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Experimental and Theoretical Analysis of Thermal Losses in A Flat Plate Solar Heater with Multi Risers and Headers

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ABSTRACT

Experimental and theoretical calculations are made to a flat plate solar heater which is manufactured from vertical copper pipes (called risers) and two horizontal copper pipes (called headers) through which distilled water passes. The risers and headers are bonded to a 1 m^2 square galvanized steel plate and mounted inside a wooden case equipped with thermal insulation and double glass covers. Two flow rates are applied 100 L/hr & 200 L/hr and the water enters the solar heater is preheated using a solar preheater so that no conventional energy is used to raise the temperature of water. The heat gain and efficiency are calculated experimentally but the top heat losses are calculated experimentally and theoretically. Accordingly, the error was calculated according to the discrepancy between the experimental and theoretical data. The results show that the maximum heat gain, outlet temperature and efficiency occurred at flow rate of 100 L/hr. The maximum heat gain obtained is 920 W/m^2, maximum outlet temperature is 73ºC and maximum efficiency of 82%. Both values occurred at 100 L/hr and at the first run hour. The reason is the maximum thermal equilibrium the solar heater reached before the experiment was run. The overall error between experimental and theoretical data is mostly laid below 20% except at the first and last hours because the theoretical calculation was based on the temperature of absorbing plate while the experimental calculations are based on inlet and outlet temperatures.

KEYWORDS

flat plate solar water heater, heat gain, efficiency, heat losses, approximate error, heat removal factor.

INTRODUCTION

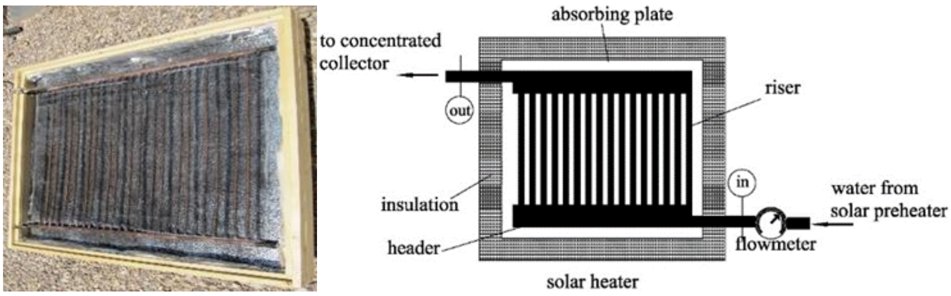
The problem of diminishing conventional energy and its negative impact on the environment is becoming so serious that researchers all over the world are seeking alternative sources of energy that is renewable and friendly to environment. In a country like Iraq, the potential and promising source of renewable energy is solar energy as the intensity of solar radiation reaches such high potential values [1]. Accordingly, researches are encouraged to take the advantages of such high incident energy in many engineering applications [2]. One of the most popular applications of solar energy is the flat plate solar heater. This kind of heater is simple in design and very practical in supplying moderately hot water for domestic use [3, 4]. Even though it requires a large absorbing surface which leads to a large exposed area, it is still of the most preferrable design for domestic use and researchers as well. One of its best advantages is the relatively high flowrate of working fluid (usually water) which is required for daily use.

Speaking of disadvantages of flat plate solar heater, the heat losses stem among others as the most influential parameter that affect the performance of heater. The fact is, the larger the absorbing surface is the higher the heat gain and the higher the heat losses too. Accordingly, the efficiency of heater reaches such a certain value that represents the maximum numerical value after which it drops even though the solar radiation beam still hits the absorbing surface with considerable high amount. This happens when the working fluid reaches a temperature which is higher than the ambient temperature so that the heat escapes out through the glazing which is at a temperature below the temperature of absorbing surface. At this point, the solar heater is said to reach its thermal restrictions where researchers attempt to enhance their designs using for instance; nanofluid instead of distilled water [5][6][7], selective absorbing surfaces that are able to absorb much heat [8] [9] or control the flow of working fluid so that heat gain is improved [10].

This research focuses on the comparison between the experimental and theoretical calculations regarding heat losses from a flat plate solar heater. The solar heater is manufactured from vertical pipes called risers and two horizontal pipes called lower and upper headers through which preheated water flows. The outlet of upper header is made smaller in diameter in order to apply a miner dynamic pressure as an attempt to enhance the temperature rise of water through the solar heater. The results of the experiment which was run on the solar heater are to be compared with theoretical calculations. Accordingly, the discrepancy between the experimental and theoretical calculations is considered as the percentage error which mainly comes from the measuring device uncertainty.

EXPERIMENT SETUP

The solar heater built for the experiment consists of a square galvanized steel plate with a thickness of 1 mm bonded to a network of copper pipes. The network consists of 28 copper pipes (called risers) with a diameter of 15 mm each connected to two copper pipes (called headers) with a diameter of 25 mm. The risers are vertical and the headers are horizontal. The lower header receives the preheated water and distributes it to the risers that take the water to the upper header which discharges the water into a tank or a concentrated collector for steam generation. In contrast to the conventional solar heater, the pipes are exposed directly to the sun instead of being bonded beneath the plate as this is expected to enhance the heat transfer between the direct solar radiation beam and the water passing through the pipes. The surface of pipes and plate that exposed to the sun is coated black using granulated carbon in order to play as a selective absorbing surface [11]. The arrangement of plate and pipes is shown in figure 1(a).



(a) **(b)**

Figure 1. (a) the solar water heater used in the experiment (b) A schematic diagram of the solar heater layout

Since the water enters the heater is preheated, its temperature is increasing gradually. Nevertheless, the preheating was done using solar energy. This was deliberately made in order to reach the situation when the temperature difference between the inlet and outlet of the solar heater becomes constant hence the heater is no longer able to receive any more heat. This situation represents the main objective of this research as this situation occurs when the heat losses increases and the water passing through the pipes is no longer able to gain more sensible heat because its temperature is well above the ambient temperature. A schematic diagram of the solar heater layout is shown in figure 1(b). In order to compare the theoretical calculations with the experimental data, the inlet and outlet temperatures of the water, mean absorbing plate temperature, ambient temperature, water flowrate and incident solar energy were measured using measuring instruments. The whole arrangement of plate and pipes is mounted inside a wooden case where 15 mm is left between the upper surface of headers and the first glass cover. The glass covers are separated by 10 mm distance. These two-glass cover play as glazing that allows the solar energy to transmit and reduce the heat that transfer from the absorbing plate to the ambience. The geographical location where the experiment was run is 31.8379ºN, 47.1421ºE.

THEORETICAL CALCULATIONS

Referring to figure 1(b), the inlet and outlet temperatures (T_{in} & T_{out}) are measured and the mass flowrate of water ($\dot{m}$) as well, then the heat gained (Q_u) by the heater can be calculated from the following formula [12]:

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

The heat lost is then calculated from the measured incident solar energy (Q_S), i.e.

$$\dot{Q}_{loss} = \dot{Q}_S - \dot{Q}_u \quad (2)$$

Notice that the heat lost calculated by equation 2 represents the experimental value as all parameters appeared in the equation were measured during the experiment. In addition, the incident solar energy (Q_S) represents the actual energy that hits the absorbing surface after being transmitted through the glass covers, see figure 2. This means the solar radiation beam (I_S) is filtered through the two glass covers so that:

$$\dot{Q}_S = I_S \times \alpha_1\alpha_2 \quad (3)$$

Where α_1 & α_2 are the transmissivity of glass cover 1 & 2 respectively. The direct solar beam (I_S) is useful in calculating the efficiency of the solar heater (η):

$$\eta = \dot{Q}_u / I_S \quad (4)$$

In equation 4 the solar radiation beam (I_S) is considered as an input heat instead of the incident solar energy (Q_S) because the glass covers represent main parts of the heater and hence, they affect the efficiency of the heater. Nevertheless, equation 4 is also calculated based on the experimental data.

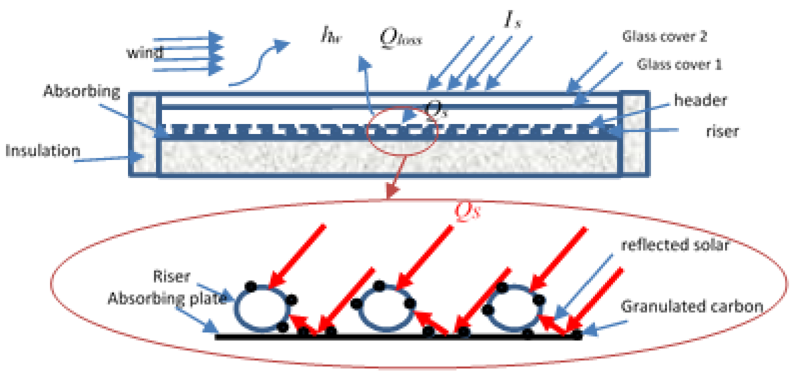


Figure 2. A schematic diagram of the parameters that affect the solar heater

The risers and headers are bonded to the front face of absorbing plate that directly faces the solar beam for some reasons among others are; there will be a direct transfer of solar energy to the working fluid. Second, because the headers are bigger than risers, the whole surface of the risers will be exposed to the incident solar radiation; part from the direct beam and the other is from the reflected beam on the absorbing plate. This is depicted in figure 2. Accordingly, the heat transfer area is enhanced since both plate and pipes receives solar radiation, i.e.

$$A = A_{plate} + N_r * \pi d_r L_r + N_h * \pi d_h L_h \quad (5)$$

Where subscripts *r* & *h* refer to risers and headers respectively.

Before proceeding with the theoretical calculations of the heat losses, the following assumption is applicable; *the solar heater is so insulated from the back and sides that only top losses through the two glass covers is considered*. Accordingly, the top heat lost is expressed as follows [13]:

$$\dot{Q}_{top} = U_t A(T_p - T_a) \quad (6)$$

Where

$$U_t = \frac{1}{R_1 + R_2 + R_3} \tag{7}$$

$$R_1 = \frac{1}{h_w + h_{r,g2-\infty}} \tag{8}$$

$$h_{r,g2-\infty} = \frac{\sigma \varepsilon_g (T_{g2}+T_s)(T_{g2}^2+T_s^2)(T_{g2}-T_s)}{(T_{g2}-T_\infty)} \tag{9}$$

$$R_2 = \frac{1}{h_{c,g1-g2} + h_{r,g1-g2}} \tag{10}$$

$$h_{c,g1-g2} = \frac{k}{L}\left\{1 + 1.44\left[1 - \frac{1708(sin1.8\beta)^{1.6}}{Ra\cos\beta}\right]\right\} \tag{11}$$

$$Ra = \frac{g\beta\Delta T L^3}{\upsilon\alpha} \tag{12}$$

$$h_{r,g1-g2} = \frac{\sigma(T_{g1}+T_{g2})(T_{g1}^2+T_{g2}^2)}{\frac{1}{\varepsilon_{g1}}+\frac{1}{\varepsilon_{g2}}-1} \tag{13}$$

Notice that L in equation 11 refers to the distance between the parallel plates (the two glass covers).

$$R_3 = \frac{1}{h_{c,p-g1} + h_{r,p-g1}} \tag{14}$$

$$h_{c,p-g1} = \frac{k}{L}\left\{1 + 1.44\left[1 - \frac{1708(sin1.8\beta)^{1.6}}{Ra\cos\beta}\right]\right\} \tag{15}$$

$$h_{r,p-g1} = \frac{\sigma(T_p+T_{g1})(T_p^2+T_{g1}^2)}{\frac{1}{\varepsilon_p}+\frac{1}{\varepsilon_{g1}}-1} \tag{16}$$

Notice that L in equation 14 refers to the distance between the parallel plates (the absorbing plate and the first glass cover). Notice also that all variables and constants appeared in equations 6 – 15 are known from the experiment and properties tables except the temperature of glass covers. To find these two unknown temperatures, the following procedure was applied [14]:

For two adjacent covers or plates, the new temperature at j can be obtained from the previously assumed temperature applying the following formula:

$$T_j = T_j - \frac{U_t(T_p - T_a)}{h_{c,i-j} - h_{r,i-j}} \tag{17}$$

The procedure runs as follows; input known variables T_p, T_a and I_s. T_{g1} and T_{g2} are assumed with values close to T_p then apply equation 16 so that $i = p$ and $j = g1$. Equations 14 and 15 are required for equation 16 which calculates T_{g1}. The second run starts with known variables T_{g1}, T_a and I_s when this time $i = g1$ and $j = g2$. Equations 9 and 11 are required for equation 16 which calculates T_{g2}. The calculated T_{g1} & T_{g2} are compared with the previously assumed ones. If they are identical the procedure is then repeated using a new measured value of T_p. otherwise, the assumed temperatures shall be replaced by the calculated ones and along with the same value of T_p a new set of T_{g1} and T_{g2} is calculated and so on. This is illustrated in the flowchart shown in figure 3

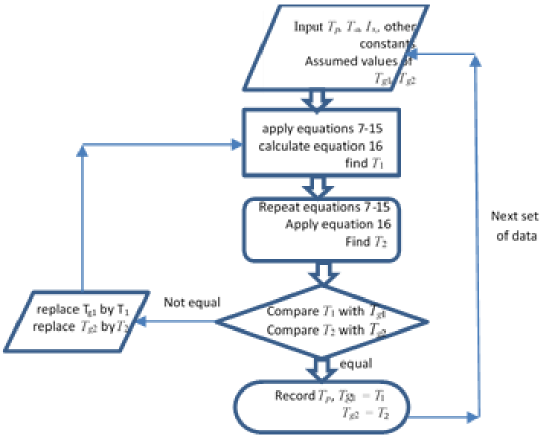


Figure 3. The flowchart which was applied to find glass cover temperatures.

Now, equation 6 is to be compared with equation 2 in order to determine the percentage error between the experimental and theoretical calculations which is expressed as follows:

$$\epsilon\% = \left|\frac{\dot{Q}_{top}-\dot{Q}_{loss}}{\dot{Q}_{top}}\right| \times 100\% \tag{17}$$

It sounds meaningful comparing the heat gain from equation 1 with the heat gain that could be obtained if the whole surface of collector was at the inlet temperature. This comparison is called the collector heat removal factor (F_R) and it is comparable to collector effectiveness. The heat removal factor can be expressed as follows [15]:

$$F_R = \frac{\dot{Q}_u}{A_c[I_S - U_L(T_{in} - T_\infty)]} \tag{18}$$

Where,

I_S = incident energy

$$U_L = \frac{1}{\left\{\dfrac{N}{\dfrac{C}{T_p}\left[\dfrac{(T_p - T_\infty)}{(N+f)}\right]^e} + \dfrac{1}{h_w}\right\}} + \frac{\sigma(T_p + T_\infty)(T_p^2 + T_\infty^2)}{\dfrac{1}{\varepsilon_p + 0.00591 N h_w} + \dfrac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_g} - N}$$

$$f = (1 + 0.089 h_w - 0.1166 h_w \varepsilon_p)(1 + 0.07866 N)$$

$$C = 520(1 - 0.000051\theta^2)$$

$$e = 0.43(1 - 100/T_p)$$

N = no. of glass covers = 2

θ = collector tilt angle = $\pi/6$

ε_p = absorbing plate emittance = 0.85

ε_g = glass cover emittance = 0.88 – 0.92

h_w = wind convective heat transfer coefficient (10 – 15 $W/m^2.C$)

RESULT AND DISCUSSION

The experimental values of heat gain, heat lost and efficiency of the solar heater are illustrated in figure 4 at two different flowrates 100 L/hr and 200 L/hr. The values were calculated applying equations 1 – 4. The corresponding theoretical values of heat lost and the overall heat lost coefficient at both flowrates along with heat removal factors are shown in figure 5. The percentage error between the theoretical and experimental values of heat losses, the average solar radiation beam during the experiment and mean absorbing surface temperature are shown in figure 6.

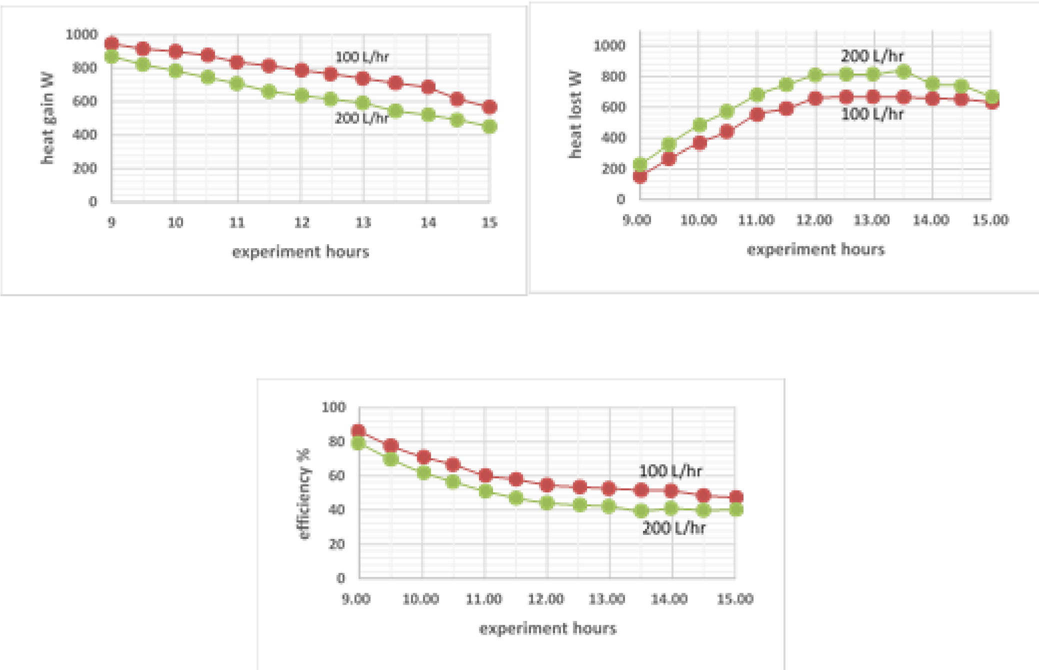


Figure 4. Experimental calculations of heat gain, heat lost and efficiency of solar heater at two different flowrates

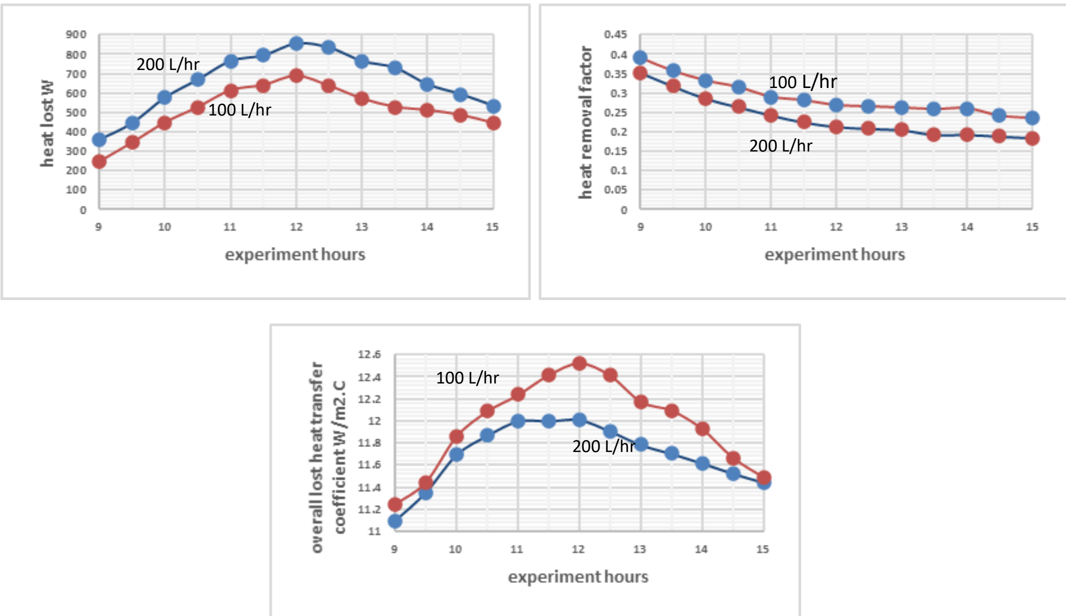


Figure 5. The theoretical values of heat lost, heat removal factors and overall lost heat transfer coefficient U_t at two different flowrates

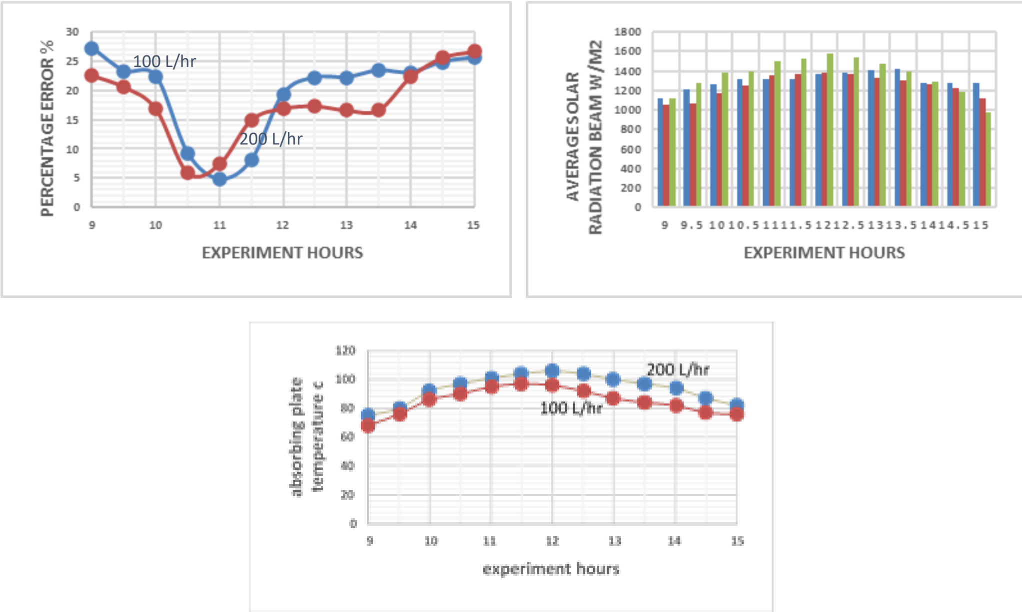


Figure 6. The percentage error between the experimental and theoretical value of heat losses, the mean solar radiation beam during the experiment and the mean absorbing surface temperature

In figure 3. There is an interesting observation regarding the first hour of experiment, i.e., 9:00 – 10:00. During this hour the experimental data shows a high value of heat gain, low heat lost and subsequently high efficiency that reaches 80%. After this hour the change in data becomes smooth, i.e. values increase / decrease gently. This situation happens because the collector was left uncovered over the night and the solar heater starts to receive the hot solar beam since 7:00 AM. Accordingly, the absorbing plate reached so high temperature that the first water running out contained a percentage of steam. Therefore, the water flowing through the heater during the first hour gains high amount of heat and thus the heat lost according to equation 2 is so low. Meanwhile, equation 6 depends on the value of overall heat transfer coefficient which has its maximum value at midday as shown in figure 4. In order to overcome this inconsistency between the experimental and theoretical calculations, the experiment should have started at 8:00 so that the data is to be taken at 9:00. The heat removal factor which is depicted in figure 5 should be compared to the efficiency that is shown in figure 4. However, the efficiency calculated in accordance with the experimental data is higher than the heat removal factor.

This inconsistency comes from the fact that heat removal factor is calculated using the temperature difference between the inlet and ambient temperatures which was decreasing continuously as the solar heater is fed by a solar preheater which causes the inlet temperature to increase. Subsequently, the denominator of equation 17 increases and hence heat removal decreases continuously. The effect of first run hour of experiment becomes clear in figure 6 when the percentage error exceeds 20% during the this hour as the theoretical calculations did not take in account the influence of the high energy amount stored in the collector during the first run hour. Nevertheless, both data can be compared to each other after 10:00 as they are below 20%. It is obvious from figure 5 the percentage error for the high flowrate is mostly below the one for low flowrate. This comes from the fact that the mean absorbing temperature was measured using two thermocouples, one was attached to the center of the plate beneath one of the risers and the other was inserted under upper header at the middle of the plate. These two points were not enough to measure the actual mean temperature on which the heat lost calculation is based. This is clearly observed in figure 6 in which the mean absorbing plate temperatures are depicted for both flowrates. The two temperatures are comparable to each other and hence the heat lost for the case of low flowrate is quite high compared to the actual value calculated from equation 2.

CONCLUSION

From the results above, it can be concluded that the maximum outlet temperature, sensible heat gain and efficiency occurs when the flowrate is 100 L/hr. Subsequently, the heat losses increase with increasing the flowrate because the water has shorter time to absorb the incident solar energy. The maximum efficiency obtained is 82% and the maximum outlet temperature is 73ºC. The heat removal factor of the collector is comparable to the efficiency but its value falls below the efficiency because the value of removal factor is related inversely to the temperature difference between inlet and ambient temperatures which is continuously decreasing because of the preheating. The percentage error between the experimental and theoretical calculations is mostly below 20% except at the first and last hours. The main source of this error is the uncertainty in the measurement instruments.

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