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Performance evaluation of a flat-plate solar collector filled with porous metal foam: Experimental and numerical analysis

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A R T I C L E I N F O

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A B S T R A C T

Experimental and numerical investigations on the effect of porous metal foam on the performance of a flat-plate solar collector have been carried out in this study. The numerical solution is based on the control-volume approach and local thermal equilibrium assumption between the fluid-porous material phase to get the optimum thickness of the porous medium and also evaluate the thermal performance and pressure drop in the porous channel collector. The numerical results exhibit that the maximum thermal performance is obtained in a porous layer dimensionless thickness greater than 0.8, which the fully filled channel is selected in the present study. In the experimental section, an ASHRAE standard is used to examine the effects of metal foam on the solar collector performance at different flow rates. The numerical solution results have been validated against the experimental results, and a reasonable agreement has been achieved. The numerical and experimental results have shown that using the porous medium enhances the maximum thermal efficiency and Nusselt number up to 18.5% and 82%, respectively.

1. Introduction

Energy has always been one of the most vital and precious commodities in the world. Finite fossil fuel sources, increased energy costs, and concerns about environmental destruction are forcing mankind to reduce its dependence on non-renewable energy sources [1,2]. For this reason, sustainable sources of energy, such as solar energy, have received more attention in recent decades [3,4].

Solar thermal systems are one of the main interests within engineering. Flat-Plate Solar Collectors (FPSCs) are the oldest and also most applicable solar thermal system, yet they have relatively high heat loss, which decreases their thermal efficiency [5]. Nowadays, optimization methods and advanced technology and materials can make this kind of solar system more efficient. Thermal performance improvement of FPSCs can decrease their dimensions and lead to higher outlet temperature of the fluid for residential and commercial water heating [6,7]. Different techniques have been investigated to enhance the thermal performance of FPSCs, with most focusing on two main parts of them: the working fluid and absorption channel. Using nanofluids with excellent thermal properties is one of these procedures which has provoked great interest for study in the recent decade [8–11].

Using porous materials is another efficient augmenting scheme. Porous materials, especially metal porous foams, have a great usage in solar systems such as solar thermochemical reactors and solar thermal collectors. Since porous material receivers have high contact surface area per unit of solar radiation and can damp the fluid vortex in the channel, hence they are effective options for power generation in solar thermochemical reactors [12]. Some valuable studies of the solar driven CO_2 methane reforming process in porous metal foam reactors are performed by Fuqiang et al. [13,14]. Also, metal porous foams have emerged as a passive thermal developer due to their nature in fluid mixing, rising the effective thermal conductivity of the fluid, and also creating a greater temperature gradient at the channel walls, which leads to lower thermal resistance [15–17]. Although there are several important studies on the use of porous media in solar collectors [18–21], only few significant studies have been conducted on the use of porous materials to enhance the thermal performance of flat-plate collectors.

Sorour [22] has designed and fabricated three models for FPSC in which the working fluid obtains the thermal energy from a transparent

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Nomenclature

A_c	solar collector surface area (m^2)
A_p	heat transfer surface of the collector (m^2)
C_F	Forchheimer coefficient
C_p	specific heat at constant pressure (J/kg·K)
D_h	hydraulic diameter (m)
f	dimensionless pressure drop (friction factor)
F_R	collector heat removal factor
H	collector channel height (m)
h	convection heat transfer coefficient ($W/m^2 \cdot K$)
I	global solar irradiation (W/m^2)
k	thermal conductivity (W/m·K)
K	permeability (m^2)
L	collector channel length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	local Nusselt number
$\overline{Nu}$	overall Nusselt number
P	pressure (Pa)
$\dot{Q}$	volume flow rate (m^3/s)
$\dot{Q}_u$	rate of heat gain (W)
S	dimensionless porous substrate thickness (porous layer thickness/H)
T	temperature (K)
u,v	component of flow velocity in x and y directions, respectively (m/s)
u^*	dimensionless axial velocity (u/u_{in})
U_L	heat loss coefficient ($W/m^2 \cdot K$)
V	velocity (m/s)
x,y	cartesian coordinates (m)
X,Y	dimensionless cartesian coordinates, ($X = x/H$, $Y = y/H$)

Greek letters

δ	uncertainty
η	thermal efficiency
θ	dimensionless temperature, ($\theta = (T-T_w)/(T_m-T_w)$)
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
$(\tau\alpha)_e$	effective transmission- absorption coefficient
ϕ	porosity

Subscripts

a	ambient
e	empty channel
eff	effective property
f	working fluid
i	inlet
m	mean
o	outlet
p	porous channel
w	wall

cover and flows perpendicularly to a porous absorber. Only one model was successful in his experiments. Also, this design had a better efficiency than a conventional collector in high flow rates, but an opposite behavior was governed in lower flow rates. Lansing and Clark [23] have offered the use of porous media to extract efficient heat in a solar air collector. They used an analytical solution to determine the temperature distribution. Analysis showed that the porous construction could improve the collector performance by 102%. Al-Nimr and Alkam [15] improved the thermal performance of a tubeless FPSC by placing porous medium layers at the boundary side of the collector. They reported that the porous substrates improved the heat transfer coefficient, and consequently, the Nusselt number increased up to 25 times. The effect of a porous medium layer at the boundary wall of a tubular FPSC have numerically studied by Alkam and Al-Nimr [24]. They concluded that the collector efficiency was enhanced about 15–130% when using porous material, especially at great heat loss coefficients. Kleinstreuer and Chiang [25] have numerically solved coupled fluid and heat transfer equations in a fully filled porous medium FPSC and compared its thermal performance with that of a tubular collector. The results indicated that the porous solar collector had higher and more sustained efficiency. A numerical study of natural convection in a porous wall solar system has been performed by Mbaye and Bilgen [26]. They investigated the effects of different geometrical factors and non-uniform heat production in porous media and declared that geometrical factors were the main parameters that affected the thermal performance of the solar wall collector. Sopian et al. [27] have experimentally studied the effect of porous media (steel wool) on the thermal efficiency and temperature increase of a double-pass solar air collector. They concluded that the thermal efficiency had improved by about 20–70% with inserting the porous material into the lower channel. Yousef and Adam [28] have theoretically studied the effects of the air flow rate, geometrical parameters and porous media on heat transfer and pressure losses of solar air collectors with single and double flow pass. Their results showed that the efficiency of a double-pass channel collector was greater than that of a single-pass one, and the efficiency increased by 8% after inserting a porous media substrate inside the lower channel. Chen et al. [29] have studied numerically a flat-plate collector with metal porous foam that had been filled with a phase-change material (paraffin) used for energy storage. The paraffin melting process was solved by a Local Thermal Non-Equilibrium (LTNE) model. According to the results, the heat transfer improved significantly when using the metal foam. Chen and Huang [30] performed a numerical investigation on the thermal performance of a tubeless solar collector with inserted partial metal foam blocks. They used LTNE assumption for the energy equation and solved the coupled governing equations by applying a stream function-vorticity analysis. The results illustrated that the inserted metal foam enhanced the heat transfer. Hirasawa et al. [31] have experimentally studied the effect of porous material in reducing heat losses. They placed a high-porosity foam above the collector plate and showed that the heat losses due to natural convection were reduced up to 7%. Kareem et al. [32] have analytically compared the thermal performance of a single-pass flat-plate air collector without porous medium and a double-pass one whose lower channel was filled with porous material. It was observed that the heat losses decreased in the double-pass porous collector. Huang et al. [6], in another numerical paper, studied the effects of flow pulsation and partial metal foam blocks in a tubeless flat plate collector. They also solved the flow and energy equations using the control volume method and through a stream function-vorticity approach. They illustrated that the flow pulsation and partial metal foam blocks considerably enhanced the thermal performance. Xu et al. [33] have presented different analytical schemes to study heat transfer in a solar collector with metal foam. They considered Darcy, Brinkman, and Forchheimer models for flow and Local Thermal Equilibrium (LTE) and LTNE assumptions for the energy equation. The results showed that as the metal foam porosity increases, the LTNE model becomes weaker in porous medium. They proposed a combined fin-LTE model to evaluate the thermal performance of metal foam. Rashidi et al. [34] have performed a sensitivity analysis to investigate the effect of three factors, including Darcy number, Reynolds number, and porous media layer thickness, on the Nusselt number and pressure drop of a solar heat exchanger. This analysis was done by utilizing the response surface method. Also, the