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# EXPERIMENTAL STUDY ON THE EFFECTS OF SURFACE ROUGHNESS ON THE BEHAVIORS OF HYDRODYNAMIC INSTABILITIES OF COUETTE-TAYLOR FLOW

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## ABSTRACT

Couette-Taylor flow is a type of fluid flow that occurs in the annulus between differentially concentric cylinders, when the outer cylinder is fixed and the inner cylinder rotates and the rotation rate exceeds a critical value. In this research we have studied the effect of surface roughness on the hydrodynamic structures of Couette-Taylor Flow. The PIV technique has been applied for flow visualization. At first, for a smooth surface, the different flow patterns include Couette flow, Taylor vortex flow, wavy vortex flow, modulated wavy vortex flow and turbulent flow. They are investigated numerically and experimentally. The transition Taylor number for every flow regime is also taken into consideration. The results showed that the numerical results correspond quite well to the experimental data. Then, the different surface conditions for inner cylinder which are studied are: a smooth one, a sandpaper-type P180, a canvas plastic with different wire-mesh roughness. They are used to study the effects of surface roughness on the flow structures and critical Taylor numbers.

The experimental results showed that the roughness causes a delay in the appearance of the first instabilities.

**Keywords:** Couette-Taylor Flow, Surface Roughness, PIV, Critical Taylor number, Hydrodynamic instability

## NOMENCLATURE

d	Length gap (m)
h	Height (m)
P	Pressure (Pa)
R	Cylinder radius (m)
t	time (s)
Ta	Taylor number
V	Velocity (m.s <sup>-1</sup> )
Greek symbols	
$\Gamma$	Aspect ratio(h/d)
$\eta$	Radial ratio (R <sub>1</sub> /R <sub>2</sub> )
$\delta$	Curvature ratio (d/R <sub>1</sub> )
$\mu$	Viscosity (Pa.s)

$\rho$  Density ( $\text{kg}\cdot\text{m}^{-3}$ )

Subscripts

1 Inner cylinder  
2 Outer Cylinder  
c Critical

## 1. Introduction

The Taylor-Couette flow remains a prototype model in the history of fluid dynamics; it is often used in rotating systems such as the transmission speeds of bearings in chemical or biological reactors, and in separation and filtration operations, etc.

For over a century, this subject has kept inspiring researchers and up to now more than 2,000 papers have been published. In defiance of simple geometry, this model has a variety of challenges with complex structures. Indeed it is the first model that provides the appearance of hydrodynamic instabilities and describes the properties of vortex structures such as shape, size, energy intensity, the impact on mass transfer and interaction with the wall.

Several studies have examined the fluid driven by a rotating cylinder, the first of them began in the late 17<sup>th</sup> century by Issac Newton [1]. Later in 1880 Lord Rayleigh, formalized this problem particularly for non-viscous fluids which illustrates the Rayleigh criterion [2].

Mallock and Couette both independently used two differentially rotating concentric cylinders to measure the fluid viscosity. Couette rotated the outer cylinder only while the inner cylinder was fixed. In this case, flow is stable and no vertical structures appear. Mallock also rotated the inner cylinder and kept the outer cylinder fixed [3 and 4].

Finally in 1923, Taylor was able to relate theory and experiment for stability in cylindrical Couette flow using linear stability theory to Navier-Stokes equations for viscous flow with no slip boundary conditions. He accurately predicted experimental results of transition from stable flow to vortical Taylor-Couette flow. Taylor showed that with small perturbations of the velocity and pressure fields, how viscosity stabilizes the flow at low rotational speeds using linear stability analysis. He introduced the critical Taylor number,  $Ta_c$ , a dimensionless number defined as the ratio of centrifugal (or inertial) to viscous forces. Below the critical Taylor number, the flow is stable with no vortical structure; above it the flow is unstable with toroidal vortices [5].

Until today many theoretical, experimental and numerical studies have addressed this issue in order to capture and analyze the diversity of vortex structures and interpret their transition mechanism.

Further studies are carried out on Couette-Taylor flow and are modified by adding external factors such as axial flow or a temperature gradient [6-11]. In this research, the influence of the surface roughness of the inner cylinder on the behavior of the flow is studied. So, different rough surfaces including a sandpaper-type P180 and canvas plastics with different wire-

mesh roughness are used to investigate the effects of surface roughness on the flow structures and critical Taylor numbers.

## 2. Experimental setup

The experimental installation is shown in Figure 1. The different parts of the experimental setup are respectively: (1) coaxial cylinders (2) Engine (3) Voltage Generator (4) Pump (5) Electromagnetic Flowmeter (6) Tank (7) Laser Source (8) current voltage converter (9) Acquisition Unit (10) switch-on button (11) Emergency stop button. The device consists of two vertical coaxial cylinders with equal lengths  $h = 450\text{mm}$ . The radius of the inner and outer cylinders are respectively  $R_1 = 97\text{mm}$  and  $R_2=100\text{mm}$ . The annular space is equal to  $d = b - a=3\text{mm}$ . The corresponding radius ratio is  $\eta = R_1/R_2= 0.97$  and the aspect ratio is  $\Gamma=h/d=150$ . The whole apparatus is made of Plexiglas to study the visualization of the Couette-Taylor flow. Inner cylinder was driven by a  $\alpha$ -step motor which imposed a variable speed with an inverter mechanical speed of up to 120 rev/min (rpm).

The PIV technique is applied for the flow visualization that is composed, a Laser source, a CCD camera and seeding particles system. A laser source KEYLIGHT green type of a wavelength equal to 530 nm is used to get a cut in the azimuthal plane ( $r, z$ ) at the annular space between the two cylinders is used. The evolution of instabilities over time is observed by acquiring snapshots using a CCD camera which is placed in front of the laser sheet. Kalliroscope particles are used as a particle system for the visualization of the flow. They are composed of reflective flat, elongated flakes and are usually organic. These particles have anisotropic dimensions ( $30\mu\text{m} \times 6\mu\text{m} \times 0.07\mu\text{m}$ ) with a high index of refraction ( $n = 1.85$ ) and provide good visibility even at a low flow rate. The sedimentation of these particles is negligible; further, these particles reflect the light well and do not alter the viscosity of the fluid.

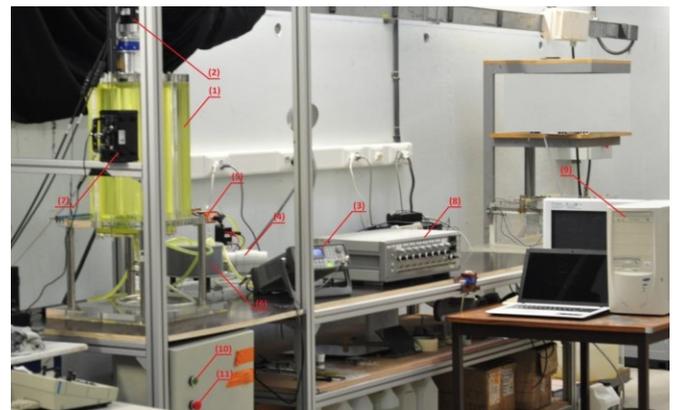


Figure 1. Experimental installation

## 3. The Rough surface

In this study, different rough surfaces are used as an inner cylinder surface. At first, a sandpaper-type P180 (Figure 2) is

used as a rough surface. This is a paper that includes glued glass beads, which are distributed non-uniformly on the surface and give an irregular and uneven roughness. The number 180 is the density of grains per cm<sup>2</sup>. By increasing the number, the grain size will become smaller. The average size of the grains is approximately 80 μm and the paper is waterproof since it will obviously be under water. In the second case, a uniform roughness, corresponding to a canvas plastic with meshes that are distributed homogeneously over the entire surface, is used. Two types of meshes with different thickness and dimension are applied. The thickness of the first wire is 0.3 mm with a width equal to 2 mm and the second coarser roughness with a thickness of 0.5mm and a width equal to 1 mm. (Figure 3).

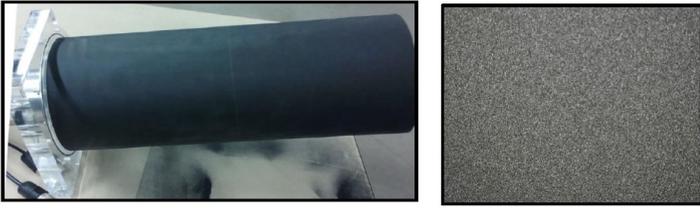


Figure 2. Internal cylinder which is covered with sandpaper P180

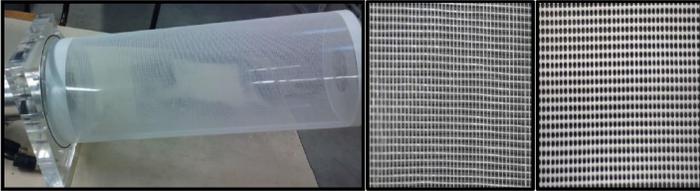


Figure 3. Internal cylinder covered with plastic canvas

#### 4. Numerical method

The numerical simulation is done only for the smooth surface. The fluid is considered incompressible and Newtonian with constant physical properties. Hence, the governing Navier–Stokes equations are:

$$\nabla \cdot \vec{V} = 0$$

$$\rho \left[ \frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} \right] = -\nabla P + \mu \cdot \left( \nabla \vec{V} + \nabla \vec{V}^T \right) + \rho \cdot \vec{g} \quad (1)$$

In this research, an open source software code was used. The top and the bottom boundary conditions of the Couette-Taylor devices used are “wall”. The SIMPLE algorithm is applied to solve the governing fluid flow equations and the second order upwind scheme is used for discretization. Also, the convergence criterion for equations is 10<sup>-5</sup>. The geometry is two concentric cylinders where the inner cylinder is rotating and the outer cylinder is stationary. The radius of the external and internal cylinders are R<sub>2</sub>=100mm and R<sub>1</sub>=97mm, respectively with the height of h=450mm (Figure. 4). The main parameters for Couette-Taylor system are: d=R<sub>2</sub>-R<sub>1</sub>=3mm, Γ=h/d=150 and δ=0.03093.

Due to high accuracy and fast convergence, the structured grid is generated to solve the governing equations. Also, to study the grid independency, velocity and pressure distributions in the radial direction are investigated for four different grids with 1200000, 2000000, 2500000 and 3100000. The conclusion is that the 2500000 cells are adequate. Figure 5 illustrates the computational grid which is used in this research.

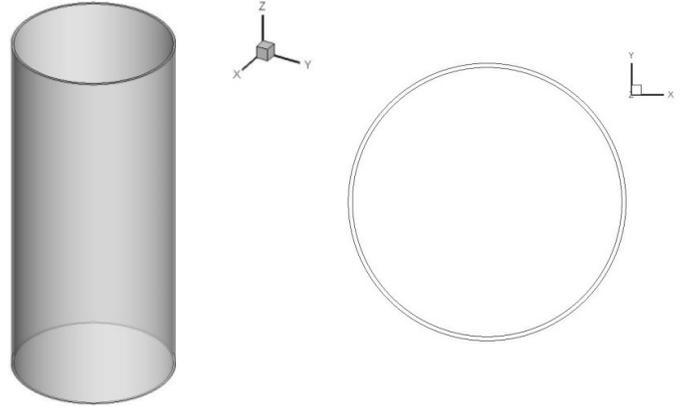


Figure 4. Schematic illustration of Couette-Taylor system

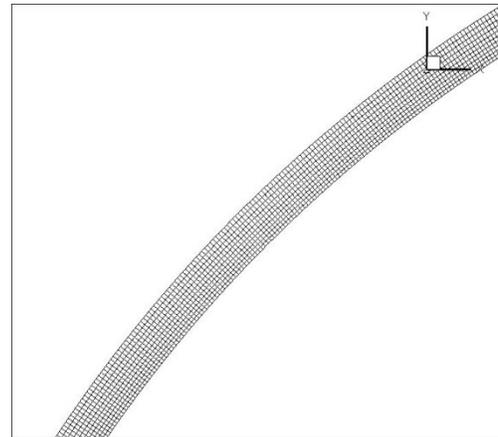


Figure 5. Computational grid for Couette-Taylor system

#### 5. Results

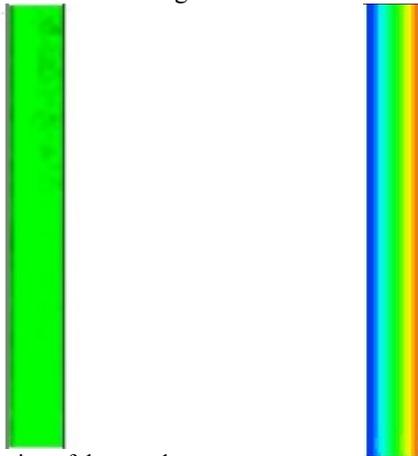
##### 5.1. Flow regimes

Firstly, different flow regimes for the inner cylinder with smooth surface are considered numerically and experimentally in order to study the hydrodynamic flow characteristics of the different flow regimes. It should be noted here that the Plexiglas walls of the Couette-Taylor system were very well polished. Thus the wall surface roughness is considered very low, so largely smooth.

##### 5.1.1. Couette Flow (CF)

Couette flow is homogeneous along the axis of rotation and axisymmetric. The distribution of particles is uniform throughout the gap. Figure 6 represents an instantaneous result of a longitudinal section of the annular space created by the application of a laser sheet in the plane (r, z) of the flow. In

addition the numerical study shows that the flow is completely homogeneous in this flow regime.



a) A laser cutting of the annular space at  $Ta = 21.93$       b) Numerical results for CF regime at  $Ta=22$

Figure 6. Experimental and numerical results for Couette Flow

### 5.1.2. Taylor Vortex Flow (TVF)

This regime is characterized by the appearance of rings that are called Vortex Roller Taylor (Taylor Vortex Flow). Experimental results represents a simulation for an inner cylinder with smooth wall,  $Ta_{c1} = 41.28$  and the regime extends to  $Ta=52.89$ . The numerical simulation showed that the first instabilities are formed at  $Ta_{c1}=41.9$  and this flow regime is continued up to  $Ta=53.8$ . The few differences between the experimental and the numerical results are due either to the mesh which should be more refined, or to the rotational speed (rpm) accuracy which directly affects the experimental Taylor number.

The following screenshots (Figure 7) are all taken at time  $t_1 = 90s$  starting the rotation of the inner cylinder for different numbers of Taylor. Vortex Taylor is characterized by an axial periodicity of wavelength  $\lambda$ , the wavelength is determined from the number  $n$  of observed rolls along the cylinder and the height  $h$  of the Couette-Taylor system ( $\lambda=h/n$ ). The experimental and numerical results represented that  $\lambda=5.8mm=1.93d$  and  $\lambda=6.1mm=2.033d$  respectively.

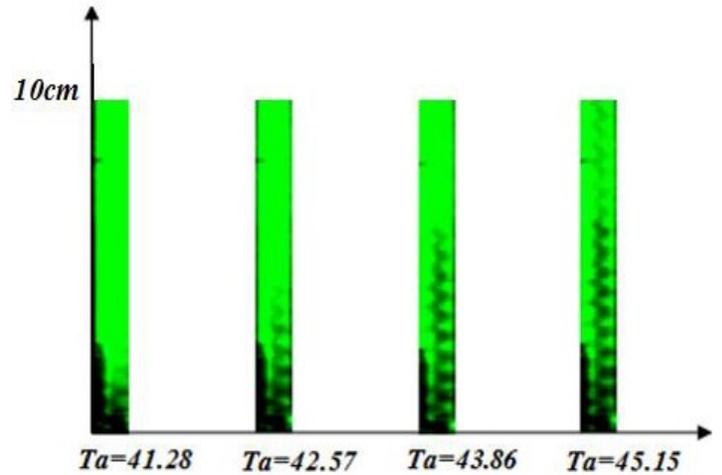


Figure 7. Evolution of the onset of Taylor rollers according to the Taylor number in a laser sheet intersecting the annular space (Experimental Results)

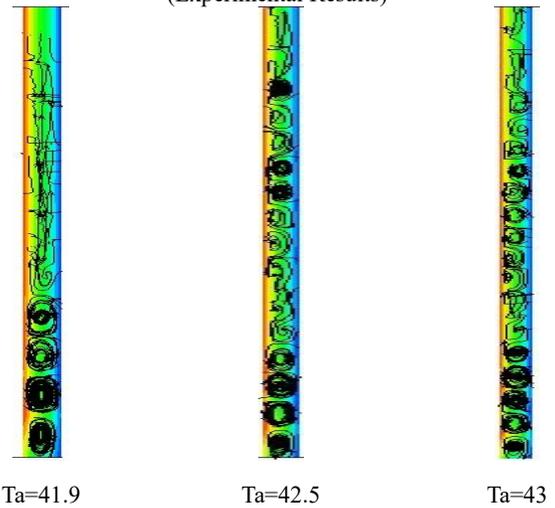


Figure 8. Numerical results for TVF regime

### 5.1.3. Wavy Vortex Flow (WVF)

This is the second instability that appears after the onset of Taylor Vortex by increasing the rotational speed of the inner cylinder. This regime is characterized by periodic azimuthal vortex in the axial direction of wavelength  $\lambda$  in the azimuthal direction with a wave number  $m$  and in time with a frequency  $f_1$ . The experimental and numerical results showed that, the WVF is started at  $Ta_{c2}=52.98$  and  $53.8$  respectively.



Figure 9. Experimental results for WVF regime at  $Ta=52.98$



Figure 10. Numerical results for WVF regime at  $Ta=53.8$

#### 5.1.4. Modulated Wavy Vortex Flow (MWVF)

By further increasing the Taylor number, the experimental and numerical results showed that the flow passes through a third transition to  $Ta_{c3} = 61.9$  and  $63.2$  respectively. This transition is detected when the main azimuthal wave that existed in the WVF regime is more homogeneous, and the vortices begin to be unstructured.



Figure 11. Experimental results for MWVF regime at  $Ta=61.9$



Figure 12. Numerical results for MWVF regime at  $Ta=61.9$

#### 5.1.5. Turbulent Taylor Vortex Flow (TTVF)

The turbulent regime appears at higher Taylor numbers. It is characterized by the homogenization of the flow and a better diffusion in the presence of turbulent structures. From experimental results it is concluded that the transition between MWVF and TTVF occurred at  $Ta=210$  and the numerical simulation showed that this transition occurred at  $Ta=225$ .

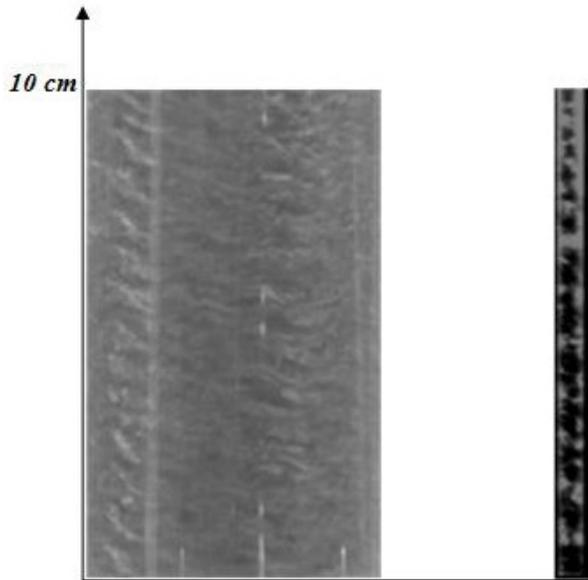


Figure 13. Experimental results for TTVF regime at  $Ta=210$



Figure 14. Experimental results for TTVF regime at  $Ta=225$

## 5.2. The Effects of rough surfaces

In the following section, the effects of the modification of the surface condition on the appearance of the instabilities are studied experimentally. Four different surface conditions for inner cylinder walls are considered as a below:

Case (1): smooth

Case (2): a sandpaper-type P180

Case (3): a canvas plastic with wire-mesh roughness of 0.3mm.

Case (4): a canvas plastic with wire-mesh roughness of 0.5mm

The following table summarizes the first critical Taylor number of the four conditions that are achieved experimentally.

Table 1. The first critical Taylor number for different rough surfaces

Case number	(1)	(2)	(3)	(4)
Experimental results for $Ta_{c1}$	41.28	44.65	47	47.46

The results show that, the roughness causes a delay in the appearance of the first instabilities. This delay has a direct relation with the size of roughness. More roughness caused more delay.

Indeed, the flow will undergo a friction when in contact with the inner cylinder. This friction will result in a reduction of the speed of the fluid particles. Therefore, the Taylor rolls will be formed with delay.

Figure 15 represents a perpendicular section of the annular space at Taylor number  $Ta = 42.57$  for the different surfaces of the inner cylinder. For  $Ta = 42.57$  and in the case of a smooth surface, the flow regime is the Taylor Vortex flow. However, with the same Taylor number, the flow does not have any instability in the case of rough surfaces (sand paper and canvas).

Figure 16 illustrates the delay that was detected at the first appearance of instabilities for different rough surfaces.

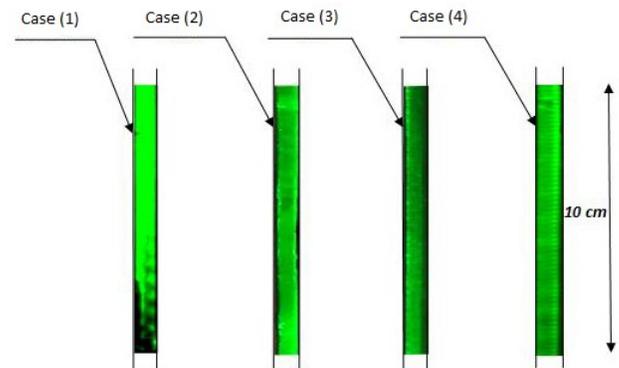


Figure 15. Experimental results at  $Ta = 42.57$  for different rough surfaces

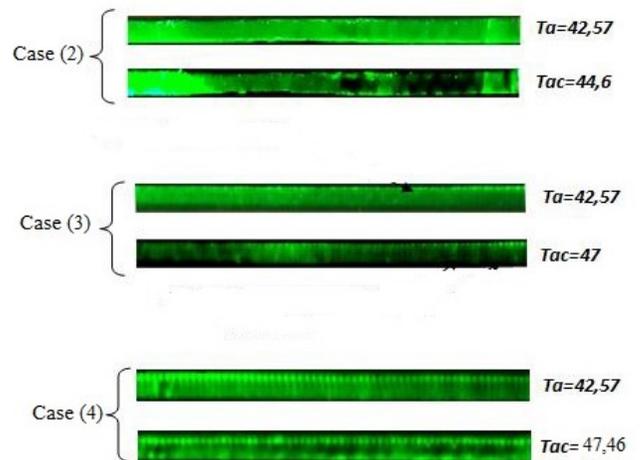


Figure 16. Delay of the first instabilities for rough surfaces (Experimental Results)

Unlike the TVF regime, for the other flow regimes, once Taylor rolls are formed, roughness does not play the role of a particle motion damper, on the contrary, it promotes the flow disturbances. Therefore, there is a quicker switching from one regime to another.

Table 2 summarizes the different Taylor transitions corresponding to each flow regime for the various rough surfaces used.

Table 1. Critical Taylor numbers for different rough surfaces

Case number	Case (1)	Case (2)	Case (3)	Case (4)
WVF	52.89	52.25	52.36	55.36
MWVF	61.90	60.80	60.69	58.76
TTVF	210	214.70	220.15	197.75

## 6. CONCLUSIONS

In this research, the effects of the surface roughness on the hydrodynamic behaviour of the Couette-Taylor flow have been studied. For this purpose, different roughnesses of surface are used as an inner cylinder wall. These surfaces include a smooth surface, a sandpaper-type P180, a canvas plastic with a wire-mesh roughness of 0.3mm and a canvas plastic with a wire-mesh roughness of 0.5mm. The experimental results showed that by increasing the size of the surface roughness, the first critical Taylor number increased too. Indeed, the surface friction has a direct influence on the surface roughness. So by increasing the friction of the surface, the fluid particles velocity decreases and the first instabilities appear with a delay. In contrast, when the Taylor vortices are formed, the role of the roughness is changed. The roughness could not damp the fluid particle motion and act as a flow disturber. Therefore, it caused a quicker switching from one regime to another.

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