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Experimental study on the flow regimes past a confined prism undergoing self-sustained oscillations

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ABSTRACT

An experimental study based on Particle Image Velocimetry (PIV) is presented with the objective of studying the flow regimes that appear in the flow past a confined prism undergoing self-sustained oscillations at low Reynolds numbers (*Re*). The square-section prism, placed inside a 3D square cross-section vertical channel with a confinement ratio of 1/2.5, was tethered to the channel walls and, therefore, it was allowed to move freely transverse to the incoming flow. *Re* (based on the prism cross-section height) was varied in the range from 100 to 700. Three different prism to fluid density ratios (m^*) were considered: 0.56, 0.70, and 0.91. These two parameters, *Re* and m^*, were used to map the results obtained. In particular, it was found that five different regimes appear: (1) steady prism with steady recirculation bubble, (2) steady prism with unsteady vortex shedding wake, (3) large amplitude low frequency oscillating prism with unsteady vortex shedding wake, (4) small amplitude high frequency oscillating prism with unsteady vortex shedding wake, and (5) irregular/chaotic motion of both the prism and the wake. The PIV results and associated numerical simulations were used to analyze the different prism and wake states.

1. Introduction

Mass transfer is a subject of interest both at the industrial and the scientific levels. For example, process engineering and life sciences are, among many others, specific fields where the development of this technical area contributes to the generation of better products and services. On the scientific side, mass transfer in laminar flow has been, and still is, studied intensively at the fundamental level and, also, from the point of view of practical applications. Broadly speaking, laminar mixing techniques, which are directly related to mass transfer, can be classified either as active, that require the input of mechanical work from an external source, and passive, that take advantage of the flow features and their associated boundary conditions. On one hand, active techniques tend to be very efficient but they introduce a certain degree of complexity on the system design and require an external power source. On the other hand, passive techniques tend to be more robust and work in the direction of stressing system autonomy, although they are not expected to be as efficient as the active ones.

One active method that has been the subject of many studies is the use, in one way or another, of pulsating flows; see, for instance, the articles published by Lee et al. (1999), Hitt and Mcgarry (2004), and Olayiwola and Walzel (2008). Regarding other methods, Woziwodzki and Jedrzejczak (2011) and Takahashi and Motoda (2009) have reported on the use of impellers. Also, the feasibility of using rotating and/or reciprocating parts has been addressed by Dieulot et al. (2002), Hirata et al. (2007), Ward and Hourigan (2009), and El Omari and Le Guer (2010). The effect caused on mixing by impinging jets has been reported by Woodfield et al. (2003) and Wang et al. (2005). Less conventional approaches such as electromagnetically induced chaotic mixing and flow topology modification via the use of a cantilevered actuator have been discussed by Gopalakrishnan and Thess (2010) and Williams et al. (2009) respectively. Regarding passive methods, they have, typically, relied on the effect of geometry to alter flow topology so as to improve mixing. This has been studied in detail by Zhang et al. (2011) (zig-zag micro-channels), Lin and Yang (2007) (serpentine channels), Yamagishi et al. (2007) (different types of bends), Senn and Poulikakos (2004) (tree-like configurations), and Mouza et al. (2008) (combination of bends and forward and backward facing steps). The theoretical aspects that underlie the Fluid Mechanics of these phenomena have been widely studied also, although it is to be noted that many of them still remain open. To get a glimpse of this very wide field see, for example, the articles of Lester et al. (2009) and Fountain et al. (2000). These two publications provide a

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quite comprehensive insight of the flow physics involved and, put together, they contain 90 references that cover most of the relevant associated theoretical aspects. Finally, it is also worth to mention the generic review articles of Hessel et al. (2005), Jayaraj et al. (2007) and Lee et al. (2011).

The objective of the present article is to explore the feasibility of using the self-sustained oscillations of a highly confined prism (confinement ratio equal to 1/2.5) inside a 3D channel having square cross-section to generate a variety of markedly different flow regimes at *Re* (based on the prism cross-section height) in the range from 100 to 700. This experimental work is, in some sense, continuation of the numerical studies published by Sanchez-Sanz and Velazquez (2009, 2011). In these two articles, the authors presented numerical evidence of the highly irregular/chaotic regime that exists in some regions of the parametric space of the 2D flow past a prismatic body that is free to move perpendicular to the incoming stream. For a given channel blockage ratio, the two control parameters were *Re* and the prism to fluid density ratio. However, differences between a 2D numerical study and a 3D experimental one might be large owing to the additional span wise confinement (presence of lateral walls). In the case of a fixed prism that does not move, this influence of the lateral walls has been experimentally highlighted by Reyes et al. (2013) that reported on the existence of three different *Re* dependent flow regimes: a steady recirculation bubble, a stream wise pulsating recirculation region and a vortex shedding regime. This is in contrast with the two regimes that appear in 2D numerical simulation studies. Then, in the present case of a free moving prism, it is worthwhile to: (a) address a realistic 3D experimental study to identify the actual flow regimes that appear, (b) to see how the results obtained compare with their 2D numerical counterparts, and (c) ascertain their implication for potential future applications regarding mixing enhancement.

From the Fluid Mechanics standpoint, the work to be described in the next sections is related to the generic problem of the flow past a tethered body. As pointed out, for example, by Ryan et al. (2004) this problem and its variants are not only of scientific relevance but, also, of practical interest in situations that involve, among others, submerged pipelines, ocean spars, and tethered lighter-than-air craft. Up to now, most of the studies in the field have dealt with unconfined flow past circular tethered cylinders or spheres in which buoyancy forces play a critical role. Regarding numerical approaches to the problem being considered, Ryan et al. (2004) performed a 2D numerical analysis on the problem of an unconfined vertically tethered buoyant circular cylinder for a range of reduced velocities of 1–22, at a fixed mass ratio of 0.833 and with a tether length to cylinder diameter ratio of 5.05. In their results, the authors reported that the presence of three different oscillation regimes corresponding to an in-line oscillation branch, a transverse oscillation branch, and a transition in-between the two. In a later article, Ryan et al. (2005) studied numerically the flow-induced vibration on a circular cylinder held free to oscillate transverse to the free stream (an idealized version of a tethered cylinder). *Re* varied in the range from 30 to 200 and the two different flow oscillation regimes observed were characterized by the amplitude of the oscillations. The effect of the mass ratio and the tether length was analyzed by Ryan et al. (2007) in a configuration similar to that of Ryan et al. (2004). In particular, they found a critical mass ratio that marks the threshold for large amplitude oscillations to be observed. Shortening the tether length caused the critical mass ratio to increase and vice versa. A detailed numerical analysis of the wake states of this very same problem has been reported by Ryan (2011). Regarding experimental studies, Van Hout et al. (2010) considered the case of a tethered sphere in a closed loop water channel. The sphere at rest was suspended vertically while the flow direction was horizontal. The authors considered a range of dimensionless reduced velocities from 2.8 to 31.1 (range of *Re* from 486 to 5655) and were able to identify three different flow regimes. Carberry and Sheridan (2007) considered a buoyant tethered cylinder in a configuration similar to one of the numerical cases mentioned above, Ryan et al. (2004). In their experimental setup, the cylinder had a diameter and a span of 16.2 mm and 594 mm respectively so the flow motion could be considered as two dimensional (the aspect ratio was 36). The rigid tethers had a length of 75 mm and their motion could be considered as one dimensional. Experiments were performed for mass ratios in the range from 0.54 to 0.97, and for each run flow velocity increased from zero to 0.46 ms^{-1} that corresponds to *Re* 7390. Regarding the results, the authors were able to identify two different states in the cylinder periodic oscillation around the mean layover angle. For any given mass ratio in the range from 0.54 to 0.72, the amplitude of the oscillation was small below certain threshold of the incoming flow velocity and the wake was consistent with the 2S Karman shedding mode. Above the threshold, the oscillations were significantly larger and the wake was different from the typical Karman wake observed at lower values of the critical mass. When the mass ratio was larger than 0.76, there was no jump in the behavior of the oscillation amplitude and this oscillation remained small for all tested flow velocities. Wang et al. (2011) studied experimentally the same type of geometry but they were also able to implement a piezoelectric load cell so as to directly measure lift and drag forces. In particular, they found a rather good single fit of drag as a function of the mass ratio and the buoyancy Froude number.

Regarding the present article, its organization is as follows: the problem details and experimental model are presented first; then, the experimental setup and methodology are described; results are given and discussed; and, finally, conclusions and some practical design guidelines for a potential mixing device are given.

2. Description of the problem and experimental model

The problem under consideration was the vertical channel water flow past a tethered buoyant square section prism in the laminar regime. The channel, manufactured in methacrylate, had an internal square cross section of 25 mm × 25 mm and a length of 1300 mm. Three different model prisms were also manufactured in methacrylate with hollow cylindrical interiors that allowed for different prism densities. The dimensions of the prisms were 24.3 mm × 10 mm × 10 mm and their weight was 1.36 g, 1.79 g, and 2.21 g respectively; which meant that the associated prism to water density ratios (m^*) were 0.56, 0.70, and 0.91. For each test, the prism was located at a station 950 mm away from the channel entrance section. The prism was tethered with two fisherman nylon strings (0.04 mm in diameter) to two small inserts placed in the channel walls. The length of the tethers was 65 mm. Distilled water was used in the experiments. Before each experimental series, the water was allowed to stay still in the test room time enough to homogenize its temperature with the room temperature (19 °C). The volume flow rate used in the experiments was varied between 0.405 l/min and 2.835 l/min. *Re* was based on the mean inlet water velocity and prism cross section height. Then, these volume flow rates yielded a set of *Re* in the range from 100 to 700. A sketch of the test section is shown in Fig. 1. There, it could be observed that the forces acting on the prism were the tether tension $\vec{T}$, the lift $\vec{F_L}$ and drag $\vec{F_D}$, and the buoyancy $\vec{B}$. The maximum peak to peak observed amplitude of the oscillation was 3 mm, which meant that the maximum tether deflection angle θ was 1.23°, and that the maximum deviation from the horizontal axis was 16 μm (nearly horizontal motion). Since both tethers were glued to the prism at the prism surface, see Fig. 1, the prism