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Unsteady wake dynamics and heat transfer in forced and mixed convection past a circular cylinder in cross flow for high Prandtl numbers

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ABSTRACT

This paper investigates the combined effect of Prandtl number and Richardson number on the wake dynamics and heat transfer past a circular cylinder in crossflow using a SUPG based finite element method. The computations are carried out for $80 < Re < 180$, $0.7 < Pr < 100$ and $0 \leqslant Ri \leqslant 2$. The results have been presented for both forced and mixed convection flows. In the case of forced convection, crowding of temperature contours with reduced spatial spread is observed for increasing Prandtl numbers. The local and average Nusselt numbers are found to increase with increasing Reynolds number and Prandtl number. The average Nusselt number and Colburn factor are found to vary as $Re^{0.548}\ Pr^{0.373}$ and $Re^{-0.452}$, respectively. The extrapolated results of the average Nusselt number for low and high Reynolds numbers are found to match quite well with the available results in literature. Effect of Prandtl number shows various interesting phenomena for the mixed convective flows. Increasing the Prandtl numbers resulted in decreasing deflection and strength in the wake structures. The effect of baroclinic vorticity production during vortex shedding has been demonstrated at the vicinity of the cylinder and near wake. The Strouhal number is found to decrease with increasing Prandtl number, in the case of buoyancy induced flow. The effect of increasing Prandtl number is manifested as the stabilizing effect in the flow. This is, perhaps, the first time that such behavior for the Prandtl number is being reported. Additionally it is observed that the average Nusselt number decreases with increasing Richardson number.

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1. Introduction

Flow past a circular cylinder and the phenomenon of vortex shedding have been the subject of voluminous computational and experimental studies. A substantial body of work has been devoted for understanding the spatial structure of cylinder wake, vortex shedding and other wake flows. Furthermore several studies have been undertaken to understand the heat transfer phenomenon at different flow conditions. In such studies, the momentum and heat transfer under cross flow situations have been identified as the subjects of considerable theoretical and practical importance. The theoretical and numerical models are practically idealizations of several industrially important applications such as heat exchanger tubes, chimney stacks, cooling towers, measuring probes and sensors. To maintain better product quality and higher productivity, sufficient knowledge of heat transfer is very important in the application of food processing industries, where food substances are thermally treated as high Prandtl number fluids (up to $Pr = 100$).

Literature shows that during the bluff-body flows, formation of more or less coherent structures is observed at the wake. These structures are advected downstream for different flow conditions to form global wake characteristics. Vortex shedding appears in the form of von Karman Vortex Street when the Reynolds number exceeds the critical value of 45 (approx). Investigations show that the vortex shedding process can be disturbed and several new structures could be found if the flow field is perturbed by external forces. Such forces cause the flow to enter in an early transition stage by forming complex flow structures. One of such forces is the thermal buoyancy force. The influence of thermal buoyancy leads to mixed convective flows. The effect of Prandtl number plays a significant role in heat transfer and wake characteristics of mixed convective flows.

Some numerical studies are available on the effect of Prandtl number on heat transfer and wake characteristics for both forced and mixed convective flows. Several studies are available in the literature using air as the working fluid. Sanitjai and Goldstein [1] determined heat transfer characteristics in forced convection from circular cylinder in cross flow for $2 \times 10^3 < Re < 9 \times 10^4$ and

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Nomenclature

D	cylinder diameter
f	vortex shedding frequency
g	acceleration due to gravity
h	heat transfer coefficient
Gr	Grashof number $\left(=\frac{g\beta(T_w-T_\infty)D^3}{\nu^2}\right)$
j_c	Colburn heat transfer factor
Nu_θ	time averaged local Nusselt number on the cylinder surface
$\mathrm{Nu}_{\mathrm{avg}}$	average Nusselt number over the cylinder surface
p	non-dimensional pressure
Pr	Prandtl number $\left(=\frac{\nu}{\alpha}\right)$
Re	Reynolds number $\left(=\frac{\rho U_\infty D}{\mu}\right)$
Ri	Richardson number $\left(=\frac{\mathrm{Gr}}{\mathrm{Re}^2}\right)$
t	non-dimensional time
T	temperature
u, v	non-dimensional velocity components in x and y directions
U_∞	inlet velocity
x, y	non-dimensional coordinates

Greek symbols

α	thermal diffusivity of a fluid
β	thermal expansion coefficient
μ	viscosity of a fluid
ρ	density of a fluid
Θ	non-dimensional temperature, i.e. $\left(\frac{T-T_\infty}{T_w-T_\infty}\right)$
τ	time period for a complete cycle
ν	kinematic viscosity of the fluid
θ	angular location on the cylinder surface from the forward stagnation point
ω	vorticity

Subscripts

∞	inlet condition
w	wall
avg	average

$7 < \mathrm{Pr} < 176$. They showed that the distribution of local heat transfer changes with the above range of Reynolds numbers and the angular location over the cylinder, but after $\mathrm{Re} > 5 \times 10^3$ the local heat transfer increases with the Prandtl number. Juncu [2] numerically analyzed the forced convective heat transfer around two tandem circular cylinders at low Reynolds numbers ($1 < \mathrm{Re} < 30$) for various Prandtl numbers ($0.1 < \mathrm{Pr} < 100$). The heat transfer characteristics for the evolution of the system for $\mathrm{RePr} > 1$ showed completely different behavior than that of $\mathrm{RePr} < 1$ in their study. As in the former case, convection dominates over conduction, while for the latter case conduction dominates over convection.

Perkins and Leppert [3] studied local heat transfer coefficients from a uniformly heated cylinder using water as a working fluid under crossflow situations for $2 \times 10^3 \leqslant \mathrm{Re} \leqslant 12 \times 10^4$ and $1 \leqslant \mathrm{Pr} \leqslant 7$. Based on the experiments, they gave several correlations for local and average Nusselt numbers over the cylinder for both constant wall temperature and constant wall heat flux conditions. They also analyzed the effect of the variation of the fluid viscosity and free stream turbulence across the boundary layer on Nusselt number distributions.

For square cylinders, numerical investigations pertaining to the effect of Reynolds and Prandtl numbers on heat transfer are available for both steady and unsteady regime [4,5]. The heat transfer characteristics for an isolated square cylinder subjected to a low Reynolds number range of 1–45 and a very high Prandtl number range of 0.7–4000 was reported by Dhiman et al. [6]. In their numerical study they showed the dependence of both Reynolds and Prandtl number on heat transfer coefficients. They also gave correlations on Colburn heat transfer factor as a function of Reynolds number for both constant wall temperature and constant wall heat flux case, respectively.

Biswas et al. [7] studied unsteady mixed convection heat transfer in a horizontal channel with a built-in square obstacle using air as the working fluid. Their results show that the mixed convection can initiate periodicity and asymmetry in the wake at lower Reynolds numbers, in contrast to forced convection alone. Using the same medium, Singh et al. [8] studied the influence of favorable and adverse buoyancy in a vertical channel with a built-in circular cylinder. For Richardson numbers less than 0.15, the flow was characterized by broadening of the wake. Richardson numbers greater than 0.15, revealed separation delay and attached twin vortices behind the cylinder. Experimental investigation by Dumouchel et al. [9] showed the dependence of effective Reynolds number and effective temperature to characterize the wake structure.

The dualism between buoyancy and viscous forces may lead to various interesting phenomena. For the case of heated cylinder under cross flow conditions it has been numerically found by Biswas and Sarkar [10] that hydrodynamic instabilities grow and flow becomes unsteady periodic if the fluid is severely influenced by thermal buoyancy. It has been reported that angle of separation and average Nusselt number oscillates with the vortex shedding frequency. Lange et al. [11] numerically calculated momentum and heat transfer from a circular cylinder in laminar cross flow for the range $10^{-4} \leqslant \mathrm{Re} \leqslant 200$ and for temperature loadings of 1.003–1.5. Kieft et al. [12] reported both numerically and experimentally the effect of heat input on the wake characteristics and vortex structure from a horizontal circular cylinder in cross flow. At a fixed Reynolds number of 75 and by setting the range of Richardson number 0 to 1, they analyzed the different vortex characteristics and production of baroclinic vorticity production terms. All the above mentioned investigations mainly deal with constant Prandtl number fluids.

Another investigation by Kieft et al. [13] described the vortex shedding process in cross flow past a circular cylinder for a Reynolds number of 75 and a Grashof number range between 0 and 5000. They reported that the strength of the vortices shed from the upper half of the cylinder is stronger than those of lower half. Shi et al. [14] numerically simulated the effect of heating on the flow and heat transfer in a two dimensional laminar flow past a circular cylinder, considering the variation of fluid properties with temperature. In the range of $0.001 \leqslant \mathrm{Re} \leqslant 170$, they showed the dependence of various overheat ratio on vortex shedding frequency.

It is obvious from the above discussion that there is a need for investigating the combined effect of Prandtl and Richardson numbers on the wake characteristics and heat transfer from a circular cylinder in the unsteady range. In the present investigation, the combined effect of Prandtl and Richardson numbers on wake characteristics and heat transfer for a circular cylinder in crossflow is investigated numerically. Blockage ratio is chosen as D/H=0.05. For the simulation, a SUPG based Finite Element technique as [15] is used. Assuming the flow situation to be completely two-dimensional, the ranges of Reynolds and Prandtl numbers

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