International Journal of Heat and Mass Transfer 123 (2018) 848–866

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The three-dimensional flow field and heat transfer in a rib-roughened channel at large rotation numbers

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ARTICLE INFO

Article history:
Received 11 November 2017
Received in revised form 1 March 2018
Accepted 2 March 2018

Keywords:
Coriolis
System rotation
Channel flow
Turbulator
Internal cooling

ABSTRACT

The turbulent velocity field in a rotating rib-roughened channel is studied by means of incompressible Large Eddy Simulations (LES). The computations are validated against Particle Image Velocimetry (PIV) measurements performed in the symmetry plane of an experimental model of the same geometry. The present simulations consider the effect of the Coriolis force on a periodic section of low aspect ratio (AR = 0.9) and one rib-roughened wall. The Reynolds number based on the bulk velocity and the hydraulic diameter is fixed to 15,000, whereas the rotation number is set to 0, 0.31 and 0.77. Beyond the analysis of the Coriolis force influence on the shear layer stability, the present simulations allow to characterize the stream-wise secondary flows that redistribute the momentum through the cross-section at the different rotation numbers, the temperature distribution, and the resulting heat transfer on the wall. The flow structure is similar at rotation numbers equal to 0.31 and 0.77 when the channel rotates in the clockwise direction, with reduced turbulence and heat transfer on the ribbed wall, which acts as leading side. Only minor differences in the secondary flows and mean velocity profiles are observed due to the different magnitude of the Coriolis force. On the other hand, it has been observed that the secondary flow structure differs significantly when the rotation number is increased from 0.30 to 0.77 under counter-clockwise rotation. In particular, Taylor-Görtler vortices are observed together with the Coriolis-induced secondary flows at the maximum rotation rate, leading to a redistribution of the mean and turbulent velocity fields, as well as a significant change in the heat transfer distribution.

1. Introduction

The study of the fluid dynamics in a rotating system requires to consider the effect of the Coriolis force on the average and fluctuating components of the fluid velocity field. Several examples are found in geophysical flows or engineering applications, like in jet engine compressors and turbines.

In the present work, our efforts focus on the flow and heat transfer of an incompressible fluid in a ribbed channel of low aspect ratio, shown in Fig. 1. The configuration investigated, although simplified, emulates the main flow phenomena in the rotating cooling channels present in the turbine blades of jet engines. With such cooling channels, high turbine inlet temperatures can be reached, leading to an increase of efficiency of the engine. The channel geometry is similar to the one investigated experimentally by Coletti et al. [5] and Mayo et al. [22,23]. One wall is roughened by means of square turbulators placed perpendicularly to the main flow direction (x direction). The channel rotates with an angular speed Ω around the z axis, perpendicular to the main flow direction and parallel to the axis of the turbulators. The angular speed Ω is considered positive if the channel rotates in the positive sense of the z axis (counter-clockwise rotation), as it is depicted in Fig. 1, and negative in the opposite case (clockwise rotation). The area near the wall leading the motion of the channel is often referred as leading side (top wall in the case of Fig. 1), whereas the opposite one is called trailing side (the ribbed wall in the case of the figure). When the density gradients are limited, the centripetal buoyancy force is negligible, the centripetal force acts as a pressure gradient and the rotational effects are only promoted by the Coriolis force. Even in those circumstances, the fluid dynamics differs greatly from the one obtained in stationary conditions. The velocity and heat transfer fields are determined by the Reynolds and Prandtl numbers, as well as by the ratio of the Coriolis force to the inertia of the fluid. The Reynolds (Re) and Prandtl (Pr) numbers are defined as

$$Re = U_b D_H / \nu \quad (1)$$

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.009
0017-9310/

Nomenclature

A	cross-section area
CW	clockwise
CCW	counter-clockwise
c_p	specific heat at constant pressure
D_H	hydraulic diameter
EF	Enhancement Factor
f	friction factor
H	rib height
h	heat transfer coefficient
k	thermal conductivity
M_T	turbulence resolution magnitude
Nu	Nusselt number
Pr	Prandtl number
Pr_t	turbulent Prandtl number
p	instantaneous pressure
q	dimensionless turbulent kinetic energy
q_{conv}	convective heat transfer per unit area
Re	Reynolds number
Ri	Richardson number
Ro	rotation number
r	distance to the axis of rotation
T	temperature
t	time
$U,\ V,\ W$	mean stream-wise, vertical and span-wise velocity components
U_b	bulk velocity
u, v, w	instantaneous value of the stream-wise, vertical and span-wise velocity components
$u_{rms},\ v_{rms},\ w_{rms}$	root mean square values of the stream-wise, vertical and span-wise velocity components
$\|V\|$	in-plane velocity modulus
x, y, z	non-dimensional Cartesian coordinates

Greek symbols

α_t	subfilter-scale eddy diffusivity
β	instantaneous driving pressure gradient
$\overline{\Delta}$	cell characteristic length
Δ	cell characteristic length
$\Delta x, \Delta y \Delta z$	cell dimensions in the x, y and z directions
δ_{ij}	Kronecker Delta
ε	dissipation rate
ε_{ijk}	Levy-Civita symbol
η	Kolmogorov length scale
Θ	dimensionless temperature
μ	dynamic viscosity
ν	kinematic viscosity
ν_t	subfilter-scale viscosity
ρ_t	fluid density
σ	standard deviation
Ω	angular velocity

Acronyms

AR	Aspect Ratio
CFD	Computational Fluid Dynamics
LDKSGS	Localized dynamic k-equation subgrid-scale
LES	Large Eddy Simulation
PIV	Particle Image Velocimetry
SFS	Sub-Filter-Scale

Subscripts and superscripts

$\sim$	spatially-filtered value
$-$	time-averaged value
B	referring to the bottom wall
b	bulk
c	center
eff	effective
T	referring to the top wall
0	reference value

$$Pr = \mu c_p / k \tag{2}$$

where U_b is the bulk velocity, D_H the hydraulic diameter, ν the kinematic viscosity, μ the dynamic viscosity, c_p the specific heat at constant pressure and k the thermal conductivity. On the other hand, the ratio of the Coriolis force to the inertia of the flow is represented by the rotation number, Ro:

$$Ro = \Omega D_H / U_b \tag{3}$$

The presence of the Coriolis force affects the velocity field first by promoting the redistribution of the mean velocity shear, $\partial U/\partial y$, U standing for the mean stream-wise velocity component.

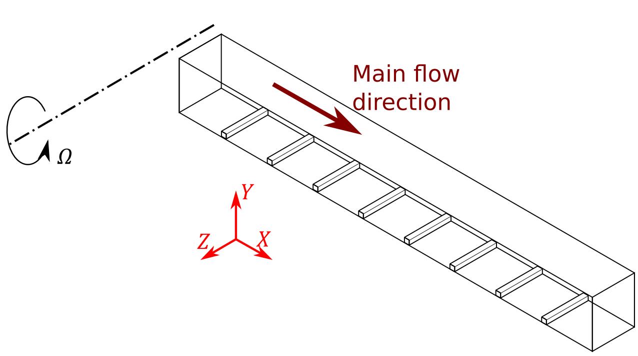

Fig. 1. Flow configuration (counter-clockwise rotation).

As shown by Johnston et al. [16] and Kristoffersen and Andersson [18], the flow in a high aspect ratio channel tends to present a core region where $\partial U/\partial y$ is equal to 2Ω. Second, the stability of any shear layer is affected by the magnitude of the rotational speed and the relative orientation of the mean flow vorticity with respect to the angular velocity vector. Lezius and Johnston [20] carried out the stability analysis of a rotating two-dimensional and inviscid flow, introducing the gradient Richardson number as the critical parameter that determines the stability of the shear layer,

$$Ri = -2\Omega \frac{\frac{\partial U}{\partial y} - 2\Omega}{\left(\frac{\partial U}{\partial y}\right)^2} \tag{4}$$

Local stability occurs as long as the Richardson number is positive. This is the case when the angular velocity vector and the local mean vorticity (represented by $\partial U/\partial y$) present the same orientation, also known as cyclonic rotation. When the angular velocity vector and the local vorticity present opposite directions, the flow can be stable or unstable depending on their relative magnitude. If the local vorticity is large compared to the angular velocity of the channel, i.e., $|\partial U/\partial y| > 2|\Omega|$, the Richardson number is positive (Eq. (4)), and therefore, the shear layer is stabilized. However, when the angular velocity is large enough so that $|\partial U/\partial y| < 2|\Omega|$, the Richardson number is positive and the shear flow tends to be stable. Finally, neutral stability is found when $Ri = 0$.