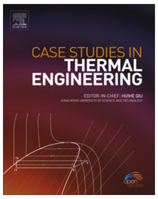
Case Studies in Thermal Engineering 12 (2018) 655–665

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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



Flow characteristics of two dimensional classical and pulsating jet in crossflow at low Reynolds number

Jianlong Chang[a,*], Xudong Shao[b], Jiangman Li[c]

[a] College of Mechatronic Engineering, North University of China, Taiyuan, China
[b] Beijing Institute of Space Systems Engineering, Beijing, China
[c] State Power Investment Corporation Shanxi New Energy Co., LTD., China

ARTICLE INFO

Keywords:
Jet in crossflow
Low Reynolds number
k-ε model
Vortex

ABSTRACT

Numerical cases are studied for the behaviors of two dimensional classical and pulsating jet in crossflow (JICF) with Reynolds number 100. The corresponding flow characteristics of two dimensional JICF are presented by k-ε model in this paper in the range of velocity ratio r $1 \le r \le 4$. Flow characteristics of vortex structure for two dimensional classical JICF have been analyzed first. The investigated vorticity field shows that the JICF falls into the turbulent flow with the increasing velocity ratio quickly. A vortex action is formed in the leeward side. The streamline field for the classical JICF have been obtained computationally and analyzed. The analysis of two dimensional pulsating JICF assumes the vorticity field at various velocity ratios, in which the ejected jet is enclosed by the fixed Strouhal number. The following analysis assumes the stream fields based on the same cases of the analyzed vorticity field. Vortex action area is also existing in the two dimensional pulsating JICF. Finally, the contrast of pulsating JICF with different Strouhal numbers have been obtained computationally and analyzed in detail to reveal the differences and connections between the pulsating JICF with different Strouhal numbers.

1. Introduction

A jet in a crossflow (JICF) is a fundamental flow phenomenon that includes significant components of many engineering applications [1–4]. The flow characteristics of a JICF in near field is very complicated. The interaction between the vertically ejected jet and the crossflow creates rich vortex structures, including the counter-rotating vortex pair (CRVP), the horseshoe vortex (HSV), the wake vortices (WV), the upright-vortices (UV) and the ring-like vortices (RLV). The investigation of flow characteristics of JICF is helpful for the application in the thermal engineering of liquid fuel atomization, jet flow control, film cooling of turbine and so on. This necessitates a better understanding of mixing in JICF, which is often complicated by different properties like fluid type as well as Reynolds number.

In previous work, lots of investigations for three dimensional JICF have been performed [5–7]. Further development of the diagnostic technique to improve spatial resolution and present images and statistics for various jets under crossflow experimental conditions are described [8]. Series images of various jets under crossflow experimental conditions reveal a near-nozzle flow field undergoing breakup and subsequent droplet formation by stripping. Results of a direct numerical simulation of a JICF with passive scalar mixing are presented [9]. The corresponding results show that the horseshoe vortex comes from the reversed jet fluid, different from high velocity ratio JICF. A useful study is done for two dimensional unsteady incompressible flow in which vorticity is

---

[*] Corresponding author.
E-mail address: changjianlong1989@126.com (J. Chang).

https://doi.org/10.1016/j.csite.2018.08.006
Received 17 July 2018; Received in revised form 22 August 2018; Accepted 29 August 2018

proportional to stream function perturbed by uniform stream [10]. It is concluded that the vortices created close to the actuators are died down before reaching to the trailing edge. two dimensional sonic injection normal to high-speed flow with a turbulent boundary layer is numerically investigated [11]. The results indicate that the separation length increases with increasing pressure ratio or increasing slot width as well as decreasing Reynolds number.

The development of large-scale structures for JICF through experiments are studied [12]. The experimental results show that the formation of reverse vortices generated at the jet nozzle could suppress the generation of vortices. DPIV is used to study the flow field of JICF with elliptical jet nozzle. The results are compared with the transverse jet [13]. The results show that the overall vortex structure of the elliptical JICF is similar to that of the circular JICF, however, the vortices matching, vorticity distribution and other aspects are quite different in near field. Flow evolution processes as well as the penetration, spread, and dispersion characteristics of elevated pulsating transverse jets are studied experimentally in a wind tunnel [14]. The corresponding results demonstrate that at low excitation Strouhal numbers, the jet column near the tube exit flap back-and-forth periodically at the excitation frequency and induced large up-down motions of the deflected jet. The study [15] investigates the influence of the velocity ratio on the flow field of a spatially oscillating jet emitted by a fluidic oscillator into a crossflow. It is found that the only parameters affecting the flow field for the given scenario are the velocity ratio and Strouhal number. Direct numerical simulation is performed to study the mixing behavior of pulsed jets in crossflow [16]. The simulation shows that at low velocity ratios, optimal pulsing conditions are related to the natural time scale on which hairpin vortices form.

There are two prominent effects on the flow characteristics of a JICF, one is the Reynolds number of the JICF, which is defined as $Re = \rho v d/\mu$. The other is the effective velocity ratio r [17], if the densities in the jet and the crossflow are the same, r can be defined as:

$$r = \frac{V_{jet}}{V_{crossflow}} \tag{1}$$

where, V_{jet} is the jet velocity, $V_{crossflow}$ is on behalf of the velocity of crossflow. If the densities in the jet and the crossflow are not the same, the effective velocity ratio r can be obtained by the square root of the momentum flux ratio as:

$$r = \sqrt{\frac{\rho_{jet} V_{jet}^2}{\rho_{crossflow} V_{crossflow}^2}} \tag{2}$$

where ρ_{jet} and $\rho_{crossflow}$ are the density of the jet fluid and crossflow fluid, respectively.

In the previous work, few researches on JICF under low Reynolds number are performed. So in this paper, k-ε model is used to calculate the two dimensional JICF with the effective velocity ratio $r = 1$–4 under low Reynolds number ($Re = 100$). The vortex structures of JICF are analyzed to reveal flow characteristics of two dimensional JICF.

2. Flow configuration and numerical methods

2.1. Flow configuration

As shown in Fig. 2, the diameter of the ejected jet for JICF is defined as D. The main channel for crossflow is rectangle, whose length and width are 65 D and 16 D respectively. The distance from the entrance of crossflow to the center of the jet nozzle is 5.5 D. The angle of the ejected jet and the crossflow angle is 90°. The fluid in the simulation is selected as water, whose Reynolds number is 100. As the formula for the Reynolds number, the diameter of the nozzle is used for the characteristic length, the effective velocity of the ejected jet for the classical and pulsating jet is the characteristic velocity. Structured grids are used for the simulation, with dense grids near the entrance of the ejected jet.

In relation to Fig. 1, the boundary conditions conducted in the cases are listed as follows. a) For the wall at bottom, no-slip boundary condition is conducted excluding the jet exit region. b) For the crossflow inlet and the jet inlet of the classical JICF, the uniform velocity/boundary layer profiles are used for the classical JICF. While the varying velocity is employed in the pulsating JICF, the detailed information is introduced below. c) At the domain exit, the pressure-outlet outflow boundary condition is adopted.

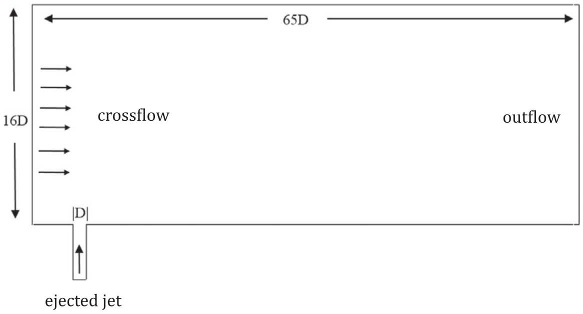


Fig. 1. Calculation area schematic for two dimensional JICF.