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Experimental Investigation of Solar Air Heater with Free and Fixed Fins: Efficiency and Exergy Loss

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Abstract: In a solar air heater, the fins located in flow area increases the heat transfer coefficient and output temperature of air. Accordingly, collector efficiency increases too. However, an increase is observed in pressure drops as wall as heat transfer. In our study, each of the fins, which are in the form of rectangular having two different surface areas, is located on the absorber surface in free and fixed manners. In the first case, the fins are located on the absorber surface in a way to be able to freely move. In the second case, it has been fixed to the absorber surface. The absorber surface area (A) is 1.64 m^2. The fixed and free fins with 8 and 32 items whose surface areas (A_f) are 0.048 and 0.012 m^2 are located on the absorber surface. Thus, the total fin area in the absorber surface is equaled (0.384m^2). Solar air heater having free and fixed fins is compared to flat-plate solar air heater as well as each other in terms of efficiency and exergy loss ratio.

Keywords: Solar air heater, Solar energy, Free and fixed fins

Sabit ve Hareketli Kanatlara Sahip Bir Havalı Güneş Kolektörünün Deneysel Olarak İncelenmesi: Etkinlik ve Ekserji Kaybı

Özet: Bir havalı güneş kollektöründe akış alanına yerleştirilen kanatlar, havanın taşınım katsayısı ve çıkış sıcaklığını artırır. Böylece kollektör etkinliği de artar. Ancak ısı transferine paralel olarak basınç kayıplarında da artış gözlenir. Bu çalışmada, iki farklı yüzey alanına sahip dikdörtgen şeklindeki kanatların her biri toplayıcı yüzeyine sabit ve hareketli olacak şekilde yerleştirilir. Birincide, kanatlar toplayıcı yüzeyine serbestçe hareket edecek şekilde yerleştirilmiştir. İkincide ise, toplayıcı yüzeyine sabitlenmişlerdir. Toplayıcı yüzey alanı (A) 1.64 m^2'dir. Yüzey alanı (A_f) 0.048 m^2 olan kanatlardan 8 tane, 0.012 m^2 olan kanatlardan 32 tane toplayıcı yüzeyine hem hareketli hem de sabit olacak şekilde yerleştirilmiştir. Böylece, toplayıcı yüzeyindeki yerleştirilen kanatların toplam alanı 0.384 m^2 ile eşitlenmiştir. Hareketli ve sabit kanatlara sahip havalı güneş kolektörü, etkinlik ve ekserji kaybı bakımından birbiriyle ve düz kolektörle karşılaştırılmıştır.

Anahtar Kelimeler: Havalı kolektör, güneş enerjisi, Sabit ve hareketli kanatlar

1. Introduction

Flat- plate collectors are classified into two groups according to fluid used. Water is usually used in liquid collectors and air, in gas collectors. Since the air has worse thermodynamic properties in terms of heat transfer compared with liquid, the efficiency of solar air heaters is naturally low. For this reason, several types of solar air heaters have been proposed over the recent years in order to improve their performance.

Solar air heaters are simple device to heat air by utilizing solar energy and employed in many applications requiring low to moderate temperature below 60 ^{o}C, such as crop drying and space heating. The principal types these heaters are; the single pass with front duct, rear duct, double duct and double pass [1].

Recently, many studies have been conducted on the efficiency and exergy analysis of solar air heater. Effect of geometrical parameters of V-shaped ribs on heat transfer and fluid flow characteristics in rectangular duct of solar air heater with absorber plate having V-shaped ribs was investigated by Momin et al. [2]. In the other studies, different fins are soldered on the collectors back [3-7].

In this study, heat transfer and pressure drop were investigated by locating free fins, which is different from the literature deal with similar studies, on the absorber of single pass solar air heater. An exergy correlation including pressure and temperature rates was developed and investigated using data of results obtained from the experiments.

2. Experimental setup and procedure

2.1. Experimental setup

Although, the collectors designed are composed of basically the same materials and dimensions (930x1920 mm) in the conventional flat-plate solar air collectors, it has free fins on the absorber surface.

The absorbers were formed by a black-painted galvanized sheet with 0.4 mm thick. For the fins, four galvanized sheet having total area ($A_{f,t}$) 0.384 m^2 were divided to 8 and 32 rectangular shape items. These fins were mounted to below side of four different absorbers in free and fixed manners. The fins were designed in two different dimensions.

Type I and II fins have 800x60 mm and 200x60 mm dimensions, respectively. Type I and II were located to be respectively 8 and 32 numbers to the below side of absorber in order to obtain the same total surface area ($A_{f,t}$=N.A_f) of the fins in flow area. Therefore, Type I and II were located with an interval of 210 mm (Fig. 1 (a)) and 120 mm (Fig. 1 (b)), respectively. Free fins were attached to the below side surface of the absorber plate by hinges and allowed to hang free in the flow area. Fixed fins were mounted by being soldered to the absorber underside. Dimensions of each collector type designed are given in Table 1.

Table 1. Dimensions of each collector type designed.

		A_f (m^2)	N (number)	$A_{f,t}$ (m^2)	A (m^2)
Type I (810x60) (mm)	Free fin	0.048	8	0.384	1.64
	Fixed fin	0.048	8	0.384	1.64
Type II (200x60) (mm)	Free fin	0.012	32	0.384	1.64
	Fixed fin	0.012	32	0.384	1.64
Flat-plate		-	-	-	1.64

a) Free fins absorber of Type I.

b) Free fins absorber of Type I

Fig. 1 Free fins of Type I and Type II.

Each of collector cases was manufactured by being joined two solar collector cases, which were purchased in the market. Besides, all the areas joined were covered by joint seal in order to prevent heat leaking. A single glazing was chosen in order to maximize the radiation impact on the absorber surface and to reduce costs. To minimize the heat losses from the sides and from the bottom of the collector were insulated by glass wool, which has low heat conductive coefficient (λ=0.038 W/m°C). The air was provided by a radial fan with a maximum 0.31 m^3/s mass flow rates. The radial fan placed at the outlet of the collectors sucked the air. The pressure drop was measured by means of a water U-manometer placed between entrance and the exit, and the velocity of the air was measured at the inlet and outlet of the collector.

2.2. Methods and Measurements

The experiments were conducted on the days of May and June in Elazığ in Turkey. The collectors were located with 37° angles with respect to south direction.

The experiments were carried out at the same time periods between 9.00 and 17.00 of the days for various mass flow rates and performed five days for each mass flow rate. However, the days having approximately the same radiation were used, when a comparison was made between collectors. The air flow through the collector was supplied by a radial fan and adjusted via a sliding valve located at the air inlet. The flow rate was kept constant and same in both the collector designed and conventional flat-plate collector.

The experiments were carried out using four different mass flow rates the flow rates were adjusted via the sliding value of the radial fan. The mass flow rate of the air was measured by rotameter. The collectors were tested according to standard [8].

The incident solar radiation was measured by a Kipp & Zonen piranometer. Copper-Constantan thermocouples were placed at the four points in the collector as well as at the inlet and outlet ports of the air to measure by a multi-channel digital micro voltmeter for 60 min. periods. The data of the relative humidity of the air and wind speed during the experiments were kindly supplied by meteorology department in Elazığ.

The accuracies of the thermocouple temperature, manometer and flow meter readings are within ± 0.1 °C , 0.75% and 1.5% of full scale, respectively. Uncertainties of temperature, pressure and mass flow rate are 1.41, 2.64 and 3.15%, respectively. Uncertainties of Nusselt number, Reynolds number, friction coefficient and exergy loss ratio are found to be 3.98, 3.42, 4.89 and 4.18%, respectively.

3. Analysis

Thermal efficiency of solar heating systems is defined as the ratio of useful energy gain by the air to solar radiation incident on the absorber of solar collector

$$\eta = \frac{Q_g}{Q_s} = \frac{\dot{m}.C_p.(T_o - T_i)}{I.A} \tag{1}$$

where Q_g is useful energy gain.

Exergy loss ratio relationship, defined as ratio of exergy loss to heat gained, was given by Kurtbaş and Durmuş [10];

$$E_R = \frac{E_L}{Q_g} = \frac{T_e}{\Delta T}.\ln\left(\frac{(T_o/T_i)}{(P_o/P_i)^{k-1/k}}\right) + \frac{1}{\eta}\left(1 - \frac{T_e}{T_s}\right) - 1 \tag{2}$$

Eq. (1) must be equal to 1 to get maximum efficiency in a solar collector, that is, heat gained should be equal to total energy intercepted by the collector (Q_g=Q_s). However, even if this state occurs, exergy loss in a solar collector can not be zero. (i) since there is a temperature difference between heating or cooling system and environment, heat always transfers from higher temperature to low temperature. (ii) the increase temperature difference between outlet and inlet of fluid results in an increase in entropy generation.

4. Results and discussion

In our study, the effect of both fixed and free fins having two different dimensions area on the collector efficiency and exergy loss was investigated. Besides, a comparison was performed in terms of exergy loss by developing a dimensionless correlation as a ratio of exergy loss to heat gain. Experiments of flat-plate, Type I and Type II collectors were carried out on the same day to make a true comparison. Solar input and environment temperature for the experiment days as a function of day times were given in Fig. 2. The radiation values change in the range of 400 and 837 W/m^2 and it reaches the maximum in the midday. These values change approximately between 14 and 26 °C for environment temperature. Flat-plate collector efficiency was found as 25 % at minimum mass flow rate

($\dot{m}$=0.03 kg/s), and 47% at maximum mass flow rate ($\dot{m}$=0.08 kg/s) during midday as shown in Fig. 4. As shown in Figs. 2. and 3, Contrary to the exergy loss ratio, solar input, environment temperature and collector efficiency reach the maximum values in the midday. However, as shown in Eq. (2), exergy loss ratio increases with increasing environment temperature due to an enhanced entropy generation. This indicates that the efficiency of air heater is more effective than environment temperature on the exergy loss ratio.

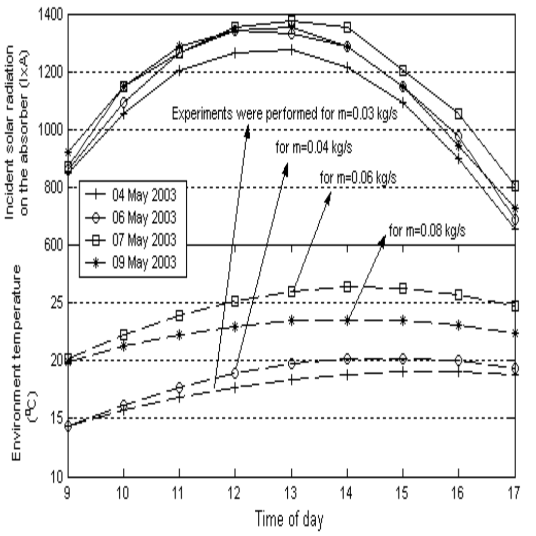


Fig. 2. Incident solar radiation on the absorber and environment temperature as a function of day times for four mass flow rates.

The experimental results revealed that collector efficiency was the most effective parameter on the exergy loss ratio and the efficiency changes depending on mass flow rate, temperature difference between outlet and inlet of fluid and solar input. Instantaneous efficiency of flat-plate at minimum mass flow rate was 16% and 25% and exergy loss was approximately 5 and 2.8 times of heat gained at 9 am. and 14 pm., respectively.

Flat-plate collector efficiency for 0.04, 0.06 and 0.08 kg/s mass flow rates increased by 28%, 32% and 47% at 14 pm, respectively. and exergy loss ratio decreased by about 2.29, 1.93 and 1.018 times, respectively. In Type I collector, efficiency and exergy loss ratio changed according to fixed and free fins and their construction as shown in Fig. 4, (a) and (b). As shown in this figures, the results of Instantaneous efficiency and exergy loss of each collector are in a form of symmetrical way appearance. Efficiency of air collector having free and fixed fins increased 1.35 and 1.44 times according to flat-plate collector, respectively. For each mass flow rate, efficiency of the collector having free fins increased approximately 1.06-1.08 times according to air collector having free fins.

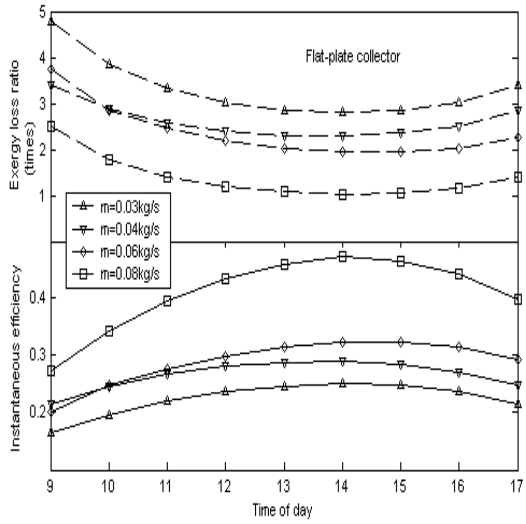
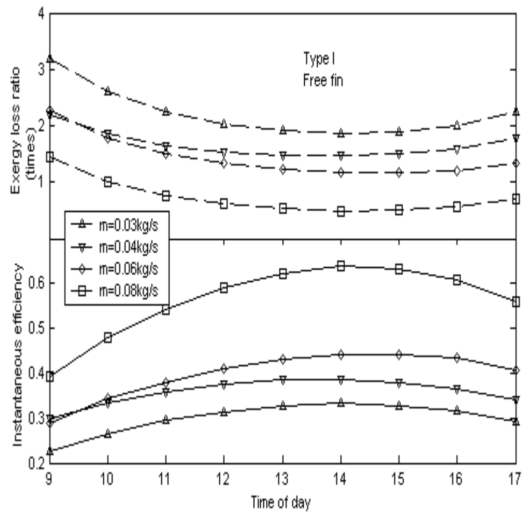
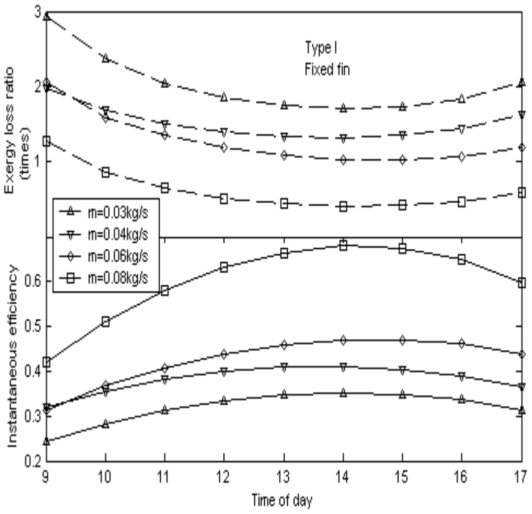


Fig. 3. For flat-plate collector, instantaneous efficiency and exergy loss as a function of day times for four mass flow rates.

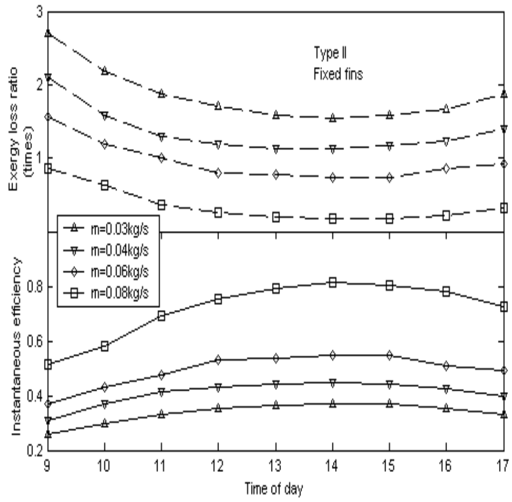


a) Free fins absorber of Type I.



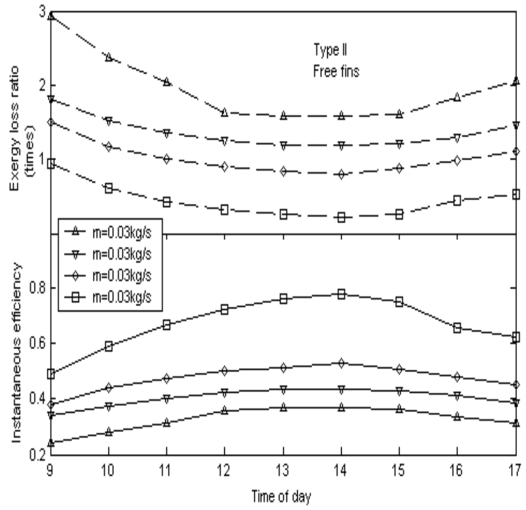
b) Fixed fins absorber of Type I.

Fig. 4. Instantaneous efficiency and exergy loss as a function of day times for four mass flow rates



b) Fixed fins absorber of Type II

Fig. 5. Instantaneous efficiency and exergy loss as a function of day times for each collector type.



a) Free fins absorber of Type II.

As shown in Eq. (2), pressure drop is a parameter of exergy loss and P_o/P_i is always less than 1. It was seen that when the fins moved, pressure drop and outlet temperature of air decreased according to the fixed fins having equal surface area. As known, the most important parameters on the collector efficiency are mass flow rate and outlet temperature of the fluid, that is, outlet temperature of the air is more effective on the exergy loss than pressure drop.

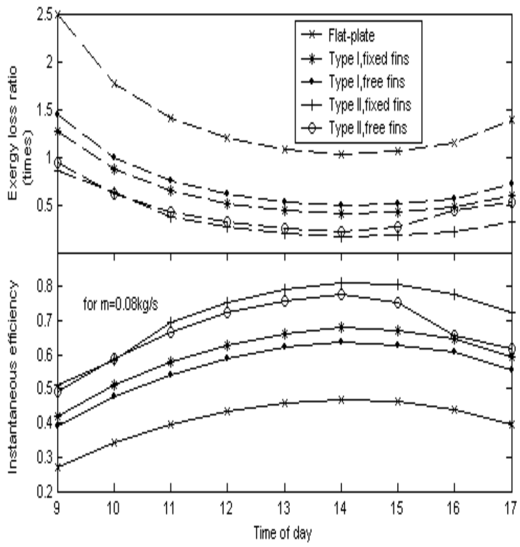


Fig. 6. Instantaneous efficiency and exergy loss as a function of day times for four mass flow rates

In Type I collector having free and fixed fins, exergy loss was 0.49 and 0.39 times of heat gained and collector efficiency was 63% and 67% at maximum mass flow rate, respectively. Collector efficiency, heat transfer and exergy loss were investigated by being located with an interval of 120 mm free and fixed fins having 200x60 mm dimensions to the absorber surface of Type II collector. The aim of this type designing was to increase convection coefficient of air locating smaller fins with a shorter distance than distance between fins of Type I. The maximum efficiency of Type II having free fins changed between 36% and 77% and fixed fins changed between 37% and 81% depending on mass flow rate of the air as seen Fig. 5 (a) and (b). Moreover, exergy loss ratio for Type I changed between 1.57 and 0.22 times and Type II changed between 1.55 and 0.17 times of heat gained.

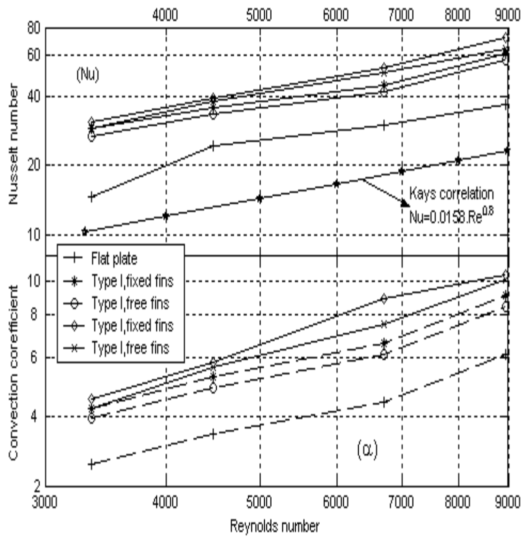


Fig. 7. Change of Nusselt number and convection coefficient with Reynolds number for each collector type

Instantaneous efficiency and exergy loss ratio of each collector type are given in Fig. 6. from this figure, efficiency and exergy loss ratio significantly changed depending on fin construction (fixed or free) and their dimensions (A_f). Both free and fixed fins of Type II were more effective than Type I and flat-plate collector. Efficiency of Type II (A_f=0.012 m^2) increased 1.2 and 1.7 times and exergy loss ratio decreased 2.3 and 6 times according to Type I (A_f=0.048 m^2) and flat-plate collector, respectively. Efficiency of Type I increased 1.4 times and exergy loss ratio decreased 2.5 times according to flat-plate collector.

Resistances are located throughout the collector. Thus, constantly swirl effect is given to the flow by being located with definite intervals in the collector. In this way, heat transfer and pressure drop change and heat transfer coefficient increases according to the type and number of resistances. Heat transfer coefficient is proportional to Nusselt number as shown in Fig. 7. For full developed turbulent flow of air between two plates with one side heated and the other side insulated, Kays and Crawford [11] give the correlation as follow.

$$Nu= 0.0158.Re^{0,8}. \quad (3)$$

According to this correlation obtained for turbulent flow, Nusselt number changes ranging 10.3 and 23 depending on Reynolds number. Heat transfer in Type I and Type II having free fins increased averagely 2.7 and 2.9 times according to Eq. (3) and 1.65 and 1.8 times according to flat-plate collector, respectively (Fig. 7). When the fins were fixed, these values changed ranging 2.9 times, 3.2 times, 1.7 times and 2 times according to the same sequence mentioned above. Heat transfer in Type I and II having fixed fins increased 1.07 and 1.12 times according to free fins. A correlation was derived based on the experimental data of flat-plate solar collector. This empirical correlation given the following is valid for Reynolds number in the range of 3000 and 9000.

$$E_R = \frac{E}{Q_g} = \frac{0.0236.\,Re^{0.314}}{\eta^{1.904}.\theta^{0.244}.P_{rt}^{\;0.12}} \quad (4)$$

Where θ is a ratio of temperature differences $((T_o-T_i)/(T_{as}-T_e))$ and P_{rt} is a ratio of pressures (P_o/P_i) in collector. This correlation has error limit 9% at 9 am. and 17 pm. and it changes randomly between 0.1% and 4% up to 16 pm. from 10 am. Correlation coefficient (r) of Eq. (4) is 0,959. Pressure ratio (P_r) changed between 0.98 and 0.99 depending on the mass flow rate and collector type. Because of this, (P_o/P_i) in Eq. (4) can be neglected. It is quite clear that the efficiency and exergy loss in a solar collector are functions of solar input, which changed according to time of day.

5. Conclusions

From the experiment results it is seen that, one of the most important parameters for exergy loss is collector efficiency. A summary of results obtained is given below:

- There is a reverse relationship between exergy loss ratio and collector efficiency as well as temperature difference of fluid.
- If pressure drop increases, both heat transfer and exergy loss also increases. However, it affects exergy loss ratio at less level since pressure drop is very little in a solar air heater.
- Fins located on the absorber increase heat transfer and pressure drop. Nevertheless, exergy loss decreases depending on its construction.
- If ratio of fin area ($A_f/A_{f,t}$) decreases, collector efficiency and heat transfer increase in spite of decreasing friction coefficient.
- Fixed fin collector is more effective than free fin collector.

Fixed fin increases both outlet temperature of air and pressure drop. That is the most probably the fixed fin to work as a fin conducted heat from the absorber and also to prevent the developing of the boundary layer. However, free fin works only as a resistance changed flow lines because of not joined on the absorber. Therefore, pressure drop decreases changing fin location depending on impulse force ($\dot{m}$.V) of fluid. This study is largely about exergy loss of collector designed. Important results can be gained to the literature as well, if free fins studies are performed on the heat transfer and friction coefficient by increasing parameters and variables.

6. References

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7. Notation

A	collector surface area (m^2)
A_h	channel cross section area (m^2)
A_f	fin surface area (m^2)
$A_{f,t}$	total surface area of fins (m^2)
C_p	specific heat (J/kg.K)
E	exergy (W)
E_L	exergy loss (W)
E_R	exergy loss ratio (-)
f	friction coefficient (-)
h	enthalpy (J/kg)
I	total solar radiation incident upon plate of the collector (W/m^2)
k	adiabatic constant of the air ≅ 1,4)(-)
L	solar air heater length (m)
N	total number of fins in a absorber
Nu	Nusselt number (-)
P	pressure (N/m^2)
Q_g	useful heat gain (W)
Q_s	total energy intercepted by the collector (W)
Pr	Prandtl number (-)
r	correlation coefficient (-)
Re	Reynolds number (-)

T	temperature (K)
T_{as}	surface temperature of the absorber (K)
V	average velocity of air (m/s)
W	work (J)
$\dot{m}$	mass flow rate of air (kg/s)

Greek symbols

α	heat convection coefficient ($W/m^2.K$)
η	efficiency of solar air heater (-)
λ	heat conduction coefficient (W/m.K)
μ	dynamic viscosity of air (Pas. s)
θ	dimensionless temperature (-)
ρ	density of air (kg/m^3)

subscripts

e	environment
f	fluid
i	inlet
o	outlet
s	solar