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PERFORMANCE CHARACTERISTICS OF A TRANSPIRED SOLAR AIR HEATER

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ABSTRACT

A unique solar air heater with a transpired slatted glass sheet cover and transpired absorber was developed and tested. The idea was to suck the air through the air slots to recover part of the short wavelength radiation absorbed by the glass sheets. Furthermore, the long wavelength emission from the absorber could also be recovered thus minimizing the total heat losses. A mathematical model was developed to predict the effects of variations in the input parameters on the collector thermal efficiency. The theoretical results showed that the thermal performance of the collector was sensitive to air flow rate, ambient temperature, solar irradiance and absorber emissivity variations. The collector was tested under a solar simulator over a wide range of air flow rate. The experimental results were in good agreement with the theoretical ones. An absorbing efficiency as high as 86% could be obtained with a reasonably low air pressure drop across the slatted glass sheet cover. The sensitivity analysis of the collector to variations in input parameters was also investigated.

Key words: Solar air heater, Transpired absorber, Transpired cover.

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ویژگی های عملکرد یک گرم کن هوایی خورشیدی متخلخل

علی زمردیان، جی. ال. وودز و محمد حسین رئوفت

به ترتیب استادیار، استاد (دربخش مهندسی زراعی دانشگاه نیوکاسل، انگلستان) و استادیار بخش ماشین های کشاورزی دانشگاه شیراز، شیراز، جمهوری اسلامی ایران.

چکیده

در پژوهش حاضر یک گرم کن هوایی خورشیدی طراحی و مورد ارزیابی قرار گرفت که مجهز به پوشش شیشه ای و صفحه جاذب متخلخل است. اصول کاری این گرم کن مبتنی بر عبور اجباری هوا از لابلای شکاف های پوشش شیشه ای به داخل گرم کن بود که بدین ترتیب قسمتی از انرژی گرمایی (در دامنه طول موج کوتاه) جذب شده توسط پوشش بازیافت می شد. علاوه بر این بخشی از انرژی گرمایی (در دامنه طول موج بلند) ساطع شده توسط صفحه جاذب نیز توسط هوای ورودی جذب می گردید که در نتیجه تلفات گرمایی به حداقل کاهش می یافت. یک مدل ریاضی جهت پیش بینی اثرات تغییر در پارامترهای مختلف برکارآیی کالکتور تهیه گردید. نتایج به دست آمده از مدل مذکور بیانگر آن است که کالکتور نسبت به میزان عبور هوا، دمای محیط، میزان تشعشع انرژی خورشیدی و خاصیت پراکنش انرژی توسط صفحه جاذب حساس می باشد. سپس کالکتور ساخته شده تحت یک شبیه ساز انرژی خورشید در محدوده وسیعی ازمیزان عبور هوا مورد آزمایش قرارگرفت. تجزیه و تحلیل انجام شده حاکی از انطباق خوب نتایج استخراج شده از مدل ریاضی بود. سایر نتایج به دست آمده بیانگر امکان استحصال راندمان گرمایی تا حد ۸۶ درصد توسط صفحه جاذب بود. قابل توجه است که راندمان فوق با افت فشاربه نسبت کمی همراه است.

INTRODUCTION

Air cooled solar energy collectors' have been in use for a very long time for different purposes such as space heating (11). Once- through solar air collectors operating in an open-loop system have been employed for industrial drying applications (10). Solar air heaters are inherently low in thermal efficiency due to low heat capacity and specific heat of the air, (13). Many researchers have tried to improve the thermal performance of these solar collectors. Close (4) and Hollands and Shewen (7) introduced the V-type corrugated absorber and investigated the effect of shape and dimensions of air flow passages on collector performance. Wijeydundera *et al.* (12) and Korir and Some (9) worked on a double pass solar air heater and reported the effect of one and two-pass of air flow above, below and both sides of the absorber plate. These studies resulted in increasing the thermal efficiency of the collectors. Matrix absorber solar air heaters were introduced by Bliss (3), Chiou *et al.* (5), Beckman (2) and Khe and Henderson (8). In these absorbers solar radiation is absorbed deeply and when arranged in a parallel flow system, their upper surface area is subjected to cool air, therefore the upper heat losses are minimized and more useful energy could be collected. An overlapped glass plate absorber solar air heater was proposed by Lof *et al.* (11). The transpired absorbing system of this air heater contained a series of single glass plates arranged in a stair-step fashion separated by spacers.

In conventional flat-plate air heaters, part of the incident radiation (both short- and long-waves) in the back of the absorber is absorbed by the glass covers and results in rising the temperature of the cover glass. This heat is simply lost to the environment by convection. The energy loss could be minimized by sucking part of the lost convective heat through an overlapped arrangement of glass sheet covers. This would recover part of the shortwave radiation absorbed by the glass sheets as well as the absorbed longwave emission from the absorber to the glass covers (14).

The present research was devoted to designing and development of a new solar air heater having high thermal performance and low pressure drop. In the new collector the air is introduced through the slots made by slatted glass sheets and absorbs convective heat otherwise from the cover lost. The slots were arranged in such a way that sheet covers did not overlap. This arrangement is referred to as zero percent overlap glass sheet cover (Fig. 1). This phenomenon cools the cover and results in a further reduction in convective and radiative heat losses from the collector cover. Furthermore, the downward movement of entering air can also sweep the convective heat from the absorber surface area and keep the absorber surface cool. To compensate for the weak heat transfer between the incoming air and the absorber, a sheet of thick black cloth stretched over a supporting black wide wire mesh was provided to serve as transpired absorber. With these arrangements, it was expected that the incident radiation would be absorbed deeply and the air would have enough time to capture the absorbed heat while passing across the absorber.

MATHEMATICAL MODELLING

A mathematical model was developed for the negligible overlap glass sheet cover solar air heater in the present study. The following simplifying assumptions were made before formulating the governing heat balance equations:

1- The collector is considered as thermally steady state and heat flow through the cover, absorber and insulator are one -dimensional.

2- The exposed area of the collector is large compared with its wall thickness, therefore, the edge and end losses could be neglected.

3- The air flow direction through the absorber is normal and downward. Furthermore, air distribution through the slots and across the absorber is uniform. Hence the flow develops both thermally and hydrodynamically.

4- Covers are opaque to infrared radiation, covers and absorber are kept at a single mean temperature.

5- Radiative properties of materials and physical properties of air are constant.

Referring to Fig. 1, the following heat balance governing equations can be written:

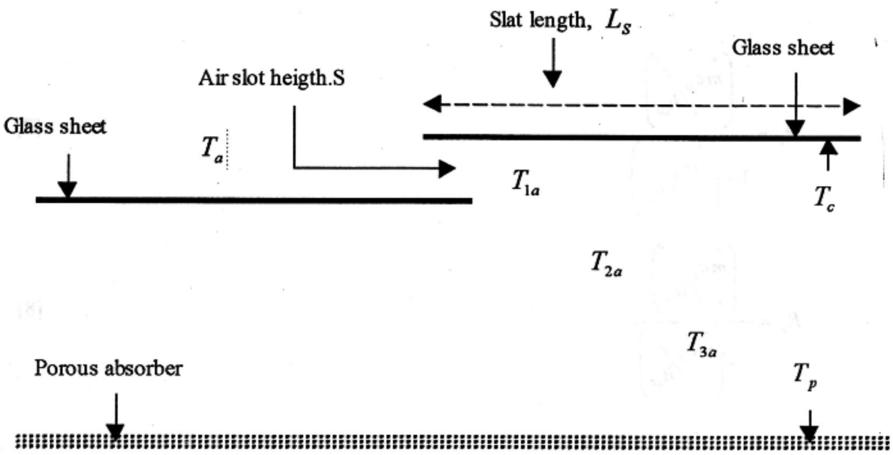

Fig.1: A schematic diagram of solar air heater.

(a) Heat balance equation on cover:

$$SWG + h_{rpc}(T_p - T_c) + (1 - R_p)h_{pc}(T_p - T_c) = h_{rca}(T_c - T_a) + h_{ca}(T_c - T_a) + h_{cl}(T_c - T1_a)$$

$$SWG = q_I \alpha_{cs}\left(1 + \frac{\tau_{cs}\rho_{ps}}{1 - \rho_{ps}\rho_{cs}}\right)$$ [1}

(b) Heat balance equation on absorber:

$$SWP = h_{rpc}(T_p - T_c) + \dot{m}c_p(T_p - T3_a) + h_{pc}(T_p - T_c)$$ [2]

$$SWP = \frac{q_I \tau_{cs}\alpha_{ps}}{1 - \rho_{ps}\rho_{cs}}$$

(c) Heat balance equations on air flow:

$$\dot{m}c_p(T1_a - T_a) = R_c h_{ca}(T_c - T_a)$$ [3]

$$\dot{m}c_p(T3_a - T2_a) = R_p h_{pc}(T_p - T_c)$$ [4]

$$\dot{m}c_p(T2_a - T1_a) = h_{cl}(T_c - T1_a)$$ [5]

and

$$q_u = \dot{m} c_p \left(T_p - T_a\right) \quad [6]$$

$$R_c = \frac{\left(\dot{m} c_p / h_{ca}\right)}{1 + \left(\dot{m} c_p / h_{ca}\right)} \quad [7]$$

$$R_p = \frac{\left(\dot{m} c_p / h_{pc}\right)}{1 + \left(\dot{m} c_p / h_{pc}\right)} \quad [8]$$

The above equations accompanied by properly selected correlation equations for convective and radiative heat transfer coefficients has to be solved iteratively to calculate the unknown values. The proper radiative properties of materials (absorber and glass) have to be chosen.

The proper correlation equations for convective heat transfer coefficients are (14):

(a) Above the slatted glass cover.

$$\overline{Nu}_L = \frac{h_{ca} L_m}{k_a} = C_1 \overline{Ra_L}^{C_2} \quad [9]$$

(b) Below the slatted glass cover (plane wall jet).

$$h_{cl} = \frac{-S A_c C_p m}{1.5 n_s L_s A_{slot} Pr^{0.666} Re_s} \left[\left(\frac{L_s}{S} + 0.0074 (Re_s - 99)^{1.3168} \right)^{-0.75} - \left(0.0074 (Re_s - 99)^{1.3168}\right)^{-0.75} \right] \times$$

$$\left[2.523 \times 10^{-4} (247.5 + Re_s)^{1.225} \times (28 + Re_s)^{1.236}\right] \quad [10]$$

(c) Between the absorber and cover.

$$\overline{Nu} = \frac{h_{pc} d}{k_a} = n_1 (Gr \times Pr)^{n_2} \times n_3 \quad [11]$$

The proper correlation equations for radiative heat transfer coefficients are:

(a) Between glass sheets and surroundings.

$$h_{rca} = \sigma \varepsilon_{cl} \left(T_c^2 + T_a^2\right)\left(T_c + T_a\right) \quad [12]$$

(b) Between absorber and glass sheets

$$h_{rpc} = \frac{\sigma\left(T_c^2 + T_p^2\right)\left(T_c + T_p\right)}{\left(1/\varepsilon_{cl}\right) + \left(1/\varepsilon_{pl}\right) - 1} \quad [13]$$

MATERIALS AND METHODS

A small solar air heater measuring 0.7 x 1.05 m was designed and fabricated. The cover of the collector consisted of several single glass sheets arranged in a slatted order (Fig. 1). The sheets were negligibly (zero) overlapped to make the slots (overlapping 5-8 mm). The heater was equipped with a removable cap. The cap was designed in such away that the slot height and slat length could be easily varied. A sheet of thick black cotton cloth stretched over a wide wire mesh was used as a transpired absorber. A solar simulator with a constant solar insulation of 886 Wm^{-2} was used to test the collector. Finally ASHREA Standards Method (1) for testing the solar collectors was adopted for evaluating the new solar air heater. To evaluate the performance of the collector several sets of experiments were conducted in UK (Agricultural Engineering Department, Newcastle upon Tyne University). The indoor experiments covering a full range of air mass flow rate (0.005-0.035 kg m^{-2} S^{-1}) with different operating conditions of S=0.003, S=0.005, or S=0.009 m and L_s= 0.1 or L_s= 0.2 m with a constant solar irradiance of 886 Wm^{2}(14) were performed. Finally, the following relation suggested by Duffie and Beckman (6) was used to calculate the thermal efficiency of the solar heater:

$$\eta = (q_u/q_i)100 \quad [14]$$

Several sets of conditions similar to those considered for testing the solar heater were selected and used as input to the mathematical model already developed. A computer simulation technique was also developed to be used as a tool to quantify the performance of the model. The computer program was run for different operating conditions. The program was able to investigate the effect of variations of air flow rate, the slot gap spacing, the slat length, the solar irradiance, the ambient temperature and the optical properties of material on the collector thermal performance. Similarly the theoretical (predicted) thermal efficiency was calculated for various conditions.

Pressure drop across the slatted glass cover sheet was measured using a capacitance miro-manometer (Farness PPFA-FC060).

RESULTS AND DISCUSSIONS

The experimental results were found to be in good agreement with the theoretical ones (Fig. 2). Both sets of results indicate that the collector

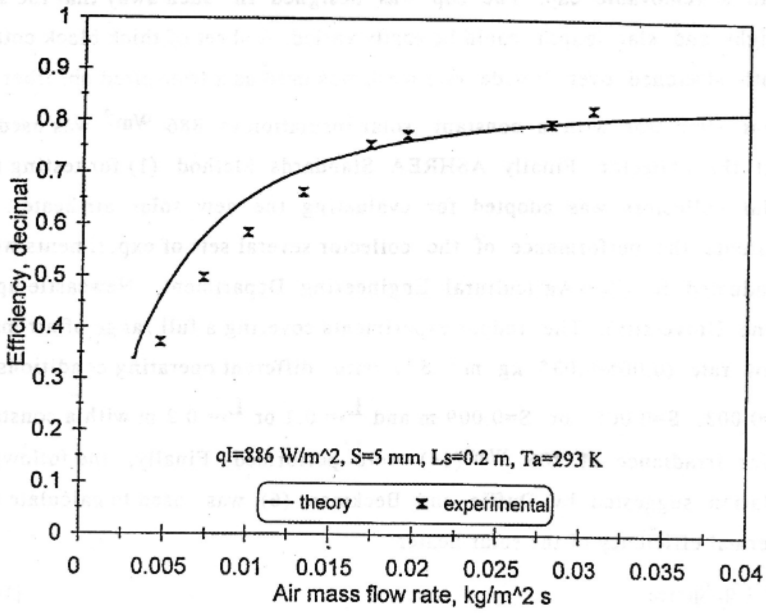

Fig. 2. The effect of air mass flow rate on absorber efficiency.

efficiency is highly sensitive to air flow rate variations but this dependency diminishes as the air flow rate increases. Both theoretical and experimental thermal performance results showed no sensitivity to slot height variations (Figs. 3 and 4), but the thermal performance of the collector was

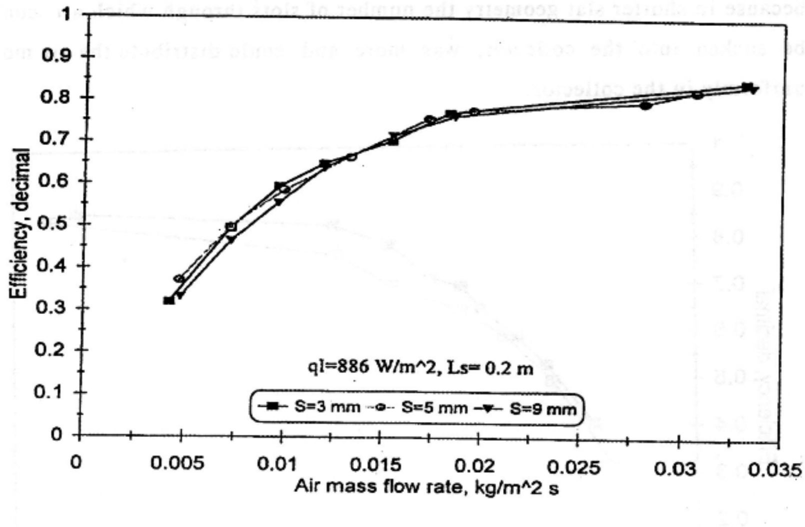

Fig. 3. The effect of air mass flow rate and slot height on absorber efficiency (measured values).

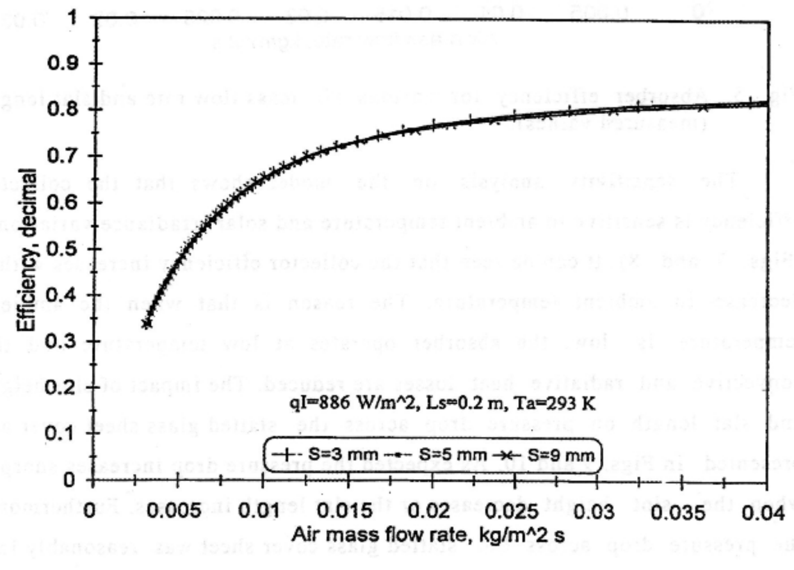

Fig. 4. The effect of air mass flow rate and slot height on absorber efficiency (predicted values).

sensitive to changes in slat length (Figs 5 and 6). These figures show that the collector with shorter slat length has a higher efficiency (up to 86%) because in shorter slat geometry the number of slots through which air could be sucked into the collector, was more and could distribute the air more uniformly in the collector.

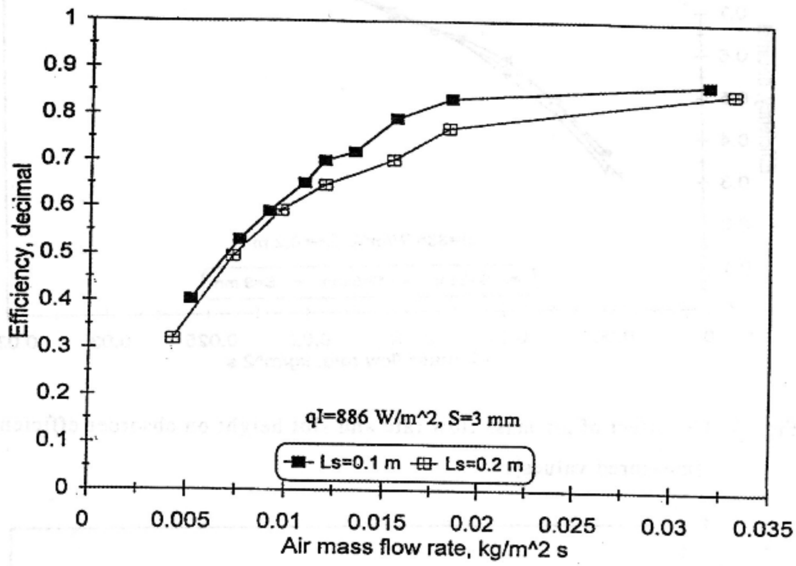

Fig. 5. Absorber efficiency for various air mass flow rate and slat length (measured values).

The sensitivity analysis on the model shows that the collector efficiency is sensitive to ambient temperature and solar irradiance variations, (Figs. 7 and 8). It can be seen that the collector efficiency increases with a decrease in ambient temperature. The reason is that when the ambient temperature is low, the absorber operates at low temperature and the convective and radiative heat losses are reduced. The impact of slot height and slat length on pressure drop across the slatted glass sheet cover are presented in Figs. 9 and 10. As expected the pressure drop increases sharply when the slot height decreases or the slat length increases. Furthermore, the pressure drop across the slatted glass cover sheet was reasonably low although a threshold pressure drop at the slot is required to guarantee the air flow inward.

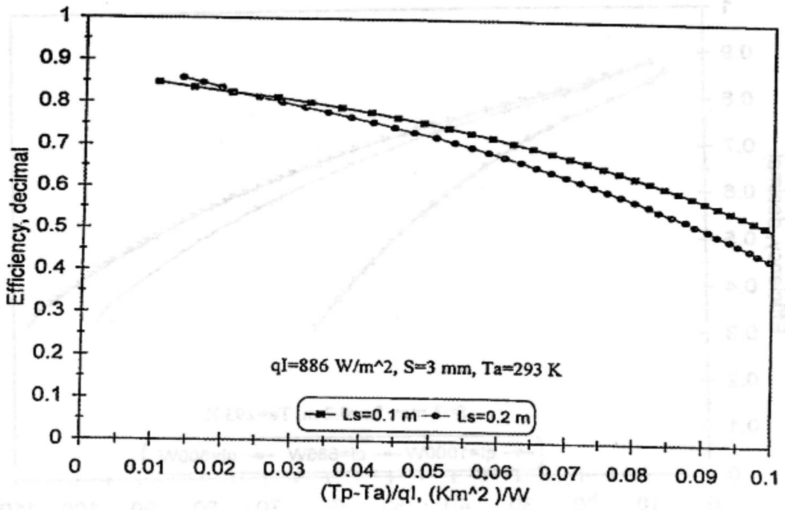

Fig. 6. Predicted absorber efficiency vs. normalized temperature difference for two slat lengths.

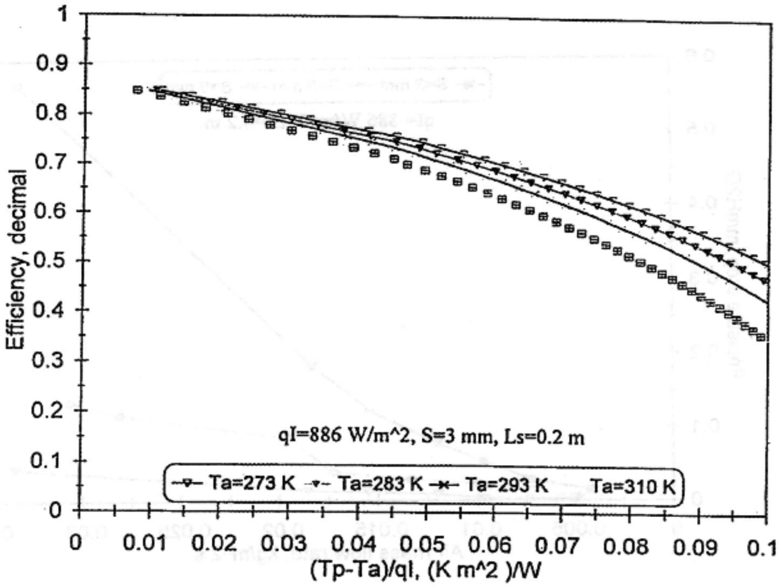

Fig. 7. The relationship between normalized temperature difference at different ambient temperatures (predicted values).

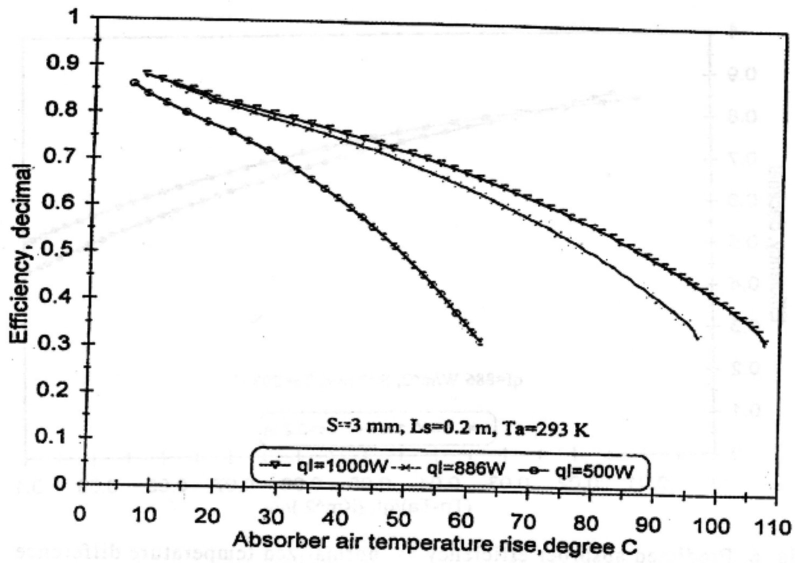

Fig. 8. Predicted thermal efficiency vs. absorber temperature rise for various solar intensities.

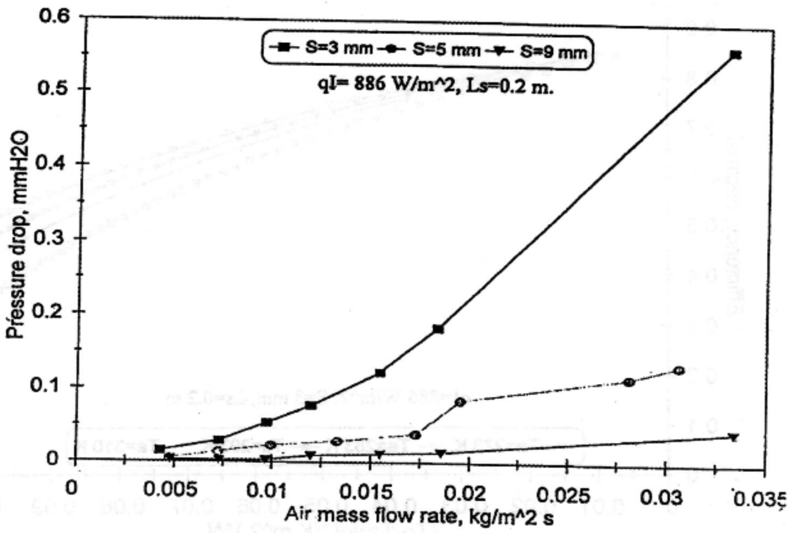

Fig. 9. Measured pressure drop across slatted glass cover for various air mass flow rates and slot heights.

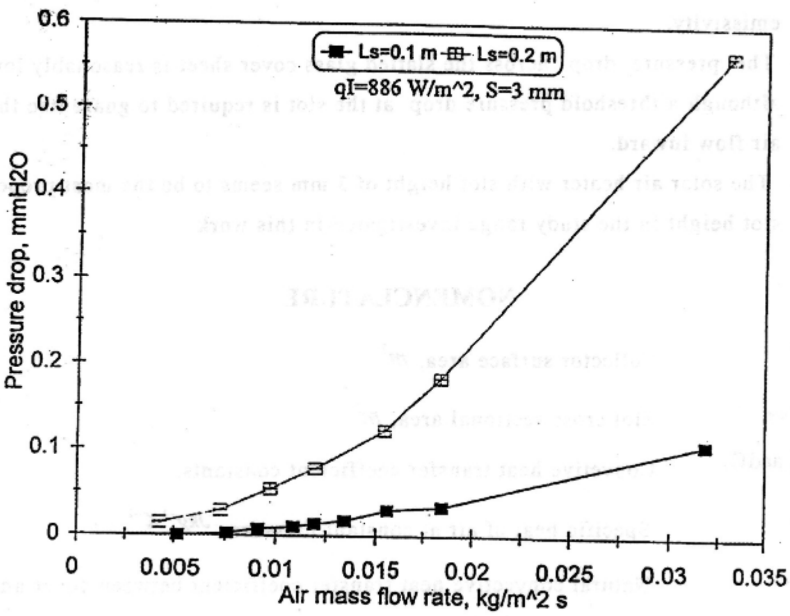

Fig. 10. Measured pressure drop across cover for various air mass flow rates and slat lengths.

CONCLUSIONS

1- The new collector showed a high performance not reported elsewhere. The keys for high performance are the transpired cover which keeps the total top heat losses down and the transpired absorber which yields a high convective heat transfer coefficient between entering air and absorber.

2- The mathematical model presented can predict the performance of the new solar air heater satisfactorily.

3- The collector thermal efficiency is an air flow rate dependent parameter. However, this dependency diminishes as the air flow rate rises.

4- The collector performance is not sensitive to slot height variation but is slightly sensitive to slat length specially at high air flow rates.

5- The collector performance is sensitive to ambient temperature and solar irradiance changes but not to the distance between absorber surface and slatted glass sheet cover.

6- The collector thermal efficiency is sensitive to absorber surface emissivity.

7- The pressure drop across the slatted glass cover sheet is reasonably low although a threshold pressure drop at the slot is required to guarantee the air flow inward.

8- The solar air heater with slot height of 3 mm seems to be the most proper slot height in the study range investigated in this work.

NOMENCLATURE

A_c	Collector surface area, m^2
A_{slot}	Slot cross sectional area, m^2
C_1 and C_2	Convetive heat transfer coefficient constants.
c_p	Specific heat of air at constant pressure, $Jkg^{-1}K^{-1}$
h_{pc}	Natural convective heat transfer coefficient between cover and absorber. $Wm^{-2}K^{-1}$
h_{cl}	Lower convective heat transfer coefficient(plane wall jet), W_m^{-2} K^{-1}
h_{ca}	Upper natural convective heat transfer coefficient, $Wm^{-2}K^{-1}$
h_{rpc}	Radiative heat transfer coefficient between cover and absorber. $Wm^{-2}K^{-1}$
h_{rca}	Radiative heat transfer coefficient between cover and surrounding, $Wm^{-2}K^{-1}$
L_s	Slat length, m or mm
$\dot{m}$	Air mass flow rate, $kgm-^{2}$ s^{-1}
n_1, n_2 and n_3	Convetive heat transfer coefficient constants.
n_s	Number of slot per module.
q_I	Incident solar radiation, Wm^{-2}
q_u	Useful (extracted) thermal energy, Wm^{-2}
R_c	Cover heat recovery factor

R_p	Absorber heat recovery factor
S	Slot height, m or mm
SWG	Short wave heat gain by glass sheet, Wm^{-2}
SWP	Short wave heat gain by absorber, Wm^{-2}
T_a	Ambient air temperature, K
$T1_a$, $T2_a$, $T3_a$	Inside collector intermediate air temperature, K
T_c	Cover temperature, K
T_p	Absorber temperature, K
U_L	Overall heat loss coefficient, $Wm^{-2}K^{-1}$
α_{cs}	Absorptivity of cover,
ρ_{cs}	Reflectivity of cover,
τ_{cs}	Transmissivity of cover,
ρ_{ps}	Reflectivity of absorber,
α_{ps}	Absorptivity of absorber,
ε_{cl}	Emissivity of cover
ε_{pl}	Emissivity of absorber
σ	Stephan-Boltzmann constant.

Gr= Grashof number, Nu= Nusselt number

Pr= Prantdl number, Re= Reynolds number,

$\overline{Ra}$ = average Rayleigh number = Gr.Pr

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