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Thermal performance analysis of a metal corrugated packing solar air collector in cold regions

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HIGHLIGHTS

- A novel solar air collector with metal corrugated packing for space heating is developed.
- Mathematical model verified by experiment is built to study the thermal performance.
- Effects of various key parameters on the thermal performance are numerically studied.
- Thermal performance and economic characteristics are compared with other collectors.

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ABSTRACT

The thermal performance of a novel solar air collector with metal corrugated packing in the buildings of cold regions is studied in this paper. Mathematical models are developed to investigate the thermal performance of the collector and the results are verified by experiments. The hydraulic analysis is conducted experimentally to study the pressure drops of the air flows in the corrugated packing. Effects of the structural and operating parameters, such as the collector width, height, specific surface area and solar radiation intensity, ambient air temperature, air inlet temperature and velocity are studied to optimize the thermal performance of the collector. Comparisons are conducted among the metal corrugated packing solar air collector, the unglazed transpired solar collector, the glazed transpired solar collector and the packed bed solar collector with iron chips. The results indicate that the metal corrugated packing solar air collector is more appropriate to be used in the rural buildings of cold regions for its advantages of large heat transfer area, high heat transfer coefficient and good economic performance.

1. Introduction

According to the statistical data of the Ministry of Housing and Urban-Rural Development in 2014, the construction area of rural buildings has reached up to 37.8 billion square meters, accounting for 63% of the total buildings in China (60 billion square meters). Coal and straw are the main primary energy in these regions. The Chinese government is facing a great challenge to reduce the consumption of traditional energy and promote the application of renewable energy in the heating season of rural regions. To improve the thermal comfort of buildings in cold regions and reduce the environmental pollution caused by burning coal, straw and so on, solar energy as a kind of clean and renewable energy is increasingly applied in the rural buildings.

The solar collector is a heat exchange device that can make absorption of solar radiation into heat energy and transfer it to the working fluid, which is widely used for the space heating, drying and many other fields [1]. One of the most important components of a solar system is the solar air collector. Various designs of solar air collectors have been proposed and studied experimentally and numerically to improve the thermal performance of the solar air collectors [2–4]. One way to improve the thermal performance of the solar air collectors is to enhance the convective heat transfer by installing the baffles inside the collectors. For example, Ucar et al. [5] reorganized the shape and layout of the absorber surface with staggered absorber sheets and attached fins, which could increase the efficiency by 10–30% in comparison with that of the conventional collector. Pakdaman et al. [6] investigated a flat-plate solar air-heater with longitudinal rectangular fins array,

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Nomenclature

a	thermal diffusivity (m^2/s)
A	area (m^2)
$C_{p,a}$	specific heat capacity (j/kg·k)
D_{eq}	equivalent diameter
E	heat transfer (w)
Ex_u	heat exergy (w)
$F_{c\sim sky}$	angle factor of transparent cover and sky
$F_{c\sim gnd}$	angle factor of transparent cover and ground
h	height of corrugation (m)
$h_{conv.c\sim a}$	convective heat transfer coefficient of transparent cover and surrounding (W/m^2·k)
$h_{conv.c\sim f}$	convective heat transfer coefficient of transparent cover and air stream (W/m^2·K)
H	height of corrugated packing (m)
h_{rad}	radiation heat transfer coefficient (W/m^2·K)
h_{conv}	convective heat transfer coefficient (W/m^2·K)
I_c	Solar radiation intensity (W/m^2)
k	ratio of expanded to projected area
$\triangle P$	pressure drop (Pa)
$q_{cond.c.x}$	conductive heat transfer of transparent cover in X direction (W)
$q_{cond.l.x}$	conductive heat transfer of corrugated packing in X direction (W)
$q_{cond.l.z}$	conductive heat transfer of corrugated packing in Z direction (W)
$q_{cond.f.x}$	conductive heat transfer of air stream in X direction (W)
$q_{cond.f.z}$	conductive heat transfer of air stream in Z direction (W)
$q_{conv.c\sim a}$	convective heat transfer between transparent cover and surrounding (W)
$q_{conv.c\sim f}$	convective heat transfer between transparent cover and air stream (W)
$q_{conv.l\sim f}$	convective heat transfer between corrugated packing and air stream (W)
$q_{conv.f.x}$	convective heat transfer of air stream (W)
$q_{rad.c\sim a}$	radiation heat transfer between transparent cover and surrounding (W)
Q	volume of air flow through collector (m^3/h)
S_c	solar radiation absorbed by transparent cover (W)
S_l	solar radiation absorbed by corrugated packing (W)
t_{dp}	Dew point temperature (K)
T_a	temperature of ambient air (K)
T_c	temperature of transparent cover (K)
T_{in}	temperature of inlet air (K)
T_l	temperature of corrugated packing (K)
T_f	temperature of air stream (K)
T_{sky}	Sky effective temperature (K)
T_{gnd}	ground temperature (K)
$\triangle T$	temperature difference between inlet and outlet air (K)
u_f	air velocity along X direction (m/s)
V_l	volume of corrugated packing (m^3)
v_{wind}	outdoor wind speed (m/s)
W	width of corrugated packing (m)
W_p	power (W)
$\triangle x$	length of control volume (m)
$\triangle z$	width of control volume (m)

Greek symbols

α	angle of inclination (°), absorptivity
δ	thickness of corrugated packing (m)
ε	emissivity
λ	thermal conductivity (w/m·k)
η	thermal efficiency
η_1	net exergy efficiency
ν	kinematic viscosity (m^2/s)
ψ_s	solar radiation heat exergy coefficient
ξ	specific surface area of corrugated packing (m^2/m^3)
ω	ratio of expanded to projected length
ρ	density (kg/m^3)
τ	transmittance

and the results showed that the heat transfer performance might be enhanced by 20% with the heat transfer area increased by 66%. Akpinar and Kocyigit [7] compared the performance of flat-plate solar air heaters with three types of obstacles and without obstacles and found that the solar radiation, surface geometry of the collectors and extension of the air flow line had significant effects on the efficiency of the collectors.

Another way to improve the thermal performance of the solar air collector is to enlarge the heat transfer area. The introduction of porous material into the solar air collector could not only enlarge the heat transfer area but also enhance the convective heat transfer for the obstacles arranged into the air channel duct. The study was firstly conducted by Bliss in 1955 [8]. Thereafter, the usage of porous/packing materials, such as stone, metal and wool, to improve the performance of solar air collector has been carried out by many studies [9–11]. The composite-wall solar-collector with porous collector was studied, in which a porous layer with vents was used between the glazing and the massive wall, or a non-convective porous layer, directly contacted to the massive wall, was conceived [12,13]. The thermal performance of a double-glass double-pass solar air heater with a packed bed above the heater absorber plate was investigated experimentally and theoretically by Ramadan et al. [14]. Limestone and gravel were used as packed bed materials. The effects of operational and configurational parameters on the thermal performance and hydraulic performance were studied. Sopian et al. [15] studied the thermal performance of a double-pass solar collector with porous media and the results indicated that the efficiency was 20–70% higher than the collector without porous media. To minimize the heat losses from the front cover and maximize the heat extraction from the absorber, Mohamad [16] studied a double-pass solar air collector with porous media. Ramania [17] compared the thermal performance of three types of the solar air collector with porous materials and found that the thermal efficiency of double-pass solar air collector with porous material was 20–25% and 30–35% higher than that of double-pass solar air collector without porous material and single pass collector, respectively. The correlations between the Nusselt and Reynolds number in the cross-corrugated solar air collectors were studied by the researchers and the results indicated that its heat-transfer coefficients were approximately 2.8 times higher than that with smooth flat channels [18].

A novel solar air collector with metal corrugated packing is developed in this paper, and its thermal performance in the cold regions is experimentally and numerically studied. The metal corrugated packing is a kind of widely used porous material in the chemical industry for its advantages of large heat transfer area, high heat transfer coefficient and good economic performance, but few studies have been conducted to investigate its thermal performance as the absorber plate. Therefore, mathematical models are developed to study the thermal performance of the collector and verified by experiments. The effects of key parameters, such as