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Experimental Study on the Performance of Evacuated Tube Solar Collectors

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Abstract. Solar energy can be gained without any restrictions. The solar collectors are the most technologies used to gain heat from solar energy, which can be used in many applications for buildings. as air-conditioning, cooling demand, heating of domestic water. The current work aims to investigate the effect of storage volume and the flow rate of heat transfer fluid on the performance of evacuated tube heat solar pipe collectors. The analysis utilizes the set of observed data for different operating conditions. The storage volume ranged from 4 to 20 *l* and the working fluid ranged from 0.87 to 1.98 *l*/min. Experiments were conducted in summer season. Five identical units were used to achieve this work. Each unit consist of three evacuated tubes solar heat pipe, circulating pump, storage tank, valve, pipe connections.

1. INTRODUCTION

Solar water heaters are more and more spreading all over the world. Many evacuated-tube designs have been developed and are being used. Water-in-glass design is exceptionally common design because of its low-cost and simple manufacturing and installation procedures. Many investigations are performed on such type of solar collectors when the flow is achieved by a natural circulation mechanism [1]. The characterization of the overall performance of water-in-glass evacuated tube collectors are found in [2-4] and the results showed that the overall efficiency is in the range of 50 to 60%.

Another design used finned copper tube (heat pipe) system with intermediate fluid used to carry heat from heating element to the tank. In this case the working fluid inside the heat pipe undergoes phase change process while it is transported up and down. Heat pipe is capable to transfer hundreds of times more energy from one location to another compared with a solid metal with the same dimensions and material. Evaluation of the overall performance of solar collectors is usually carried out experimentally using proven procedures according to international standards [5-7]. Various researches have been performed to estimate the thermal behavior of evacuated-tube solar collectors. Also, their thermal performances were compared with their corresponding flat plate counterparts [8]. Hayek et al. [9] experimentally studied the performance of water in glass and heat pipe designs of evacuated tube solar collectors. Their study was in eastern coast of the Mediterranean Sea, during (November-January) period. The results showed that the heat pipe-based collectors are more efficient than water in glass by 15% to 20%. Also, their payback periods are higher due to their primary cost. Chow et al. [10] reported their results for single phase open thermosyphon system and the two-phase closed thermosyphon (heat pipe) that are used for domestic hot water applications. The results were based on experiments and numerical modelling for assessing the performance of the two sorts. Their results showed that the heat pipe type is slightly better than the single phase open thermosyphon even they are less economically attractive.

Daughigh and shafieian [11] evaluated the thermal behavior of a solar heating system with evacuated tube heat pipe collector. First, they presented a mathematical model based on the energy and exergy analysis to show the collector performance. Then the system was constructed.

Xiowu and Ben [12] analyzed the thermal performance of solar water heating system of a domestic scale based on exergy analysis. They showed that the exergy efficiency is small since the output exergy is of low quality. Large exergy losses occur in the storage tank. It is also necessary to weigh carefully the choices of exergy efficiency and cost. Ayompe and Duffy [13] analyzed the thermal behavior of the solar water heating system with heat pipe evacuated tube collector using data a field trial installation over a year. Nkwetta et al. [14] evaluated the experimental performance and performed a comparative analysis of two different types of internal concentrator augmented solar collectors. Their results showed that the evacuated and non-evacuated heat pipe augmented concentrator prove to be better option for medium temperature applications due to higher temperature response, lower heat loss and high collector efficiency.

2. Experimental Test Setup

An outdoor experimental set up was designed and installed to investigate the thermal behavior of evacuated tube solar collector. The experiments are installed on the roof of the west part of the main building of the Faculty of Engineering at Shoubra, Benha University, in Cairo, Egypt. The setup consists of 5 identical modules. Each model is schematically illustrated in Fig. (1a). It is a closed loop circuit, where the water is drawn and pumped from the storage tank to a manifold in which three condensers parts of heat pipes are inserted via a circulating pump. Fig. (1b) shows the schematic diagram for the evacuated tube heat pipe. Three calibrated type T thermocouples are used to measure the inlet and outlet water of the manifold as well as the water tank temperature. The water flow rate is controlled through the use of a gate valve. The valve position is calibrated to get the water flow rate. Two groups of experiments are carried out to illustrate the effect of the water quantity in the storage tank and the second group to show the effect of water flow rate. A data acquisition card having the following specifications (National Instruments, NI USB-6210, 32-inputs, resolution of 16-bit and scanning rate of 250 kS/s) and a laptop are used to record temperatures through the thermocouples. The temperature readings at inlet, outlet of the collector manifold and tank temperature were recorded each second. The solar radiation was measured by a pyranometer and its readings were taken manually each 15 minutes.

3. Theoretical Analysis

The heat gained (output) by the water in the collector manifold is given by:

$$Q_o = m\, c_p\, (T_o - T_i) \qquad (1)$$

The solar energy is energy source and the input power is the irradiation, G, received by the collector surface then it is absorbed and then transferred to the heat transfer working fluid.

$$Q_i = G.\, A_c \qquad (2)$$

The efficiency of the solar collector is calculated as:

$$\eta = \frac{Q_o}{Q_i} = \frac{\dot{m} c_p (T_o - T_i)}{G A_c} \qquad (3)$$

The net power output can be written an input power minus the power lost due to heat loss [15]

$$Q = A_c\, F_R\, [G - U_L(T_m - T_a)] \qquad (4)$$

Where;

F_R is the collector removal factor

U_L is the overall heat loss coefficient.

T_m is the mean temperature of the heat transfer working fluid flowing inside the collector, generally it is the average between the inlet and the outlet temperatures of the collector manifold. Using Eq. (3) and Eq. (4) and noting that U_L is a function of temperature, gives the following expression:

$$\eta = \eta_o - a\frac{(T_m - T_\infty)}{G} - b\left(\frac{(T_m - T_\infty)}{G}\right)^2$$

In which η_o, a, and b are constants to be determined either analytically or experimentally. Developing an empirical correlation is step of the collector testing process. Some correlations used for predicting the thermal efficiency of the heat pipe system under consideration are listed in Table (1).

Table (1): Typical experimental coefficients of efficiency correlation for heat pipe collectors

Correlation	η_o	a	b	Source
Manufacturer	0.8	1.20	0.007	Manufacturer recommendation
Teknikum	0.84	2.02	0.0046	Teknikum Rapperswill [16]
Florida	0.81	1.23	0.0122	FSEC [16]

4. Results and Discussion

A typical set of data collected with heat pipe collector titled at 45° in North-South orientation is depicted in Fig. (2) On 14 June 2018. The figure shows the temporal variation of the solar irradiance and the ambient temperature. Even the solar radiation starts to decrease in the early afternoon the ambient temperature still increasing and it will decrease after about ….

The variation of tank temperature with time is illustrated in Fig. (3). It is noticed from the figure that the temperature is higher for small quantity of water in the tank. Also, the temperature increases as the time proceeds till it reaches a maximum where it reaches to 60ºC for 4 *l* and about 40ºC for 20 *l*.

Figure (4) illustrates the results for the five test units having storage tanks with different quantity of water 4, 8, 12, 16 and 20 liters respectively while the water flow rate was kept at 1.98 liter/min. the results were compared with manufacturer and previous correlations that found in [16]. It is noted that in Fig. (4a), where, water quantity of the storage volume is 4 liters, the efficiency of the present system is lower than that of manufacturer and previous studies [16] correlations by about 12-15% for all the period of experiment. From Figs. (4b-e), the present results show higher slop that that of the previous correlations. It is observed from the figures that higher values of collector efficiency at smaller values of $(T_m-T_\infty)/G$ which occurs early and late time apart from noon time due to either higher heat gain by water as illustrated from the variation water temperature in the tanks shown in Fig. (3) as well as the lower values of solar radiation reaching the minimum value of collector efficiency is observed. It is also noted that, the experiments occur at no load conditions and under transient behavior for the inlet temperature to the collector and this explains the discrepancy between the present data and the previous correlations at which steady state conditions are prevailed.

The solar irradiation and the ambient air temperature during experiments investigating the effect of working fluid flow rate on the performance of heat pipe solar collector are illustrated in Fig. (5). It is observed from the figure that there is a lag between the air temperature and the irradiation. The temporal variation of water tanks temperatures for different working fluid flow rates are depicted in Fig. (6). Also, the figure shows insignificant change in the water tanks temperatures for working fluid flow rate ranging from 0.87 to 1.52 liter/min. for working fluid flow rate of 1.77 and 1.98 liter/min as the flow rate increases the water tank temperature decreases and this may be due to the heat loss either from mixing in the tank or through the flow passage.

Figure (7) shows the variation of the collector efficiency with the value of $(T_m-T_\infty)/G$ for different working fluid flow rate versus the correlations of the previous studies [16]. For flow rate of 0.87 up to 1.52 liter/min gives the same behavior keeping the trend with the previous studies with noticeable differences which may be due to the transient behavior of the inlet water temperature of the present work and weather conditions while the previous correlations are based on steady state condition. For volume flow rate of 1.77 and 1.98 liter/min exhibits similar behavior for the variation of the collector efficiency with $(T_m-T_\infty)/G$ for smaller and larger values of the quantity $(T_m-T_\infty)/G$ that corresponds to early and late times of the day gives higher efficiency is obtained and generally the efficiency increases with the increase of the flow rate.

5. Conclusions

From the above results and discussion, the following conclusions can be drawn:

- The increase of the storage volume by 500% results in reduction of the maximum attainable water temperature by about 50%.
- The storage tank temperature decreases with the increase in working fluid flow rate.
- The thermal efficiency of the evacuated tube solar collector increases with the increase of working fluid flow rate.
- The thermal efficiency of the evacuated tube solar collector decreases with the increase of the value of $(T_m-T_\infty)/G$ till a certain value depending on design and working condition then increases with its increase.
- Noticeable differences between the current results and the previous ones due to the transient nature of the present work while the previous was under steady state conditions.

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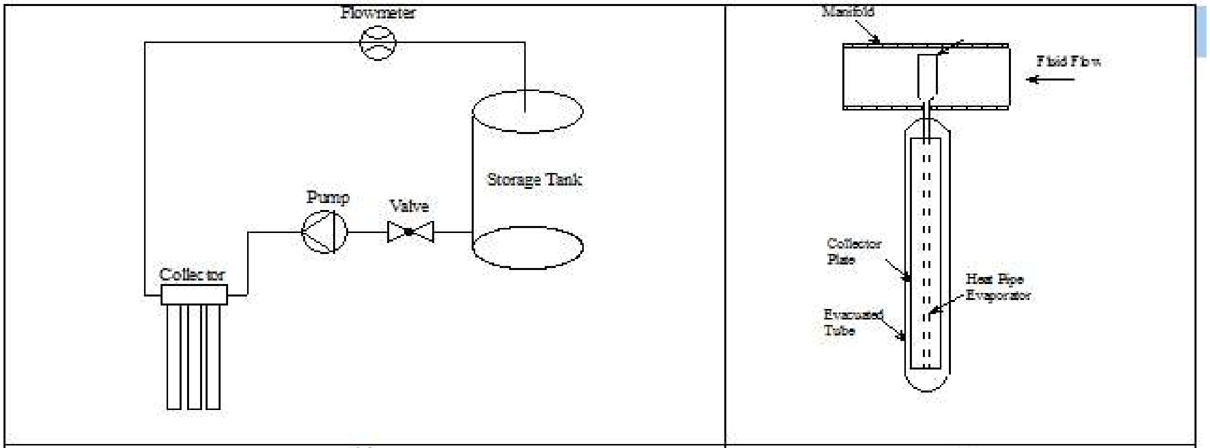


(a) (b)

Fig. (1): a) Schematic diagram for the test rig **b)heat pipe**

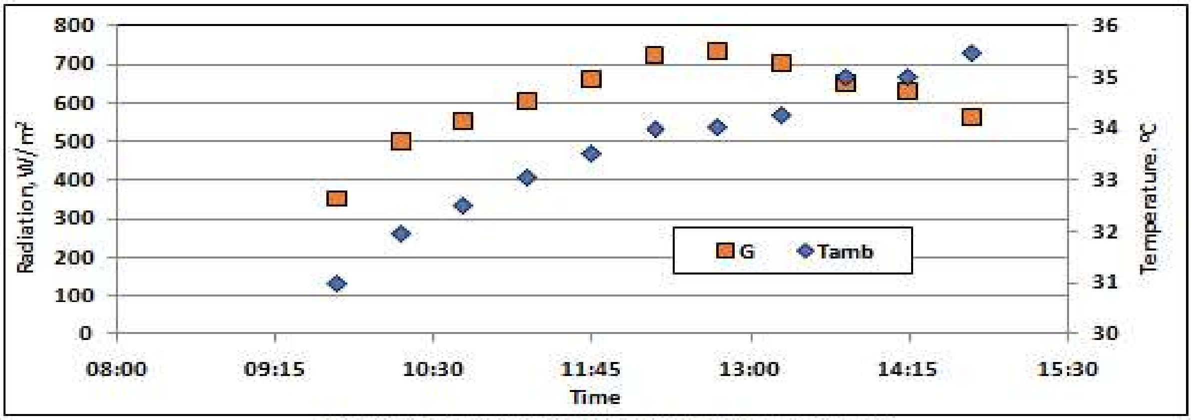


Fig. (2): Measured irradiation and ambient temperature

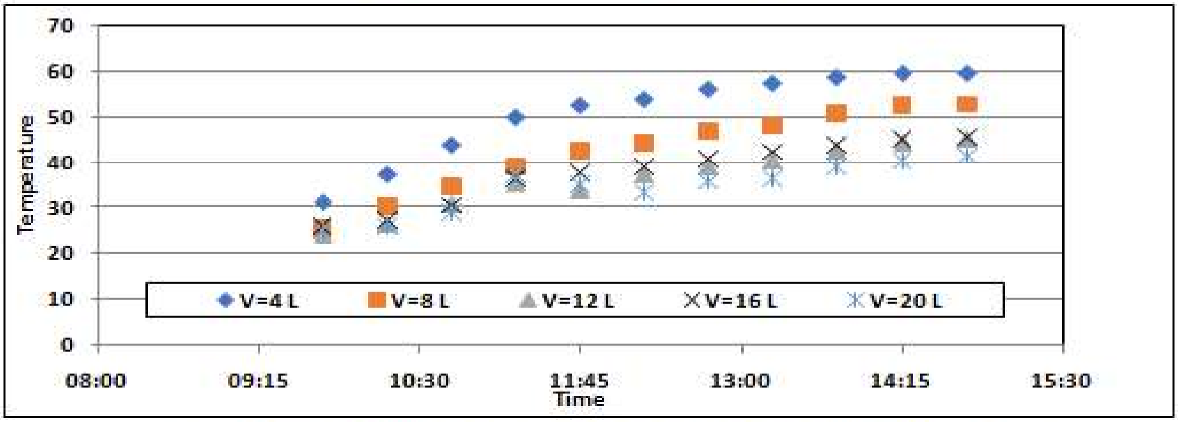
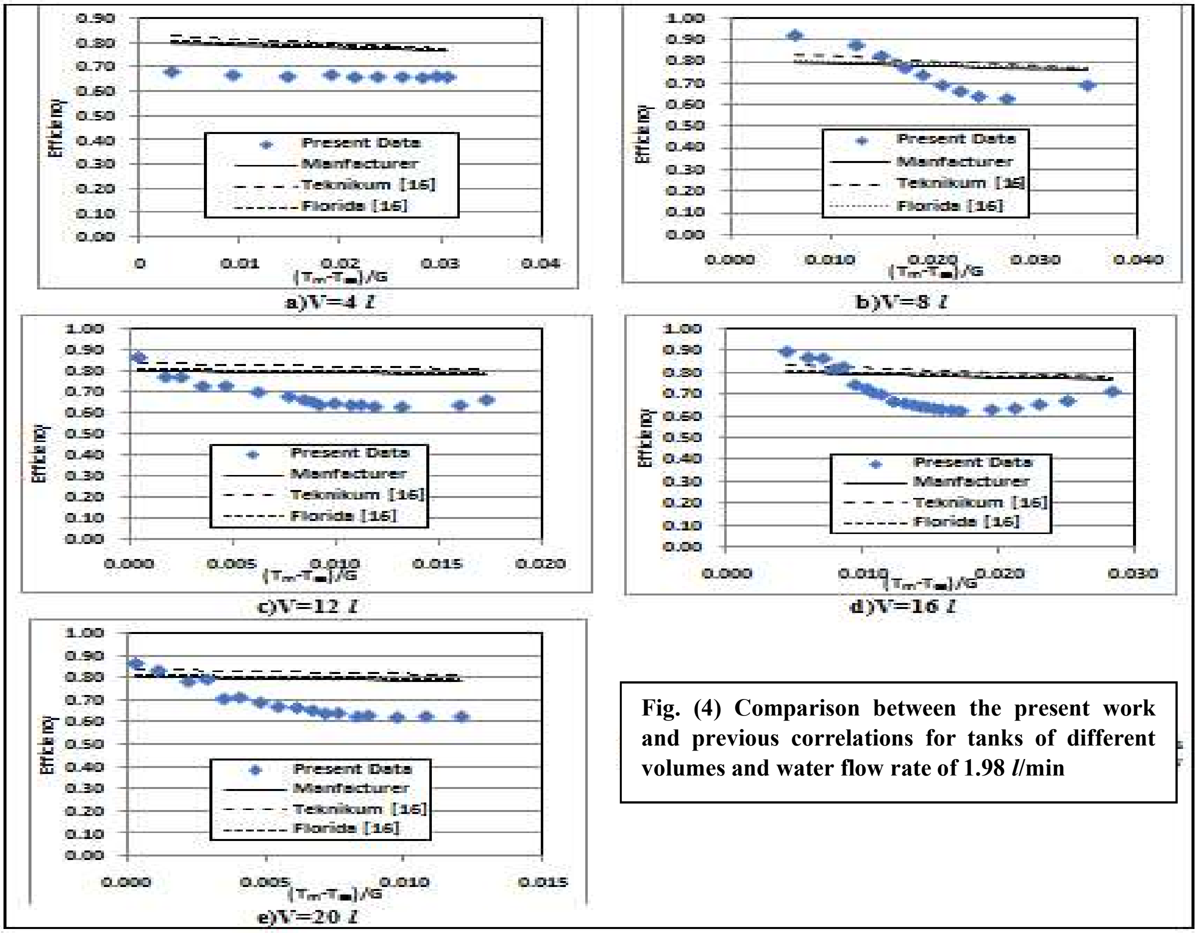


Fig. (3): Temporal variation of water temperature in the tanks of different water volume



a)V=4 *l*

b)V=8 *l*

c)V=12 *l*

d)V=16 *l*

e)V=20 *l*

Fig. (4) Comparison between the present work and previous correlations for tanks of different volumes and water flow rate of 1.98 *l*/min

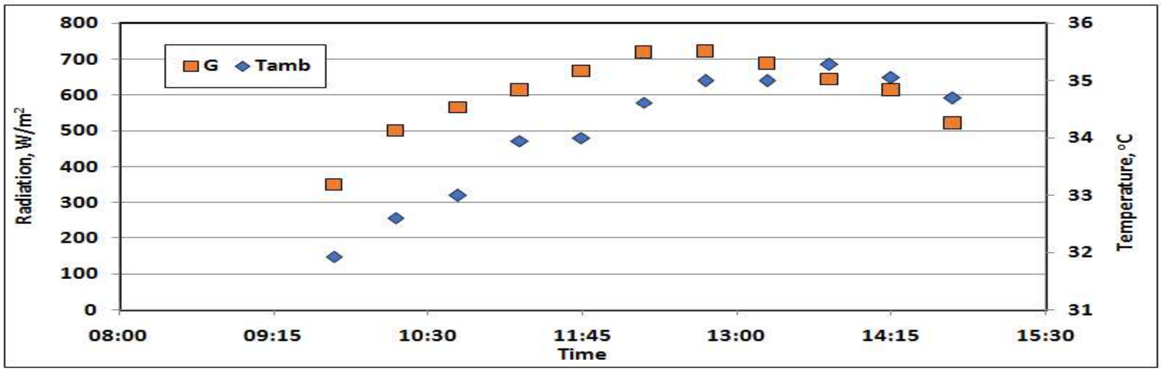


Fig. (5): Temporal variation of water temperature in the tanks of different water volume

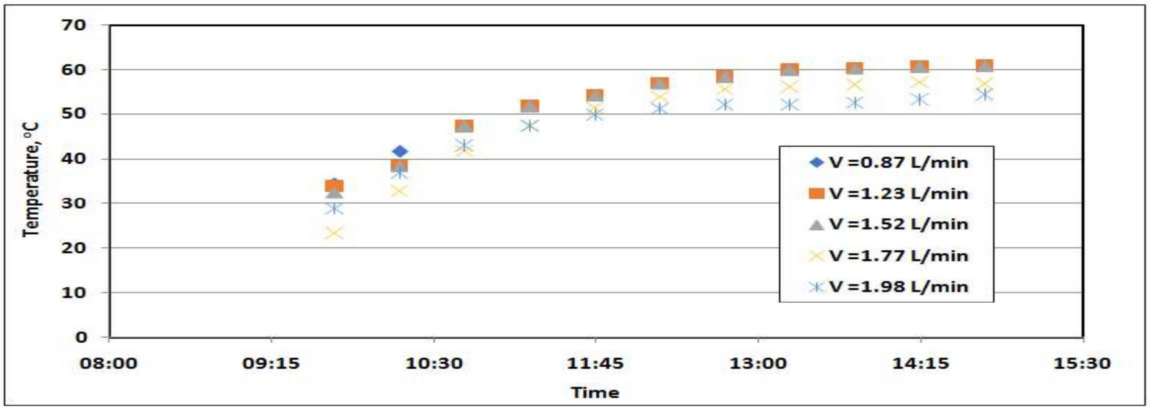
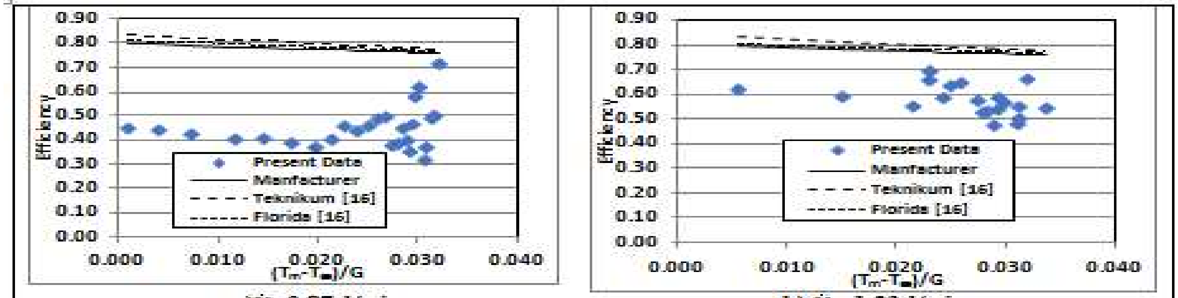
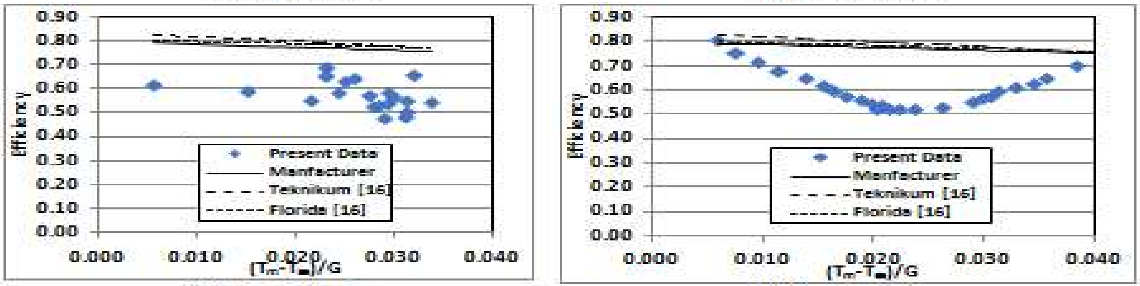


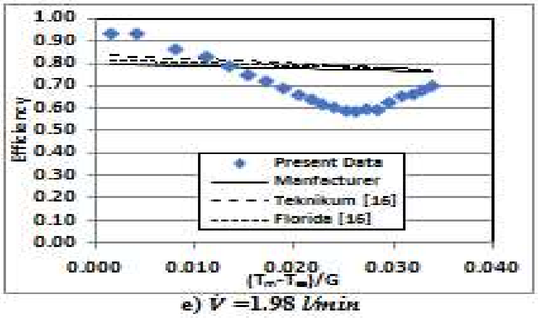
Fig. (6): Temporal variation of water temperature in the tanks of different water volume



a) $\dot{V}$=0.87 *l/min* b) $\dot{V}$ =1.23 *l/min*



c) $\dot{V}$ =1.52 *l/min* d) $\dot{V}$ =1.77 *l/min*



e) $\dot{V}$ =1.98 *l/min*

Fig. (7) Comparison between the present work and previous correlations for tanks of constant volumes and different water flow rates