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Forced convection from a circular cylinder in pulsating flow with and without the presence of porous media

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ABSTRACT

This paper examines the changes to the flow and heat transfer induced by a non-zero mean sinusoidally varying flow past a cylinder. This is done by simulating steady and pulsatile forced convective flows over a circular cylinder placed in either a horizontal empty or a porous medium filled channel. The incompressible Navier–Stokes equations are used for the empty channel, and the Darcy–Brinkmann–Forchheimer momentum and the two-equation energy *LTNE* models in the porous-material filled channel. The effects of pulsation frequency *St* and amplitude *A* on heat transfer are quantified, as the Reynolds number (Re_D = 1–250) and type of porous material (k_r = 0.1, 1.0, 10, 100) are varied, whilst keeping the structural properties of the porous medium constant. In the empty (non-filled) channel, initially steady and then unsteady wakes evolve with an increase in Reynolds number. For the time-dependent case, two kinds of wake structure, namely fully periodic and quasi-periodic shedding, are observed depending on the values of Reynolds number, oscillation amplitude and forcing frequency. For the porous-medium filled channel simulations, a highly stable flows results, i.e., without forming extended wakes in the regions behind and in front of the cylinder, due to the damping from the porous medium. This is true even at high amplitudes, e.g., $A > 1.0$, which generates reverse flow in the channel. In general, using porous media promotes much higher heat transfer enhancement from the cylinder than that promoted by using pulsating flow, particularly at higher Reynolds number. But, a significant thermal benefit can be achieved by combining both schemes; however, only at the higher Reynolds numbers studied.

1. Introduction

There has been a growing need in many modern technological thermal applications for using highly effective cooling techniques to achieve a satisfactory heat transfer enhancement with a minimum frictional losses, including a variety of passive or active cooling techniques. Among the heat transfer enhancement schemes, one of the promising techniques is the use of porous media subjected to flow pulsation. Porous media has emerged as a convincing passive cooling enhancer due to its large contact surface area to volume ratio and intense mixing of fluid flow. Also, the forced pulsation of incoming fluid at the entrance of the 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 transports in the direction normal to the heated surface.

Generally, the research that has been done on oscillating flow with porous media is really scarce and incomplete. Efforts have been given to exploring the use of porous media as a heat sink in a confined channel subjected to a pulsating flow due to the increasing demand to achieve higher heat transfer removal from chips used in high-performance high-power electronic devices. These studies are related to the aspect of forced-pulsating convection flow over full- or partial-porous systems. Paek et al. [26] performed an experimental study of pulsating flow through an insulated horizontal packed bed of spherical beads. It is indicated that the heat transport from the porous material is little affected by the introduction of flow pulsation if the pulsating amplitude is small; however, the heat transfer is decreased when the amplitude becomes large enough to cause a backward flow. Also, for a given amplitude, the pulsating frequency shows a positive effect on the rate of heat transfer between the packed bed and the flowing fluid; yet, these rates are still less than that for the case of steady flow. Fu et al. [10] and Leong and Jin [22,23] reported the experimental results for heat transfer in porous channels subjected to steady and oscillating air flows with reticulated vitreous carbon and metal foam materials. They found that the length-averaged Nusselt number for oscillating flow is higher than that for steady flow. The effects

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Nomenclature

A	dimensionless oscillating amplitude of axial inlet velocity
a_{sf}	specific interfacial area (m^{-1})
Bi	Biot number, $Bi = h_{sf}a_{sf}D_{cy}^2/k_s$.
c_p	specific heat capacity (J/kg K)
C_F	inertial coefficient, $C_F = 1.75/\sqrt{150\varepsilon^3}$
d_p	particle diameter (m)
D_{cy}	cylinder diameter (m)
Da	Darcy number, $Da = K/D_{cy}^2$
$\acute{f}$	pulsating frequency (Hz)
h_{cy}	cylinder surface heat transfer coefficient (W/m^2 K)
h_{sf}	interfacial heat transfer coefficient (W/m^2 K)
H	channel height (m)
k_d	dispersion thermal conductivity (W/m K)
k_f	fluid thermal conductivity (W/m K)
k_s	solid thermal conductivity (W/m K)
k_st	stagnant thermal conductivity (W/m K)
k_r	solid/fluid thermal conductivity ratio, $k_r = k_s/k_f$
K	permeability of the porous medium, $K = \varepsilon^3 d_p^2/150(1-\varepsilon)^2$ (m^2)
L	channel length (m)
Nu	Nusselt number
$\acute{P}_f$	fluid pressure (N/m^2)
P_f	dimensionless fluid pressure, $P_f = \acute{P}_f/\rho_f\acute{u}_o^2$
Pr	Prandtl number, $Pr = \nu_f/\alpha_f$
Re_D	Reynolds number, $Re_D = \acute{u}_o\rho_f D_{cy}/\mu_f$
S	circumference of the cylinder (m)
St	dimensionless oscillating frequency parameter, Strouhal number, $\acute{f}D_{cy}/\acute{u}_o$
St_{res}	the resonant frequency
$\acute{t}$	time (s)
t	dimensionless time, $t = \acute{t}\acute{u}_o/D_{cy}$
$\acute{T}$	temperature (K)
$\acute{\mathbf{u}}$	vectorial fluid velocity (m/s)
$\mathbf{u}$	dimensionless vectorial fluid velocity, $\mathbf{u} = \acute{\mathbf{u}}/u_o$
$\acute{u}$	horizontal velocity component (m/s)
u	dimensionless horizontal velocity component, $u = \acute{u}/\acute{u}_o$
$\acute{u}_o$	horizontal fluid velocity at the inlet of the channel (m/s)
$\acute{v}$	vertical velocity component (m/s)
v	dimensionless vertical velocity component, $v = \acute{v}/\acute{u}_o$
$\acute{x}$, $\acute{y}$	horizontal and vertical coordinates (m)
x, y	dimensionless horizontal and vertical coordinates, $x = \acute{x}/D_{cy}$, $y = \acute{y}/D_{cy}$

Greek symbols

α_r	thermal diffusivity ratio, $\alpha_r = \alpha_s/\alpha_f$
ε	porosity
θ	dimensionless temperature, $\theta = (\acute{T} - \acute{T}_o)/(\acute{T}_h - \acute{T}_o)$
μ_f	fluid dynamic viscosity (kg/m s)
ρ_f	fluid density (kg/m^3)
ν_f	fluid kinematic viscosity (m^2/s)
φ	angular coordinate (°)

Subscripts

eff	effective
f	fluid
o	inlet of the channel
s	solid
t	total
w	wall of the channel

of thermal conductivity and permeability for different metal foam materials, and the kinetic Reynolds number based on the oscillating frequency and the amplitude, on heat transfer are also analyzed. It is shown that heat transfer from porous channel subjected to an pulsating flow can be enhanced by using materials of lower permeability and high thermal conductivity, and this enhancement increases with increasing the amplitude, and also with increasing the frequency but for relatively low values. Khodadadi [18] analyzed analytically a fully developed oscillatory flow through a porous medium channel bounded by two impermeable parallel plates, showing that the velocity profiles exhibit maxima next the wall. However, this study is not dealt with the issue of associated heat transports.

Numerically, Sozen and Vafai [28] simulated compressible flow of an ideal gas through an adiabatic packed bed. The effect of oscillating hydrodynamic and thermal inlet boundary conditions on the transport phenomena is examined. Once again, the average energy storage characteristics are found to be very close, without major differences, for both oscillating and constant boundary conditions. Another numerical data on heat transport of forced pulsating flow in a porous channel with a uniform temperature walls was provided by Kim et al. [19]. Their results show that the effect of pulsating on heat transfer between the channel wall and flowing fluid is more pronounced in the case of small pulsating frequency and large amplitude. Jue [14] tested oscillatory driven-cavity flow with mixed convection in a fluid-saturated porous medium. They found that the largest heat transfer occurs at a particular frequency which is known as the resonant frequency, and they also mentioned that the trend of the variation of heat transfer versus the oscillating frequency is seriously affected by Darcy number. Also, Huang and Yang [12] who examined fluid flow and thermal characteristics of oscillatory flow through a channel with two porous-block-mounted heat sources in tandem indicted to the presence of a critical value of Strouhal number (oscillating frequency) to obtain a maximum heat transfer enhancement factor. Below and above this critical value, the enhancement factor decreases afterward. This is occurred at low amplitude ($A = 0.6$). They also indicated to that the heat transfer enhancement factor for both heaters increases considerably with the pulsating amplitude. It is worth noting that their results show that the values of the pulsating heat transfer enhancement factor are not always larger than that of steady non-pulsating heat transfer enhancement factor depending on the values of the amplitude and frequency of the pulsating flow.

Steady and Pulsatile flow in a channel partially filled with two porous layers subjected to constant wall heat flux was also investigated numerically by Forooghi et al. [9]. Although, their results show the same finding for the pulsating amplitude which has a positive influence on heat transfer, entirely different trend of average Nusselt number against the Womersley number or frequency is observed. It has a minimum in a particular frequency, but surprisingly the maximum average Nusselt number occurs at the lowest frequency. This case is examined at high pulsating amplitude ($A = 1.5$). Therefore, from the above-mentioned studies, it seems that the influence of the pulsating frequency on heat transfer depends on the amplitude of pulsation. Such a finding would require further investigation since such observation has been not reported in the literature.

The problem of convective heat transfer over circular cylinder embedded in porous media has been the major topic for various studies in the past decades due to its relevance in a wide range of applications such as chemical catalytic reactors, nuclear waste repositories, solar power collectors, and heat exchangers. Most of these studies have been conducted on steady forced convection