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Parameter optimization of solar air collectors with holes on baffle and analysis of flow and heat transfer characteristics

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A B S T R A C T

This paper aims to improve the thermal performance of baffle-type solar air collector (BSAC) by opening holes on baffle based on the principle of windbreak walls. Small jets were created when fluid flowing out of the holes, which can weaken or blow away the vortexes behind baffle avoiding the generation of hot spots, and the bypass effect caused by these holes can reduce the flow resistance simultaneously. Moreover, these small jets strengthen the mixing and flow disturbance, which can enhance the heat transfer between the airflow and absorber plate leading to efficiency improvement. In this paper, the impact of hole parameters on thermal performance of BSAC was studied by orthogonal numerical tests. The analysis of variance shows that the mutual interaction among the factors of opening hole is insignificant and the influence of inlet flow rate and the hole size on collector efficiency is significant. The optimal parameter combination under different flow rates was obtained. When the inlet flow rate is 0.0044, 0.0088, and 0.0132 $kg{\cdot}s^{-1}{\cdot}m^{-2}$, the optimal collector efficiencies is 69.63%, 81.71%, and 86.83% respectively. A numerical comparison was made between the BSAC with and without holes on baffle, which explains the reason why the improved BSAC can promote the thermal efficiency and reduce the flow resistance simultaneously, providing a theoretical basis for the performance improvement of BSAC.

1. Introduction

The flat-plate solar air collector (FSAC) is simple in structure, conveniently installed, and easy to maintain. There are no leakage, blockage, and freezing problems in its application. As a result, it is widely used in auxiliary building heating (Liang et al., 2011; Abedi, 2012), domestic hot-water supplies, agricultural products drying (Karsli, 2007; Ayadi et al., 2014; Gulcimen et al., 2016; Bhattacharyya et al., 2017), liquid desiccant (Ben-Amara et al., 2005; Al-Sulaiman et al., 2015), and other fields. However, for the low heat transfer rate between the absorber plate and air, the collector efficiency of FSACs is relatively low. Numerous ideas have been put forward to improve the thermal performance of FSACs.

The concept of double-pass arrangement is widely employed by many investigators. Yang et al. (2012) compared the influence of five critical parameters on thermal performance of FSACs with a single pass. The results show that decreasing heat transfer resistance in the airflow channel plays the most significant role in improving thermal efficiency. Ramani et al. (2010) conducted the theoretical and experimental analysis of a double-pass FSAC with and without porous material. Results show that the thermal efficiency of double-pass FSACs with porous absorbing material is 20–25% and 30–35% higher than that of double-pass FSACs without porous absorbing material and single-pass collectors, respectively.

Adding internal structures have been suggested by many researches to improve the thermal performance of FSACs. Peng et al. (2010) designed a FSAC with a pin-fin integrated absorber plate, and compared the collection efficiency of 26 collectors, including the original FSAC. The experimental results indicate that the heat transfer coefficient of the best model can reach three times that of the original FSAC, which provides a good method for performance optimization.

It has been proposed by many investigators that changing the structure on absorber plates could enhance the heat transfer of FSACs. Ravi and Saini (2016) conducted an experimental study on the effect of roughness parameters on thermo-hydraulic performance of double-pass duct collectors which have discrete multi-V shaped and staggered rib. When compared with the single-pass flow collector, the increase in the heat transfer rate is significant. However, the increase in pressure drop is also significant. Li et al. (2015) presented a FSAC with hemispherical protrusions/dimples on the absorber plate, and analyzed the performance from two aspects of optics and thermodynamics. The conclusions showed that the hemispherical dimple is better in terms of the optics, and the heat transfer rate can be enhanced considerably. Pandey et al. (2016) conducted an experimental study on heat transfer and the

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Nomenclature

A	size of hole
B	location of hole
C	number of hole
D	inlet flow rate
$\vec{v}$	fluid velocity
t	flow time
H	enthalpy
k	thermal conductivity
S_V	a spatial source term
C_P	specific heat of air
y_p	distance from point P to the wall
P	fluid density
m	mass flow rate
C_p	heat capacity of air at constant pressure
T_{out}	fluid temperature of the outlet
T_{in}	fluid temperature of inlet
T_{wall}	local wall temperature
T_{ref}	reference temperature
A	total area of top glass cover
G	total solar irradiance.
u_τ	friction velocity
h_{eff}	local surface heat transfer coefficient (HTC)
D_{hyd}	characteristic length
q	combined convective and radiative heat flux
k	the mean of each factor in every level
P_{total}	total inlet pressure
P_{local}	total local pressure
$\bar{\rho}_{out}$	outlet average density
$\bar{U}_{out}$	outlet average speed

Greek letter

η_c	heat collecting efficiency
ξ	total pressure loss coefficient
ρ	fluid density
μ	fluid viscosity
λ_a	thermal conductivity coefficient of air

friction factor in a rectangular-channel collector having multiple-arc-shaped structures as roughness elements. Li et al. (2017) implemented a comparative study on the performance of a FSAC with five surface shapes: sinusoidal corrugated plate, protrusion plate, sinusoidal corrugated protrusion plate, and a base flat-plate. The conclusion was that the thermal performance of collectors adopting the above methods were all improved. However, the flow resistance was also increased.

Some novel ideas have been introduced to improve the collecting efficiency of FSAC. Zheng et al. (2016) presented a type of serpentine compound parabolic concentrator which is a combination of a compound parabolic concentrator and a flat-plate solar collector. Zhu et al. (2017a, b) proposed a type of FSAC with micro-heat pipe arrays (MHPA), and experimentally and theoretically investigated the heat transfer and friction characteristics of the MHPA-FSAC. Chauhan et al. (2016) studied the effect of impinging air jets on the thermal performance of FSACs. Gorji and Ranjbar (2017) summarized the latest development and research on the optical properties and application of nanofluids in direct-absorption solar thermal collectors. Dissa et al. (2016) investigated a SAC with composite absorber coupling of a non-porous absorber made of corrugated iron sheets or a porous absorber made of mesh of aluminum. Osorio et al. (2017) introduced the transparent insulation materials (TIM) into flat-plate collectors. The effects of TIM properties, such as the emittance, thermal conductivity, and extinction coefficient on the collector's performance were analyzed.

In 2007, Romdhane (2007) introduced a new FSAC with the introduction of suitable baffles in the collector chamber. He compared different baffle arrangement patterns on collector efficiency, pressure drop, and temperature rise. However, the detailed flow and heat transfer features of this FSAC were not illustrated in this paper. Since 2011, a detailed numerical simulation was conducted by our group on the internal flow and heat transfer characteristics of FSACs with internal baffles (Hu et al., 2013). The influence of structural parameters on collector efficiency was discussed. The results show that the introduction of internal baffles can effectively improve the collector efficiency. However, strong flow separation was found behind the baffles, which could result in local vortexes. The fluid rotates in the local area, trapping heat in the vortex, which can form hot spots and cause great heat loss. Therefore, removing or weakening the local vortexes is an important way to improve collector efficiency of the baffle-type solar air collector (BSAC).

Opening holes on the baffle without changing the macro structure was proposed with the purpose to improve the thermal performance of BSACs. This approach is inspired by the principle of windbreak walls, which can screen the wind without leaving a large vortex behind it. Jet flows were created when air flows through the holes. The jet flows can strengthen the disturbance and mixing in the flow passage, and blow away the local vortexes behind the baffles. These effects can inhibit the formation of high-temperature zones (hot spots) and reduce heat loss. At the same time, the jet flows can intensify the convective heat transfer between the airflow and absorber plate. This introduces more heat into the air, allowing for higher collector efficiency to be obtained.

This work is an extension of the first part of the author's research on the same research topic (Hu et al., 2013). Numerical simulation was employed as the main research technique in this paper. The impact of hole parameters on the thermal performance of BSACs was studied using the numerical orthogonal test. Twenty-seven numerical models were designed and developed, and three-dimensional numerical simulation was subsequently conducted. Using the statistics method, the significance of the four factors, such as hole size, location, number of holes, and inlet flow rate to collector efficiency was analyzed. The optimal parameter combination under different flow rates were obtained. A detailed comparison was made between BSACs with and without holes on baffle to discuss the influence of holes on flow and heat transfer characteristics of BSAC. The results reveal the mechanism of heat transfer enhancement and provide the theoretical basis for the optimization of BSACs.

2. Original model introduction

The original model studied in previous paper is a self-designed BSAC with total cavity size of 1 m × 2 m × 0.12 m, as shown in Fig. 1 (Hu et al., 2013). Four internal baffles with lengths of 0.7 m are equipped in the collector, which divide the cavity into five chambers. The black chromium coating is coated on the surface of the absorber plate, 60 mm-thick polystyrene boards are used in the periphery and bottom for heat insulation, and single-glass with the thickness of 4 mm is used as the top glass cover. The heat and flow characteristic of this BSAC has been investigated by experiment and numerical methods in previous paper.

3. Computational model

The computational model studied in this paper is abstracted from the actual device introduced above (Hu et al., 2013). In this paper, square holes were opened along with the length direction of baffle with the purpose to improve the flow behind baffles and increase the thermal