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Analytical and experimental studies of wire mesh packed double-pass solar air heaters under recycling operation

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Abstract

The device performance of a solar air heater featured with recycling as well as wire mesh packed was investigated experimentally and theoretically. The deviations between the theoretical predictions and experimental measurements were calculated within 1.07-9.32%. Comparisons were made among different designs including the single-pass, flat-plate double-pass, and recycling wire mesh packed double-pass operations. The applications of wire mesh and recycle-effect concept to the present study were proposed in aiming to strengthen the convective heat transfer coefficient due to the turbulence enlargement. The collector efficiency of the recycling wire mesh packed double-pass operation is much higher than the other configurations under various recycle ratios and mass flow rates.

Keywords: Wire mesh packed; Heat-transfer efficiency; Recycling double-pass; Solar air heater.

1. Introduction

Various configurations of solar air heaters have been implemented to enhance the collector efficiency as compared to a simple flat-plate device consisting of glass covers, an absorber plate and air flowing channels [1]. The improved devices were accomplished taking into account the design parameters of strengthening the convective heat-transfer coefficient, enlarging heat-transfer area, and increasing flow turbulence. The technical feasibility of the recycle-effect application to heat transfer devices and reactors has been confirmed by several investigators [2,3]. The recycling double-pass design has been proposed in the present study to increase the turbulent flow, and thus, the convective heat-transfer coefficient [4,5]. A new design of solar air heater adopting the wire mesh packed double-pass design under recycling operation is proposed and studied, as shown in Fig. 1.

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The purposes of the present study are: (a) to obtain theoretical predictions and carry out the experimental results for the recycling wire mesh packed solar air heater; (b) to study the effects of the recycle ratio and air mass flow rate on the heat transfer behavior, heat-transfer efficiency improvement and the power consumption increment.

Nomenclature

A_c	surface area of the collector = LW (m^2)
C_p	specific heat of air at constant pressure (J/(kg K))
D_e	equivalent diameter (m)
d_w	wire diameter of screen(m)
E	deviation of the experimental measurements from theoretical predictions
f_F	Fanning friction factor
I_0	incident solar radiation (W/m^2)
I_P	power consumption increment, defined in Eq. (15)
I_W	collector efficiency improvement index, defined in Eq. (9)
L	channel length (m)
ℓ_{wf}	friction loss of double-pass device (J/kg)
$\dot{m}$	total air mass flow rate (kg/h)
P_S	power consumption of downward-type single-pass device (W)
P_W	power consumption of wire mesh double-pass device (W)
Q_u	useful energy gained by air (W)
R	recycle ratio
Re	Reynolds number
$T_{a,i}$	inlet air temperature (K)
$T_{a,0}$	the mixing temperature of the subchannel a at x=0 (K)
$T_{a,L}$	the temperature of the subchannel a at x=L (K)
$T_{b,0}$	the temperature of the subchannel b at x=0 (K)
$T_{b,L}$	the temperature of the subchannel b at x=L (K)
$T_a(z)$	axial fluid temperature distribution in the lower subchannel (K)
$T_b(z)$	axial fluid temperature distribution in the upper subchannel (K)
T_{c1}	temperature of glass cover 1 (K)
T_p	temperature of absorbing plate (K)
$T_{p,m}$	mean temperature of absorbing plate (K)
T_R	temperature of bottom plate (K)
T_s	ambient temperature (K)
U_L	overall loss coefficient (W/m^2 K)
$\bar{v}$	mean air velocity (m/s)
W	width of both upper and lower subchannels (m)
z	axial coordinate (m)

Greek Letters

α_p	absorptivity of the absorbing plate
η_D	collector efficiency of the flat-plate type double-pass device
η_S	collector efficiency of the downward type single-pass device
η_W	collector efficiency of wire mesh solar air heater, defined in Eq. (7)
τ_g	transmittance of glass cover
ξ	dimensionless channel length

2. Theoretical treatment

The new design of double-pass solar air heaters uses the absorbing plate to divide the air flowing conduit into two subchannels and inserting wire mesh into the lower subchannels. The method for the theoretical prediction of collector efficiencies and experimental studies in the present work are similar to those performed in our previous work [6], except instead of inserting wire mesh. Before entering the lower subchannel, the inlet air mass flow rate and inlet temperature of $\dot{m}$ and $T_{a,i}$ is premixed with the recycling air flow $R\dot{m}$ exiting from the lower subchannel with the outlet temperature is $T_{b,L}$.

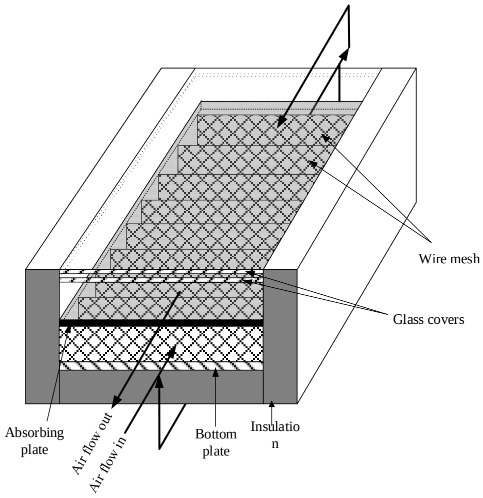

Fig. 1 Configuration of a double-pass solar air heater with recycle.

A schematic configuration is depicted in Fig. 1 while the air flow arrangement is shown in Fig. 2. After the following assumptions are made in the present analysis: (1) the temperatures of the absorbing plate, bottom plate and air streams are functions of the flow direction only, (2) the glass covers and fluid do not absorb radiant energy, and (3) all outside surfaces of the solar air collector, except the glass cover, are well insulated thermally, the steady-state one-dimensional mathematical formulation was obtained making the energy balance on a finite system element as follows:

$$\frac{-\dot{m}C_p}{W}\frac{dT_b(z)}{dz} = h_b(T_p - T_b(z)) - h_b(T_b(z) - T_{c_1}) \text{, the upper subchannel} \tag{1}$$

$$\left[\frac{(R+1)\dot{m}C_p}{W}\right]\frac{dT_a(z)}{dz} = h_a(T_p - T_a(z)) - h_a(T_a(z) - T_R) \text{, the lower subchannel} \tag{2}$$

The boundary conditions for solving Eqs. (1) and (2) are

$$z = 0,\ \ T_a(0) = T_{a,0} = \frac{T_{a,i} + RT_{a,L}}{1+R} \tag{3}$$

$$z = L,\ T_a(1) = T_{a,L} = T_b(1) = T_{b,L} \tag{4}$$

The useful energy gained by the flowing air was estimated from the energy balance on the lower subchannel, upper subchannel and whole solar air heater with the known inlet and outlet temperatures, respectively

$$Q_u = \dot{m}(1+R)C_p(T_{a,L} - T_{a,0}) + \dot{m}C_p(T_{b,0} - T_{b,L}) \tag{5}$$

or

$$Q_u = \dot{m}C_p(T_{a,L} - T_{a,i}) + \dot{m}C_p(T_{b,0} - T_{b,L}) = \dot{m}C_p(T_{b,0} - T_{a,i}) \tag{6}$$

The collector efficiency η_W of the wire mesh double-pass solar air heater with external recycle was obtained from the actual useful energy gained by the airflow and the incident solar radiation as

$$\eta_W = \frac{Q_u(\textit{Useful gain of energy carried away by air})}{I_0 A_c(\textit{Total solar radiation incident})}$$

$$= \frac{\dot{m}C_p(T_{b,0} - T_{a,i})}{I_0 A_c} = \frac{I_0 \tau_g^2 \alpha_p - U_L(T_{p,m} - T_s)}{I_0} \tag{7}$$

The average absorber temperature was readily obtained equating the terms of Eq. (7) as

$$T_{p,m} = T_s + (I_0 \tau_g^2 \alpha_p / U_L) - \frac{\dot{m}C_p(T_{b,0} - T_{a,i})}{A_c U_L} = T_s + (I_0 / U_L)(\tau_g^2 \alpha_p - \eta_W) \tag{8}$$

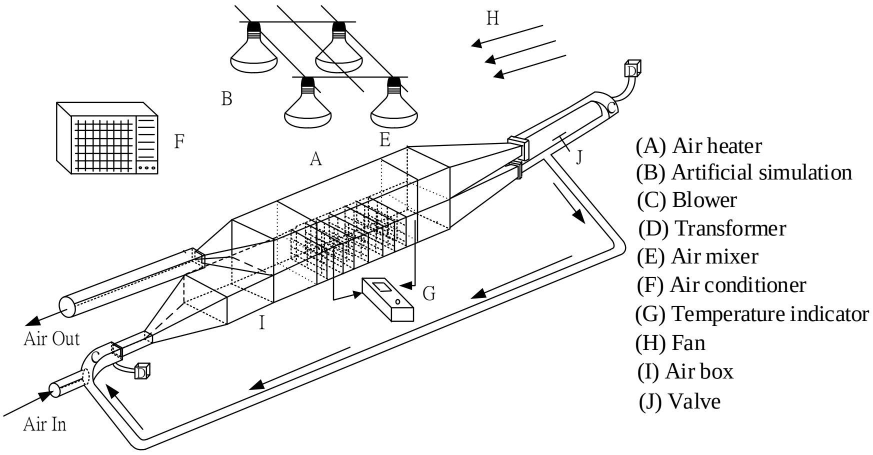

Fig. 2 Schematic diagram of a double-pass solar air heater with artificial simulation

3. Experimental setup

The experimental setup of the recycling double-pass wire mesh packed solar air heater was shown in Fig. 2. Before entering the lower subchannel, the airflow with mass flow rate $\dot{m}$ and temperature $T_{a,i}$ will premix the air flow exiting from the lower subchannel with $R\dot{m}$ and $T_{a,L}$ which is regulated by means of a valve situated at the end of the lower subchannel. Twenty pieces of the wire mesh were welded into the lower subchannel using the mesh interval of 0.015 m and mesh pitch of 0.003 m. The experimental runs were carried out supplying the ambient air by a blower (Teco 3 Phase Induction Motor) which was measured by an anemometer (Kanmax Japan Inc., Osaka, Japan). By substituting the specified values into the appropriate equations, the theoretical predictions were obtained and are also represented in Figs. 3 and 4 for comparisons.

4. Results and Discussion

The comparisons of the theoretical predications and experimental results of the device of flat-plate type and wire mesh packed for incident solar radiation variations and mass flow rates of air were presented in good agreement, as observed from Figs. 3 and 4. The deviation analysis results are calculated within $1.33\times10^{-2} \leqq E \leqq 9.32\times10^{-2}$. The collector efficiencies η_W increase with increasing recycle ratio and mass flow rate due to the fluid velocity enlargement and resulting in convective heat transfer coefficient enhancement. The theoretical predictions of I_W for the wire mesh packed double-pass devices are best illustrated by calculating the percentage increase in collector efficiency based on that of the downward single-pass device under the same operating conditions with various incident solar radiation, airflow mass flow rate and recycle ratio as parameters as follows:

$$I_W = \frac{\eta_W - \eta_S}{\eta_S} \times 100\% \tag{9}$$

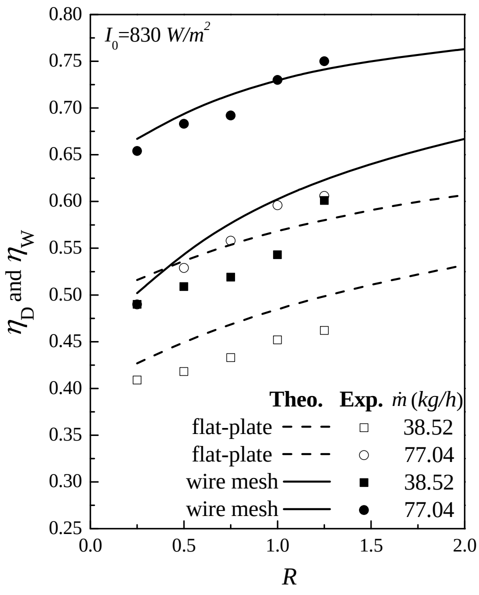

Fig. 3 Effect of recycle ratio on collector efficiency (I_0=830 W/m^2)

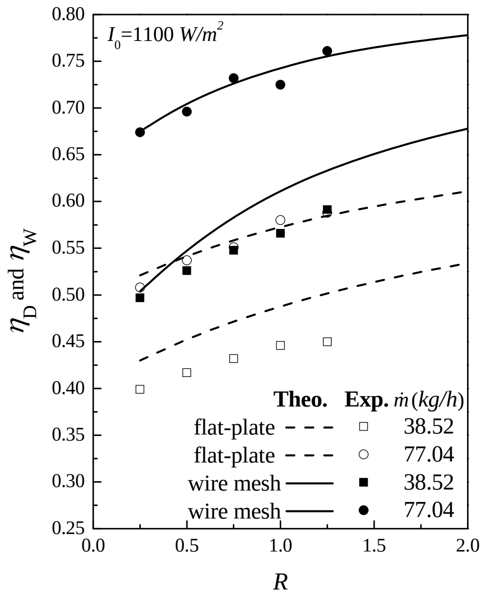

Fig. 4 Effect of recycle ratio on collector efficiency (I_0=1100 W/m^2)

Moreover, the power consumption increment was

$$P_S = \dot{m}\ell w_{f,s} = \frac{2 f_{F,S}\bar{v}^2 L}{D_{e,S}} \text{, single pass} \tag{10}$$

$$P_W = \dot{m}(1+R)\ell w_{f,a} + \dot{m}\ell w_{f,b} = \dot{m}(1+R)\frac{2 f_{F,a}\bar{v}^2 L}{D_{e,a}} + \dot{m}\frac{2 f_{F,b}\bar{v}^2 L}{D_{e,b}} \text{, double pass} \tag{11}$$

in which

$$f_{F,a} = 3.5722\times(1/nP)^{1.0431}(P_t/d_w)^{1.1507}\mathrm{Re}_a^{-0.43} \text{, for wire mesh device} \tag{12}$$

$$f_{F,i} = \frac{24}{Re}\text{, laminar flow, for flat-plate device} \tag{13}$$

$$f_F = 0.0790\,Re^{-0.25}\text{, turbulent flow for flat-plate device} \tag{14}$$

The power consumption increment for the wire mesh packed devices I_P is defined as compared to that in the downward single-pass operation

$$I_P = \frac{P_W - P_S}{P_S} \text{ for solar air heaters with wire mesh packed} \tag{15}$$

Considering both the efficiency improvement I_W and the power consumption increment I_P in the economic sense to obtain the suitable selections of the operating parameters, the ratio of I_W / I_P was calculated and presented with the recycle ratio and air mass flow rate as parameter. The results indicate the optimal ratio of I_W / I_P occurs at R=0.5~1.0 for various mass flow rates, as indicated in Fig. 5. The present work is actually the extension previous work [6] except the recycle configuration. The graphical representation for comparisons with some experimental results and theoretical predictions obtained in Ref. [6] under the same design and operating parameters to illustrate explain how the present device improvement was achieved, as referred to the previous work. The advantage of the present results is evident for all mass flow rates and recycle ratio, as confirmed by Fig. 6.

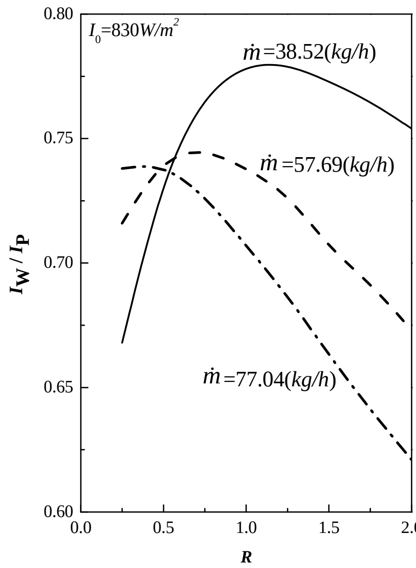

Fig. 5 The ratio of I_W / I_P vs. recycle ratio R

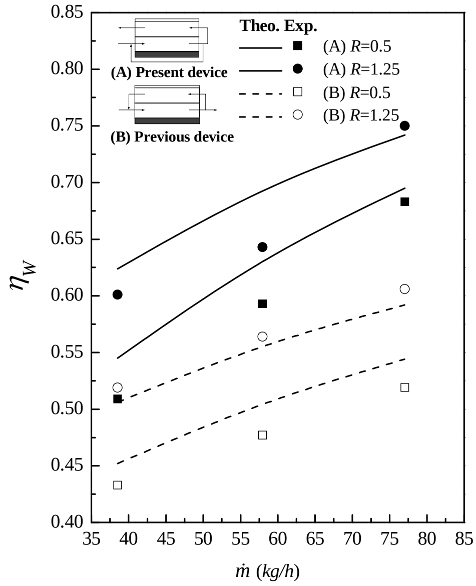

Fig. 6 Comparisons of collector efficiency between the present and previous work (I_0=830 W/m^2)

5. Conclusions

The collector efficiency improvement in recycling double-pass solar air heaters with wire mesh packed have been developed analytically and experimentally. The comparisons of double-pass configurations with and without attaching wire mesh were made to investigate the device performance improvement. Consequently, applications of the recycle effect with wire mesh attachment for operating double-pass device are technically and economically feasible.

Acknowledgement

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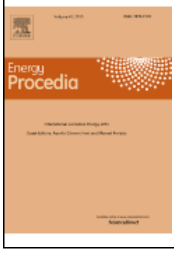

Chii-Dong Ho received his B.Sc. from National Taiwan University in 1981, and his M.Sc. and Ph.D. in Chemical Engineering from New Mexico State University in 1984 and 1986, respectively. He then became a faculty member at Tamkang University in New Taipei, Taiwan. He has served as the Dean of the College of Engineering since 2010. He has published many papers in various journals and conferences. Currently, his interests are solar energy engineering, membrane separation processes and heat and mass exchanger designs.

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