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Three-dimensional numerical study of heat transfer and mixing enhancement in a circular pipe using self-sustained oscillating flexible vorticity generators

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HIGHLIGHTS

- Self-sustained oscillations of flexible vortex generators without any external force except that of the fluid flow.
- Complex three dimensional fluid structure interaction simulation as a novel concept for heat transfer and mixing applications.
- High Efficiency Vortex (HEV) static mixer performance improvement by using elastic trapezoidal vortex generators.

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ABSTRACT

In this paper, heat transfer and mixing performances are studied using three-dimensional numerical simulations of fluid-structure interactions. To this aim, a multifunctional heat exchanger/reactor geometry is investigated, consisting of a circular pipe where five arrays of four equally spaced trapezoidal vortex generators are inserted and inclined in a reversed position opposite to the flow direction with an angle of 45° with respect to the pipe wall. A periodic rotation of 45° is applied to the tabs arrays. Two cases are numerically studied: one using flexible vortex generators (FVG) that deform due to fluid forces applied on the structures and the other using conventional non deformable rigid vortex generators (RVG). For the FVG configuration, the tabs oscillate without addition of any external source of energy except that of the fluid flow itself, leading to a passive but dynamic way to perform vortex formation to disturb the flow. Both flow regimes are laminar with a constant Reynolds number of 1500. The flow structures are analyzed using the proper orthogonal decomposition (POD) technique and the effect of tabs oscillation on vortices creation, suppression and dislocation is highlighted.

The effect of self-sustained free elastic tabs oscillation on heat transfer and mixing performances is numerically investigated by comparing the FVG with its corresponding RVG configuration. The Nusselt number comparison shows that the free tabs oscillation can improve the overall heat transfer of about 118% with respect to an empty pipe whereas it is about 97% for the RVG study. Finally, to assess the mixing performance, the transport of a passive scalar initially divided into two different concentrations in the pipe is numerically analyzed through the mixing index value. The FVG configuration shows a drastic improvement of the mixture quality at the exit of the pipe with an increase of 195% with respect to the RVG case, leading to much shorter and compact mixers and reactors.

1. Introduction

Instabilities such as vortex-induced vibrations (VIV), galloping and fluttering occur when a fluid surrounding a structure supplies energy to the structure instead of absorbing it (Williamson and Govardhan, 2004; Huang, 1995). Usually, most of the studies in

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Nomenclature

a_i^k	POD mode coefficients (–)
c	scalar (–)
c_p	specific heat (J kg^{-1} K^{-1})
CFD	computational fluid dynamics
CSD	computational structure dynamics
$\mathbf{d_s}$	solid displacement vector (m)
d	pipe diameter (m)
D_m	mass diffusivity (kg m^{-1} s^{-1})
e	thickness of the elastic flap (m)
E	Young's modulus (Pa)
f	friction factor (–)
f_e	structural oscillation frequency (Hz)
f_N	structural natural frequency in vacuum (Hz)
f_v	vortex shedding frequency (Hz)
$\mathbf{F}$	deformation gradient tensor (–)
FVG	flexible vortex generators
$\mathbf{G}$	Green lagrangian strain tensor (–)
GCI	grid convergence index (–)
h_g	grid size (m)
H	helicity field (m s^{-2})
$\mathbf{I}$	unity tensor (–)
k_{th}	thermal conductivity (W m^{-1} K^{-1})
L	length of the computational domain (m)
l	cell distance to the nearest moving boundary (m)
$\dot{m}$	mass flow rate (kg s^{-1})
MA	mean displacement amplitude (m)
MI	mixing index (–)
N	total number of snapshots (–)
Nu	Nusselt number (–)
p	pressure (Pa)
p_c	apparent order of convergence (–)
Pr	Prandtl number (–)
q''	average heat flux between top and bottom walls (W m^{-2})
r	grid refinement factor (–)
Re	Reynolds number (–)
RVG	rigid vortex generators
S	maximum number of POD modes (–)
T	temperature (K)
t	time (s)
$\mathbf{u}$	velocity vector (u, v) (ms^{-1})
$\overline{U}_f$	mean flow velocity (ms^{-1})
v_k^i	k^{th} component of the eigenvector (–)
(x, y)	Cartesian coordinate system (m)
$()^*$	dimensionless position: $X^* = x/H, Y^* = y/H$ (–)
$()$	row index: A, B, C, D, E (–)
$()$	standard cardinal directions: $n, ne, e, se, s, sw, w, nw$ (–)

Greek symbols

γ	mesh diffusion coefficient (–)
ϵ	relative flow energy (–)
η	thermal performance factor (–)
λ	eigenvalue (–)
ν_f	fluid kinematic viscosity (m^2 s^{-1})
ν_s	Poisson's ratio (–)
ϕ	normalized basis function (–)
ρ	mass density (kg m^{-3})
Σ	Piola-Krichhoff stress tensor (–)
ζ	cumulative relative flow energy (–)

Subscripts

ave	spatial average
b	bulk
f	fluid
i	POD mode index
m	mesh
s	solid
w	wall

engineering disciplines intend to suppress such instabilities either by adding weights or by operating below a critical speed. When operating at this particular velocity, the instability indeed leads to self-sustained flapping motions of the structure in the flow and potentially causes damage to it. Recently some authors think about using this phenomenon and benefit from this flapping motion instead by harvesting electricity using patches of piezoelectric materials attached to the structure surface (Michelin and Doaré, 2013; Akcabay and Young, 2012).

In the particular context of multifunctional heat exchangers/reactors, specific non deformable rigid vortex generators (RVG) are usually inserted in order to create secondary flows and disrupt the growth of the thermal boundary layer (Ahmed et al., 2012; Lei et al., 2010; Anxionnaz et al., 2008; Allison and Dally, 2007). These RVGs are usually fixed and stay passive without any external control. Moreover, to add more flexibility to this technique, one can also think about making the vortex generators (VG) move by actively controlling the frequency and amplitude of oscillation of these VGs by relying on an external source of energy. This kind of study has been achieved for example by Lambert and Rangel (2010) who studied the effect of actively oscillating thin elastic flaps on fluid mixing in a microchannel. They found that the mixing is the greatest when one flap oscillates with the largest amplitude displacements. The addition of another flap also lead to the highest mixing performance when the flaps oscillate out of phase with an angle of $\pi/2$. Furthermore, Yang and Chen (2008) numerically studied the effect of a transversely oscillating cylinder on heat transfer of heated blocks in a two-dimensional channel flow. They concluded that heat transfer is remarkably enhanced when the lock-in regime is reached, i.e. when the vortex shedding frequency synchronizes with the structural oscillation frequency. However, in these above-mentioned studies, the flaps oscillate using an external source of energy. Previous studies have furthermore put in evidence that self-sustained oscillations can be obtained by relying on the flow energy itself. Indeed, Ali et al. (2015) proposed an innovative concept using passive-dynamic control of flexible vortex generators (FVG) by creating an instability able to sustain the oscillatory motion in a two-dimensional channel. Their results show that the free elastic oscillations could improve the mixture quality up to 98% when comparing the corresponding configuration but using RVG instead. Moreover, the heat transfer displayed for the FVG case an increase up to 56% in the thermal performance and up to 134% in the overall heat transfer when compared to its relative RVG case. Furthermore, this fluid-structure interaction (FSI) problem caught the attention of several other authors. In fact, Shi et al. (2014) performed numerical simulations on a benchmark for FSI problems already available in the literature and proposed by Turek and Hron (2006), which consists of a two dimensional laminar flow around a flexible structure attached to a rigid cylinder. They included the effect of heat transfer to assess the thermal performance of the FSI benchmark and simulations were carried out at different Reynolds numbers calcu-