24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2350
FORCED TURBULENT CONVECTION AROUND PLAIN, GROOVED, STATIONARY AND SPINNING CYLINDERS BASED ON MAGNUS EFFECT

Paulo Mohallem Guimarães
Patrick Santos Silva
Ana Luísa Torres
Universidade Federal de Itajubá - Campus Itabira
Av. Irmã Ivone Drumond, 200, Distrito Industrial
35903087 - Itabira, MG, Brazil
pauloguimaraes@unifei.edu.br
santos1patrick@gmail.com
torres_alg@hotmail.com

Abstract. *The purpose of this work is to investigate the flow around plain and ribbed rotating cylinders based on Magnus Effect. Some features are parameterized such as the free flow velocity, the cylinder angular velocity and the wall average roughness. CFD study with Comsol Multiphysics® is carried out to approximate solutions to the velocity field and the drag and lift coefficients. A validation and independency mesh analysis are proceeded. It is important to mention that this kind of study has its application on wind mills with cylindrical-bladed turbines for low wind velocities. It is found that increasing the angular velocity of the cylinders augments lift forces. Complex surface structures such as roughness, and grooves may strongly affect forces on the blade surface.*

Keywords: *Wind mill, Magnus effect, Lift coefficient, Drag coefficient.*

1. INTRODUCTION

Fluid flow over bodies plays an important role in engineering due to lift and drag forces that are brought about over them. For that being so, to study its behavior is demanding to know, apply and develop structures in order to produce renewable energy such as wind energy, for instance. Wind turbines has played an important role in the clean energy production for not only it does not emit pollutants and hazardous residuals, but it is also an endless energy resource. The demanding innovation from this promising and ascending energy market comes from the need of generating energy at low costs. Due to this, rotating cylinders with complex surface structures are being studied as an alternative energy generation when compared to conventional blades.

The rotating cylinders based on the Magnus effect have long been used by Flettner to aid in the propulsion of ships. Since then, many researchers have been conducting experiments using the Magnus Effect in several physical fields of applications, one of them, mentioned by Seifert (2012), is the use of rotating cylinders in aircraft. With this, it was realized that this phenomenon could be applied in wind turbines. Other authors, such as Sedaghat (2014), developed studies on several models and performed several experiments using cylinders with complementary structures in order to confer a higher lift coefficient and, with that, to maximize the sustentation force to increase the efficiency of wind turbines of vertical axes based on the Magnus Effect.

According to Seifert (2012), Gustav Magnus was a Professor at Berlin University from 1844 to 1869, where he started his studies on such phenomenon that takes his name. His experiment consists of a cylinder mounted over a rotating arm supported by two stems (superior and inferior ones). He submitted the cylinder to air flow using a blower. Professor Magnus noticed that there was a lateral deviation due to the cylinder rotation.

Seifert (2012) used rotating cylinders in airplanes and with that study it was perceived that this technology could be used in wind turbines. Sedaghat et al. (2014) studied some models of rotating cylinders with complementary structures. They found that lift forces were increased and so was the vertical axis wind turbine efficiency based on the Magnus effect.

Wind turbines that use rotating cylinders as their blades recently started to be studied by Bychkov et al. (2007), where they presented a 6-rotating-cylinder wind turbine with optimum tangential velocity of 8000rpm. The cylinders had an aspect ratio of 15. He believed that this kind of turbine could operate at wind speed of 8m/s. It is also believed that this wind turbine may work for wind speeds over 2 m/s which could make it possible to be used near urban and farm areas (SEDAGHAT, 2014). Later, Murakami et al. (2010) patented a wind turbine based on the Magnus effect with 5 and 6 rotating cylindrical blades with some structures on their surfaces in order to increase lift coefficients and so the turbine performance. Again in 2010, Murakami et al. presented a new model with 5 cylinders that produced about 3kW of electrical energy with wind speeds from 4 m/s to 8 m/s. This model presented twisted-tapes on the cylinder surface.

The goal of this work is provide a numerical study of the velocity and pressure fields around rotating cylinders with complex surface structures in order to increase lift forces in the blades and to decrease the Von Kárman vortexes, by varying wind velocities, cylinder angular velocity and the cylinder surface roughness.

2. FORMULATION

Initially, the problem to be studied is shown in Fig. 1. It consists of transient turbulent flow around a rotating cylinder. The uniform and steady free flow velocity is Uin at the volume control inlet. The cylinder is rotated counterclockwise with an angular velocity of Vtang. All distances are based on the cylinder diameter (D). The upper and bottom surfaces are open boundaries.

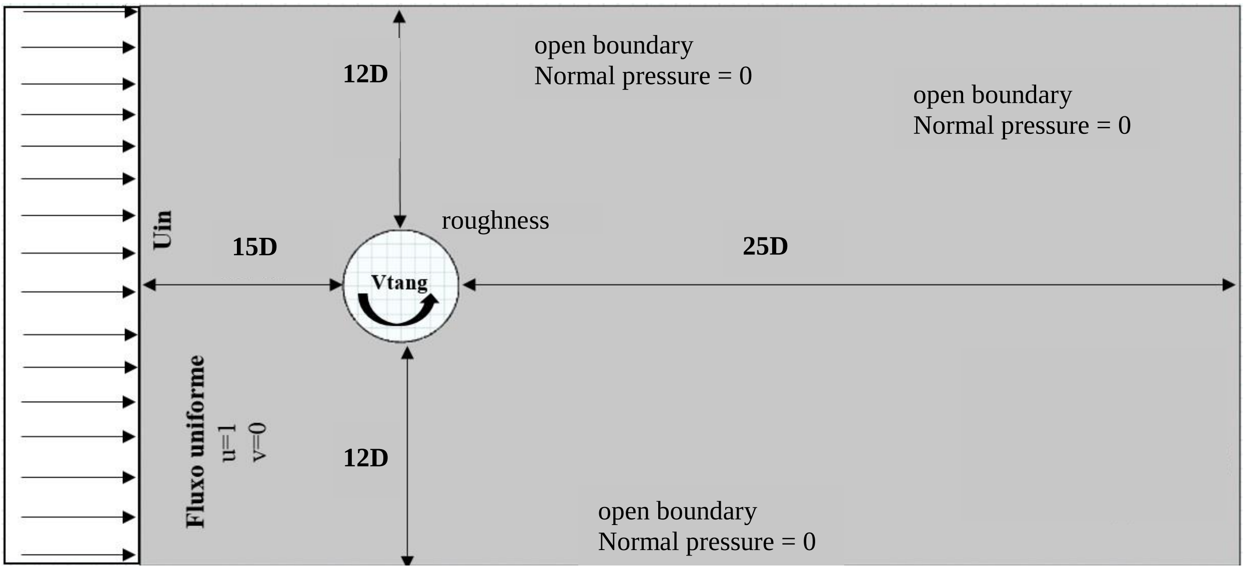

Figure 1. Geometry of the problem to be studied and boundary conditions.

The governing equations are:

The continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{01}$$

The momentum equations:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho}\left[-\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)\right] \tag{02}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho}\left[-\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)\right] \tag{03}$$

where u and v are the velocities in the x and y directions, respectively, t is time, p is pressure, ρ is the density and μ is the dynamic viscosity, and g is the gravity acceleration.

Some parameters are varied as follows:

Table 1. Parameters of analysis.

Uin [m/s]	2	5	11
Vtang [rpm]	1350	1575	2100
Roughness [mm]	0.1	2	4
Re x (10^3)	5.3038674	13.5596685	29.1712707

Re is the Reynolds number given by:

$$Re = \frac{\rho V D}{\mu} \quad (04)$$

where V is the fluid velocity and D is a characteristic length which is the cylinder diameter.

The Drag (C_D) and Lift (C_L) coefficients are given by:

$$C_D = \frac{F_D}{1/2 \rho V^2 A} \quad (05)$$

$$C_L = \frac{F_L}{1/2 \rho V^2 A} \quad (06)$$

where F_D and F_L are the drag and lift forces which can be obtained from the pressure field on the cylinder surface, V is the free stream velocity and A is the frontal area.

3. NUMERICAL PROCEDURE

The finite element method is used to approximate solutions to the velocity and pressure fields taking ito account a turbulent regime that is approached by the K-ε turbulence model, which is not shown here. Linear elements are used for every dimension considered. The software Comsol Multiphysics® is used. In the following, the validation and mesh independency study are shown. The rotation velocity α is given by $\alpha = \dot{\theta} \cdot D/2 \cdot U_\infty$, where $\dot{\theta}$ is the angular velocity of the cylinder, D is the cylinder diameter and U_∞ is the inlet velocity Uin, that is, the free stream velocity.

Tables 2 and 3 compare values of CD ad CL for stationary and rotating plain cylinders, respectively, for Re = 100 and Uin = 1 m/s. Excellent agreement is found.

Table 2. Validation 1 - With stationary plain cylinder - Re = 100, Uin = 1 m/s

	Liu et al. (1998)	Shaaf et al. (2017)	Present work
C_D	1.35±0.012	1.41±0.011	1.3713±0.2936
C_L	0±0.339	0±0.35	0±0.3423

Table 3. Validation 2 - With rotating plain cylinder - Re = 100, Uin = 1 m/s and α = 1

	Kang et al. (1999)	**Shaaf et al. (2017)**	**Present work**
C_D	1.10±0.098	1.178±0.010	1.153±0.2309
C_L	2.483±0.360	2.627±0.382	2.4685±0.3723

Non-structured mesh method controlled by the physics is chosen. The reference values to observe the independency are the lift and drag coefficients as it is shown in table 4. Mesh M4 is chosen.

Table 4. Mesh independency study for Re = 100, α = 1, rotating plain cylinder, Uin = 1m/s

Mesh	**M1**	**M2**	**M3**	**M4**	**M5**
Total number of elements	3200	7446	15896	27806	49900
Number of triangular elements	3144	7366	15896	27726	49900
Number of quadrilateral elements	56	80	0	80	0
Number of boundary elements	148	234	344	452	586
C_L	2,0436	2,465	2,0436	**2,4685**	2,182
C_D	1,238	1,2163	1,238	**1,1536**	1,1931

4. RESULTS

Figure 2 shows the velocity field and streamlines for rotating cylinders with roughness equal to 0.1mm and Uin = 2 m/s. One can see the effect of the rotation velocity of the cylinder. Clearly, the downstream flow changes its direction as the tangential velocity of the cylinder is increased. As the fluid is considered to be viscous, and because of the adherence principle, this behavior is expected. This may also play an important effect on the pressures distribution which can be seen in Fig. 3. Hence, the Magnus effect appears.

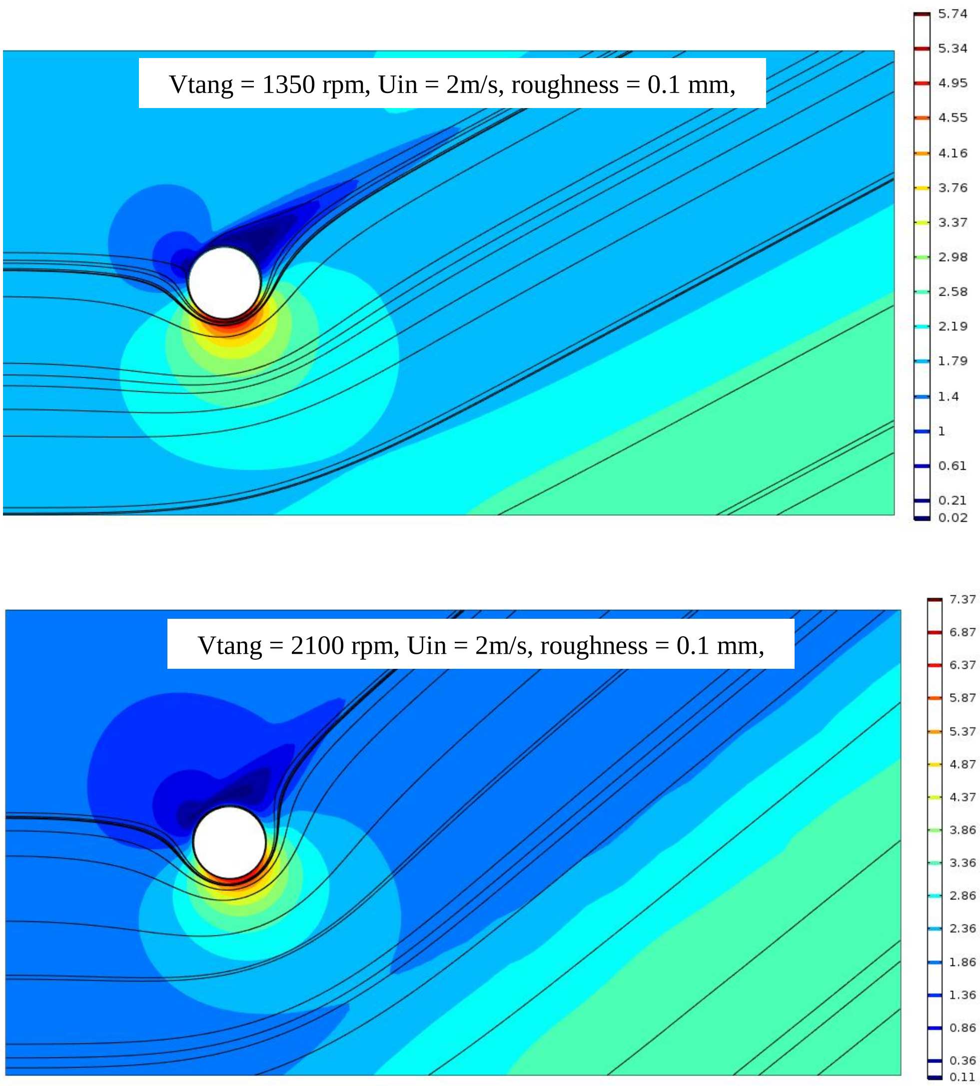

Figure 2. Velocity field and stream lines for rotating cylinders with U_{in} = 2m/s, V_{tang}=2100 rpm and roughness = 0.1mm

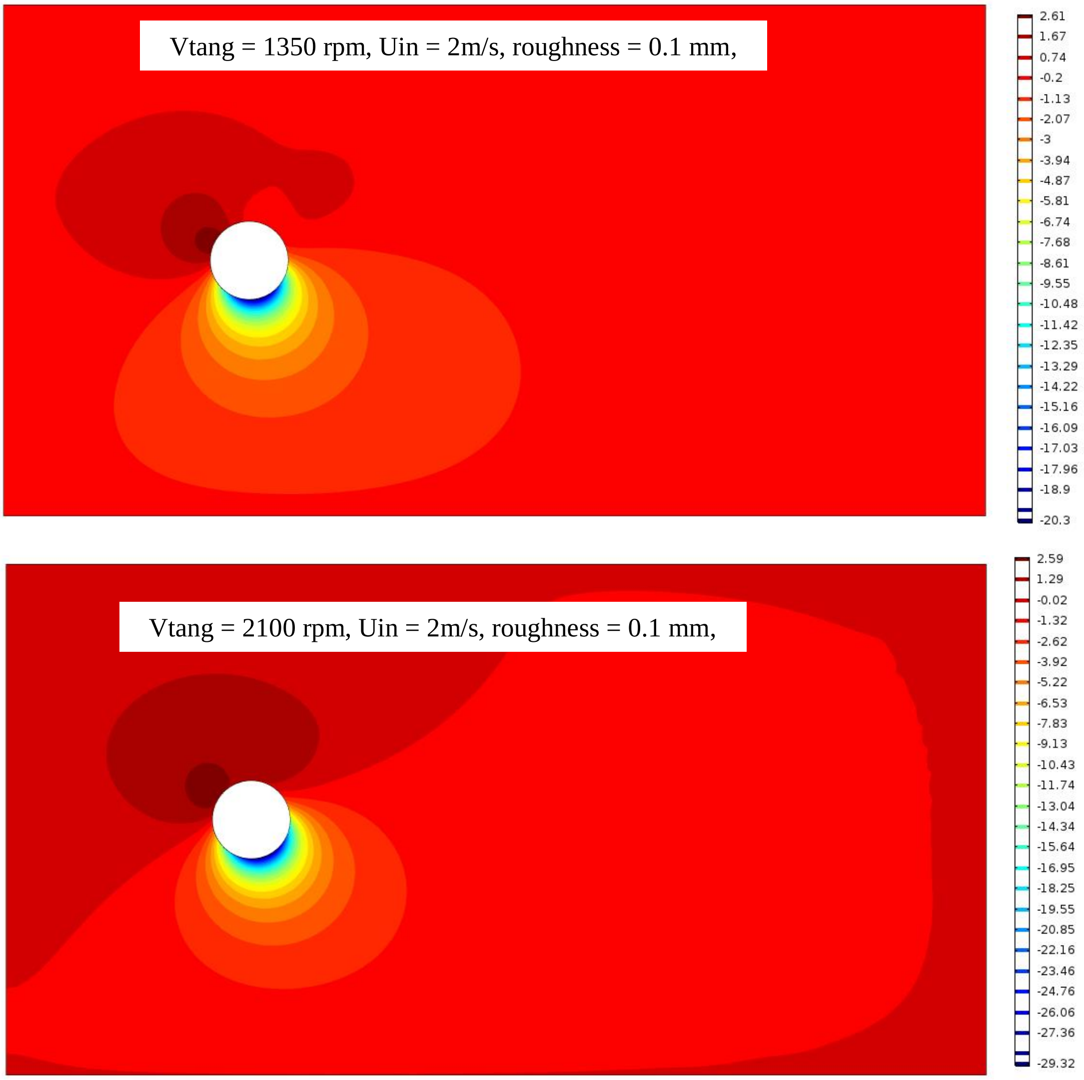

Figure 3. Pressure field for rotating cylinder with U_{in} = 2m/s, V_{tang}=2100 rpm and roughness = 0.1 mm

One can observe that there is an increase of about 10% from the range of the two pressure fields. This is due to the fact that the Magnus effect increases for this situation. The question that arises is that if it will continue to increase and what the tendency of this behavior is. This will reflect on the lift and drag coefficients.

Figure 4 depicts the drag coefficient behavior in time for roughness = 0.1, Uin = 2, 5, 11 m/s, and 1350, 1575 and 2100 rpm. By fixing Uin, it is seen that CD increases as the cylinder rotation is augmented. This effect is more significant for lower wind velocities where the CD range is sparser. For Uin = 11 m/s, one may observe the oscillatory behavior of CD. This is due to the Vón Kárman vortex downstream the cylinder.

Figure 5 depicts the lift coefficient behavior in time for roughness = 0.1, Uin = 2, 5, 11 m/s, and 1350, 1575 and 2100 rpm. It shows a similar behavior when CD was just studied. Afterwards, some complex structures will be implemented in order to reduce the Vón Kárman vortexes so that more significant Lift Coefficients are achieved. One example is to include grooves on the cylinders surface to soften boundary layer detachment.

Figure 6 presents CL behavior in time for Uin = 2, 5 and 11m/s, roughness=0.1, 2 and 4 mm, and 2100rpm. By fixing Uin, one may observe that roughness plays an important role on the lift coefficient so that CL increases as the cylinder surface is rougher. By keeping Uin constant, the difference in CL between two consecutive roughness values tends to decrease. For future works, it is interesting to study till what roughness the effect losses its significance.

Figure 7 shows the velocity field around a 3D-stationary grooved cylinder. Each groove is 5mm wide and 4 mm deep. The cylinder length is 300mm. Then, there are 29 grooves equally spaced of 5mm and displayed in parallel with the free stream. Figures 8 and 9 provides the CL ad CD, respectively, for the same 3D-stationary grooved cylinder. The case here is the same as that one for the plain cylinder with Re = 100, α = 1, and Uin = 1 m/s where CL = 2.4685 and CD = 1,1536. One may observe that grooves almost canceled drag forces and doubled lift ones.

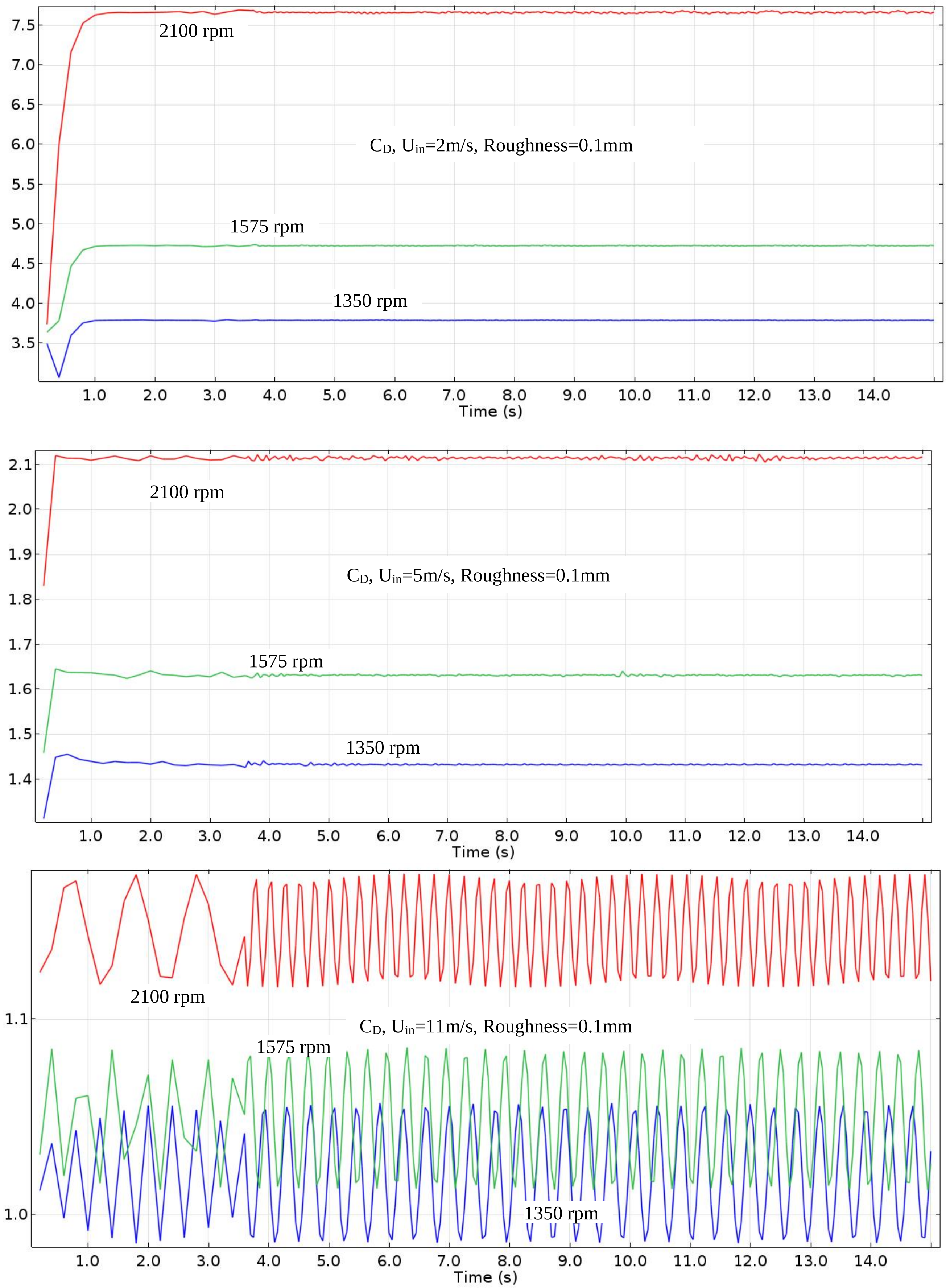

Figure 4. C_D versus Time for Uin = 2, 5 and 11m/s, roughness=0.1mm, 1350, 1575, and 2100rpm

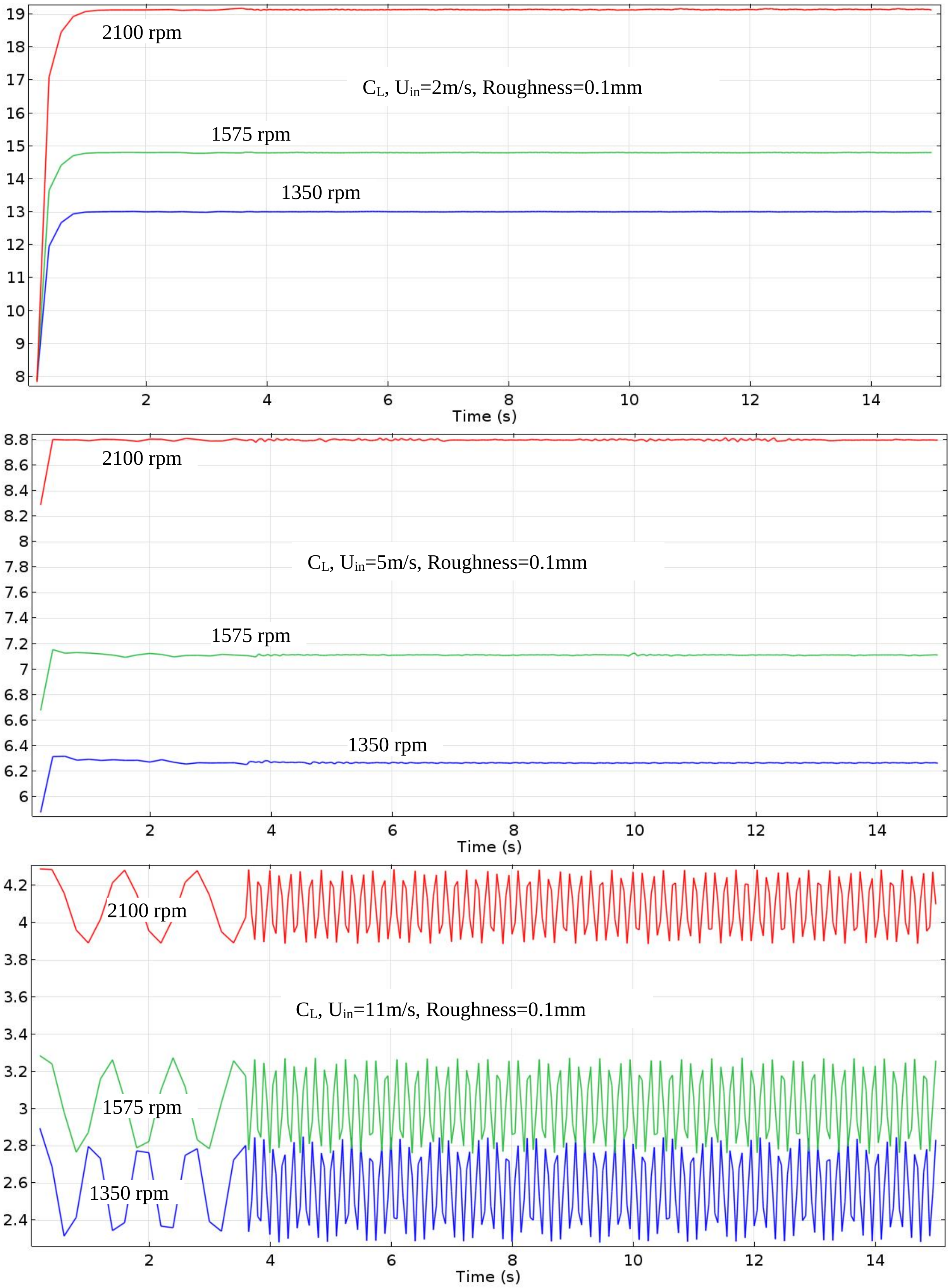

Figure 5. C_L versus Time for Uin = 2, 5 and 11m/s, roughness=0.1mm, 1350, 1575, and 2100rpm

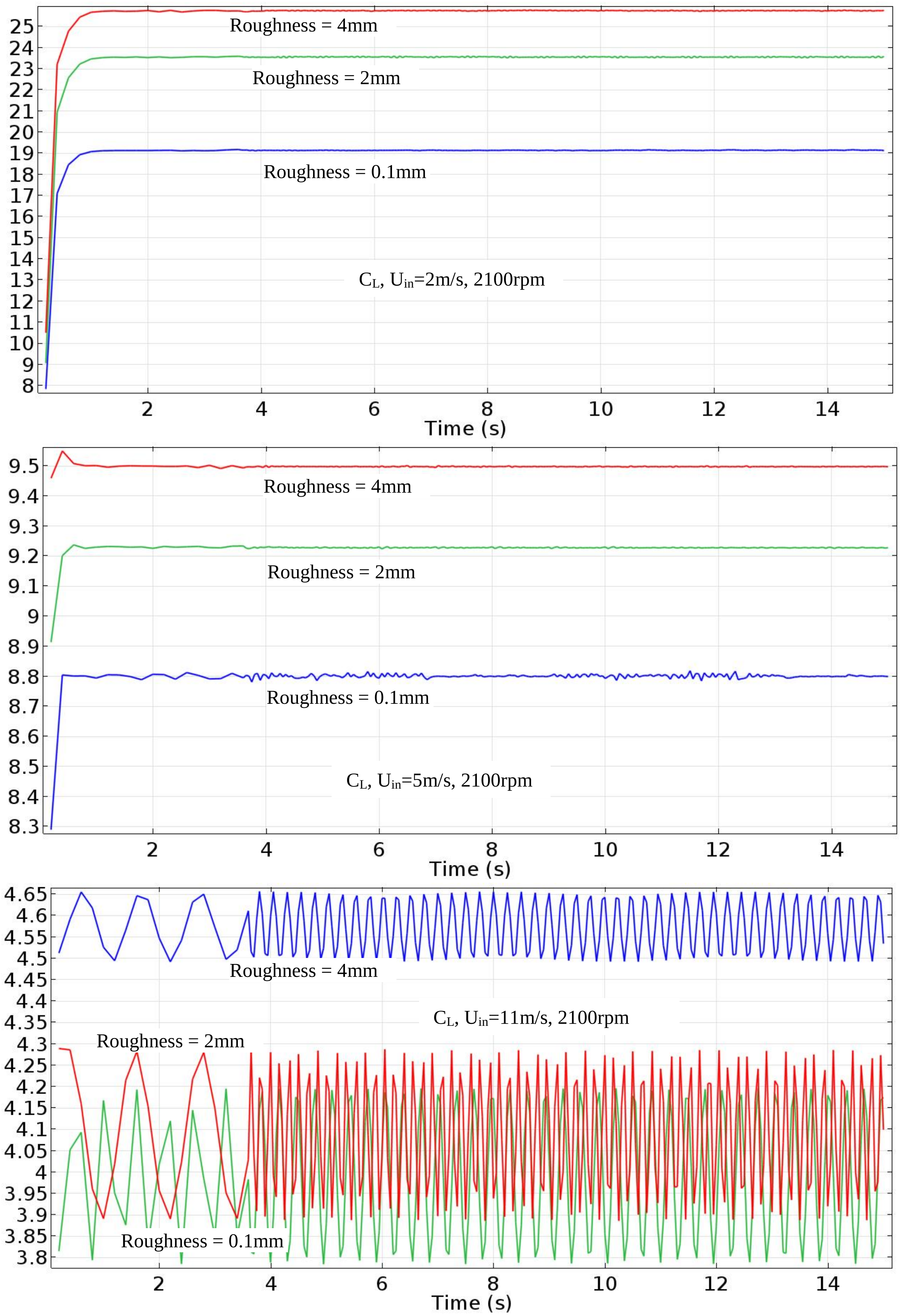

Figure 6. C_L versus Time for Uin = 2, 5 and 11m/s, roughness=0.1, 2 and 4 mm, and 2100rpm

In Figure 7, one can observe the velocity behavior and streamlines for the case with grooves. This case is for Uin = 2 m/s, Re = 5330, Vtang= 5.65 m/s (1350 rpm) and roughness = 0.1 mm.

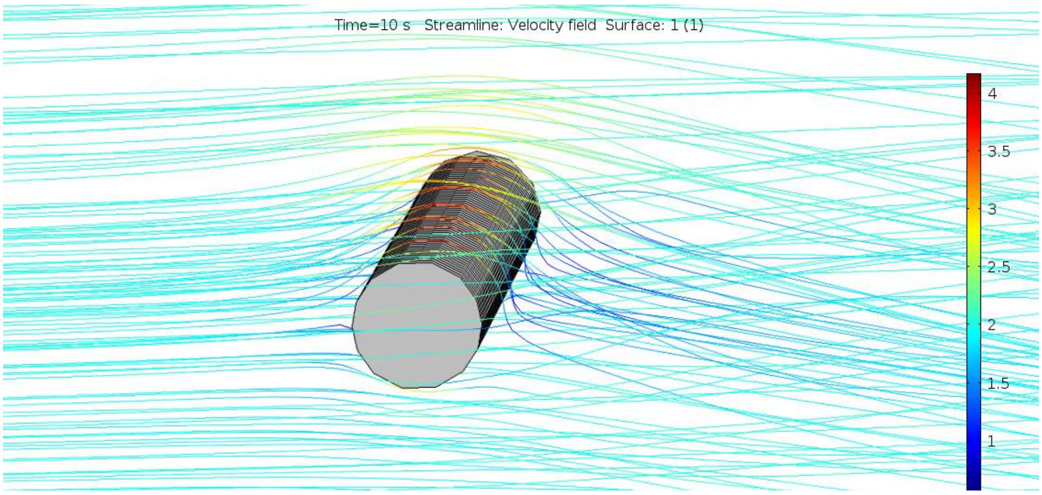

Figure 7. Velocity field over rotating grooved cylinders.

Figure 8 depicts the CL behavior in time. The average value for CL is 5.586.

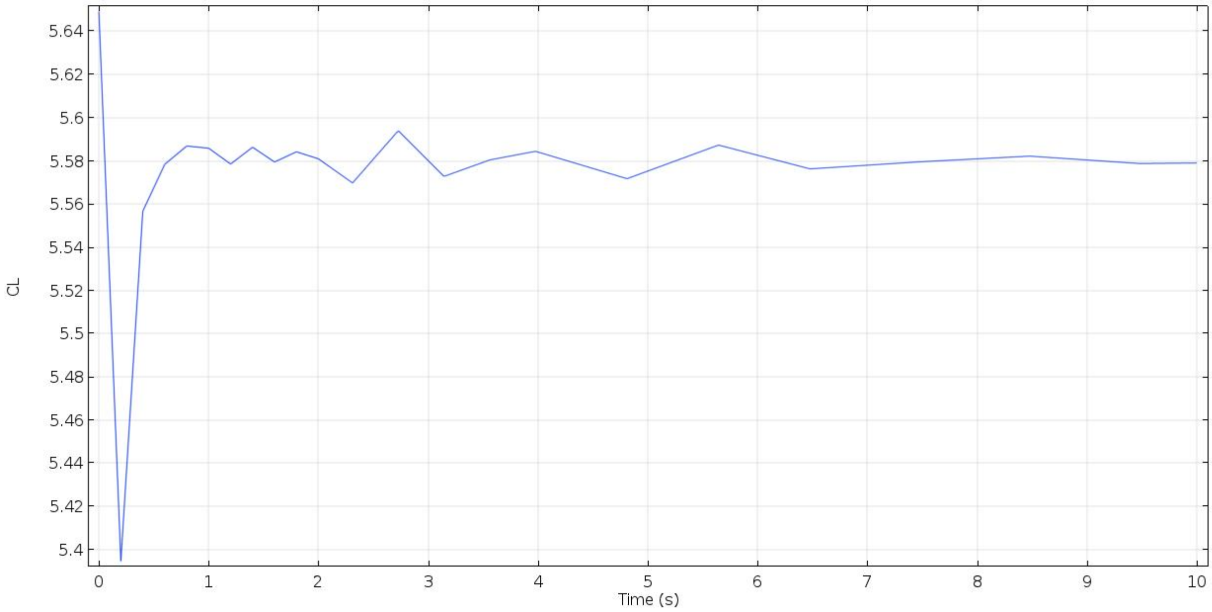

Figure 8. Lift coefficient for rotating grooved cylinders.

This value compared to an analogous case with plain surface, CL is lower. It was expected that the case with grooves would present a higher CL. It was expected that the case with grooves would present a higher CL. It is worth mentioning that Vin is 2 m/s which may not be enough to bring about the beneficial effect of grooves in terms of augmenting CL. Nonetheless, it is believed that if more turbulent flow is present, grooved cylinder may perform better. For that being so, more studies need to be carried out in future works.

5. ACKNOWLEDGEMENTS

The authors thank FAPEMIG and CNPq.

6. REFERENCES

BYCHKOV, N M; DOVGAL, A V; KOZLOV, V V. Magnus wind turbines as an alternative to the blade ones. Journal Of Physics: Conference Series, [s.l.], v. 75, n. 0, p.012004-012011, 1 jul. 2007. IOP Publishing. http://dx.doi.org/10.1088/1742-6596/75/1/012004.

KANG, S., CHOI, H., LEE, S., 1999. Laminar flow past a rotating circular cylinder. Phys. Fluids 11, 3312–3321.

LIU, C., ZHENG, X., SUNG, C.H., 1998. Preconditioned multigrid methods for unsteady incompressible flows. J. Comput. Phys. 139, 35.

MURAKAMY, N., AKITA, J.P. Magnus type wind power generator, US Patent, 2010, 0038915:A1.

SEDAGHAT, Ahmad. Magnus type wind turbines: Prospectus and challenges in design and modelling. Renewable Energy, [s.l.], v. 62, n. 8, p.619-628, fev. 2014. Elsevier BV. http://dx.doi.org/10.1016/j.renene.2013.08.029.

SEIFERT, Jost. A review of the Magnus effect in aeronautics. Progress In Aerospace Sciences, [s.l.], v. 55, p.17-45, nov. 2012. Elsevier BV. http://dx.doi.org/10.1016/j.paerosci.2012.07.001.

SHAAFI, K.; NAIK, Sandeep N.; VENGADESAN, S.. Effect of rotating cylinder on the wake-wall interactions. Ocean Engineering, [s.l.], v. 139, p.275-286, jul. 2017. Elsevier BV. http://dx.doi.org/10.1016/j.oceaneng.2017.04.044.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.