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Heat transfer from a heated non-rotating cylinder performing circular motion in a uniform stream

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ABSTRACT

Forced convection from a heated non-rotating circular cylinder of radius a performing a circular motion of radius A^* and placed in a uniform cross flow of constant properties fluid is investigated numerically. The two-dimensional governing equations of flow motion and energy are solved numerically using Fourier spectral analysis together with finite difference approximations to determine the flow field characteristics and the heat transfer parameters. The flow and thermal fields are mainly influenced by Reynolds numbers, Re, Prandtl number, Pr, amplitude of circular motion, $Ar = A^*/a$, and the frequency ratio, $Fr = f^*/f^*_0$, which represents the ratio between the frequency of circular motion, f^*, and the natural vortex shedding frequency, f^*_0. The ranges considered for these parameters are $60 \leqslant Re \leqslant 180$, $0.1 \leqslant Ar \leqslant 1.0$ and $0.5 \leqslant Fr \leqslant 3.0$, while the Prandtl number is kept constant at 0.7. The study, in general, showed that the heat transfer rate increases appreciably in the high range of Re, Ar and Fr. Comparisons with previous numerical and experimental results verify the accuracy and the validity of the present study.

1. Introduction

Fluid flow around a circular cylinder has inspired numerous researchers as a successful model for studying various interesting and important phenomena related to heat transfer and hydrodynamics associated with unsteady flows over bluff bodies. More precisely, the prediction of heat transfer from a heated circular cylinder has been intensively studied because of their practical importance in aerodynamics and heat transfer applications such as space heating, flow around arrays of nuclear fuel rods, smokestacks and many other thermal applications; for more details the reader is referred to Bao et al. [1], Mahfouz and Badr [2] and Elnajjar et al. [3].

A major key feature of interest for flow around bluff bodies is the periodic vortex shedding phenomenon and how it can enhance both heat transfer and hydrodynamics. For instance, it is well-known that in the case of flow past a fixed cylinder at Reynolds number greater than 47, two vortices are shed periodically from both sides of the cylinder and arranged downstream in a Karman vortex street. This vortex shedding process is found to enhance heat transfer rate. Later, this heat transfer enhancement under natural shedding process has inspired many researchers to study the effect of cylinder excitations (i.e. using forced oscillations) on heat convection enhancement, see Mahfouz and Badr [2].

The literature reveals large number of experimental, theoretical and computational studies on the problem of a cylinder performing rectilinear or rotational oscillations in the presence of uniform flow; see, by way of example not exhaustive enumeration, Bao et al. [1], Sarpkaya [4], Bearman [5], Williamson and Govardhan [6], Bishop and Hassan [7], Lu and Dalton [8], Guilmineau and Queutey [9], Barrero-Gil and Fernandez-Arroyo [10], Al-Mdallal et al. [11], Al-Mdallal [12–14], Mahfouz and Badr [2,15,16], Baranyi [17], Leontini et al. [18], Konstantinidis and Bouris [19], Ongoren and Rockwell [20], and the references there in. The majority of these studies focused on exploring the phenomenon of vortex lock-on or "synchronization" (where the shedding frequency is dictated by the vibration frequency) via the analysis of hydrodynamics forces acting on the cylinder and the formation of the vortex shedding modes. In fact, most of these studies demonstrated the existence of lock-on regions when $f^* \cong 2f^*_0$ for the case of a cylinder performing forced streamwise oscillation while when $f^* \cong f^*_0$ for the case of a cylinder performing forced transverse or rotational oscillations. For comprehensive summary of findings of lock-on regions and the vortex shedding modes on a forced streamwise or transverse oscillations of a circular cylinder in a uniform flow,

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Nomenclature

a	radius of the cylinder
A^*	dimensional radius of circular path (amplitude)
Ar	dimensionless radius of circular path ($= A^*/a$)
f_0^*	natural frequency of vortex shedding from a stationary cylinder
f^*	forced frequency of cylinder motion
Fr	frequency ratio ($Fr = f^*/f_o^*$)
F_0, F_n, f_n	Fourier coefficients for stream function
G_0, G_n, g_n	Fourier coefficients for scalar vorticity
$h, \bar{h}$	local and average heat transfer coefficient
H_0, H_n, h_n	Fourier coefficients for fluid temperature
k	thermal conductivity
$Nu, \overline{Nu}$	local and average Nusselt number
$\bar{\bar{Nu}}$	time averaged Nusselt number
Pr	Prandtl number
Re	Reynolds number
S_0	Strouhal number ($= 2af_0^*/U$)
S	dimensionless forced frequency of cylinder motion ($S = 2af^*/U$)
t^*	dimensional time
t	dimensionless time ($= Ut^*/a$)
T	temperature
U	velocity of free stream
x, y, z	Cartesian coordinates

Greek symbols

α	thermal diffusivity
ϕ	dimensionless temperature ($= (T - T_\infty)/(T_w - T_\infty)$)
θ, ξ	modified polar coordinates
ν	kinematics viscosity
ρ	density
ψ', ψ	dimensional and dimensionless stream functions
ζ', ζ	dimensional and dimensionless vorticity

Subscripts

w	at the cylinder surface
∞	at an infinite distance from the surface

the reader is referred to the works of Williamson and Govardhan [6], Al-Mdallal et al. [11], Al-Mdallal [14] and the references therein.

The problems of forced convection from a cylinder performing streamwise or transverse oscillations were investigated experimentally by several researchers. For instance, in the case of streamwise oscillation, Zijnen [21] reported a decrease in the heat transfer for $60 < Re < 25,800$, while Leung et al. [22] observed that the heat transfer rates may be enhanced as either the frequency or amplitude of oscillation is increased for high values of Reynolds number $Re < 15,000$. Takahashi and Endoh [23] observed an increase in heat transfer when the velocity amplitude is above a certain limit. On the other hand, the case of transverse oscillation is investigated experimentally by Kezios and Prasanna [24], Sreenivasan and Ramashandran [25], Saxena and Laird [26], Chin-Hsiang et al. [27], Quintino [28]. Kezios and Prasanna [24] observed about 20% increase in heat transfer rates. Saxena and Laird [26] considered a 22-mm diameter cylinder oscillated in an open water channel at $Re = 3500$. Their investigation demonstrated a 60% increase in heat transfer when the frequency and amplitude of oscillation tend to force eddies to lock-on to the cylinder oscillation. Chin-Hsiang et al. [27] considered $0 \leqslant Re \leqslant 4000$. Their results show that the heat transfer coefficient can be significantly increased by the oscillation of the cylinder. Moreover, they reported that the lock-on and turbulence effects played critical roles in enhancement the heat transfer performance. Quintino [28] reported that, when $433 \leqslant Re \leqslant 1300$, the effect of Re on optimal position is very limited, depending mainly from grid geometry and cylinder diameter.

On the other hand, the literature review of forced convection problems from a heated rectilinear (streamwise or transverse) oscillating cylinder showed several numerical investigations but restricted to laminar flows at low Reynolds numbers. It is well-known that the first numerical study of forced convection from a rectilinear oscillating cylinder was referred to Karanth et al. [29] at fixed Reynolds number $Re = 200$. In their study, they considered forcing frequency f^* to be exactly the natural shedding frequency f_0^*. They reported an increase in heat transfer rates that they have reported for both types of oscillations. For the case of transverse oscillation case, Cheng et al. [30] implemented the SOLA method to solve the unsteady velocity field in a non-inertial reference frame, and the energy equation is solved by a finite-volume method. The ranges of the Reynolds considered in this study are $0 \leqslant Re \leqslant 300$. They observed that, in the lock-on regime, an appreciable heat transfer increase caused by the oscillation is observed; however, outside this regime, the heat transfer is almost unaffected by the oscillation. Fu and Tong [31] studied numerically the flow structures and heat transfer characteristics of a heated transversely oscillating cylinder in a cross flow using finite element method. Their results showed that the heat transfer of the cylinder in the lock-on regime is enhanced remarkably. Bao at al. [1] studied numerically the convective heat transfer from a streamwise oscillating circular cylinder at $Re = 100 - 200$ using the lattice Boltzmann method. They reported that the heat transfer is enhanced when the cylinder oscillates with small amplitude and low frequency, while it is reduced at large amplitude and high frequency. In addition, they found that the average Nusselt number decreases as the oscillation frequency increases.

The intensive literature survey reveals that there are no papers studying the heat convection process from a circular cylinder performing circular motion in a uniform stream. Therefore, the motivation of this paper is to give an overall coverage of this problem. In this study, the work of Al-Mdallal [12] has been extended to consider the forced convection in the range of parameters $Re = 60 - 180$, $Ar = 0.1 - 1.0$, $0.5 \leqslant Fr \leqslant 3.0$ while the Prandtl number is kept constant at 0.7.

This paper is organized as follows: In Section 2, problem statement and governing equations are discussed. The numerical method of solution is presented in Section 3. Section 4 provides the physical results and discussion followed by conclusion remarks in Section 5.

2. Problem statement and governing equations

The physical model and coordinate system is shown in Fig. 1. The figure shows a circular cylinder of radius a and of infinite extent immersed in a uniform, constant properties fluid flow that approaches the cylinder with uniform velocity U and uniform temperature T_∞. The cylind X^* er is placed horizontally with its longitudinal axis coinciding with the $z-$ axis of the Cartesian coordinate system. At $t^* = 0^+$ the cylinder impulsively acquires both constant surface temperature, T_w and two-dimensional motion in $xy-$ plane.