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Heat transfer augmentation and vortex-induced vibration in a block-heated channel

Shiang-Wuu Perng [a], Horng-Wen Wu [b],*, Tswen-Chyuan Jue [c]

[a] Department of Mechanical Engineering, Kun Shan University, No. 949, Dawan Rd., Yongkang Dist., Tainan 710, Taiwan, ROC
[b] Department of Systems and Naval Mechatronic Engineering, National Cheng Kung University, Tainan, Taiwan, ROC
[c] Department of Vehicle Engineering, National Formosa University, Yunlin, Taiwan, ROC

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ABSTRACT

The finite element method is used to solve the general Darcy–Brinkman–Forchheimer model and energy equation for the heat transfer augmentation and vortex-induced vibration from the square vortex-generator wrapped by a porous sheath in the block-heated channel. The heat transfer augmentation and vortex-induced vibration have been investigated by varying Darcy number, porosity, porous sheath thickness, and Reynolds number. The results show that as Reynolds number and porous sheath thickness increase, heat transfer augmentation and vortex-induced vibration increase. Nevertheless, the porosity slightly influences the heat transfer augmentation and vortex-induced vibration. As Darcy number equals 10^{-4}, a small vortex-generator wrapped with a porous sheath of $E_P/w = 0.125$ best augments overall heat transfer from the heated-block surfaces with a reduction of 53.94% in vortex-induced vibration.

1. Introduction

Employing a bluff body leading to heat transfer augmentation in the channels has been a topic of numerous engineering applications such as heat exchangers, heat pipes, catalytic reactors, solar heating systems, air cooling, and electronic cooling. In the vicinity of a bluff body, the shedding of vortices induces unsteady forces of small amplitude with excitation near a structural resonant frequency that stimulates structural failures [1]. On a bluff body, the porous media is used to reduce the vortex-induced vibrations (VIV) or to regularize the vortex shedding in engineering applications [2,3]. A porous vortex-generator for enhancing heat transfer and reducing the VIV in a thermal system is then a significant topic of engineering interest.

In the recent two decades, some researchers examined the influence of various thermo-fluid and geometric parameters on the heat transfer for porous media. Hadim [4] explored the steady forced convection in a channel with fully and partially porous material, which contained porous layers above the heat sources and non-porous elsewhere. The heat transfer was discovered almost the same as if the channel was totally porous, which was a fascinating case due to about 50% reduction of the pressure drop. Huang and Vafai [5] employed multiple porous heated-blocks on the channel wall to explore the steady heat transfer. In the next step, Huang et al. [6] reported that steady heat transfer was augmented from multiple heated-blocks installed on one channel wall by porous shelters. Fu et al. [7] examined the steady heat transfer and flow through an obstacle with a heat source installed on one channel wall. Sung et al. [8] investigated how the location and size of the porous block enhanced heat transfer from the heat source inlaid on one channel wall. Yen et al. [9] explored the periodically steady heat transfer from a porous-obstacle-inlaid heat source dependent on the pulsating flow in a channel. They observed that the periodic variation in the structure of recirculation flows were generated by both pulsating flow and porous obstacle directly affecting the fluid flows around the porous obstacle and the heat transfer rate. Zehforoosh and Hossainpour [10] numerically investigated the steady laminar forced convection and pressure drop reduction in a partially porous channel with four dissimilar porous-blocks attached to the strip heat sources at the bottom wall. Yang and Hwang [11] numerically analyzed the turbulent heat transfer phenomena in a periodic-staggered way of a rectangular channel with porous ribs which were mounted on the top and bottom channel walls. Yang and Hwang [12] employed the standard $\kappa-\varepsilon$ turbulent model to study the augmentation of turbulent heat transfer from the pipe stuffed with porous media.

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* Corresponding author.
E-mail address: z7708033@email.ncku.edu.tw (H.-W. Wu).

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Nomenclature

$\mathbf{A}_{\alpha\beta}$	diffusion matrix of energy equation
B	length of side of the small square vortex-generator wrapped with a porous sheath ($B = B_1 + 2E_P$)
B_1	length of side of the small square vortex-generator
C_D, C_L	drag coefficient ($F_D/1/2\rho u_0^2 w$) and lift coefficient ($F_L/1/2\rho u_0^2 w$)
c_S	solid specific heat of the porous sheath
Da	Darcy number (K/w^2)
E_P	dimensionless porous sheath thickness ($E_P = E_P^*/w$)
E_P^*	porous sheath thickness
F_D	drag force ($F_D = \int_{\text{top surface}} \tau \, dB - \int_{\text{bottom surface}} \tau \, dB + \int_{\text{right surface}} p \, dB - \int_{\text{left surface}} p \, dB$)
F_L	lift force ($F_L = \int_{\text{left surface}} \tau \, dB - \int_{\text{right surface}} \tau \, dB + \int_{\text{bottom surface}} p \, dB - \int_{\text{top surface}} p \, dB$)
f_S	frequency of the vortex shedding
h	height of each heated block
h_1	distance between heated block and center of mass of the small square vortex-generator
H	channel height
$\mathbf{H}_{\alpha i\beta}$	pressure gradient matrix
k	thermal conductivity
K	permeability of the porous medium
$\mathbf{K}_{\alpha\beta\gamma j}$	conduction matrix
L	channel length
L_1	distance between inlet and center of mass of the small square vortex-generator
$\mathbf{M}_{\alpha\beta}$	mass matrix
n	normal vector
$[Nu]$	time-mean local Nusselt number ($\int Nu dt / \int dt$)
p	dimensionless static pressure ($p^*/\rho u_0^2$)
Pr	Prandtl number (ν/α)
q	dimensionless heat flux
q_0	reference heat flux
R_k	thermal conductivity ratio (k/k_f)
Re	Reynolds number ($u_0 w/\nu$)
$\mathbf{S}_{\alpha i\beta j}$	diffusion matrix of the momentum equation
t	dimensionless time ($t^*/(w/u_0)$)
u, v	dimensionless velocity components ($u = u^*/u_0$, $v = v^*/u_0$)
w	width of each heated block
x, y	dimensionless Cartesian coordinates ($x = x^*/w$, $y = y^*/w$)

Greek symbols

Δt	dimensionless time increment
ν	kinematic viscosity of fluid
ρ	density of fluid
θ	dimensionless temperature [$(T^* - T_0)/(q_0 w/k_f)$]
ε	porosity of porous medium
α	thermal diffusivity ($k/\rho c_P$)
σ	effective capacity ratio ($(\varepsilon \rho_f c_{Pf} + (1-\varepsilon)\rho_s c_s)/\rho_f c_{Pf}$)
η	tangential vector
ζ	normal vector

Superscript

$n+1$, n, $n-1$	$(n+1)$th, nth, $(n-1)$th time step
$*$	dimensional parameters

Subscript

e	effective
f	fluid
p	porous
w	indication of heated block boundary
α	nodal point

Additionally, several studies have been done on the vortex shedding from cylinders made of porous media. Jue [13] used a finite element method with a semi-implicit projection technology to obtain the 2D transient flow through a porous square cylinder. The results indicated that a higher permeability cylinder led to a later vortex shedding as well as a shorter shedding period. Chen et al. [14] numerically observed the fluid flow over a porous square block based on the stress leap interfacial conditions. Their results showed that a stress leap interface condition caused flow instability. Bhattacharyya et al. [15] numerically examined the fluid transport through a porous cylinder varying Reynolds number between 1 and 40, Darcy number (Da) $10^{-6} \leqq Da \leqq 1.5$, as well as porosity $0.629 \leqq \varepsilon \leqq 0.999$. Bruneau and Mortazavi [16] numerically explored the effects of a passive control introducing a porous ring around a circular cylinder, and showed that the passive control using a porous ring was a very efficient tool to prevent the VIV around a pipe. Perng et al. [17] numerically investigated the unsteady laminar flow and forced convection heat transfer across the porous square cylinder with the heated cylinder bottom at the axis in the channel for various cylinder-to-channel height ratios. They observed that the heat transfer for the square porous cylinder was enhanced for a higher cylinder-to-channel height ratio, Darcy number, and porosity.

The application of porous media to heat and mass transports has been investigated but few studies were focused on a solid vortex-generator wrapped with a porous sheath to investigate the transient convective heat transfer and fluid flow in a block-heated channel. Therefore, to realize how a vortex-generator wrapped with a porous sheath affects heat transfer and the VIV in a thermal system motivates this study. A non-Darcy porous media model is used to handle the transient fluid flows both outside and inside the porous sheath. The influence of Darcy number, porosity, porous sheath thickness, and Reynolds number on Nusselt number, drag and lift coefficients, and Strouhal number has been investigated numerically. For a transient incompressible thermal flow, a semi-implicit projection finite element method [18,19] is powerful, and this study then employs this numerical method. The observations of this study may be of interest to engineers endeavoring to develop thermal and vibration control of electronic devices or thermal energy storage systems and to researchers interested in the heat transfer augmentation and VIV through a vortex-generator wrapped by a porous sheath in a block-heated channel.

2. Physical model

The two-dimensional, laminar, transient, and incompressible flow is assumed for the forced convective heat transfer and the VIV through a vortex-generator wrapped with a porous sheath in a block-heated channel. The major geometry and the pertinent dimensions employed for this study are schematically indicated in Fig. 1. The assumptions in the model are given as follows [20].

(1) The fluid is Newtonian and fluid properties keep constant.
(2) The porous sheath is isotropic, homogeneous, and saturated with a single-phase fluid.