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On the onset of vortex shedding from 2D confined rectangular cylinders having different aspect ratios: Application to promote mixing fluids

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ABSTRACT

This work deals with a numerical study to characterize the onset of vortex shedding from a rectangular cylinder with different length-to-width aspect ratios (AR) and confined in a channel under the consideration of constant blockage ratio ($BR = 1/5$). For AR ranging from 1/8 to 4, it has found that the onset of vortex shedding can be promoted and can take place at lower Reynolds numbers by reducing the aspect ratio of the cylinder, decreasing the critical Reynolds number almost linearly with AR for $AR \leq 2$, being the lowest critical Reynolds number around 30 for an aspect ratio of 1/8. The drag coefficient, Strouhal number and pumping power needed to run the channel have been also characterized and correlations proposed to fit both the drag coefficient and pumping power as function of AR and critical Reynolds number. The gained knowledge has been later applied to mix two fluids in the channel at constant Reynolds number. The mixing has been characterized in terms of the mixing efficiency and mixing energy cost. It has been observed that configurations with vortex shedding can intensify mixing with efficiencies between 50% and 100% higher and two order of magnitude cheaper than those without vortex shedding.

1. Introduction

Motivated by the fact that in many industrial processes, such as those specially related with mixing and heat transfer, the pumping power to flow the involved fluids along the geometry should be as low as possible while the highest process efficiency is wanted, in this study we look for the optimum rectangular cylinder aspect ratio (AR) which gives, on the one hand, a well defined oscillatory wake, with frequency $\hat{f}$, due to vortex shedding from it, which is supposed will play an important and good role in the efficiency of the process under consideration and, on the other, the lowest mass flow rate as possible for the vortex shedding to happen in order to have the lowest pumping power needs as possible. Firstly and regarding the desired oscillation frequency of the wake, it will be characterized by means of the dimensionless Strouhal number so that the higher the frequency the higher the Strouhal number. Secondly, for a given fluid and geometry, low mass flow rate values also means low values of the Reynolds number. Additionally, low Reynolds number values are specially related with geometries with small dimensions such as microfluidic devices, so the potential use of the device under consideration as micromixer will be also assessed. In particular, it will be shown how the mixing mechanism based on the oscillatory wake downstream the cylinder can help to promote mixing efficiency. In that sense, the optimal configuration should have well defined wake oscillations, at a frequency given by a certain Strouhal number, and the lowest Reynolds number as possible, i.e., the lowest mass flow rate.

Since the pioneering experimental observations of vortex shedding by Mallock [1], and Bènard [2], Bènard [3], which later was explained by Kármán [4], reason why the phenomenon is since then associated to his name, many works have been published related with such phenomenon. One just has to look for the right words on the internet and thousands of works are available at one-click distance. It is remarkable that the last general review on this phenomenon was published, at least to the author's knowledge, at the end of the last century [5], although some, related with specific aspects of vortex shedding, have been published recently, as will be shown later. From the vast available literature, one can see that vortex shedding has been studied from different points of view. Specially related with the work addressed in this manuscript are: firstly, those where vortex shedding from objects with different shapes are studied; secondly, those related with different mechanisms to suppress the vortex shedding from an object; thirdly, those related with the use of vortex shedding in applications such as heat transfer or fluid mixing; and last but not least, those related with the characterization of the critical Reynolds number above which the vortex shedding starts.

Regarding the shape of the object involved in the vortex shedding, not only rectangular [6], as in this work, or circular [7] cylinders have been analyzed, but also other shapes such as hexagonal [8], triangular

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Nomenclature

Roman symbols

$\hat{\ }$	Dimensional variable
$\langle\ \rangle$	Time-averaged value
$\mathbf{v}$	Velocity vector
AR	Rectangular cylinder aspect ratio
BR	Channel blockage ratio
Cd	Drag coefficient
Cl	Lift coefficient
D	Mass diffusivity coefficient of fluids
ds	Size of the uniform mesh
F	Force
f	Cl oscillation frequency
F_s	GCI security factor
g	Arbitrary magnitude
H	Channel width
L	Rectangular cylinder length
L_d	Channel length downstream the cylinder
L_u	Channel length upstream the cylinder
mec	Mixing energy cost
Pe	Peclet number
q	Flow rate
R^2	Coefficient of determination
Re	Reynolds number
Sc	Schmidt number
St	Strouhal number
t	Time
t_0	Reference time
U	Channel inlet mean velocity
u, v	Velocity components
W	Cylinder width
Y	Solute mass fraction
x, y	2D Cartesian coordinates

Subscripts

$adjust$	Adjusted coefficient
cr	Critical value
H	Channel width-based property
i	Grid number
Poi	Channel property under fully developed Poiseuille flow
pp	Peak-to-peak value
rms	Root mean square value
x, y	Direction of the corresponding magnitude

Greek symbols

Δt	Time step increment
Δp	Channel pressure drop
η	Mixing efficiency
μ	Viscosity
ν	Kinematic viscosity
Π	Pumping power
ρ	Density
σ	Standard deviation

Superscripts

d	Lower limit of the critical band
L	Magnitude per channel unit length
max	Maximum value
u	Upper limit of the critical band

[9,10], square cylinders with rounded corners [11] or flat plates normally oriented to the flow [12]. Even arrays of rectangular objects have been also tested [13].

Regarding the suppression of vortex shedding from cylinders, motivated by the vortex induced vibration the cylinder may undergo (see [14,15] for a review about this kind of induced motion and governing parameters), different mechanisms have been proposed such as: by blowing and suction techniques from the cylinder surface [16,17]; by placing little objects in the downstream near wake of the cylinder [18,19]; by using splitter plates both upstream [20] and downstream [21,22] the cylinder; by using slits with different sizes [23]; by using a cylinder with an helical steel wire around it [24]; or by locating the cylinder close to a stationary [25] or moving [26] wall. Additionally, if the reader is interested, other vortex shedding suppression mechanisms can be found in the recent review by Rashidi et al. [27].

Vortex shedding phenomenon has been also involved in many heat transfer studies both with square cylinders [28–30] and with different shapes [31,9], and many correlations have been proposed to quantify the heat transferred from the cylinder in terms of the Nusselt number [32,33]. They show that the higher the Reynolds number the higher the Nusselt number. Regarding mixing applications, Zhang [34], studied how vortex streets downstream a square cylinder at the end of a splitter plate help to enhance mixing fluids. Additionally, Scholz and Barz [35], also with mixing purposes, studied a confined cylinder subjected to an externally-applied electric field which causes electroosmosis around the cylinder surface. They showed that the electroosmotic slip velocity has certain impact in the cylinder near wake flow and also on the formation and shedding of vortexes from the cylinder.

Regarding the onset of vortex shedding, different authors have given the critical value of the Reynolds number for the shedding to start for certain configurations and objects. This information could be considered as the more relevant for the present work. Due to that, different authors, their configurations and their results related to the critical Reynolds number for vortex shedding is summarized in what follows. Sohankar et al. [36], studied the onset of vortex shedding from a square cylinder at different incidence angles and found that the critical Reynolds number was around 51 and 42 for zero incidence and 45°, respectively, when the blockage ratio (BR) was of 5%. Turki et al. [37], found, again for a square cylinder, the critical Reynolds number for different values of the channel blockage ratio, being the critical Re around 80, 57 and 41 for $BR = 1/4$, 1/6, and 1/8, respectively, which shows that the higher the blockage the higher the critical Reynolds number (for $BR = 1/5$ as in this work, the critical Re would be between 57 and 80). Sharma and Eswaran [29], reported, for an unconfined square cylinder, that the critical Reynolds number was between 40 and 50, while in [30], the same authors reported a band where the critical Reynolds number must be as a function of the blockage ratio, being for a blockage of 1/5 the critical Reynolds value between 50 and 55. Kelkar and Patankar [38], by means of numerical linear stability analysis and for unconfined square cylinders, found a critical Reynolds number of 53. Yoon et al. [39], carried out a parametric study to find the critical Reynolds number for periodic vortex shedding from an unconfined square cylinder at different angle of incidence and found it was around 45 and 40, for 0 and 45° of incidence, respectively. Suzuki et al. [40], for a square cylinder and different channel blockage ratios, reported, for a blockage of 1/5, a band where the critical Reynolds number must be, ranging between 55 and 65. Patil and Tiwari [41], carried out a numerical study on the behaviour of the wake downstream a confined square cylinder for different channel blockage ratios, and gave the critical Reynolds number for each studied blockage ratio, being for a blockage of 1/5 the critical Re around 45. As can be seen, special attention has been paid when data for the same blockage ratio than this