International Journal of Heat and Mass Transfer 115 (2017) 854–870

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Mixed convective heat transfer from a permeable square cylinder: A lattice Boltzmann analysis

T.R. Vijaybabu, K. Anirudh, S. Dhinakaran *

The Centre for Fluid Dynamics, Discipline of Mechanical Engineering, Indian Institute of Technology Indore, Khandwa Road, Simrol, Indore, Madhya Pradesh 453 552, India

A R T I C L E I N F O

Article history:
Received 10 February 2017
Received in revised form 28 June 2017
Accepted 11 August 2017

Keywords:
Square porous cylinder
Mixed convection
Steady flow
Darcy-Forchheimer force term
LBM
D2Q9 lattice model

A B S T R A C T

The flow and mixed convection heat transfer from a two-dimensional porous square cylinder under the influence of aiding buoyancy in an infinite stream are analysed employing a mesoscopic approach. Reynolds number (*Re*) and Darcy number (*Da*) considered in this study vary from 2 to 40 and 10^{-6} to 10^{-2}, respectively. The flow and heat transfer characteristics at the Prandtl number value of 0.71 (air) is compared for three different values of Richardson number (*Ri*) i.e. 0, 0.5 and 1. The numerical experiments in this study are carried out by using Lattice Boltzmann technique with two distribution functions. The BGK collision operator with Darcy-Forchheimer and Boussinesq force terms are added to the LB collision equation. Mach number annealing process is also carried out to accelerate the simulations. Flow and heat transfer characteristics are found to be a function of non-dimensional permeability (*Da*), buoyancy condition and Reynolds number. It is observed that a monotonous reduction occurs in the wake length and drag coefficient values at higher permeability levels. Whereas, aiding buoyancy depicts a pronounced reduction in wake length and an increment in drag coefficient values. The heat transfer enhancement ratio for all surfaces of the cylinder and mean Nusselt number were calculated to compare the thermal behaviour at various *Ri* and *Da* values. A significant augmentation in heat dissipation is reported for increasing values of *Ri* and/or *Da*. The percentage increment in mean Nusselt number at $Re = 40$, $Da = 10^{-2}$ is found to be 18% and 34% for $Ri = 0.5$ and 1, respectively with reference to the forced convection case. Also, heat transfer is maximum at $Da = 10^{-2}$ and $Ri = 1$ for the flow regime considered in this study. Correlations for mean Nusselt number, valid for the range of parameters considered in the present study, are also provided. The key results obtained from this study can be helpful for further research in different realms of engineering sciences, especially thermal engineering, aided by porous media modeling approach.

1. Introduction

Diverse engineering applications can be modeled or approximated as transport through porous media. Such instances can be found in packed bed heat exchangers, drying technology, catalytic reactors, thermal insulation, petroleum industries and electronic cooling. These modeling techniques can be an invaluable tool for the designers in different fields of engineering. Transport phenomena in porous media has been predominantly used in the field of geothermal engineering such as underground flow and filtration. However, more recently, attention is being paid for the application of porous media theory in thermal engineering, specifically for the purpose of heat transfer enhancement in compact devices. This occurrence accounts due to the inherent property of porous bodies, providing more surface area for heat dissipation in the same volume compared to solid bodies. A vast amount of books and articles, depicting typical case studies for application and numerical tools based on porous medium, are available in the literature [1–11]. Additionally, recent research works related to porous medium [12,13] have shown its ability on heat transfer magnification. Another prime advantage with the porous media modeling technique is that, it can be used to simplify a complex system with numerous elements into a single porous object. This empowers the engineer to discover experimentally unapproachable problems with significant computational economy. A relevant example would be of a nuclear reactor core, wherein the arrangement of fuel and control rods resemble a porous square system, as shown in Fig. 1. Such arrangements can be tuned to receive required flow and heat transfer characteristics. Thus, numerous research attempts are in progress to capture enhancement in the heat transfer performance by using porous media.

---

* Corresponding author.
E-mail address: ssdhinakar@gmail.com (S. Dhinakaran).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.08.033

Nomenclature

Notations

AB	front face of the cylinder
BC	right face of the cylinder
CD	rear face of the cylinder
DA	left face of the cylinder
C_D	coefficient of drag, $\frac{F_D}{0.5\rho v_0^2}$
c_F	non-dimensional Forchheimer form-drag coefficient
c_s	speed of sound, [m s^{-1}]
Da	Darcy number, $\frac{K}{H^2}$
d_p	particle diameter, [m]
e_i	discrete lattice velocity in direction i, $\frac{\delta x_i}{\delta t}$
F_b	Boussinesq force term, [N]
f_i	particle density distribution function along i^{th} link direction
f_i^{eq}	equilibrium distribution function of density along i^{th} link direction
F	body force due to the presence of the porous medium, [N]
F_i	total force term due to porous medium, [N]
g	gravitational acceleration, [m s^{-2}]
g_i^{eq}	equilibrium distribution function of temperature along i^{th} link direction
g_i	temperature distribution function along i^{th} link direction
G	body force due to gravity, [N]
H	height of the cylinder, [m]
K	permeability of the material, [m^2]
L_D	downstream length, [m]
L_U	upstream length, [m]
Ma	Mach number, $\frac{v}{c_s}$
N	number of lattices on the cylinder
Nu	local Nusselt number, $\frac{\partial\theta}{\partial n}$
Pr	Prandtl number, $\frac{\nu}{\alpha}$
Re	Reynolds number, $\frac{v_\infty H}{\nu}$
Ri	Richardson number, $\frac{g\beta\triangle\theta H}{v_0^2}$
T	dimensional temperature, [°C]
u^*	dimensional x-component velocity, [m s^{-1}]
v^*	dimensional y-component, [m s^{-1}]
u	non-dimensional x-component velocity, [m s^{-1}]
v	non-dimensional y-component velocity, [m s^{-1}]
V	auxiliary velocity, [m s^{-1}]
w_i	weighing factor in direction i
x^*, y^*	dimensional horizontal & vertical coordinate
x, y	non-dimensional horizontal & vertical coordinate

Greek symbols

ρ	fluid density, [kg m^{-3}]
τ	dimensionless relaxation time for density
τ'	dimensionless relaxation time for temperature
$\triangle x$	lattice space
$\triangle t$	time step
ν	fluid kinematic viscosity, [m^2 s^{-1}]
ϕ	porosity
θ	dimensionless temperature, $\frac{T-T_\infty}{T_w-T_\infty}$
β	thermal expansion coefficient, [°C^{-1}]
τ_t	non-dimensional time, $\frac{tv_\infty}{H}$

Subscripts

∞	far field value
o	inlet value
M	mean value
i	lattice link direction
w	wall
f	front face
r	rear face
$s1$	left face
$s2$	right face

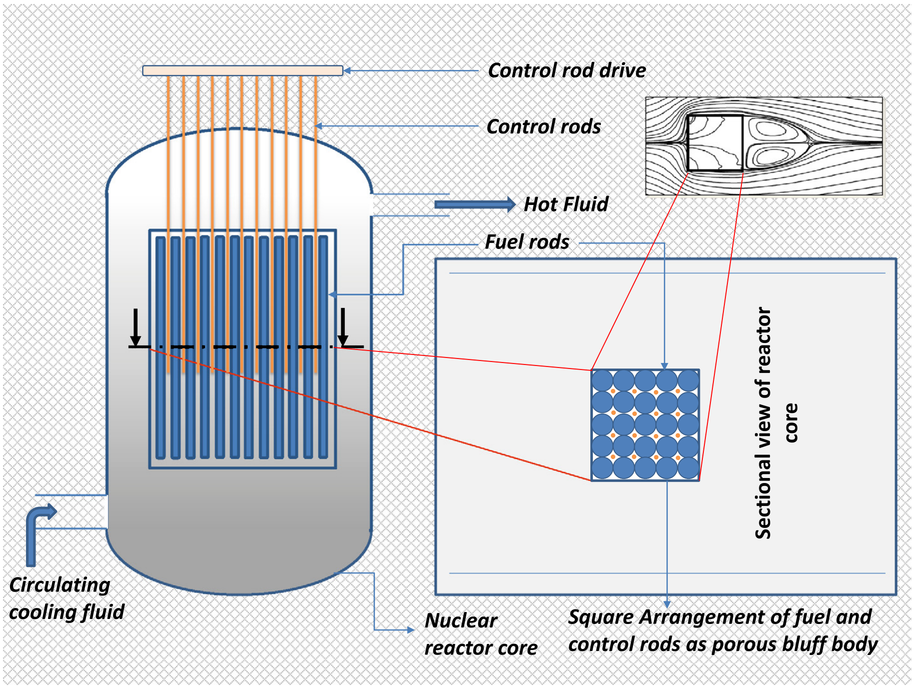

Fig. 1. An example of a scenario of flow around and through square shaped porous body - Fuel and control rods of a nuclear reactor mimic this situation.