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Solar air heaters with external recycle

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ABSTRACT

The effect of external recycle on the collector efficiency in solar air heaters has been investigated theoretically. The application of external-recycle operation to solar air heaters actually has two conflict effects. One is the desirable effect of increasing fluid velocity to decrease the heat transfer resistance. The other is the undesirable effect of decreasing the driving force (temperature difference) of heat transfer, due to the remixing at the inlet. It is found that considerable improvement in collector efficiency is obtainable if the operation is carried out with an external recycle, where the desirable effect overcomes the undesirable effect. The enhancement increases with increasing reflux ratio, especially for operating at lower air flow rate with higher inlet air temperature.

1. Introduction

The solar air heaters, in which energy transfer is from a distant source of radiant energy to air, may be used for space heating, drying and paint spraying operations [1,2]. Without optical concentration, the flux of incident radiation is approximated up to 1100 W/m^2, and flat-plate solar collectors are designed for application requiring energy delivery at moderate temperature. The solar air heater occupies an important place among solar heating systems because of minimal use of materials, and the direct use of air as the working substance reduces the number of required system components. In many industrial applications where recirculation of air is not practical because of contaminate, outside air is heated and used directly, especially for supplying fresh air to hospitals. Further, heating of ambient air is an ideal operation for a collector, as it operates very close to ambient temperature.

In addition to the essential effects of free and forced convections [3–5], considerable improvement in collector efficiency is also obtainable to increase the transfer area by adding fins [3,6], and to create the turbulence inside the flow channel by using baffles [7], or corrugated surfaces [8–11].

It was pointed out that applications of the recycle-effect in the design and operation of the equipment with external or internal recycle can effectively enhance the effect on heat and mass transfer, leading to improved performance [12–18]. Actually, there are two conflict effects of recycle operation. One is the desirable effect of increasing fluid velocity, resulting in enhancement of convective heat or mass transfer, while the other is the undesirable effect of decreasing the driving force (temperature or concentration difference) due to remixing. It was found that the increase in convective heat or mass transfer by increasing the reflux ratio can generally compensate for the decrease of driving force, leading to improved performance. It is the purpose of this work to investigate the influence of the external-recycle effect on the performance in a flat-plate solar air heater.

2. Theoretical analysis

The structure of a flat-plate solar air heater with external recycle may be illustrated by the schematic diagram of Fig. 1. An actual panel of solar air heater is shown in Fig. 2. A black absorbing plate was welded at the center of the collector. The air was heated in a pre-heater for temperature control and supplied steadily at the inlet. Two blowers and two transformers were used to regulate the flow rates as well as the reflux ratio *R*, which were measured using anemometers. The ambient temperature was controlled using an air conditioner. The wind was provided by a fan. The solar radiation incident was simulated and controlled by the artificial simulation consisted with a set of bulbs, as shown in part B in Fig. 2. The temperatures of the absorbing surface and outside glass covers were measured with probes. Eight mercury thermometers were employed to measure the air temperature within the heater and at the inlet and outlet. The steady-state energy balance will be taken under the following assumptions: the temperature of the absorbing plate is uniform, bottom plate and bulk fluids are functions of the flow direction only, and both the glass cover and fluids do not absorb radiant energy. Furthermore, except the glass cover, all parts of the outside surface of the solar air collector, as well as the flow channel of recycle, are well thermally insulated.

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Nomenclature

A_c	surface area of the absorbing plate with fins (m^2)
B	the width of absorber surface area (m)
C_p	specific heat of air at constant pressure (J/kg K)
$D_{e,0}, D_{e,a}, D_{e,b}$	equivalent diameter of the single-pass operation, lower channel and upper channel for double-pass operation, respectively (m)
f_F	Fanning factor
F'	efficiency factor of the solar air heater
F_R	heat-removal factor for the solar air heater
H	height of the air tunnel in the solar collector (m)
h_1, h_2, h	convective heat-transfer coefficient for fluid flowing over a 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)
E_P	increment of power consumption
E_R	improvement in collector efficiency
I_0	solar radiation incident (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
P_R, P_S	hydraulic dissipated power in the double- and single-pass devices, respectively (hp)
Q_u	useful gain of energy carried away by air per unit time (W)
R	reflux ratio
Re_0, Re_a, Re_b	Reynolds number of the single-pass operation, lower channel and upper channel for double-pass operation, respectively
T	ambient temperature (K)
U_L	overall loss coefficient (W/m^2 K)
U_t	loss coefficient from the top of the solar collector to the ambient, $h_w + h_r$ (W/m^2K)
$\overline{v_0}, \overline{v_a}, \overline{v_b}$	average air velocity in the open single-pass operation, lower channel and upper channel for double-pass operation, respectively (m/s)
V	wind velocity (m/s)
z	axis along the flow direction (m)

Greeks

η	collector efficiency
σ	the 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	transmittance of glass cover
α	absorptivity of the absorbing plate

Subscript

a	ambient
c	glass cover
f	fluid
i	inlet
o	outlet
p	absorbing plate
R	bottom plate
0	the operation without recycle

Superscript

o	mixed

2.1. Temperature distribution for the fluid in the flow direction

The steady-state energy balance for differential sections of the absorbing plate, bottom plate and flowing fluid are, respectively.

$$I_0\tau\alpha - h_1(T_p - T_f) + h_{r,p-R}(T_p - T_R) + U_t(T_p - T_a) = 0, \tag{1}$$

$$h_{r,p-R}(T_p - T_R) = h_2(T_R - T_f), \tag{2}$$

$$[\dot{m}(1+R)C_p]\frac{dT_f}{dz} = h_1 B(T_p - T_f) + h_2 B(T_R - T_f). \tag{3}$$

Solving Eqs. (1) and (2) for $(T_p - T_f)$ and $(T_R - T_f)$, we obtain

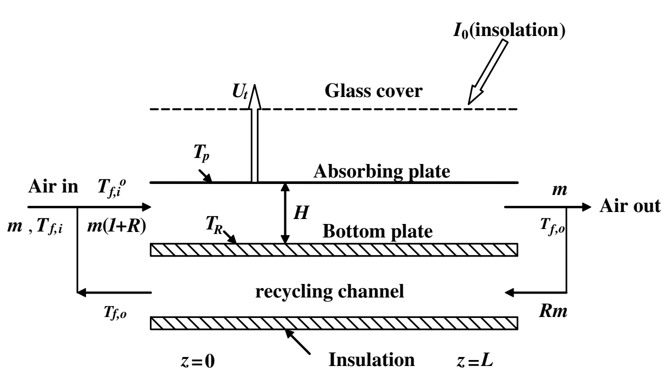

Fig. 1. Schematic diagram of a solar air heater.

$$T_p - T_f = \frac{[I_0\tau\alpha(h_2 + h_{r,p-R}) - (h_2U_t + h_{r,p-R}U_t)(T_f - T_a)]}{[h_1(h_2 + h_{r,p-R}) + h_2(h_{r,p-R} + U_t) + h_{r,p-R}U_t]} \tag{4}$$

$$T_R - T_f = \frac{[I_0\tau\alpha h_{r,p-R} - h_{r,p-R}U_t(T_f - T_a)]}{[h_1(h_2 + h_{r,p-R}) + h_2(h_{r,p-R} + U_t) + h_{r,p-R}U_t]} \tag{5}$$

Substituting Eqs. (4) and (5) into Eq. (3), one has

$$[\dot{m}(1+R)C_p]\frac{dT_f}{dz} = BF'[I_0\tau\alpha - U_L(T_f - T_a)], \tag{6}$$

where

$$F' = \frac{[h_1(h_2 + h_{r,p-R}) + h_2h_{r,p-R}]}{[h_1(h_2 + h_{r,p-R}) + h_2(h_{r,p-R} + U_t)]}, \tag{7}$$

$$U_L = \frac{[h_1(h_2U_t + h_{r,p-R}U_t) + h_2h_{r,p-R}U_t]}{[h_1(h_2 + h_{r,p-R}) + h_2h_{r,p-R}]}, \tag{8}$$

in which F' is called efficiency factor and U_L is the overall heat-loss coefficient. The collector efficiency factor is essentially constant for any design and fluid flow rate [1]. Furthermore, if U_L is assumed to be constant along the flow direction, Eq. (6) can be easily integrated for boundary condition

$$T_f = T_{f,i}^o \quad \text{at } z = 0. \tag{9}$$

The result is

$$\frac{T_f - T_a - I_0\tau\alpha/U_L}{T_{f,i}^o - T_a - I_0\tau\alpha/U_L} = \exp\left[-\frac{F'U_LBz}{\dot{m}(1+R)C_p}\right]. \tag{10}$$