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Downward-type solar air heaters with internal recycle

Ho-Ming Yeh, Chii-Dong Ho *

Energy and Opto-Electronic Materials Research Center, Department of Chemical and Materials Engineering, Tamkang University, Tamsui, Taipei 251, Taiwan

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ABSTRACT

The effect of internal-recycle operation on the collector efficiency in flat-plate solar air heaters has been investigated theoretically. It is found that considerable improvement in collector efficiency is obtainable if the operation is carried out with an internal recycle, where the desirable effect of increasing fluid velocity to decrease the heat transfer resistance compensates for the undesirable effect of decreasing the driving force (temperature difference) of heat transfer, due to the remixing effect at the inlet by recycle operation. The enhancement increases with increasing reflux ratio, especially for operating at lower air flow rate, as well as with higher solar radiation incident and inlet air temperature. Further, the performance in a solar air heater operated with internal recycle overcomes that in the same-size device operated with external recycle.

1. Introduction

In solar air heaters, energy is transferred from a distant source of radiant energy directly into air (Belusko *et al.*, 2008; Gary and Adhikari, 1999). The flat-plate solar air heater is a simple device consisting of one or more glasses or transparent material covers situated above an absorbing plate with the air flowing either over or under the absorbing plates (Close and Dunkle, 1976; Seluck, 1977; Tan and Charter, 1970; Whillier, 1963). The heated air is subsequently used for space heating and drying (Duffie and Backman, 1980).

Considerable improvement in collector efficiency is obtainable to enhance the effects of free and forced convections (Tonui and Tripanagnostopoulos, 2007), to increase the transfer area (Mohamad, 1997) and to create the turbulence inside the flow channel using fins (Yeh and Ting, 1986), baffles (Yeh, 1992), multi-pass operation (Ho *et al.*, 2005) or corrugated surfaces (Gao *et al.*, 2000). It was pointed out that recycle-effect applications in the design and operation of equipment with external or internal reflux can effectively enhance the heat and mass transfer rate, leading to improved performance such as air lift reactors (Atenas *et al.*, 1999), loop reactors (Santacesaria *et al.*, 1999), draft-tube bubble columns (Kikuchi *et al.*, 1999) and heat and mass exchangers (Ho *et al.*, 1998, 1999; Yeh *et al.*, 1986, 1987; Yeh and Ho, 2009) which are widely applied to absorption, fermentation, polymerization, and heat and mass transfer operations. The purpose of present work is to investigate the influence of the internal recycle effect on the performance in a flat-plate solar air heater.

2. Theoretical analysis

Consider an internal-recycle solar air heater with flow channel of width B, length L, and height H, as shown in Fig. 1. An insulated plate with negligible thickness is placed in vertical to the absorbing plate and bottom plate, at the centerline to divide the flow channel into subchannel 1 and subchannel 2 of equal width $B/2$, and that a pump is installed for recycling part of the exiting fluid with reflux ratio R from the end of subchannel 1 into subchannel 2. The designed solar air heater consists of one glass cover, an absorbing plate, a recycling channel with well insulation, and a recycle device was situated at the end of subchannel 1. Before entering subchannel 1, the fluid of the mass flow rate $\dot{m}$ and inlet temperature T_{fi} mix with the fluid exiting from subchannel 2 of the mass flow rate Rm regulated by a blower situated at the end of subchannel 1. The radiant energy on the absorbing plate was removed when the flowing air passed under the absorbing plate. The overall heat loss coefficient, in which the edge and bottom heat losses were neglected, was estimated by an empirical correlation from an absorbing plate across the glass cover to ambient surrounding. The following assumptions are made in this analysis: (1) the absorbing-plate, bottom-plate and bulk-fluid temperatures are functions of the flow direction (z) only; (2) both glass cover, all parts of the outside surface of the solar air collector, as well as the thin plate for separating both subchannels, are well thermally insulated; and (4) the physical properties of the fluid and materials are constant.

* Corresponding author. Tel.: +886 2 26215656x2601; fax: +886 2 26209887.
E-mail address: cdho@mail.tku.edu.tw (C.-D. Ho).

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Nomenclature

A_c	surface area of the absorbing plate (m^2)
B	the width of absorber surface area (m)
C_p	specific heat of air at constant pressure (J/kg K)
D_{eq}	equivalent diameter of the channel (m)
E	improvement in collector efficiency
F	efficiency factor of the solar air heater
H	height of the tunnel in the solar collector (m)
h	convective heat-transfer coefficient for fluid flowing over the flat plate (W/m^2 K)
$h_{r,P-R}$	radiant heat-transfer coefficient between two parallel plates (W/m^2 K)
h_w	convective heat-transfer coefficient between glass cover and the ambient (W/m^2 K)
I_0	incident solar radiation (W/m^2)
k	thermal conductivity of air (W/m K)
L	collector length (m)
$\dot{m}$	mass-flow rate of air (kg/s)
Nu	Nusselt number
Q_u	useful gain of energy carried away by air per unit time (W)
R	recycle ratio
Re	Reynolds number of flow channel
T	temperature (K)
U_t	loss coefficient from the top of the solar collector to ambient (W/m^2 K)
$\bar{v}$	average air velocity in the flow channel (m/s)
V	wind velocity (m/s)
z	axis along the flow direction (m)

Greek Symbols

η	collector efficiency
σ	Stefan–Boltzmann constant ($W/m^2 K^4$)
ε_g	emissivity of glass cover
ε_p	emissivity of absorbing plate
ε_R	emissivity of bottom plate
τ_g	transmittance of glass cover
α_p	absorptivity of the absorbing plate

Subscripts

a	ambient
c	glass cover
f	fluid
i	inlet
m	mean value
o	outlet at subchannel 2 ($z = 0$), or single-pass operation without recycle
p	absorbing plate
R	bottom plate
1, 2	flow subchannel 1, subchannel 2

Superscripts

0	mixed
$'$	outlet at subchannel 2 ($z = 0$)

2.1. Temperature distribution for the fluid in both subchannels

The temperature distribution of subchannel 1 was derived using the energy balance in a finite fluid element, as shown in Fig. 2. The steady-state energy balance for differential sections of the absorbing plate, bottom plate and flowing fluid are, respectively.

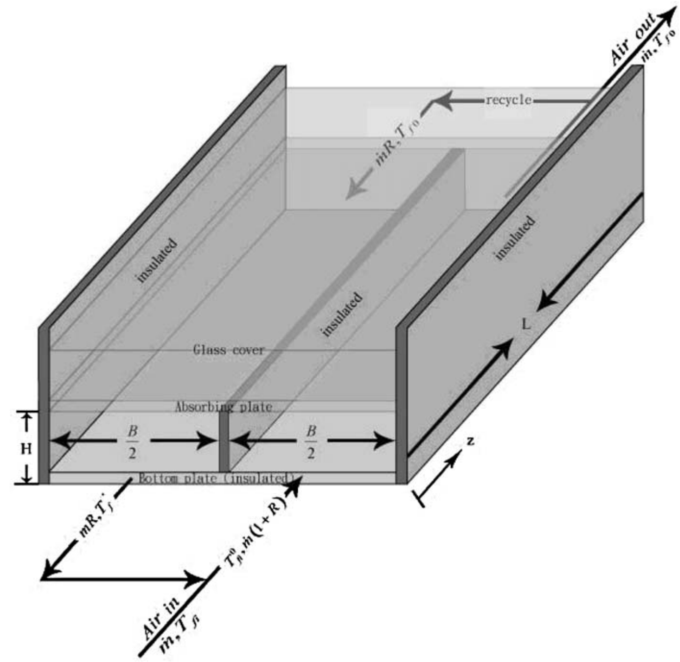

Fig. 1. Solar air collector with internal recycle.

$$I_0 \tau_g \alpha_p dz\left(\frac{B}{2}\right) - h_1\left(\frac{B}{2}\right)dz(T_P - T_{f1}) - h_{r,P-R}\left(\frac{B}{2}\right)dz(T_P - T_R) - U_t\left(\frac{B}{2}\right)dz(T_P - T_a) = 0 \quad (1)$$

$$h_{r,P-R}\left(\frac{B}{2}\right)dz(T_P - T_R) - h_1\left(\frac{B}{2}\right)dz(T_R - T_{f1}) = 0 \quad (2)$$

$$\dot{m}(1+R)C_P\left(\frac{dT_{f1}}{dz}\right)dz = h_1\left(\frac{B}{2}\right)dz(T_P - T_{f1}) + h_1\left(\frac{B}{2}\right)dz(T_R - T_{f1}) \quad (3)$$

Solving Eqs. (1) and (2) for $(T_p - T_{f1})$ and $(T_R - T_{f1})$ and substituting into Eq. (3), one has

$$[2\dot{m}(1+R)C_P]\frac{dT_{f1}}{dz} = BF_1[I_0 \tau_g \alpha_p - U_L(T_{f1} - T_a)] \quad (4)$$

where

$$F_1 = \frac{h_1(h_1 + 2h_{r,P-R})}{h_1(h_1 + 2h_{r,P-R} + U_t) + h_{r,P-R}U_t} \quad (5)$$

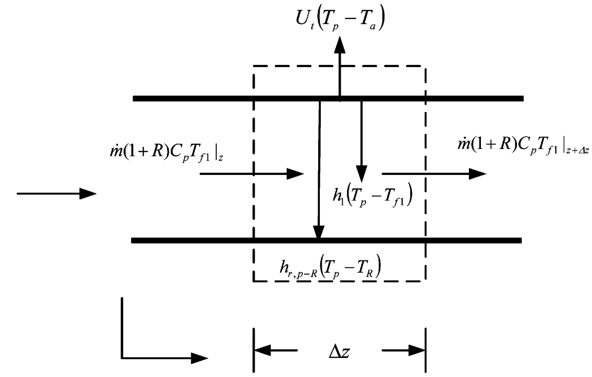

Fig. 2. The energy balance in a finite fluid element on the subchannel 1.