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Vorticity and convective heat transfer downstream of a vortex generator

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ABSTRACT

Vorticity generation has been identified, since the 80's, as an efficient means for enhancing heat transfer; the mean radial velocity component due to the induced flow pattern contributes to the heat removal. In the present work, momentum and heat transfer are studied in a test section designed to mimic the industrial HEV (High-Efficiency Vorticity) mixer. It consists of a basic configuration with a unique vorticity generator inserted on the bottom wall of a heated straight channel. The aim of this work is to analyze to which extend the convective heat transfer is correlated to the vorticity, as it is presumed to cause the intensification. In this case, the driving vorticity is the streamwise vorticity flux Ω, and the heat transfer is characterized by the Nusselt number Nu, both quantities being spanwise averaged. The study is mainly numerical; we have used the previous PIV measurements and DNS data from the open literature to validate the numerical simulations. It is shown that there exists a strong correlation between the vorticity flux and Nusselt number close to the vortex generator. However, the axial variation diverges for these quantities when moving downstream. The Nusselt number presents a sharp peak over the VG and decreases nearly to its basic level just behind the VG, while the vortex persists far downstream from the tab and relaxes very slowly. Heat transfer intensification at the Nusselt peak is about 100%, and reduces to about 6% downstream of the VG, the intensity of the vorticity momentum being decreased only to about 50% of its peak value at the test section outlet.

1. Introduction

Vorticity is an inherent feature of fluid flow and is often considered as an efficient mechanism in the heat and mass transfer phenomena. In many situations of practical interests vorticity is artificially generated to enhance heat and mass transfer [1–10], but also vorticity exists naturally in many types of fluid flows such as in the near-wall region of turbulent boundary layers [11,12] or surfaces with curvature and/or rotation [13–15]. Physical understanding of the mechanism of heat transfer by vorticity is therefore crucial for active and passive control in numerous technological applications [16–20]. However, most of previous studies consider a global relationship between the velocity field and heat transfer coefficient, and little attention was paid to the role of the vorticity intensity.

Some studies investigated the analogy between the heat transfer and different flow parameters describing the strength of secondary flow such as the vortex circulation and vorticity flux. It was shown from experimental studies by McCroskey [21] that the theoretical predictions of the temperature-vorticity analogy agree well with the experimental results in laminar flows, but the theory failed in the transitional and turbulent flows. Song and Wang [22] defined a dimensionless secondary flow intensity (Se) that is the ratio of inertial force to viscous force induced by the characteristic velocity of secondary flow to study the relation between vorticity and heat transfer in laminar flow. They obtained a fair correlation between the local and global dimensionless secondary flow intensity and the Nusselt number. Chang et al. [23] suggest the use of the span-averaged absolute streamwise vorticity flux to characterize the intensity of the secondary flow produced by vorticity generators. It was shown qualitatively that a similar behavior is observed between the longitudinal variation of the streamwise vorticity flux and the span-averaged Nusselt number downstream from the vortex generators. Actually, this spanwise-averaged absolute streamwise vorticity flux characterizes the convective heat transfer caused only by longitudinal vorticity, and does not account for the effects of transverse vorticity. Actually, it was shown [2,24] that most of the heat transfer enhancement is caused essentially by the streamwise vortices, while the transverse stationary vortices, e.g. the wake recirculation, are globally "hot fluid traps", that poorly exchange.

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Nomenclature

D_h	channel hydraulic diameter, m
h	vorticity generator (tab) height, m
J	streamwise vorticity flux, s^{-1}
k	turbulent kinetic energy (TKE), m^2/s^2
Nu	Nusselt number
Nu_0	Nusselt number for straight channel
Q_w	wall heat flux, W/m^2
Re	Reynolds number based on channel hydraulic diameter, $\mathrm{Re} = W\ D_h/\upsilon$
Re_h	Reynolds number based on the tab height, $\mathrm{Re}_h = W\ h/\upsilon$
S	cross section area, m^2
$T(x, y)$	local temperature, K
$\overline{T}_{inlet}$	averaged temperature at the inlet, K
$\overline{T}_{outlet}$	averaged temperature at the outlet, K
U	convective heat transfer coefficient, W/m^2K
W_0	mean flow velocity, m/s
$x,\ y,\ z$	Cartesian coordinates, m
y^+, y^*	dimensionless wall distance

Greek symbols

ε	turbulent kinetic energy dissipation rate, m^2/s^3
λ	fluid thermal conductivity, W/mK
υ	kinematic viscosity, m^2/s
Θ	dimensionless local temperature
ω_z	streamwise vorticity, s^{-1}
Ω	dimensionless streamwise vorticity flux

In the present study, the spanwise-averaged absolute streamwise vorticity flux is computed only with the longitudinal vortex component, and is used for the discussion on the relationship between the heat transfer and the flow structure. The aim is to assess whether, in the VG case, this parameter is a relevant criterion for the heat transfer intensification.

The test section used in this study is designed based on the industrial HEV (High-Efficiency Vorticity) static mixer [25] that is a well-studied device and is used as multifunctional heat exchangers/reactors [26,27]. This apparatus is being increasingly incorporated in process industry for its mixing and heat transfer capabilities.

Static mixers are composed of a series of identical stationary inserts (called elements) fixed on the inner wall of pipes, channels, or ducts. The role of the elements is to redistribute the fluid flow in the directions transverse to the main flow, that is the radial and tangential directions. Static mixers divide and redistribute streamlines in a sequential fashion using only the pumping energy of the flowing fluid. The inserts can be tailored and optimized for particular applications and flow regimes. Commercial designs typically use standard values for the different parameters that provide high performance throughout the range of possible applications. In the particular case of the HEV static mixer, it is composed of a tube equipped with a series of four trapezoidal vorticity generators attached on the wall. The presence of inserts produces a complex vortex system in which concomitant phenomena simultaneously enhance mass and heat transfer. The study of such a flow is difficult because the longitudinal evolution of the streamlines is drastically modified by the presence of the vorticity generators. The complete geometry of this type of static mixer being complex to study, a simplified design where only one vorticity generator is included is proposed in this work. This flow type mimics the main feature, i.e. pressure driven longitudinal vorticity, of many heat transfer devices such as multifunctional heat exchangers/reactors [26,27]. Studying a geometry equipped with only one vorticity generator allows analyzing the longitudinal evolution of the flow characteristics without the perturbations brought about by other VGs downstream of the studied VG.

Numerical simulations are performed with the ANSYS Fluent CFD software to compute the convective heat transfer and the vorticity flux. The present flow arrangement is of particular interest since it allows studying this complex relationship in a vortical flow for which we can readily quantify the vorticity distribution.

Section 2 elaborates on the numerical procedure and experimental validation. In section 3, results about the vortex strength and the temperature distribution are presented and the relationship between vorticity and heat transfer is discussed. The final section gives the concluding remarks.

2. Numerical procedure

2.1. Physical domain

The flow configuration studied here consists on a square duct flow of 7.62 cm each side, i.e. hydraulic diameter D_h = 7.62 cm, and 33.15 cm long, in which a vorticity generator of trapezoidal shape is inserted on the bottom wall with an inclination angle of 24.5° relative to the wall plane. The leading edge of the vorticity generator is located at z = 13.0 cm. The dimensions of the vortex generator and the duct used here are adopted from Yang et al. [28] and Dong and Meng [29] for the sake of comparison and validation of the present numerical results with these previous studies. The dimensions of the physical domain and of the vorticity generator are schematically shown on Fig. 1 in the Cartesian frame of reference. In the following sections all spatial scales are scaled with the tab height h = 1.3 cm. The vortex generator thickness is 0.5 mm.

2.2. Numerical method

Numerical simulations in the present study are performed by the CFD code Fluent® 6.3 [30]. The computational mesh is a cell-centered finite volume discretization. The conservation equations for mass, momentum, and energy are solved sequentially with double precision [31], segregated and second-order accuracy [32]. Pressure-velocity coupling is performed by finite volumes with the SIMPLE algorithm [33].

The choice of the RSM model – Reynolds stress model – is based on a previous study by Mohand Kaci et al. [34] who have tested different turbulence models to predict the flow dynamics in a HEV static mixer in the case of trapezoidal vortex generators. It was shown that the RSM model [35–37], associated with a two-layer model for the wall region computation, provides a satisfactory description of the flow pattern and turbulence statistics of the flow downstream multiple trapezoidal vortex generators. The Reynolds stress model requires a second order closure hypothesis as the Reynolds stresses are directly computed from the transport equations.

The flow in the near-wall region is computed by using a two-layer model. Following this model, in the viscous sub-layer, the one-equation model of Wolfstein [38] is used, in which only the turbulent kinetic energy transport equation is solved and the turbulent viscosity and energy dissipation rate are computed from empirical correlations based on length scales, given by Chen and Patel [39]. This two-layer model avoids the use of semi-empirical wall standard functions, which are not assessed for three-dimensional complex flows.

Similar numerical methods and turbulence model were used by several authors [40–44] to simulate the fluid flow and heat transfer in different geometries, including flow separation and shear flows which