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Thermal characteristics of a glazed transpired solar collector with perforating corrugated plate in cold regions

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A B S T R A C T

Solar heating applied to rural buildings is without a doubt an interesting alternative for reducing energy consumption in cold regions. The thermal performance of transpired solar collector is enhanced by the impingement of jet. To make a better use of the jet impingement, a GTC (glazed transpired solar collector) with perforating corrugated plate is developed. A mathematical model based on the energy balance equations is built to predict the thermal performance of the collector. The simulated results are validated by experiments and they show good agreement with each other. The effects of various key parameters, such as inlet and ambient temperature, total volume flow of air, radiation intensity, height and width of the collector and porosity of the absorber plate, on the thermal performance of the GTC are studied. The thermal performance and economic characteristics of the collector are compared with other transpired solar collectors. The results indicate that the GTC with perforating corrugated plate is applicative enough for its advantages in economy and thermal performance in rural areas of cold regions.

1. Introduction

Solar energy technologies provide promising solutions for the reduction of buildings energy consumption, and the solar air heater is considered to be one of the most potential applications. As there are nearly 60% people living in rural areas and the traditional heating mode for the northern rural areas is coal-fired heating system, which is inefficient and environmentally-unfriendly. The Chinese government is facing a great challenge to reduce the application of traditional energy and promote the application of renewable energy in rural areas. And also, they have done lots of attempts to improve the indoor thermal environment of the buildings in cold rural regions. The flat-plate solar air heaters are the best choice for space heating as to their simple and inexpensive technology [1]. However, the thermal performance of the flat-plate solar air heaters is unsatisfactory for the significant heat loss and low convective heat transfer coefficients [2–4]. Therefore, the transpired solar air collectors are a potential replacement for flat-plate solar air heaters in the cold rural regions.

The transpired solar air collectors can be categorized into two types: UTC (unglazed transpired solar air collectors) and GTC (glazed transpired solar air collectors). Many researches have been focused on the thermal performance, heat loss, parameters and structure optimization of the unglazed solar air heaters. Kutscher et al. [5] developed a numerical model to analysis the efficiencies of the unglazed transpired solar collector. Whereafter, Decker et al. [6] improved the model of Kutscher and developed a wider range and higher accuracy model to predict the efficiencies of collectors. The effects of wind on an unglazed transpired solar collector performance were studied by Fleck et al. [7]. The results showed that the increase of fluctuation intensity would lead to a monotonic decrease in the efficiency of the collector. Collins et al. [8] numerically studied the effectiveness and heat loss of an unglazed transpired solar collector with a trapezoidal corrugation and the occurrence of separated or attached flows can be predicted by their model. The thermal performance of the unglazed transpired solar collectors was investigated by Li et al. [9,10] and compared with the unglazed transpired solar collectors with PV panels. The results indicated that the parameters such as corrugation wavelength and slope length have the largest effect on the thermal performance of unglazed transpired solar collectors while the PV panel height and wavelength have the most significant impact on unglazed transpired solar collectors with PV panels. Kumar et al. [11] experimentally investigated the heat transfer and friction in the flow of

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Nomenclature

a	Thermal diffusivity of air [m^2/s]
A	Annual operation cost [RMB]
C	Life cycle cost [RMB]
$C_{p,a}$	Specific heat capacity of air [J/kg K]
d_{f1}	Depth of in z direction of plenum 1 [m]
d_{f2}	Depth of in z direction of plenum 2 [m]
D_{f1}	Equivalent diameter of plenum 1 [m]
D_{f2}	Equivalent diameter of plenum 2 [m]
$F_{c\sim sky}$	Angle factor of transparent cover and sky
$F_{c\sim gnd}$	Angle factor of transparent cover and ground
Gz_{hole}	Graetz number
$h_{conv,c\sim a}$	Convective heat transfer coefficient of transparent cover and surrounding [W/m^2 K]
$h_{conv,c\sim f1}$	Convective heat transfer coefficient of transparent cover and air in plenum 1 [W/m^2 K]
$h_{conv,p\sim f1}$	Convective heat transfer coefficient of absorber plate and air in plenum 1 [W/m^2 K]
$h_{conv,p\sim f2}$	Convective heat transfer coefficient of absorber plate and air in plenum 2 [W/m^2 K]
$h_{conv,hole}$	Convective heat transfer coefficient of perforation [W/m^2 K]
$h_{conv,b\sim f2}$	Convective heat transfer coefficient of insulation backboard and air in plenum 2 [W/m^2 K]
$h_{rad,c\sim p}$	Radiation heat transfer coefficient between transparent cover and absorber plate [W/m^2 K]
$h_{rad,b\sim p}$	Radiation heat transfer coefficient between insulation backboard and absorber plate [W/m^2 K]
$h_{rad,c\sim a}$	Radiation heat transfer coefficient between transparent cover and surrounding [W/m^2 K]
H	Collector height [m]
i	discount rate
I_c	Solar radiation intensity [W/m^2]
n	life cycle
Nu	Nusselt number
p	porosity
P	Initial cost [RMB]
ΔP	Pressure drops [Pa]
Q_f	volume flow of air [m^3/h]
$q_{cond.c}$	Conductive heat transfer of transparent cover [W]
$q_{cond.b}$	Conductive heat transfer of insulation backboard [W]
$q_{conv.f1}$	Convective heat transfer of air in plenum 1 [W]
$q_{cond.f1}$	Conductive heat transfer of air in plenum 1 [W]
$q_{cond.p}$	Conductive heat transfer of absorber plate [W]
$q_{conv.f2}$	Convective heat transfer of air in plenum 2 [W]
$q_{cond.f2}$	Conductive heat transfer of air in plenum 2 [W]
$q_{rad.c\sim a}$	Radiation heat transfer between transparent cover and surrounding [W]
$q_{conv.p\sim f1}$	Convective heat transfer of absorber plate and air in plenum 1 [W]
$q_{conv.c\sim a}$	Convective heat transfer between transparent cover and surrounding [W]
$q_{conv.c\sim f1}$	Convective heat transfer between transparent cover and air in plenum 1 [W]
δ_p	Thickness of absorber plate [m]
$q_{rad.c\sim p}$	Radiation heat transfer between transparent cover and absorber plate [W]
$q_{conv.p\sim f2}$	Convective heat transfer of absorber plate and air in plenum 2 [W]
$q_{rad.b\sim p}$	Radiation heat transfer between insulation backboard and absorber plate [W]
$q_{conv.b\sim f2}$	Convective heat transfer of insulation backboard and air in plenum 2 [W]
R	Perforation radius [m]
T_a	Temperature of ambient air [K]
S_c	Solar radiation absorbed by transparent cover [W]
S_p	Solar radiation absorbed by absorber plate [W]
T_b	Temperature of insulation backboard [K]
T_c	Temperature of transparent cover [K]
T_{db}	Dew point temperature [K]
T_{f1}	Temperature of air in plenum 1 [K]
T_{f2}	Temperature of air in plenum 2 [K]
T_{gnd}	Ground temperature [K]
T_p	Temperature of absorber plate [K]
T_{sky}	Sky temperature [K]
u_{f1}	Velocity of air in plenum 1 [m/s]
u_{f2}	Velocity of air in plenum 2 [m/s]
v_{wind}	Wind speed [m/s]
W	Collector width [m]

Greek symbols

α_c	Absorptivity of the transparent cover
θ	Inclination angle of absorber plate [°]
υ	Dynamic viscosity of air [m^2/s]
ρ_a	Air density [kg/m^3]
τ_c	Transmissivity of transparent cover
δ_b	Thickness of insulation backboard [m]
δ_c	Thickness of transparent cover [m]
λ_a	Thermal conductivity of air [W/m K]
λ_b	Thermal conductivity of insulation backboard [W/m K]
λ_c	Thermal conductivity of transparent cover [W/m K]
λ_p	Thermal conductivity of absorber plate [W/m K]
ε_b	Emissivity of insulation backboard
ε_{c1}	Emissivity of transparent cover outer surface
ε_{c2}	Emissivity of transparent cover inner surface
ε_{p1}	Emissivity of absorber plate outside surface
ε_{p2}	Emissivity of absorber plate inside surface
ε_{sky}	Emissivity of air near the ground

Abbreviations

UTC	unglazed transpired solar air collector
GTC	glazed transpired solar air collector

air in rectangular ducts having multi v-shaped with gap rib on one broad wall. The effects of different geometrical parameters on thermal performance and roughness were discussed to optimize the designing of the solar air heater.

The performance of unglazed transpired solar air heaters in cold regions is feeble for the convection and radiation loss from the absorber to the environment is larger than that in the moderate climate regions. The usage of transparent glass was proved to be a most promising candidate to improve the efficiency of transpired solar air heaters [12]. A transparent glass plays a vital function to allow the access of the incident radiation and restrict the infrared energy losses through re-radiation. The thermal performance of perforated glazed solar air heaters and unglazed transpired solar air heaters was experimentally studied by Vaziri et al. [13]. The results proved that the thermal efficiencies of perforated glazed solar air heaters with different inner collector colors were significantly