International Journal of Heat and Mass Transfer 127 (2018) 357–374

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A numerical study of forced convection from an isothermal cylinder performing rotational oscillations in a uniform stream

H.V.R. Mittal, Qasem M. Al-Mdallal *

Department of Mathematical Sciences, United Arab Emirates University, P.O. Box 15551, Al Ain, Abu Dhabi, United Arab Emirates

ARTICLE INFO

Article history:
Received 1 January 2018
Received in revised form 12 June 2018
Accepted 4 July 2018

Keywords:
Navier-Stokes equations
HOC
Rotational oscillation
Forced convection
Vortex shedding
Lock-on

ABSTRACT

Forced convection from a heated rotationally oscillating circular cylinder placed in a uniform cross flow of constant properties fluid is investigated. The two-dimensional governing equations of flow motion and energy are solved numerically on non-uniform polar grids using a higher order compact (HOC) formulation. The flow and thermal fields are mainly influenced by Reynolds number, *Re*, Prandtl number, *Pr*, maximum angular velocity of the cylinder, α_m, and the frequency ratio, f/f_0, which represents the ratio between the oscillation frequency, *f*, and the natural vortex shedding frequency, f_0. The numerical simulations are performed at $Re = 200, Pr = 0.5 - 1.0, \alpha_m \in [0.5, 4.0]$ and $f/f_0 \in [0.5, 3.0]$. The resulting lock-on phenomena behind the cylinder is detected and thermal field is determined. Comparisons with previous numerical and experimental results verify the accuracy and the reliability of the present study. Variations in heat transfer coefficients within the lock-on ranges are investigated to build a connection between the heat transfer and the lock-on regimes.

1. Introduction

The last few decades have seen a tremendous growth in the modelling and simulation of fluid flows around circular cylinders. The major reason behind this surge of interest is their practical applications in flows around long and slim structures like tall buildings, submarine periscopes; industrial significant devices like heat exchanger tubes, cooling towers; arrays of nuclear fuel rods. A few examples of numerous studies at microscale are micro hot wire anemometers, lab-on-a-chip systems, engineering applications such as process intensification systems involving an increase in heat transfer rates, or inkjet printing heads [23]. The relevance of the studies at microscale lies in their advantages such as low consumption of resources, the reduction of the size of equipment, fast analysis, high sensitivity, and short reaction times [37]. For more details, the readers are referred to Al-Mdallal and Mahfouz [3], Baranyi [10], Mahfouz and Badr [40] and Yan and Zu [57]. Though such structures may collapse due to alternate vortex shedding because they are prone to large amplitude oscillations, it has a significant effect on heat transfer between the structures and outside air too. It is therefore very important to study the hydrodynamics related to unsteady flows over bluff bodies is order to explore the relationship between heat transfer and vortex shedding.

The key feature of interest for flow around oscillating bodies is the periodic vortex shedding phenomenon and how it can lead to better understanding of both heat convection and unsteady hydrodynamics. For example, in the case of flow past a fixed cylinder, as Reynolds number exceeds 40, alternating vortices are shed periodically and are arranged downstream in a Karman vortex street. This phenomenon is found to induce unsteady flow dynamics near the cylinder surface and in turn enhance the heat transfer rate. This heat transfer enhancement under natural shedding process has inspired numerous researchers to study the potential of heat convection using forced oscillations and other different forms of unsteady excitations such as streamwise oscillations by Zijnen [58], Leung et al. [39], Takahashi and Endoh [55]; transverse oscillations by Kezios and Prasanna [22], Sreenivasan and Ramashandran [51], Saxena and Laird [52], Chin-Hsiang [14], Quintino [48], and references there in. It is noteworthy to mention that most of these studies reported conflicting results. As compared to transverse or stream wise oscillations, rotational oscillations are especially advantageous for applications with severe space constraints. A literature survey reveals the existence of many numerical and experimental studies related to the problem of cylinder performing rotational oscillations in a uniform stream, see the recent work of Okajima et al. [53], Taneda [54], Tokumaru and Dimotakis [35], Cheng et al. [12], Lu and Sato [28], Baek and Sung [7,8], Mahfouz and Badr [36,40], Chang et al. [13], Shiels and Leonard [33], Srinivas and Fujiswa [38], Fujisawa et al. [16],

* Corresponding author.
E-mail address: q.almdallal@uaeu.ac.ae (Q.M. Al-Mdallal).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.022
0017-9310/

Nomenclature

R_0	radius of the circular cylinder
R_∞	radius of the circular far-field boundary
U_∞	free stream velocity
$\tilde{\alpha}$	dimensional oscillatory velocity
α	dimensionless oscillatory velocity ($= R_0\tilde{\alpha}/U_\infty$)
$\tilde{\alpha}_m$	dimensional maximum angular velocity
α_m	dimensionless maximum angular velocity ($= R_0\tilde{\alpha}_m/U_\infty$)
$\tilde{f}$	dimensional oscillation frequency
f	dimensionless oscillation frequency ($= R_0\tilde{f}/U_\infty$)
f_0	natural frequency of vortex shedding
τ	dimensional time
t	dimensionless time ($= \tau U_\infty/R_0$)
Re	Reynolds number($= 2R_0U_\infty/\nu$)
Pr	Prandtl number
k	thermal conductivity
$h, \overline{h}$	local and average heat transfer coefficient
$Nu, \overline{Nu}$	local and average Nusselt number
$\overline{\overline{Nu}}$	time averaged Nusselt number
T	oscillation period of the cylinder
ν	kinematic viscosity of the fluid
C_L	lift coefficient
C_D	drag coefficient
r, θ	Polar coordinates
$\tilde{\psi}$, ψ	dimensional and dimensionless stream functions
$\tilde{\omega}$, ω	dimensional and dimensionless vorticities
$\tilde{u}$, u	dimensional and dimensionless radial velocities
$\tilde{v}$, v	dimensional and dimensionless tangential velocities

Al-Mdallal and Kocabiyik [2], Haji and Janajrich [15], Lu et al. [29,30], Kumar et al. [26], Sellappan and Pottebaum [34], Kumar [27], Konstantinidis and Bouris [24], Mittal et al. [41,43,44], Mittal [42], and the references therein. Most of these studies primarily focused on the phenomenon of vortex lock-on or "synchronization" (where the shedding frequency is dictated by the vibration frequency). Various frequency lock-on regions are determined by investigating different vortex shedding modes and nature of hydrodynamic forces acting on the cylinder.

Despite its importance, a limited number of studies on the problem of forced convection from a heated rotationally oscillating circular cylinder are available in the literature. Childs and Mayle [11] performed first theoretical analysis on this model based on boundary layer simplifications. They reported no substantial enhancement in heat transfer rates. Mahfouz and Badr [40] numerically studied the effect of lock-on phenomenon on heat convection for $40 \leqslant Re \leqslant 200$ and $0 \leqslant f/f_0 \leqslant 2$. Significant enhancement in the heat transfer rates was reported in the lock-on regime. For $Re = 750$, recent experimental investigations carried out by Sellapan and Pottebaum [49] reported that forced oscillation frequency and amplitude play a significant role in the enhancement of heat transfer rates. Beskok et al. [4] conducted a numerical study to investigate heat convection from the uniformly heated walls of a straight channel in presence of a rotationally oscillating cylinder at $Re = 100$. Their results showed the feasibility of using rotationally oscillating cylindrical actuators with air flow for electronic chip cooling applications. It has been well documented and proved in the literature that the heat convection mechanism is almost unaffected by the forced oscillations of the cylinder outside the lock-on regime [14,40].

A review of literature reports little knowledge about the effect of rotational oscillations on heat convection in the wake structure. Therefore, the motivation of this paper is to provide a comprehensive study of the relationship between unsteady motion of the wake and heat convection from a rotationally oscillating circular cylinder. Vortex shedding phenomena, though dependent on oscillating amplitude and forced oscillation frequency, directly influences heat transfer process since certain amount of heat is carried with every vortex which sheds into the wake. This work is an extension of the work of Mittal et al. [44] to consider the forced convection in the range of parameters $0.5 \leqslant \alpha_m \leqslant 4.0$ and $0.5 \leqslant f/f_0 \leqslant 3.0$ for $Re = 200$. In [44], the effects of oscillation frequency and maximum angular velocity on the vortex structures are studied, and the occurrence of new multiple lock-on regions is demonstrated in detail. When the flow properties become periodic after a certain time, it is referred to as lock-on regime. Present numerical simulations are conducted the forcing parameters lying in the lock-on regimes to address the main factors accountable for the increase or decrease in the heat transfer rates.

The question arises about the relevance of laminar, two dimensional flow simulations at a moderate $Re = 200$ to turbulence and three dimensional studies. It is noteworthy to mention that three-dimensional effects are reported by some researchers in the far wake when $Re > 178$; see Williamson [56] and Henderson [18]. However, forcing the cylinder to oscillate in the uniform stream is a type of wake control that suppresses the three-dimensionality and produces a two-dimensional flow at least in the near-wake region of the cylinder [5,6,25,32,20,26]. Hydrogen bubble technique based experimental observations of Kumar et al. [26] reported that rotational oscillations are proficient in fetching the vortex shedding back to a nominally two-dimensional state imposed by certain forcing conditions even for relatively small aspect ratio cylinders at a moderately high Re. Further, Newman and Karniadakis [31] reported weak dependence of many fluid structure interaction phenomena on Re. This implies that low Re investigations can be used in important applications like flow past tubes of heat exchangers and flows in hot wire anemometry (Baranyi and Baranyi [9]). The dominance of laminar flow studies in micro-scale applications also puts our study into perspective. Turbulence effects are assumed to be associated with the unsteadiness in the three dimensional wake or boundary layer of the cylinder. Therefore, based on the current mathematical model and forcing parameters, we believe that the two dimensional, laminar flow studies at $Re = 200$ hold relevance in turbulence and three dimensional studies involving heat transfer.

The paper is arranged in the following sequence. In Section 2, we discuss the governing equations along with initial and boundary conditions. Section 3 deals with the numerical method of solution and their finite difference discretizations. Section 4 deals with validation of our numerical scheme followed by results and discussion in Section 5. At the end, we summarize our observations in the concluding remarks.

2. Governing equations

We consider the two-dimensional unsteady, laminar, incompressible, viscous flow of a constant property Newtonian fluid over an infinitely long heated cylinder, whose axis coincides with the z-axis, placed horizontally in a cross-stream of an infinite extent. The two-dimensional flow configuration of the physical model is shown in Fig. 1. The fluid flow approaches the cylinder with a uniform velocity U_∞ and uniform temperature T_∞. Here, R_0 denotes