EXERGY ANALYSIS OF A VACUUM TUBE SOLAR COLLECTOR SYSTEM HAVING INDIRECT WORKING PRINCIPLE

by

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In this study, the energy and exergy analysis of a hot water preparation system, which is a boiler assisted vacuum tube solar collector, has been conducted. The obtained data were compared with reported results in the literature related to direct operating principle system. Average energy and exergy efficiencies of the experimental system were founded 12% and 0.3%, respectively. The average energy and exergy efficiencies of the vacuum tube solar collectors were founded 13.6% and 1.3%. Energy and exergy efficiencies of the vacuum tube solar collectors, which have indirect operating principle, are lower than direct system working with solar collectors. Maximum exergy loss has occurred in the vacuum tube solar collectors and followed it boiler and pump, respectively.

Keywords: *exergy analysis, 40% antifreeze-water mixture, indirect working principle, vacuum tube solar collector*

Introduction

Renewable energy sources are inexhaustible. These energy sources provide many environmental benefits, compared to fossil fuels. Solar energy is one of the cheap and environment friendly alternative energy resource. Solar water heating technology is a solar energy using method. Hot water is produced by using solar energy collectors. Flat plate collectors are widely used in water heating systems. These type of collectors are, directly, affected from the cold weather conditions. So, this situation decrease the performance of the water heating systems. The performance of vacuum tube solar collectors is compared to flat plate collectors in the cold weather conditions. Due to they have vacuum insulation which preventing heat losses to ambient.

There are two types of water heating systems running with solar collectors, according to their circuit types. These are direct (open-loop) circuit types and indirect (closed-loop) circuit types [1]. Direct circuit system, working fluid is circulated throughout collector and storage tank without any heat exchanger and domestic water is used as working fluid. Direct circuit types are used in regions, where water is not limeless and no freezing problems, fig. 1.

However, in indirect circuit system, a fluid is circulated through the collector and heat exchanger. An intermediate fluid (working fluid) having low freezing point is used in the collector loop instead of domestic water. Intermediate fluid (working fluid) which is heated in the collector transmits its heat to the domestic water via a heat exchanger located in the stor-

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age tank. Indirect circuit systems are used in cold climate regions where there exist freezing problems. Moreover, these systems are also used for preventing calcification and corrosion, fig. 2.

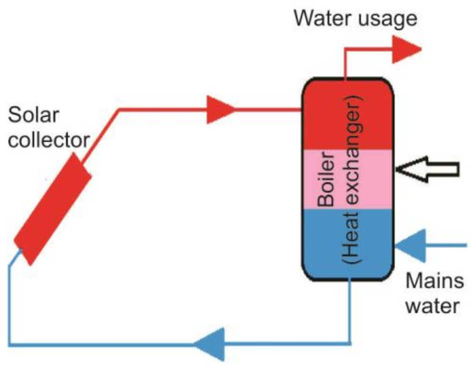

Figure 1. Direct (open-loop) system

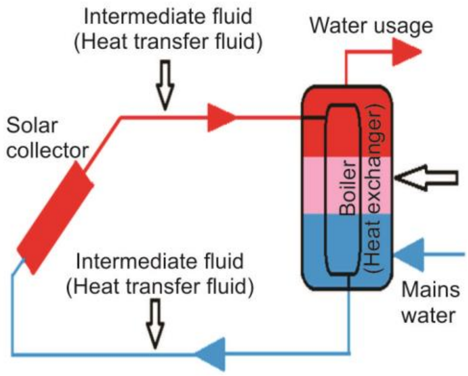

Figure 2. Indirect (closed-loop) system

This study covers the energy and exergy analysis of a boiler assisted vacuum tube solar collector system, the production of which was done in a way having an indirect working principle. In the experimental system, 40% antifreeze-water mixture was used as intermediate fluid (working fluid) and was circulated between the boiler and the collector via a pump, at the mass flow rate of 0.383 kg/s. Exergy analysis were conducted from the experimental data and the results were compared and assessed with direct working system.

Literature review

Vacuum tube solar collectors are getting prevalently used worldwide in the domestic hot water production, with the vacuum insulation preventing heat loss, with their selective surface covers and with their effective heat transmission [2-4]. So far, the related studies of vacuum tube solar collectors consists rather the array of the vacuum tubes in the panels and the studies towards their optical designs and heat transfer. Shah and Furbo [5] have indicated that the vacuum tubes put into the panel one next to the other are hindering the radiation coming from the Sun and this situation decreases the performances of the vacuum tube solar collectors. Morrison *et al*. [6] have stated that the most important difficulty related to the application of the vacuum tube solar collectors is to draw the heat from the vacuum tubes. Kim and Seo [7] have drawn attention to the fact that the performances of the vacuum tube solar collectors are affected from the shape of absorber plate, from the solar radiation incident angle and the array of the vacuum tubes in the panels. Han *et al.* [8] have drawn attention to the fact that a necessity for a good vacuum milieu is needed, in order to attain higher thermal gain, in the vacuum tube solar collectors. Ma *et al*. [9] have indicated that surface heat of absorbing cover is a significant parameter in the thermal performance evaluation of the vacuum tube solar collectors. Liang *et al*. [10] have indicated that activity of U-tube vacuum solar collector with Cu fin has 12% more activity compared to U-tube vacuum solar collector without Cu fin.

Prevalently, the performance evaluation of solar energy is made as energy analysis, based on 1st law of thermodynamics. However, the importance of the quality of the energy rather than the amount of it, has been drawn attention. Many researchers emphasizes the necessity of exergy analysis base on the 2nd law of the thermodynamics [11-13]. In the open literature scanning, there is no study regarding the performance analysis of a heat water production system assisted with the vacuum tube solar collector having an indirect working principle. In the exergy analysis of hot water production systems of both flat plate collectors and vacuum tube collectors direct loop circulation was considered. Average exergy efficiencies were found by the researchers to work with direct principle flat plate collectors; Xiaowu and Ben [14] 2.1%, Gunerhan and Hepbasli [15] 2.4%, Badescu [16] 1.5%, Farahat and Sarhaddi [17] 3%, Jafarkazemi and Ahmadifard 4% [18], and Luminosua and Farab [19] 2.7%. Exergy efficiency of evacuated tube solar collector with direct working principle is evaluated as 5% by Pei *et al*. [20]. It has been noted by the authors that in all studies carried out, in all collector types of hot water production systems, the most exergy loss happened in the collectors.

The material and method

The working principle of the system

The hot water production system which was produced was installed in the garden of Hakkari University Vocational High School, Hakkari, Turkey [21]. Collector field of hot water production system is given in fig. 3. The boiler assisted vacuum tube collector system was constructed according to indirect circuit and active working method. Due to the indirect circuit working principle of the system, intermediate fluid was used. A 40% antifreeze-water mixture was used as intermediate fluid (working fluid) in the collector loop. This intermediate fluid was circulated through vacuum tube solar collector and boiler. The intermediate fluid has lower freezing point and higher boiling point, compared to water. In line with system’s active working principle, the intermediate fluid (40% antifreeze-water mixture) was circulated via a pump. The intermediate fluid was circulated at the constant mass flow rate of 0.383 kg/s by using a pump. The intermediate fluid coming from the collector transmitted its energy to the water, via the boiler. Heated domestic water was circulated through the building. The collector is oriented facing towards south, inclined at an angle equal to 45^o in city of Hakkari, Turkey (latitude 37^o 34, N: longitude 43^o 45, E).

Figure 3. Outlook of the vacuum tube solar collectors from the front

The experimental measurements

Due to the indirect circuit working principle of the experiment system, intermediate fluid was used. The intermediate fluid is 40% antifreeze-water mixture. In the antifreeze-water mixture, the ratio of 40% antifreeze and in the ratio of 60% water was used. The reason why this intermediate fluid is that it has lower freezing point and high boiling point, when compared to water. The thermodynamic properties of 40% antifreeze-water mixture and the domestic water were found by the database of EES program. The information regarding 40% antifreeze-water mixture used in the experiment system has been given in tab. 1.

In the system, between the boiler and the vacuum tube solar collector a pump was used. The electricity power for the pump was read with wattmeter. The power and flow rate values inherent to the pump used in the experiment system have been given in tab. 2.

The measuring tools used in the experiments have been given in tab. 3.

The total uncertainties of the measurements are estimated to be ±0.424% for temperatures, ±0.141% for volumetric flow rates and ±0.144% for solar radiation.

Table 1. Some properties of 40% antifreeze-water mixture found by EES Program

Property	Typical value
Thermal conductivity At 40 °C At 100 °C	 0.440 W/mK 0.483 W/mK
Specific heat capacity At 40 °C At 100 °C	 3.59 kJ/kgK 3.78 kJ/kgK

Table 2. The properties of the pump used in the experiment system

Name of the pump	The value measured with wattmeter [kW]	The measured flow rate value [kgs^{-1}]
Aquadis (VPM50)	0.7	0.383

Table 3. The names and properties of the measuring tools used in the experiment systems

Name	Properties
Field type ultrasonic flow-meter	Model: TFM4100-W Line Diameter: DN25 Outlet: 4-20 mA Measurement Range: ±16 m/sn, liquids not consisting particles Sensitivity: ±1%, –20 to 160 °C, max 120 °C is advised.
J-type headed thermocouple	Sensitivity ±0.4 Maximum temperature for using 300 °C
Ahlborn global radiation probe	Model: FLA613GS Measurement Range: 0-1200 W/m² Sensitivity: ±3% W/m² Working Temperature: Between –20 and +60 °C
Almemo portative datalogger	3 Almemo socket inlet 2 Almemo socket outlet Able to read100 different measurement parameters 12.000 measurement capacity (59 KB)

Exergy analysis of the system

The reasons of exergy losses in solar energy systems are optical losses of the collector heat losses because of the temperature differences between the absorber and ambient, friction losses and the events of fast expansion or reduction.

Flow (specific) exergy of pure substance can be written [22]:

$$\Psi = (h - h_0) - T_0 (s - s_0) \tag{1}$$

where h is the enthalpy, s – the entropy, and the subscript 0 indicates properties at the restricted dead state of T_0.

In the experimental system, two different fluids were circulated. These fluids are water and 40% antifreeze-water mixture. Since these two different fluids are incompressible substances, the specific exergy equation in eq. (2) can be transformed to [23]:

$$\Psi = C_p \left(T - T_0 - T_0 \ln \frac{T}{T_0} \right) \tag{2}$$

where C_p is the specific heat at the constant pressure.

Multiplying flow or specific exergy given in eq. (1) by the mass flow rate of the fluid gives the exergy rate:

$$\dot{E}x = \dot{m}[(h - h_0) - T_0 (s - s_0)] \text{ or} \tag{3}$$

$$\dot{E}x = \dot{m} C_p \left[\left(T - T_0 - T_0 \ln \frac{T}{T_0} \right) \right] \tag{4}$$

If each component comprising the boiler assisted vacuum tube solar collector system (collector, boiler, and the pump) is thought as control volume, the irreversibility or the exergy loss can be calculated:

$$\dot{I} = \dot{E}x_{\text{dest}} = \sum \left(1 - \frac{T_0}{T_\text{k}} \right) \dot{Q}_\text{k} - \dot{W} + \sum \dot{m}_{\text{in}\,\psi\text{in}} - \sum \dot{m}_{\text{out}\,\psi\text{out}} \tag{5}$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature T_k at location k and $\dot{W}$ is the work rate. The eq. (5) is the expression of general exergy balance [24]:

In order to simplify the analysis, the following assumptions have been made.

– All processes are in the steady-state, the effects of potential and kinetic energy have been ignored. There are no chemical reactions.

– The specific heat of the domestic water has been accepted as a constant value. And this value is 4.18 kJ/kg°C.

– In the pump's analysis calculation, the values read in the Wattmeter were used.

– Since the system was insulated with the insulation materials, the heat loss between the collector and boiler was ignored.

The exergy analysis of the experiment system was divided into three subsections shown as in the tab. 4 and fig. 4 and the irreversibilitie's of each section (exergy losses) were calculated.

Table 4. The subsections of the experiment system

Subsection	Control volume
1	Vacuum tube collectors
2	Boiler
3	Pump

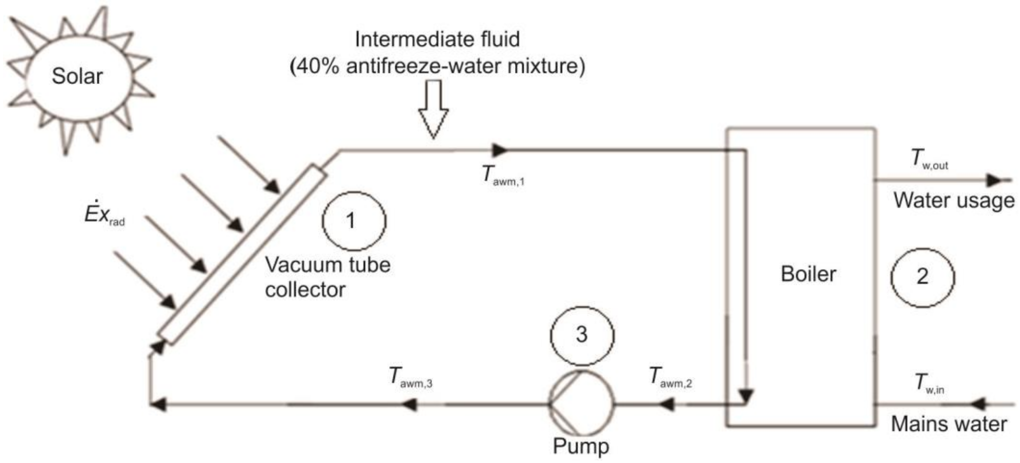

Figure 4. The scheme of all exergy flow in the experiment system

Vacuum tube solar collectors: Loss of exergy

When fig. 4 is investigated, the exergy flows coming to the vacuum tube collectors are the solar flows of $\dot{E}x_{rad}$ and the flows of ψ_3 coming from the pump. The exergy flow going outside from the vacuum tube collectors is ψ_1. If so, the exergy loss expression for the vacuum tube solar collector can be written:

$$\dot{I}_{col} = \dot{m}_{awm}\left(\psi_{awm,3} - \psi_{awm,1}\right) + \dot{E}x_{rad} \tag{6}$$

In eq. (5), the equals of the indicated ψ_3, ψ_1, and $\dot{E}x_{rad}$ are given:

$$\Psi_{awm,1} = \left(h_{awm,1} - h_0\right) - T_0\left(s_{awm,1} - s_0\right), \qquad \psi_{awm,1} = C_{awm}\left[\left(T_{awm,1} - T_0\right) - T_0\left(\ln\frac{T_{awm,1}}{T_0}\right)\right] \tag{7}$$

$$\Psi_{awm,3} = \left(h_{awm,3} - h_0\right) - T_0\left(s_{awm,3} - s_0\right), \qquad \psi_{awm,3} = C_{awm}\left[\left(T_{awm,3} - T_0\right) - T_0\left(\ln\frac{T_{awm,3}}{T_0}\right)\right] \tag{8}$$

and

$$\dot{E}x_{rad} = A_{col}B\left[1 + \frac{1}{3}\left(\frac{T_0}{T_{sr}}\right)^4 - \frac{4}{3}\frac{T_0}{T_{sr}}\right] \tag{9}$$

Amongst the expressions indicated in the eq. (9), A_{col} indicates the total surface area of the vacuum tube solar collectors, B [Wm^{-2}] indicates the radiation intensity, T_{sr} is the solar radiation temperature and taken to be 6000 K, while the Petela expression is used in calculating the exergy of solar radiation as the exergy input to the vacuum tube solar collector [25].

Exergy loss of the boiler

Specific exergy flows to the boiler can be written:

$$\Psi_{awm,1} = \left(h_{awm,1} - h_0\right) - T_0\left(s_{awm,1} - s_0\right), \qquad \psi_{awm,1} = C_{awm}\left[\left(T_{awm,1} - T_0\right) - T_0\left(\ln\frac{T_{awm,1}}{T_0}\right)\right] \tag{10}$$

$$\Psi_{\mathrm{w},1} = \left(h_{\mathrm{w},1} - h_0\right) T_0 \left(s_{\mathrm{w},1} - s_0\right), \qquad \psi_{\mathrm{w},1} = C_\mathrm{w} \left[\left(T_{\mathrm{w},1} - T_0\right) - T_0 \left(\ln \frac{T_{\mathrm{w},1}}{T_0}\right)\right] \tag{11}$$

The specific exergy flows going outside the boiler can be defined:

$$\Psi_{\mathrm{awm},2} = \left(h_{\mathrm{awm},2} - h_0\right) - T_0 \left(s_{\mathrm{awm},2} - s_0\right), \quad \psi_{\mathrm{awm},2} = C_\mathrm{awm} \left[\left(T_{\mathrm{awm},2} - T_0\right) - T_0 \left(\ln \frac{T_{\mathrm{awm},2}}{T_0}\right)\right] \tag{12}$$

$$\Psi_{\mathrm{w},2} = \left(h_{\mathrm{w},2} - h_0\right) T_0 \left(s_{\mathrm{w},2} - s_0\right), \qquad \psi_{\mathrm{w},2} = C_\mathrm{w} \left[\left(T_{\mathrm{w},2} - T_0\right) - T_0 \left(\ln \frac{T_{\mathrm{w},2}}{T_0}\right)\right] \tag{13}$$

So, the next equation can be written for the exergy loss in the boiler:

$$\dot{I}_\mathrm{boy} = \dot{m}_\mathrm{awm} \left(\psi_{\mathrm{awm},1} - \psi_{\mathrm{awm},2}\right) + \dot{m}_\mathrm{w} \left(\psi_{\mathrm{w},1} - \psi_{\mathrm{w},2}\right) \tag{14}$$

The exergy loss of the pump

The specific exergy, ψ_2, and the pump power, $\dot{W}_\mathrm{pump}$, enter the pump:

$$\Psi_{\mathrm{awm},2} = \left(h_{\mathrm{awm},2} - h_0\right) - T_0 \left(s_{\mathrm{awm},2} - s_0\right), \quad \psi_{\mathrm{awm},2} = C_\mathrm{awm} \left[\left(T_{\mathrm{awm},2} - T_0\right) - T_0 \left(\ln \frac{T_{\mathrm{awm},2}}{T_0}\right)\right] \tag{15}$$

$$\dot{W} = \dot{W}_\mathrm{pump} \tag{16}$$

The specific exergy, ψ_3, going outside the pump can be defined:

$$\Psi_{\mathrm{awm},3} = \left(h_{\mathrm{awm},3} - h_0\right) - T_0 \left(s_{\mathrm{awm},3} - s_0\right), \quad \psi_{\mathrm{awm},3} = C_\mathrm{awm} \left[\left(T_{\mathrm{awm},3} - T_0\right) - T_0 \left(\ln \frac{T_{\mathrm{awm},3}}{T_0}\right)\right] \tag{17}$$

As a consequence, the exergy loss in the pump [26-28]:

$$\dot{I}_\mathrm{pump} = \dot{W}_\mathrm{pump} - \dot{m}_\mathrm{awm} \left(\psi_{\mathrm{awm},3} - \psi_{\mathrm{awm},2}\right) \tag{18}$$

is attained as previous.

Energy and exergy efficiencies

Energy and exergy efficiencies of the experimental system are constituted by two parts which are vacuum tube solar collector efficiency and the efficiency of the system. The work done by the pump is neglected, thus it is not included in the calculation of efficiency.

The vacuum tube solar collector's instantaneous thermal efficiency can be defined as a ratio of the actual useful energy collected, $\dot{Q}_\mathrm{u,col}$ from the collector and absorbed solar energy by the collector gross area, A_col, *i. e.* and is calculated [29]:

$$\eta_\mathrm{en,col} = \frac{\dot{Q}_\mathrm{u,col}}{A_\mathrm{col} B} \tag{19}$$

with the instantaneous usable energy collected by vacuum tube solar collector given by:

$$\dot{Q}_\mathrm{u,col} = \dot{m}_\mathrm{awm} C_\mathrm{awm} \left(T_\mathrm{awm,out} - T_\mathrm{awm,in}\right) \tag{20}$$

where $T_\mathrm{awm,out} - T_\mathrm{awm,in}$ is the input and output temperatures of the 40% antifreeze-water mixture through the vacuum tube solar collector and C_awm is the specific heat of the 40% antifreeze-water mixture.

Instantaneous thermal efficiency of the system can be defined as a ratio of the actual useful energy collected $\dot{Q}_{\text{u,sys}}$ from the system and absorbed solar energy by the collector gross area, A_{col}, *i. e.* and is calculated:

$$\eta_{\text{en,sys}} = \frac{\dot{Q}_{\text{u,sys}}}{A_{\text{col}} B} \tag{21}$$

with the instantaneous usable energy collected by experimental system is given by:

$$\dot{Q}_{\text{u,sys}} = \dot{m}_{\text{w}} C_{\text{w}} \left(T_{\text{w,out}} - T_{\text{w,in}} \right) \tag{22}$$

where $T_{\text{w,out}} - T_{\text{w,in}}$ is the input and output temperatures of the water through the boiler, respectively, and C_{w} is the specific heat of the water.

The exergy efficiencies inherent to the experiment system were found for the second section. These are the collector efficiency and the experimental system efficiency. The exergy efficiency of the vacuum tube solar collector is the ratio of the instantaneous exergy increase with the solar radiation exergy hitting the collector surface [30].

If fig. 4 is investigated, the instantaneous exergy increase in the vacuum tube solar collector becomes $\psi_{\text{awm,1}} - \psi_{\text{awm,3}}$. And the solar radiation exergy provided by the collector is attained through the equation below:

$$\dot{E}x_{\text{rad}} = A_{\text{col}} B \left[1 + \frac{1}{3} \left(\frac{T_0}{T_{\text{sr}}} \right)^4 - \frac{4}{3} \frac{T_0}{T_{\text{sr}}} \right] \text{ so} \tag{23}$$

$$\dot{E}x_{\text{in}} = \dot{E}x_{\text{rad}} \text{ and} \tag{24}$$

$$\dot{E}x_{\text{u,col}} = \dot{m}_{\text{awm}} \left(\psi_{\text{awm,1}} - \psi_{\text{awm,3}} \right) \tag{25}$$

$$\Psi_{\text{awm,1}} = \left(h_{\text{awm,1}} - h_0 \right) - T_0 \left(s_{\text{awm,1}} - s_0 \right), \quad \psi_{\text{awm,1}} = C_{\text{awm}} \left[\left(T_{\text{awm,1}} - T_0 \right) - T_0 \left(\ln \frac{T_{\text{awm,1}}}{T_0} \right) \right] \tag{26}$$

$$\Psi_{\text{awm,3}} = \left(h_{\text{awm,3}} - h_0 \right) - T_0 \left(s_{\text{awm,3}} - s_0 \right), \quad \psi_{\text{awm,3}} = C_{\text{awm}} \left[\left(T_{\text{awm,3}} - T_0 \right) - T_0 \left(\ln \frac{T_{\text{awm,3}}}{T_0} \right) \right] \tag{27}$$

It becomes just as previous. And the exergy efficiency of the collector:

$$\eta_{\text{ex,col}} = \frac{\dot{E}x_{\text{u,col}}}{\dot{E}x_{\text{in}}} \tag{28}$$

can be calculated with the eq. (28).

The instantaneous exergy efficiency of the experimental system can be defined as the ratio of the increased water exergy to the exergy of the solar radiation [29]. If fig. 4 is investigated, the instantaneous exergy increase in the experimental system becomes $\psi_{\text{2water}} - \psi_{\text{1water}}$. So, it becomes:

$$\dot{E}x_{\text{in}} = \dot{E}x_{\text{rad}} \text{ and} \tag{29}$$

$$\dot{E}x_{\text{u,sys}} = \dot{m} \left(\psi_{\text{w,2}} - \psi_{\text{w,1}} \right) \tag{30}$$

$$\Psi_{\text{w,2}} = \left(h_{\text{w,2}} - h_0 \right) - T_0 \left(s_{\text{w,2}} - s_0 \right), \quad \psi_{\text{w,2}} = C_{\text{w}} \left[\left(T_{\text{w,2}} - T_0 \right) - T_0 \left(\ln \frac{T_{\text{w,2}}}{T_0} \right) \right] \tag{31}$$

$$\Psi_{\mathrm{w,1}} = \left(h_{\mathrm{w,1}} - h_0\right) - T_0\left(s_{\mathrm{w,1}} - s_0\right), \qquad \psi_{\mathrm{w,1}} = C_{\mathrm{w}}\left[\left(T_{\mathrm{w,1}} - T_0\right) - T_0\left(\ln\frac{T_{\mathrm{w,1}}}{T_0}\right)\right] \tag{32}$$

and the system efficiency becomes:

$$\eta_{\mathrm{ex,sys}} = \frac{\dot{E}x_{\mathrm{u,sys}}}{\dot{E}x_{\mathrm{in}}} \tag{33}$$

Case study

Performance of the experimental set-up was observed for five days. Experiments were conducted between 8:00 a. m. and 5:30 p. m.. Measurements were recorded in every 30 minutes. Water temperature at input and output of the collector, feed water temperature at input and output of the boiler, water temperature at input and output of the pump, ambient temperature, mass flow rates, and solar radiation on the inclined surface were recorded. Daily average of the recorded values was used to investigation of performance of the experimental set-up. The data obtained from the tests in the solar water heating system are based on August 2012 from 08:00 a. m. to 5:00 p. m., as listed in tab. 5.

Table 5. The input and output temperatures of the 40% antifreeze-water mixture through the vacuum tube solar collector

Date	Local time, [hour]	Temperature, [°C]	
		Inlet	Outlet
20.08.2012	08:00	42.6	50.4
	10:00	58.2	70.9
	12:00	63.5	77.2
	14:00	64.1	77.2
	16:00	57.1	66.3
	17:30	40.2	42.5
21.08.2012	08:00	42.2	50
	10:00	57.8	70.9
	12:00	62.6	76.7
	14:00	63.1	76.2
	16:00	55.4	64.9
	17:30	38.9	41.5
22.08.2012	08:00	42.4	50.2
	10:00	58	70.7
	12:00	63.2	76.9
	14:00	63.8	77
	16:00	56.8	66.1
	17:30	40	42.3
23.08.2012	08:00	42.2	49.7
	10:00	58.7	71.3
	12:00	63.9	77.5
	14:00	64	77.1
	16:00	56.7	65.6
	17:30	40.1	42.8
24.08.2012	08:00	42.5	50.1
	10:00	58.2	70.6
	12:00	63	76.8
	14:00	63.9	77.3
	16:00	55.4	64.5
	17:30	40	42.7

In tab. 6, energy and exergy performance values, according to 40% antifreeze-water mixture at the flow rate of 0.383 kg/s of the intermediate fluid on certain dates were given. The energy and exergy efficiencies of the vacuum tube solar collector and the system are low. Moreover, the exergy losses of the boiler of the vacuum tube solar collector and the pump are high. It is seen that the highest loss in the system calculated in the vacuum tube solar collector, which was followed by the losses in the boiler and the pump.

The solar radiation intensity is important for energy and exergy efficiency the vacuum tube solar collector and the system. However, ambient temperature is affect just exergy efficiencies.

Table 6. The exergy analysis results according to 40% antifreeze-water mixture at the flow rate of 0.383 kg/s of the experimental system

Date (Year 2012)	Solar radiation intensity [Wm^{-2}]	Temperature [°C]	Boiler exergy loss [kW]	Exergy loss of the pump [kW]	Collector exergy loss [kW]	Collector 1st law efficiency [energy]	Collector 2nd law efficiency [exergy]	System 1st law efficiency [energy]	System 2nd law efficiency [exergy]
20.08.	799.00	28.190	1.3164	0.6386	143.130	0.1303	0.0128	0.1135	0.003206
21.08.	804.75	28.400	1.3247	0.6406	144.726	0.1378	0.0127	0.1180	0.003072
22.08.	788.50	27.924	1.3175	0.6383	143.099	0.1375	0.0132	0.1198	0.003312
23.08.	790.00	26.798	1.3179	0.6355	143.396	0.1382	0.0135	0.1272	0.003816
24.08.	769.50	27.497	1.2849	0.6534	141.498	0.1400	0.0130	0.1223	0.003111

In figs. 5 and 6, the daily energy and exergy efficiencies of the collector and the system have been given as percentage, according to 40% antifreeze-water mixture at the flow rate of 0.383 kg/s.

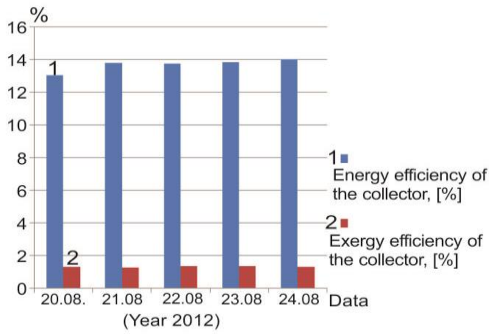

Figure 5. Average daily energy and exergy efficiencies of the collector according to 40% antifreeze-water mixture at the flow rate of 0.383 kg/s

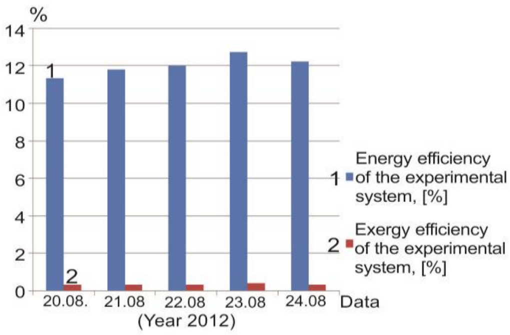

Figure 6. Daily average energy and exergy efficiencies of the experiment system according to 40% antifreeze-water mixture at the working flow rate of 0.383 kg/s

When fig. 5 is investigated, it is seen that there are great differences between the energy and exergy efficiencies of the vacuum tube solar collector. This situation is also seen in the experimental system.

Conclusions and suggestions

We have presented exergetic aspects of a vacuum tube solar collector system having ındirect working principle in general and have evaluated the performance of a vacuum tube solar collector system having indirect working principle. The experimental values are utilized in the analysis.

We can extract some concluding remarks from this study as follows.

- Energy and exergy efficiencies of experimental set-up and evacuated tube solar collector are strongly influenced from solar irradiation. On the other hand ambient temperature has dominant effect on the exergy efficiency of the experimental set-up and evacuated tube solar collector.
- At the exergy analysis duration of the experiment, it has been ascertained that the most exergy loss among the processes of the system was in the vacuum tube solar collectors. The average exergy loss in the vacuum tube collectors is approximately 143 kW. The exergy loss of the collector is over %90 in the total exergy loss. Respectively, boiler and pump followed the vacuum tube solar collectors. Average exergy loss of the boiler is around 1.3 kW and average exergy loss of the pump is approximately 0.64 kW.

The obtained data were compared with direct operating principle of the system results in the literature. Energy and exergy efficiencies of the vacuum tube solar collectors, which indirect operating principle, are lower than direct system working solar collectors. Average energy and exergy efficiencies of the experimental system founded 12% and 0.3%, respectively, (tab. 6). The average energy and exergy efficiencies of the vacuum tube solar collectors founded 13.6% and 1.3% (tab. 6). Therefore, in order to make the energy and exergy efficiencies of both experimental system and the vacuum tube solar collector at optimum levels. It is necessary that the collector surface area must be reduced in this kind of solar power systems and in order to let the intermediate fluid circulating between the collector and the boiler. It is necessary that the volume of the boiler and the surface area of the serpentine which is in the boiler must be increased. So, with the increase in boiler's volume and the serpentine surface within the boiler the collector heat difference increase. In this case the vacuum tube solar collectors will have a positive impact to increase the energy and exergy efficiencies.

Nomenclature

A – area, [m^2]
B – incidence of solar radiation on a unit area of surface, [kWm^{-2}]
C_p – specific heat at the constant pressure, [kJkg^{-1}K^{-1}]
$\dot{E}x$ – exergy rate, [kW]
h – specific enthalpy, [kJkg^{-1}]
$\dot{I}$ – rate of irreversibility, [kW]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
$\dot{Q}$ – heat transfer rate, [kW]
s – specific entropy, [kJkg^{-1}K^{-1}]
T – temperature, [K or $^{\circ}$C]
$\dot{W}$ – work rate or power, [kW]

Greek symbols

η – efficiency
Ψ – specific exergy, [kJkg^{-1}]

Subscipts

awm – 40% antifreeze-water mixture
boy – boiler
col – collector
dest – destroyed (destruction)
en – energy
ex – exergy
in – inlet

k – location
out – outlet
rad – radiation
sr – solar radiation
sys – experimental system
u – useful
w – water
0 – dead (reference) state

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