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Energy modeling and simulation including particle technologies within single and double pass solar air heaters

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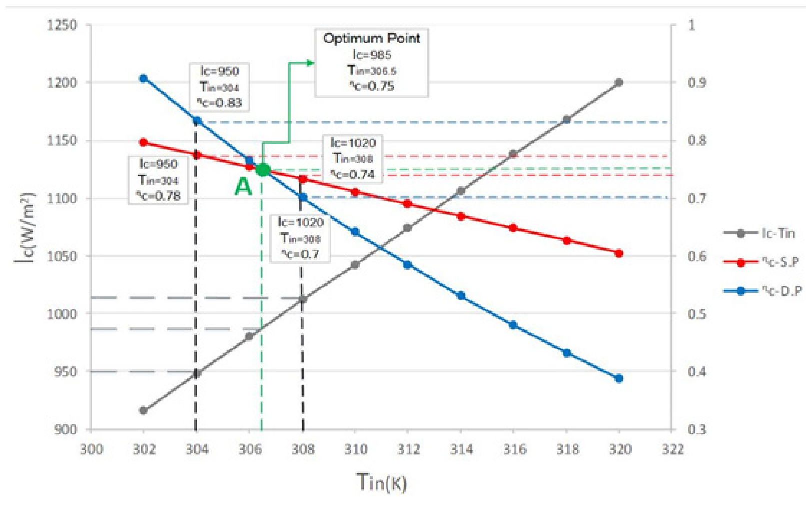
HIGHLIGHTS

- Quantitative compare of the efficiencies in one and double pass solar air heaters.
- Target optimum performance & decide to select number of passes in solar air heaters.
- Double pass efficiency is higher in more inlet air temperature & lower solar irradiation.

GRAPHICAL ABSTRACT



ABSTRACT

In order to obtain the best performance of the solar air heaters, it is necessary to find optimum performance conditions. The aim of this research paper is to achieve optimum conditions, by comparing single and double pass solar air heaters. Also, a brief review study of various related research works of all scenarios for a single and double pass and packed bed (including particle technologies) solar air heaters was carried out to observe the challenges of the mentioned systems. Energy modeling and simulation with EES and MATLAB open source code software indicated significant results in efficiency. According to the obtained results, it can be explained that double pass duct not necessarily always increases the overall system energy efficiency. Results of this work indicate, higher ambient air temperature (inlet air temperature) and lower solar irradiation can increase overall energy efficiency of solar double pass systems. More precisely at solar irradiation of 916 W/m^2 and inlet air temperature of 302 K, the system achieves the targeted optimum value in energy efficiency, approximately 90%, which is considerably more than the 65% as an average value.

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1. Introduction

One method to develop and improve solar air heaters is to increase the heat transfer rate by increasing the number of air channels (Pass). The mentioned method has its advantages and disadvantages. Although improvement in heat transfer due to increasing surface area assumes an advantage but pressure drop and therefore momentum energy reduction is a disadvantage of this method. Therefore, there is an optimized range that is being addressed in this study [1].

In the field of double and single pass solar air heaters, many studies have been carried out, where they compare solar air heaters in different conditions and features, some of them are as follow;

C.D. Ho et al. [2] have investigated double pass solar air heaters by using recycling system. This model of double pass air heater is designed in order to increase inlet air temperature by premixing of inlet air and partially recycled outlet air. The results of their study show that this design increases thermal driving force and subsequently, increases the heat loss which is not useful for solar air heater energy efficiency at all. On the other hand, it increases heat transfer coefficient in forced convection approach that causes to improve energy efficiency. As mentioned, this design can cause a considerable increase in efficiency.

In research work of Prashant Dhiman et al. [3], in order to analyze the system, a Parallel Flow Packed Bed Solar Air Heater (abbreviated PFPBSAH) has been considered. That consist of two glass covers, two plates, and two air channels, above and between the plates with porous media, which is above the absorber plate. A packed bed is a volume of porous media obtained by packing particles of selected material into a duct. Also, PFPBSAH is found to perform more efficiently than the conventional non-porous double flow solar air heaters with 10%~20% increase in its thermal efficiency. Significant improvement in the packed bed solar air heater performance can be obtained through a careful choice of packed bed particles parameters and the fraction of mass flow rate [4].

A.A. El-Sebaii et al. [5] investigated double pass air heaters with two glass cover in two scenarios, First one with packing only in lower air ducts, the other in both upper and lower air ducts. Investigated parameters in this paper include: outlet air temperature, outlet heat power, pressure drop and hydraulic efficiency. Mass flow rate of air and filled porous materials are effective in the energy efficiency of the system. B.M. Ramani et al. [6] have implemented and simulated double pass solar air heater with parallel flow. In this research, not any comparison between single and double pass solar air heaters has not been done, but Ravi Kant Ravi et al. [7] and Ghadimi, M., et al. [8] have investigated a variety of different techniques to improve energy efficiency of double pass solar air heaters such as using packed-bed, extended surfaces and corrugated absorbent surfaces. These works include cost analysis, thermo-hydraulic properties and design of these type of air heaters. They used developed correlations for comparison purposes among energy efficiency of different designs. Besides, double pass air heater with one added glass cover (air heater with two glass covers) was investigated in their studies.

In summary, many research works, double pass solar air heaters with various features are compared. However, as a challenge of comparison, it is necessary to compare the performance of single and double pass air heaters by energy modeling and numerical solution, in terms of temperature (thermal) and energy.

The new opinion of this study is quantitative comparison and optimization between single and double pass solar air heaters, as a challenge which has not been done up to now. The result of this research issued that in a certain range of performance and application, each of single and double pass can have better efficiency. This viewpoint (kind of comparison) is not available in the previously mentioned investigations. In fact, innovative results of this work can provide the ability to predict optimum solar air heater type according to the required solar irradiation and inlet temperature range.

2. System energy modeling

The overall Figures of single and double pass solar air heaters are shown in Fig. 1 & 2. Double pass air heaters can have different designs, the model shown in Fig 2, has been applied in the coding procedure [9].

To simplify and solve the systems equations, the following assumptions are considered [10].

1. The air heater operates under steady state conditions;
2. The capacitance of the absorber plate is negligible;
3. The temperature of air varies only in the direction of the flow (x direction);
4.The area of the absorber plate is equal to the aperture area of the air heater;

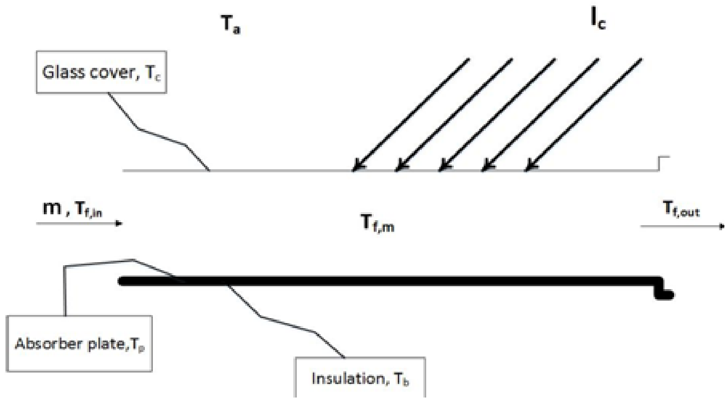

Fig. 1. Single pass solar air heater

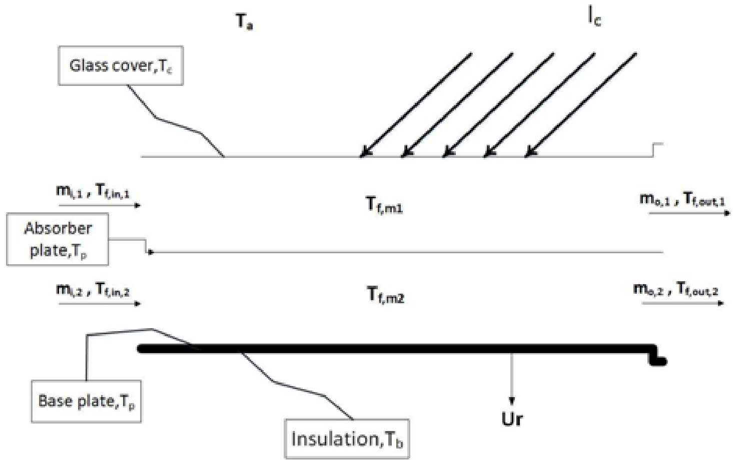

Fig. 2. Double pass solar air heater

5. The heat flow through the glazing and the base plate is one dimensional and in the y-direction.

To peruse the aim of energy modeling of single pass solar air heater, the extracted equations from resources were coded in EES software. Simultaneously, the energy modeling of double pass air heater is done in MATLAB software. Both of software are open source codes type. But double pass energy modeling has been concluded in MATLAB software because of limitations in EES software. Furthermore, the governing equations that used in energy modeling, for example, convection and radiation heat transfer coefficients (Equations 1~3), are presented in Table 1 [10-12].

Table 1.
Heat Transfer Coefficient Equations

$h_w = k(75 + 0.42\,\mathrm{Re}^{0.6}) / \mathrm{X}$	(1)
$h_{r,\mathrm{cs}} = \sigma\varepsilon_c(\mathrm{T}_c^{\,2} + \mathrm{T}_s^{\,2})(\mathrm{T}_c + \mathrm{T}_s)$	(2)
$h_{r,pc} = \sigma(\mathrm{T}_P^{\,2} + T_c^{\,2})(\mathrm{T}_P + \mathrm{T}_c) / \{1/\varepsilon_P + 1/\varepsilon_i - 1\}$	(3)

Heat loss coefficients (Equations 4 & 5) are used to calculate the waste heat from the air heater.

Table 2.
Heat Loss Coefficient Equations

$U_e = (\mathrm{k}/\,\mathrm{x}_1) \times \mathrm{s}/\,\mathrm{W}$	(4)
$U_b = \dfrac{1}{(\mathrm{x}_1/\,\mathrm{k}) + (1/h_b)}$	(5)

Energy and heat balances in different parts of solar air heaters are applied to execute Equations 6~10 in Table 3[10-12].

Energy efficiency in the solar air heater is obtained from the Equation 12. Furthermore, Equation 11 is applied to calculate mass flow inlet of each channel in double pass solar air heater [10-12].

Regarding the assumptions, simplified equations are solved in the mentioned program, based on an algorithm that is shown in Fig. 3.

Table 3.
Heat and Energy balances

$\overline{S}_c + h_{r,pc}\left(T_p - T_c\right) - h_1\left(T_f - T_c\right) = h_w\left(T_c - T_a\right) + h_{r,cs}\left(T_c - T_s\right)$	(6)
$\overline{S}_p = h_3(\mathrm{T}_p - \mathrm{T}_{f,2}) + h_2\left(T_p - T_{f,1}\right) + h_{r,pc}\left(T_p - T_c\right) + h_{r,pb}\left(T_p - T_b\right)$	(7)
$h_2 \times A_c \times \left(T_p - T_f\right) = h_1 \times A_c \times \left(T_f - T_c\right) + \dot{m} \times C_{pa} \times \left(T_{f1,out} - T_{f1,in}\right) + U_e \times L \times s \times \left(T_f - T_a\right)$	(8)
$h_3\,\mathrm{A}_c(\mathrm{T}_P - T_{f,2}) = \mathrm{h}_4\mathrm{A}_c(\mathrm{T}_{f,2} - \mathrm{T}_b) + \dot{\mathrm{m}}_2\, C_{pa}(\mathrm{T}_{f2,out} - \mathrm{T}_{f2,in}) + U_{e,2}s_2\,\mathrm{L}(\mathrm{T}_{f,2} - \mathrm{T}_a)$	(9)
$h_4(\mathrm{T}_{f,2} - \mathrm{T}_b) + \mathrm{h}_{r,pb}(\mathrm{T}_p - \mathrm{T}_b) = \mathrm{U}_b(\mathrm{T}_b - \mathrm{T}_a)$	(10)

Table 4.
Energy efficiency and Mass flow rate

$\dot{m}_i = \rho_i W_{s_i} C_{V,i} F_{V,i} \sqrt{2\left\{233.9\rho_a h\left(\dfrac{T_{f,out} - T_a}{T_{f,out} + \dfrac{7}{13}T_a}\right)\right\}}$	(11)
$\eta_c = \dfrac{\dot{m}_1 C_{p,1}\left(T_{f,1out} - T_{f,1in}\right) + \dot{m}_2 C_{p,2}\left(T_{f,2out} - T_{f,2in}\right)}{I_c \times A_c}$	(12)

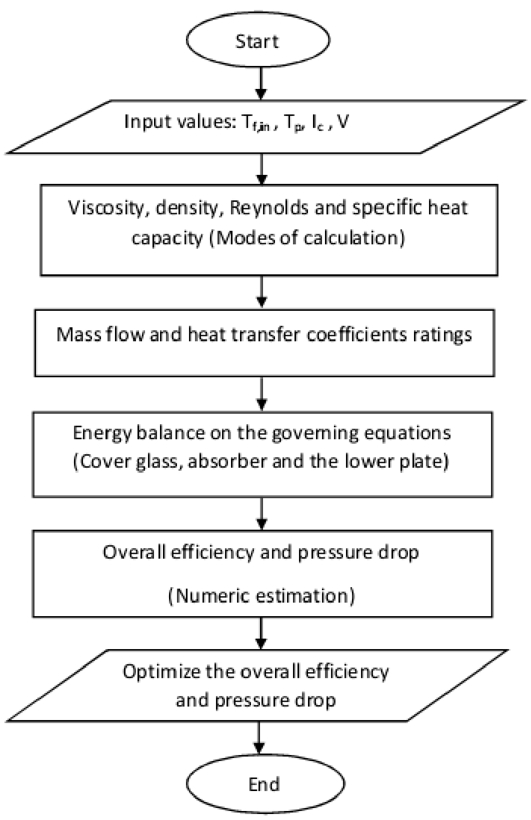

Fig. 3. The algorithm of simulation

3. Results and discussion

According to the algorithm in Fig. 3, coding procedure has been carried out in EES and MATLAB software, the obtained results are shown in Table 2. Regarding the studies, the parameters that have the most effect on final energy efficiency and outlet temperature are inlet air temperature (T_{in}) and inlet solar irradiation (I_c) to the solar air heater. Therefore, graphs are depicted based on these two parameters [13]. Fig. 4, 5 & 6 are demonstrating diagrams that concluded by numerical solution of single and double pass studied systems. Fig. 4 shows energy efficiency diagram according to inlet solar irradiation and air temperature to the single pass air heater. In Fig. 5, outlet air temperature versus inlet solar irradiation and air temperature in double pass air heater is depicted in EES software. In Fig. 6, the energy efficiency curve versus inlet irradiation and air temperature is shown for double pass air heater in MATLAB software.

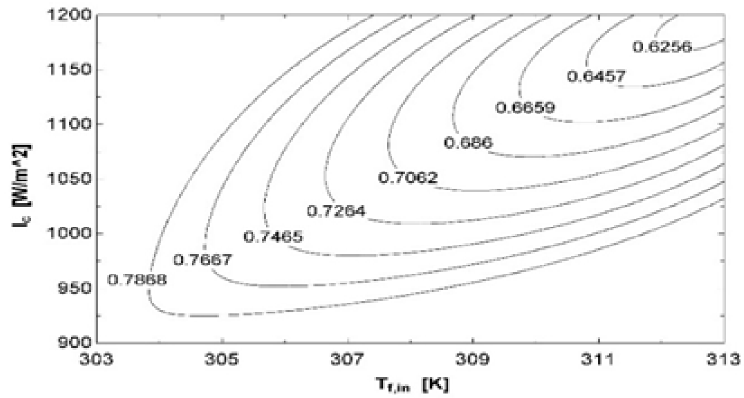

Fig. 4. Thermal efficiency diagram of one pass solar air heater

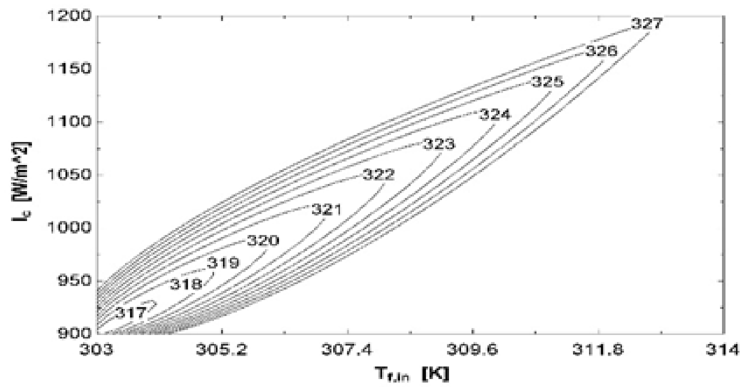

Fig. 5. Outlet air temperature diagram of one pass solar air heater

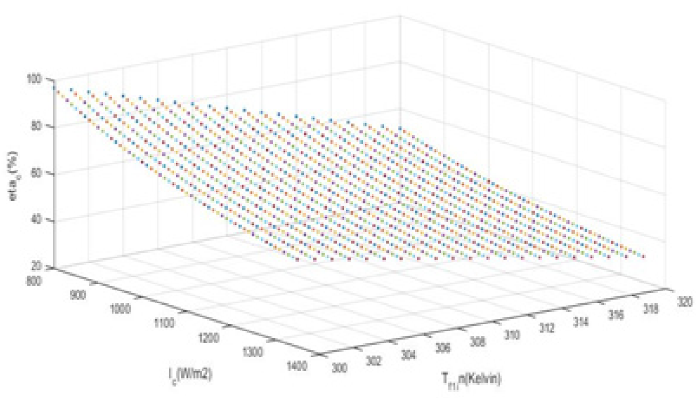

Fig. 6. Thermal efficiency diagram of double pass solar air heater

The results of calculations are given in the following Table 5.

Table 5.
Results of energy modeling

Inlet air temperature (K)	Inlet Irradiation (W/m^2)	Single pass air heater thermal efficiency	Double pass air heater thermal efficiency	Double pass packed bed (with particles) air heater overall efficiency [3]
300	888	0.8174	0.9106	0.48*1
302	916	0.7964	0.9083	N.A.*2
304	948	0.7752	0.8345	0.50*1
306	980	0.7539	0.7656	0.41*1
308	1012	0.7327	0.7011	N.A.*2
310	1042	0.7115	0.6417	0.44*1
312	1074	0.6903	0.5845	N.A.*2
314	1106	0.6691	0.5307	N.A.*2
316	1388	0.6478	0.4799	N.A.*2
318	1168	0.6266	0.4326	N.A.*2
320	1200	0.6054	0.3869	N.A.*2

*1: As a challenge, the generally overall efficiency of packed bed particles type, in comparison with none-packed is lower than in rate, that is because of more pressure drop taking place in bed type. As an issue, the bed type is always followed is thermal efficiency instead of overall efficiency, which assist them to ignore the important term of pressure drop, that affects the significant drop in overall efficiency. This research article considers all terms for purpose of comparison. [3]
*2: Not Available data based on previously referred studies. [3]

According to the Fig. 4, 5 & 6 in both single & double systems, rising in temperature and solar irradiation, negatively affects the efficiencies. It is observed that the effect of decreasing in energy efficiency, the solar irradiation is more than the inlet temperature value. According to the results of this research and the implemented model, generally double passed solar air heaters are better options, but as a challenge, it should be considered that this is valid only at low solar irradiation and higher temperature conditions. In this situation, the system shows a more rational energy efficiency; Such as the Iran northern regions and the tropics. While in the single pass air heater, any increase in solar irradiation as well as inlet air temperature results in lower inlet and outlet temperature difference. Also in low irradiation intensity and inlet air temperature, we observe an increase in energy efficiency. This suggests that outlet air temperature rising is not necessarily reflect the increasing energy efficiency of the single pass solar air heaters, But the appropriate range of both can increase energy efficiency.

Optimizing process for air heater contains two independent variables, temperature and solar radiation, besides, one dependent variable is outlet efficiency (outlet temperature). Efficiency functions for double and single pass systems are non-linear and those are strongly depended on endogenous variables contain and single pass systems are non-linear and those are strongly depended on endogenous variables contain geometry, an absorber plate and etc. The regression of the performance functions of one and double passes system, and finding their cross (optimum) point A, (I_c=965 W/m^2, T_{in}=306.5 K, η_c=0.75) is obtained and demonstrated in Fig. 7. The results of the study show that the efficiency of double pass system is higher in the range of T_{in}<306 and/or I_c <985, whereas for a range of T_{in} >306 and/or I_c >985, the efficiency of a single pass is higher. It is understood, by the functional range in Fig. 7, often, double passes systems is not effective in higher inlet solar irradiations and air temperatures ranges. This fact is because of absorber inherent opposite behavior. By these means, in this mentioned conditions, that works like thermal shield rather than absorber.

According to the results of Table 5, for the double pass air heater performance, appropriate temperature range and solar irradiation for optimum performance are under 306 K and 1000 W/m^2, respectively. As it shown in Fig. 7, The Best energy efficiency in double pass solar air heater is marked at point A (I_c=965 W/m^2, T_{in}=306.5 K, η_c=0.75). The quantitative results indicate that the double pass air heater has better energy efficiency in areas with higher air temperature and lower irradiation. While temperature and irradiation rising has less impact on single pass air heater.

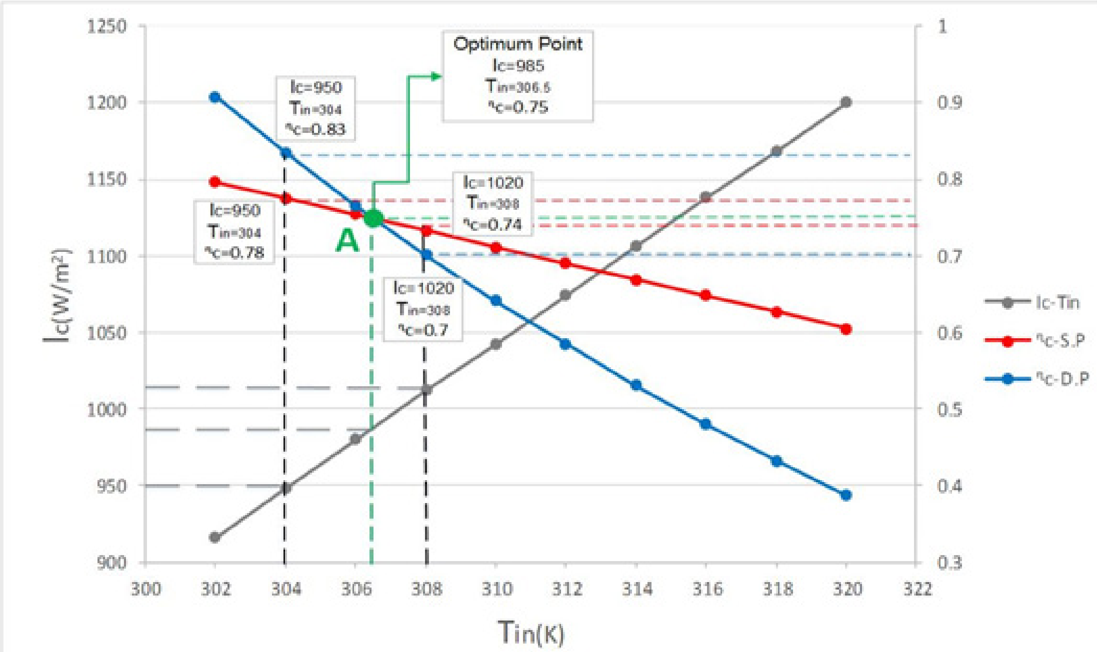

Fig. 7 .Single & double pass comparison in efficiency (Optimum point achievement)

heater. It should be noted that the energy efficiency does not fall extremely with sharp steep, such as double pass system.

4. Conclusions

The following conclusions are obtained that the foregoing theoretical studies and numerical calculations:

• Based on the above results, the double passed system does not necessarily increase the energy efficiency and it strongly depends on inlet situations.

• Double pass air heater in areas with higher inlet temperature and lower irradiations, shows better in performance.

• With the inlet air temperature of 302 K and inlet solar irradiation 916 W/m^2, the system energy efficiency of 90% is achieved in double pass systems as a considerable result.

• With lower solar irradiations & inlet air temperature values, the double pass packed bed type solar air heater shows lower overall efficiency compare with none packed bed types, based on critical obligatory pressure drop taking place inside the bed.

Nomenclature

A_c	(m^2)	absorber surface area
Δp	(pa)	pressure drop
Re		Reynolds number
V	(m/s)	air velocity
I_c	(W/m^2)	energy incident per unit area per unit time
T_a	(K)	ambient temperature
$T_{f,in}$	(K)	inlet air temperature
$T_{f,out}$	(K)	outlet air temperature
T_p	(K)	absorber plate temperature
T_b	(K)	base plate temperature
T_c	(K)	glass cover temperature
T_s	(K)	sky temperature
m_i	(kg/s)	mass flow rate inlet to each channel
h_w	(W/m^2.K)	Wind heat transfer coefficient
$h_{r,cs}$	(W/m^2.K)	Radiant heat transfer from solar air heater cover to sky
$h_{r,pc}$	(W/m^2.K)	Radiation heat transfer coefficient from air heater absorber plate to cover
$h_{r,pb}$	(W/m^2.K)	Radiation heat transfer coefficient from air heater absorber plate to base plate
U	(W/m^2.K)	heat lose coefficient
η_c		energy efficiency
σ	(kW/m^2.K^4)	Stefan-Boltzman constant
ε		emittance
k	(W/m K)	thermal conductivity
ρ	(kg/m^3)	density of air
s	(m)	the depth of air heater channel
W	(m)	the width of the air heater
$\overline{s}$	(W/m^2)	monthly average absorbed solar irradiation per unit area
C_p	(J/kg K)	specific heat capacity of air

Subscripts

1	top (upper) channel

2	bottom (lower) channel
a	ambient
b	base plate
c	glass cover
p	absorber plate
s	sky
in	inlet
out	outlet

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