. A set of experimental tests is used which were fully discussed to evaluate the accuracy and validity of the results. The dimensions of the simulated tube and reservoir were in accordance with the dimensions of the test tube and reservoir. For the reservoir, a horizontal cylinder with a radius of 14 cm and a length of 13 cm is considered and for the tube, a cylinder is considered whose diameter is equal to the actual vacuum tube's diameter of inner tube (inner tube's diameter is 5.4 cm and outer tube's diameter is 6.5 cm) and its length is equal to the length of the actual vacuum tube (180 cm). The equations of this problem respectively continuity, momentum, and energy are as following:

$$\frac{dE_{CV}}{dt} = \sum_j Eqj - W_{CV} + \sum m_i e_{fi} - \sum m_e e_{fe} - E_d - E_{loss} \quad (2)$$

$$\frac{\partial u}{\partial t} + \nabla(\rho\bar{u}) = 0 \quad (1)$$

$$\rho\frac{\partial u}{\partial t} + \rho\bar{u}(\bar{u}) = -\nabla P + \frac{u}{\rho}\nabla^2\bar{u} + \rho\bar{f} \quad (5)$$

$$\rho\frac{\partial C_p T}{\partial t} + \rho\bar{u}\nabla(C_P T) = -\rho\nabla\bar{u} + \bar{\bar{\tau}}:\nabla\bar{u} + \nabla(\mathrm{k}\nabla\mathrm{T}) \quad (6)$$

Where $\bar{u}$ is the velocity vector, P is pressure, ρ is fluid density, C_ρ is the thermal capacity of the fluid, T is the local temperature of the fluid, and t is the time [17].The type of the algorithm used in the problem-solving is SIMPLE. The reason of using this algorithm type is the rapid convergence, the use of this type of solution in similar cases, and also compliance of the results with the experimental results.

5. Exergy Analysis

The exergy analysis for the receiver model showed in the Figure1 can be calculated by the equations of 9 to 11.

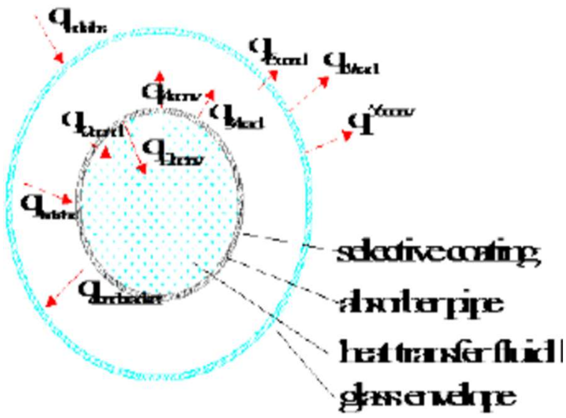

Figure1. The model of a section of the collector receiver's thermal resistance

$$\dot{E}_{qj} = \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j \quad (3)$$

$$e_f = h - h_0 - T_0(s - s_0) + \frac{V^2}{2} + gz \quad (4)$$

2.1.1. The input exergy

The input exergy consists of the exergy originating from the operating fluid and the exergy originating from the sun radiations. The total input exergy is as following:

$$\dot{E}_i = \dot{m}\left[\left[\int_{T_0}^{T_i} C_p(\mathrm{T})\mathrm{dt} + \mathrm{v}(P_i - P_0) - T_0\int_{T_0}^{T_i}\frac{C_p(T)}{T}dT + \frac{V_i^2}{2}\right]\right] + I_b A_a \varphi \quad (7)$$

$$\varphi = 1 - \frac{4}{3}\frac{T_0}{T_s} + \frac{1}{3}\left[\frac{T_0}{T_s}\right]^4 \quad (8)$$

Here, T_s is equal to the temperature of the sun planet (6000). The output exergy includes the exergy resulting from the difference between the output temperature and the reference temperature and also from the kinetic exergy from which the amount of entropy damage is reduced (Moran and Shapiro, 2014)

$$\dot{E}_e = \dot{m}\left[\left[\int_{T_0}^{T_e} C_p(T)\,dt + \mathrm{v}(P_e - P_0) - T_0\int_{T_0}^{T_e}\frac{C_p(T)}{T}dT + \frac{V_e^2}{2}\right]\right] + I_b A_a \varphi \quad (9)$$

$$\dot{E}_{gain} = \dot{m}\left[\left[\int_{T_i}^{T_e} C_p(T)dt + v(P_e - P_i) - T_0\int_{T_0}^{T_e}\frac{C_p(T)}{T}dt\right]\right] \quad (10)$$

In the above equations $\dot{E}_e$ suggests the amount of exergy resulting from the operating fluid flow and $\dot{E}_{gain}$ is the amount of exergy received by the collector resulting from direct radiation of the sun that this exergy is made from the increasing temperature of the operating fluid and the loss of the mechanical exergy induced by frictional flow. The efficiency rate of the exergy is defined as the ratio of receiving exergy to total exergy originating from the sun radiations.

$$\eta_{ex} = \frac{E_{gain}}{E_{sr}} \quad (11)$$

$$\eta_{ex} = \frac{\dot{m}\left[\left[\int_{T_i}^{T_e} C_p(T)dt + v(P_e - P_i) - T_0\int_{T_0}^{T_e}\frac{C_p(T)}{T}dT\right]\right]}{I_b A_a \varphi} \quad (12)$$

The latest equation does not show the amount of the losses and damages which is needed for determining the location and the reason of the occurrence. The exergy losses include the loss of heat transfer to the environment, while exergy destruction is due to the internal irreversibility. For the steady-state, following equation can be rewritten as:

$$\eta_{ex} = 1 - \frac{E_d + E_{gain}}{I_b A_a \varphi} \quad (13)$$

6. Results

The evaluation of the effective parameters on the vacuum tube of the solar water heater system

- The effect of the tube’s distance from center to the diffuse flat reflector (DFR) on the annual collectible radiation

Figure2 shows the central distance between the adjacent tubes on the collectible annual radiation on the length of each tube.

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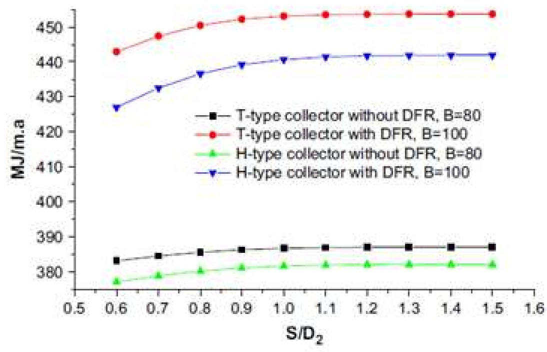

Figure 2. The effects of central distance between the adjacent tubes on the collectible annual radiation on the length of each tube

As shown in the Figure2, the annual collectible radiation on per length unit has increased with the increase of S, the distance between the tube's distance to center and the diffuse flat reflector (DFR); but this increase is very slight and when S grows, the annual collectible radiation is reduced by half.

- The effects of the central distance among the tubes on the annual collectible radiation

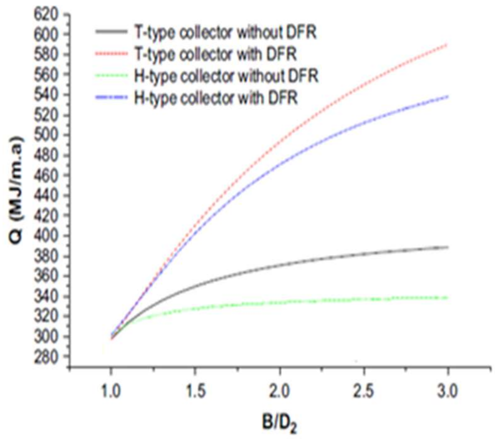

Figure 3. The effects of the central distance among the tubes on the annual collectible radiation

As illustrated in Figure 3, the collectible radiation (Q) has increased with the increase of the central distance between the tubes (B), especially for the collectors with DFR. For the collectors without DFR, this increase is very little. This could be due to the fact that the increased B decreases the allowed amount of shade between the adjacent tubes and therefore, more radiation occurs on DFR. The Figures 1 and 2 also indicate that among the solar collectors with the same geometric parameters and structures, T-type vacuum tube collectors collect the milder radiations than the horizontal H-type collectors. The use of DFR can significantly lead to the increase of annual collectible radiation.

- The optimal tilt angle of the collectors to the south

For the collectors facing south with provided geometric and structural parameters, the annual collectible radiation (Q) in the intended area only depends on the tilt angle and an optimal tilt angle is find to gather the annual energy of the collectors. The effects of the tilt angle of collectors facing south on the annual collectible radiation are the R_β ratio of the annual collectible radiation facing south with any tilt angle which is called optimal tilt angle. Figure4 illustrates the effects of the tilt angle of the collectors facing south on the annual collectible radiations.

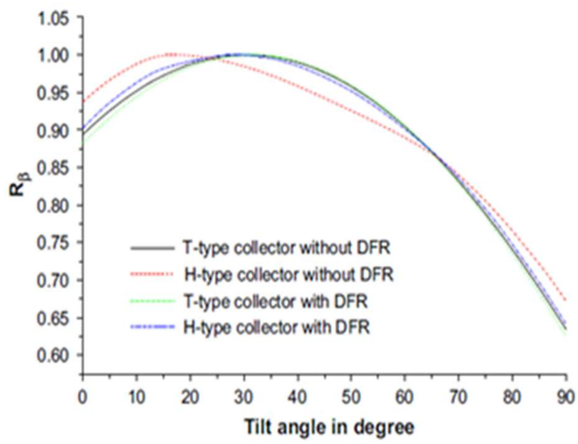

Figure 4. The effects of tilt angle of the collectors facing south on the annual collectible radiations

As shown in Figure4, tilt angle's 10-degree deviation from the optimal tilt angle (less than 5%) has reduced the annual collectible radiation of collectors.

- The impacts of the collectors' azimuth angle on the annual collectible radiation

The collectors with the tilt angle of annual collectible radiation are affected by the azimuth angle. Evaluating these effects, a Rø ratio is obtained which is the ratio of annual collectible radiation on the collectors with any azimuth angle of the collectors facing south named optimal azimuth angle.

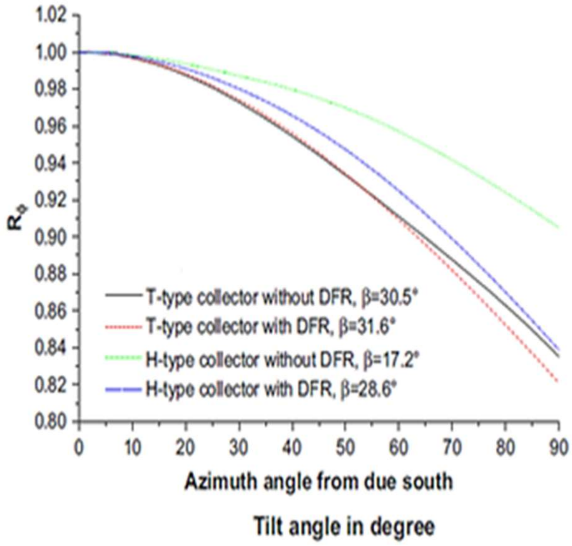

Figure 5. The effects of diagonal collectors' azimuth angle on the annual collectible energy

The impacts of the collectors' azimuth angle with β=90˚ on the annual collectible energy is demonstrated in Figure6.

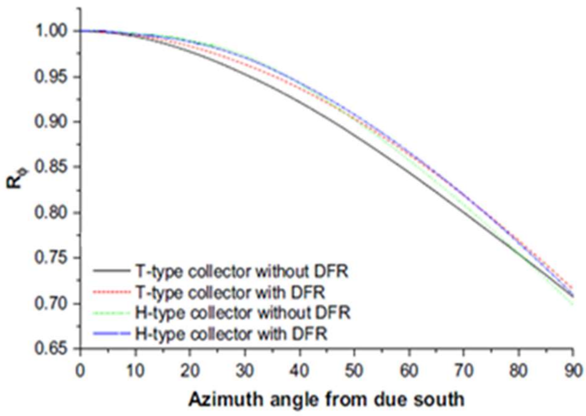

Figure 6. The effects of the collectors' azimuth angle with β=90˚ on the annual collectible energy

Regarding Figure5 and Figure6, the increase of azimuth angle from south decreases the annual collectible radiation. Hence, this effect is significantly evident with the increase of tilt angle.

A remarkable point in this type of collectors is that the fluid is warmer at the end of the tubes. It can be because of normal movement in this area; in the other words, as approaching to the end part of the tubes, the heat transfer caused by natural is reduced.

7. Discussion

There are various ways of using the solar energy, but heating the air and water using the solar water and air heaters may be the most simple and most economical method; because having the enough knowledge about the solar radiations can be effective in using the solar energy for heating the water and the air of the homes and even can be applied in industry. Yekta [15] in his study declared that since the vacuum tubes with different dimensional ratios are not available in order to experimental investigation of this parameter's impact, the numerical modeling of the problem is used. The results show that thermal performance of the vacuum tubes decreases with the increase of the tubes' length. In fact, increased dimensional ratio from 40 to 40 decreases the thermal performance about 34%. Delfan et al. [9] studied the experimental impact of the tilt angle on the efficiency of the vacuum tubes of the solar collectors. The results indicated that the maximum harvest of the solar energy for this type of collectors is 87% and the collectors and for per unit, the ratio of the ambient temperature difference and reservoir fluid to the radiation will have yield loss of 7.6 percent. Selmi et al. [19] simulated the heat transfer phenomenon in a solar flat plate collector using the computational fluid dynamics software and techniques. Their results were in a good accordance with the experimental results. The results of this research suggest that the annual collectible radiation in the length unit of solar collector's each tube is affected by many factors including structural parameters such as collector type and central distance between the adjacent tubes and the geometric parameters such as the size of solar collector's vacuum tubes, tilt angle and azimuth, usage of the diffuse flat reflector (DFR), latitude, and weather conditions. The use of DFR can significantly increase the annual collectible radiation. Among the collectors with the same parameters, T-type collectors annually collect the radiations a little more than H-type collectors. In contrast to the flat plate collectors which have favorable tilt angle close to the latitude in most areas, the vacuum tube solar collectors generally must be installed with a tilt angle of less than location's latitude to maximize the annual energy collection, particularly in the areas with the weak solar resources. The results also show that for the south-facing collector, 10-degree deviation from the desired tilt angle results in less than 5% reduction of annual collectible radiation which implies that the most of the installation areas of T-type collectors in tilt angle equal to the location's latitude seems acceptable, but such installation is not reasonable for the H-type collectors without DFR.

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