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Free stream flow and forced convection heat transfer around a rotating circular cylinder subjected to a single gust impulse

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ABSTRACT

The effect of a single gust impulse on free stream flow and forced convection heat transfer across a two dimensional steadily rotating circular cylinder is numerically investigated. Reynolds number is varied between 80 and 160 while the non-dimensional steady rotation rate is restricted to a maximum value of 5 for a fluid with constant Prandtl number of 7. The governing equations namely continuity, momentum and energy equations have been solved using the Constant Wall Temperature boundary condition. Interesting results are presented depicting the behavior of the stretched boundary layer and the temperature field around the rotating cylinder. The convective heat transfer is observed to evolve differently for different combinations of the aforementioned parameters under the influence of the upstream gust.

1. Introduction

Flow past a circular cylinder has been the focus of intensive research for a while now. Wake dynamics and heat transfer patterns have been widely studied using varying flow configurations; for example stationary cylinders and rotating cylinders, cylinders subject to CWT boundary conditions and UHF boundary conditions, flow past a single cylinder and flow past different arrangements of multiple cylinders, to identify a few. Wide spread engineering applications as well as slightly advanced problems including flow control and wake dynamics grant this field of science exceptional interest. Cylindrical cooling devices in glass and plastic industries, textile, food processing, contact cylinder driers in paper industry and chemical processing industries are some of the applications of this problem. An important parameter used to characterize such problems is the Reynolds number, typically defined as $Re = \frac{\rho U_\infty D}{\mu}$, where ρ is the fluid density, U_∞ is the mean free stream velocity, D is the characteristic length which in this case is the cylinder diameter and μ is the fluids dynamic viscosity. As the Reynolds number of the system increases, the flow physics evolves noticeably. Firstly, the flow evolves from being steady to two dimensional periodic and then from being two dimensional periodic to three dimensional periodic at Reynolds number of 47 and 160 respectively, Baranyi [1]. Some other authors have reported slightly higher but comparable values of Reynolds number for the onset of three dimensional instability, see for example Barkley and Henderson [2] and Williamson [3]. The present study is therefore restricted to a maximum Reynolds number of 160.

Heat transfer and fluid flow across a stationary circular cylinder have been widely investigated by several researchers. Table 1 highlights some pertinent contributions to this topic. Heat transfer from the cylinder surface in such problems has been known to be a function of Reynolds number, Prandtl number and the choice of the thermal boundary condition i.e. Uniform Heat Flux (UHF) or Constant Wall Temperature (CWT). Considering the steady flow regime, the local and average Nusselt numbers are directly proportional with the Reynolds number of the problem. Sahu et al. [12] used a semi-implicit finite volume method on a non-uniform collocated grid to investigate the effects of Reynolds number and Prandtl number on the rate of heat transfer from a square cylinder in the unsteady two dimensional periodic flow regime. The authors observed that the Colburn heat transfer factor varies linearly with the Reynolds number for the range $60 \leqslant Re \leqslant 160$. Meanwhile, Behara and Mittal [13] focused on the oblique vortex shedding from a circular cylinder at low Reynolds number. It was noted that the oblique shedding angle varies linearly with the thickness of the boundary layer on the side wall which in turn can be controlled by controlling the length of the end plate and the flow Reynolds number. Buoyancy plays an important role in the forced heat transfer

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Nomenclature

$a_{0,1}$	gust amplitudes
$b_{0,1}$	gust peak coordinate
$c_{0,1}$	gust peak center coordinate
c_p	specific heat of the fluid [Jk g^{-1} K^{-1}]
C_D	total drag coefficient
C_L	total lift coefficient
D	diameter of the circular cylinder (m)
h	average heat transfer coefficient (Wm^{-2} K^{-1})
K	thermal conductivity of fluid (Wm^{-1} K^{-1})
$\overline{Nu}$	average Nusselt number (=hD/k) (–)
Pr	Prandtl number, $Pr = \frac{\mu c_p}{k}$ (–)
p	non-dimensional pressure (p^*/pU_∞^2), (–)
p^*	pressure (Pa)
Re	Reynolds number $Re = \frac{\rho U_\infty D}{\mu}$, (–)
t	time (s)
T_∞	temperature of the fluid at the inlet (K)
T_w	Constant Wall Temperature at the surface of cylinder
U	non-dimensional stream-wise velocity ($= u/U_\infty$), (–)
U_∞	free-stream velocity (ms^{-1})
u	longitudinal gust component (ms^{-1})
V	non-dimensional cross stream velocity ($= v/U_\infty$)
v	vertical gust component (ms^{-1})
x	stream-wise dimension of coordinates (m)
X	non-dimensional stream-wise dimension of coordinates (=x/D)
Y	non-dimensional cross-stream dimension of coordinates (=y/D)

Greek symbols

α	non-dimensional rotation rate, $\alpha = \frac{D\omega}{2U_\infty}$
ρ	density of fluid (kg/m^3)
θ	non-dimensional temperature ($\theta = \frac{T-T_\infty}{T_W-T_\infty}$).
μ	dynamic viscosity of fluid (kg/m-s)
τ	non-dimensional time (=$\frac{tU_\infty}{D}$)
ω	constant angular velocity of cylinder surface, (rad/s)

Abbreviations

CWT	Constant Wall Temperature
UHF	Uniform Heat Flux
SIMPLE	semi implicit method for pressure linked equation

from a heated circular cylinder. Soares et al. [14] explored parallel and contra flow directions with respect to the buoyant force for the case of a heated circular cylinder. It was observed that for the case of parallel flow, an increase in Richardson number resulted in an increase in the Nusselt number and the drag coefficient. However, a reversal in this behavior was observed for the case of contra flow.

We now consider the case of heat transfer and fluid flow across a circular cylinder which has been set to rotate. Table 2 presents some relevant contributions. Rotation of the circular cylinder is known to offset the stagnation point along the circle circumference and induce the Magnus effect both of which in turn effect the downstream wake pattern and the forced convection heat transfer from the cylinder surface. Mahfouz and Badr [23] investigated free stream flow and forced convection heat transfer from a rotationally oscillating circular cylinder in a two dimensional regime. The rotational oscillation frequency varied between 0 and twice the natural Strouhal number. The authors observed that the vortex shedding frequency locked-into the rotational oscillation frequency of the cylinder. It was observed that within the lock-in range, higher frequencies resulted in an enhanced heat transfer rate while lower frequencies resulted in a lower heat transfer rate. Outside the lock-in region, the effect of rotational oscillations on convection heat transfer was negligible. Paramane and Sharma [24] and [25] used a finite volume frame work to investigate the flow and heat transfer around a rotating circular cylinder. Heat transfer suppression due to rotation can be enhanced by increasing the Reynolds number or the rotation rate or both. The authors noted that as the rotation rate increases, forced convection heat transfer from the cylinder surface becomes independent of Reynolds number and thermal boundary conditions i.e. Constant Wall Temperature or Uniform Heat Flux.

As stated above, the literature offers sufficient guidance to address the fluid flow and forced convection heat transfer from rotating objects. A large bulk of the existing studies address such problems using firstly, objects with circular cross sections and secondly, two dimensional flow approximation. However, in reality steady stream of fluid is a rarity and fluctuations do arise. Therefore the transient or unsteady influence of gust has relevance. Most

Table 1
Heat transfer and fluid flow past a stationary cylinder.

Authors	Reynolds number range	Dimensionless rotation rate	Findings
Badr (1983), [4]	$1 < Re < 40$	–	Proposed a mathematical model to predict time development of the velocity and the temperature boundary layer in the Reynolds number range $1 \leqslant Re \leqslant 40$
Williamson (1996), [5]	$150 < Re < 270{,}000$	–	Three dimensional instabilities in the cylinder wake may be classified as extrinsic i.e. due to end conditions and intrinsic i.e. 3 D motion due to natural instabilities
Lange et al. (1998), [6]	$10^{-4} \leqslant Re \leqslant 200$	–	Drastic variation in the darg coefficient curve at the beginning of the vortex shedding regime. The critical Reynolds number was found to be 45.9. Innovative formulation was recommended for $0.3 \leqslant Re \leqslant 45$
Zhou et al. (1999), [7]	$Re = 200$	–	Fluid damping was answerable for limit cycle oscillations. Cylinder fluctuations could be large as 0.57 diameter of the cylinder under definite flow circumstances
Barkley (2006), [8]	$46 \leqslant Re \leqslant 180$	–	Eigen frequency of the mean flow matches the Strouhal number of vortex shedding. 2D vortex shedding in the cylinder wake is a marginally stable state over the entire range of Reynolds number
Bharti et al. (2007), [9]	$10 \leqslant Re \leqslant 45$	–	For the same Reynolds number and the Prandtl number, UHF shows high heat transfer by the value of 15–20% as compared to CWT
Jalil et al. (2007), [10]	$Re = 1.08 \times 10^4$	–	Heat transfer and the pressure drop swells with the increment in angle of attack. Using winglets enhanced the heat transfer by 14%
Haeri and Shrimpton (2013), [11]	$10 \leqslant Re \leqslant 250$	–	Proposed a correlation to estimate the local Nusselt number around circular cylinders with uniform circumferential temperature distribution