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Effects of a porous medium on forced convection of a reciprocating curved channel☆

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ABSTRACT

Enhancement of heat transfer rates of a reciprocating curved channel partially installed by a porous medium is investigated numerically. The distribution of heat transfer rates on the heat surface of the reciprocating curved channel is rather non-uniform that easily causes a thermal damage to destroy the channel. A method of using the porous medium to enhance heat transfer rates of the channel is then developed to solve the thermal damage. The arbitrary Lagrangian–Eulerian method is firstly modified for treating a moving boundary problem of the porous medium. Main parameters of Reynolds numbers, porosities, frequencies and amplitudes are examined. The results show that the enhancements of heat transfer rates of most porous medium situations are achieved. However, heat transfer rates of a few porous medium situations are unexpectedly inferior to those of without porous medium situations.

1. Introduction

In order to fulfill a demand of lots of functions concentrated in a tiny device, heat loading of the device is then hugely increased. A topic for increasing heat transfer rates to decrease a damage caused by the huge heat generation of the device naturally becomes urgent and important. A porous medium, which is often used in solar cells, electric devices, heat exchangers, etc., possesses two characteristics of a thinly staggered and connected structure which provides a large convective heat transfer surface, and lots of connected porosities, which provide cooling fluids to flow through them freely to execute convective heat transfer with the structure. Unfortunately, the huge surface area of the porous medium usually results in severe drag resistance of cooling fluids. Therefore, the characteristics of the porous medium should be carefully taken into consideration for achieving enhancement of the heat transfer rates of heated devices by the porous medium.

In the past, lots of related literature investigated heat transfer mechanisms of the porous medium in situations of forced convection [1–15], mixed convection [16–21], natural convection [22–30], and obtained remarkable results. Heat generation devices mentioned in the above literature were fixed and not affected by dynamic motions. However, devices used in moving structures or portable equipment are difficult to avoid the influence of dynamic motions. Although lots of literature [31–36] investigated heat transfer mechanisms of the device subject to the reciprocating motion, which is a kind of dynamic motion and easily simulated, and clarified detailed phenomena. A method, which applies the porous medium to the device subject to the reciprocating motion for enhancing heat transfer rates, is not proposed yet, because the method needs to solve the effects of the reciprocating motion and porous medium on the heat transfer mechanism of the device simultaneously. It causes solution methods to be more complicated than those used in the above literature. Accordingly, related investigations are hardly conducted.

The aim of the study investigates the enhancement of heat transfer rates of a reciprocating curved channel partially installed by the porous medium numerically. The arbitrary Lagrangian–Eulerian method (ALE), which is firstly derived to be used in the porous medium, is adopted as the solution method to treat a moving boundary problem induced by the reciprocating curved channel. Parameters of the Reynolds numbers, porosities, frequencies and amplitudes are examined. The results show that the enhancements of heat transfer rates of most porous medium situations are achieved. In a few situations with the high porosity, heat transfer rates are unexpectedly inferior to those of without porous medium situations.

2. Physical model

A physical model of this study is a two dimensional curved channel which is composed of two vertical and one horizontal channels and is shown in Fig. 1. The total width and length are w_1 and h_0, respectively, and the width of the channel is w_0. A high and constant temperature T_h is assigned on the top surface $\overline{BC}$, and the other surfaces are adiabatic. A porous medium is partially installed on the top surface in order to achieve heat transfer rates of the top surface. The height and porosity of the porous medium are h_2 and ε, respectively. Cooling fluids, of which the temperature and velocity are T_0 and v_0, respectively, via the left vertical channel flow into the curved channel. The region between

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Nomenclature

Da	Darcy number ($Da = K/w_0^2$), Eq. (1)
D_p	dimensionless diameter of a copper bead
e	element number in finite element method
En	enhancement factor for reciprocating motion of the channel, Eq. (27)
f_C	dimensional reciprocating frequency of the horizontal channel (s^{-1})
F	porous inertia factor used in momentum equation
F_C	dimensionless reciprocating frequency of the horizontal channel
g	acceleration of gravity ($m\ s^{-2}$)
h_0	dimensional height of the channel (m)
h_1	dimensional height of the right vertical channel (m)
h_2	dimensional height of the porous medium (m)
k_e	equivalent thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_f	thermal conductivity of work fluid ($W\ m^{-1}\ K^{-1}$)
K	permeability
l_C	dimensional reciprocating amplitude of the horizontal channel (m)
L_c	dimensionless reciprocating amplitude of the horizontal channel
m	number of non-linear iterations of the N–S equation
$Nu_{p,x}$	local Nusselt number (porous medium), Eq. (24)
$\overline{Nu}_{p,x}$	average Nusselt number (porous medium), Eq. (26)
Nu_x	local Nusselt number (without porous medium), Eq. (23)
$\overline{Nu}$	average Nusselt number (without porous medium), Eq. (25)
p	dimensional pressure ($N\ m^{-2}$)
P	dimensionless pressure
P_P	dimensionless pressure of porous medium
Pr	Prandtl number ($=\rho c \upsilon/k_f$), Eq. (1)
Pr_e	equivalent Prandtl number in porous medium ($=\rho c \upsilon/k_e$), Eq. (1)
p_f	dimensional pressure of porous medium ($N\ m^{-2}$)
p_∞	dimensional reference pressure ($N\ m^{-2}$)
Re	Reynolds number ($=\rho_0 \omega_0/\upsilon$), Eq. (1)
RP	ratio index of driving forces, Eq. (29)
t	dimensional time (s)
T	dimensional temperature (K)
T_0	surrounding temperature (K)
T_h	dimensional high temperature (K)
T_p	dimensional temperature in porous medium
ΔT	temperature difference between T_h and T_0 ($=T_h - T_0$)
u, *v*	dimensional velocities of *x*- and *y*- directions (ms^{-1})
u_p, v_p	dimensional velocities in porous medium (ms^{-1})
U, V	dimensionless velocities of X- and Y- directions
U_p, V_p	dimensionless velocities in porous medium (ms^{-1})
$\lvert\vec{U}\rvert$	dimensionless velocity magnitude ($=(U_p^2 + V_p^2)^{1/2}$)
v_0	dimensional velocity of the inlet cooling air (ms^{-1})
V_0	dimensionless velocity of the inlet cooling air
v_C	dimensional reciprocating velocity of the piston (ms^{-1})
V_C	dimensionless reciprocating velocity of the piston
v_m	dimensional maximum velocity of the piston (ms^{-1})
V_m	dimensionless maximum velocity of the piston
$\hat{v}$	dimensional mesh velocity in *y*- direction (ms^{-1})
$\hat{V}$	dimensionless mesh velocity in Y- direction
V_η	dimensionless node velocity of the moving mesh region
w_0	dimensional width of the channel (m)
w_1	dimensional length of the horizontal channel (m)
x, *y*	dimensional Cartesian coordinates (m)
X, Y	dimensionless Cartesian coordinates

Greek symbols

υ	kinematic viscosity ($m^2\ s^{-1}$)
α	thermal diffusivity ($m^2\ s^{-1}$)
ε	porosity ($m^3\ m^{-3}$)
τ	dimensionless time
$\Delta\tau$	dimensionless time step interval
τ_P	dimensionless time interval of a periodic cycle
ρ_0	dimensional density of air ($kg\ m^{-3}$)
ρ_f	dimensional density of air in porous medium ($kg\ m^{-3}$)
η_i	vertical position of the node in the moving mesh region
η_0	vertical total length of the moving mesh region
θ	dimensionless temperature
θ_p	dimensionless temperature in porous medium
φ	dimensionless computational variables U, V and P

Superscripts

–	mean value
→	velocity vector

Subscripts

f	working fluid
p	porous medium
0	surroundings

the $\overline{OP}$ and $\overline{MN}$ is flexible and can be elongated from w_0 to $w_0 + l_C$. The magnitude of l_C is the reciprocating amplitude. Therefore, computational grids in this region are extensible. As the horizontal channel moves upward that means that the $\overline{MN}$ will be fixed and the $\overline{OP}$ to move upward, and the maximum moving distance is l_C. Afterward, the $\overline{OP}$ moves downward and returns to the original location. The moving velocity is v_C expressed in terms of $v_C = v_m \sin(2\pi f_C t)$ in which v_m and f_C are the maximum velocity and frequency, respectively. The maximum velocity is equal to $2\pi l_C f_C$. The reciprocating motion of the channel affects behaviors of fluids transiently, thus phenomena become time-dependent and could be classified into a kind of moving boundary problem. For satisfying convergence criteria of computation processes, the length of the right vertical channel h_1 is long enough to hold fully developed conditions of temperature and velocity at the exit. For facilitating the analysis, the assumptions are described as follows:

(1) An incompressible laminar flow is adopted.
(2) Fluid properties are constant and the effect of the gravity is neglected.
(3) The no-slip condition is held on all surfaces. The fluid velocities on moving boundaries equal to the boundary moving velocities.
(4) The porous medium is made of spherical copper beads which do not chemically react with fluids.
(5) The transverse thermal dispersion is modeled by the Van Driest's wall function. The effective viscosity of the porous medium is equal to the viscosity of the fluids [9].

Based upon the characteristic scales of w_0, v_0, $\rho_0 v_0^2$ and T_0, the dimensionless variables are defined as follows

$$X = \frac{x}{w_0}, Y = \frac{y}{w_0}, U = \frac{u}{v_0}, V = \frac{v}{v_0}, V_C = \frac{v_C}{v_0}, U_p = \frac{u_p}{v_0}, V_p = \frac{v_p}{v_0}$$
$$P_p = \frac{p_f - p_\infty}{\rho_f v_0^2}, P = \frac{p - p_\infty}{\rho_0 v_0^2}, \tau = \frac{t v_0}{w_0}, \theta = \frac{T - T_0}{T_h - T_0}, \theta_p = \frac{T_p - T_0}{T_h - T_0}, Re = \frac{v_0 w_0}{\upsilon},$$
$$Pr = \frac{\rho c \upsilon}{k_f}, Pr_e = \frac{\rho c \upsilon}{k_e}, F_C = \frac{f_C w_0}{v_0}, Da = \frac{K}{w_0^2}, \left|\vec{U}\right| = \left(U_p^2 + V_p^2\right)^{1/2} \quad (1)$$