ARTICLE IN PRESS
Alexandria Engineering Journal (2016) **xxx**, xxx–xxx

HOSTED BY
ELSEVIER

Alexandria University
Alexandria Engineering Journal
www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Numerical investigation of flow past a row of rectangular rods

S.Ul. Islam [a],*, H. Rahman [a], W.S. Abbasi [a], S.C. Saha [b], T. Shahina [c]

[a] *Mathematics Department, COMSATS Institute of Information Technology, Islamabad 44000, Pakistan*
[b] *School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, Brisbane, QLD 4001, Australia*
[c] *Department of Meteorology, COMSATS Institute of Information Technology, Islamabad 44000, Pakistan*

Received 19 November 2014; revised 4 April 2016; accepted 4 May 2016

KEYWORDS

Aspect ratio;
Flow patterns;
Force statistics;
Gap spacing;
Lattice Boltzmann method;
Rectangular rods

Abstract A numerical study of uniform flow past a row of rectangular rods with aspect ratio defined as R = width/height = 0.5 is performed using the Lattice Boltzmann method. For this study the Reynolds number (Re) is fixed at 150, while spacings between the rods (g) are taken in the range from 1 to 6. Depending on g, the flow is classified into four patterns: flip-flopping, nearly unsteady-inphase, modulated inphase-antiphase non-synchronized and synchronized. Sudden jumps in physical parameters were observed, attaining either maximum or minimum values, with the change in flow patterns. The mean drag coefficient (Cdmean) of middle rod is higher than the second and fourth rod for flip-flopping pattern while in case of nearly unsteady-inphase the middle rod attains minimum drag coefficient. It is also found that the Strouhal number (St) of first, second and fifth rod decreases as g increases while that of other two have mixed trend. The results further show that there exist secondary interaction frequencies together with primary vortex shedding frequency due to jet in the gap between rods for $1 \leqslant g \leqslant 3$. For the average values of Cdmean and St, an empirical relation is also given as a function of gap spacing. This relation shows that the average values of Cdmean and St approach to those of single rectangular rod with increment in g.

1. Introduction

Bluff structures, for example, circular and rectangular rods are the most common configuration in numerous practical applications. At high Reynolds numbers (Re) these applications can be found in bridges, chimneys, tall buildings, fences, overhead power-line bundles, masts, chemical-reaction towers, etc. Flow around a bluff body often involves various fluid dynamic phenomena, such as reattachment, separation and vortex shedding, while at low Re these applications can be found in micro-devices, such as in micro-electro-mechanical-system (MEMS) and cooling of fibers. Due to these applications the study of bluff body flow gained attractiveness in both science and engineering. Numerous studies have concentrated on flow past a square rod [1–3]. However, much less work has been conducted for a rectangular rod. The flow around a rectangular rod can result various local instabilities which can lead to global instabilities [4]. A small change in aspect ratio (R) can result drastic changes in the fluid dynamic characteristics

---

* Corresponding author.
E-mail address: islam_shams@comsats.edu.pk (S.Ul. Islam).
Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2016.05.003
1110-0168 © 2016 Faculty of Engineering, Alexandria University. Production and hosting by Elsevier B.V.

Please cite this article in press as: S.U. Islam et al., Numerical investigation of flow past a row of rectangular rods, Alexandria Eng. J. (2016), http://dx.doi.org/10.1016/j.aej.2016.05.003

Nomenclature

c_1	first rod
c_2	second rod
c_3	third rod
c_4	fourth rod
c_5	fifth rod
c_s	speed of sound
Cd	drag coefficient
Cl	lift coefficient
Cdmean	mean drag coefficient
Cdrms	root-mean-square value of the drag coefficient
Clrms	root-mean-square value of the lift coefficient
D	space dimension
E	spectrum energy
$\mathbf{e}_i$	particle velocity directions
f_i	particle distribution function
$f_i^{(eq)}$	equilibrium particle distribution function
f_s	vortex shedding frequency
Fd	force component in the in-line direction
Fl	force component in the transverse direction
g	gap spacing between rods
H	height of the computational domain
h	height of the rectangular rods
L	length of the channel
Lu	upstream distance from inlet to five rods
Ld	downstream distance from five rods to outlet boundary
p	pressure
Q	number of particles
Re	Reynolds number
s	surface-to-surface distance between rods
St	Strouhal number
$\mathbf{u}$	macroscopic velocity components
U_∞	uniform inflow velocity
w	width of the rectangular rods
w_i	weighting coefficients
$\mathbf{x}$	position of particle
τ	single-relaxation-time parameter

around the rod [5–7]. Further, the wakes of multiple bluff bodies placed next to each other create complex flow structures which also create instabilities and may cause acoustic noise or structural vibrations, which in some cases can trigger structure failure. Okajima [1] and Islam et al. [7] found that the drag coefficient undergoes significant changes in the range of $R = 0$–1. Abdollah et al. [5] experimentally and Islam et al. [7] numerically observed that the vortex formation region is smaller in the case of small aspect ratio compared to square rod ($R = 1$). Islam et al. [7] also observed that the physical parameters, such as drag coefficient (Cd) and Strouhal number (St) values for $R < 1$ are higher than those at $R = 1$ case. On the basis of above mentioned findings we chose the middle value of R from 0 to 1 in this numerical investigation.

Numerous experimental and numerical studies around two, three and four circular as well as square rods have been widely carried out. In spite of its great relevance to practical engineering problems, the flow past rectangular rods with different aspect ratios has received much less attention. Zdravkovich [8] categorized the flow interference between rods in proximity interference, wake interference and a combination of these two. To cite a few more examples, Sumner et al. [9] examined the wake of two and three side-by-side circular rods in a range of gap spacing (g) from 1 to 6 with $Re = 500$–3000 using particle image velocimetry and hot film anemometry. In their studies, for two rods case, single vortex street flow, deflected gap flow and synchronized vortex shedding, observed as g increased. In case of three rods, symmetric and asymmetric biased flow patterns were observed at $g = 1.25$. Alam and Zhou [10] studied the wake features, gap vortices, flow switch, and merging of two streets into one and also gave the quantitative information for flow around two side-by-side square rods using water tunnel experiment at $Re = 300$. In their investigation, they found four flow patterns, each characterized in terms of wake mechanism and vortex formation length. Agrawal et al. [11] found the inphase and antiphase vortex shedding behind two rods at $g = 3$, and biased flow pattern at $g = 1.7$, at $Re = 73$. Kang [12] investigated the wake of three side-by-side circular rods at a Reynolds number of 100 at $g < 5$. He observed five different kinds of flow patterns: single bluff-body ($g < 0.3$), deflected ($g \approx 0.3$), flip-flopping ($0.3 < g \leqslant 1.2$), inphase synchronized ($g \approx 1.5$) and modulation synchronized patterns ($g \geqslant 2$). The effects of gap spacing and Reynolds number on flow past three side-by-side square rods were investigated by Rahman et al. [13] and Islam et al. [14]. They found that the flow structure is strongly dependent on Reynolds number and gap spacing while the later one is more effective in case of unequal g.

On the other hand, investigations on flow past row of rods (more than three rods) are relatively scarce. In most of the studies emphases were on flow patterns for varying gap spacing in terms of wake structures and experimentally Guillaume and LaRue [15] observed flopping regime for flow past two, three and four rods array. Investigation in terms of physical parameters and time-trace analysis of each rod has not been well documented in the literature. Huang et al. [16] investigated vortex shedding characteristics on flow around row of circular rods, at a Reynolds number of 150, using FLUENT. They found that the vortex streets are stable and keep the same form for large distance at downstream of the computational domain for $g = 4$ and for $g < 2.5$ the wake behind the rods merges to form clusters and moves in a synchronized inphase pattern. Awale [17] observed that the inner two circular rods experience high drag compared to outer two rods in his study of flow past row of circular rods using ANSYS software. He investigated synchronized flow at $g \geqslant 6$, Quasi-Periodic-I flow at $3 \leqslant g \leqslant 5$, Quasi-Periodic-II flow at $g = 2$ and chaotic flow at $g \leqslant 1$. Mizushima and Akinaga [18] experimentally and numerically investigated the interactions of flow past a row of square and circular bars. They identified the inphase vortex shedding at $g = 1$ and antiphase vortex shedding at $g = 3$. In the aforesaid studies mostly emphasis was given on flow patterns but in some studies the time-trace analysis of drag and lift coefficients and spectrum analysis are also given [19,20].

Please cite this article in press as: S.U. Islam et al., Numerical investigation of flow past a row of rectangular rods, Alexandria Eng. J. (2016), http://dx.doi.org/10.1016/j.aej.2016.05.003