# THE EFFECT OF THE INTERMEDIATE FLUID-FLOW RATE ON THE SYSTEM PERFORMANCE IN THE CLOSED CIRCUIT APPLICATIONS OF THE SOLAR COLLECTOR

by

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*Solar collector water heating system use solar thermal energy to provide hot water for domestic and industrial use. These systems are operated either as open-loop or closed-loop flow circuit. The former loop systems are not recommended for the cold climates having water freezing problem. Although previous studies on solar collectors have used closed-loop operation with water as the working fluid. However, it must have high boiling and low freezing points for the colder regions and thus arises the need for antifreeze mixtures of water. Another solution the same problem is the use of heat transfer oil as intermediate working fluids. In the present study, the energy and exergy analysis of a boiler supported vacuum tube solar collector system working with closed-loop in different working fluid-flow rates have been performed and evaluated. Heat transfer oil has been used as an intermediate working fluid in the closed loop system at different flow rates of 0.277 kg/s, 0.383 kg/s, and 0.494 kg/s. The results show that the collector temperature difference as well as the outlet temperature decrease. However, the collector inlet temperature increases by increasing the flow rate. Moreover, with the increase in flow rate, it was ascertained that the energy and exergy efficiency of the system and the collectors increase. The main finding of the present study is that the intermediate fluid used in the closed-circuit operation of the solar collectors has a direct effect on the energy and exergy efficiency of the system.*

Key words: *energy and exergy analysis, heat transfer oil,*
*closed-loop vacuum tube solar collector*

## Introduction

Studies on RES have become compulsory for a sustainable development in energy. Solar energy is one such source which is inexhaustible, easy-to-use, and environment friendly. Solar water heaters (SWH) are one of the applications of solar thermal technologies. In SWH, thermal energy of Sun is absorbed and delivered by solar energy collectors. Solar collectors are classified as passive and active circulation systems depending on the circulation method of heat transfer fluid (HTF). Each ciruclation method may be designed either as open or closed loop system [1]. Passive circulation systems are self-circulating and work on the principle of variable HTF density. Therefore, in such systems, the HTF reservoir must be elevated above

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the collector. In active circulation systems, HTF is circulated by a pump and therefore, they do not require overhead reservoir. Open-loop systems circulate the same amount of water circulating in the collector which is required for use and for this reason such systems are preferable in regions that are free from water freezing problems [2]. Closed-loop systems use two different fluids: one of which gets heated by the solar energy absorbed in the collector and then transfers the same to the other fluid by means of a heat exchanger. Such systems are used as solutions to frost and corrosion [3]. Heating fluids used in the closed systems are also referred as intermediate fluids. These fluids must have lower freezing temperatures and higher boiling temperatures than water.

Flat plate solar collectors are the most researched technology in producing domestic hot water [4]. However, vacuum tube solar collectors perform better than flat plate collectors due to the vacuum insulation that prevents heat loss [5]. Study on vacuum tube collectors has been increasing in recent years. The studies mostly focus on the arrangement of vacuum tubes on the panels, their optical designs, heat transfer and performance. Budihardjo *et al.* [6] reported that the temperature of the tank strongly influenced the circulation flow rate in the tubes in applications where the vacuum tube collectors were attached to the direct storage tank. Ma *et al.* [7] pointed out that the surface temperature of the absorbent coating is an important parameter for evaluating the thermal performances of glass evacuated tube solar collector. Liang *et al.* [8] have indicated that the efficiency of the copper-finned *U*-tube vacuum solar collector is 12% higher than that of the *U*-tube vacuum solar collector. Kim and Seo [9] pointed out that the performances of vacuum tube solar collectors are influenced by the shape of the absorbent plate and the arrangement of the vacuum tubes in the panels. Han *et al.* [10] pointed out that vacuum tube solar collectors should require a good vacuum environment to achieve higher thermal efficiency.

In the past, solar collectors have been mostly investigated as open-loop solar energy systems [11-16]. However, there are a few studies that used the closed-loop methods for evaluation of such collectors [17]. One of the major evaluation methods for these collectors have been the exergy analysis. For example, Badescu [11] conducted an exergy analysis of open-plate solar collectors during the winter and spring seasons at different times of the day. He found an average exergy yield of 1.5% for flat plate collectors. Moreover, he also suggested that the flat plate collectors had a maximum exergy yield less than 3% during both winter and spring seasons at different temperatures. In another study, Xiaowu and Ben [12] determined the average exergy yield of the domestic scale open-circuit flat plate solar collectors to be 2.1%. Also, Farahat *et al.* [13] obtained maximum exergy yield of 3.988% using open-loop flat plate solar collectors in their study of different flat plate areas at different flow rates. Similarly, Ge *et al.* [14] found that exergy yield of open collector flat plate solar collectors was 5.96% . In another study, Jafarkazemi and Ahmadifard [15] open-circuit flat plate collectors obtained exergy efficiency of 4.7% . In summary, the aforementioned exergy studies show that the lowest and the highest exergy efficiencies of open-circuit flat plate collectors ever found are 1.5% and 5.96%, respectively. On the other hand, for open-circuit vacuum tube collectors Gang *et al.* [16] conducted an exergy analysis of combined parabolic condenser reflector of vacuum tube solar collectors. At the end of the analysis, they concluded that the exergy yield (average 5%) of the reflector vacuum tube collector in low heat applications is better than the reflectorless vacuum tube collector (4.5% on average). However, in high temperature applications, they found that the efficiency of reflectorless vacuum tube collectors (average 6.5%) was better than the efficiency of reflector vacuum tube collector (average 5.5%) . Yildizhan and Sivrioglu [17] conducted energy and exergy analysis of a closed-circuit vacuum tube solar collector system.

They used a 40% antifreeze-water mixture as an intermediate fluid in the experimental investigation and determined average energy and exergy yield of experimental system to be 12% and 0.3%, respectively. However, the average energy and exergy efficiency of the vacuum tube solar energy collector, found to be 13.6% and 1.3%, respectively.

To operate closed-circuit solar collector systems at high temperatures and low freezing points, it becomes necessary to use different types of intermediate fluids that can work at these points. The water does not have high boiling and low freezing points and for this reason, the closed circuit systems of solar collectors, widely use antifreeze-water mixture for the intermediate fluid [18-20]. In such systems, the heat transfer oil (HTO) is used as an intermediate fluid [18, 21]. In the present study, the effect of the intermediate fluid-flow rates on the system performance in the closed circuit applications of the solar collectors is examined. In addition, the effect of the working fluid-flow rate on the exergy loss and the efficiency of the experimental system has been investigated. Also, the temperature difference between inlet and outlet of the collectors has been examined at different flow rates.

## Materials and methods

The schematic of the experimental system used in the present study is shown in fig. 1. It includes a hot water production system, established in Hakkari, Turkey. It is a closed-loop and active type of system that involves a boiler-assisted vacuum tube solar collector [22]. Due to an active and closed circuit operation of the system, HTO has been used as an intermediate fluid, circulated by a pump between the vacuum tube solar collector and the boiler. In general, HTO provides excellent thermal stability and provide good heat transfer properties through a heat exchanger in a closed-loop low pressure systems [23].

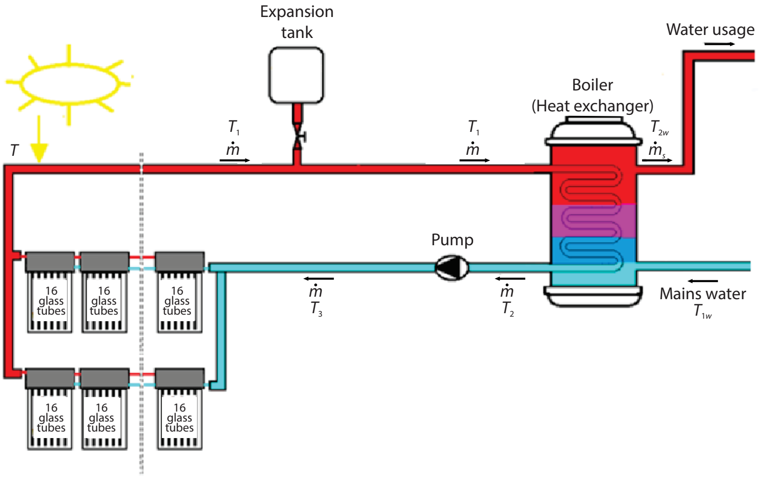

**Figure 1. The schematic of the vacuum tube hot water production system**

The accuracy of measuring any parameter during experiments was ensured through an error analysis [24]. The total error $W_R$ uncertainty for errors occurring in this case can be found [25]:

$$W_R = \left[ \left( \frac{\partial R}{\partial x_1} w_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots + \left( \frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \tag{1}$$

where $R$, $x_1$, $x_2$, ... $x_n$ is a given function of independent variables. The $W_1$, $W_2$, .., $W_n$ are the uncertainties of the independent variables. The total errors of the measurements were obtained as ±0.424 for temperatures, ±0.141 for flow rate and ±0.144 for solar radiation.

In the present study, BP Transcal N, an HTO has been used as an intermediate fluid because it has lower freezing and higher boiling points than water. Its thermophysical properties are provided in tab. 1. Its fuction is to transfer thermal energy from the collector to the water via the boiler at 0.277 kg/s, 0.383 kg/s, and 0.494 kg/s flow rate.

**Table 1. Some features of the BP Transcal N an HTO [26]**

| Feature | Typical value |
|---|---|
| Density (15,5 °C) | 0,875 g/ml |
| Flash point | 243 °C |
| Thermal conductivity | |
| 40 °C | 0.131 W/mK |
| 100 °C | 0.128 W/mK |
| 200 °C | 0.120 W/mK |
| 300 °C | 0.113 W/mK |
| Specific heat capacity | |
| 40 °C | 1.89 kJ/kgK |
| 100 °C | 2.16 kJ/kgK |
| 200 °C | 2.52 kJ/kgK |
| 300 °C | 2.88 kJ/kgK |

### *Analysis of the experimental system*

Conditions that cause exergy losses in solar collector systems include the optics of collectors because of which access to full solar energy is denied, large temperature difference causing heat loss, frictional losses in pipes and fast expansion or compression events.

The specific exergy of a flowing can be written [27]:

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{v^2}{2} + gz \tag{2}$$

where $h$ and $s$ is the enthalpy and entropy at a given temperature $T$, $v$ – the velocity of the fluid, g – the gravitational constant, and $z$ – the elevation, 0 – the subscript shows the properties at dead state temperature $T_0$. In eq. (2), the kinetic and potential energy terms may be neglected because the pressure changes in the system are too small and there is no significant elevation difference. Hence, eq. (2) is reduced:

$$\psi = (h - h_0) - T_0(s - s_0) \tag{3}$$

Two different intermediate fluids *i. e*. HTO and water circulate in the experimental system which may be regarded as incompressible substances. Therefore, the eq. (3) can be transformed [28]:

$$\psi = C_p\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) \tag{4}$$

Considering each element (collector, boiler, and pump) that constitute the boiler-supported vacuum-tube solar collector system as the control volume, the total irreversibility rate or rate of exergy loss can be calculated using a given mass-flow rate $\dot{m}$ [27, 28]:

$$E\dot{x}_{\text{loss}} = \sum\left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k - \sum\dot{W} + \sum\dot{m}_{\text{in}}\psi_{\text{in}} - \sum\dot{m}_{\text{out}}\psi_{\text{out}} \tag{5}$$

where $\dot{Q}_k$ is the heat transfer rate at a temperature $T_k$ and $\dot{W}$ – the work rate.

The exergtic evaluation of the experimental system is composed of the determination of exergetic efficiency of two subsystems of the entire set-up, *i. e.*, vacuum tube solar collector and experimental system. Exergetic efficiency of the solar collector systems is defined as the ratio of the increase in water exergy to the exergy of solar radiation falling on the collector surface [29].

The instantaneous exergy increase of HTO $E\dot{x}_{\text{u,col}}$ can be calculated:

$$E\dot{x}_{\text{u,col}} = \dot{m}_{\text{oil}} C_{p_{\text{oil}}} (T_1 - T_3) - T_0 \left( \ln \frac{T_1}{T_3} \right) \tag{6}$$

Exergy efficiency of solar systems is largely dependent on solar radiation [30-33]. Exergy of solar radiation provided by the collector [34]:

$$E\dot{x}_{\text{in,rad}} = A_{\text{col}} I \left[ 1 + \frac{1}{3} \left( \frac{T_0}{T} \right)^4 - \frac{4}{3} \frac{T_0}{T} \right] \tag{7}$$

where $A_{\text{col}}$ is the surface area of collectors, $I$ – the radiation intensity, and $T$ – the solar radiation temperature.

Hence, the collector's exergy efficiency $\eta_{11,\text{col}}$ may be given:

$$\eta_{\text{u,col}} = \frac{E\dot{x}_{\text{u,col}}}{E\dot{x}_{\text{in,rad}}} \tag{8}$$

The exergetic efficiency of the system is the ratio of instantaneous exergy increase of system using water to the rate of exergy of solar radiation coming to the collector surface. Instantaneous exergy increase of the system using water can be written [35]:

$$E\dot{x}_{\text{u,sys}} = \dot{m}_{\text{w}} C_{p_{\text{w}}} \left[ \left( T_{2\text{w}} - T_{1\text{w}} \right) - T_0 \left( \ln \frac{T_{2\text{w}}}{T_{1\text{w}}} \right) \right] \tag{9}$$

Hence, the system's exergetic efficiency can be calculated [29, 35]:

$$\eta_{\text{u,sys}} = \frac{E\dot{x}_{\text{u,sys}}}{E\dot{x}_{\text{in,rad}}} \tag{10}$$

## Results and discussion

In the present study, a comparison of the energy and exergy performance of vacuum tube solar collecting system at different flow rates has been presented. In addition, the inlet and outlet temperatures of the collector and the temperature difference in the collector of the intermediate fluid circulating in the collector have been examined. In the analysis of the experimental system, the determined parameters include: exergy losses of the collector, the boiler and the circulation pump, energy and exergy efficiency of the collector, and energy and exergy efficiency of the system. The investigations have been conducted by determining collector inlet and outlet temperatures, ambient temperature and radiation intensity values obtained at 0.277 kg/s operational flow rate on August 4, 2012 from the test system and are plotted in figs. 2-4.

From figs. 2 and 3, it can be observed that the inlet, outlet and the difference of temperatures increase up to 12 o'clock and reach the maximum level at this time. These results are endorsed by the increasing trend of the intensity of the solar radiation incident on the collector surface for the same time duration. This intensity is also maximum at 12 o'clock thus giving the maximum temperatures in the collector. The maximum temperature difference observed is

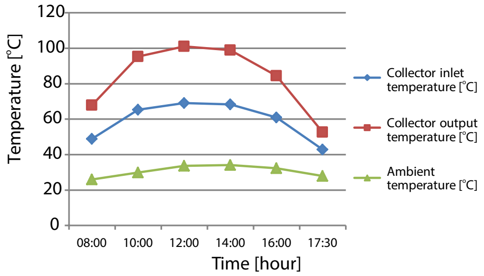

**Figure 2. Variations of collector inlet, outlet, and ambient temperatures during the day time on August 4, 2012**

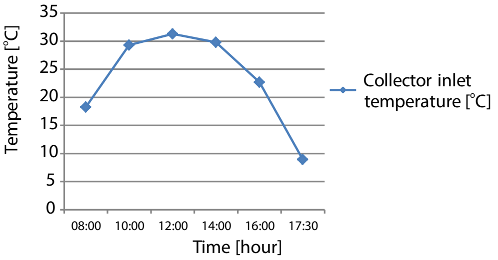

**Figure 3. Variations of collector temperature difference values during the day time on August 4, 2012**

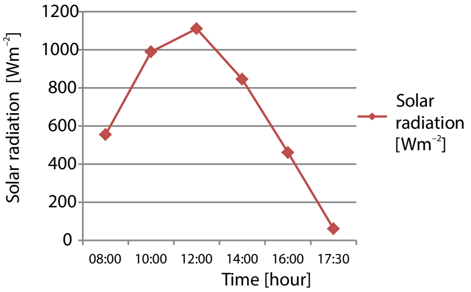

**Figure 4. Values of solar radiation incident on the collector during the day time on August 4, 2012**

slightly more than 30 °C which is equivalent of the difference between the collector inlet temperature and the outlet temperature, *i. e.* 70 °C and 100 °C, respectively. After 12:00 p. m., all the temperatures start decreasing in accordance with the trend of intensity of solar radiation. Hence, it can be inferred that the collector temperatures are a strong function of intensity of solar radiation.

Similar trends can be observed at a different flow rate of 0.383 kg/s on different day on August 18, 2012 as shown in figs. 5-7. However, there is a reduced temperature values for collector inlet and outlet, despite increased intensity of solar radiations on August 18, 2012. These reductions in temperatures and corresponding differences of the collector may be attributed to the increased mass-flow rate. It means that the fluid inside the collector does not get enough time to absorb heat from the incident solar radiations because of the increased flow rate.

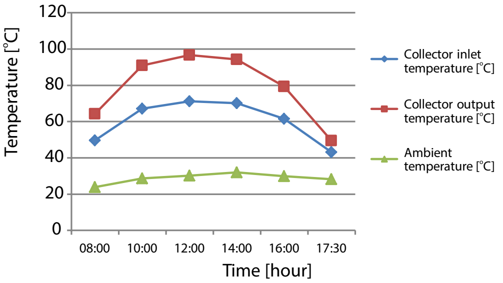

**Figure 5. Variations of collector input, output, and ambient temperature values during the day time on August 18, 2012 at a flow rate of 0.383 kg/s**

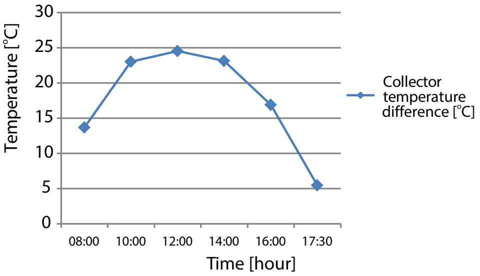

**Figure 6. Variations of collector temperature difference values during the day time on August 18, 2012 at a flow rate of 0.383 kg/s**

The same is true for another different flow rate of 0.494 kg/s used for the investigation of collector temperatures conducted on August 10, 2012 as shown in figs. 8-10, although the intensity of solar radiations is small. Here, a further reduction in temperatures is found with a further increase of flow rate thereby showing that the fluid-flowing through the system has smaller contact time required for heat exchange.

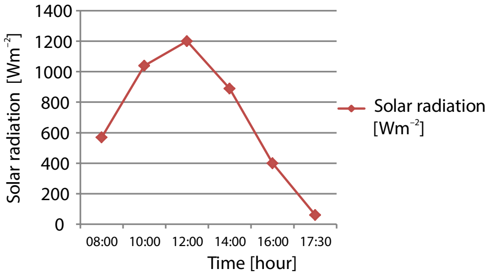

**Figure 7. Values of solar radiation incident on the collector during the day time on August 18, 2012 at a flow rate of 0.383 kg/s**

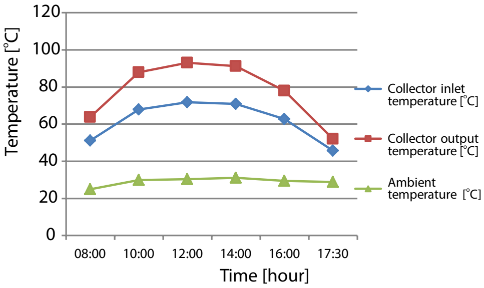

**Figure 8. Variations of collector input, output, and ambient temperature values during the day time on August 10, 2012 at a flow rate of 0.494 kg/s**

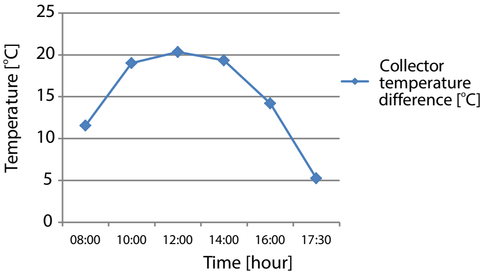

**Figure 9. Variations of collector temperature difference values during the day time on August 10, 2012 at a flow rate of 0.494 kg/s**

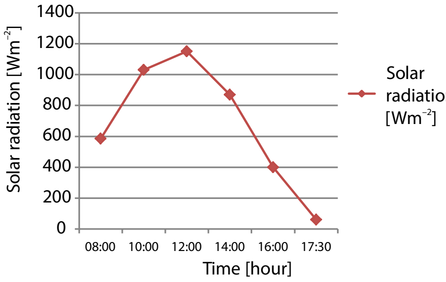

**Figure 10. Values of solar radiation incident on the collector during time on August 10, 2012 at a flow rate of 0.494 kg/s**

In conclusion, it can be inferred that the solar radiation intensity values directly affect the performance of the collectors. The collector inlet temperature, collector outlet temperature and the collector temperature difference values are increased or decreased depending on the increase or decrease of the solar radiation intensity incident on the collector surface. In all cases, it is observed that the solar radiation incident on the collector surface increases up to 12:00 p. m. and is at the maximum level at that time. Later, the radiations incident on the collector surface decrease. A slow decline in collector inlet-outlet temperatures has been observed, although the intensity of radiation at the collector surface drops rapidly after 12:00 p. m. However, the ambient temperature does not drop immediately and the specific heat of the intermediate fluid used in the system (HTO = 1.89 kJ/kgK) is not very low.

From the experiments, it has been observed that because of the increase in flow rate, the inlet temperature of the HTO to the vacuum tube collector increases and the outlet temperature decreases. However, the temperature difference of the circulating HTO in the solar collector decreases by the increase of the flow rate. Moreover, from the experimental results it can be found that the decrease in the temperature difference of the vacuum tube collector, the energy and exergy efficiency of the experimental system increases.

Energy and exergy efficiencies of the collector and system at different flow rates when HTO is used as an intermediate fluid has been tabulated in tab. 2 and are plotted in figs. 11 and 12. The experimental results have been analyzed according to the near climatic conditions (solar radiation and environmental temperature) based on average values of single day. The tab. 2 clearly shows that most loss of exergy occurs in vacuum tube solar collector, followed by boiler and pump. Also, it was determined that the ambient temperature and radiation intensity value

**Table 2. Energy and exergy efficiencies of the collector and system at different flow rates for using HTO as a intermediate fluid**

| Date | Flow rate [kgs$^{-1}$] | Solar radiation [Wm$^{-2}$] | Ambient temperature [°C] | Boiler exergy loss [kW] | Pump exergy loss [kW] | Collector exergy loss [kW] | Collector energy efficiency | Collector exergy efficiency | System energy efficiency | System exergy efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| 04/08/2012 | 0.277 | 764.50 | 31.325 | 1.3840 | 0.363 | 135.931 | 0.138 | 0.016 | 0.065 | 0.0004 |
| 18/08/2012 | 0.383 | 791.0 | 29.229 | 2.5200 | 0.6273 | 139.714 | 0.1475 | 0.0181 | 0.0852 | 0.0014 |
| 10/08/2012 | 0.494 | 775.50 | 29.579 | 2.6394 | 0.8950 | 136.933 | 0.1527 | 0.0187 | 0.0856 | 0.0015 |

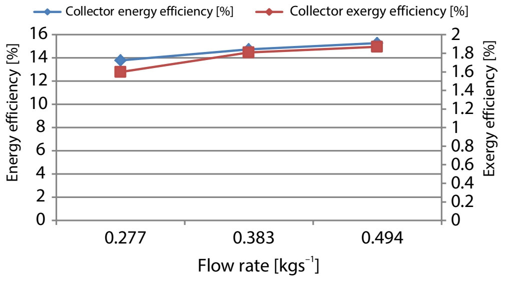

**Figure 11. Effect of flow rate on energy and exergy of collector**

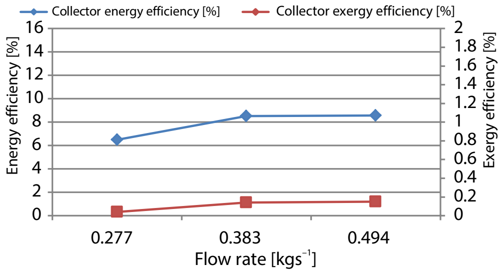

**Figure 12. Effect of flow rate on energy and exergy of system**

of 0.383 kg/s flow rate on August 18, 2012 is smaller than the ambient temperature values on other days and the radiation intensity value is larger than the other days. For this reason, it has been determined that the exergy efficiency values at 0.383 kg/s flow rate of the experimental system are close to the exergy efficiency values at 0.494 kg/s flow rate. This result shows the effect of ambient temperature and solar radiation intensity on the exergy yield of solar collector systems. Especially in the exergy analysis of the experimental system, it has been determined that the ambient temperature has a significant influence on the efficiency results. For example, in two solar collector systems with the same solar radiation value, the system with low ambient temperature value has a high exergy efficiency. Therefore, the higher ambient temperature values negatively affects the exergy efficiency of solar collectors. As a result, in the exergy analysis of solar collector applications, solar radiation intensity and environmental temperature have a significant effect.

Referring to figs. 11 and 12, it can be observed that the energy and exergy efficiencies of the system and collector are increased due to the increase of the flow rate. The increase in energy and exergy yields seems to be parallel to each other. However, looking at figs. 11 and 12, it can be seen that there are big differences between the energy and exergy yields of the experimental system and the collector. It can also be observed that the energy efficiency of the collector is between 13.8-15.27% and the exergetic efficiency is between 1.6-1.87%. In addition, when the energy efficiency of the experimental system is 6.5-8.56%, the corresponding exergy efficiency is 0.04-0.15%. These results show that the availability (exergy) of the energy transferred to the utility water of a closed-circuit solar collector system is very low.

## Conclusions

In the present study, energy and exergy analysis of vacuum tube solar collector system working with closed-loop in different working fluid-flow rates have been performed and evaluated. The HTO has been used as an intermediate working fluid in the closed loop system at different flow rates of 0.277 kg/s, 0.383 kg/s, and 0.494 kg/s. The results show that the increase in flow rates have increased the efficiency of the system as well as the energetic and exergetic efficiences by an increase of energy supplied to the water. The efficiencies obtained in the present study are less than the open-loop circuit type collector systems. It has also been found that the exergetic efficiency of the experimental system is less than that of the solar collector because of the irreversibility of the heat transfer at the finite temperature difference [28]. As a result, the the exergy transferred to the water from the vacuum tube solar collector through a boiler is decreased. It has been found that the collector temperature difference and the collector outlet temperature are increased by decreasing the flow rate, and at the same time, the collector inlet temperature is decreased. At different working flow rates of the HTO used as an intermediate fluid in the experimental system, the collector temperature difference values at 12 o'clock at the highest solar radiation intensity, were 30°C, 20°C, and 20°C at 0.277 kg/s, 0.383 kg/s, and at 0.438 kg/s, respectively.

A comparison between the results of the present study and the study of Yildizhan and Sivrioglu [17] shows that the system efficiency obtained by latter study is higher than the former study. However, the collector efficiency obtained in the present study is higher than the latter. Since specific heat capacity of HTO (1.89 kJ/kgK at 40 °C) is less than the 40% mixture of antifreeze-water (3.59 kJ/kgK at 40 °C). Therefore, it responded to the solar radiation in a faster and better way. For this reason, 40% antifreeze-water mixture takes more time in getting heated and cooled than that of HTO. The fact that HTO being used as intermediate fluid has increased the efficiency values of vacuum tube collectors more than the 40% antifreeze-water mixture. With the use of HTO, the collector energy and exergy efficiency is around 14.63% and 1.77%, respectively. Contrary to this, with 40% antifreeze-water mixture; collector energy and exergy efficiency is around 14.36% and 1.33%, respectively. On the other hand, the thermal conductivity of HTO (0.131W/mK, at 40 °C) is less than that of 40% antifreeze-water mixture (0.440 W/mK, at 40 °C). For this reason, in the boiler functioning as heat converter, the energy transmitted to the water by the HTO is better than the 40% antifreeze-water mixture. The use of 40% antifreeze-water mixture as the intermediate fluid in the experiment system has more efficiency than the use of HTO. For the former intermediate fluid, the energy and exergy efficiency of the system is around 12.32% and 0.37%, respectively. However, for the latter fluid use in the present study, the energy and exergy efficiency of the system is around 8.16% and 0.13%, respectively.

In short, in solar collector applications, the increase in system efficiency is directly related to the working fluid-flow rates. In closed-loop circuit solar collecting systems, the working fluid is the intermediate flow and therefore, the properties of the intermediate fluid directly affect the efficiency of the systems. For future, it is recommended to use different intermediate fluids for performance analysis of such systems.

## Nomenclature

$A$ – area, [m$^2$]
$I$ – amount of solar radiation per unit area surface, [kWm$^{-2}$]
$C_{p\mathrm{w}}$ – specific heat of water at constant pressure, [kJkg$^{-1}$K$^{-1}$]
$C_{p\mathrm{oil}}$ – specific heat at constant pressure of the HTO, [kJkg$^{-1}$K$^{-1}$]
$E_{\dot{x}}$ – exergy rate, [kW]
$h$ – specific entalpy, [kJkg$^{-1}$]
$\dot{m}_{\mathrm{oil}}$ – mass-flow rate of HTO, [kgs$^{-1}$]

$\dot{m}_w$ – mass-flow rate of water, [$kgs^{-1}$]
$s$ – specific entropy, [$kJkg^{-1}K^{-1}$]
$T$ – temperature, [K or °C]
$\dot{W}$ – work or power, [kW]
$\dot{Q}$ – heat transfer rate, [kW]

*Greek symbols*

$\eta_{11}$ – exergy efficiency
$\psi$ – specific exergy, [$kJkg^{-1}$]

*Subscripts*

col – collector
u,col – instantaneous exergy increase of collector
u,sys – Instantaneous exergy increase of system
sys – experimental system
0 – dead (reference) state
k – location

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