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Exergetic Optimization of a Flat Plate Solar Collector Design

Sia Tohching*1, Sanjayan Velautham* and Amer Nordin*

Abstract- *It has been established that energy efficiency of a flat plate solar collector increases without extremum points with the flow rate and likewise the fluid outlet temperature increases with the collecting area. Thus, it provides no maximum points for the purpose of optimization of solar collector design. In contrast, exergy analysis presents various local points for* $\eta_{ex} = f(\dot{m}, A_c)$ *, and with a global maximum point. Based on these findings, this paper further develops the exergy analysis of a flat plate solar collector by outlining the correlation between the exergy efficiency of a flat plate solar collector,* η_{ex} *,with the outlet and inlet fluid temperature variation,* ΔT*, with respect to the influence of fluid flow rate,* $\dot{m}$ *, and collector area,* A_c*. In addition, the inter-relation between the fluid flow rate and the collector area is also examined as a ratio, R, where* $R = \dot{m} / A_c$ *, thus, giving* $\eta_{ex} = f(R)$ *and* $\Delta T = f(R)$*. From these evaluations, it seems that there is a precise value of R which will give the optimum operating mode for the solar collector, either with maximum exergy efficiency or maximum temperature variation, or both, for a fixed design specification. The value of R and the corresponding values of exergy efficiency and temperature variation are evaluated in this paper for Malaysia meteorological conditions.*

Keywords - Energy, exergy, flat plate solar collector, ratio R.

1. INTRODUCTION

The vulnerability of oil price and the remaining fossil fuel reserves, together with the environment have become a real concern. Due to the robust growth of economy worldwide and in Malaysia, there is a concern that nations could be faced with another energy crisis. Based on the World Oil Reserves, Production and Consumption in year 2004 [1]-[2], and Malaysia's Oil Production and Consumption, 1980-2005 [3] as depicted in Table 1 and Fig. 1, it is estimated that the resource will be totally exhausted in 50-60 years time and Malaysia is anticipated to change from being an oil exporter to importer by around year 2008 [4]. Renewable energy resources can diversify the usage of the non-renewable energies thus creating a more sustainable environment. In fact, Malaysia has acted pro-actively by formulating a Five-Fuel Policy in the 8th Malaysia Plan [5] where renewable energies are emphasized to avoid over dependence on non-renewable energies.

Geographically, solar energy can be easily obtained in Malaysia and thus could be a viable option to replace the non-renewable energies. Fig. 2 shows the minimum and maximum mean daily solar radiation recorded in Malaysia from August 2004 to July 2005 [6]. From the chart, it can be noticed that the solar radiation received in the country does not fluctuate a lot from month to month. The mean daily solar radiation received in a certain month is assumed equals to the average of the minimum and maximum solar radiation recorded in that particular month. Thus, taking into account the data for 12 months, the actual mean daily solar radiation is obtained by summing up the mean daily solar radiation for each month and taking the average. It has the value of 16.86 MJ/m^2.

Solar energy is an absolutely clean energy resource that has been most emphasized on in the challenges of developing sustainable energy in the new era. One of the most common implementation of solar energy is on the solar water heating systems. In certain countries, solar water heating systems have been used widely. In Taiwan, for instance, the total area of solar collectors installed was more than one million square meters [7].

Despite the wide usage of the system, there is still a lot to be done to fully utilize the solar energy by increasing the efficiency of the system, i.e. to maximize the conversion of solar energy into thermal use or electrical energy. The collector is the core of a solar water heating system and it constitutes half of the total investments on the system. Thus, it is wise to carry out analysis on it. Many studies on the domestic-scale water heating systems were based on the first law of thermodynamics; however, studies have found that it is the quality rather than the quantity of energy that is more meaningful.

In Refs. [8]-[10], different methods have been developed to design a flat plate collector. I. Luminosu and L. Fara [8] found the difficulties in the design of flat solar collectors using the solar-thermal energy efficiency in the absence of maximum points. Thus, exergy analysis is used to obtain the global maximum point for the optimum operation of a flat plate collector.

Torres- Reyes [9] introduced a specific method based on the minimum entropy generation to establish the optimal performance parameters during the collection of solar energy. Two dimensionless parameters: Entropy Generation Number and Mass Flow Number are presented and applied to characterize the performance of the solar collector.

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Table 1. World oil reserves, production and consumption, 2004

	Crude oil reserves (billion barrels)	Reserve share	Petroleum production (million barrels per day)	Production share	Petroleum consumption (million barrels per day)	Consumption share
U.S.	21.9	2%	7.2	9%	20.5	25%
OPEC	876.6	70%	32.7	41%	7	8%
Rest of the world	357.7	28%	40.0	50%	55.1	67%

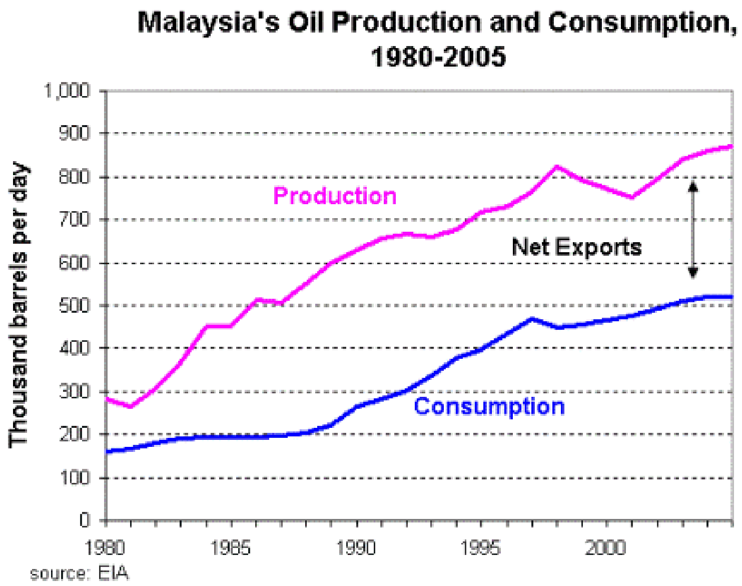

Fig. 1. Malaysia's Oil Production and Consumption from 1980 to 2005.

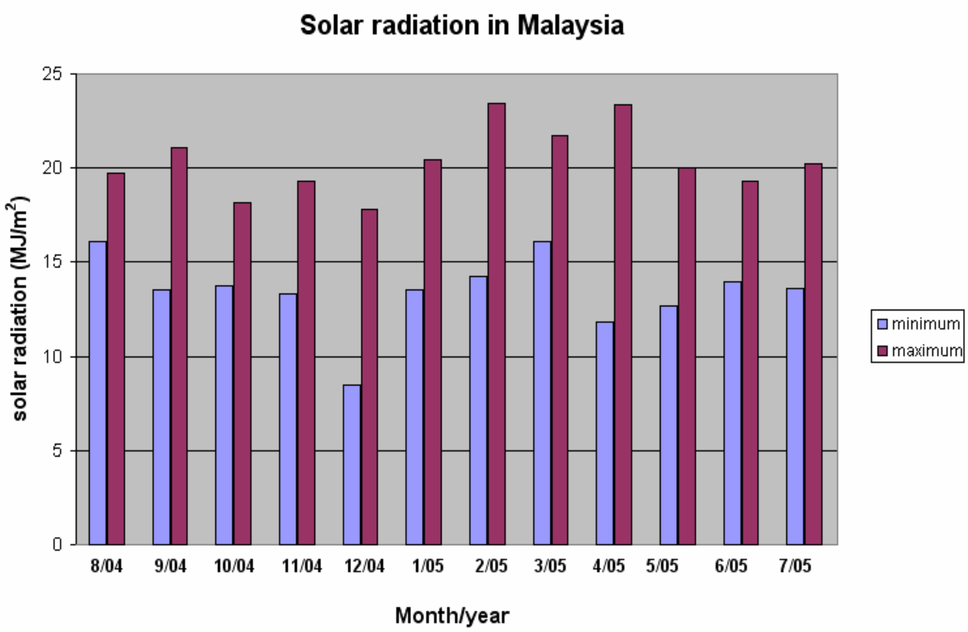

Fig. 2. Solar radiation in Malaysia from August 2004 to July 2005.

Wang Xiaowu [10] has also presented an exergy analysis on domestic-scale solar water heaters based on the 'Three Procedure Theory' represented by Professor Hua Ben. The theory relates the sun (conversion procedure), collector (utilization procedure) and storing barrel (recycling procedure), and thus provides methods to save cost and retain the whole system efficiency to desired extent by examining the exergy losses.

In this paper, an exergetic analysis is conducted to obtain the optimal design parameters of a flat plate to maximize the efficiency by simplifying the mathematical model presented by I. Luminosu and L. Fara [8]. The correlation between the exergy efficiency of a flat plate solar collector, η_{ex}, with the temperature variation of the outlet and inlet fluid, ΔT, is examined, with respect to the influence of fluid flow rate, $\dot{m}$, and collector area, A_c. Herein a parameter R is introduced to constitute an optimised design method of a flat plate solar collector.

2. ANALYSIS

Generally, exergy change of a fluid stream can be expressed as [11]

$$E=(h-h_a)-T_a(s-s_a)+\frac{v^2}{2}+gz \qquad (1)$$

Assuming that the fluid stream has negligible kinetic and potential energies, the flow rate of exergy from the Sun to the operating fluid within the tubes is given by Eq. (2).

$$\dot{E}_f=\dot{m}\left[\left(h_{f,o}-h_{f,i}\right)-T_a\left(s_{f,o}-s_{f,i}\right)\right] \qquad (2)$$

Substituting

$$h_{f,o}-h_{f,i}=C\,(T_{f,o}-T_{f,i}) \text{ and } s_{f,o}-s_{f,i}=C\,\ln\left(\frac{T_{f,o}}{T_{f,i}}\right),$$

hence,

$$\dot{E}_f=\dot{m}C\left[\Delta T-T_a\ln\left(\frac{T_{f,o}}{T_{f,i}}\right)\right] \qquad (3)$$

According to Takashima [12], exergy flow rate for the global solar radiation $\dot{E}_S$ can be assumed to equal the solar flux, $\dot{E}_S=A_c(HR)$. Thus, exergy efficiency of a flat plate solar collector is:

$$\eta_{ex}=\frac{\dot{E}_f}{\dot{E}_S}=\frac{\dot{m}C\left[\Delta T-T_a\ln\left(\frac{T_{f,o}}{T_{f,i}}\right)\right]}{A_c(HR)} \qquad (4)$$

Fig. 3 illustrates a typical domestic scale solar water heater. According to Duffie and Beckman [13], the temperature distribution in the direction of the fluid flow is given by the Eq. (5), with assumption that *F'* and U_L are independent of position [14],

$$\frac{T_f-T_a-S/U_L}{T_{f,i}-T_a-S/U_L}=\exp(-U_L nWF'y/\dot{m}C) \qquad (5)$$

where $\dot{m}$ is the total collector flow rate and *n* is the number of parallel tubes. For a flat plate solar collector with parallel tubes of length *L*, the outlet fluid temperature can be obtained by substituting *L* for *y* in Eq. (5), giving

$$\frac{T_{f,o}-T_a-S/U_L}{T_{f,i}-T_a-S/U_L}=\exp(-A_cU_LF'/\dot{m}C) \qquad (6)$$

where $A_c = nWL$. Assuming $T_{f,i}=T_a$, the inlet and outlet fluid temperature variation, ΔT, can be expressed as:

$$\Delta T=T_{f,o}-T_{f,i}=\left(\frac{S}{U_L}\right)\left(1-\exp\left(-\frac{A_cU_LF'}{\dot{m}C}\right)\right) \qquad (7)$$

which then can be substituted into Eq. (4) to gives η_{ex} as:

$$\eta_{ex}=\frac{\dot{m}C}{A_cHR}\left[\frac{S}{U_L}\left(1-\exp\left(-\frac{A_cU_LF'}{\dot{m}C}\right)\right)-T_a\ln\left(1+\frac{S}{T_aU_L}\left(1-\exp\left(-\frac{A_cU_LF'}{\dot{m}C}\right)\right)\right)\right] \qquad (8)$$

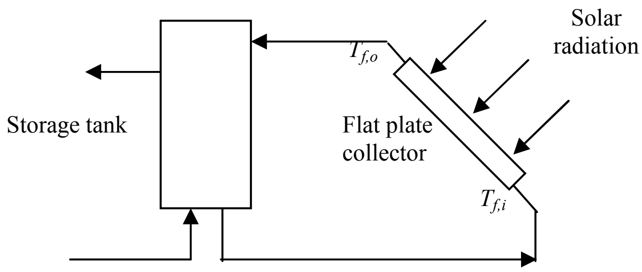

Fig. 3. A typical domestic scale solar water heater.

The model presented in Fig. 3 can be transposed into a computation program using Matlab with the following conditions:

(a) constant parameters: specific heat of working fluid, solar radiation intensity, coefficient of thermal losses, effective product absorptance-transmittance, efficiency factor and environmental temperature, inlet fluid temperature

(b) variable parameters: exergy efficiency, outlet fluid temperature, fluid flow rate, collecting area

Fig. 4. shows the flow chart of the simulation.

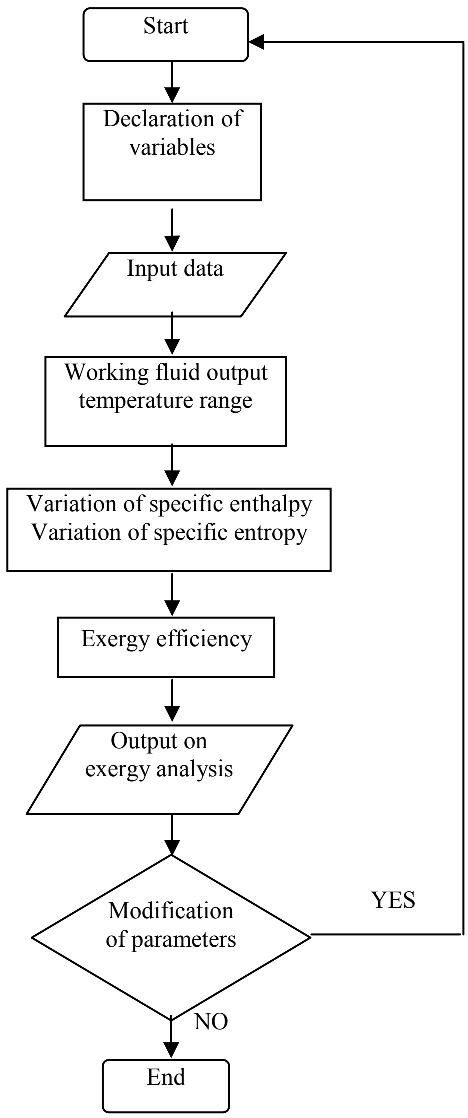

Fig. 4. Flow chart of simulation.

3. RESULTS AND DISCUSSION

Influence of mass flow rate on the flat solar collector efficiency for different collector areas

The global maximum points can be obtained from Fig. 5 by plotting exergy efficiency to the mass flow rate for different collector areas as per the design specifications shown in the box. The calculated quantity is the exergy efficiency whereas the incremented quantities are: the collector area from 2 to 8 m^2 and the mass flow rate from 0.001 to 0.013 kg/s (3.6 to 46.8 liter / hr). For any collector area, the exergy efficiency increases rapidly at lower flow rate until it reaches the global maximum point, after which it slowly decreases with the increases in mass flow rate. The gradient after the global maximum points for each curve decreases from smaller collector areas to larger ones.

One point to be highlighted here is that regardless how the mass flow rate changes (for different collector areas), the maximum exergy efficiency that can be achieved, stabilizes at 0.0319 or 3.19% for the given conditions. The maximum point for each curve seems to be moving from left to right when the collector area is increasing from 2 to 8 m^2. In other words, for a specific collector area, there is a fixed mass flow rate which gives the maximum exergy efficiency (e.g. for a collector area of 2 m^2, the mass flow rate should be designed at 0.0018 kg/s to give maximum exergy efficiency, as shown by the arrow in Fig. 5). This then indicates that there exists a directly proportional correlation between mass flow rate and collector area with the aim of obtaining maximum exergy efficiency.

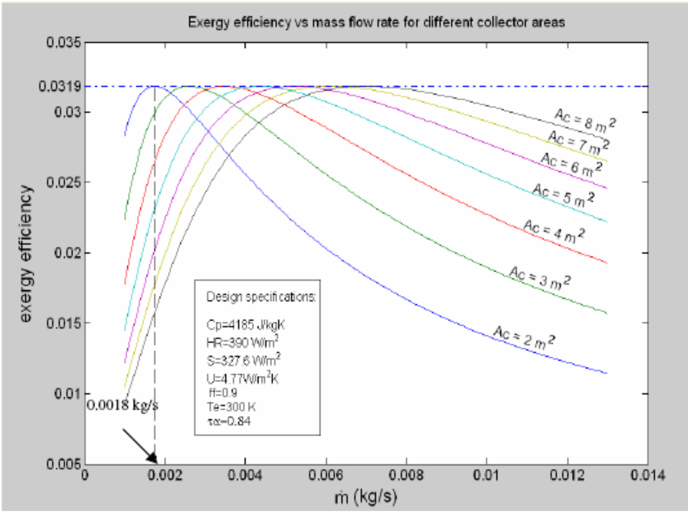

Fig. 5. Exergy efficiency versus mass flow rate for different collector areas.

Influence of collector area on the flat solar collector efficiency for different mass flow rates

To validate the findings from the preceding section, a graph of η_{ex} versus A_c was plotted as shown in Fig. 6. It is noticed that for both graphs in Fig. 5 and Fig. 6, the global maximum point for each curve can be obtained at different pair values of flow rate and collector area (as shown in the box in Fig. 6). Considering the fluid temperature variation, ΔT, as another important output for flat plate solar collectors, it would be wise to investigate the optimum pair value (global maximum point) which will give the highest outlet fluid temperature. This is done by substituting the different pair values into Eq. 2 to determine the value of ΔT. The calculated result then shows that for all the different pair values, there exist only one value of ΔT, that is 47.5°C. Investigating the reason, it is discovered that the contributing factor is that the ratio for different pair values yields a constant value.

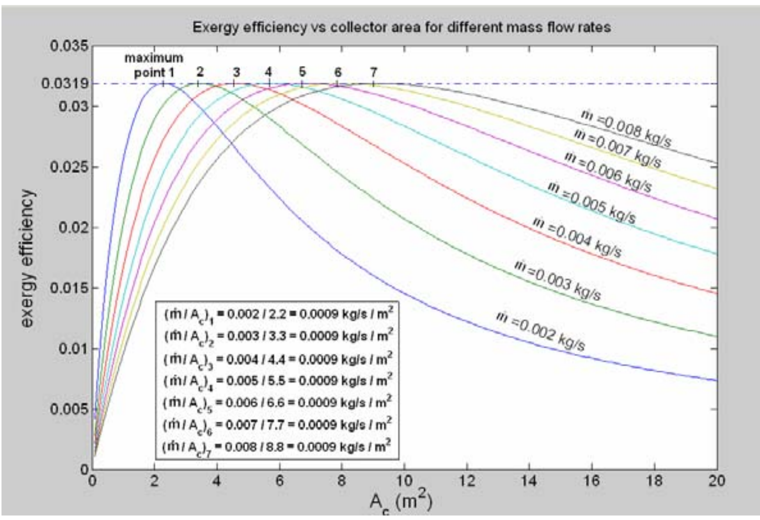

Fig. 6. Exergy efficiency versus collector area for different mass flow rates.

Correlation between exergy efficiency and temperature variation

To further investigate the correlation between flow rate and collector area, exergy efficiency is plotted against fluid temperature variation ΔT for three selected mass flow rates (0.1 kg/s, 0.01 kg/s, 0.001 kg/s) without limiting collector area size that is fixing ΔT range from 0 ^{o}C to about 70^{o}C as shown in Table 2. Three curves are obtained respectively and all the curves fall along the same line as shown in Fig. 7. The maximum exergy efficiency is 0.0319 or 3.19% with ΔT is 47.5 ^{o}C.

Table 2. Range of simulation parameters

$\dot{m}$ (kg/s)	ΔT range (^{o}C)	A_c range (m^2)
0.1	0 – 68.7	0 to 1000
0.01	0 – 68.7	0 to 100
0.001	0 – 68.7	0 to 10

It is then realized that this result is exclusively due to the changes in the ratio of $\dot{m}/A_c$ which means that only the ratio is varying along the curve as shown in Fig. 7. From the figure, it can be seen that there exists a global maximum point which gives the ratio of $\dot{m}/A_c$ as 0.0009 kg/s/m^2 for maximum exergy efficiency. To simplify the analysis, the ratio of $\dot{m}/A_c$ can actually be taken as a single value, R, where $R = \dot{m}/A_c$, as such it can be concluded that $\Delta T = f(R)$ and $\eta_{ex} = f(R)$ as shown by Eq. (9) and (10), where all the other parameters are constants.

$$\Delta T = T_{f,o} - T_{f,i} = \left(\frac{S}{U_L}\right)\left(1-\exp\left(-\frac{RU_L F'}{C}\right)\right) \quad (9)$$

$$\eta_{ex} = \frac{RC}{(HR)}\left[\frac{S}{U_L}\left(1-\exp\left(-\frac{RU_L F'}{C}\right)\right) - T_a \ln\left(1+\frac{S}{T_a U_L}\left(1-\exp\left(-\frac{RU_L F'}{C}\right)\right)\right)\right] \quad (10)$$

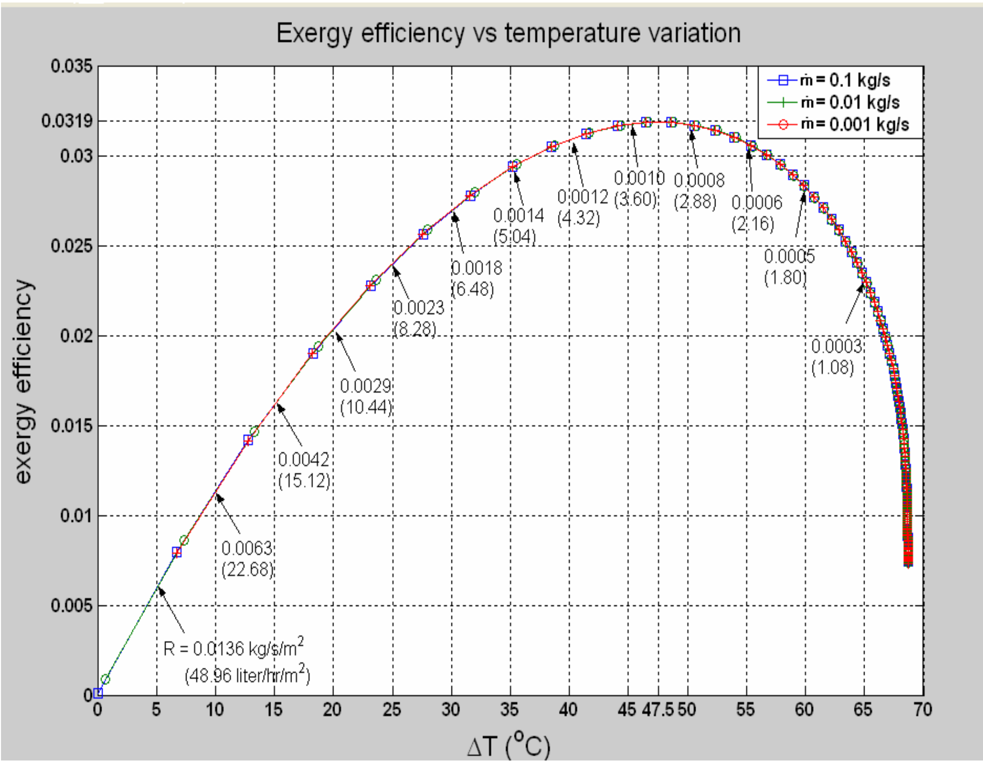

Fig. 7. Exergy efficiency versus temperature variation.

R as an important parameter in designing a flat plate collector

From Figs. 5, 6 and 7, it is established that η_{ex} and ΔT are actually functions of the ratio, R. Hence, when designing a flat plate collector, R is a meaningful parameter to be considered. It is predicted that there will be an optimum value of R that gives maximum exergy efficiency and the relevant ΔT for any set of design specifications.

Although the main concern in designing a solar collector is to obtain higher exergy efficiency, a higher ΔT yielding a higher outlet fluid temperature, is another key factor of interest. Thus, there should be a trade-off between these two main concerns in the design of the flat plate collector.

Fig. 8 shows the dependences of η_{ex} and ΔT, when R is varied. For maximum exergy efficiency of 3.19%, the designed R has to be 0.0009 kg/s/m^2 (3.24 liter/hr/m^2) and the relevant ΔT obtained is 47.5 ^{o}C. To obtain larger difference of ΔT (say 68.7^{o}C), the R has to be set at 0.00015 kg/s/m^2 (0.54 liter/hr/m^2) and the relevant exergy efficiency is 1.00%. This yields a 44.6% increment in ΔT, with an exergy efficiency drop of 68.7%. The intersection point of the two curves is in fact another important point to be analyzed. The R value at the intersection point is 0.0006 kg/s/m^2 (2.16 liter/hr/m^2). It gives ΔT of 58.5 ^{o}C and exergy efficiency of 2.93%. Making a similar comparison with the point of maximum exergy efficiency, the ΔT increases 23.2% whereas the exergy efficiency drops 8.2%. Further investigation indicates that the intersection point seems to be the optimization point for the design of a flat plate solar collector for the specified condition.

4. CONCLUSION

An exergetic optimisation of a flat plate solar collector has been presented in this paper. The ratio of mass flow rate over collector area, *R*, determines the exergy efficiency and the fluid outlet temperature from the flat plate collector for a specific design specification. Trade off between exergy efficiency and fluid outlet temperature is the main consideration to determine the value of *R*. From this analysis, the intersection point, with R = 0.0006 kg/s/m^2, is suggested to be the optimization point for the design of a flat plate solar collector. Applying the appropriate *R* in the solar collector design not only helps to increase the efficiency, but most importantly, it gives the optimum collector area to help in the reduction of both the capital and operational cost.

NOMENCLATURE

A	area (m^2)
C	specific heat (J/kg K)
F'	efficiency factor
HR	solar flux density (solar radiation intensity) in collector plane (W/m^2)
$\dot{m}$	mass flow rate (kg/s)
n	number of tubes for solar collector
R	ratio of mass flow rate over collector area (kg/s /m^2)
S	power absorbed by area unit (W/m^2)
T	temperature (K)
U	global heat loss coefficient (W/m^2 K)
W	width (m)

Greek symbols

Δ	finite differences
η	efficiency
y	variable length (m)

Subscripts

a	ambient
c	collector
e	environment
ex	exergy
f	fluid
f,i	inlet fluid
f,o	outlet fluid
L	losse

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