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Exergy analysis of a flat plate solar collector

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Abstract
In this study, exergetic performance analysis of flat plate solar collector has been carried out analytically. A comprehensive mathematical modelling of thermal performance is simulated using MATLAB simulink and optimal geometrical and thermodynamic parameters are predicted pertaining to optimum performance of the system. The optimization procedure was applied to a typical collector and the optimum design points were extracted. The optimum values of collector inlet temperature, mass flow rate, absorber plate area, and fluid outlet temperature for maximum exergy inflow from the system have been obtained.

Keywords: exergy, optimization, solar collector, solar energy

1. Introduction

The role of energy becomes increasingly important to fulfil needs of modern societies and to sustain fast economic and industrial growth worldwide. In view of the world's depleting fossil fuel reserves and environmental threats, development of renewable energy sources receives importance. Of many alternatives, solar energy stands out as a conspicuous energy source for meeting the demand. Though it is located and time dependent, it requires efficient collection and storage systems for economic utilization. The easiest way to utilize solar energy for heating applications is to convert it into thermal energy by using solar collectors.

The performance of solar collectors can be examined from the standpoint of exergy, which is a useful method to complement, not to replace the energy analysis. The amount of useful energy (exergy) delivered by solar collectors is found to be affected by heat transfer irreversibility between the sun and the collector, between the collector and the ambient air and inside the collector. Exergy analysis quantifies the collection and useful consumption of exergy and pinpoints the unrecoverable losses, leading the way to improve the system. The rate at which the exergy is collected by a solar collector can be increased by increasing the mass flow rate of the fluid through the collector and/or the collector area. Since the collector is an expensive component of any solar thermal system which needs advanced material technology to build it and hence, requires large investment in the form of capital cost. We have to optimize the collector area in order to reduce the capital cost of the system, as the fuel (sunlight) is free. Again, for large mass flow rates the fluid outlet temperature is very low and requires more power to pump the fluid through the collector. At the other limit low flow rates result in high fluid outlet temperatures with high specific work potential but the energy losses increase due to the temperature differences, therefore, the optimum mass flow rate is required.

Farahat *et al.* (2005) have done exergetic optimization of a flat plate solar collector, which is developed to determine the optimal performance and design parameters of the solar to a thermal energy conversion system. Exergetic optimization has been carried out under design considerations and optimum values of mass flow rate, absorber plate area and the maximum exergy efficiency have been found.

Ucar (2006) has done an experimental investigation carried out for the shape and arrangement of absorber surfaces of the collectors that were reorganized to provide better heat transfer surfaces suitable for the passive heat transfer augmentation techniques. The performance of such solar air collectors with staggered absorber sheets and attached fins on absorber surface were tested. The exergy relations are delivered for different solar air collectors. It is seen that the largest irreversibility is occurring at the conventional solar collector in which collector efficiency is smallest.

Hikmet (2008) does an experimental energy and exergy analysis for a novel flat plate solar air heater (SAH) with several obstacles and without obstacles. For increasing the available heat-transfer area, this may be achieved if air is flowing simultaneously and separately over and under the different obstacle absorbing plates, instead of only flowing either over or under the different obstacle absorbing plates, leading to improved collector efficiency. The measured parameters were the inlet and outlet temperatures, the absorbing plate temperatures, the ambient temperature, and the solar radiation. Further, the measurements were performed at different values of mass flow rate of air and different levels of absorbing plates in the flow channel duct. After the analysis of the results, the optimal value of efficiency is the middle level of the absorbing plate in the flow channel duct for all operating conditions and the double-flow collector supplied with obstacles appears significantly better than that without obstacles. At the end of this study, the exergy relations are delivered for different SAHs. The results show that the largest irreversibility is occurring at the flat plate (without obstacles) collector in which collector efficiency is smallest.

Kahrobaian (2008) proposed a new method of optimization on linear parabolic solar collectors using exergy analysis that is presented. A comprehensive mathematical modelling of thermal and optical performance is simulated and geometrical and thermodynamic parameters were assumed as optimization variables. By applying a derived expression for exergy efficiency, exergy losses were generated and the optimum design and operating conditions were investigated. The objective function (exergy efficiency) along with constraint equations constitutes a four-degree freedom optimization problem. Using the Lagrange multipliers method, the optimization procedure was applied to a typical collector and the optimum design point was extracted.

To study the effect of changes in optimization variables on the collected exergy, the sensitivity of optimization to changes in the collector parameters and operating conditions is evaluated and variation of exergy fractions at this point are studied and discussed in the present study.

2. Energy analysis

The energy analysis of a flat plate solar collector is given by Sukhatme (1993). The useful heat gain from working fluid is:

$$Q_u = \dot{m}\, C_p (T_o - T_i) \tag{1}$$

Where $\dot{m}$, C_p, T_o, T_i is the mass flow rate, specific heat, Outlet and Inlet temperature of working fluid. The Hottel-Whiller equation for the useful heat gain from solar collector is:

$$Q_u = A_p F_R [I_T(\tau\alpha) - U_L(T_i - T_a)] \tag{2}$$

Where A_p, F_R, T_a, U_L, I_T, $(\tau\alpha)$ are the area of the absorber plate, Heat removal factor, ambient temperature, overall heat loss coefficient, incident solar radiation and the transmittance absorptance product.

Heat removal factor is defined as:

$$F_R = \frac{\dot{m}C_p}{U_L A_p}\left[1 - \exp\left\{-\frac{F' U_L A_p}{\dot{m}C_p}\right\}\right] \tag{3}$$

Where F' is the collector efficiency factor.

Thermal efficiency of solar collector is defined as

$$\eta_e = \frac{Q_u}{I_T A_p} \tag{4}$$

3. Exergy analysis

Application of exergy analysis to a solar collector helps designers to achieve an optimum design and gives direction to decrease exergy losses. The Exergy concept is one of the two ways to the second law analysis, and entropy generation from irreversibility's is the other method. However, both techniques fundamentally give identical results. Decreasing exergy destructed during thermodynamic processes can be achieved by the view point of maximizing exergy efficiency. By applying exergy balance on a solar collector (shown in Figure 1a), exergy efficiency can be derived and the shares of irreversible factors are defined as well. Exergy balance on a flat plate solar collector, as depicted in Figure 1a, can be generally expressed as Suzuki (1987):

$$\sum \dot{E}_{in} - \sum \dot{E}_{out} - \sum \dot{E}_{loss} - \sum \dot{E}_{change} - \sum \dot{E}_{des} = 0 \tag{5}$$

The associated exergy losses of a system shown in Figure 1a are given in Figure 1b.

The exergy input rate $\sum \dot{E}_{in}$ includes the exergy accompanying mass flow rate and the exergy of solar radiation and exergy out rate includes exergy mass flow. The $\dot{E}_{gain}$ is the exergy accumulated by the fluid flow:

$$\dot{E}_{gain} = \dot{E}_{out,f} - \dot{E}_{in,f} \tag{6}$$

Exergy efficiency is the ratio of gain exergy to solar radiation exergy.

$$\eta_{Ex} = \frac{\dot{E}_{gain}}{\dot{E}_{in,r}} \tag{7}$$

A dimensional less parameter is defined as $\bar{\bar{E}} = \frac{\dot{E}}{\dot{E}_{in,r}}$, is the ratio of exergy to the incoming radiation exergy from the sun.

$$\eta_{Ex} = \bar{\bar{E}}_{gain} = 1 - \sum \bar{\bar{E}}_{loss} - \sum \bar{\bar{E}}_{change} - \sum \bar{\bar{E}}_{des} \tag{8}$$

The inlet exergy rate includes the inlet exergy rate with fluid flow and the absorbed solar radiation

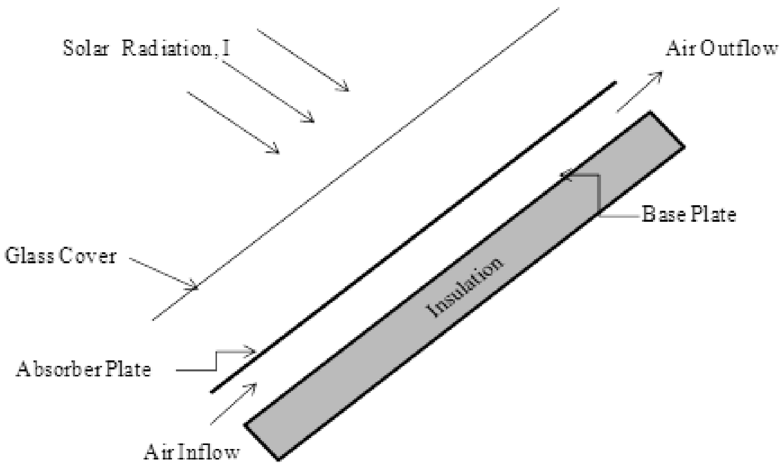

Figure 1a: Conventional flat plate solar collector

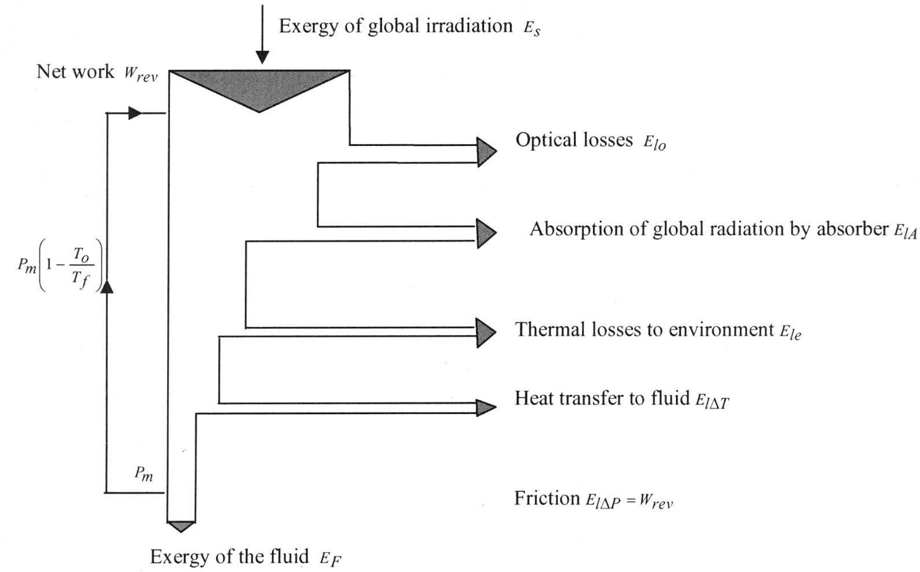

Figure 1b: Exergy flow diagram of a solar air heater

The inlet exergy rate includes the inlet exergy rate with fluid flow and the absorbed solar radiation exergy rate. The inlet exergy rate with fluid flow is given by:

$$\dot{E}_f = \dot{m}C_p\left(T - T_a - T_a\ln\left(\frac{T}{T_a}\right)\right) + \frac{\dot{m}\Delta p}{\varrho} \qquad (9)$$

According to Petela's theory, the exact exergy income by solar radiation for a typical collector with surface area of A_p becomes:

$$\dot{E}_{in,r} = I_T A_p \eta_p \qquad (10)$$

η_p is Petela's efficiency of converting radiation energy (i.e.$I_T A_p$) into work as Bejan (1988):

$$\eta_p = 1 - \frac{4T_a}{3T_s} + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 \qquad (11)$$

Where T_s is the sun temperature.

Considering the exergy at inlet and outlet then exergy efficiency is expressed as

$$\eta_{Ex} = \frac{\dot{m}}{I_T A_p \eta_p}[\mathrm{C_p}\left(\mathrm{T_o} - \mathrm{T_i} - \mathrm{T_a}\ln\frac{\mathrm{T_o}}{\mathrm{T_i}}\right) - \frac{\Delta \mathrm{p}}{\varrho} \qquad (12)$$

the exergy efficiency should be expressed in terms of lost and destructed exergy to illustrate which exergy fractions are major, and consequently take direction to decrease them. Exergy leakage rate out to the surroundings due to optical errors and heat transfer to ambient in a solar collector and is undesirable:

$$\sum \overline{\overline{E_{Loss}}} = \overline{\overline{E_{L,opt}}} + \overline{\overline{E_{L,th}}} \qquad (13)$$

Due to optical error and surface properties of the absorber tube in collector parts of solar radiation do not reach absorber tube. The fraction of optical exergy rate is:

$$\overline{\overline{E_{l,opt}}} = \frac{\dot{E}_{l,opt}}{\dot{E}_{in,r}} = 1\text{-}\eta_o \quad (14)$$

$$\text{Where } \overline{\overline{E_{l,th}}} = \frac{U_L A_t(\bar{T}_t - T_a)^2}{I_T A_p \eta_p \bar{T}_t} \quad (15)$$

Studying the collector in steady state conditions is thus $\sum \overline{\overline{\dot{E}}}_{change} = 0$ however, exergy change rate of the tube and fluid can be approximately neglected in every condition due to low values.

Exergy destruction is caused by irreversibility's in the system and there are two ways of exergy destruction in solar collectors; exergy destructed due to friction of viscous fluid and exergy destructed due to heat transfer processes. Since the viscous fluid causes pressure drop between inlet and outlet of the tube, considering correspondent entropy generation, exergy destructed during this process can be stated as

$$\dot{E}_{des,\Delta p} = T_a \frac{\dot{m}\Delta p}{\varrho} \frac{ln\left(\frac{T_o}{T_i}\right)}{T_o - T_i} \quad (16)$$

Exergy is also destructed while heat is transferred from hot to cold temperatures. There are two heat transfer processes in the collector; 1) heat transfer of solar energy absorbed by the surface of the tube, 2) heat transfer conduction from outer tube surface to fluid flow. The exergy destructed rate due to absorption and conduction process is defined as:

$$\dot{E}_{des,abs} = \eta_o I_T A_p T_a \left(\frac{1}{\bar{T}} - \frac{1}{T_s}\right) \quad (17)$$

$$\dot{E}_{des,con} = \dot{m} C_p T_a \left(\ln\left(\frac{T_o}{T_i}\right) - \frac{(T_o - T_i)}{\bar{T}_t}\right) \quad (18)$$

Thus rate of exergy destruction is

$$\sum \overline{\overline{E}}_{des} = \frac{\dot{E}_{des,\Delta p} + \dot{E}_{des,abs} + \dot{E}_{des,cond}}{\dot{E}_{in,r}} \quad (19)$$

Substituting (16-19) in equation (8), the exergy efficiency can be depicted as:

$$\eta_{Ex} = 1 - \left[1 - \eta o + \frac{U_L A_t(\bar{T}_t - T_a)^2}{I_T A_p \eta_p \bar{T}_t} + T_a \frac{\dot{m}\Delta p}{\varrho} \frac{ln\left(\frac{T_o}{T_i}\right)}{T_o - T_i} + \eta_o I_T A_p T_a \left(\frac{1}{\bar{T}} - \frac{1}{T_s}\right) + \dot{m} C_p T_a \left(\ln\left(\frac{T_o}{T_i}\right) - \frac{(T_o - T_i)}{\bar{T}_t}\right)\right] \quad (20)$$

The right term of equation (20) indicates the exergy losses.

4. Results and discussion

Thermal analysis of a solar collector has been carried out using a mathematical simulation technique. The effect of operating parameters on exergy efficiency has been investigated. An optimization of exergy efficiency has been carried out to evaluate the optimum values of operating parameters by using MATLAB computational program.

Table1: The specification of the solar collector and environmental parameters

Collector parameters	**Value**
Glazing	Double glass
Fluid in pipes	water
Bond conductance	Neglected
Length of plate	L_1=1m
Wind velocity, V_w	5 m/s
Collector tilt, β	30^0
Fluid inlet and ambient temperature,	300K
Sun temperature, T_s	4350K
Plate thickness	0.002m
Transmittance- absorptance product,	0.84
Absorber plate emittance, ε_p	0.92
Glass cover emittance, ε_c	0.88
Glass cover spacing, s	0.04m
Thickness of back insulation, s_b	0.08m
Thickness of side insulation, s_s	0.04m
Thermal conductivity of plate,	384W/m-K
Incident solar radiation, I_T	550W/m^{2}K
Tube pitch, W	0.015m
Inner tube diameter, d_i	0.04m

Figure 2 shows the behaviour of the exergy efficiency as a function of the mass flow rate of fluid and the absorber plate area. It is presented to a range of operational and design conditions where the exergy efficiency takes a global maximum value. The incremented quantities are the absorber plate area from 1 to 9 m^2 and the mass flow rate of fluid from 0.001 to 0.009 kg/s. The calculated values for the global maximum point are A_p= 9 m^2, m= 0:008 kg/s, η_{Ex}=4%. Increasing the mass flow rate above the value of m=0.008kg/s shows the no change of exergy efficiency for A p=9 m^2. This subject allows the designer to optimize the solar collector regarding other conditions such as design limitations and thermal applications. Whereas, decreasing the mass flow rate below the value of m=0.008kg/s determines the sensible decrease of exergy efficiency for A_p=9m^2 and this subject shows the danger range.

Figure 3 shows the effect of fluid inlet temperature on the exergy efficiency. By increasing the fluid inlet temperature until the value of T_i=300 K, the exergy efficiency increases and then decreases sharply.

Figure 4 shows the ambient temperature effect on the exergy efficiency. Increasing the ambient

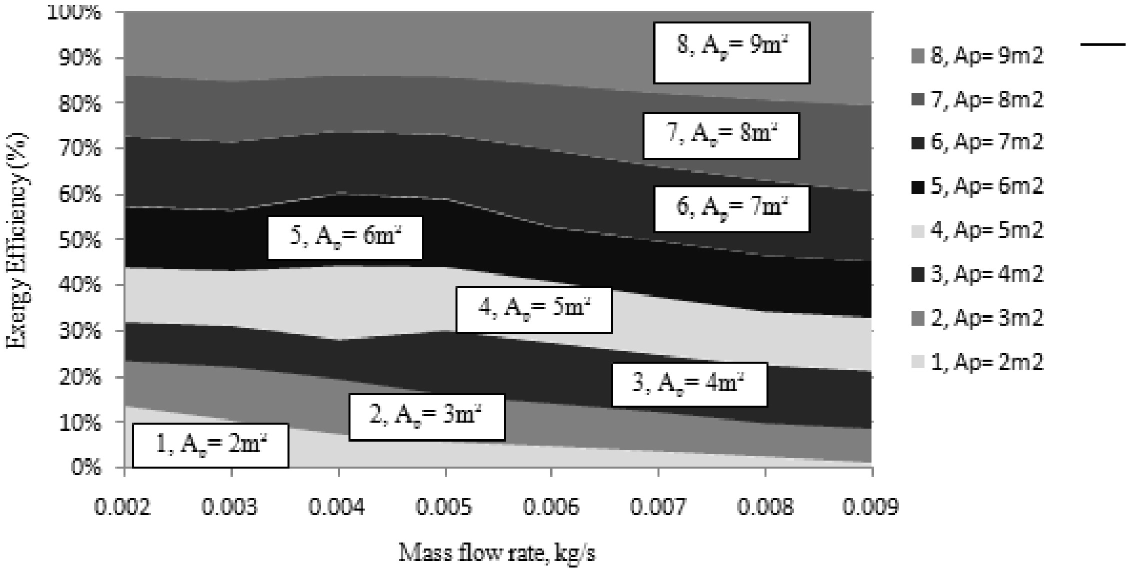

Figure 2: Variation of energy efficiency with mass flow rate and absorber plate area

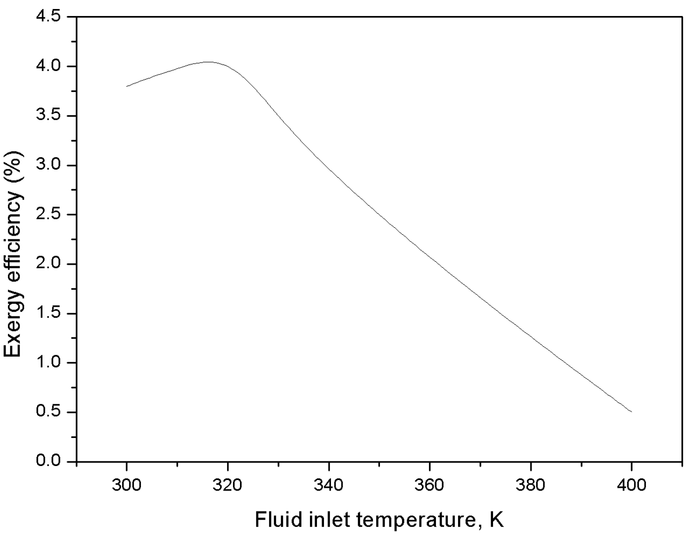

Figure 3: Variation of exergy efficiency with fluid inlet temperature

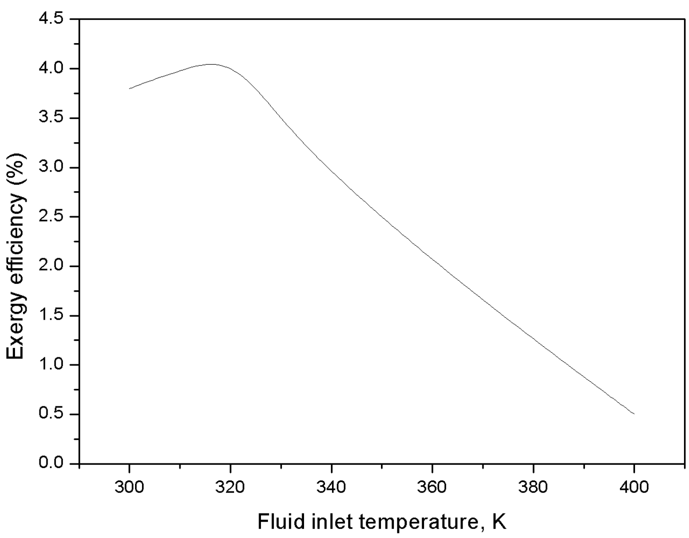

Figure 4: Variation of exergy efficiency with ambient temperature

temperature from 300 to 313 K determines the sensible decrease of the exergy efficiency. Since the ambient temperature changes during the day, for having the maximum exergy efficiency, other parameters and the solar collector operating conditions should change during the day.

Figure 5 shows the variations of the exergy efficiency versus the wind speed. Increasing the wind speed from 0.001 to 50 m/s determines the sensible decrease of the exergy efficiency from 5 to 4%.

Figure 6 shows the variations of the exergy efficiency with respect to the incident solar energy per unit area of the absorber plate. By increasing this parameter from 100 to 1000 W/m^2, the exergy efficiency increases.

Table 2: The results at optimum design point and operating conditions

Optimum exergy efficiency ($\eta^{Opt}{}_{Ex}$)	4%
Optimum plate area ($A^{Opt}{}_{p}$)	9m^2
Optimum mass flow rate ($\dot{m}^{opt}$)	0.008kg/s
Optimum outlet fluid temperature ($T^{Opt}{}_{o}$)	360K

5. Conclusion

In this paper, a new and comprehensive method for defining design and operating conditions for a flat plate solar collector was presented. The proposed method consists of an objective design approach, and simulation of thermal performance of the col-

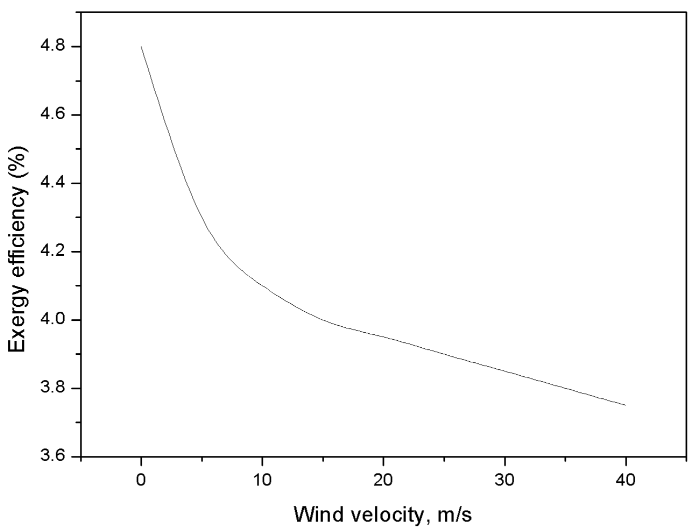

Figure 5: Variation of exergy efficiency with wind velocity

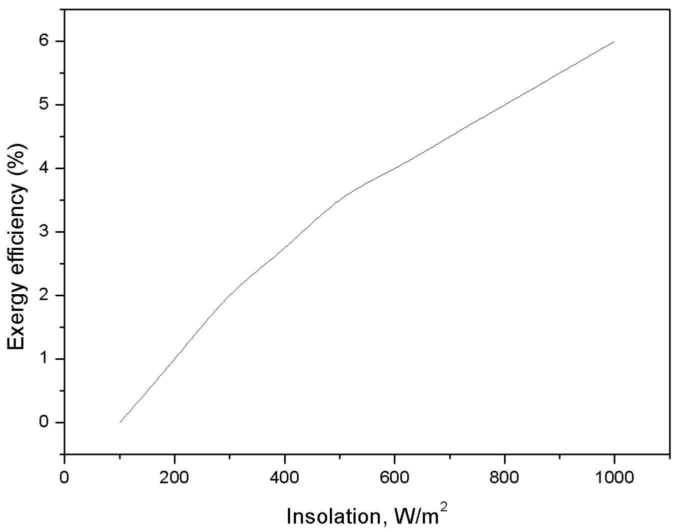

Figure 6: Variation of exergy effiency with insolation

lector. Exergy efficiency was introduced as an objective function and regarding thermal aspects, mathematical modelling for real performance of the collector implemented.

In the optimization procedure, optimum values of collector inlet temperature, mass flow rate, fluid outlet temperature as main variables, were extracted in the presence of environment conditions, material selected and design constraints. The optimum design plots are prepared for operating parameters so that the maximum value of exergy efficiency of the collector was gained.

Nomenclature

A	area (m^2)
Cp	heat capacity of the fluid (kJ/kgK)
D	diameter (m)
E	exergy rate (J/s)
F'	collector effciency factor
F_R	heat removal factor
I_T	solar radiation intensity (W/m^2)
k	conductivity (W/mK)
m	mass flow rate (kg/s)
Q	heat transfer rate (W)
S	radiation absorbed flux (W/m^2)
T	temperature (K)
U	collector loss coefficient (W/m^{2}K)
V	speed, velocity (m/s)

Greek symbols

a	absorptance
Δ	difference in pressure or temperature
η	efficiency (%)
τ	transmittance
ϱ	density (kg/m^3)
($\tau\alpha$)	effective product transmittance-absorptance

Subscripts

a	ambient
en	energy
ex	exergy
exp	exponential
f	fluid
i	inlet
l	overall
o	outlet
p	absorber plate, Petela
u	useful

References

Bejan, A., (1988). Advanced Engineering Thermodynamics, John Wiley & Sons, 488-491.

Farahat, S., Sarhaddi S., & Ajam H., (2009). Exergetic Optimization of Flat Plate Solar Collector, *Renewable Energy*, 34, 1169-1174.

Ucar, A., & Inalli L., (2006), Thermal and exergy analysis of solar air collectors with passive augmentation techniques, International Communication in Heat and Mass Transfer, 33, 1281-1290.

Hikmet, E., (2008). Experimental energy and exergy analysis of a double-flow solar air Heater having different obstacles on absorber plates, *Building and Environment*, 43, 1046-1054.

Kahrobaian, A., & Malekmohammadi H., (2008). Exergy Optimization Applied to Linear Parabolic Solar Collectors, *Journal of Faculty of Engineering*, 2008, 42, 131-144.

Sukhatme, S.P., (1993). Solar Energy, New York TMH, 1993, 83-139.

Suzuki, A., (1987). General Theory of Exergy Balance and Application to Solar Collectors, 123-128.

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