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Numerical simulation and global linear stability analysis of low-Re flow past a heated circular cylinder

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ABSTRACT

We perform two-dimensional unsteady Navier–Stokes simulation and global linear stability analysis of flow past a heated circular cylinder to investigate the effect of aided buoyancy on the stabilization of the flow. The Reynolds number of the incoming flow is fixed at 100, and the Richardson number characterizing the buoyancy is varied from 0.00 (buoyancy-free case) to 0.10 at which the flow is still unsteady. We investigate the effect of aided buoyancy in stabilizing the wake flow, identify the temporal and spatial characteristics of the growth of the perturbation, and quantify the contributions from various terms comprising the perturbed kinetic energy budget. Numerical results reveal that the increasing *Ri* decreases the fluctuation magnitude of the characteristic quantities monotonically, and the momentum deficit in the wake flow decays rapidly so that the flow velocity recovers to that of the free-stream; the strain on the wake flow is reduced in the region where the perturbation is the most greatly amplified. Global stability analysis shows that the temporal growth rate of the perturbation decreases monotonically with *Ri*, reflecting the stabilization of the flow due to aided buoyancy. The perturbation grows most significantly in the free shear layer separated from the cylinder. As *Ri* increases, the location of maximum perturbation growth moves closer to the cylinder and the perturbation decays more rapidly in the far wake. The introduction of the aided buoyancy alters the base flow, and destabilizes the near wake shear layer mainly through the strain-induced transfer term and the pressure term of the perturbed kinetic energy, whereas the flow is stabilized in the far wake as the strain is alleviated.

1. Introduction

Low Reynolds number (*Re*) flow past an isolated cylinder is undoubtedly one of the most classical problem in fluid mechanics, and has been extensively investigated in both academic and industrial contexts during the past decades [1]. The incoming two-dimensional steady-state flow past the cylinder changes to a two-dimensional time-periodic unsteady flow as the Reynolds number exceeds a critical value Re_{cr}, (≈47 for the circular cylinder [2] and ≈45 for the square one [3]). The unsteady flow exerts fluctuating forces on the cylinder and possibly produces vortex induced vibrations, which are undesirable since they may result in structural failure. The investigation and understanding of the stability characteristics of the flow are crucial in developing new techniques to stabilize the flow and alleviate unwanted unsteadiness [4,2].

Most of the previous studies on incompressible flow past an isolated cylinder or similar geometries have focused on the development and interaction of three shear layers: namely, the boundary layer, the separated free shear layer and the wake, and analyzed their roles in the development of flow unsteadiness. It has been found that the flow in the separated free shear layer and wake can be stabilized by the aided buoyancy in flow past a heated cylinder (e.g. [5–11]), thus the results are physically significantly in a number of relevant fields, such as flow control, heat transfer enhancement and geometry optimization. The physical model is schematically shown in Fig. 1. The temperature of the upward inflow θ_{in} is lower than the cylinder surface temperature θ_w. The flow is heated through the mixed convection process over the cylinder and an upward (aided) buoyancy force is exerted mainly on the shear layer and wake flow. The aided buoyancy imposes additional momentum to the deficit flow in the free shear layer and wake thereby reducing the strain. The free shear layer is consequently more stable in the sense that the vortex shedding commences at a location further downstream of the cylinder.

The upward flow past an isolated heated cylinder has been numerically studied due to its wide applications in civil and industrial circumstances. The essential non-dimensional number, denoting the relative importance of natural convection to forced

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Nomenclature

B	blockage ratio
C_D	mean drag coefficient
D	cylinder diameter
Gr	Grashof number
k	kinetic energy
L_r	recirculation bubble size
Nu	mean Nusselt number
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
St	Strouhal number
t	time
u, v	velocity components
x, y	Cartesian coordinates

Greeks

α	azimuthal angle
θ	temperature
λ	complex circular frequency
ω	vorticity

Superscripts

$'$	perturbation

Subscripts

in	inflow
w	wall
loc	local
rms	root-mean-square

convection in a mixed convection process, is the Richardson number defined as $Ri = Gr/Re^2$, in which Gr is the Grashof number and Re is Reynolds number defined based on the cylinder diameter and the free-stream flow velocity. A large value of Ri corresponds to pronounced natural convection and significant buoyancy. Typically, the Richardson number is chosen positive after a non-dimensionalization using cold flow past a heated body. The earliest studies of the physical problem of upward flow past a heated circular cylinder was performed several decades ago [12]. Noto et al. [5] experimentally studied the flow past a heated circular or triangular cylinder at $Re \geq 800$. The wake flow is stabilized as it is accelerated by the buoyancy provided by the heated cylinder, while there is no significant variation of the separation point. Beyond a critical Richardson number Ri_{cr} the wake flow transforms from the unsteady vortex street pattern to the steady-state plume pattern: a process dubbed as the "breakdown of Kármán vortex street". The Strouhal number increases with Ri in the unsteady flow regime but abruptly ceases when the plume pattern is formed.

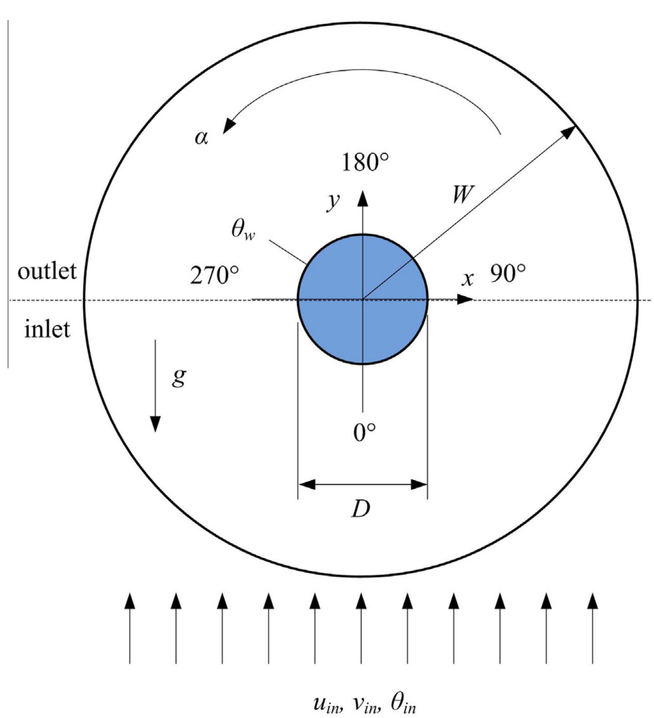

Fig. 1. Schematic of the physical problem.

Chang & Sa [6] numerically simulated the flow past a circular cylinder at $Re = 100$. The degeneration of the wake flow from time-periodic unsteady to steady-state symmetric twin vortices is observed at $Ri = 0.15$. The heating of the cylinder accelerates the boundary layer flow and also the flow velocity in the wake region. The smaller velocity difference between the wake and the ambient flow weakens the roll-up process of the shear layer, and consequently reduces the entrainment of the ambient flow into the wake until the degeneration of the shedding vortices. The heat transfer between the cylinder and the fluid is also reduced. However, it is found that the streamwise size of the wake recirculation bubble of the steady-state flow (plume pattern) substantially reduces as Ri increases, and the heat transfer rate, represented by the surface-averaged Nusselt number, increases monotonically. These conclusions are also supported by the numerical simulation results of Singh et al. [7] for the upward flow past a circular cylinder placed in a vertical channel at $Re = 100$ and a blockage ratio (ratio between the cylinder diameter and the transverse dimension of the channel) $B = 0.25$; the critical Richardson number $Ri_{cr} = 0.15$ is the same as the flow in the unconfined medium. Gandikota et al. [11] carried out comparative simulations in a nearly unconfined medium at $B = 0.02$, and a confined vertical channel at $B = 0.25$. Their results, for $Re = 50$—150, reveal that the presence of the channel walls stabilizes the wake flow in that Ri_{cr} is smaller for the confined channel case.

Apart from the circular configuration, the upward flow past a heated square cylinder has also been studied: here the flow experiences separation at the front corners. Sharma & Eswaran [8] numerically studied the upward flow past a square cylinder at $Re = 100$. The critical Richardson number Ri_{cr} for the transition to steady flow is in the range 0.125–0.15, somewhat close to the value for a circular cylinder. The streamwise size of the recirculation bubble increases with Ri in the unsteady regime, while it decreases with Ri in the steady regime. The same stabilization mechanism is valid for the square configuration as it is for the circular one: heating reduces the entrainment of the ambient fluid into the wake and weakens the roll-up of the free shear layer. In a follow-on study, Sharma & Eswaran [9] numerically studied the effect of the channel confinement on the flow at $Re = 100$ and $B \leq 0.5$. Both the Strouhal number and surface-averaged Nusselt number increase with Ri and the blockage ratio. Ri_{cr} decreases with the blockage ratio until $B = 0.3$, indicating that the channel walls stabilize the flow in addition to the aided buoyancy. However, Ri_{cr} increases with the blockage ratio in the range $0.4 \leq B \leq 0.5$ attributed to the interaction between the free shear layer on the cylinder and the boundary layer on the channel side walls. Singh et al. [10]