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Residence time distribution and heat transfer in circular pipe fitted with longitudinal rectangular wings

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ABSTRACT

Numerical simulations are used to analyze the heat and mass transfer in a circular pipe fitted with longitudinal rectangular vortex generators for Reynolds number between 7500 and 15,000 based on the pipe diameter. The aim of the present study is to test and quantify the mixing efficiency of a new solution able to avoid the bypass region that exists in the center of the high efficiency vortex static mixer (HEV), and also to enhance the heat transfer without increasing the pressure losses. The rectangular wings used here generate each a streamwise counter-rotating vortex pair sweeping the volume of the mixer and act as internal agitator on the flow. The particle dispersion is investigated by analyzing Poincaré sections and by studying the residence time distribution (RTD). The two approaches show much better mass transfer performance and better mixing homogeneity for the new wings arrangement. The heat transfer is also investigated and it is shown that the thermal enhancement factor in the new arrangement is much greater than that of the conventional systems used in the industry. When compared to the HEV heat exchangers it is shown that the thermal enhancement in the present configuration reaches about 40% relative to the classic HEV and 15% relative to the reversed HEV.

1. Introduction

Multifunctional heat exchangers/reactors (MHER) are based on the concept of continuous process where passive method is used to generate secondary flows enhancing thus the heat and mass transfer simultaneously. Several passive methods have been introduced such as Dean instabilities in curved pipes flows [1–3], swirl flows induced by helical and plate inserts [4–7] and longitudinal vortex generators [8–10].

MHER are widely used in many engineering applications such as pharmaceuticals, food processing, waste water treatment, nuclear reactors, petrochemicals, vehicles and airplanes cooling modules. Their main advantages are their compactness and their ability to enhance the thermal homogeneity. On the other hand, continuous processes reduce byproducts and provide better safety compared to batch systems [11–15].

The main idea of process intensification in MHER relies on increasing the heat and mass transfer efficiency with moderate increase in the pressure losses. The heat transfer enhancement means increasing the thermal exchange and improving the homogeneity of the temperature distribution at the MHER outlet. Mixing intensification is directly related to the particle dispersion and to the final product homogeneity. In MHER both processes must be enhanced while maintaining moderate pressure losses to insure better global performance.

The performance of MHER depends on the flow structure which is induced by its geometry and the method used to generate secondary flows. It is found that vortex generators are very efficient to increase heat and mass transfer, while the induced pressure drop increase is generally smaller than other methods such as in the SMV and SMX static mixers and in tubes fitted with helical inserts [10,16,17].

When using vortex generators, two types of vortices may be distinguished; transverse and streamwise vortices. Transverse vortices, also called recirculation flow, are perpendicular to the flow direction and form generally circulation regions in the wake of the vortex generator. The main drawback of this type of vortices is that the fluid particles will stay trapped inside the vortex core and will not be mixed with the surrounding fluid. This may also induce overheated region which is critical, especially when using for example exothermal chemical reaction. Streamwise or longitudinal vortices with axes in the main flow direction are three-dimensional

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Nomenclature

c_p	thermal capacity (J/kg K)
D	diameter of the heat exchanger (m)
D_{ax}	axial diffusion coefficient (m^2/s)
f	friction factor (–)
k	turbulence kinetic energy (m^2/s^2)
L	length of computational domain (m)
Nu	Nusselt number based on tube diameter ($= hD/\lambda_f$) (–)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
Pe_L	Péclet number (–)
Pr	Prandtl number (–)
Re	Reynolds number based on tube diameter ($= U_m D/\upsilon$) (–)
T	temperature (K)
$\bar{T}$	average temperature (K)
u	velocity vector (m/s)
U_m	mean flow velocity (m/s)
V	computational domain volume (m^3)
$\dot{V}$	volumetric flow rare (m^3/s)
(x, y, z)	Cartesian coordinate system

Abbreviations

CoV	coefficient of variation
CVP	counter-rotating vortex pair
HEV	high-efficiency vortex mixer
MHER	multifunctional heat exchanger/reactor

Greek symbols

β	vortex generator inclination angle (°)
η	thermal enhancement factor (–)
ε	turbulence energy dissipation rate (m^2/s^3)
$\bar{\varepsilon}$	global power dissipation rate per fluid mass unit (W/kg)
λ	thermal conductivity (W/m K)
λ_{eff}	effective thermal conductivity (W/m K)
μ_{eff}	effective viscosity (kg/m s)
υ	fluid kinematic viscosity (m^2/s)
$\Re_{ij}$	deviatoric stress tensor (1/s)
ρ	mass density (kg/m^3)
σ	temperature standard deviation (K)
τ_{ij}	Reynolds stress tensor
Σ	modulus of the mean strain rate tensor (1/s)

Subscripts

0	empty pipe
b	bulk
f	fluid
s	solid
inlet	heat exchanger inlet
outlet	heat exchanger outlet
mean	mean value
w	wall

structures that play the role of internal agitators to the flow, enhancing thus the thermal exchange and mixing process. This enhancement is due to the fact that streamwise vortices combine the main mechanisms of heat-transfer enhancement: the development of highly turbulent boundary or shear layers, the reduction of the laminar sub-layer thickness near the wall, and the swirl movement of the streamwise vortex that enhances convective transfer [16,18].

The high efficiency vortex (HEV) static mixer is designed [19] in such a way to exploit this type of vortices to enhance mixing and heat transfer while preserving relatively low pressure losses [10,20]. The coherent flow structures inside the HEV are produced by a succession of trapezoidal vortex generators inserted on the inner wall of an empty pipe with an inclination angle. The pressure gradient between the front and back sides of the tab, caused by the velocity gradient between the low-momentum fluid in the tab wake and the high-momentum fluid in the bulk region, generates two longitudinal counter-rotating vortices. Moreover, the shear layer generated at the tab edges produces a Kelvin–Helmholtz instability and gives raise to periodic hairpin vortices moving downstream [21,22]. It was found that the macro-mixing and heat transfer are mainly controlled by the streamwise vortices while meso and micro-mixing are enhanced by the transient vortices caused by the Kelvin–Helmholtz instability [22].

Many studies were conducted to enhance the mixing and heat transfer in the HEV MHER by modifying the shape and orientation of the vortex generators and even by adding protrusions [10,14,23]. Despite these improvements, the major issue of the HEV is the presence of two distinct flow regions: a low momentum region in the wake of the vortex generators and a high momentum region, or bypass flow, in the center of the HEV. This induces a lack of homogeneity of both the temperature and the mixing process in the center area. Fig. 1 shows the aligned and reversed HEV MHER studied by Habchi et al. [10].

Thus to solve this issue, an innovative concept is proposed in the present paper based on using rectangular wings to generate streamwise vortices crossing the whole tube. This aims to suppress the bypass region without increasing the pressure losses while maintaining good heat and mass transfer. For this end, three-dimensional numerical simulations are conducted for Reynolds number ranging between 7500 and 15,000. The analysis focuses on the mixing process by studying passive particle dispersion and residence time distributions; and also on heat transfer and pressure losses.

The manuscript is organized as follows. Section 2 describes the numerical method, the computational domain and boundary conditions. The results are discussed in Section 3. Section 4 is devoted for the concluding remarks.

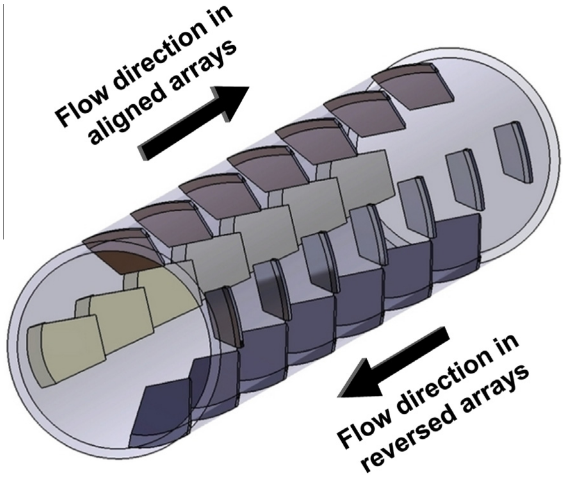

Fig. 1. Three-dimensional view of the aligned and reversed HEV [10].