Asociación Argentina
de Mecánica Computacional

Mecánica Computacional Vol XXXVII, págs. 1119-1130 (artículo completo)
A. Cardona, L. Garelli, J.M. Gimenez, P.A. Kler, S. Márquez Damián, M.A. Storti (Eds.)
Santa Fe, 5-7 Noviembre 2019

STUDY AND VALIATION OF THE SPATIAL LAMINAR-TURBULENT TRANSITION IN CHANNEL FLOW WITH UNIFORM ROUGHNESS

William I. Machaca Abregu[a,b], Federico E. Teruel[a,b,c] and Enzo A. Dari[a,b,c]

[a]*Instituto Balseiro,Universidad Nacional de Cuyo, Av. Ezequiel Bustillo 9500, 8400 San Carlos de Bariloche, Rio Negro, Argentina.*

[b]*Departamento de Mecánica Computacional, Centro Atómico Bariloche, Av. Ezequiel Bustillo 9500, 8400 San Carlos de Bariloche, Rio Negro, Argentina.*

[c]*CONICET, Centro Atómico Bariloche, Av. Ezequiel Bustillo 9500, 8400 San Carlos de Bariloche, Rio Negro, Argentina.*

Keywords: Spatial Laminar-Turbulent Transition, IBM, Incompact3D, DNS.

Abstract. The laminar turbulent transition on a channel flow depends on many factors such as disturbances at the channel entrance, roughness and Reynolds number between others. In the present work, the effect of the roughness is studied using Direct Numerical Simulation (DNS). The numerical tool employed is the Incompact3d code, which solves the incompressible Navier-Stokes equations and allows to model roughness at the wall with the Immersed Boundary Method (IBM) . First, numerical simulations are performed for $Re_o = 6300$ in a periodic channel in order to validate the code. Results are well compared with data from the literature. Then, three simulations (two with roughness and one without roughness) are performed using the same Reynolds number (i.e. the same flow rate), on a channel with an inflow-outflow boundary condition in the streamwise direction to calculate the evolution of the friction coefficient from the laminar state to the fully turbulent one. Results show that right after the entrance a disturbed laminar regime is presented. The evolution of this regime to a fully turbulent state is then compared with the case without roughness to evaluate the effect of the roughness on the transition phenomenon. It was found that the roughness increases the friction coefficient by a factor of 1.8 and accelerates the transition in the streamwise direction for approximately 18.5 channel half-heights.

1 INTRODUCTION

The study of laminar-turbulent transition is very important in engineering problems and in the scientific field. In this regime, parameters like the Nusselt number Nu or the friction coefficient Cf have a large variation (Tam and Ghajar, 2006). For this reason the design and operation in this regime is not desirable, for example, in thermohydraulic devices. However, in many applications such as wings of airplanes, in space vehicles, in heat exchangers, etc., the transition cannot be avoided (Schlatter, 2005). In Argentina, the RA6 Research Nuclear Reactor operates in a transition regime and may possibly present spatial transitions in the coolant of the Fuel Elements (Silin et al., 2010, 2012). Therefore, the study of this phenomenon is of interest to the personnel that operates the Nuclear Reactor. In this paper the roughness effect on this phenomenon will be studied.

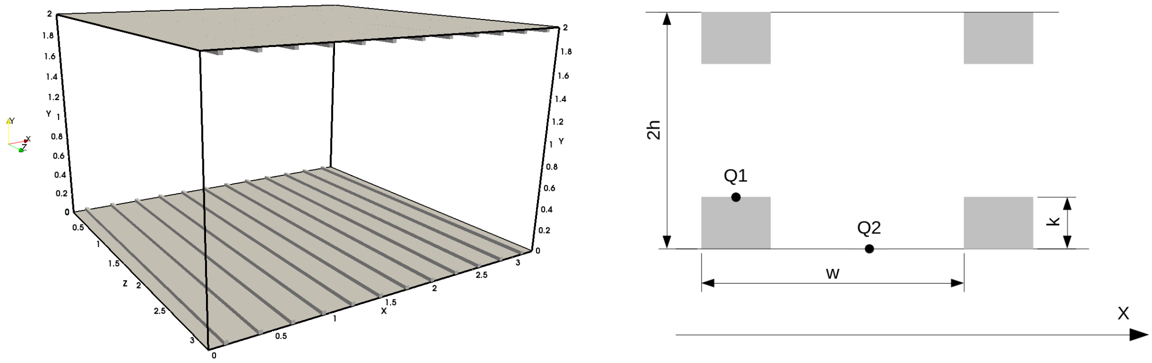
The study of the effect of roughness in rectangular channels is extensive found in the literature. Orlandi (2007) showed that the roughness can be modeled with transverse square bars, which can be classified into K-type and D-type. He also found that the main difference between both types of roughness is related to the different contribution from the frictional drag and pressure drag to the total stress. Smalley et al. (2002) showed that the Anisotropy Invariant Map (AIM) signature for K-type differs significantly from that for a smooth wall. For D-type roughness, the AIM signature is much more similar to that for a smooth wall. Ashrafian et al. (2004) studied the influence of roughness on high order statistics. They found that the roughness tends to increase the intensity of vorticity fluctuations in the vicinity of roughness. Ashrafian and Anderson (2006b) studied the influence of roughness on the dynamics of the flow and on the lengths of the scales. He found that structures outside the rough sublayer are strongly affected by the condition of the walls. The study of laminar-turbulent transition with roughness is hardly found in the literature. Orlandi (2014) studied the transition phenomenon in periodic turbulent channel flow with roughness effect. He found condition on the velocity fluctuations in the crest of the roughness element and on the height of the roughness so that a flow becomes turbulent. He found that the value of the fluctuation has to be greater than 0.6 and the height of the roughness has to be greater than 15, both in wall units.

In this paper, the effect of uniform K-type roughness on the spatial laminar-turbulent transition is studied numerically. The outline of the work is divided in 4 sections. In the section 2 the numerical method is presented. Then the principal results of the present study are shown in section 3. Finally the main conclusions of the work are presented.

2 NUMERICAL METHOD

The numerical study of laminar-turbulent transition with uniform roughness is performed in a rectangular domain (see figure 1a). The roughness parameters are taken from Ashrafian and Anderson (2006a). The parameters of roughness are $k/w = 0.125$ and $k/h = 0.034$, where k is the height of the roughness, w is the width between two obstacles and h is the half height of the channel (see figure 1b). These parameters lead to the K-type roughness. The Navier-Stokes equations are solved in the fluid field. For this purpose, a precise numerical tool, Incompact3d (Laizet et al., 2010; Laizet and Li, 2011), and linear stability theory (Schmid and Henningson, 2001; Schlatter, 2005), that allows the transition from laminar flow to turbulent flow in affordable computational times, are used. To model uniform roughness the IBM based on the method of Direct Force of type $u = 0$ (Gautier et al., 2014) , available in the numerical tool, is employed.

The hydrodynamic field is modeled using the Navier-Stokes equations and the continuity



(a) (b)

Figure 1: Sketch of the domain for the study of laminar-turbulent transition with uniform roughness, where x is the streamwise direction. a) domain and b) the roughness parameters (w and k) where $Q1$ is the middle of the crest and $Q2$ is the middle between two bars.

equation. The distance, the instantaneous velocity, the pressure and the time are dimensionless with the half height of the channel h , the maximum velocity in the streamwise direction U_o, the density ρ and the cinematic viscosity ν. The dimensionless equations are shown below:

$$\frac{\partial \vec{u}^*}{\partial t^*} + \frac{1}{2}(\nabla(\vec{u}^* \otimes \vec{u}^*) + \vec{u}^* \cdot \nabla)\vec{u}^* = -\nabla p^* + \frac{1}{Re_o}\nabla^2 \vec{u}^*, \tag{1}$$

$$\nabla \cdot \vec{u}^* = 0, \tag{2}$$

where: $\vec{u}^* = \frac{\vec{u}}{U_o}$ is the velocity field ($\vec{u}^* = (u^*, v^*, w^*)$), $\vec{x}^* = \frac{\vec{x}}{h}$ ($\vec{x}^* = (x^*, y^*, z^*)$), $t^* = \frac{tU_o}{h}$ is the time, $p^* = \frac{p}{\rho U_o^2}$ is the pressure field, $Re = Re_o = \frac{U_o h}{\nu}$ is the Reynolds number. Note that in the equation 1 the convective term is written in its antisymmetric form. This specific form allows a better conservation of the kinetic energy for the spatial discretization used in the code (Kravchenko and Moin, 1997).

The boundary condition are: inflow/outflow in the streamwise direction (x), periodic in z and no-slip in y ($u^*(x^*, 0, z^*) = u^*(x^*, 2, z^*) = 0$). The inflow condition, in the present work, is a disturbed Poiseuille flow (Schlatter, 2005; Machaca Abregu, 2015; Machaca Abregu and Teruel, 2016). For the outflow boundary condition, the convective condition (Lamballais, 2014; Machaca Abregu, 2015) is used.

With the equation of hydrodynamic field and the boundary condition, the results of the present study are presented in the next section. For simplification purpose we will use the variables without ($*$).

3 RESULTS

First, a case of a periodic turbulent rough channel is presented as validation. Then the spatial laminar-turbulent transition is analyzed.

3.1 IBM validation

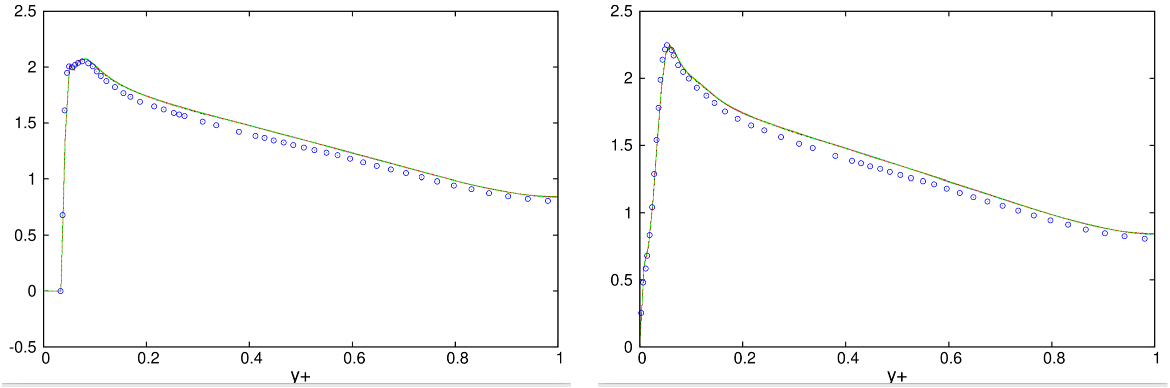
Previous simulations in periodic turbulent channel (Machaca Abregu and Teruel, 2017; Machaca Abregu, 2015) flow were performed by imposing a constant flow rate (CFR) (the present spatial laminar-turbulent transition use that force too). The CFR approach, according to Quadrio et al. (2016), has a fast convergence to the steady state than the Constant Pressure Gradient (CPG). However, in the literature the CPG force is widely used (Jin and Herwing, 2013; Ashrafian et al., 2004; Ashrafian and Anderson, 2006a). For this reason the CPG is implemented in Incompact3d to carry out the validation.

Periodic simulations were performed in the domain of figure 1 using the CFR and CPG conditions. The domain used is $3.264 \times 2 \times 3.14$ with discretization of $384 \times 237 \times 128$ in x, y and z, respectively. The roughness parameters on both walls were $k/w = 0.125$ and $k/h = 0.034$, which correspond to 12 bars in both walls. The Reynolds number used was $Re_o = 6300$. The Um, $dpdx$ and Re_τ were calculated. The results in the statistically steady state are shown in the table 1, where there is a good agreement between both simulations (CPG and CFR) suggesting that both conditions can be employed to simulate the flow.

Re	CPG			CFR		
	$dpdx$	Um	Re_τ	Um	$dpdx$	Re_τ
6300	-0.004031	**0.623**	**400**	0.623	**-0.004114**	**404.1**

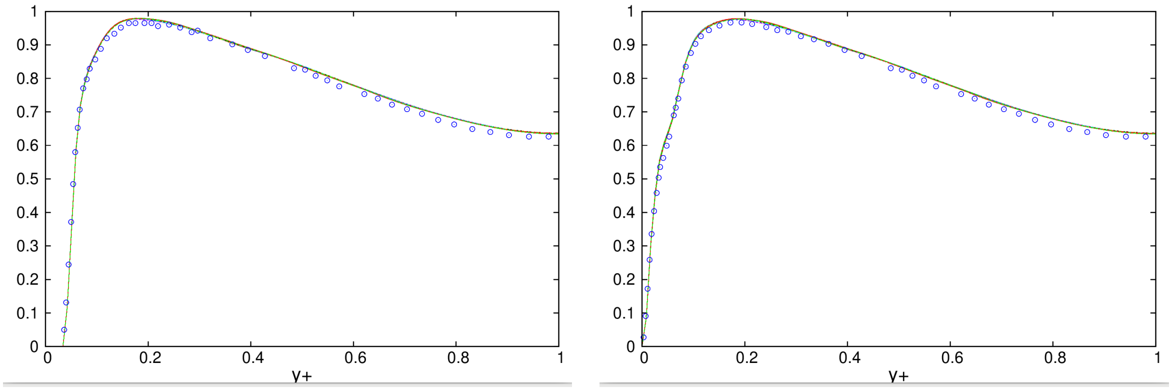
Table 1: Results using CPG and CFR for $Re = 6300$ with uniform roughness effects. Bold numbers show the calculated parameters.

Velocity fluctuations in wall units (+) were calculated in the middle of the crest ($Q1$) and in the middle between two bars ($Q2$) (see figure 1b), and compared with the data calculated by Ashrafian and Anderson (2006a). Results are shown in the figures 2,3 and 4 (the results were calculated using the CPG because similar results were obtained with CFR). An excellent agreement is observed between present results and those found in the reference. This gives support to present results to simulate a rough channel with both, the CFR and CPG approaches.



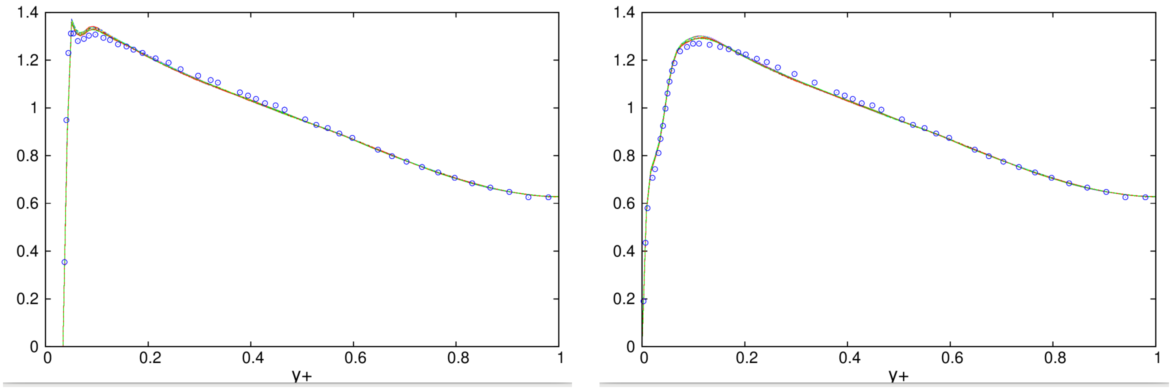
(a) Q1 (b) Q2

Figure 2: $< u'^{+} u'^{+} >$ fluctuations calculated in the present work (lines) and those calculate by Ashrafian and Anderson (2006a) (symbols).



(a) Q1 (b) Q2

Figure 3: $< v'^{+}v'^{+} >$ fluctuations calculated in the present work (lines) and those calculated by Ashrafian and Anderson (2006a) (symbols).



(a) Q1 (b) Q2

Figure 4: $< w'^{+}w'^{+} >$ fluctuations calculated in the present work (lines) and those calculated by Ashrafian and Anderson (2006a) (symbols).

3.2 Roughness in channel flow with inlet-outlet boundary condition

Spatial laminar-turbulent transition simulations are performed for three cases: two with the roughness parameter of Ashrafian and Anderson (2006a) and one without roughness. The perturbation parameters are shown in the table 2. Using these parameters, the disturbance is calculated for $Re_o = 6300$. The domain and discretization are shown in the table 3. The simulations with roughness were run for 360000 time steps with $\Delta t = 0.001$. Statistics were taken during the last 40000 time steps when the flow was in statistically steady state. Case I was carried out in the TUPAC cluster employing 8 nodes with 64 processes each. This simulation lasted for approximately 30 days. Case II was carried out in the new cluster of the Department of Computational Mechanics of the Bariloche Atomic Center employing 10 nodes with 20 processes each. The simulation lasted approximately 21 days. The simulation without roughness was run at the LNCC cluster and lasted approximately 1 day employing 8 with 16 processes each.

Re	ω_{2d}	ω_{3d}	β	A_{2d}	A_{3d}
6300	0.3	0.3	2.0944	0.8	0.1

Table 2: Perturbation parameters to destabilize the flow in spatial laminar-turbulent transition (Schlatter, 2005; Machaca Abregu, 2015).

Case	$L_x \times L_y \times L_z$	$n_x \times n_y \times n_z$	Δt
I	$65.28 \times 2 \times 3$	$7681 \times 237 \times 64$	0.001
II	$97.92 \times 2 \times 3$	$11521 \times 237 \times 64$	0.001
III	$90.0 \times 2 \times 3$	$1801 \times 65 \times 64$	0.001

Table 3: Parameters for laminar-turbulent transition simulations with uniform roughness (case I and II) and without roughness (case III).

The pressure in the statistically steady state $< p >$ is calculated for the three cases analyzed. The results are shown in figure 5. We can see that the case without roughness (case III) presents a different evolution from the other two. This is expected, since at the same flow rate the roughness increases the pressure drop. In the fully developed region the pressure gradient is approximately increased by a factor of 3.2 respect to the smooth channel.

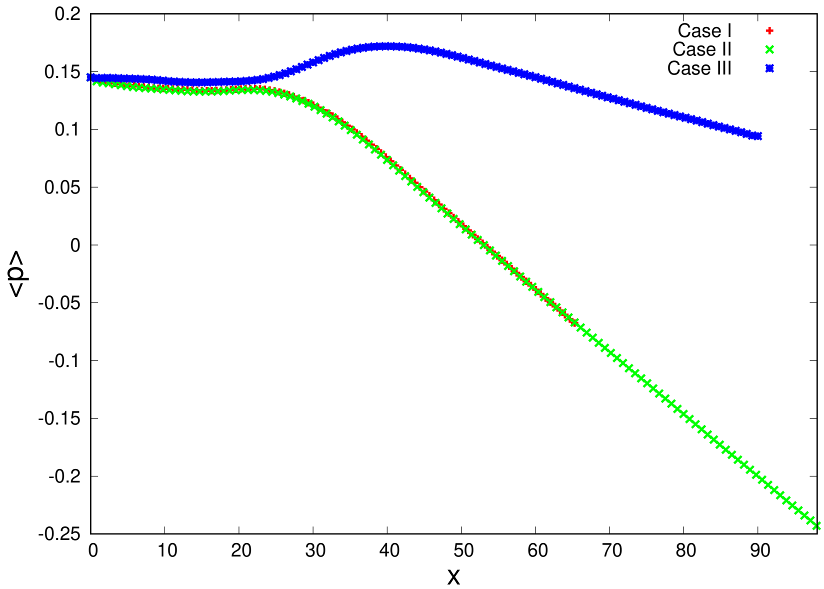


Figure 5: Re_τ in function of streamwise direction.

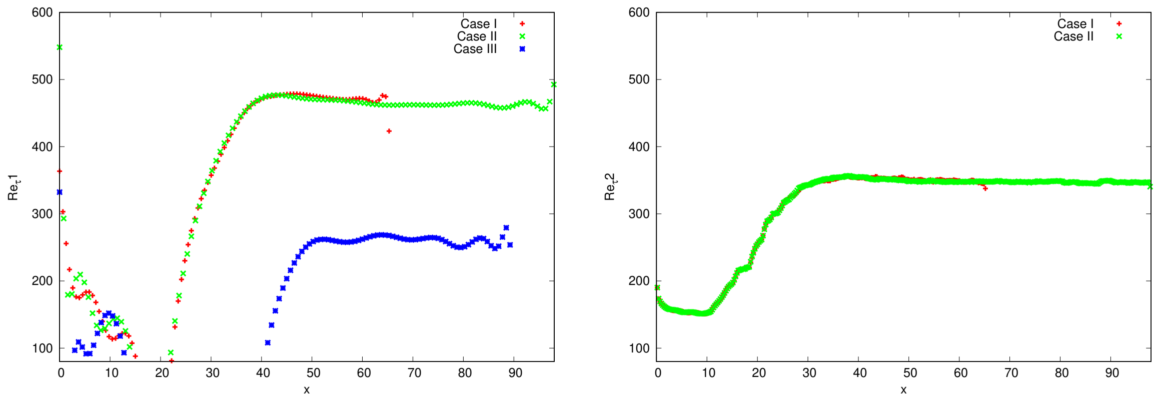
The local friction coefficient (i.e. shear stress at the wall) in the rough channel is strongly dependent on the location where it is calculated respect to the bars that are employed to simulate roughness. Therefore, we propose to Re_τ is calculated using the following equation where the pressure gradient is extracted from figure 5:

$$Re_\tau 1 = Re\sqrt{-\frac{\partial < p >}{\partial x}}. \tag{3}$$

Results are shown in figure 6a together with the smooth channel case (note that we have not applied a filter to the numerical calculation of the pressure gradient and for these reason there is some noise in the result). On the other hand, the Re_τ is also calculated using the equation 4,

$$Re_\tau 2 = \sqrt{Re\frac{\partial u}{\partial y}|_{y=2}}. \tag{4}$$

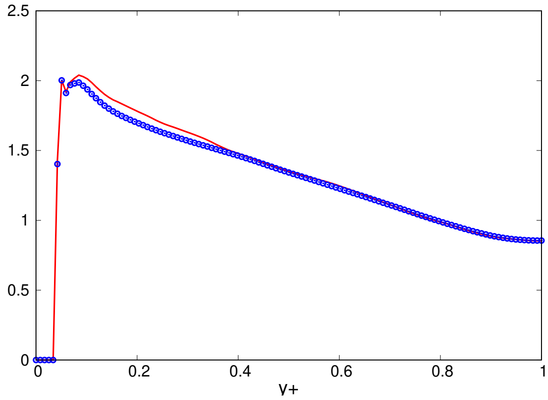
Additionally, for cases I and II, $Re_\tau 2$ is calculated in the middle of the crest of each bar. Result are shown in the figure 6b and suggest that the spatial evolution of the friction coefficient can be obtained considering discrete points at the wall that corresponds to the periodicity of the roughness. In both figures, downstream the inlet a laminar zone is observed, then a transition zone and finally a turbulent zone. It is also observed that the roughness increases the friction coefficient (Re_τ) by a factor of 1.8 and accelerates the transition for approximately 18.5 channel half-heights.



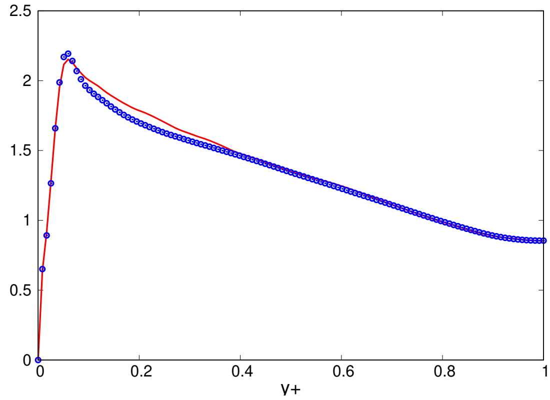
(a) $Re_\tau 2$ (b) $Re_\tau 1$

Figure 6: Re_τ in function of streamwise direction for spatial laminar-turbulent transition with uniform roughness (case I and II) and without roughness (case III)

To validate the results of the spatial transition with uniform roughness effects, the velocity fluctuations and velocity in wall units (u^+) are calculated in the fully turbulent zone. The calculation of these amounts are made in $x = 62.73$ (Q_1) and $x = 62.87$ (Q_2) (see figure 1b) for the case I. The results are compared with those calculated in a periodic turbulent channel flow with the same parameters than those used to study the spatial transition. All results (spatial laminar-turbulent transition and periodic turbulent channel flow) were dimensioned with the Re_τ calculated in the periodic case ($Re_\tau = 436$). The results are shown in the figures 7, 8, 9 and 10. A good agreement is observed between the transition case and the periodic turbulent channel flow case suggesting that the laminar-turbulent transition simulations is well resolved.

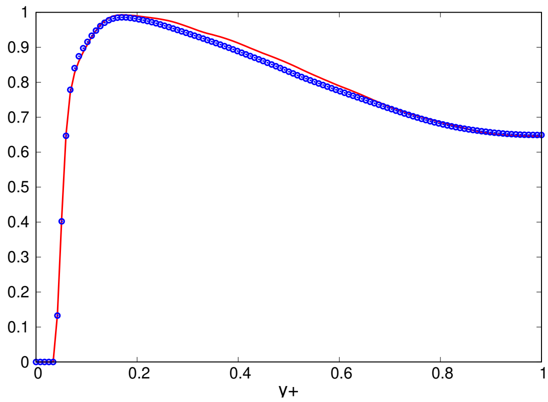


(a) Q1

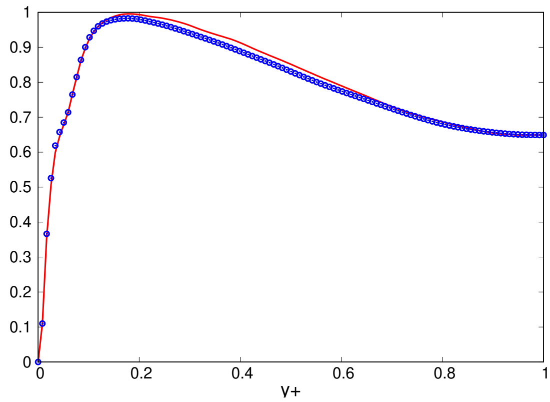


(b) Q2

Figure 7: $< u'u' >$ fluctuations calculated in the turbulent zone of spatial laminar-turbulent transition (lines) and those calculated in periodic turbulent channel flow (symbols).

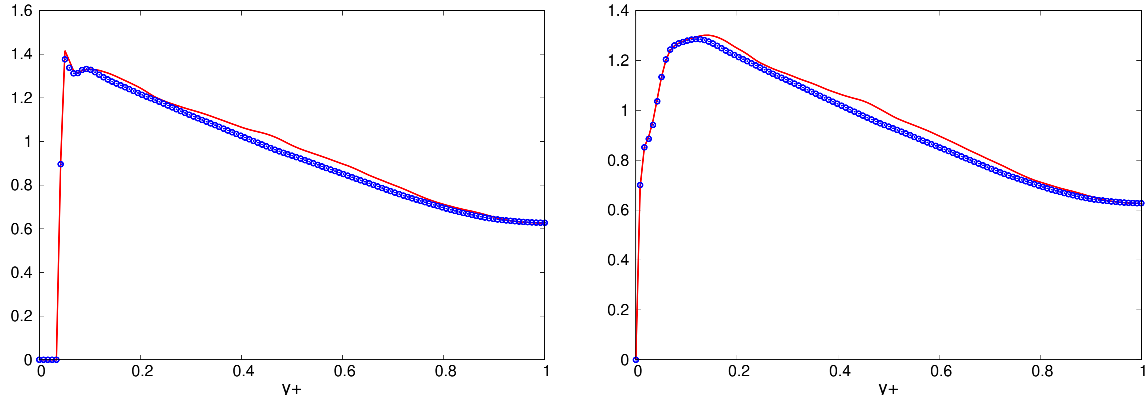


(a) Q1



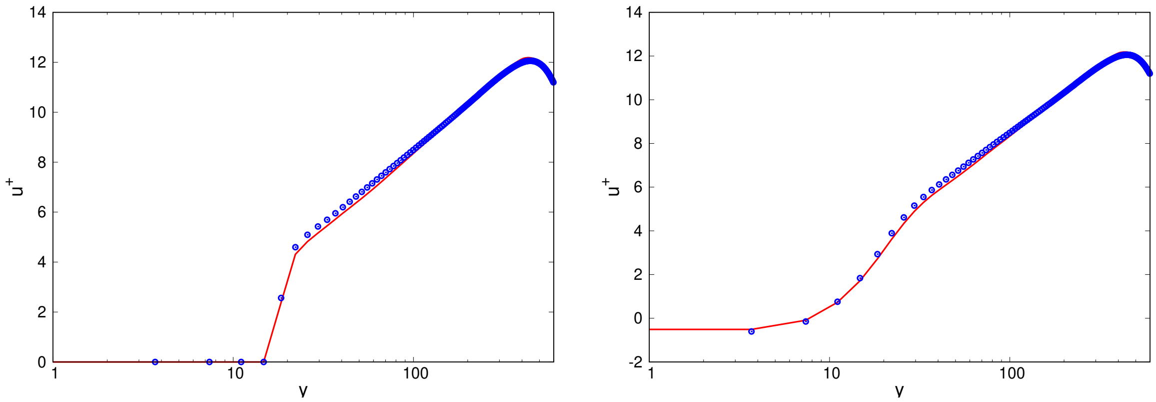
(b) Q2

Figure 8: $< v'v' >$ fluctuations calculated in the turbulent zone of spatial laminar-turbulent transition (lines) and those calculated in periodic turbulent channel flow (symbols).



(a) Q1 (b) Q2

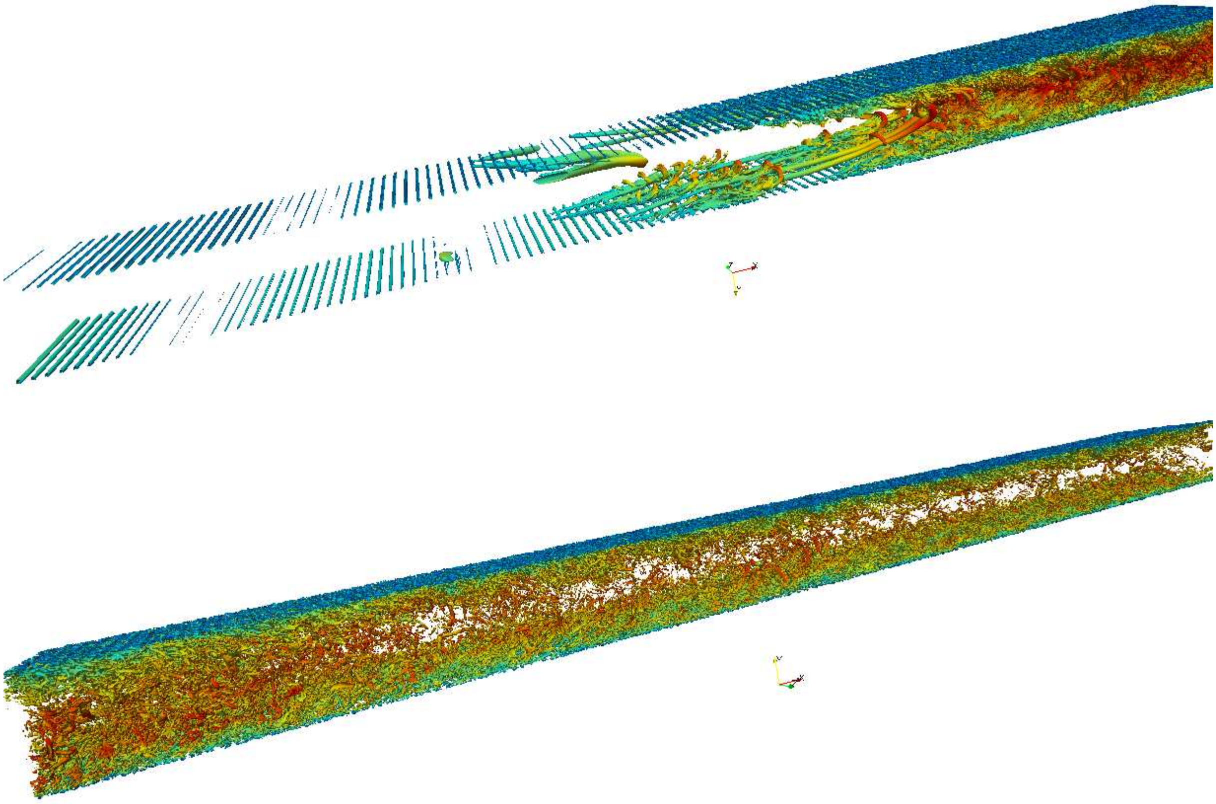
Figure 9: $< w'w' >$ fluctuations calculated in the turbulent zone of spatial laminar-turbulent transition (lines) and those calculated in periodic turbulent channel flow (symbols).



(a) Q1 (b) Q2

Figure 10: Velocity in wall units u^+ calculated in the turbulent zone of spatial laminar-turbulent transition (lines) and those calculated in periodic turbulent channel flow (symbols).

Finally, in figure 11 the vortex in laminar-turbulent transition is shown. Similarly to the smooth channel case (Machaca Abregu and Teruel, 2016) there is a presence of Λ and *hairpin* type coherent vortices in the transition zone ($x \approx 16$). In turbulent zone, upstream the outlet, coherent structures are lost.



(a)

Figure 11: Vortices in a rough channel in spatial laminar-turbulent transition. The figure is the isosurface of λ_2 (Chakraborty et al., 2005) colored with the streamwise velocity. The isosurfaces of $\lambda_2 = -0.4$ in $x \in [0 : 32]$ are shown at the top. The isosurfaces for $\lambda_2 = -4$ in $x \in [32 : 64.24]$ are shown at the bottom.

4 CONCLUSIONS

The Incompact3d numerical tool was first validated to simulate a rough channel employing both, the CFR and CPG conditions. The Re_τ and the velocity fluctuation were calculated and compared with reference data in excellent agreement.

Then, a spatial laminar-turbulent transition simulations were carried out in three cases: two simulations with roughness effects and one without roughness. The pressure in the statistically steady state was calculated for all cases. It was found that the pressure drop is greater for cases with roughness effects than the case without roughness by a factor of 3.2. The Re_τ in streamwise direction was also calculated using the pressure gradient $\frac{\partial<p>}{\partial x}$ (cases I, II and III) and using the streamwise velocity gradient $\frac{\partial<u>}{\partial y}|_{y=2}$ in the middle of the crest (cases I and II). Downstream the inlet a laminar zone is presented, then a transition zone and finally a turbulent zone. It was found that the roughness increases the friction coefficient by a factor of 1.8 and accelerates the transition for approximately 18.5 channel half-heights. The velocity fluctuations and velocity in wall units were calculated in turbulent zone. These quantities were in excellent agreement with the results calculated in periodic turbulent channel flow. Finally the vortices in the spatial transition were shown. The Λ and *hairpin* type vortices were found in the transition zone.

REFERENCES

Ashrafian A. and Anderson H.I. Roughness effects in turbulent channel flow. *Progress in Computational Fluid Dynamics*, 6:1–20, 2006a.

Ashrafian A. and Anderson H.I. The structure of turbulence in a rod-roughned channel. *International Journal of Heat and Fluid Flow*, 27:65–79, 2006b.

Ashrafian A., Anderson H.I., and Manhart M. DNS of turbulent flow in a rod-roughned channel. *International Journal of Heat and Fluid Flow*, 25:373–383, 2004.

Chakraborty P., Balachandar S., and Adrian R.J. On the relationships between local vortex identification schemes. *J. Fluid Mech.*, 535:189–214, 2005.

Gautier R., Laizet S., and Lamballais E. A DNS study of jet control with microjets using an immersed boundary method. *Int. J. of Computational Fluid Dynamics*, 28:393–410, 2014.

Jin Y. and Herwing H. From single obstacles to wall roughness: some fundamental investigations based on DNS results for turbulent channel flow. *Math. Phys.*, 64:1337–1351, 2013.

Kravchenko A.G. and Moin P. On the effect of numerical errors in Large Eddy simulation of turbulent flows. *J. Comp. Phys.*, 131:310–332, 1997.

Laizet S., Lamballais E., and Vassilicos J.C. A numerical estrategy to combine high-order schemes, complex geometry and parallel computing for high resollution DNS of fractal generated turbulence. *Computers and Fluids*, 39-3:471–484, 2010.

Laizet S. and Li N. Incompat3d, a powerful tool to tackle turbulence problems with up to O(10^5) computational cores. *Int. J. of Numerical Methods in Fluids*, 67-11:1735–1757, 2011.

Lamballais E. Direct numerical simulation of a turbulent flow in a rotating channel with a sudden expansion. *J. Fluid Mech.*, 745:92–131, 2014.

Machaca Abregu W.I. *Esquemas compactos de alto orden para el estudio de la transferencia de calor en régimen de transición*. Tesis de Maestría en Ingeniería, Instituto Balseiro, Universidad Nacional de Cuyo, 2015.

Machaca Abregu W.I. and Teruel F.E. *Estudio de las estructuras de vorticidad en la transición espacial laminar-turbulenta en canales angostos*. ENIEF 2016, Códoba, Argentina, 2016.

Machaca Abregu W.I. and Teruel F.E. *Estudio de la transferencia de calor en régimen de transición temporal laminar-turbulento en canales angostos para Reynolds moderados*. ENIEF 2017, La Plata, Argentina, 2017.

Orlandi P. Properties of d- and k-type roughness in a turbulent channel flow. *Physics of Fluids*, 19 (125101):1–6, 2007.

Orlandi P. DNS of transitional rough channels. *Journal of Turbulence*, 12(29):1–20, 2014.

Quadrio M., Frohnapfel B., and Hasegawa Y. Does the choice of the forcing term affect flow statistics in DNS of turbulent channel flow. *European Journal of Mechanics B/Fluids*, 55:286–293, 2016.

Schlatter P.C. *Large-Eddy simulation of transition and turbulence in wall-bounded shear flow.* PhD tesis, Swiss Federal Institute of Technology, Zurich, 2005.

Schmid P.J. and Henningson D.S. Stability and Transition in Shear Flows. In *Applied Mathematical Sciences*, volume 142. Springer, 2001.

Silin N., Masson V., and García J.C. Convection in a rectangular channel with a flow of water in laminar-turbulent transition with high heat fluxes. *Latin American Applied Research*, 40:125–130, 2010.

Silin N., Masson V., and Marino R. Heat transfer in a short parallel-plate channel in the transition regime. *Experimental Heat Transfer*, 25(1):12–29, 2012.

Smalley R.J., Leonardi S., Antonia R.A., and Orlandi P. Reynolds stress anisotropy of turbulent rough wall layers. *Experiments in Fluids*, 33:31–37, 2002.

Tam L.M. and Ghajar A.J. Transitional heat transfer in plain horizontal tubes. *Heat Transfer Engineering*, 27(5):23–38, 2006.