Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
ISSN (online): 2289-7879 | Vol. 16, No. 1. Pages 15-32, 2015

Modelling of Energy and Exergy Analysis for a Double-Pass Solar Air Heater System

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Abstract – *Energy is conserved in every device and in every action we are doing. The energy itself cannot be abandoned nor destroyed. However, energy conservation alone by using the first law of thermodynamics is insufficient in order to depict the internal losses for maximizing energy usage. Nevertheless, the second law analysis, exergy, provides important information about the optimum conditions and sources of inefficiencies together with their values and locations. The purpose of this study was to perform an exergy analysis of a solar air heater. The geometric and operation parameters including wind speed, solar radiation, collector area, ambient temperature and optical efficiency were considered as variables in this analysis. The focus was to determine the exergy efficiency of a double-pass solar air heater under forced flow condition by considering the affecting factors. The analysis was performed numerically using MATLAB simulation. Results of exergy efficiency were obtained and compared with the thermal efficiency of the solar air heater. It was found that exergy losses could be reduced by altering the variables until it reached the maximum efficiency. Solar collector area has been found to have the minimum effect on both thermal and exergy efficiencies, whereas incident solar radiation has the maximum effect. Values of 10% and 70% of exergy and energy efficiencies respectively have been obtained in the average solar radiation of about 4500 W/m*^{2}.

Keywords: Exergy Analysis, Solar Air Heater, Flat Plate Heater, Energy Analysis, Exergy Losses, Efficiency

1.0 INTRODUCTION

The increasing need for energy and reduction of some of the conventional energy supplies especially oil has forced the world to find ways of using non-conventional energy sources. One of the energy sources that offer promise for a better future is solar energy. Solar energy is practically safe and clean, as it can be captured everywhere and able to generate energy in places where other sources cannot. The renewable concept that it brings makes the environment greener and safer. In the meantime, solar energy is completely free, thus creating an intermittent source of energy. On the other hand, there are some problems with the usage of solar energy. It is rather diffuse form of energy, irregularly available and the intensity itself changes with time, seasons and locations [1].

To maximize the usage of solar energy, solar air heaters have been widely used for agricultural and industrial applications where high temperatures are not required [2]. Solar air heater is a device that transfers energy from the sun to heat, which uses air as its heat transfer medium. In order to prove the efficiency of a solar heater, exergy analysis is used rather than the energy conservation theory. The quality of energy, which is how much energy could be extracted to use for work [3], is the major concern in exergy analysis. This is the main reason why exergy analysis is used rather than energy analysis. Exergy analysis is used to provide better sight for design, analysis and optimization of the systems. Moran and Shapiro [4] defined exergy as the maximum theoretical work obtained as they interact in the equilibrium. In addition, they also stated that the definition of exergy would not be completed until the reference environment is defined and how numerical values of exergy can be determined is shown.

Several studies have been conducted in order to implement exergy usage. Rosen and Dincer [5] stated that exergy-based efficiencies, compared to the efficiencies based on energy, are measures on the approach to true ideality, and then when the performance of an energy system is assessed, it provides significant information. Besides, exergy losses clearly identify the locations, causes and sources of deviation of ideality in a system. Rosen et al. [6] explained the exergy role in increasing the efficiencies and sustainability and decreasing the environmental impact. The results from their study strongly suggest that it is wise to utilize the exergy in activities pertaining to the system design and enhancement. Rosen and Dincer [5] and Wall et al. [7] also came up with the usefulness of exergy for environment and sustainable development.

Akbulut and Durmus [8] studied the energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer by using the first and second law of thermodynamics. This analysis was done by using different mass air flow rates varied from 0.014 kg/s to 0.036 kg/s.

Baghernejad and Yaghoubi [9] simulated 17 MW solar thermal power plants at Yazd, Iran on the Integrated Solar Combined Cycle System (ISCCS) using the design plant data. They evaluated the plant performance by energy and exergy analyses. Exergy efficiencies and destructions of different components of the plant were also calculated in order to assess their individual performances. This study is an improved version of the simulation done by Yaghoubi et al. [10] on the solar thermal power plant in Shiraz, Iran that produced only 250 kW power.

Many studies have been conducted on the performance of flat plate solar collectors. Esen [11] presented the study of a novel flat plate solar air heater with several obstacles and without obstacles. Four types of absorber plates were used with 38° slope of the collector. The theoretical model employed for the solar collector was made using the thermal energy balances, whereas the exergy balances that comprised of the first and second law of thermodynamics were used in order to obtain the irreversibility and efficiencies of the collector.

To improve the low thermal efficiencies of the conventional solar collector, Ramani et al. [2] proposed a solar air collector with two passes. The improvements were carried out by using the double-pass counter flow solar air collector with porous material in the second air passage. The analysis was done by using two solar air collectors with one of them was filled with porous absorbing material in the second passage. The porous material offers large surface area for heat transfer and extremely high volumetric heat transfer coefficient. The uncertainty in the experiment was estimated based on the uncertainties in various primary experimental measurements. Basic physical equations were developed from the conservation of energy to describe the heat transfer coefficient.

Naphon [12] performed a study on a double-pass flat plate solar heater with longitudinal fins. The characteristics of the heater's heat transfer were described by mathematical models derived from the conservation of energy. The predictions of air mass flow rate ranged from 0.02 kg/s

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
ISSN (online): 2289-7879 | Vol. 16, No. 1. Pages 15-32, 2015

to 0.1 kg/s. The author found that increasing height and number of fins would result in increased thermal efficiency as the entropy generation reduced with the increase of the number of fins.

The efficiencies and exergy analysis of five solar heaters were studied by Kurtbas and Durmus [13]. The efficiencies of four different designs of collectors were compared with the conventional flat plate collector on the same day of experiment and with the same radiation of the collectors. The exergy analyses were used on the four different designs and it was found that the exergy losses decreased with increasing the efficiencies of the solar collectors. Therefore, different designs in the shape and number of absorbers will affect the heat transfer and pressure loss because the heat transfer due to temperature difference, pressure loss and collector efficiency are the important parameters in decreasing the exergy loss.

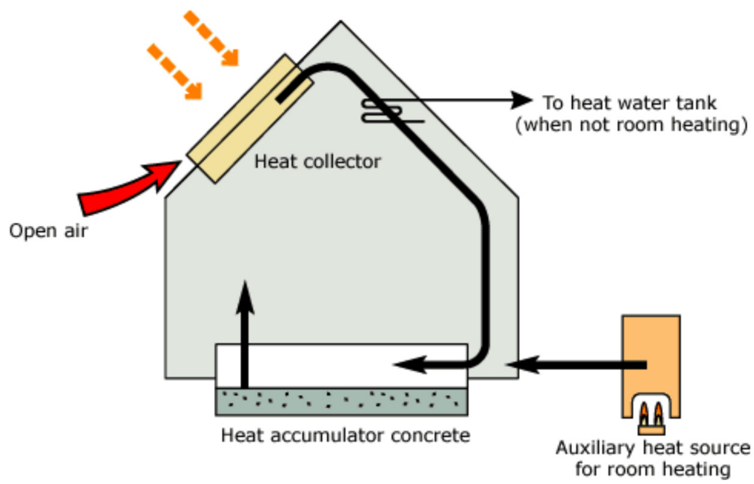

Figure 1: Schematic diagram of a basic solar air heater working flow [14]

Solar air heaters are basically heat exchangers that transfer the radiant energy of incident solar radiation to the sensible heat of a working fluid, which is air. The main principle used in the solar air heater is heat transfer. Using air as its transferring medium, this type of heater is suitable for applications requiring low to moderate temperatures below 60°C. Logically, compared to the fluid type flat plate collector, a solar air heater is used because the latter eliminates the need to transfer heat from one liquid to another. Solar air heaters are simple in design and require less maintenance. Since the air is used as its main transfer medium, a solar air heater has advantages when operating at temperatures below the freezing point. Corrosion and leakage problems are also less severe [15]. A schematic diagram of a basic solar air heater system is shown in Fig. 1.

Exergy analysis is a powerful tool for optimizing the energy usage by providing valuable information about the exergy for each device, loss of potential energy (exergy destruction) and efficiency of the device. This analysis can be used as a comparison with the real thermal performance of a system based on the second law of thermodynamics

2.0 GEOMETRIC CONFIGURATION

The heater used in this study is a flat plate solar air heater of a double pass-type in a steady and forced convective flow system. The two- and three-dimensional schematic views are shown in Fig. 2. All the thermal properties of the solar air heater are assumed constant.

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ISSN (online): 2289-7879 | Vol. 16, No. 1. Pages 15-32, 2015

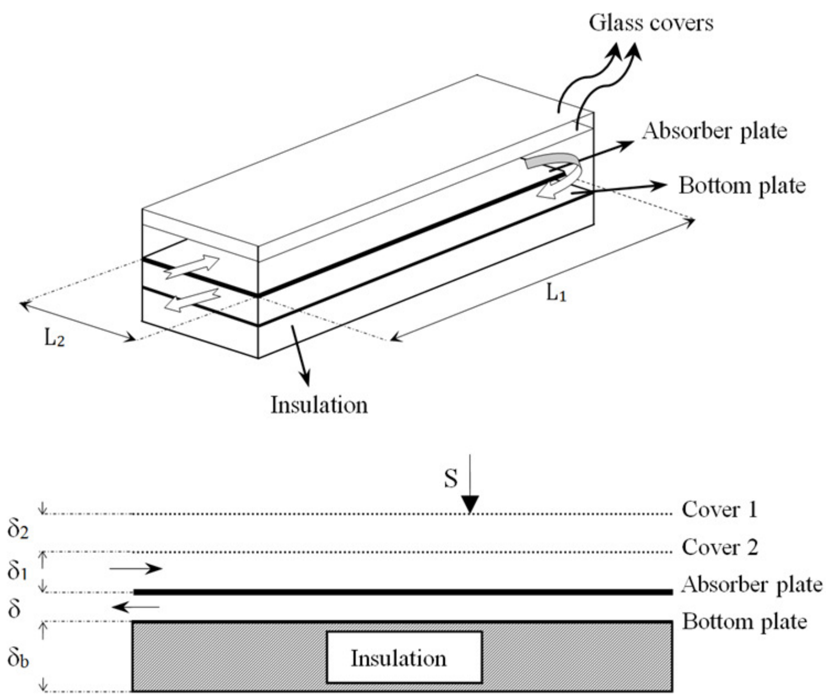

Figure 2: 3D and 2D schematic views of the flat plate solar air heater with double covers

3.0 ENERGY ANALYSIS OF A SOLAR AIR HEATER

According to Ajam et al. [16], exergy analysis of an air heater is only possible when both optical and thermal performance of the heater are evaluated. Therefore, the optical and thermal analyses have been conducted in this paper.

3.1 Thermal Analysis

The efficiency of a solar air heater is defined as the ratio of the obtained useful energy to the solar radiation incoming to the heater. This can be formulated by following the equation proposed by Duffie and Beckman [17]:

$$\eta_{th} = \frac{Q_u}{I_T A_p} \tag{1}$$

Alta [18] obtained the useful energy by considering heat loss from a heater to the ambient as Eq. [2]:

$$Q_u = A_p F_R [s - U_1 (T_{in} - T_a)] \tag{2}$$

Heat removal factor is the ratio of useful heat by the collector to the total heat collected by the collector when the absorber surface temperature is equal to fluid entire temperature of the collector surface and is expressed as:

$$F_R = \dot{m} C_p \left[1 - e^{-F' A_P U_1 / \dot{m} C_P}\right] / A_P U_1 \tag{3}$$

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
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Alta [18] defined the collector efficiency, F' as:

$$F' = (1 + \frac{U_1}{h_e})^{-1} \tag{4}$$

Where h_e is the heat transfer coefficient between the absorber plate and the fluid flow, which is expressed in Eq. (5):

$$h_e = \left[h_{c,fp} + h_r h_{c,fb}/(h_r + h_{c,fb})\right] \tag{5}$$

Farahat et al. [19] defined equivalent radiative heat transfer coefficient, h_r by Eq. (6):

$$h_r = \frac{4\sigma T_{avg}^3}{\left(\frac{1}{\varepsilon_p}+\frac{1}{\varepsilon_b}-1\right)} \tag{6}$$

Where:

$$T_{avg} = (T_p + T_b)/2 \tag{7}$$

3.1.1 Collector Overall Loss

The collector overall loss coefficient, U_1 is equal to the total of the loss coefficient from the top, bottom and edge, which is represented as:

$$U_1 = U_t + U_b + U_e \tag{8}$$

The top loss coefficient U_t, is a function of the absorber plate temperature, number of glass covers and other parameters [20], and is evaluated by:

$$U_t = \left[\frac{M}{(\frac{C}{T_{pm}})\left[(T_{pm}-T_a)/(M+f')\right]^{0.252}} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma\left(T_{pm}^2+T_a^2\right)\left(T_{pm}+T_a\right)}{\left[1/\left(\varepsilon_p+0.0425M\left(1-\varepsilon_p\right)\right)\right]+\left[(2M+f'-1)/\varepsilon_c\right]-M} \tag{9}$$

Where:

$$f' = [(9/h_w) - (9/h_w^2)](T_a/316.9)(1 + 0.091M) \tag{10}$$

$$C = 204.429(\cos\beta)^{0.252}/L^{0.24} \tag{11}$$

$$T_{pm} = T_i + \frac{Q_u}{A_c F_R U_l}(1 - F_R) \tag{12}$$

The top loss coefficient given by Farahat et al. [19] is:

$$U_t = (Q_t/A_p)/(T_p - T_a) \tag{13}$$

Swinbank [21] related the sky temperature to the local ambient temperature by Eq. (14)

$$T_{sky} = 0.0552 T_a \tag{14}$$

Watmuff et al. [22] related the forced convection heat transfer coefficient, h_w due to wind by Eq. (15):

$$h_w = (2.8 + 3V_w) \text{ for } 0 \leq V_w \leq 7\ (m/s) \tag{15}$$

Besides, the bottom loss coefficient, Ub , according to Alta [18], is focused on the insulation area of the heater expressed in Eq. (16):

$$U_b = {}^{k_i}/_{\delta_b} \tag{16}$$

The edge loss coefficient involves the heater perimeter. Therefore, it can be expressed as:

$$U_e = (L_1 + L_2)L_3K_i/L_1L_2\delta_e \tag{17}$$

$$L_3 = \delta_1 + \delta_2 + \delta + \delta_b \tag{18}$$

3.2 Optical Analysis

Optical analysis was conducted due to the fact that not all the shining sunlight on the plate was absorbed by the heater. The parameter "S" from Eq. (2) is the radiation flux absorbed through the absorber plate. Sukhatme and Nayak [15] stated this parameter as:

$$s = (\tau\alpha)I_T \tag{19}$$

I_T is the incident solar radiation per absorber plate unit area, whereas $\tau\alpha$ is the effective transmittance-absorptance product, which also represents the optical efficiency, η_0.

4.0 EXERGY ANALYSIS

The maximum work, which can be theoretically obtained from a reversible process in equilibrium with the environment, is called exergy [13]. It carries the maximum useful work that can be extracted from the amount of energy given. It is different from the conservation of energy in the first law that only uses energy conversion, in which it states that energy cannot be created nor destroyed but can only change its form. Therefore, the real energy of the whole system cannot be estimated. This leads to the application of exergy using the approach of the second law of thermodynamics. By deriving the exergy efficiency, the quality of energy can be determined [3].

Ajam et al. [16] generally divided the exergy exchange with the heater into two methods. The first one is through the fluid flow and the second method is through heat transfer. Exergy exchange with the heater by the fluid flow at temperature, T and pressure, P is given by Farahat et al. [19] as:

$$\dot{\psi} = \dot{m}C_p\left(T - T_a - T_a ln\frac{T}{T_a}\right) + \dot{m}RT_a ln\left(\frac{p}{p_a}\right) \tag{20}$$

The general form of exergy balance was proposed by Cengel and Boles [3], which later affirmed by Ajam et al. [16] in the form of Eq. (21).

$$\dot{\psi}_{in} + \dot{\psi}_s + \dot{\psi}_{out} + \dot{\psi}_l + \dot{\psi}_d = 0 \tag{21}$$

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
ISSN (online): 2289-7879 | Vol. 16, No. 1. Pages 15-32, 2015

4.1 Inlet Exergy

At the inlet, exergy rate includes two parts; the fluid flow exergy rate and the solar radiation exergy rate absorbed by the heater.

$$\dot{\psi}_{in,f} = \dot{m}C_p\left(T_{in} - T_a - T_a ln\frac{T_{in}}{T_a}\right) + \dot{m}RT_a ln\left(\frac{p_{in}}{p_a}\right) \tag{22}$$

$$\dot{\psi}_{in,r} = \eta_0 I_T A_p\left(1 - \frac{T_a}{T_s}\right) \tag{23}$$

The term in the bracket in Equation (23) is the corrected Petela efficiency given by Gupta [23]. The correction is done by this assumption that the sun is an unbounded source. The summation of Eqs. (22) and (23) gives the total inlet exergy rate of the solar air heater.

4.2 Stored and Outlet Exergy

Our solar heater was assumed to be in the steady state condition. Therefore, the stored exergy rate was equal to zero, whereas at the outlet, the exergy rate of the fluid flow was included.

$$\dot{\psi}_{out,f} = -\dot{m}C_p\left(T_{out} - T_a - T_a ln\frac{T_{out}}{T_a}\right) + \dot{m}RT_a ln\left(\frac{p_{out}}{p_a}\right) \tag{24}$$

4.3 Leakage Exergy

Flat plate solar air heaters are heat exchangers, which are non-adiabatic; therefore, there would be leakage exergy due to the heat leakage rate from the absorber plate to the environment, which is given by Altfeld et al. [24] as in Eq. (25):

$$\dot{\psi}_l = -U_1 A_p(T_p - T_a)(1 - {}^{T_a}\!/_{T_p}) \tag{25}$$

4.4 Destroyed Exergy

Destroyed exergy represents the lost work or irreversibility [3]. The irreversibility generates entropy, and this irreversibility cannot be used again for later application. Ajam et al. [16] defined the destroyed exergy rate by three terms. The first term is destroyed exergy due to the difference between the temperatures of the sun and the surface of the absorber plate given by Eq. (26):

$$\dot{\psi}_{d,a} = -\eta_0 I_T A_p T_a\left(\frac{1}{T_p} - \frac{1}{T_s}\right) \tag{26}$$

Secondly, according to Altfeld et al. [24], exergy is destroyed due to the duct pressure drop. Then, the equation reduces to:

$$\dot{\psi}_{d,d} = -\dot{m}\Delta P T_a/\rho T_m \tag{27}$$

Pressure drop, ΔP can be calculated by the equation given by Sukhatme and Nayak [15]:

$$\Delta P = 2f\rho L_1 V_{avg}^2/D_e \tag{28}$$

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Where, f is the fraction factor, which can be calculated from Blasius equation:

$$f = 0.079Re^{-0.25} \tag{29}$$

$$\dot{\psi}_{d,h} = -\eta_{th} I_T A_p T_a \left(\frac{1}{T_m} - \frac{1}{T_p}\right) \tag{30}$$

Where the temperature average is:

$$T_m = (T_{in} - T_{out})/2 \tag{31}$$

4.5 Exergy Efficiency

Eqs. (22) to (27) were correlated in the exergy balance equation, Eq. (21), and then simplified to gain the full exergy balance with all the parameters. Gupta et al. [20] derived a new equation for the exergy efficiency by considering the definition of the efficiency, which is the rate of inlet exergy minus the rate of outlet exergy, and gains the rate of exergy losses [3]:

$$\eta_{\mathrm{II}} = \frac{\dot{m}C_p\left(T_{out} - T_{in} - T_a ln\frac{T_{out}}{T_{in}}\right)}{I_T A_p\left(1 - \frac{T_a}{T_s}\right)} - \frac{\dot{m}RT_a ln\left(\frac{p_{out}}{p_{in}}\right)}{I_T A_p\left(1 - \frac{T_a}{T_s}\right)} \tag{32}$$

Therefore, the efficiency of the solar air heater according to Ajam et al. [16] is defined as:

$$\eta_{\mathrm{II}} = 1 - \left[\left(\dot{\psi}_s + \dot{\psi}_l + \dot{\psi}_d\right)/I_T A_p\left(1 - \frac{T_a}{T_s}\right)\right] \tag{33}$$

By rearranging the equations and adding all exergy in Eqs. (32) and (33), the efficiency of the solar air heater becomes:

$$\eta_{\mathrm{II}} = 1 - \left[\begin{array}{c} (1-\eta_0) + \frac{\eta_0 T_a\left(\frac{1}{T_p} - \frac{1}{T_s}\right)}{\left(1 - \frac{T_a}{T_s}\right)} + \frac{U_1(T_p - T_a)\left(1 - {T_a}/{T_p}\right)}{I_T\left(1 - \frac{T_a}{T_s}\right)} + \\ \frac{\dot{m}\Delta P T_a}{\rho T_m I_T A_p\left(1 - \frac{T_a}{T_s}\right)} + \frac{\eta_{th} T_a\left(\frac{1}{T_m} - \frac{1}{T_p}\right)}{\left(1 - \frac{T_a}{T_s}\right)} \end{array}\right] \tag{34}$$

5.0 SYSTEM SIMULATION

Exergy analysis of the solar air heater was performed using MATLAB simulation. During the analysis, the air was assumed to be ideal with constant specific heat. Simulation of the solar air heater using numerical method was done in order to obtain the value of the unknown parameters. The results of simulation were compared with the results from experiments and simulations done by other researchers.

The basic variables for the heater parameters were the input to the exergy analysis, which included:

Tin , $Vavg$, FR , Ta , εc , εp , σ, τ, α, S, ki,Ap , A, $L1$, $L2$, $L3$,δ, De, hfp , hr , hfb , IT.

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ISSN (online): 2289-7879 | Vol. 16, No. 1. Pages 15-32, 2015

By using all of the variables as constraints in the thermal analysis, the degree of freedom of the system was determined. These equations were nonlinear and could be solved numerically. The optical and thermal efficiency were solved by using Eqs. (1) to (18).

The outputs from the thermal and optical analysis were used as the constraints in calculating the exergy efficiency. The exergy analysis was then performed by solving the losses. All the losses were found by solving Eqs. (21) to (30). To calculate the pressure drop occurred in the duct, Eq. (27) was used together with the Blasius equation in Eq. (28). The exergy efficiency was determined by using Eqs. (31) and (33). Modifying the heater parameters would affect exergy efficiency; therefore by adjusting the heater parameters, optimum exergy efficiency could be obtained.

5.1 Flow Chart of the Simulation

The flow chart for simulation of the considered solar air heater is given in Fig. 3. To calculate the important parameters used for the exergy analysis, the simulation first started with energy and optical analysis.The analyses were performed in order to gain the correlation between the affecting parameters and the performance of the solar air heater by using exergy approach. The energy analysis was performed prior to exergy analysis in order to compare the results between them and to prove that exergy analysis is a powerful tool [20].

5.2 Physical Parameters

Parameter values used for the simulation are shown in Table 1.

Table 1: Input of climate, design and operational parameters used for the simulation

Parameters	Values
$\varepsilon_p, \varepsilon_{g1}, \varepsilon_{g2}$	0.95,0.88,0.88
k_i	0.042 W/m.K
σ	$5.67 \times 10^{-8}\ W/m^2.K^4$
β	10^o
$\delta_b, \delta_e, \delta_1, \delta_2, \delta$	0.05,0.025,0.025,0.025,0.015 m
$\delta_p, \delta_{g1}, \delta_{g2}$	0.002,0.025,0.025 m
L_1, L_2	1, 1 m
T_a	27°C
ρ	1.2

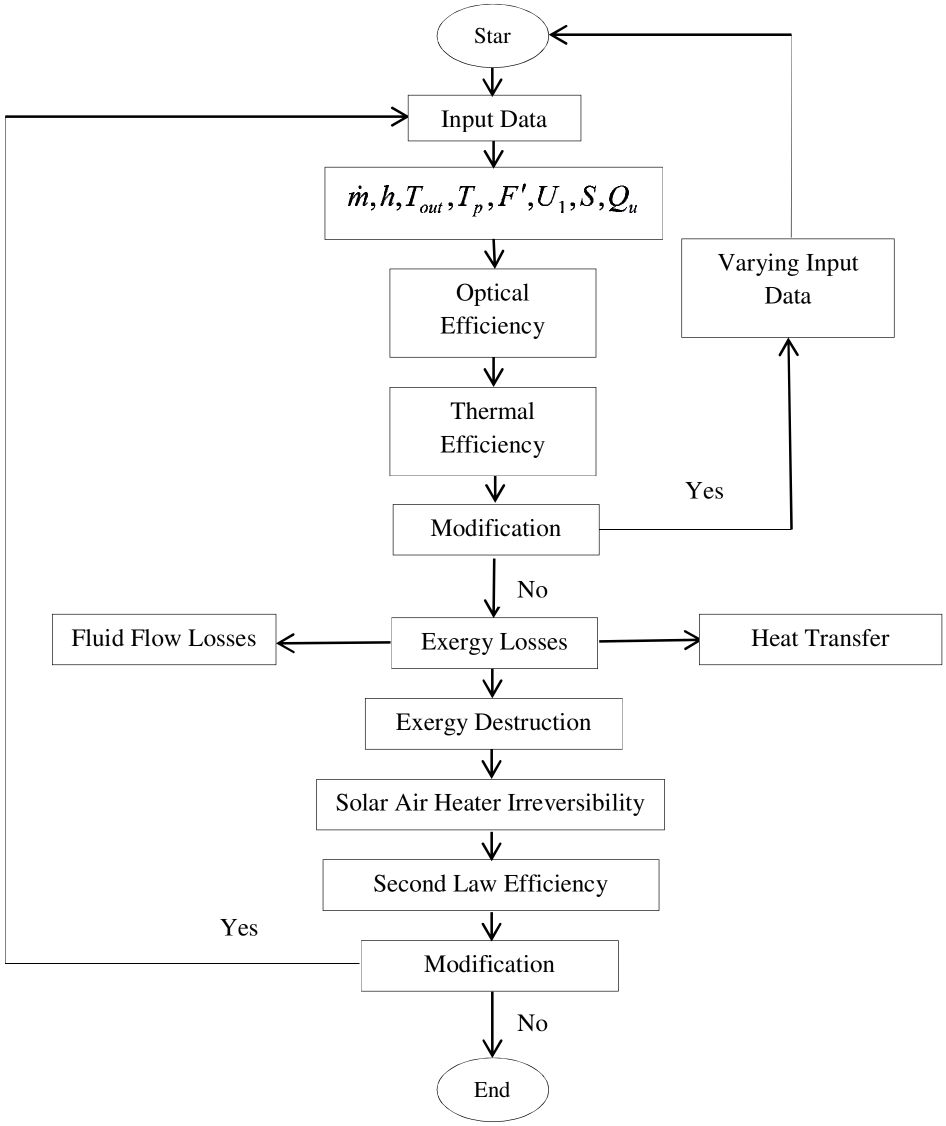

Figure 3: Flow chart of the simulation model

In order to achieve the efficiency of the solar air heater, the parameters listed below were varied. While changing the single parameter, other parameters remained constant in order to find the parameters that most affected the efficiency of the solar air heater. The ranges of varied parameters are summarized in Table 2.

Table 2: Range of varied parameters

Parameters	Values
I_T	600 ~ 6400 W/m^2
A_p	1~5 m^2
T_a	12 ~ 52 °C
V_w	0 ~ 3 m/s
η_o	0.40 ~ 0.98

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
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6.0 Results and Discussion

6.1 Effect of Wind Speed

Fig. 4 illustrates the effect of wind speed on the thermal and exergy efficiencies. By increasing the wind speed from 0 to 3 m/s, both thermal and exergy efficiencies decreased, but thermal efficiency was more affected compared to exergy efficiency. The optimum efficiency was reached when the wind speed was low. The maximum value that exergy efficiency could obtain was about 12%, whereas the thermal efficiency was about 68%. These results are in agreement with Ajam et al. [16], in which a decrease in thermal and exergy efficiency is observed as the wind speed increased.

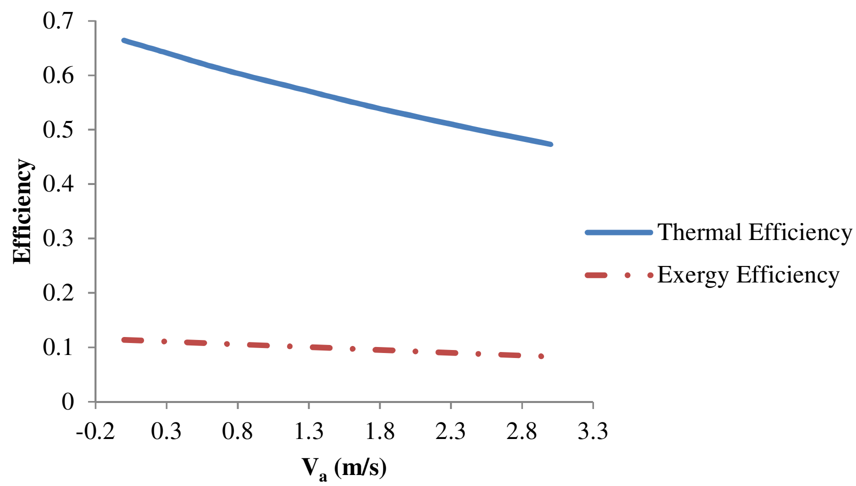

Figure 4: Variation of thermal and exergy efficiencies versus wind speed

The temperature between the plate and air flow decreased easily when the wind speed increased. Wind speed is energy in the kinetic form. The exergy content in the air is equal to the kinetic energy, which is the availability of exergy in the system. However, even though the temperature increased as shown in Fig. 4, increase in the wind speed would reduce the temperature, thus lowered the heat transfer rate between the air and the plate. This result of simulation agreed with the study done by Baskut et al. [25], in which lower wind velocity will result in higher exergy efficiency.

6.2 Effect of Incident Solar Radiation

Fig. 5 presents the variation of thermal and exergy efficiencies over incident solar radiation per unit absorber area. The highest thermal efficiency for the solar air heater was about 80%, but this could be achieved only when the solar radiation was very high. The average solar radiation of about 4000 W/m² to 5000 W/m² produced about 70% thermal efficiency and about 10% exergy efficiency.

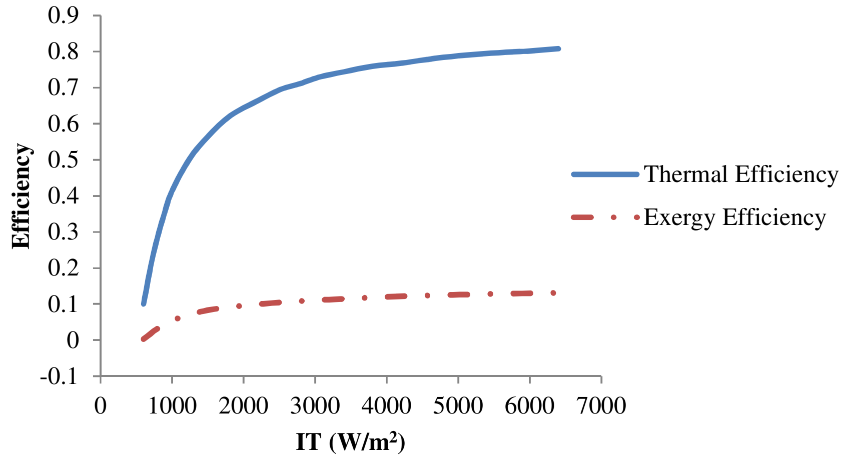

Figure 5: Variation of thermal and exergy efficiencies versus incident solar radiation energy per absorber unit area

Thermal efficiency was largely affected by the increase in solar radiation. This can be seen at 1500 W/m² to 4500 W/m² solar radiation where thermal efficiency increased very rapidly. At 700 W/m² to 1800 W/m², exergy efficiency showed an increase from just 2% up to 10 %. When solar radiation increased, exergy still increased, but the increment was small. Esen [11] also agreed that an increase in solar radiation boosts collector efficiency. Raising solar radiation also increases the output temperature of the air from the heater; hence, thermal efficiency is elevated.

6.3 Effect of Ambient Temperature

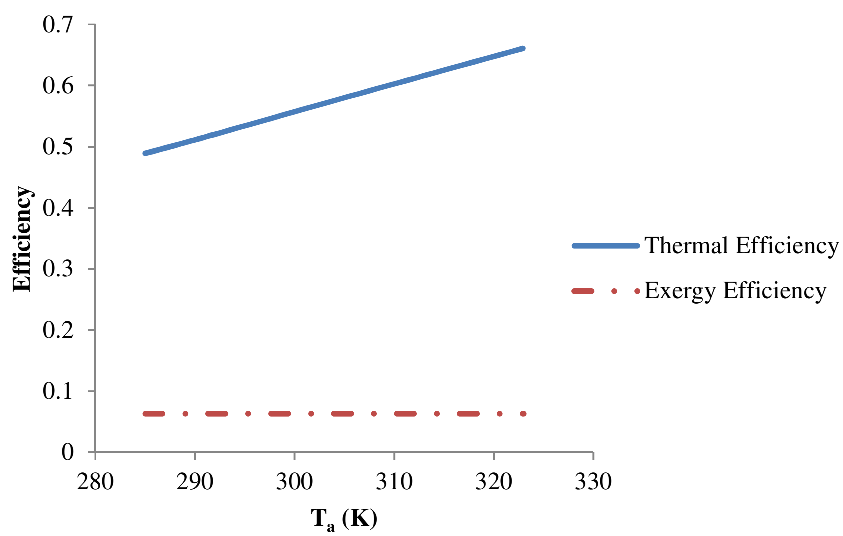

Figure 6: Variation of thermal and exergy efficiencies versus ambient temperature

The effect of ambient temperature on exergy and thermal efficiencies of the solar air heater is presented in Fig. 6. It can be seen that by increasing the ambient temperature, the exergy efficiency decreased slightly. On the other hand, increasing ambient temperature would

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
ISSN (online): 2289-7879 | Vol. 16, No. 1. Pages 15-32, 2015

enhance the thermal efficiency. This is because as the temperature increases, the temperature of the plate tends to increase. The useful heat gain increases; thus, the thermal efficiency will be increased.

In contrast, there was a slight decrease in the exergy efficiency when the ambient temperature increased. This is because of the fact that by extending the temperature to larger values, exergy loss increases due to increased entropy generation. When the temperature is greater than the ambient temperature, heat transfer from the system decreases. Therefore, when ambient temperature is increased, exergy destruction will increase due to the difference between the inlet temperature from ambient and the dead state. Consequently, more exergy is destroyed and exergy efficiency decreases.

6.4 Effect of Optical Efficiency

Fig. 7 shows the effect of optical efficiency on the thermal and exergy efficiencies. According to the graph, by increasing optical efficiency, the thermal and exergy efficiencies increased. The optical efficiency ranged from 0.4 to 0.98. If the absorber plate is a perfect absorber, then the optical efficiency will be equal to 1, but due to the losses that happen between the plate and the glass cover, and also between the air streams, the optical efficiency will not be equal to unity. The highest thermal efficiency was 0.6, which could be achieved by using black paint, whereas the exergy efficiency was about 0.09m which could be reached in a clear day with extremely dry air [26].

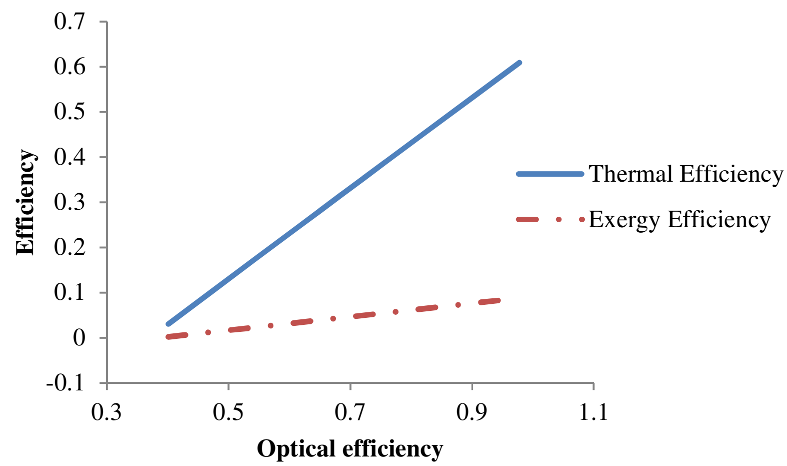

Figure 7: Variation of thermal and exergy efficiencies versus optical efficiency

Optical efficiency is measured by how much the solar radiation is absorbed by the absorber plate for the use of work. From Eq. (18), the radiation flux is the multiplication of $\tau\alpha$ and I_T, where $\tau\alpha$ is the product of transmittance-absorptance that equals to optical efficiency. In order to increase the efficiency of the solar air heater, the values of these two parameters should be considered to obtain the highest value of optical efficiency. From a study by Brogren [26], the collector efficiency increased with a high absorptance in the solar radiation, which is equal to low emittance. Low thermal emittance reduces the fraction of thermal energy that is re-radiated from the absorber surface; thus, improving the thermal and exergy efficiencies.

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6.5 Effect of Area of Heater Surface

The effect of area of the total heater surface on the thermal and exergy efficiencies is shown in Fig. 8. Thermal efficiency was almost independent of the heater area. However, by increasing the area of heater surface from 1 m² to 5 m², the exergy efficiency increased slightly from 7% to 9%.

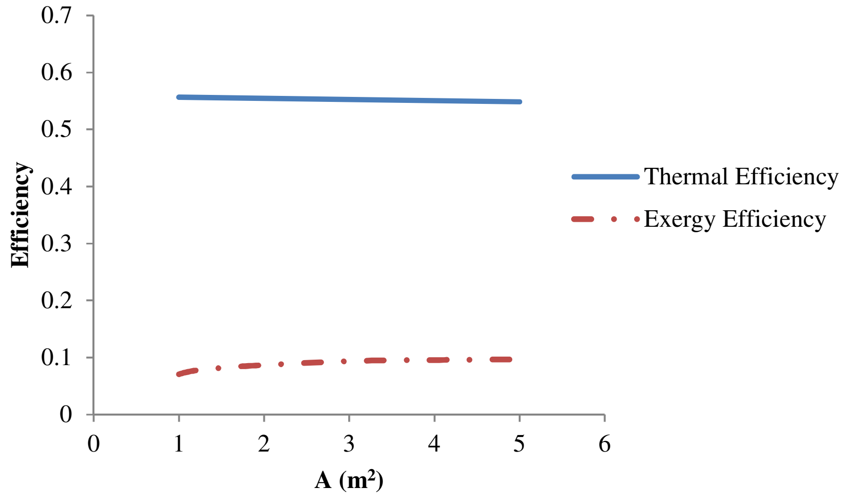

Figure 8: Variation of thermal and exergy efficiencies versus area of heater surface

Increasing the heater surface area resulted in reduced thermal efficiency, but the values were very small and hard to be seen on the graph. This is because when the area is wider, more contact area could be achieved by the wind; thus, the absorber plate tends to cool quickly. The thermal losses occurred with the increase in area and this reduced the thermal efficiency, whereas the exergy efficiency just increased by a portion to its whole efficiency. The only noticeable increase in exergy was at the area of 1 m² to 1.5 m². Beyond that, the exergy efficiency kept increasing until 5 m², but the gradient was small. From the heater surface area equation, area is equal to the product of the length and width of the absorber plate, thus changing the width or length of the absorber plate does not affect the efficiency of the solar air heater. Sarhaddi et al. [27] also showed the same result of energy efficiency reduction, with almost no effect on exergy efficiency when the area increases. Thus, this parameter is not a main factor in optimizing the heater efficiency.

6.6 Effect of Exergy Losses

From Fig. 9, the effect of exergy losses on the thermal and exergy efficiency can be observed. The thermal and exergy efficiencies decreased with increasing exergy losses. The losses ranged from 0.87 until 0.98 for 10% to 80% of thermal efficiency and 10% to 13% of exergy efficiency respectively. According to Cengel and Boles [3], exergy losses represent the lost work potential and is also known as the irreversibility or lost work. In this solar air heater, the losses are due to the leakage exergy, destroyed exergy caused by the temperature difference between the absorber plate surface and the sun, destroyed exergy due to the duct pressure drop, as well as the heat transfer rate from the absorber plate to the air. If all the supply energy is equal to the losses, then solar air heater is no longer efficient. Studies performed by Kurtbas and Durmus [13] showed minimum pressure loss as the minimum exergy loss. In order to reduce the exergy

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
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losses to increase the thermal and exergy efficiencies, the heater surface area and optical efficiency could be increased to obtain the optimum solar air heater efficiency.

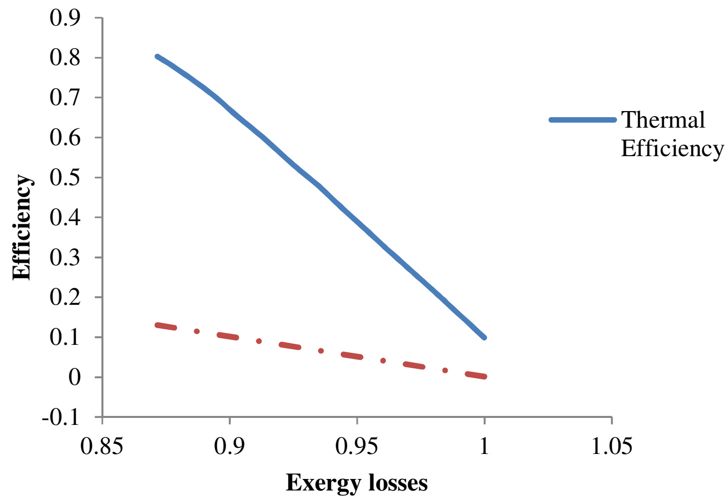

Figure 9: Variation of thermal and exergy efficiencies versus exergy losses

7.0 VALIDATION

For the purpose of validation, some of the results of the simulation have been compared with the work of other researchers. In Fig. 10, the thermal efficiency obtained from the simulation was compared with the experimental result of Essen [11] and a good agreement was observed. Changes of exergy efficiency by ambient temperature were compared with the results of Ajam et al. [16] in Fig. 11. The agreement between the results was more noticeable at higher temperatures.

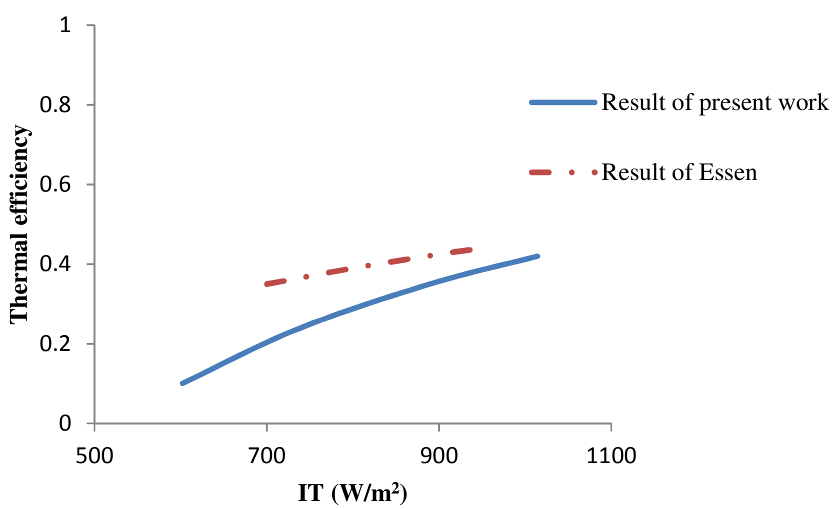

Figure 10: Variation of thermal efficiency versus solar radiation from the present work and the experimental results of Essen [11]

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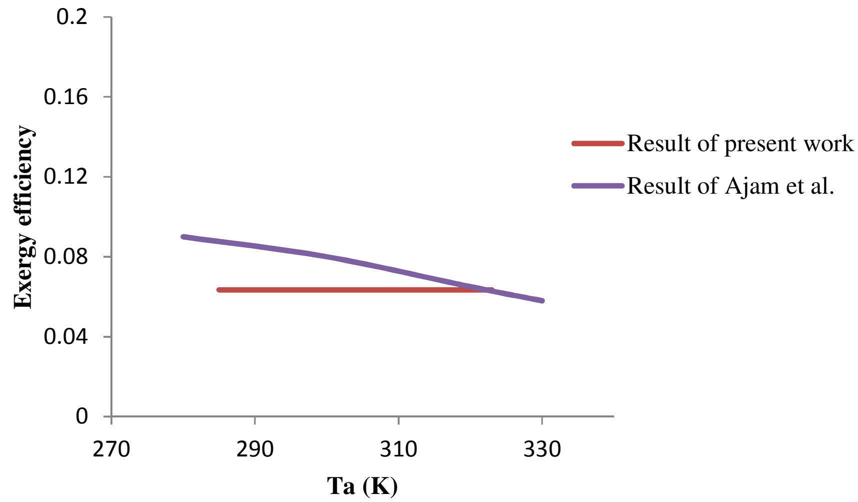

Figure 11: Comparison of the variation of exergy efficiency versus ambient temperature between the present work and the work of Ajam et al. [16]

8.0 CONCLUSION

An exergy analysis is presented together with the thermal analysis. Thermal analysis has been performed in order to obtain the overview of the characteristics of the parameters affecting exergy efficiency. The following conclusions have been obtained:

1- The solar air heater needs to be designed in such a way that the wind entering the heater area has the lowest speed.

2- Incident solar radiation is the most affecting factor of exergy efficiency. For the radiation of 6400 W/m^2, the values of about 80% and 13% could be obtained for thermal efficiency and exergy efficiency, respectively. This implies a change of 12.7% in the exergy efficiency compared to solar radiation of 600 W/m^2.

3- The effect of ambient temperature needs to be considered in conjunction with the solar radiation. Higher ambient temperature results in higher thermal efficiency with a negligible decrease in exergy efficiency.

4- Selection of the type of absorber plate is important in order to obtain high optical efficiency. By increasing optical efficiency from 40% to 98%, thermal and exergy efficiencies improved from 3% to 60% and 0.2% to 8.7%, respectively.

5- The area of heater surface is not a major parameter in designing and optimizing the solar air heater efficiency. Nevertheless, in order to reduce cost, the optimum surface area should be selected. The solar air heater is preferably designed within the specific range of area in order to gain optimum efficiency.

6- By varying the parameters, the losses could be reduced. When the exergy loss was at its highest value of 0.98, the lowest thermal and exergy efficiencies of about zero and 10% were obtained. By decreasing the losses by 11%, the exergy efficiency increased to 13% and thermal efficiency increased by 8 times.

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ISSN (online): 2289-7879 | Vol. 16, No. 1. Pages 15-32, 2015

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