Performance Investigation of Solar Evacuated Tube Collector Using TRNSYS in Tehran

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Abstract- Outlet temperature of the collector for efficiency of water-in-glass evacuated tube solar domestic hot water system with natural circulation is generally more than the flat plate collector systems. Additionally, this type of evacuated tube solar collectors with the free circulation is economically cheaper than heat pipes collector systems, this system is widely used in the world. This paper is dedicated to simulation of evacuated tube solar water heating system with natural circulation under the climatic conditions in Tehran city with TRNSYS software. Diagram of the components used in the simulation of the TRNSYS has fully been studied including Type71 for evacuated tube collector with horizontal tank above it with natural circulation and five nodes in the vertically tank stratified in order to control the temperatures out of the collector. Vertical tank increases the tank temperature out of the collector for the household uses. After the simulation we obtain the regression linear curve of the efficiency of the evacuated tube solar domestic hot water system against heat loss of this system in spring and summer seasons with the solar irradiation and mean and ambient temperature in each selected day.

Keywords- Evacuated Tube, Solar Collector, Thermosyphon Flow, Natural Circulation, Efficiency.

1. Introduction

Evacuated tube solar collector consists of two concentric tubes that annular vacuum space between them prevents of heat transfer conduction and convection inside the glasses tube. Evacuated tube solar domestic hot water system generally consists of 14-40 single ended tubes that water circulates naturally between each tube and horizontal tank [1, 3]. The outer and inner glass tubes of two concentring tubes respectively called cover tubes and absorbent surfaces that inner tubes is exposed to solar radiation. Natural circulation is seen in both types of vacuum tubes that called respectively single-phase thermosyphon (water circulating) and two-phase thermosyphon (heat-pipe) [2].

With the sunlight in the morning, water-in-glass vacuum tube solar water heater starts work slowly, the procedure is as follows that when the solar radiation reaches to the selective surface absorber on the outer surface of the inner tube, causes the tube warming and heated water slowly goes from the collector to storage tank. On the other hand cold water slowly goes from storage tank to the collector [1]. This reciprocating movement from each evacuated tube solar collectors to storage tank and from storage tank to the each vacuum tube solar collectors called natural circulation between tubes (Fig.1). As the sun rises, mass flow rate slowly causes naturally water circulation rate between tubes and storage tank. With the passage of time and getting closer to noon, each evacuated tubes solar collector will become extremely hot. Natural circulation in each evacuated tubes solar collectors is due to the density difference of hot and cold water fluid, since density of the hot water is lighter than cold water, heated water goes from each vacuum tube collector to the storage tank and cold water from the storage tanks to each collector [1, 3].

For the large-scale of evacuated tubes SDHWS, we generally use horizontally arranged collectors that called H-type collector, whereas for normal and conventional expenditures such as the use of domestic consumption and practical application we use tilt-arranged that called T-type collector [4, 5]. In this paper we use T-type collector due to the low level of the collector. Two of the most common sizes of vacuum tube collectors are 37/47 (diameter of inner glass is 37 and diameter of cover glass is 47) and 47/58 (diameter of inner and cover glasses respectively). The second type is mostly used for water-in-glass open water circulating pipe that called single phase evacuated tube SDHWS with the natural circulation [4, 5]. Numerous papers have expressed the mass flow rate inside the evacuated tubes [6-8]. Other papers have expressed the performance of the heat-pipe collectors [9-13]. Past papers shows that overall efficiency of the water-in-glass SDHWS with natural circulation is in the range of 50% to 60% [3, 4]. Also in hybrid solar hot water systems are investigated in past literatures [14, 15]. Evacuated tube SDHWS that is simulated includes these components: vacuum tubes, horizontal and vertical tanks. We want to obtain efficiency curve of the evacuated tube solar collector against the mean and ambient temperature. The heat loss of the water-in-glass SDHWS in spring and summer seasons is very low because solar radiation on tilted surface and instantaneous efficiency levels are high.

2. Describing the model and numerical evaluation

Natural circulation from storage tank to each evacuated tube and from each vacuum tube to horizontal tank is shown in (Fig.1)

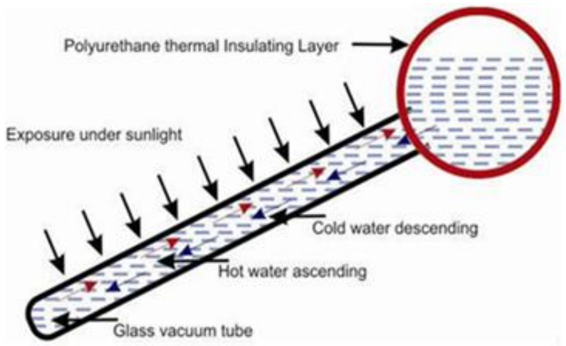

Fig. 1. Evacuated tube SDHWS with natural circulation

Rate of reached heat from each pipe to the tank is given by from the Eq. (1), [2]:

$$\dot{Q}_{in} = \dot{m}C_p(T_{out} - T_{in}) \tag{1}$$

That m,t ,Tin (K), Cp(kJ/kgK)are mass flow rate inside the tubes, outlet and inlet water temperature in the collector and specific heat of fluid respectively. by having Nt that is number of tubes, general heat gain all around the tubes is [2]:

$$\dot{Q}_{coll} = N_t.\dot{Q}_{in} \tag{2}$$

Efficiency of the water-in-glass solar domestic hot water system is given by two equations [1, 2]:

$$\eta = \eta_o - \frac{a_1(T_m - T_a)}{G} - \frac{a_2(T_m - T_a)^2}{G} \tag{3}$$

$$\eta = \frac{Q_{useful}}{A_a G} \tag{4}$$

where, G is solar irradiation (W/m2) and η_o is optical efficiency. Also a_1,a_2 are constants that experimentally determined in the computational efficiency of the evacuated tube solar collector. since we want to simulation ETCs with the TRNSYS software, for the calculation of water-in-glass SDHWS efficiency, we used Eq.(4). since we obtain useful energy gain and solar radiation with the Eq.(4), we can obtain hourly and monthly performance of water-in-glass SDHWS.

Also we will obtain dimensionless parameters Re_d, Nu_d, Gr_d, Pr_d and $Ra^*{}_d$ from Eq.(5 to 9) respectively following [2]:

$$Re_d = b_o \times \{[Nu_d.Gr_d/Pr_d\,] \times cos\theta \left(\frac{L}{d}\right)^{1.2}\}^{b_1} \tag{5}$$

$$Nu_d = (\,h\,.d\,)\;/\;k \tag{6}$$

$$Gr_d \;= \left(g\beta\left(\,T_t - T_w\right)d^3\rho^2\right)/\mu^2 \tag{7}$$

$$Pr\;_d = \;C_p\,\mu\;/\;k \tag{8}$$

$$Re_d \;=\; b_o(Ra^*{}_d)b_1 \tag{9}$$

In the above equations coefficients bo and b1 are 0.1914 and 0.4084 respectively. also d , ρ , L , θ , h , μ and β are diameter of inner tube (m) , density of the water (kg/m^3) , length of each tube (m), tilt angle of solar collector , heat transfer convection, dynamic viscosity of the water (Pa.s) and thermal expansion coefficient of water (1/K) respectively.

Outlet temperature flow from collector to storage tank is given by two equations following [2]:

$$T_{out} = T_{in} + \dot{Q}_{in}/\dot{m}C_p \tag{10}$$

$$T_{out} = T_{in} + (4 \times A_a.G.K.\eta/N_t)/(C_p.Re_d.\pi.d.\mu) \tag{11}$$

3. TRNSYS model

The TRNSYS model of water-in-glass evacuated SDHWS is simulated with natural circulation under the climatic conditions in Tehran city. The simple diagrams below shows that how we simulate evacuated tube SDHWS:

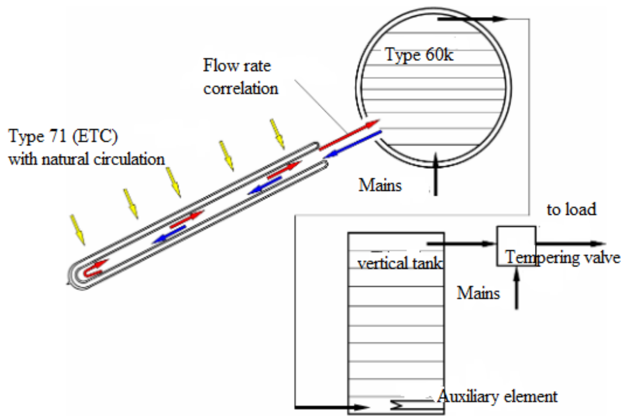

Fig. 2. Evacuated tube SDHWS with vertical tank

3.1 Type71 in TRNSYS software

In some papers water-in-glass evacuated tube solar water heating system is simulated by using Type1 as collector with horizontal tank above it. due to natural mass flow rate water circulation inside the inner glass tube SDHWS [1], these authors expressed their result using Type1. but this is wrong, because type1 is just taken into consideration for thermosyphon systems that maybe consist of thermosyphon flat plate SDHWS and water-in-glass evacuated tube SDHWS. TRNSYS only intended Type71 as single phase evacuated tube solar collector.

Table.1. Type 71 for ETC with natural circulation

Description	Value
Surface area	2 m^2
Aperture area	1.45 m^2
intercept efficiency	0.53
Fluid specific heat	4190 KJ/Kg ºK
Number in series	1
Diameter of inner tube when collector surface area is 2m^2	47 mm
Length of vacuum tubes	1800mm
Average mass flow rate	25 Kg/h
Load profile	200

3.2 Type60k in TRNSYS software

We used horizontal cylinder because it is inter-connected to ETC and it makes thermosyphon system. This simulated SDHWS, is containing Type60k above the vacuum tubes, because Type60k has two inlet flow inside and two outlets flow outside of its own. Features of ETC is simulated by TRNSYS is below:

Table.2. Specification of Type60k in TRNSYS

Description	Value
Flow rate at inlet 1	35 Kg/h
Flow rate at inlet 2	35Kg/h
Fluid specific heat	4190 KJ/Kg º K
Fluid density	1000 Kg/m^3

3.3 Vertical tank in TRNSYS software

At these papers we used vertical tank in order to increase the outlet water temperature from the collector [16]. due to transferring hot water from each evacuated tube collector to the vertical tank, we used five nodes in stratificated tank. this type of system uses an auxiliary element when the outlet water temperature from the collector decreases, if collector to the vertical tank outlet water temperature be appropriate and suitable, auxiliary heater element will not work. If collector outlet water temperature is colder than set point temperature which was already adjusted for this system, auxiliary heater compensates the lack of outlet water temperature of collector.

Table.3. Vertical tank that includes five nodes in order to improve the outlet water temperature of collector

Description	Value
Hot-side temperature	45º C
Hot-side flow rate	35 Kg/h
Cold-side temperature	15º C
Cold-side flow rate	35 Kg/h
Fluid specific heat	4190 KJ/Kg º K

Computational flow chart of the water-in-glass evacuated tube SDHWS with water circulating in the inner tube under climatic solar radiation and ambient temperature of Tehran city is expressed using TRNSYS.

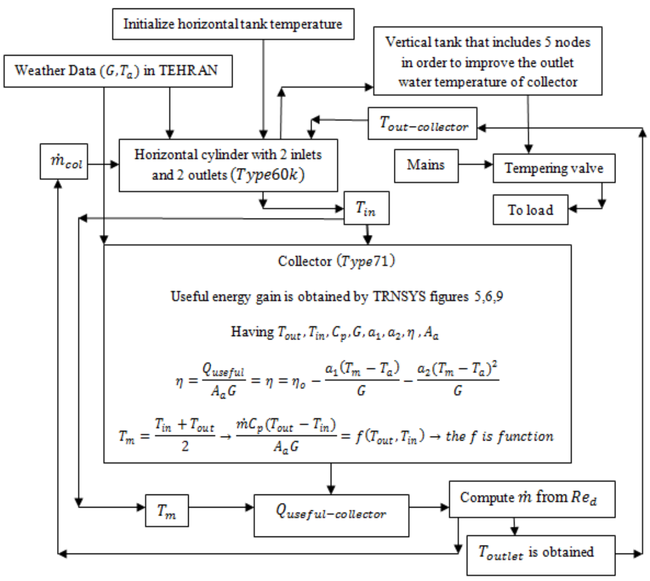

Fig. 3. Computational procedure for water-in-glass SDHW

3.4 Water-in-glass SDHWS which is simulated using TRNSYS

As seen schematically in Fig.3, the transferred heat reciprocally from each evacuated tube into the storage tank that inter-connected above the vacuum tubes and from storage tank to the ETCs [1], this mutually motion called thermosyphon circulation [2]. This type of circulation in ETCs distinct from thermosyphon flat plate collector system.

There are two ways to obtain the efficiency of the water-in-glass SDHWS. one way is to find the optical efficiency from their catalugs which is generally between 0.50 to 0.60 [1,3,4]. In this way heat losses parameters obtain from experimental data based on climatic conditions all over the world. Instantaneous efficiency of the water-in-glass ETCs varies throughout days and months, but this changes is not too much. Changes of the optical efficiency of water-in-glass evacuated tube SDHWS throughout days and months depends on some of parameters such as tube dimensions, tube spacing and distance between the tubes. The second way is that we must first have the area under the useful energy gain curve during the desired time. having the area under the curve of the useful energy gains in one of the election days of summer and winter seasons, difference between the two curves is characterized. also we have Ambient and mean temperature and solar irradiation during the required times by using weather information in Tehran city in TRNSYS software. We can obtain curve of the instantaneous efficiency against heat loss in any desired time that is expressed by subtracting ambient temperature from mean temperature divides by the solar radiation on a tilted-surface on the collector plan. Then we obtain efficiency of this system with TRNSYS software.

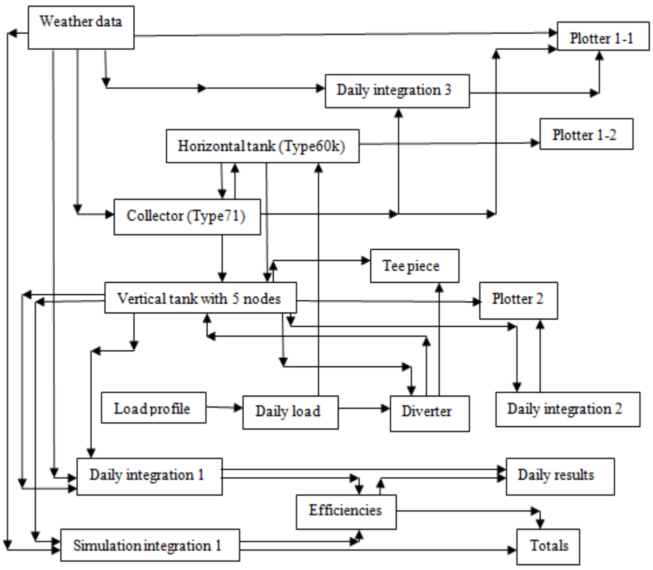

Fig. 4. Water-in-glass evacuated tube solar domestic hot water system

4. Result and Discussion

4.1. Radiation and useful energy gain in summer and winter seasons in TRNSYS

In this paper election days are 1 August and 20 February that these days which are located in summer and winter seasons respectively. Solar radiation and useful energy gain are shown in Figs. 5 and 6. Curves of Solar radiation and useful energy gain in Fig.5 are very close together, so solar radiation on the collector plan and useful energy gain in Fig. 5 are closer than in Fig. 6. In Fig.5 the proximity of the radiation and useful energy gain causes less heat loss than Fig.6. Due to the optical efficiency value in each collector is constant, so when heat loss in the vacuum tubes is higher than the standard value, the efficiency value becomes low, because the heat loss and efficiency values are inversely proportionate. Found in the literature demonstrate that the efficiency curve generally is intended with less than 0.04 heat loss [3]. Typically water temperature in horizontal tank reaches about sixty degrees in twenty-four hours period in a day as shown in Fig.7. By the simulation in TRNSYS software we know that number of the vacuum tubes is 20 with a horizontal tank above the collector. Area of the collector and aperture area of the evacuated tubes SDHWS are 2m2 and 1.45 m2 respectively. In winter season amount of the irradiation is much lower than the summer season, thereby heat loss is increased. Founds in the literatures shows that range of the efficiency in water-in-glass evacuated tube SDHWS is between 0.5 and 0.6 [1, 3, 4]. Also with the instantaneous rise of the heat loss in the vacuum tubes SDHWS, effect of reducing the efficiency in the evacuated tubes SDHWS is less than flat plate collector system [17].

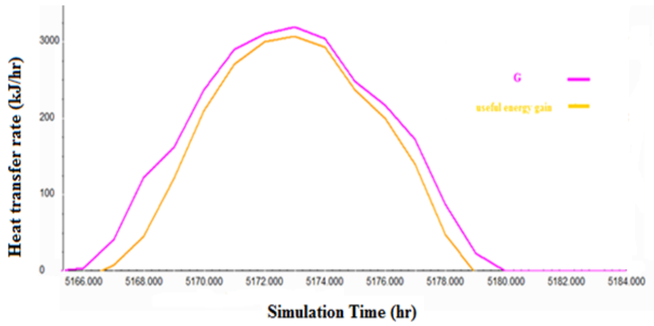

Fig. 5. Radiation and useful energy gain for typical day 1 August

In Fig.6, with low radiation, difference between useful energy gain and solar radiation become greater than Fig.5 that causes loss of heat value becomes slightly more than summer season.

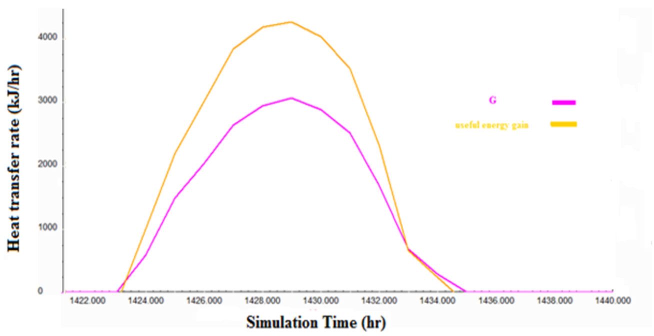

Fig. 6. Radiation and useful energy gain for typical day 20 February

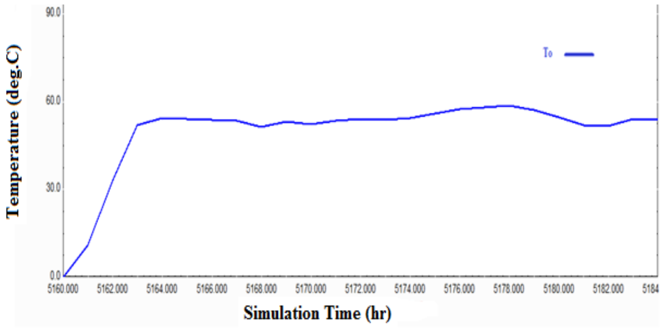

Fig. 7. Water temperature at horizontal tank for typical day 20 February

4.2. Five nodes temperature in vertical tank

In this paper we used five nodes at different heights in vertical tank to determine the water temperature at these nodes, scilicet vertical tank in TRNSYS software is classified by five nodes to specify water temperature which is called Ttop, T1, T2, T3, T4 and T5. Also the bottom water temperature of vertical tank is measured by T5.

Each of the nodes are placed at different heights in vertical tank. When the sun rises the heat is absorbed in the inner tubes of each vacuum tube. Due to the density difference between hot and cold water, hot water goes to the horizontal tank and cold water goes from horizontal tank to the collector, this natural circulation have been established between these tubes. When the sun rises, the nodes move slowly towards each other, until water temperature in the vertical tank reach an equilibrium temperature. These Ttop and Tbottom are exclusively located at top and bottom of the vertical tank respectively, the other nodes will become closer together at the end of the day.

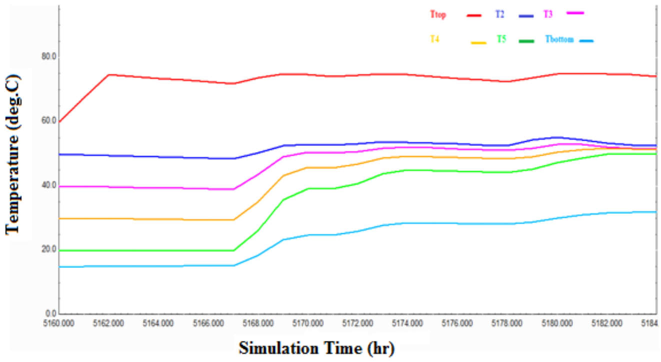

Fig. 8. Five nodes for determine the water temperature in the vertical tank in 20 February.

4.3. Ambient temperature

Ambient temperature is measured by TMY2 which is included in TRNSYS weather. Since heat loss in winter season is greater than summer season, we select summer season for monthly performance, because values of the heat loss are low and solar radiation on collector plan is high. For the monthly performance of this paper we considered one month period, from 17 July to 16 August. Since there is more radiation in the summer season in comparison with winter season, we've showed Fig.9 with numerical parameters such as solar radiation in any time of a day or every day of a month on the collector plan, useful energy gain, outlet water temperature of the collector and ambient temperature. also following figure shows that distance between solar irradiation on each vacuum tube SDHWS and useful energy gain in any time of a day is short, so values of the heat loss in Fig.9 are less than the values of the heat loss in the winter season, that causes instantaneous efficiency in each point of the following figure becomes slightly more than standard mode. Values of the instantaneous efficiency in earlier articles are expressed between 0.5 to 0.6 [1, 3, 4].

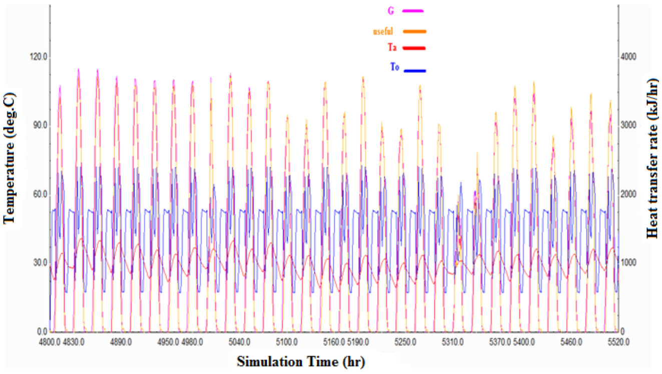

Fig. 9. This graph shows that values of the solar radiation in collector plan, useful energy gain, ambient and outlet temperature from 17 July to 16 August.

4.4. Efficiency curve against Heat loss and validation

In previous articles efficiency curve against Heat loss is obtained from Eq.3. Since values of the optical efficiency in the each water-in-glass SDHWS is constant according to catalogue, values of the solar collector efficiency coefficients that are called a_1, a_2 are obtained from the experimental way. The optical efficiency of each vacuum tube across months or days is related to some factors which may include configuration of the vacuum tubes solar collector, inner and glass tubes dimension, distance between two adjacent tubes and the reflector plane [1]. In this paper we obtained efficiency curve based on the heat loss at any time of a day or every day of a month on the collector plan and values of the heat loss and instantaneous efficiency. In this article efficiency curve against heat loss is typically expressed in spring and summer seasons. In order to reaching this purpose the following curve is obtained from six different selected days of spring and summer seasons. We have investigated the performance of the instantaneous efficiency curve against heat losses in the 19 different points. Each of these different points are located in these six selected days and there is only one instantaneous efficiency for every single heat loss point. The selected days that have been investigated in this paper are: April 28, May 18, June, June 17, June 27 and July17. Also this paper is validated by past literatures when the values of the heat loss are lower than 0.04 that is expressed by Hayek et all [3].

The past literature has experimentally measured the performance of heat loss against the instantaneous efficiency in 19 different points and this experiment was carried out during the period of November to January. Then the linear regression of these 19 points is drawn [3]. In this paper we showed that the theoretical results the performance of the instantaneous efficiency curve against each of the 19 heat loss in spring and summer season is very close to experimental values, which is obtained from 19 selected different points with TRNSYS software.

In both cases the slopes of the linear regressions are very close to each other that are shown in Fig.9.

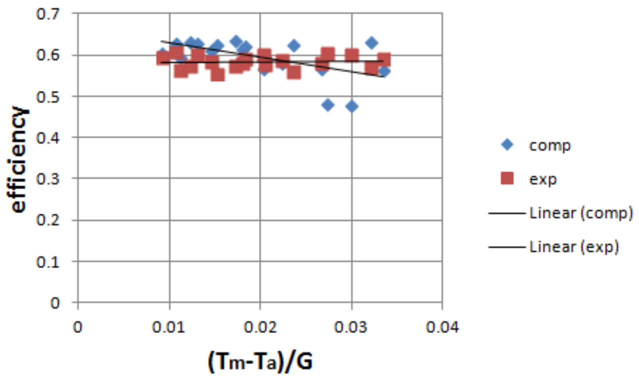

Fig. 10. Comparison of the instantaneous efficiency against heat loss in both cases computational and experimental methods.

5. Conclusion

In this paper we have investigated the instantaneous efficiency of the vacuum tubes SDHWS using the TRNSYS and by defining Type71 and horizontal tank on top of it, that is most appropriate type for the natural circulation between the tubes. Meteorological data in our simulation has been set for Tehran city in the designated days of spring and summer seasons. In summer season the distance between useful energy gain and solar radiation on tilted surface is less than winter season, which makes the heat loss become less than the winter season. Also instantaneous efficiency and outlet temperature of the collector in warm months is greater than cold months. Results shows that the five nodes in vertical tank become closer to each other at the end of the day, and this is because of the thermal equilibrium in this tank. Results show that At any time of specified days we can obtain useful energy gain, outlet and ambient water temperature and solar radiation on surface plan, then knowing heat loss in the 19 arbitrary points the instantaneous efficiency in these points can be obtained. The linear regression of our 19 selected points is validated by the experimental linear regression work, which our 19 values of heat losses are same as 19 values of heat losses of that experiment work, but in these two cases the instantaneous efficiency is different. The inclination of the linear regression in this work is very close to experimental work.

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Nomenclature

A	surface area (m^2)
A_a	aperture area (m^2)
C_p	specific heat of water (kJ/KgK)
D	diameter of inner tube
G	incident solar radiation (W/m^2)
L	length of each tube (m)
N_t	number of vacuum tubes in collector
Nu_d	Nusselt number
Pr_d	Prandtl number
Gr_d	Grashof number
Re_d	Reynolds number
$Ra^*{}_d$	Rayleigh number
T_{in} , T_{out}	inlet and outlet temperature (K)
T_m	average in and out temperature (K)
ρ	density (kg/m^3)
μ	dynamic viscosity of water $(Pa.s)$
b_o, b_1	constants in mass flow rate equation
β	thermal expansion $(1/K)$
η	efficiency of the evacuated tube collector
η_o	optical efficiency of the tube collector
Q_u	useful energy gain (W)
K	bi-axial incidence angle modifier
k	thermal conductivity $(W/m.K)$
$\dot{m}$	mass flow rate (Kg/s)
g	acceleration due to gravity (m/s^2)
θ	tilt angle of evacuated tube collector

Subscript

a	ambient temperature , aperture
in	inlet
out	outlet
col	collectible
w	water