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The Kármán vortex street inversion and heat transfer around a square cylinder at low Reynolds and magnetic interaction numbers

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ABSTRACT

Three-dimensional numerical simulations, for confined flows and unconfined flows, have been carried out to study the Kármán vortex street inversion in the wake of a square cylinder. This paper is aimed to analyze the cause of the vortex inversion and to investigate the physical mechanisms. As two independent factors for the inversion, the wall confinement and the incoming flow conditions have been proved in a more rigorous way. It is shown that the interaction between the primary vortex and the incoming flow or the wall vortex layer is the fundamental cause. In order to compare the thermal transport phenomenon between the inversion and non-inversion cases, the top wall of a channel is kept at the free stream temperature and the bottom wall is set heated, while the cylinder is maintained adiabatic. The results indicate that the inversion phenomenon is not good for the heat transfer. Additionally, the effects of streamwise magnetic field on the vortex street inversion has been considered.

1. Introduction

Using the cylindrical obstacles to induce vortices and to enhance heat transfer rates has been applied in engineering and industrial process for a long time. Numerous numerical and experimental investigations have been carried out on the non-MHD [1–3] or MHD (MagnetoHydroDynamics) [4–7] flows over circular or square cylinders and excellent reviews are available. Attention has been paid on the effects of blockage ratio $\beta = D/H$, the ratio between the length of the cylinder sides D and the channel height H [8], as well as wall confinement [9,11,10], on the flow patterns, the flow instability, the wake structures [12–14], the heat transfer [15,16], and so on. Moreover, the evolution of the flow regimes and three-dimensional instability have been widely studied with or without magnetic fields [17–19]. However, the Kármán vortex street inversion, for which the vortexes shed from the upper and lower sides of cylinder intersect at a certain place of further downstream and their positions with respect to the symmetry line are inverted, remains relatively unexplored.

The definition of "inversion" was mentioned firstly by Suzuki et al. [20], in which this phenomenon had been studied in detail. They pointed out that the inversion of the Kármán street occurs only for $\beta \geqslant 0.1$ and is essentially caused by the effect of the lift-up of the vortices layers that are adjacent to the confining walls (thereafter defined as vortex layer). Still by Suzuki & Suzuki [21], a configuration with a high blockage ratio ($\beta = 0.3$) and a Poiseuille profile at the inflow had been considered, in which a strong interaction exists between the wake and the confining walls. They indicated that for the case with constant inflow velocity and low blockage ratio $\beta = 0.1$, no inversion can be observed. However, under the same condition, inversion phenomenon appears in the present study. In addition, it seems that their testify on the effects of vortexes layer for inversion is not rigorous, which motives us with a further study as well.

Only one study, quite recently, focused on the generation of the inversion of the vortex street [22]. Camarri & Giannetti carried out confined cases, for low to moderate blockage ratios ($1/10 \leqslant \beta \leqslant 1/6$), to identify that the amount of vorticity in the incoming upstream flow plays the leading role in the inversion. In fact, the present work indicate that the interaction between the wake and the vortexes generated by the confining wall or introduced by the incoming flow is the fundamental cause of the inversion. In addition, the artificial incoming vorticities can be considered as the results of confining wall, by adjusting the inlet length (L_i), the distance from inlet to the upstream side of cylinder, which would be illustrated particularly in Section 4.1.1. Moreover, combining with our opinion mentioned above, more detailed inter-

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pretation would be provided on the incoming vorticity, e.g. the distance between the incoming vortex layer (ΔL).

Researches on the heat transfer involving the inversion phenomenon are available [23–25]. However, to the best of our knowledge, the inversion is always ignored during the analysis of heat transfer and no published study has been focused on comparing the heat transfer efficiency caused by inversion and regular von Kármán vortex street. Moreover, our results indicate that the difference of heat transfer rates between the inversion and regular case is relatively considerable.

The last part of the paper is aimed to investigate the MHD effects on the inversion, which can be found in the self cooled blankets of fusion reactors [7,16]. Studies on the flow around a square cylinder under magnetic fields are available [7,26], in which all the simulations are two-dimensional. In the present paper, three-dimensional simulations have been conducted to analyze how the streamwise magnetic fields suppress the inversion, dissipate the vorticity, affect the heat transfer rates and drag or lift force. In addition, the physical mechanisms of the Lorentz force on the wake structures has been investigated.

Therefore, the aim of the present work can be summarized as: (i) studying the fundamental cause of the von Kármán vortex street inversion in detail combining the effects of confining walls and incoming conditions; (ii) investigating the inversion effects on the heat transfer; (iii) investigating the effects of magnetic fields on the inversion phenomenon.

2. Problem statement and formulation

2.1. Flow configuration and mathematical formulation

The physical model studied in the present work is shown in Fig. 1. The geometry consists of a square cylinder of dimension D, which is symmetrically placed in a duct. In order to avoid peculiar flow features related to a complex interaction between the wake and the confining walls, but still considering wall confinement effects, moderate blockage ratios $\frac{1}{20} \leqslant \beta \leqslant \frac{1}{5}$ are preferred. Moreover, results for $\beta = \frac{1}{10}$ can be directly used to compare with the experiment or simulation of Suzuki et al. [20]. By choosing the lower blockage ratio, $\beta = \frac{1}{20}$, for the unconfined flow, we can bring into focus on the incoming velocity profile effects, including intensity (Δu) and ΔL.

In the present study, the channel length is not uniform. In order to identify the wall confinement effect with a lower blockage ratio, the total length ($L = L_i + D + L_o$) could be large enough, 175D. Here, L_o represents the distance from outlet to the rear of cylinder. But in the presence of magnetic field, the channel can be short, for instance, as 44D. And this choice of parameters ensures minimal distortion of the flow structure due to the boundary conditions, while maintaining a reasonable computational cost, and is in line with those used by others in the literature [10,27,28]. The spanwise length is considered $W = H$.

The flow of an incompressible, electrically conducting Newtonian fluid, with the density ρ, the kinematic viscosity ν, the thermal diffusivity α and the electrical conductivity σ, is considered. An external homogeneous magnetic field of amplitude B_0 is applied along the streamwise direction x. The walls of the cylinder and the duct are assumed to be electrically insulating. In general, the magnetic Reynolds number for most cases of liquid metal flow encountered in industrial applications is very small, thus the induced magnetic field can be negligible when compared to the imposed magnetic field. Hence, in this study, it is also assumed that the magnetic Reynolds number is much smaller than unity, $Rm = \mu\sigma U_0 D \ll 1$, where μ stands for the fluid magnetic permeability, therefore the quasi-static approximation is invoked [29].

In addition, using the following typical scales, the magnetohydrodynamic governing equations can be non-dimensionalized: the cylinders diameter D for length, the mean velocity U_0 for velocity, ρU_0^2 for pressure, the imposed field B_0 for magnetic field, $U_0 B_0 D$ for the electrical potential, $\sigma U_0 B_0$ for electrical current density, and the temperature difference between the two parallel planes, $\Delta T = T_w - T_\infty$, for temperature, where T_w represents the heated wall temperature and T_∞ is the free stream temperature.

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla \cdot (\boldsymbol{uu}) = -\nabla p + \frac{1}{Re}\nabla^2 \boldsymbol{u} + N(\boldsymbol{j} \times \boldsymbol{e}_B) \tag{2}$$

$$\boldsymbol{j} = -\nabla \Phi + \boldsymbol{u} \times \boldsymbol{e}_B \tag{3}$$

$$\nabla \cdot \boldsymbol{j} = 0 \tag{4}$$

$$\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T = \frac{1}{PrRe}\nabla^2 T, \tag{5}$$

where the variable $\boldsymbol{j}, \Phi, \boldsymbol{u}, T$ denote the current density, electric potential, velocity and temperature, respectively.

In MHD flows involving the heat transfer, the different cases that we considered can be characterized by three non-dimensional numbers. One is the Prandtl number, $Pr = \nu/\alpha$, representing the ratio of viscous diffusivity and thermal diffusivity. Another is the Reynolds number, $Re = U_0 D/\nu$, representing the ratio of inertial to viscous forces. And the interaction parameter, $N = \sigma D B_0^2/\rho U_0$, standing for the ratio of electromagnetic to inertial forces. In addition, the Hartmann number, which can be expressed in terms of interaction parameter and Reynolds number $Ha = \sqrt{NRe} = DB_0\sqrt{\frac{\sigma}{\rho\nu}}$, characterizing the ratio of electromagnetic to viscous forces, appears important as well. In the present simulation, cases with $Re \leqslant 200$ are considered, in which range the three-dimensional instability in the spanwise direction does not appear.

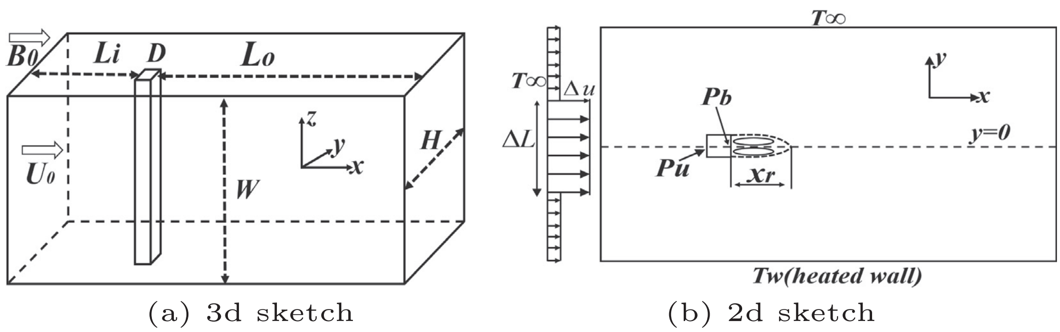

Fig. 1. Computational domain and definition of the main geometrical and flow parameters for the flow over a square cylinder.