International Journal of Thermal Sciences 125 (2018) 405–418

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

A comprehensive investigation of vortex induced vibration effects on the heat transfer from a circular cylinder

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ARTICLE INFO

Keywords:
Vortex induced vibration
Convective heat transfer
Circular cylinder
Reduced velocity
Damping ratio

ABSTRACT

In this paper, the effect of vortex induced vibration (VIV) on convective heat transfer from an elastically mounted rigid circular cylinder in cross-flow is investigated numerically. The motion of cylinder is modeled by using a mass-spring-damping system. The effect of reduced velocity and damping ratio on the vortex formation, vortex shedding process, cylinder displacement amplitude, Nusselt number and the position of maximum local Nusselt number is studied. In this study the Reynolds Number and the mass ratio are 150 and 2, respectively. Furthermore, different values of reduced velocity and damping ratio are investigated (U_r= 3, 4, 5, 6, 7, 8 and ζ= 0. 0.01, 0.05, 0.1). The numerical results demonstrate that the reduced velocity and damping ratio can affect the heat transfer considerably. The beating phenomenon is occurs at U_r= 4 and ζ= 0.05 which leads to changes in the displacement amplitude and Nusselt number widely with respect to the time. In the beating phenomenon the total Nusselt number decreases in comparison with a stationary cylinder. The maximum heat transfer enhancement is obtained at $U_r = 4$, $\zeta = 0$.

1. Introduction

Nowadays, the heat exchangers are utilized in a wide range of industrial applications such as power plants, oil and gas industry, chemical processing, food and pharmaceutical industries, refrigeration and air conditioning devices, etc. The shell and tube and the tube-fin heat exchangers are the most common types of the heat exchanger in which fluid flows past the tubes, and vortex shedding phenomenon occurs at certain Reynolds number. Shedding vortices exert periodic forces on the tube that causes it to oscillate, so-called vortex induced vibration. Synchronization or lock-in phenomenon occurs when the vortex shedding frequency is close to the natural frequency of the structure, which leads to significant oscillation in amplitude.

In the recent years, several studies were accomplished on the vortex induced vibrations. Bishop and Hassan [1], Feng [2], Griffin and Ramberg [3], Williamson and Roshko [4] and Koopmann [5] were the first researchers that have investigated the vortex-induced vibration of a cylinder and have demonstrated that the vortex-induced vibration is a self-limiting motion. Chen [6] reported the various states that are related to the flow induced vibration of a circular cylinder.

Jiang et al. [7] simulated the flow induced vibrations of a square cylinder in a channel at Reynolds number of 200 by using the Lattice-Boltzmann method. They founded that two types of vibration exist for transversal movement cylinder, namely, periodical and non-periodical ones, which depend on the density ratio of the cylinder to the fluid. Chung [8] examined the wall effect on the vibrations of a circular cylinder with the Reynolds number of 200 and found that by decreasing the gap ratio, the vibration amplitude decreases and the lock-in domain increases. Also for the smaller gap ratio the maximum vibration amplitude happens at a larger reduced velocity.

The vortex-induced vibration of the circular cylinder for turbulent flow at three ranges of Reynolds number was studied numerically by Wanderley and Soares [9]. Their results show the strong influence of Reynolds number on the vibration amplitude, lift coefficient, and response frequency for a low mass-damping parameter. Zhao et al. [10] investigated the VIV of two and three-dimensional circular cylinder at Reynolds number ranging from 150 to 1000, the mass ratio $m^* = 2$ and zero-damping. Their results show that for a cylinder undergoing VIV at a fixed reduced velocity of 6 in the lock-in region, the transition of the flow from 2D to 3D occurs at the higher Reynolds number in comparison with a stationary cylinder. So it can be deduced that the cylinder vibrations lead to increase in the critical Reynolds number, ranging from 250 to 300.

Zhao [11] studied the effect of the inclination angle of 0° and 45° on the VIV of a circular cylinder at Re = 150 and 1000, a mass ratio m_r=2 and zero-damping, numerically. They found that the response

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https://doi.org/10.1016/j.ijthermalsci.2017.12.011
Received 24 December 2016; Received in revised form 10 July 2017; Accepted 11 December 2017

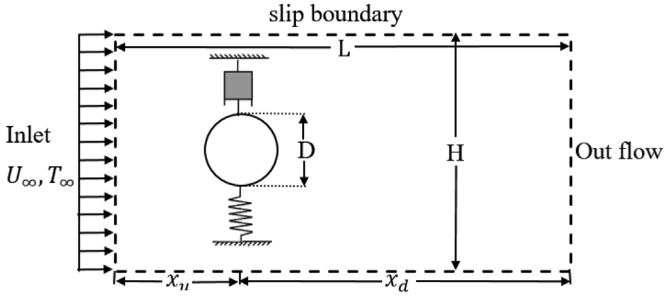

Fig. 1. Schematic diagram of the computational domain and its boundary condition.

amplitude and frequency at Re = 150 for two inclination angles are the same, both inside and outside of the lock-in region. But for Re = 1000 these parameters are slightly different. The effect of using a pair of synthetic jets (SJs) on control the VIV of cylinder at the Reynolds number of 100, the mass ratio m_r=2 and zero-damping were studied by Wang et al. [12]. They observed that the VIV of cylinder can be effectively suppressed by using SJ control with three parameter combinations.

Cui et al. [13] investigated the flow induced vibrations (FIV) of a square and rectangular cylinder with different incidence angle. They found that for square and rectangular cylinder the galloping, a self-excited instability with strong vibration at a lower frequency, occurs at the incidence angle of zero. The galloping was not observed at the incidence angle of 45 for rectangular cylinder and incidence angles of 22.5 and 45 for a square cylinder. Joly et al. [14] studied about the galloping phenomenon, too. Zhao et al. [15,16], Zhou et al. [17], Franzini et al. [18] and Jain and Modarres-Sadeghi [19] reported about the effect of the flow incidence angle on the VIV of the cylinder in their researches. Zhu et al. [20] studied the effect of a free-to-rotate dartlike overlay on the VIV of a circular cylinder. They found that the rotation of dartlike overlay is counterclockwise and leads to disturb the boundary layer near the body and suppress the vibration response to critical reduced velocity.

Recently, the effect of the free surface on VIV of the cylinder [21], the Wake-induced vibration of a small cylinder located in the wake of a larger cylinder [22] and flow-induced vibrations of circular cylinders arranged in a tandem configuration [23] were investigated, numerically.

As aforementioned, the influence of VIV on the aerodynamic and hydrodynamic aspects of cylinders was studied in the literature, widely. However, there are many situations where the heat transfer characteristics of the cylinder are essential. For example, when the tubes of heat exchangers vibrate due to the vortex shedding, their heat transfer coefficient are changed. The change in the heat transfer coefficient is critical for heat exchanger and should be examined. The heat transfer characteristics of stationary cylinders was studied by many authors [24–28]. But based on the authors' knowledge, the influence of VIV of cylinders on the heat transfer coefficient are not studied, yet. In the present work, the effect of cylinder oscillation on the quantity of heat transfer are investigated. In this study, the fluid is taken as water, and different values of damping coefficient and the reduced velocity are considered. The Reynolds number of the present work is taken to be 150. Since this value is under the critical Reynolds number, the 2D numerical solution is performed [10].

2. Problem description and formulation

The external flow over the circular cylinder investigated numerically. The cylinder is allowed to vibrate only in cross-flow direction. The computational domain is schematically shown in Fig. 1. At the inlet, the x-component of the velocity and the temperature are considered uniform U$_\infty$ and isothermal T$_\infty$, respectively. The cylinder is

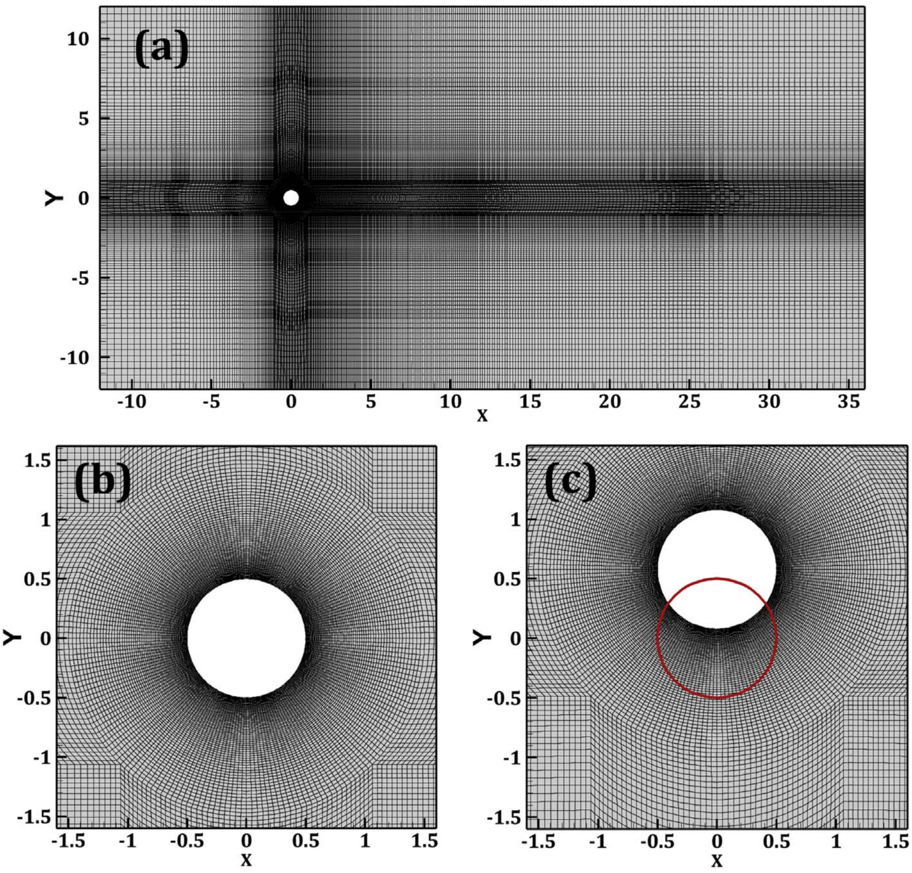

Fig. 2. Grid distribution (a) in the computational domain, (b) Enlarged view of the cylinder in the initial position (c) Enlarged view of the cylinder in the maximum displacement.