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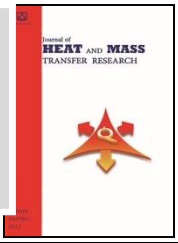

An experimental investigation of a 3-D solar conical collector performance at different flow rates

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ABSTRACT

The shape of a solar collector is an important factor in solar-to-thermal energy conversion. The Conical shape is one of the stationary symmetric shapes that can be employed as a solar water heater. Flow rate of working fluid on the solar collector has a significant effect on the efficiency of the collector. The present study is an experimental study of the performance of the solar conical collector with $1m^2$ of absorber area at different volumetric flow rates. Water was used as the working fluid with the volumetric flow rate between 0.35-2.8 lit/min and the experiment was held in the ASHRAE standard conditions. The results showed that the efficiency of the conical collector is increased as the flow rate of the working fluid increases; in addition, the difference between inlet and outlet temperatures is decreased. The maximum recorded outlet-temperature of the collector during the experimental tests was 77.1 ^{0}C and the maximum value of thermal efficiency was about 60%.

1. Introduction

Solar energy is the most powerful among the renewable energy sources. Due to increasing demand for energy and the growing cost of fossil fuels, solar energy is considered as a popular source of renewable energy which can be used for water heating domestically and industrially. Solar water heating systems are the cheapest and most affordable types of existing clean energies. These systems generally consist of a solar radiation collector, working fluid, a storage tank, a pump, piping unit, and auxiliary heating unit [1, 2]. The most important factor in solar water heating is what is called efficiency. The efficiency of a solar water heating system depends on the ratio of the received useful energy from the heated water to solar irradiance [3]. Solar collector properties play an important role in efficiency value [4]. Scientists and engineers are seeking the new ways to increase the efficienvy in order to increase the performance and decrease the expenses.

A large body of literature exists on the methods of increasing the efficiency of solar collector all over the world. Scientists studied different types of solar thermal collectors that are used commonly and carried out researches on relative thermal analysis and applications of each type [5, 6].

The absorbent surface of solar collector is very effective on the efficiency value [7]. The absorber colour, configuration factor, and the heat transfer between the absorbent and working fluid are of extremely importance [8, 9]. The heat transfer depends on the kind of working fluid, the kind of contact

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between absorbent and working fluid, area and shape of absorbent and collector [10, 11]. Many of studies focused on the heat transfer between absorbent and working fluid while others investigated the shape of the absorbent and the collector. These studies proposed the using of gas-particle suspension [12], fluid-film [13], and metal-foam [14] to increase this heat transfer. An experimental study on the effect of Cu-synthesized/EG nanofluid on the efficiency of flat-plate solar collectors has been carried out by Zamzamian et al. [15]. They figured out that by increasing the nanoparticle weight fraction, the efficiency of the collector was improved. In addition, they discovered that the lowest removed energy parameter could be reached by using 0.3 wt% Cu/EG nanofluid at 1.5 Lit/min and the highest absorbed energy parameter is achieved under the same conditions.

Jamal-Abad et al. [16] studied the performance of a flat-Plate collector by using Cu–Water nanofluid in an experimental research. They found that the collector efficiency was higher when the concentration of nanoparticles was raised. The results also revealed that the efficiency of the collector at 0.05 wt% was approximately 24% more than that the pure base fluids in the same conditions. Their study confirmed that nanofluids have considerable potential to solar collectors.

One of the other methods to increase the collector's performance is increasing the collector ability to absorb all parts of sun radiation. For maximizing the incident global radiation for a surface, solar tracking mechanisms can be used. This can increase the yearly solar radiation gain up to 1.45 times more compared to an optimal tilted solar collector [17]. Eliminating the tracking mechanism and keeping its advantages can be possible by using suitable and symmetric surfaces such as spherical or conical. The spherical solar collector has been investigated by some researcher [18, 19]. They concluded that this type of stationary collector was more efficient than flat plate solar collectors. Kumar et al. [20] investigated a multipurpose truncated pyramid non-tracking type of solar cooker/hot water system. They used their collector for a dual purpose: cooker and hot water; and showed that the maximum efficiency of system was about 54%. Pelece [21] designed and introduced a specific type of fixed solar collector with a semi–spherical shape. He proved that it is not necessary to place the collector on the roof and the semi-spherical collector can be simply put on the ground near the south wall of the building. Goudarzi et al. [22] and Ranjbar et al. [23] studied heat transfer in helical tubes and concluded that the secondary flow in these type of tubes can improve the convective heat transfer which is useful in heat exchanger or solar collectors.

Volumetric and mass flow rates have an impact on the performance of solar collectors. Different flow rates cause different efficiencies. Accordingly, choosing the optimum flow rate in every collector should be considered as one of the significant factors in selecting and using of the collectors.

There are many studies about the effect of flow rate on collector's efficiency. Yousefi et al. [2] investigated three flow rates for flat plate collector and showed that the efficiency of collector increases as the mass flow rate increases. Mintsa et al. [24] conducted a research on polymer flat plate collectors and revealed that by increasing the flow rate, the performance of the collector will be increased; these results are similar to experimental work of Cristofari [25].

In this study, the efficiency of the conical collector as a stationary and symmetric solar collector is experimentally investigated at different flow rates. The main benefit of the conical collector is that has symmetric sections in every side and has a circular section when the incident beam radiation is normal to it at the top of the collector. Employing the conical shape for solar collector can improve the ability of heat transfer via curved tubes. In this configuration, the centrifugal forces generate the secondary flow that causes to increase the convection heat transfer coefficient. In order to achieve the efficiency of conical collector, the water as a working fluid, pass through the collector and the heat is transferred from collector to water. The collector efficiency is the ratio between transferred heat from the collector to the working fluid and the amount of the received solar energy by the collector.

2. Materials and methods

2.1. Materials

In the present study, a new type of stationary collector, namely, a *solar conical collector* is used. It consists of a conical body, a glass cover, piping around the absorbing plate, isolated surface and working fluid. The schematic of the conical collector is shown in the Fig. 1. Being symmetric is the most important advantage of the conical collector; and when the solar irradiation is perpendicular to the collector, it has circular cross-section, Fig. 2.

This configuration leads to conical collector be able and suitable to collect any week or powerful incidental beam and diffuse radiation during the day. The collector's other benefit is being stable and no need any fixture and structure to install. The solar conical collector used in this work is made by the authors in Shahid Chamran University of Ahvaz, Iran.

2.2. *Experimental procedure*

The relative collector position is shown in the Fig. 3 and the schematic of the experimental are shown in the Fig. 4. The solar conical collector was experimentally investigated at the Behbahan city in the south of Iran (latitude is $30^0\,36^{'}\,0^{"}$ N and longitude is $50^0\,15^{'}\,0^{"}$ E).

The characteristics of the solar conical collector used in this experimental test are given in Table 1. Due to the 90^0 angle between the conical collector and the ground, the collector position is always vertical.

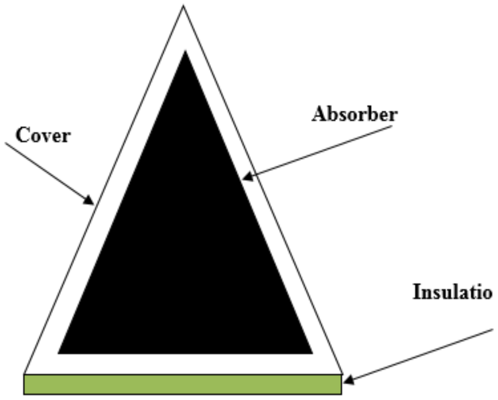


Fig. 1 The schematic scheme of conical solar collector

Fig. 2 Piping and cover install on a conical solar collector.

Fig. 3 The conical solar collector used in this study

Table 1. The characteristics of the conical solar collector

Characteristics	Dimension	Unit
absorber Diameter (Conical body)	0.6	m
Absorber area	1.0	m^2
Absorber high (Con altitude)	1.07	m
Absorber thickness	1.5	mm
Frame (Totally glass)	t= 4	mm
Pipe	D= 6.2, t= 1.1	mm
Weight	34	kg
Working fluid (Water)	C_p=4181	J/kg.K
specific heat capacity of Tubes (Cupper)	C_p=385	J/kg.K
Insulation (Polystyrene and wood)	t=20	mm

The solar system is a convection force system with an electrical diaphragm pump (6 in Fig. 4). The nominal maximum pressure of this pump is 12.4 bars and its flow rate is between 0-4 litres per minute. As shown in Fig. 4, the solar system has not any cycle, so the system is open. Water was used as a working fluid in this collector. A flow meter (4 in Fig. 4) was connected to the water pipe before the electrical pump. Three K thermocouple was used to measure the fluid temperature in the inlet (3 in Fig. 4) and outlet (2 in Fig. 4) of the conical collector and also the air temperature (10 in Fig. 4). These sensors were connected to a channel data logger (TES data logger model). The solar radiation was recorded by a solar meter. Calibration of measuring instruments were undertaken before, during and after the experimental data collection. Thermocouples were calibrated by using an independently calibrated platinum resistance thermometer; flow meter used a data logging subroutine to draw water from the systems into a container and measuring the mass with accuracy scales, and solar meter used a calibrated reference solar meter with a valid calibration certificate. The accuracy of thermometer data logger is 0.1 ^{0}C and accuracy of flow meter is 0.05 kg/min. Tracking of total solar radiation was implemented by a TES 132 solar meter type with an accuracy of 1 w/m^2.

3. Testing method

ASHRAE Standard 86-93 for testing the thermal performance of collector is certainly the most often used to evaluate the performance of stationary solar collectors [26] (shown in table 2). The thermal performance of the solar collector is determined by obtaining the values of instantaneous efficiency for different combination of incident radiation, ambient temperature and inlet fluid temperature [27, 28].

This requires experimental measurement of the rate of incident solar radiation as well as the rate of energy addition to the working fluid as it passes through the collector, all under steady state or quasi-steady-state conditions.

Table 2. Required environmental conditions (ASHRAE 93)

Variable	Absolute limits
Total solar irradiance normal to sun(W/m^2)	790(minimum)
Diffuse fraction (%)	20
Wind speed	2.3<U<4.8
Incidence angle modifier	98%<normal incidence, value<102%

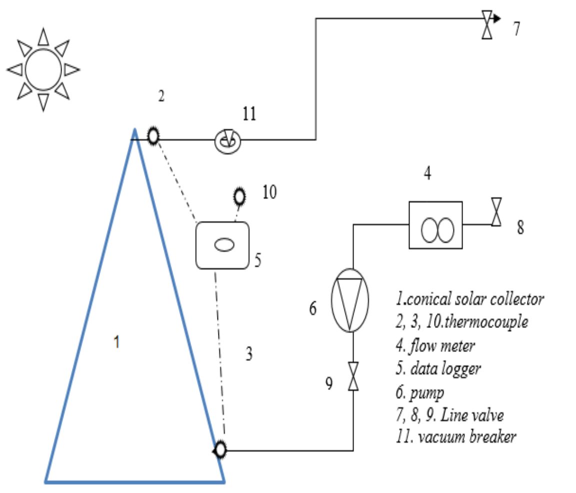


Fig. 4 The schematic of the experiment

3.1. Time attempt

According to ASHRAE Standard 86-93, steady-state conditions should be prepared during the data period and also during a specific time interval prior to the data period, this is called pre-data period. To reach steady-state conditions the mass flow rate, irradiation and other variables must be in a specific limitation as defined in Table 3 in the entire test period.

Table 3. Maximum variations of key variables (AHRAE 93).

Variables	Maximum variations
Total solar irradiance normal to surface (W/m^2)	±32
Ambient temperature (K)	±1.5
Volumetric flow rate	The greater of ±2% or ±0.005(gpm)
Inlet temperature	The greater of ±2% or 1 (K)

3.2. Governing equations

ASHRAE Standard suggests performing the tests in various inlet temperatures. After steady state conditions, the mean of data for each test is calculated and used in the analysis as a single point while other data are rejected. As the inlet and outlet fluid temperatures and mass flow rate of the water are measured, the useful energy could be calculated by using Eq. (1). The useful energy can also be expressed in terms of the energy absorbed by the absorber and the energy lost from the absorber as given by Eq. (2).

$$Q_u = \dot{m}C_p(T_o - T_i) \tag{1}$$

$$Q_u = A_c F_R[G_T(\tau\alpha) - U_L(T_i - T_a)] \tag{2}$$

Where, G_T is the incident radiation to the surface of collector. C_p is the heat capacity of the water and $\dot{m}$ is the water mass flow rate (kg/s). Also F_R is the heat removal factor and A_c is the surface area of solar collector. $\alpha\tau$ is an absorption-transmittance product. The instantaneous collector efficiency relates the useful energy to the total radiation incident on the collector surface by:

$$\eta_i = \frac{Q_u}{A_c G_T} = \frac{\dot{m}C_p(T_o - T_i)}{I_T} \tag{3}$$

$$\eta_i = F_R(\tau\alpha) - F_R U_L\left(\frac{T_i - T_a}{I_T}\right) \tag{4}$$

I_T is the received solar radiation in solar collector. Measuring this parameter in flat plate collector is easy and it can be measured by an ordinary solar meter. The conical collector has an curved geometry and the received sun radiation can be calculated as following [27]:

$$I_T = I_{T.b} + I_{T.d.iso} + I_{T.d.cs} + I_{T.d.hz} + I_{T.refl} \tag{5}$$

In this equation, the first term is the beam contribution, the second is the isotropic diffuse, the third is the circumsolar diffuse, the fourth is the contribution of the diffuse radiation from the horizon from a band and the fifth is the reflected radiation from the ground and surroundings. The ground surface is assumed to be a diffuse reflector. Calculation of this parameter may have some error. For measuring the total incident radiation, the conical geometry is modelled by the longitude and latitude on the conical surface. In this approach, the absorber of the conical collector is divided into 8 longitudinal sections and 10 latitudinal sections. Thus, the conical collector is divided into 80 pieces, with each piece being between two neighbouring longitudes and latitudes. Each piece can be considered as a flat trapezoidal surface, as shown in Fig. 5. The experimental measurement of the total incident radiation on the conical collector, which is performed for 80 semi-flat parts, takes ~6 min. In this procedure, the solar meter is placed on each piece and records the incident radiation on that piece. After recording the incident radiation on all the pieces, the total incident radiation on the conical collector is calculated by using Eq. (6).

$$\mathrm{I}_T = \sum_{k=0}^{80} \mathrm{A}_k \; I_k \qquad (6)$$

Here, A_k and I_k are the area and incident radiation of the k^{th} piece, respectively.

The pressure drop throughout the solar collector is specified by $\Delta p,$ that is calculated through the following equation [29];

$$\Delta p = f \frac{\rho V^2}{2} \frac{\Delta l}{d} + k \frac{\rho V^2}{2} \qquad (7)$$

Where *k* is the loss coefficient that consist of entrance effect, bends, elbows, exit effect, etc. The *k* coefficient is often taken in tables of fluid handbooks. In Eq. (7) *f* is the frictional factor, ρ is the density of coolant, Δl and d are pipe length and pipe diameter, respectively. Also V is the mean flow velocity of coolant in the collector and is determined by:

$$V = \frac{\dot{m}}{\rho \pi d^2/4} \qquad (8)$$

The frictional factor, *f*, in laminar and turbulent flows is as follows [30, 31];

$$f = \frac{64}{Re} \quad \text{for laminar flow} \qquad (9)$$

Fig. 5 Longitudes and latitudes of conical absorber

$$f = \frac{0.079}{(Re)^{1/4}} \quad \text{for turbulent flow} \qquad (10)$$

In Eqs. (9) and. (10), R_e is Reynolds number which is defined by:

$$Re = \frac{\rho V D_H}{\mu} \qquad (11)$$

Where μ and ρ are the viscosity and density of the coolant, respectively. D_H is the hydraulic diameter (m). In present study, D_H = pipe diameter (d).

3.3. Experimental uncertainty analysis

Due to ASME guidelines, there are not absolute measurements and errors in any experimental measurement. Some of the usual sources of error are: the errors of calibration, data recording errors and inappropriate instruments. The uncertainty of the experimental results in the present study was calculated by following ASME guidelines on reporting uncertainties in experimental measurements based on the deviation in experimental parameters [32, 33]. Errors in flow rate measurement, temperature measurement and solar radiation measurement are the main components to uncertainty in collector efficiency. The uncertainty results of the measurements including all the sources of errors are shown in Table 4.

Table 4. Results of uncertainty in the present work

Parameter	Uncertainty (%)
Volumetric flow rate	±1.6
Solar radiation	±6.5
Difference between inlet-outlet temperatures	±1.2

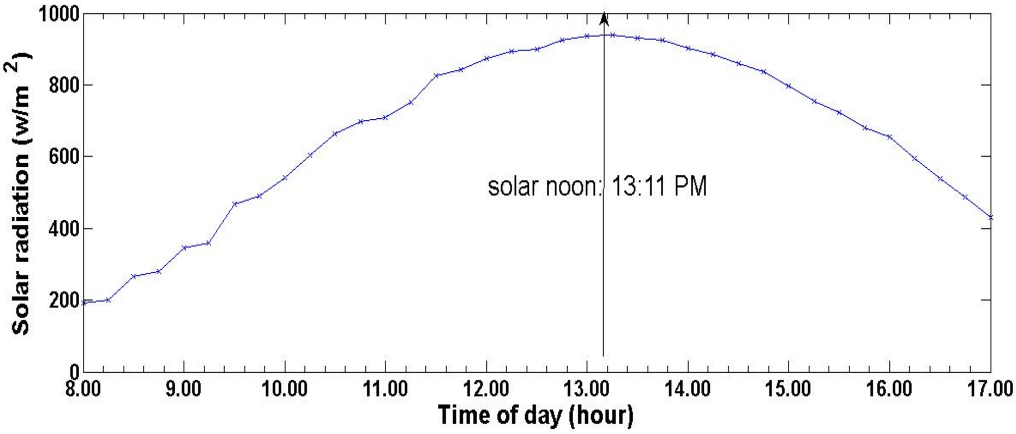
The combined uncertainty for calculation the collector efficiency, S_η, was determined by the root sum square method (RSS), based on Eq.(3). This analysis is as Eq. (12). We assume that errors in C_p and A_c are negligible.

$$\left(S_\eta\right)^2 = \left[\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta(T_o - T_i)}{(T_o - T_i)}\right)^2 + \left(\frac{\Delta I}{I}\right)^2\right] \qquad (12)$$

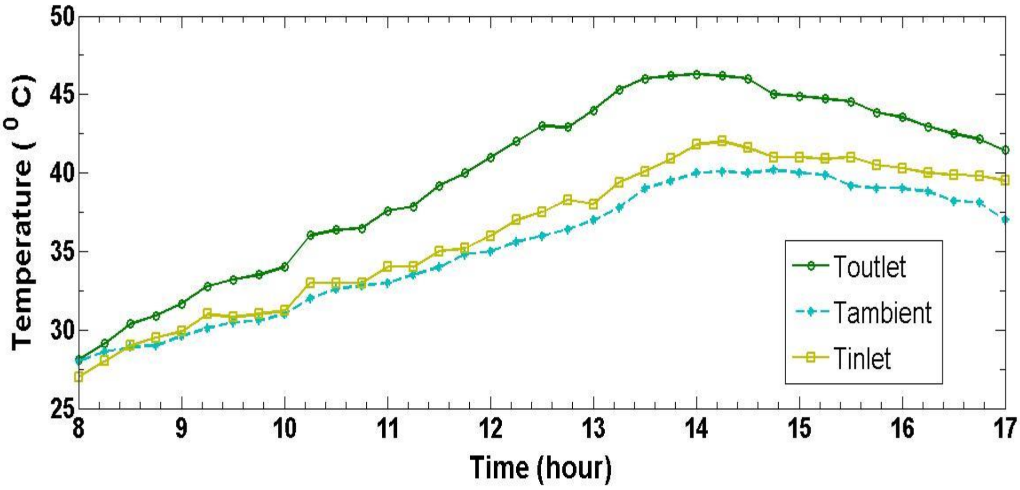
The maximum uncertainty determined in the present work in calculation the collector efficiency, at several tests was about 6.8%.

4. Results and discussions

The experimental results consist of performance, temperatures variation and effect of volumetric flow rates in the solar conical collector. All the data are tested in a quasi-steady state condition. The collector is perpendicular to the ground and used water as working fluid. The tests of the collector took place during several days in winter 2015 which were carried out during the day from 8.00 to 17.00 o'clock. The data were logged every 15 minutes. The experimental results are presented in the form of graphs and equation that describe the collector's efficiency and temperatures. Fig. 6 presents the solar radiation and temperatures profile in one the test days. In this figure, sun radiation and key temperatures of a selective day versus local time are shown. It is clear that the maximum received radiation is near the solar noon.



(a)



(b)

Fig. 6 Experimental data of a selected test day. (a) Solar radiation. (b) Temperature profile for 1.4lit/min flow rate

Fig. 7 shows that the volumetric flow rate has a non-linear effect on the performance of solar conical collector. According to this figure, the volumetric flow rate value that causes to best efficiency is the highest one and the maximum value of efficiency in this work was about 60%, while these values for flat plate collectors in studies of Meibodi et al. [34] and Yousefi et al. [2] were about 55% and 54%, respectively. By increasing the flow rate, the efficiency inclines to an asymptotic value. This trend shows that as the Reynolds number increases, the efficiency also increases. Also, heat transfer increases due to increasing Reynolds number because the secondary flow causes the convectional heat transfer to increase [22, 23]. On the other hand, the difference between inlet-outlet temperatures decreases, as the volumetric flow rate increases. This is shown in Fig. 8. These results are similar to research work of Mintsa et al. [24], Cristofari et al. [25] and Gupta et al. [35] where they have studied the mass flow rate influence on the efficiency of flat plate solar collector. They explained that the higher flow rates cause to gain more energy and by using the low flow, the difference between inlet-outlet temperatures increases. The results were concluded by the entrance length and Reynolds number effect on the energy exchange in the collector.

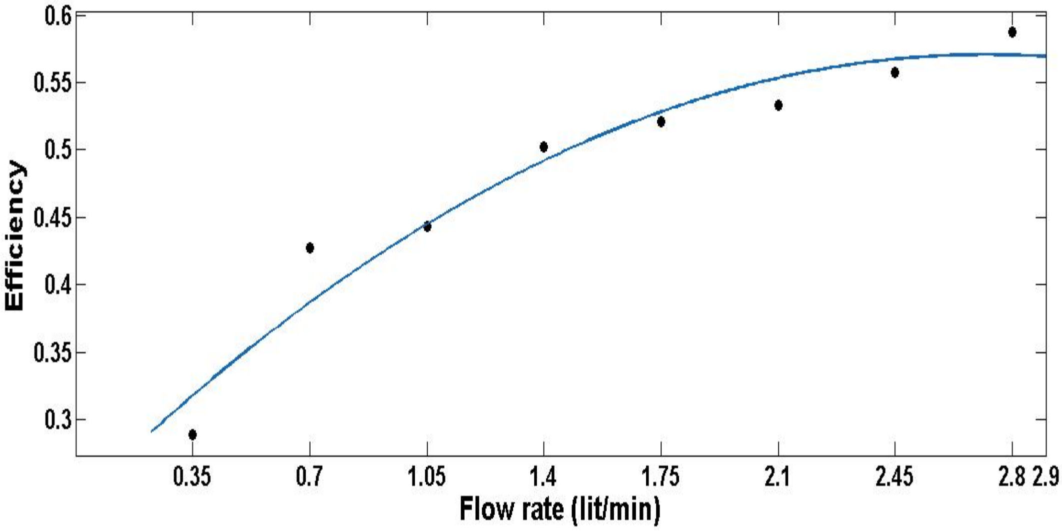


Fig. 7 Influence of flow rates on conical collector efficiency

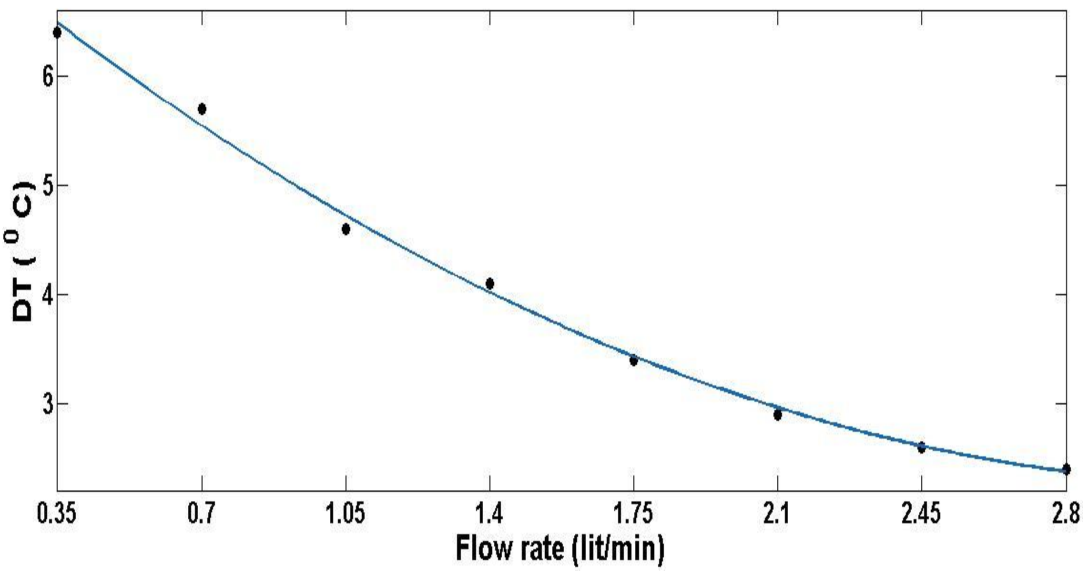


Fig. 8 Difference between inlet-outlet temperatures versus flow rate

The efficiency variations of solar conical collector versus inlet-ambient difference temperature are shown in Fig. 9. In this figure the efficiency has nonlinear behaviour and by increasing in the inlet-ambient difference, the collector efficiency will decrease. This trend can be explained with the Eq. (4). In this equation the big value of the difference between inlet and ambient temperature means that the collector energy losses are big so the collector efficiency will be increase. Besides, in the current study on conical collector, in 0.35-2.8 lit/min flow rates, the pressure drop has been more than 5 kPa. These values of pressure drops was about 2.8 times that of values in Alim et al. [31] and Ko et al. [36] studies. Fig. 10 shows that the experimental data are fitted with linear equations to calculate the characteristic parameters of the solar conical collector at different flow rates.

The collector efficiency parameters, $F_R U_L$ and $F_R(\tau\alpha)$and the parameter of goodness of fit, R^2, can be calculated through this figure and are shown in Table 5. It should be mentioned that the maximum temperature that has been obtained from solar conical collector in the present study was about 77.1 ^{0} C in 0.35 lit/min flow rate.

Table 5. $F_R U_L$ and $F_R(\tau\alpha)$ of the conical collector at different flow rates

Volumetric flow rate (lit/min)	τ (min)	$F_R(\tau\alpha)$	$F_R U_L$	R^2
0.35	5.25	0.301	8.35	0.966
1.4	4.16	0.510	11.28	0.968
2.8	2.11	0.598	16.01	0.981

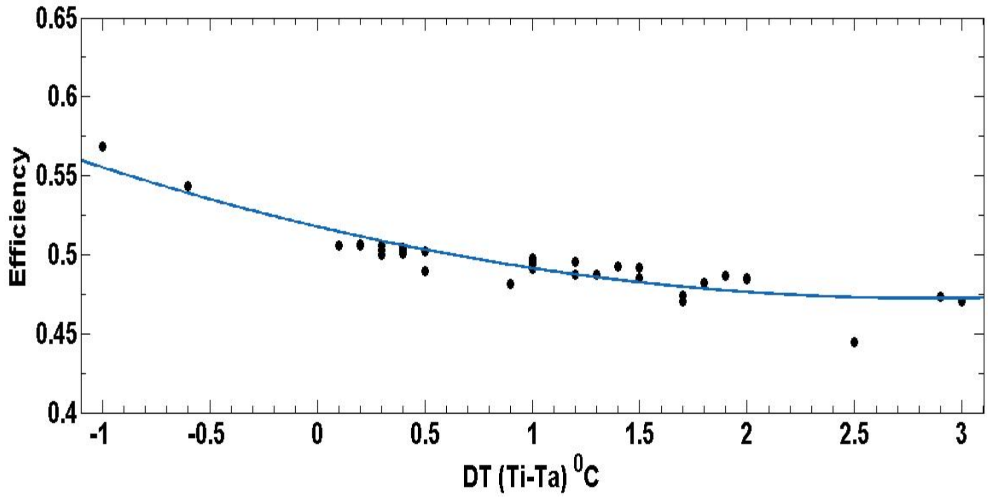


Fig. 9 Efficiency versus inlet and ambient temperature

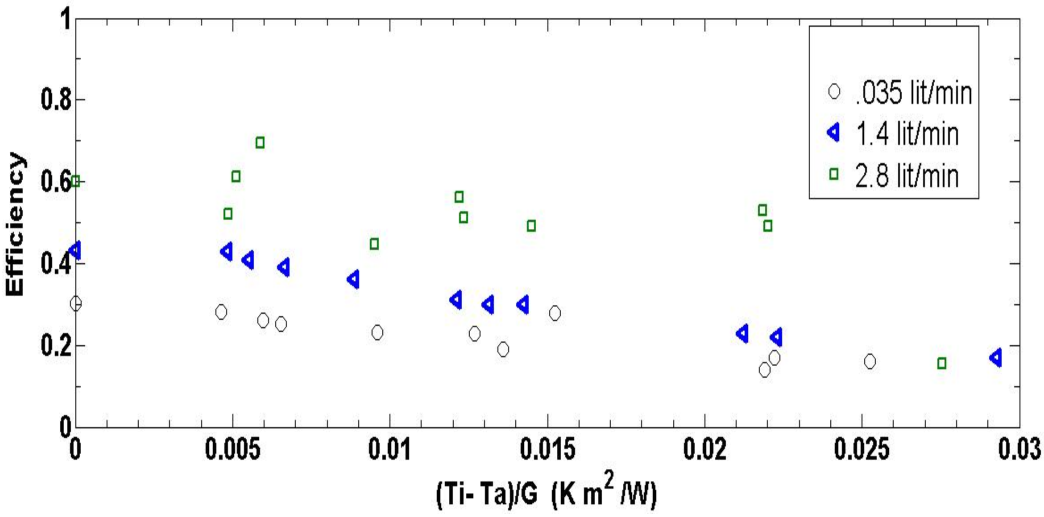


Fig. 10 Efficiency of the conical collector versus (T_i – T_a)/ G_T at different flow rates (Selective data)

5. Conclusion

In this research, the effect of different volumetric flow rates on the efficiency of a new stationary solar collector with conical geometry is experimentally investigated. To evaluate the volumetric flow rate effect, eight values of flow rate between 0.35 to 2.8 lit/min in a conical collector with 1 m^2 of absorber plate and 0.6 m diameter were used. The total incident sun radiation on conical collector was experimentally measured by 80 semi-flat parts. The results show that the performance of conical collector have increased greatly as opposed to flow rate growth. This improvement in efficiency is because of the specific shape that absorbs all parts of sun radiation and the centrifugal forces with a secondary flow generated by longitudinal vortices.

Another important conclusion of this article is that the maximum temperature and efficiency of the present conical collector were about 77.1 ^{0} C and 60%, respectively and pressure drop via conical collector was more than 5 kPa.

According to aforementioned results, solar conical collector can be used as suitable water heater. When the high value temperature in outlet is needed, the flow rate should be low and when the high efficiency of collector is needed, the flow rate should be high.

Nomenclature	
Surface area of solar collector(m^2)	A_c
Area of the k^{th} piece of conical collector	A_k
Heat capacity (J/kg K)	C_p
Hydraulic diameter (m).	D_H
Pipe diameter (m)	d
Friction factor	f
Heat removal factor	F_R
Incident radiation per surface of collector (W/m^2)	G_T
Beam contribution (W)	$I_{T.b}$
Isotropic diffuse term (W)	$I_{T.d.iso}$
Circumsolar diffuse term (W)	$I_{T.d.cs}$
Contribution of the diffuse radiation from the horizon (W)	$I_{T.d.hz}$
Reflected radiation from the ground and surroundings (W)	$I_{T.refl}$
Measured total radiation of k^{th} space of conical collector (W)	I_k
Global solar radiation(W)	I_T
Loss coefficient	k
Pipe length (m)	l
Mass flow rate(lit/s)	$\dot{m}$
Coolant pressure (Pa)	p
Rate of useful energy gained(W)	Q_u
Goodness correlation	R
Reynolds number	R_e
Uncertainty of efficiency (%)	S_η
Ambient temperature(K)	T_a
Inlet fluid temperature of solar collector (K)	T_i
Mean flow velocity (m/s)	V
Overall loss coefficient of solar collector (W/m^2 K)	U_L
Greek symbols	
Coolant density (kg/m^3)	ρ
Coolant viscosity (kg/m.s)	μ
Absorption-transmittance product	$\boldsymbol{\tau\alpha}$
Instantaneous collector efficiency	η_i
Time constant of conical collector	$\boldsymbol{\tau}$

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