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Performance of wickless heat pipe flat plate solar collectors having different pipes cross sections geometries and filling ratios

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Abstract

In the present study, the effect of wickless heat pipe cross section geometry and its working fluid filling ratio on the performance of flat plate solar collectors has been investigated experimentally. Three groups of wickless heat pipes having three different cross section geometries (namely, circular, elliptical and semi-circular cross sections) were designed and manufactured. Each group of three wickless heat pipes was charged with three different distilled water filling ratios of 10%, 20% and 35%. Each wickless heat pipe was then incorporated into a prototype flat plate solar collector developed for the purpose of the present study. The prototypes wickless heat pipe flat plate solar collectors have been investigated experimentally at different inlet cooling water temperatures, two different cooling water mass flow rates and under the meteorological conditions of Cairo, Egypt. The experimental results indicate that the elliptical cross section wickless heat pipe flat plate solar collectors have better performance than the circular cross section ones at low water filling ratios. The optimum water filling ratio of the elliptical cross section wickless heat pipe solar collector is about 10%, while it is very close to 20% for the circular cross section one. Also, the water filling ratio corresponding to the flooding limit of the elliptical wickless heat pipe solar collector is lower than that of the circular one. At 20% water filling ratio, the semi-circular cross section wickless heat pipe solar collector has bad performance compared with that of the other cross sections.

Keywords: Experimental investigation; Flat plate solar collector; Wickless heat pipe; Two phase closed thermosyphon; Pipe cross section; Filling ratio

1. Introduction

Solar thermal utilization is of great importance for environmental protection and conventional energy saving. A variety of flat plate solar collectors and evacuated tubular solar collectors have been produced and applied around the world. However, they suffer from some drawbacks, such as reversed cycle during cloudy periods of the day and the night, high heat capacity, high pumping requirements, scale formation, freezing and corrosion.

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Nomenclature

A_{coll}	collector effective area, m^2
C_w	specific heat of cooling water, J/kg K
Cir.	circular cross section wickless heat pipe
Ell.	elliptical cross section wickless heat pipe
F_R	heat removal factor, dimensionless
I_t	total solar radiation intensity, W/m^2
$\dot{m}_w$	cooling water mass flow rate, kg/s
Semi.	semi-circular cross section wickless heat pipe
T_a	ambient air temperature, °C
T_{wi}	inlet cooling water temperature, °C
T_{wo}	outlet cooling water temperature, °C
Q_g	rate of energy gain, W
Q_{in}	rate of energy input, W
U_L	overall heat loss coefficient, $W/m^2 K$
V^*	filling ratio of distilled water with respect to total tube inside volume
η	collector instantaneous efficiency, dimensionless
$(\tau_g\alpha_p)_e$	collector effective transmittance–absorptance product, dimensionless

The gravity assisted wickless heat pipe is a two phase closed thermosyphon tube with a liquid reservoir at its bottom. The addition of heat to the liquid in the lower part of the wickless heat pipe (evaporator section) causes the liquid to evaporate. The vapor rises to the top of the wickless heat pipe (condenser section) where it is condensed, and the condensate returns to the evaporator section as a falling film on the wickless heat pipe inner surface [1]. As a result, the wickless heat pipe has the ability to transport heat at high rates over considerable distances (i.e. several meters) in the presence of a small temperature difference. Besides, as the wickless heat pipe is working under gravity assisted conditions, it behaves as a thermal diode. So, the wickless heat pipe is recommended to be used in flat plate solar water heaters as a solution to the drawbacks of conventional solar collectors [2–8].

De Vries et al. [2] investigated theoretically the influence of the pump control unit of a conventional flat plate solar collector and the diode resistance of a planar wickless heat pipe solar collector on their efficiencies during periods of transient insolation. They concluded that the performance of the wickless heat pipe collector was as good as that of a conventional solar collector with fluid circulation control. Akyurt [3] designed, manufactured and tested numerous prototypes wickless heat pipe flat plate solar collectors made of different materials and filled with different working fluids. An extensive testing program, lasting for more than a year, revealed that the wickless heat pipe performs satisfactorily as heat transfer elements in solar collectors without start up difficulties or gas generation problems. From a heat transfer analysis and experimental study, Henyue [9] concluded that increasing the heat transfer surface of the condenser section of the wickless heat pipe was an effective way to improve the instantaneous efficiency of wickless heat pipe flat plate solar water heaters. The performance of two R-11 charged integrated solar water heaters with horizontal and inclined condenser was investigated experimentally for forced and natural circulation water flows [10]. The experimental results showed that the effect of the condenser inclination on the system efficiency was remarkable for natural circulation, while it had no significant effect for forced circulation. Hussein et al. [11,12] investigated theoretically and experimentally a wickless heat pipe flat plate solar collector under the actual field conditions of Cairo, Egypt. The characteristics of the main design parameters of their collector were based on the optimum results of their theoretical analysis [12]. The comparison between the experimental results and their corresponding simulated values showed considerable agreement [11]. Also, the theoretical results indicated that the effect of the collector pitch distance/pipe diameter ratio on the collector efficiency decreases as the wickless heat pipe diameter decreases and the inlet cooling water flow increases [12]. A wickless heat pipe flat plate solar water system having a heat exchanger–condenser built in the system tank was investigated theoretically and experimentally by Mathioulakis and Belessiotis [13]. The results showed that the system can reach satisfactory efficiencies. Abreu and Colle [14] investigated experimentally the transient thermal behavior of a wickless heat pipe flat plate solar water heater characterized by a semi-circular condenser and a straight evaporator. The effects of the cooling water temperatures, slope, filling ratio and evaporator length were determined for different heat fluxes.

From the current literature, it is noticed that all of the previous studies of wickless heat pipe flat plate solar collectors were limited to circular cross section wickless heat pipes. To the authors' knowledge, no previous data on the performance of wickless heat pipe flat plate solar collectors with non-circular cross section wickless heat pipes are available. Therefore, the present work aims to investigate experimentally some prototype wickless heat pipe flat plate solar collectors having different wickless heat pipes cross-sectional geometries and different working fluid filling ratios. Three different cross-sectional geometries of wickless heat pipes will be investigated, namely circular, elliptical and semi-circular cross sections. The transient thermal performance of the present wickless heat pipe flat plate solar collectors will be experimentally investigated at different inlet cooling water temperatures and mass flow rates.

2. Manufacture of wickless heat pipes

For manufacturing the wickless heat pipes of the present work, nine commercial copper tubes of 18 mm outside diameters were cut to 1.5 m lengths. Three of these tubes were used in the present work with their circular cross section. In contrast with using special dies, another three of these tubes were deformed to have elliptical cross sections of 14×22 mm dimensions, and the remaining three tubes were deformed to have semi-circular cross sections of 22 mm outside diameter. An end cap was brazed to one end of each tube, and a copper filling tube of 2 mm outside diameter was brazed to this end cap. The filling tube ended with a charging needle. Each wickless heat pipe with its filling tube assembly was then flame heated to above 400 °C to burn off any traces of organic materials. Pickling by sulfuric acid and trichloroethylene and then rinsing by distilled water completed the cleaning operation [1,15]. Another end cap was then brazed to the other end of the tube.

Charging the wickless heat pipes with distilled water (as the working fluid that was used in the present study) was performed using a two stage vacuum pump of an evacuation and charging rig, as shown in Fig. 1. During the charging process, each pipe was heated to the operating temperature limit of flat plate solar

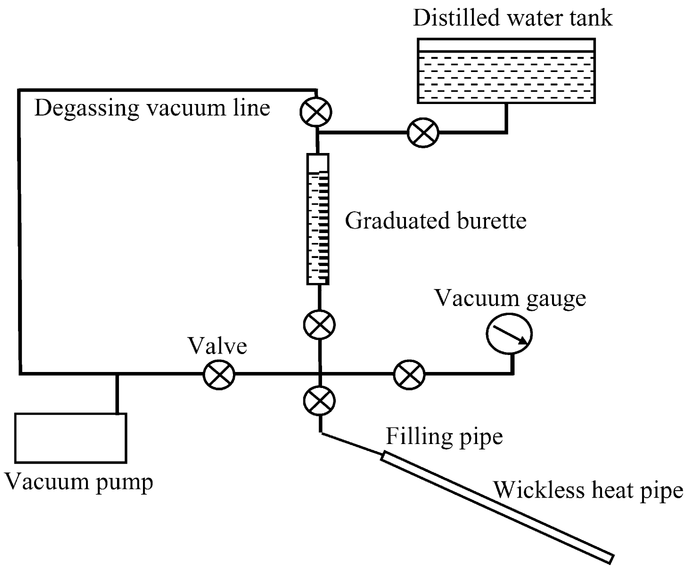

Fig. 1. Schematic diagram of the evacuation and charging rig.

collectors (i.e. to about 90 °C) and brought to a high vacuum of about 10^{-1} Torr. Then, 10%, 20% and 35% liquid filling ratios (V^*) of previously degassed distilled water were admitted into the three pipes of each of the three cross section groups of wickless heat pipes, respectively. The filling tubes were then crimped, sheared off and brazed. Finally, the products were nine wickless heat pipes manufactured with three different distilled water filling ratios of 10%, 20% and 35% for each three wickless heat pipes have the same cross section.

3. Experimental set up and procedure

To investigate experimentally the transient performance of the nine wickless heat pipes under actual insolation conditions, each wickless heat pipe was incorporated into a prototype flat plate solar collector. Fig. 2 shows cross-sectional views of the collector. Each wickless heat pipe was designed to have an evaporator, adiabatic and condenser sections of lengths 1.2, 0.05 and 0.25 m, respectively. The evaporator section of each wickless heat pipe was welded to an absorber plate made of a copper sheet of 0.4 mm thickness and 0.19 m width. The absorber plate and the evaporator section of the wickless heat pipe were treated and painted black to absorb a maximum amount of the incident solar radiation. Nine commercial copper tubes of 38 mm outside

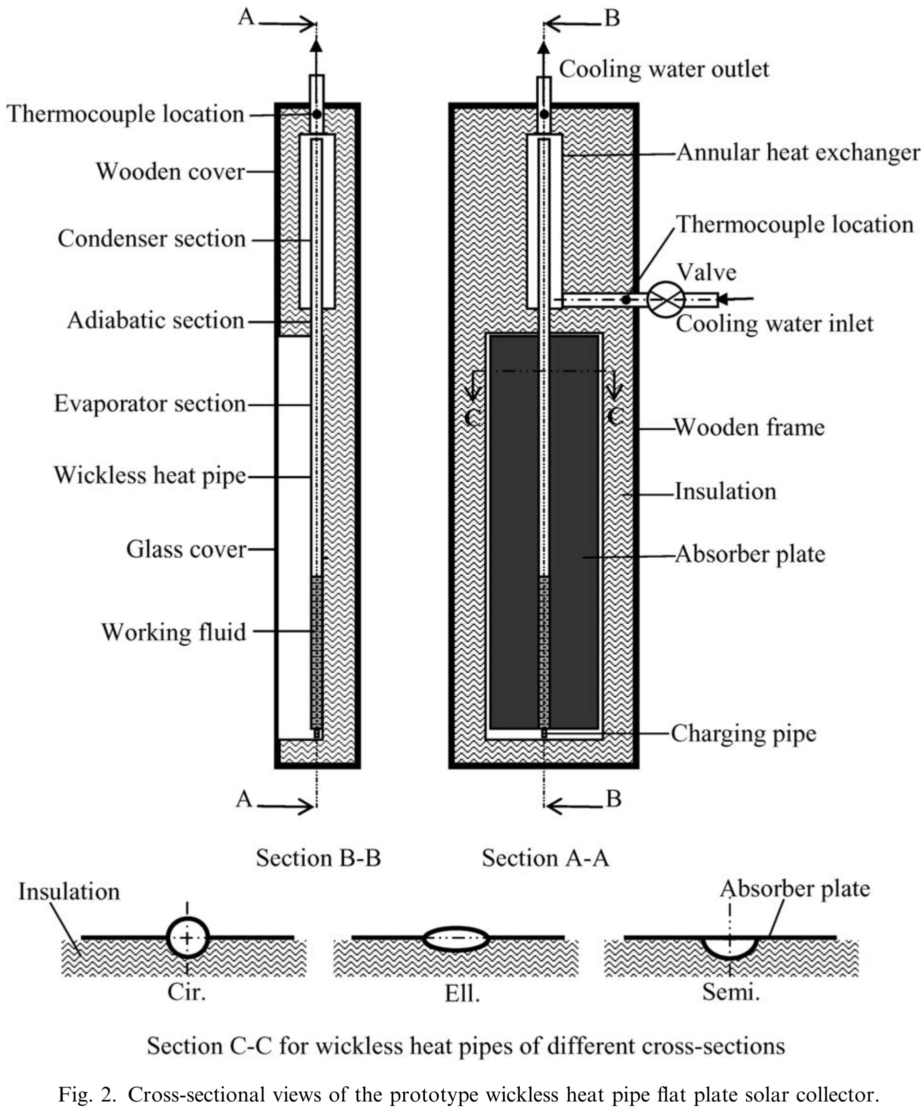

Fig. 2. Cross-sectional views of the prototype wickless heat pipe flat plate solar collector.

diameters and 0.26 m lengths were used to construct the heat exchangers of the nine prototypes solar collectors. Each tube was brazed to two concentric end caps and to two copper tubes of 18 mm outside diameters for inlet and outlet cooling water as shown in section A-A of Fig. 2. Each heat exchanger assembly was then brazed onto the condenser section of each wickless heat pipe as shown in Fig. 2.

Each wickless heat pipe assembly was incorporated into an insulated casing. The casing was made of wood plates 0.02 m thick. The wooden casing of each collector was insulated on the back and sides by 0.05 m thick glass wool insulation. Then, the condenser section/heat exchanger assembly and the adiabatic section of each collector were covered by 0.05 m thick glass wool insulation and a wooden cover of 0.02 m thick as shown in section B-B of Fig. 2. In contrast, the evaporator section/absorber plate assembly of each collector was covered by ordinary window glass of 4 mm thick. The glass cover was secured to the collector casing by silicon rubber to permit thermal expansion and to prevent the entrance of dust and rain to the collector. Table 1 summarizes the similar main design parameters of the nine prototypes wickless heat pipe flat plate solar collectors. The prototypes wickless heat pipe solar collectors were then installed and mounted on a tiltable stand of a test rig shown in Fig. 3. The stand was oriented N–S and tilted 30° toward the south. The test rig is comprise of a water tank of 500 L capacity equipped with an electric heater, a thermostat, a circulating pump, control valves, safety instruments and a measuring system as shown in Fig. 3.

The measuring system used in the present work included: K-type thermocouples/digital thermometer connection, a pyranometer, an ambient air sensor and a flow meter. The thermocouples/digital thermometer connection was used to measure the cooling water temperatures at the inlet and outlet of each wickless heat pipe solar collector. The digital thermometer has an automatic compensating reference junction and an accuracy of ±0.1 °C. Calibration of the thermocouples/digital thermometer connection was performed using a well insulated flask and a mercury in glass thermometer of ±0.1 °C accuracy. The calibration results showed a +0.2 °C maximum deviation between the digital thermometer readings and the mercury in glass readings in the temperature range of 15–90 °C. Another K-type thermocouple placed in a well ventilated shelter was used as an ambient air sensor to measure the ambient temperature as shown in Fig. 3. A thermopile pyranometer of type Kipp & Zonen was used to measure the instantaneous value of the global solar radiation intensity. It was connected to a millivoltameter of ±0.1 mV accuracy. The output voltage of the pyranometer is 6.09×10^{-3} mV/W m^{-2} for the millivoltameter resistance range of 10 Ω. The pyranometer was mounted at

Table 1
Summary of similar main design parameters of the nine prototypes wickless heat pipe solar collectors

Case		
Material: wood	Thickness 0.02 m	
Gross length 1.64 m	Gross width 0.33 m	Gross depth 0.12 m
Transparent cover		
Material: white glass		
Length 1.21 m	Width 0.2 m	Thickness 0.004 m
Effective area 0.228 m^2	Air gap 0.05 m	
Absorber plate		
Material: copper	Coating: velvet black	
Length 1.2 m	Width 0.19 m	Thickness 0.0004 m
Wickless heat pipes		
Material: copper	No. of pipes 1	Total length 1.5 m
Evaporator length 1.2 m	Adiabatic length 0.05 m	Condenser length 0.25 m
Working fluid: distilled water		
Heat exchanger		
Material: copper	Outer diameter 0.038 m	Length 0.26 m
Type: annular	Inner diameter 0.036 m	
Insulation		
Material: glass wool	Thickness 0.05 m	
Position: back, sides and front of heat exchanger		

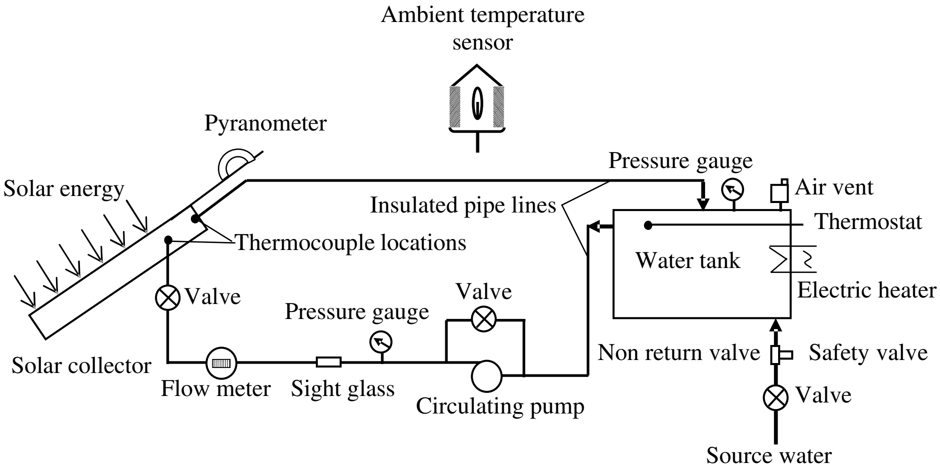

Fig. 3. Schematic diagram of the test rig.

the top of the tiltable stand, slightly above and parallel to the collector surfaces as shown in Fig. 3. The mass flow rate of cooling water passing through the heat exchanger of each collector was measured by means of a flow meter, built in the test rig as shown in Fig. 3, having an accuracy of ±0.1 l/min. The flow meter was calibrated using a stop watch of ±0.01 s accuracy and a graduated glass bottle of tolerance ±2 cm^3.

A preliminary test program was first conducted on the nine prototypes wickless heat pipe flat plate solar collectors for several days to test their effectiveness. The test program indicated that two of these collectors developed non-condensable gases (i.e. air) and soon became inactive. These two collectors were those having semi-circular cross section wickless heat pipes with 10% and 35% distilled water filling ratios. So, these two prototypes collectors were excluded from the present investigation.

The experiments on the seven prototypes wickless heat pipe flat plate solar collectors were conducted during the period from Sept. to Nov. 2004. During each experiment, the mass flow rate of cooling water was kept constant, and the solar radiation intensity (I_t), ambient air temperature (T_a), inlet cooling water temperature (T_{wi}) and outlet cooling water temperature (T_{wo}) of each collector were recorded. The experiments were classified into the following main groups:

1. Experiments throughout the day at low inlet cooling water temperatures and at the ASHRAE standard mass flow rate (i.e. $\dot{m}_w = 0.02\ A_{coll}$ kg/s [16]). These experiments were performed to study the effect of the working fluid filling ratio and cross section geometry of the wickless heat pipe on the instantaneous performance of the wickless heat pipe flat plate solar collectors.
2. Experiments at two different mass flow rates and at different inlet cooling water temperatures. These experiments were performed along several selected clear days during the quasi-steady state period around solar noon. This was done to compare the performance curves of each of the studied prototypes collectors at two different cooling water mass flow rates.

During each experiment, the rate of solar energy input (Q_{in}), the rate of thermal energy gain (Q_g) and the instantaneous efficiency of each collector were calculated as follows:

$$Q_{in} = I_t A_{coll} \quad W \tag{1}$$

$$Q_g = \dot{m}_w C_w (T_{wo} - T_{wi}) \quad W \tag{2}$$

$$\eta = Q_g / Q_{in} \tag{3}$$

For the range of the primary measurements of the present work and following the procedure of Abernethy and Thompson [17], the maximum uncertainty of the rate of energy gain and efficiencies of the collectors were found to be less than 2.5% and 5.6%, respectively.

4. Results and discussion

For three selected days of the first group of experiments, Figs. 4–6 show the instantaneous variation throughout each day of the rate of solar energy input, ambient air temperature, inlet cooling water temperature and the rate of thermal energy gain of the seven prototypes wickless heat pipe flat plate solar collectors. Figs. 4 and 5 show the effect of the working fluid filling ratio on the rate of thermal energy gain for the circular and elliptical wickless heat pipe flat plate solar collectors, respectively. Fig. 4 indicates that a filling ratio (V^*) of 20% gives the higher rate of instantaneous thermal energy gain throughout the day. This result was supported by the results obtained by Negishi and Sawada [18] and Fedlman and Srinivasan [19] where an optimum distilled water filling ratio in the range of 18–20% was obtained for circular wickless heat pipes. Fig. 4 shows also that the 35% water filling ratio has a slightly positive effect on the rate of thermal energy gain of the collector during afternoon periods. This can be attributed to its higher heat capacity compared with the other two filling ratios. On the other hand, Fig. 5 indicates that a water filling ratio of 10% gives the higher instantaneous rate of thermal energy gain throughout the day for the elliptical wickless heat pipe flat plate solar collectors. This means that the optimum water filling ratio of elliptical cross section wickless heat pipe flat plate solar collectors tends to be lower than that of circular cross section wickless heat pipe solar collectors (i.e. it is about 10% for elliptical cross section wickless heat pipe flat plate solar collector as shown in Fig. 5). This result

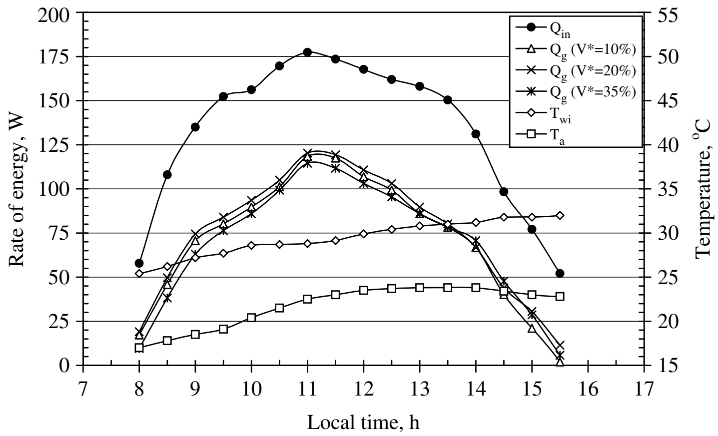

Fig. 4. Effect of V^* on Q_g of the circular cross section wickless heat pipe solar collector.

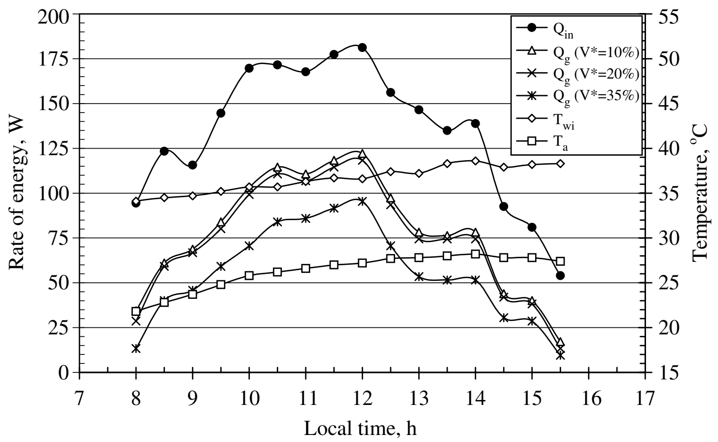

Fig. 5. Effect of V^* on Q_g of the elliptical cross section wickless heat pipe solar collector.

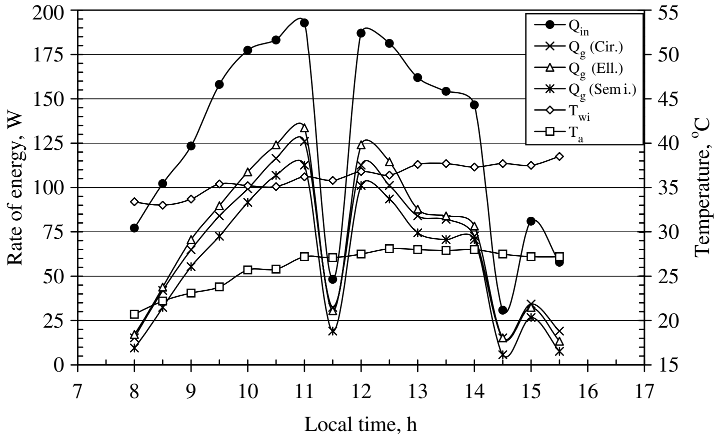

Fig. 6. Effect of cross section geometry of the wickless heat pipe solar collector on Q_g at 20% water filling ratio.

may be attributed to the higher surface area to volume ratio of the elliptical wickless heat pipe over the circular wickless heat pipe. This leads to higher pressure and, consequently, higher temperature inside the elliptical wickless heat pipe compared to the circular one for the same filling ratio and heat flux. This makes the rate of thermal energy gain of the elliptical wickless heat pipe solar collector higher than that of the circular wickless heat pipe solar collector at the same filling ratio. Increasing the water filling ratio of the elliptical wickless heat pipe flat plate solar collector from 10% to 20% slightly decreases the instantaneous rate of thermal energy gain as shown in Fig. 5. This can be attributed to the increase of the collector heat capacity with the increase of its filling ratio, which leads to a decrease of the wickless heat pipe temperature and, consequently, the inside pressure for the same heat flux. The higher increase of the water filling ratio from 20% to 35% dramatically decreases the rate of thermal energy gain of the elliptical cross section wickless heat pipe solar collector as shown in Fig. 5. This can be attributed to the flooding limit effect. This flooding limit was confirmed by a strange sound, like smacking, heard inside the 35% elliptical cross section wickless heat pipe flat plate solar collector. This phenomenon was also noticed by Negishi and Sawada [18] for circular cross section wickless heat pipes but at a higher water filling ratio. The occurrence of the flooding limit of the elliptical cross section wickless heat pipe at a lower filling ratio compared to that of the circular cross section one can also be attributed to the elliptical higher surface area to volume ratio, which leads to higher pressure, vapour generation rate and vapour velocity for the same heat flux.

For a constant water filling ratio of 20%, Fig. 6 shows the comparison between the rates of thermal energy gain of the three prototypes wickless heat pipe flat plate solar collectors with three different cross section geometries of wickless heat pipes. The figure indicates that the elliptical cross section heat pipe significantly improves the instantaneous thermal energy gain of the collector. During intermittent cloudy periods, Fig. 6 indicates that the instantaneous rate of heat gain of the circular wickless heat pipe solar collector is very close to that of the elliptical wickless heat pipe solar collector. This can be attributed to the significant effect of the higher heat capacity of the circular cross section wickless heat pipe as compared to the elliptical one. Also, Fig. 6 shows that the prototype solar collector with semi-circular cross section wickless heat pipe has the smallest instantaneous heat gain. This may be due to its higher surface area to volume ratio as compared to the elliptical and circular wickless heat pipes, which may lead to the smaller filling ratio corresponding to its flooding limit.

To confirm the above results of the first group of experiments, a second set of experiments was conducted on the prototypes wickless heat pipe solar collectors at the quasi-steady state period around solar noon for different inlet cooling water temperatures and cooling water mass flow rates. The results of this group of experiments are represented graphically in Figs. 7 and 8. Figs. 7 and 8 demonstrate the comparison between the experimental efficiency curves of the present prototypes TPCT solar collectors at two different cooling water mass flow rates of 0.02 A_{coll} and 0.04 A_{coll} kg/s, respectively. By using a curve fitting technique, it can be found that the instantaneous efficiency of each collector can be represented linearly as a function of the measuring

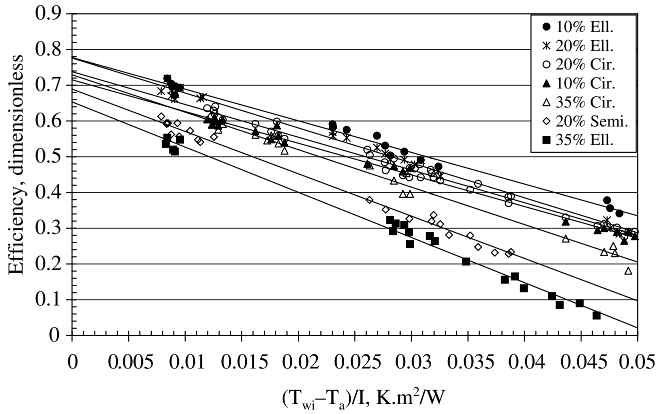

Fig. 7. Comparison between collectors efficiency curves at ASHRAE standard mass flow rate (0.02 A_{coll} kg/s).

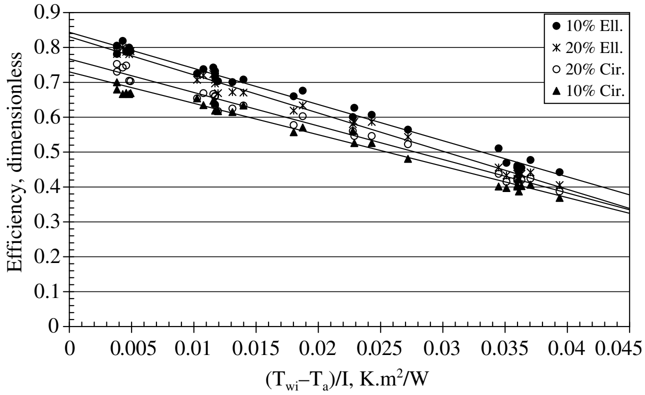

Fig. 8. Comparison between collectors efficiency curves at mass flow rate of 0.04 A_{coll} kg/s.

parameter $[(T_{wi} - T_a)/I_t]$ as shown in Figs. 7 and 8. The intercept of each efficiency line with the y-axis represents the product $F_R(\tau_g\alpha_p)_e$, while its slope represents the product $F_R U_L$. The intercept and slope values of the collectors efficiency curves shown in Figs. 7 and 8 are summarized in Table 2 for the two different cooling water mass flow rates.

For different inlet cooling water temperatures and a mass flow rate of 0.02 A_{coll} kg/s, Fig. 7 and Table 2 indicate that: (1) The elliptical cross section wickless heat pipe flat plate solar collectors have higher

Table 2
Intercept and slope values of the collectors efficiency curves at two different cooling water mass flow rates

Collector	V^* (%)	$\dot{m}_w = 0.02\ A_{coll}$ kg/s		$\dot{m}_w = 0.04\ A_{coll}$ kg/s	
		$F_R(\tau_g\alpha_p)_e$	$F_R U_L$	$F_R(\tau_g\alpha_p)_e$	$F_R U_L$
Cir.	10%	0.7151	8.8622	0.7299	9.01
	20%	0.7379	9.1615	0.767	9.6035
	35%	0.7294	10.48		
Ell.	10%	0.7776	8.8528	0.8436	10.36
	20%	0.7761	9.7756	0.8308	10.941
	35%	0.6534	12.643		
Semi.	20%	0.6892	11.845		

performance than the circular ones at 10% and 20% water filling ratios; (2) The circular cross section wickless heat pipe flat plate solar collector has a higher performance than the elliptical one at 35% water filling ratios; (3) The semi-circular cross section wickless heat pipe solar collector with 20% water filling ratio had bad performance when compared to the elliptical and circular cross section ones with the same filling ratio; (4) The optimal filling ratios (i.e. filling ratio that gives higher performance) of the elliptical and circular cross section wickless heat pipe solar collectors are 10% and 20%, respectively; These results support the results of the first group of experiments. Also, the first result is confirmed at another cooling water mass flow rate as shown in Fig. 8 and Table 2. Fig. 7 indicates also that the filling ratio corresponding to the flooding limit for the elliptical cross section wickless heat pipe solar collector is smaller than that of the circular cross section ones as concluded by the results of the first group of experiments.

For the circular cross section wickless heat pipe solar collector, Figs. 7 and 8 indicate that the increase of water filling ratio from 10% to 20% improves the collector performance at low inlet cooling water temperatures and high solar radiation intensity (i.e. low measuring parameter $(T_{wi} - T_a)/I_t$. This improvement diminishes at high measuring parameter $(T_{wi} - T_a)/I_t$ as shown in Figs. 7 and 8. This may be due to a dry out limit, which occurs at low working fluid filling ratios and high heat fluxes. This means that the optimum water filling ratio is very close to 20% for the circular cross section wickless heat pipe solar collector. On the other hand, for an elliptical wickless heat pipe solar collector, Figs. 7 and 8 indicate that the increase of water filling ratio from 10% to 20% has a negative effect on the collector performance at high measuring parameter $(T_{wi} - T_a)/I_t$, and this effect diminishes at low measuring parameter. This means that the optimum water filling ratio and water filling ratio corresponding to the flooding limit of the elliptical cross section wickless heat pipe solar collector are very close to 10% and 35%, respectively.

5. Conclusions

From the present experimental investigation on wickless heat pipe flat plate solar collectors with different wickless heat pipes cross section geometries and different water filling ratios, it is concluded that:

1. Deforming the circular cross section wickless heat pipes to have an elliptical cross section significantly improves the performance of wickless heat pipe flat plate solar collectors at low water filling ratios.
2. The optimum water filling ratio of the elliptical cross section wickless heat pipe flat plate solar collectors is about 10%, while it is very close to 20% for the circular cross section wickless heat pipe flat plate solar collectors.
3. The water filling ratio corresponding to the flooding limit of the elliptical cross section wickless heat pipe solar collector is very close to 35%, while it is higher than 35% for circular cross section ones.
4. At 20% water filling ratio, the semi-circular cross section wickless heat pipe solar collector had bad performance compared with the circular and elliptical cross section ones.
5. More experimental results are needed to investigate the optimum filling ratio of wickless heat pipe solar collectors of different cross-sectional geometries with different working fluids.

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