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Numerical simulation of turbulent flow in a channel containing a small slot

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ABSTRACT

A three-dimensional unsteady simulation was carried out to predict the main features of the turbulent flow inside a closed channel connected to a lateral slot. The incompressible turbulent flow was modelled using a hybrid Detached Eddy Simulation (DES), that uses an LES/URANS approach to predict the turbulence. The calculations were performed using ANSYS® CFX. In this work the main channel has a size of 180 mm x 136.20 mm. The small subchannel is characterized by its deepness, p = 77 mm and width, d = 10 mm. The Reynolds number, based on the hydraulic-diameter, D_h, the bulk velocity, and the kinematic viscosity, ν, in the main channel was $Re = 2.25 \times 10^5$. Inside the small slot the velocity distribution was found to depart from the law of the wall and the normal Reynolds stresses, $\overline{u'u'}$ and $\overline{v'v'}$, were found to dominate the mixing process. Velocity time-traces extracted at locations as far as y/p = 1.125 inside the gap evidenced the presence of large eddies travelling inside the small channel. It was shown that periodic streamwise boundary conditions can be applied to this problem, and good results were obtained by using a channel length that was approximately twice the wavelength of the experimentally observed coherent structures. The results were found to be in fair agreement with the results presented in Meyer and Rehme (1994), though a certain lack of information on turbulence in single channels connected to a gap still remains.

1. Introduction

Compound channels are found in many branches of engineering. These channels are characterized by the presence of a narrow region connected to one or more wider regions. Double-pipe heat exchangers, assembles of rod bundles in nuclear reactors and water supply channels with shallow inundated planes are some examples of applications of compound channels in real life. Also, arteries containing catheters or stents might be thought of as compound channels in biological systems.

The structure of turbulent flow in compound channels is significantly affected by the presence of narrow gaps. The gaps are responsible for a change in mass flux distribution inside the channel producing an inflexional mean velocity field which is a source of instability resulting in turbulence production (Meyer and Rehme, 1994, Goulart and Möller, 2007, Goulart et al., 2013, Home and Lightstone, 2014, Home et al., 2009, Merzari et al., 2008). Unusually high turbulence intensities are measured in the vicinity of the gap. This turbulence intensity is much higher than the usual levels found in pipe flow implying an enhanced mixing between channels (Rehme, 1992).

Secondary flows were once thought to be the main responsible for the high mixing rates that were found in the gap region. However, they were found to be too weak, less than 1% of bulk velocity, to promote such mixing (Meyer, 2010). Hence, the increased mixing rates in the gap must be due to a different mechanism. In fact, one of the most impressive characteristics of flow in compound channels are the gap instabilities and the turbulence they produce, which according to Meyer (2010), is the true reason for increased mixing rates in the gap region.

Flow pulsations (or “gap instabilities” as recently termed by Tavoularis, 2011) in rod bundles were first reported by Rowe (1974). In his experiments a periodic path in the axial velocity was found in a 3 × 3 square-array rod bundle for P/D = 1.10 (P is the pitch, distance between the centres of adjacent rods and D the diameter of the rod). The frequency associated with this phenomenon was found to increase when the distance between the rods was reduced, however, for P/D = 1.25 these alternating motions were found to vanish, thus providing some evidence of the dependence of this instability on the geometric parameters. Since then many experimental works were carried out to study and understand the mixing processes in rod bundles, the oscillating flow

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Nomenclature

p	depth of small subchannel, m
d	width of small subchannel, m
W	width of main channel, m
H	height of main channel, m
D_h	hydraulic-diameter, m
L	length of computational domain, m
Re	Reynolds number, Re = $\frac{U_{bulk} D_h}{\nu}$
Coeff	coefficient of correlations
f	frequency, Hz
t	time, s
Q	Q-criterion, $1/s^2$
U_c	convection velocity of the large vortices, m/s
U_{bulk}	bulk velocity, m/s
$\dot{m}$	mass flow rate, kg/s
t_c	convective time, s – L/U_{bulk}
uu^+, vv^+, ww^+	dimensionless normal Reynolds stresses, $\overline{u'u'}/u_*^2$, $\overline{v'v'}/u_*^2$, $\overline{w'w'}/u_*^2$
uv^+, uw^+, vw^+	dimensionless Reynolds stresses, $\overline{u'v'}/u_*^2$, $\overline{u'w'}/u_*^2$, $\overline{v'w'}/u_*^2$
k^+	dimensionless total turbulent kinetic energy, k_T/u_*^2
k_{Coh}, k_{nc}	Coherent and non-coherent part of turbulent kinetic energy, m^2/s^2
u_*^2	square of velocity friction, m^2/s^2 - τ_{wall}/ρ
x, y, z	coordinates, m
Δx	streamwise grid size, m
y^+	Wall coordinate, yu_*/ν

Greek symbols

ρ	density of the fluids, kg/m^3
μ	dynamic viscosity, Pa.s
ν	kinematic viscosity, μ/ρ, m^2/s
λ	wavelength distance between two consecutive vortices with same sign, m

characteristics, as well as the dependence on the geometry and Reynolds number e.g., Hooper and Rehme (1984), Möller (1991), Rehme (1992), Wu and Trupp (1994), Rehme and Meyer (1998), Guellouz and Tavoularis (2000a).

Hooper and Rehme (1984) concluded that mass, momentum and energy in the vicinity of the gap are ruled by an energetic and almost periodic turbulent velocity component, and that there is no relation with mean secondary flow velocities generated by Reynolds stress gradients. A similar conclusion was reached by Möller (1991), who applied hot wire anemometry to measure the Reynolds stresses and to determine the origin and characteristics of large eddies in a matrix of four rod bundles with P/D ratio ranging from 1.007 up to 1.224. Regions with relatively higher axial turbulence intensity were found at about 25° from the gap between the rods and 35° from gap between the rods and channel walls. Furthermore, Möller (1991) concluded that the large vortices originated from instantaneous gradients formed on each side of the gap. A number of years later Guellouz and Tavoularis (2000a), in their experimental work in a channel containing a single rod, showed that large scale structures are arranged in the form of a vortex street on either side of the gap.

A series of single channels containing lateral slots and twin channels connected by a narrow gap were experimentally studied by Meyer and Rehme (1994, 1995). The main dimensionless geometrical parameters were the depth and the width of the slot, p and d, respectively. The investigations were performed for several p/d-ratio ranging from 1.00 to 8.28. The amount of turbulent kinetic energy and the intensity of Reynolds stresses generated near the gap were higher than anywhere else in the channel. The kinetic energy was found to be three times stronger than in a square channel. The normal Reynolds stresses were found to be highly anisotropic, implying that URANS models would not be able to accurately describe turbulence in these channels.

The large-scale structures appearing near the gap were also investigated by the authors of both papers. They concluded that large-scale flow oscillation exists for, p/d > 2.

Years later, Goulart and co-workers (Goulart and Möller, 2007 and Goulart et al., 2013) published the outcomes of their experimental research on 10 rectangular closed compound channels showing that the flow inside the channels is prone to the instability due to the inflexional velocity profile. The authors also concluded that the flow is quite similar to a spatial mixing layer formed between the slower fluid (inside the gap) and the faster fluid from main channel. One year later Choueiri and Tavoularis (2014) attributed the “gap vortex street” formation in an eccentric annular channel to the instability of two mixing layers on both sides the gap.

Various numerical codes have been used to investigate the flow in compound channels, mostly in the last decade. Unsteady simulations have been carried out in twin channels by Home et al. (2009), Home and Lightstone (2014) and Derksen (2010), in channels with a single rod by Chang and Tavoularis (2005, 2008, 2012), while Merzari et al. (2008) studied flow in a tight-lattice fuel bundle. All these works aimed to qualify and quantify the turbulent flow phenomenology, in some cases by employing various turbulence models.

The thorough work carried out by Chang and Tavoularis (2012) was aimed at understanding the onset of flow gap instabilities in a channel containing a single rod, using the results published in Guellouz and Tavoularis (2000a) as a benchmark. The numerical study was performed using several turbulence models, various inlet conditions (developed and non-developed velocity profiles, as well as transient inflow). Despite the fact that LES produced the most accurate results, URANS also appeared to be suitable to predict turbulent flow characteristics in compound channels. However, the hybrid models (SAS and IDDES) were found to predict an earlier onset of gap instabilities.

Chang and Tavoularis (2012) also identified the presence of a mixing layer in the equidistant plane between the bottom channel and the rod. They concluded that it is acceptable to use URANS to calculate flow in tightly packed rod bundles, and that a uniform inflow velocity is preferable over fully-developed profiles. Also, inlet/outlet boundary conditions should be applied rather than streamwise periodic boundary conditions.

The present work is aimed to investigate numerically the structure of the turbulent flow in a rectangular channel with a lateral slot.

Mean average quantities distributions and the dynamics of the large scale structures, such as the main frequency, Strouhal number, wavelength and the convection velocity were studied in detail. The numerical calculations were carried out using the ANSYS® CFX package using a hybrid (LES/RANS) turbulence modelling approach. The Reynolds number, based on the bulk velocity, U_b, the hydraulic-diameter, D_h and the kinetic viscosity was $Re = 2.25 \times 10^5$. To minimise computational costs we decided to apply periodic boundary conditions in the streamwise direction, thereby shortening significantly the domain in comparison with the experimental work performed by Meyer and Rehme (1994). Experimental results of the dynamics of the turbulent flow, which were published in 1994 by Meyer and co-worker, were used for comparison.

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