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Thermal enhancement in a flat-plate solar water collector by flow pulsation and metal-foam blocks

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ABSTRACT

This study presents a numerical analysis of forced pulsating convection flow in a parallel-plate channel of solar water collector mounted with multiple metal-foam blocks. Both transient Darcy–Brinkman–Forchheimer flow model and two-equation energy model based on local thermal non-equilibrium (LTNE) are used to characterize the thermo-flow fields inside the porous regions. Solution of the coupled governing equations for the fluid/porous composite system is obtained by utilizing a control-volume method through the use of a stream function-vorticity approach. This study details the effects of variations in the Darcy number, pulsation frequency and amplitude, Reynolds number, and porosity, to illustrate important fundamental and practical results. The results show that the periodic alteration in the structure of recirculation flows, caused by metal-foam blocks and flow pulsation, will significantly enhance the heat transfer rate on heat source surface. For fixed *Re*, the findings show that an increase in the solid–fluid interfacial heat exchange results in a more obvious local thermal equilibrium (LTE) phenomenon, and a larger heat transfer augmentation of solar thermal collector. Besides, two useful correlated equations to predict Nu_m are proposed.

1. Introduction

At present, fossil fuels provide the most energy demand. The burning of fossil fuels releases emissions CO_2 into the environment to promote global warning. Extreme weather conditions are becoming more and more frequent. Energy prices for oil, gas and fuel have been rising consistently due to the scarcity of fossil fuels. This incontestable fact forces us to use the valuable nature resources more effectively and explore alternative renewable energy. One such option is solar energy. The major component of any solar system is the solar thermal collector. The solar thermal collector is a device that absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector [1]. Flat-plate solar collectors are commonly used for residential water, space heating, and commercial or industrial applications [2]. They have been in service for the last 40–50 years without significant changes in their design and operation principles [3]. The efficiency improvement for flat-plate solar collector can reduce its size and obtain higher temperature fluid at outlet for wider application. In response to these demands, different highly effective techniques have been used in the past to obtain heat transfer enhancement, such as the double-pass channels, porous finned receiver, V-grooves absorber, porous media, porous disc receiver, metallic mesh insertion, and so on [3–7]. Among the thermal enhancement schemes, one of the promising techniques is the application of metal porous materials subjected to flow pulsation. The porous medium has emerged as an effective passive thermal enhancer due to its large ratio of surface area to volume in the heat transfer process, the high thermal conductivity in the metal foam matrix, and the enhanced flow mixing, caused by the tortuous path of the porous matrix, in the thermal dispersion process. The forced pulsation of incoming fluid at the entrance of channel is another active augmenting method due to the hydrodynamic instability in a shear layer, which substantially increases lateral, large-scale flow mixing and hence augments the convective thermal transport in the direction normal to the heated surface.

The problem of convective heat transfer in fluid-saturated porous media has been a major topic for various studies during the past decades due to its relevance in a wide range of application such as heat pipe technology, cooling of electronic equipment, the thermal insulation, geothermal energy systems, heat exchanger, drying processes, unclear waste disposal etc. Extensive studies have been conducted on the steady forced convection flow through a channel fully or partially filled with a porous material as a heat sink for heat transfer augmentation. Koh and Colony [8] analyzed the cooling effectiveness for a porous material in a cooling passage.

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Nomenclature

a_{sf}	surface area of the fluid–solid interface per unit volume (m^{-1})
A	oscillating amplitude of axial inlet velocity
A_i	surface area (m^2)
C_p	specific heat at constant pressure (J/kg K)
Da	Darcy number, K/R^2
d_f	fiber diameter (m)
d_p	mean pore diameter (m)
f	dimensional forcing frequency (Hz)
F	function used in expression inertia terms
h	convective heat transfer coefficient (W/m^2 K)
H	height (m)
k	thermal conductivity (W/m K)
K	permeability of the porous medium (m^2)
L	length (m)
L_h	the length of absorber plate under solar energy (m)
LTE	local thermal equilibrium
LTNE	local thermal non-equilibrium
Nu	Nusselt number, hR/k_f
P	pressure (N/m^2)
Pr	Prandtl number, v/α
q''	heat flux (W/m^2)
R	height of channel (m)
Rc	heat capacity ratio, $(\rho C_p)_s/\ (\rho C_p)_f$
Re	Reynolds number, $u_o R/v$
S	spacing between porous blocks (m)
St	dimensionless pulsating frequency, Strouhal number, fR/u_o
t	time (s)
T	temperature (K)
u, v	velocity component (m/s)
V	velocity vector (m/s)
W	width (m)
x, y	Cartesian coordinates (m)

Greek symbols

α	thermal diffusivity (m^2/s)
γ	dispersion coefficient
ε	porosity of the porous medium
ζ	vorticity (1/s)
λ	thermal conductivity ratio, k/k_f
μ	dynamic viscosity (kg/m s)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ψ	stream function (m^2/s)
ω	angular velocity (1/s)

Superscripts

$*$	dimensionless quantity

Subscripts

d	dispersion
d_f	based on fiber diameter
eff	effective
f	fluid
fe	effective value for the fluid
i	inlet
m	cycle-space averaged overall mean
non	nonporous
$non\text{-}ss$	nonporous in steady flow
o	outlet
p	porous
s	solid matrix
se	effective value for the solid matrix
sf	fluid–solid interface
ss	steady state
t	instantaneous or total
w	wall
x	local

Symbol

$\langle\ \rangle$	volume-averaged quantity
$\lvert\ \rvert$	magnitude or absolute value

Kaviany [9] dealt with convective heat transfer from a steady laminar flow through a porous channel bounded by two isothermal parallel plates. Huang and Vafai [10] simulated steady forced convection problem in an isothermal parallel plate channel with porous block array. Angirasa [11] numerical reported forced convection in a channel filled with metallic fibrous materials. Their results showed that porous substrate substantially enhance the thermal performance in a channel. A majority of these studies relate to the aspect of forced convection over a fully/partial porous channel system with one-energy-equation model based on the local thermal equilibrium (LTE) assumption.

In recent years, man-made porous medium-metal foams have gained attention as potentially excellent candidates for meeting the high thermal dissipation demands in the thermal applications, such as multi-functional heat exchangers [12], compact heat sinks for electronic cooling [13], thermal shielding etc. Calmidi and Mahajan [14] conducted an experimental and numerical study of force convection in a fully aluminum metal-foam porous channel with a single heat source. Nusselt number data has been obtained as a function of the Reynolds number based on permeability. Jeng and Tzeng [15] studied numerically about a confined slot jet impinging on full porous aluminum foam heat sink. The simulation results exhibited that the heat transfer performance of the aluminum foam heat sink is $2 \sim 3$ times as large as that without heat sink, and the thermal resistance is also 30% less than that of convectional plate heat sink. Most of these studies, the heat transfer problems of a fully metal porous channel were studied with two-energy-equation model based on the local thermal non-equilibrium (LTNE) assumption. Phanikumar and Mahaian [16] numerically and experimentally studied the buoyancy-induced flow in a high porosity aluminum foam heated from below and indicated the two-equation energy model is a better model when fluid/porous interfaces are involved.

More recently, due to the needs of reaping the benefits from abundant and free solar energy and the limitation of space, there has been an increasing demand to achieve higher heat transfer removal from the fully/partially porous channel flow for the development of an efficient and low cost solar collector, especially for small-size installations. One of such efforts has been given to exploring the use of porous heat sink subjected to pulsation flow. Here, a pulsating channel flow, i.e. an oscillating component superposed on the mean flow in a confined passage, can enhance the axial transfer of energy because of large oscillating temperature gradients in the direction normal to the heated wall. Pulsating flow is frequently encountered in natural system (human respiratory and vascular system) and engineering system (exhaust and intake manifolds of IC engines, regenerator, Stirling engine etc.). The related characteristics studies on pulsating confined flow heat