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Thermal and thermohydraulic performance evaluation of a novel type double pass packed bed solar air heater under external recycle using an analytical and RSM (response surface methodology) combined approach

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ABSTRACT

In the present study, an analytical and RSM (response surface methodology) combined approach has been applied to investigate the thermal and thermohydraulic performances of a novel type double pass packed bed solar air heater under external recycle with wire mesh screen as a packed bed material. An analytical model describing the various temperatures and heat transfer characteristics of such a double pass packed bed solar air heater under external recycle has been developed and employed to study the effects of mass flow rate, recycle ratio and varying channel depth between the top (upper and lower) glass covers for a fixed 95% porosity of the packed material on its thermal and thermohydraulic performances. The analytical model employs an iterative solution procedure to solve the governing energy balance equations describing the complex heat and mass transfer involved. Furthermore, RSM is then applied for developing mathematical models based on simulation results obtained from analytical study. The effect of parameters and their interactions on the responses are studied using RSM. The results obtained from RSM revealed that proposed mathematical model is significant and good agreement is achieved with reasonable accuracy.

1. Introduction

Heat-transfer characteristics and the thermal performance of double pass solar air collectors can be improved using porous material such as wire mesh as an absorbing media [1–3]. The addition of the porous media in the upper and lower channels increases the performance of the double pass collector [4–9]. An important parameter that has to be considered while employing the porous material for the purpose of heat transfer rate augmentation is the penalty arising from the increased pressure drop. The high heat transfer rate and low mechanical pumping power are the exigencies of good solar air collector designs [1,3]. Modeling of double-pass channel solar air heater through least-squares support vector machines and artificial neural network approach was proposed by Esen et al. [10,11]. Ozgen et al. [12] experimentally investigated the thermal performance of double flow solar air heater by inserting an absorber plate made of aluminum cans. Yeh et al. [13] proposed a device with recycle which improves the heat-transfer efficiency, significantly. Experimental and theoretical investigations into the device efficiency were presented. Results revealed a significant improvement in heat-transfer efficiency and power consumption. Ho et al. [14,15] presented a heat-transfer enhancement and performance improvement in the double-pass flat-plate and multi-pass solar air heaters with recycle, respectively. It was reported that the recycle of the outlet flowing air substantially improves the collector efficiency by increasing fluid velocity. The desirable effect of increasing convective heat transfer rate and the undesirable effect of reducing heat transfer driving force are the two conflict effects produced by recycle operation. Increasing recycle ratio could generally compensate for the decrement of the temperature difference, leading to improved performance, especially for low flow rate.

Considerable enhancement in the collector efficiency can be achieved by attaching fins [16–18] and fins with baffles [19–21] to the different types of the flat-plate solar air heater. Different designs of single and double-pass solar air heaters have been proposed under recycle operation, which plays an important role in influencing the fluid velocity, and thus, the forced convection

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Nomenclature

A	area (m^2)
A_c	collector surface area (m^2)
C_p	specific heat (kJ/kg K)
d	depth of the channel (m)
D_h	hydraulic diameter (m)
d_w	wire diameter of screen (m)
G_o	mass velocity (kg/s m^2)
h	heat transfer coefficient (W/m^2 K)
I	global solar radiation (W/m^2)
k	thermal conductivity (W/m K)
L	length of the heater (m)
M	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
n	number of layers of wire mesh
N	number of iteration
Nu	Nusselt number
P_t	pitch of wire mesh (m)
Pr	Prandtl number
Q_u	thermal power output (W)
Re	Reynold's number
T	temperature (°C)
u	velocity of air inside the duct, (m/s)
U_b	back loss coefficient (W/m^2 K)
v	velocity (m/s)
V	volume (m^3)
w	width of the collector (m)

Subscripts

a	ambient
c	convective, channel
f	fluid, flow
g	glass
i	inlet, grid point
l	lower duct
m	packed bed material
o	outlet
p	absorber plate
r	radiative
th	thermal
THE	thermohydraulic
u	upper duct
w	wind
1	first

Greek symbols

α	absorptivity
τ	transmissivity
ϕ	porosity
η	efficiency
δ	thickness (m)
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)

strength, as well as in increasing the heat transfer area. Yeh et al. [22,23] investigated the effects internal and external recycle operations on the thermal efficiency of solar air heaters theoretically. The obtained results depict that considerable collector efficiency improvement was obtained under recycle operations. Ho et al. [24] demonstrate the thermal performance of double pass collector with wire mesh as porous media in the lower channel for fixed bed porosity theoretically and validated experimentally under external recycle. Effects of the mass flow rate of air and recycle ratio on the heat transfer efficiency and power consumption were also presented.

Premixing the inlet air using recycle and mixing with the hot outgoing air produces an extra inlet fluid heating (temperature driving force decrement) and increases the heat loss to the surrounding [14]. The main objectives behind this study are; (1) to recover heat lost due to recycle operation by providing a single pass of air flow through the top glass covers which creates a temperature driving force increment and further increases the efficiency; (2) to increase the efficiency of the DPPBSAH (double pass packed bed solar air heater) by considering a porous material such as wire mesh as an absorbing media in the upper channel; (3) to develop an analytical model capable of providing solution to predict the thermal and thermohydraulic performances of a novel type DPPBSAH under recycle operation; (4) to optimize the parameters to yield best performance for the solar air heater of present interest using RSM (response surface methodology) approach. Moreover, mathematical model is solved by using a constructed computer program that uses an iterative solution procedure. Interaction of the three parameters such as recycle ratio, air mass flow rate and varying channel depth between top glass covers with the thermal and thermo-hydraulic performance of the solar air collector has been investigated using RSM. It is reported that the proposed analytical model is significant with reasonable accuracy. Comparisons of the results obtained from the present study with that obtained from the previous study [24] have been also presented and significant improvement has been obtained.

2. Theoretical analysis

In the present analysis, a new design of the double pass packed bed solar air heater (DPPBSAH) under external recycle is considered for analytical study. The schematic and energy balance for the proposed solar air heating system is presented in Fig. 1(a) and (b) respectively. The design consists of three air flow channels (first channel, upper channel and lower channel) and two air flow passes (single and double pass). The first channel is formed between the upper and lower glass covers, whereas the upper and lower channels are formed by inserting an absorber plate between the lower glass cover and the back plate. The single pass of air with mass flow rate $\dot{m}$ and inlet air flow temperature T_a is provided in the first channel. A double-pass operation is provided by introducing air flow with mass flow rate $\dot{m}$ and inlet air flow temperature T_a in the upper channel. Before entering the upper channel, air with mass flow rate $\dot{m}$ mix with the fluid exiting from the lower channel with the mass flow rate $\dot{m}G$. A conventional blower situated at the beginning of the lower channel regulates the recycled mass flow rate $\dot{m}G$ in the lower channel. The heat balance is accomplished across each component of the given air heater model, i.e. the glass covers, forced air stream in the first channel, recycled air stream in the both upper and lower channels, the absorber plate and the back plate. The following assumptions are made: (i) The system operates under steady state conditions. (ii) The heat capacities of the glass cover, absorber plate, back plate and insulation are negligible. (iii) The flow is one dimensional i.e. the temperature of the flowing air varies only in the direction of flow (x-direction). (iv) Thermo-physical properties of the flowing air are assumed to be varying linearly with temperature. (v) There is no temperature gradient across the thickness of the glass covers, absorber and back plates.