International Journal of Thermal Sciences 129 (2018) 266–279

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Control of vortex shedding, forces and heat transfer from a square cylinder at incidence by suction and blowing

A. Sohankar[*], M. Najafi

Department of Mechanical Engineering, Isfahan University of Technology, Isfahan, 84156-83111, Iran

ARTICLE INFO

Keywords:
Active flow control
Blowing and suction
Heat transfer
Perforated square cylinder
Incidence angle
Vortex shedding

ABSTRACT

This numerical investigation aims to study the control of the vortex shedding, heat transfer and the reduction of oscillatory forces from a perforated square cylinder at incidence ($\alpha = 0 - 45°$) via blowing and suction, Re = 100–200 and Pr = 0.71. At the early stage of investigation, four control cases are studied for Re = 150 and $\alpha = 45°$, where blowing or suction is applied only on the front or rear sides of the cylinder. The advantages of these cases are used to find the optimum conditions, where vortex shedding suppression occurs and a reduction of about 39% in the drag coefficient is provided. For the optimum control case, the effect of Reynolds number (Re = 100–200) is investigated and it is observed that vortex shedding is suppressed and the fluctuations in forces are removed for all Reynolds numbers employed. Also by increasing the Reynolds number from 100 to 200, the drag coefficient decreases about 10%, while the average Nusselt number increases about 85%. In addition, the optimum conditions are also found for different incidence angles ($\alpha = 0 - 45°$). The maximum and minimum reductions on the drag coefficients occur at angles of 5° and 20°, which are about 95% and 31% at Re = 150, respectively.

1. Introduction

At very low Reynolds numbers ($Re \leq 1$), the flow over a bluff body such as circular or square cylinder is fully attached with no separation [1–3]. At higher Reynolds numbers ($Re \approx 1 - 5$), the separation occurs and the symmetric vortices are formed behind the body while the flow remains steady [1–3]. The recirculation region behind the body grows with increasing Re and at a critical one in order of 50, the asymmetric shedding of these vortices in the wake region induces oscillatory forces on the cylinder [3–6]. This transition contains a 2D instability from a steady wake to a periodic wake [5,6]. The near-wake flow unsteadiness gives rise to fluctuating drag and lift forces and they are amplified at higher Reynolds numbers. By increasing the Reynolds number, a 3D transition is developed at a Re between 150 and 200 for circular and square cylinders, and the three-dimensional wake flow effects appear [7–10]. This fluid excitation is source for fatigue and flow-induced noise for many engineering applications. If the vortex shedding frequency becomes equal to the natural frequency of object, the resonance phenomenon occurs which can trigger the failure of structures. The structure of the wake and the shape of vortex formation are main factors for the value of the fluctuating forces exerting on the bodies. Thus, the elimination or reduction of the fluctuating forces and vortex shedding from such bodies is necessary to have safe structures with low extracted forces on them. Generally, various passive or active flow-control methods are used to achieve this aim.

Passive flow control methods require no external energy input, typically changing the geometrical configurations. Zdravkovich [11] reported a review on a classification of various aerodynamic and hydrodynamic means for suppression of the vortex shedding. He classified these passive means into three categories: 1) Surface protrusions for control of boundary layer, which affect the separation lines and/or separated shear layers, e.g. tripping wire, fin, etc.; 2) Shrouds, which affect the entrainment layers to supply fluid necessary for the growth of vortices, e.g. axial rod, axial slat, etc.; and 3) Near wake stabilizers, which prevent interaction of entrainment layers, e.g. splitter plate, guiding van, etc. Various passive controls have been employed by researchers to prevent vortex shedding and reduce fluid forces. For example, a control rod was set upstream of a square cylinder by Igrashi [12] and a remarkable drag reduction was achieved via an experimental work at Re = 32000. A passive slot control technique was numerically (LES) investigated by Hangan and Kim (Re = 22000, 52000) [13]. In this work, it was shown that the slot flow penetrates in the near-wake region generating a Kelvin–Helmholtz-type instability that mitigates the vortex shedding formation. They also reported the reduction on the drag and fluctuating lift coefficient via this flow control. The effect of a T-shaped plate on the reduction of fluid forces on two

---

[*] Corresponding author.
E-mail address: asohankar@cc.iut.ac.ir (A. Sohankar).

https://doi.org/10.1016/j.ijthermalsci.2018.03.014
Received 18 March 2017; Received in revised form 11 February 2018; Accepted 15 March 2018

tandem circular cylinders in a uniform cross-flow was examined at a Reynolds number of 6.5×10^4 by Mahbub Alam et al. [14]. They reported that when the T-shaped plate with a trail length of 0.70–1.00 times the cylinder diameter was used, an optimum reduction in fluid forces occurs, and the interference effect of the downstream cylinder on the upstream cylinder is completely suppressed. Drag reduction on a circular cylinder using dual detached splitter plates is numerically studied by Hwang and Yang (Re = 100) [15]. They employed two splitter plates with the same length as the cylinder diameter and placed along the horizontal centerline, upstream and downstream of the cylinder, respectively. The maximum drag reduction compared to the case without splitter plates has been reported to be 38.6%. Malekzadeh and Sohankar [16] studied the reduction of the fluid forces on a square cylinder in a laminar flow regime (Re = 50–200) by a vertical control plate placed upstream of the body. The largest reductions in the drag coefficient, rms lift and drag coefficients were reported to be 43%, 97%, and 93%, respectively.

Active flow control methods require an energy input. Solid wall motion, blowing or suction from a surface, the injection of micro bubbles or particles, acoustic excitation, periodic rotation or oscillation of a body, and electromagnetic forces are as examples for active control methods. A few researches have been published reporting the effects of blowing or suction through cylinders on the flow and heat transfer characteristics. Ling et al. [17] numerically analyzed the effects of normal surface suction and blowing through all surfaces of a square cylinder on the vortex shedding frequencies at Re = 250. They showed that an initial increase followed by a decreasing behavior in the Strouhal number with increasing the suction velocity occurs. In addition, a decrease in the Strouhal number with increasing the blowing velocity was observed. Mathelin et al. [18] numerically studied the flow around a porous circular cylinder in a cross-flow when complete blowing was applied through the cylinder at Reynolds number range of $3900 < Re < 31000$. They revealed that the pressure defect at the rear of the circular cylinder tended to “fill up” with blowing, leading to lower transverse static pressure gradients in the near wake. Ling and Fang [19] numerically investigated the effects of surface injection's position and strength on the vortex structure in flow around a circular cylinder, as well as the drag and lift forces at Re = 100. The results of this study show that either the suction on the shoulder of the cylinder or the blowing on the rear of the cylinder causes the lift force to reduce greatly. They also revealed that applying suction through the shoulder of the cylinder, when its strength is properly chosen, could reduce the drag force significantly, too. Fransson et al. [20] conducted experiments on the flow around a porous circular cylinder subject to continuous suction or blowing at the range of Reynolds numbers of $8.5–25 \times 10^3$. Their results show that the drag coefficient of the cylinder increases linearly with the blowing rate, whereas for suction there is a drastic decrease at a specific rate. In addition, it was observed that the Strouhal number decreases with blowing and increases with suction. Cuhadaroglu et al. [21] experimentally presented the pressure coefficient distributions around a horizontal square cylinder at Reynolds number Re = 10000, 16000 & 24000, where the injection through front, top and rear surfaces of the cylinder were applied. They found that applying injection through the front face increases drag coefficient while the blowing through the rear one decreases it. They also found that injection through the bottom and top faces has no considerable effect on drag coefficient. Dong et al. [22] numerically investigated an effective technique for suppressing the vortex-induced vibrations of a circular cylinder at Re = 500, 1000. One result of this study revealed that small amounts of combined windward suction and leeward blowing around the body modify the wake instability and lead to suppression of the fluctuating lift force. Cuhadaroglu and Turan [23] numerically found that the applying the injection or suction through various surfaces of the square cylinder significantly influences on the drag coefficient and vortex shedding frequency as well as heat transfer at Re = 21400. Cuhadaroglu [24] numerically investigated the effects of uniform injection or suction through a porous square cylinder on the flow field and on some aerodynamic parameters at Re = 21400. The results show that increasing suction velocity decreases drag coefficient for all suction configurations except that of suction through rear surface. The author also found that applying suction through top and bottom surfaces weakens the vortex shedding motion. Turhal and Cuhadaroglu [25] experimentally investigated the flow around perforated horizontal and diagonal square cylinder with surface injection through various surfaces for Re = 10000, 16000 and 24000. They revealed that surface injection through the top-rear, rear and all surfaces of a diagonal square cylinder reduces the drag coefficient while the injection through all surfaces only reduces the drag of a horizontal square cylinder. Sohankar et al. [26] numerically investigated the effects of uniform suction and blowing through the surfaces of a square cylinder at zero incidence angle on the vortex shedding, wake flow and heat transfer, Re = 70–150, Pr = 0.7. To find the optimum conditions, where vortex shedding suppression occurs and the maximum reductions on the forces and their fluctuations provide, three simple cases were examined. Based on the obtained advantages of these simple cases, different combinations of the suction and blowing on the cylinder sides were considered and an optimum case was introduced. In this case, suction was applied on the top and bottom surfaces and blowing is employed on the front and rear faces. The effect of the Reynolds number on the results for the optimum configuration was also investigated. This study showed that the lift and drag fluctuations for the optimum configuration decay and the maximum reduction on the drag force are 61%, 67% and 72% for Re = 70, 100, 150, respectively. Mao et al. [27] studied two- and three-dimensional incompressible flow past a circular cylinder for $Re \le 1000$. To suppress the unsteadiness of the flow, they employed a nonlinear optimal open-loop control driven by surface-normal wall transpiration. They suggested that the optimal control at small magnitude was achieved by applying suction upstream of the upper and lower separation points and blowing at the trailing edge. The large-magnitude optimal control was observed to spread downstream of the separation point and draw the shear layer separation towards the rear of the cylinder through suction, while blowing along the centerline eliminates the recirculation bubble in the wake. They demonstrated that the vortex shedding in two- and three-dimensional flow past a circular cylinder up to Re 1000 was suppressed, accompanied by 70% drag reduction when a nonlinear optimal control of moderate magnitude was applied. Wang et al. [28] studied the control of two-dimensional vortex-induced vibrations (VIVs) of a single circular cylinder at a Reynolds number of 100 using a novel windward suction-leeward-blowing (WSLB) concept. A lattice Boltzmann method based numerical framework was adopted for this study. Both open-loop and closed-loop controls were implemented. In the open-loop control, three types of actuation arrangements, including the pure suction on the windward side of the cylinder, the pure blowing on the leeward side, and the general WSLB on both sides, were implemented and compared. It was found that the general WSLB is the most effective, whereas the pure suction is the least effective. In the closed-loop control, the proportional (P), integral (I), and proportional-integral (PI) control schemes were applied to adjust the WSLB velocities according to the flow information obtained from a sensor. It was found that the use of only P control fails to completely suppress the VIV, the use of only I control can achieve the complete suppression, and the PI control performs the best in terms of both the control effectiveness and efficiency.

Based on the literature review, it is observed that the active flow control via suction and blowing over a square cylinder at zero incidence angle has not been broadly investigated especially at low Reynolds numbers (Ling et al., [17] for Re = 250 and Sohankar et al. [26] for Re = 70–150). In this work, the laminar unsteady flow is considered as employed in many previous studies mostly for flow over cylinders without flow control (e.g. see Refs. [1–10,26–33]). In addition, only one study was reported for square cylinder at incidence, where Turhal and Cuhadaroglu [25] investigated flow control via suction at angle of 45°