Experimental Study and Visualizations of Flow with Taylor Vortices

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Abstract: *Taylor vortex flow has multiple applications, primarily in the field of turbomachinery, in flows through labyrinths or sealing elements, but also in the protection of sliding bearings, ensuring their proper lubrication. Other applications of vortex flow can also be found in the pharmaceutical industry, in mixing different fluids, but also in cooling systems, in avoiding fluid crystallization, in nano fluidics, etc. The present paper presents theoretical aspects, visualizations and experiments related to the appearance of Taylor vortices, carried out on a laboratory installation with rotating cylinders. The Reynolds and Taylor numbers are essential indicators in identifying the behavior of fluids in vortex flow. The visualizations confirm the theory, namely that the appearance of vortices is dependent on the fluid viscosity, the speed, the Re, Ta numbers and the variation in time of these quantities.*

Keywords: *Taylor vortices, visualizations, experimental study, technical applications*

1. Introduction - Theoretical aspects

The present paper presents theoretical aspects, visualizations and experiments related to the emergence of Taylor vortices, carried out on a laboratory installation with rotating cylinders. Hydrodynamic phenomena accompanied by instability in the flow of a fluid between two rotating concentric cylinders were observed by Sir G.I. Taylor and first published in 1923 in the paper [1]. Later the topic was studied more extensively by Buhler et al. [2], Larson [3], Koschmieder [4] and Muller [5] and R. Kadar, 2010 [6].

"Most of the time, the movements of real fluids are accompanied by rotational movements caused by the appearance of vortex threads, which then, due to small frictional forces, break up into numerous other vortices that propagate throughout the mass of the fluid. The origin of vortices is generally in discontinuities of contour, velocity or pressure. Thus, we see vortices appearing at the edges of a body in a moving fluid, at the edges of an orifice, when the fluid is displaced by the movement of a solid body and even when a fluid moves around continuously curved profiles. These potential vortical movements create a special type of resistance" [7].

As a result of these considerations, it was possible to define notions of thread, line, vortex surface, vortex tube, characterized by the angular velocity vector ω which characterizes the rotational movement of the fluid particle around the instantaneous axis of rotation, defined by the three-dimensional components [7]:

$$\omega_x = \frac{1}{2}\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right); \quad \omega_y = \frac{1}{2}\left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}\right); \quad \omega_z = \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \tag{1}$$

The vortex line is tangent to the vectors describing the angular velocity ω at a given time, described by the equations of a vortex line:

$$\frac{dx}{\omega_x} = \frac{dy}{\omega_y} = \frac{dz}{\omega_z} \tag{2}$$

The intensity of the vortices and their time duration are important. Thus, we can also define two quantities that characterize the vortices and the circulation along a closed curve - the circulation Γ and the potential U, thus from the Thomson - Lagrange theorem we have the mathematical expression between the two quantities with respect to time in differential form, equation (3) from [7]:

$$\frac{d\Gamma}{dt} = -\int_A^B \left[dU + \frac{dp}{\rho} - d\left(\frac{V^2}{2}\right)\right] \quad (3)$$

where the potential U is uniform, p is the pressure and V is the velocity are uniform functions, the derivative of the circulation on a closed curve is canceled and it follows that the circulation Γ is constant. From Stokes' theorem on a closed contour, the velocity circulation is equal to the rotor flux of the velocity that crosses the support surface of the contour, given by the expression for a vortex tube of finite section by integration results [7]:

$$\Gamma = \int_S rot\overline{V}\, dS_n = \int_S \Omega\, dS_n \quad (4)$$

The circulation on the contour that encloses the cross-sectional area Sn is equal to the vortex rotor flux. By definition, this expression is called the vortex intensity [7].

Parallel vortex threads have parallel movements at different speeds due to their interaction.

a) The parallel vortices in a system are reduced to two parallel threads with the circulations Γ1 and Γ2 of the same direction, or opposite directions, as in Figure 1, with the velocities induced thus:

$$V_1 = \frac{\Gamma_1}{2\pi l}\ , \quad V_2 = \frac{\Gamma_2}{2\pi l} \quad (5)$$

The complex potential of the motion resulting from parallel vortex strands is given by equations (6):

$$f(z) = \frac{\Gamma}{2\,\pi l}\ln(z - z_1) - \frac{\Gamma}{2\,\pi l}\ln(z - z_2)\ ;$$

$$f(z) = \frac{\Gamma}{2\,\pi l} l\,n\frac{(z-z_1\,)}{(z-z_2} = \frac{\Gamma}{2\,\pi l}\ln\left(\frac{r_1}{r_2}\,e^{i\,(\theta_1-\theta_2}\right) \quad (6)$$

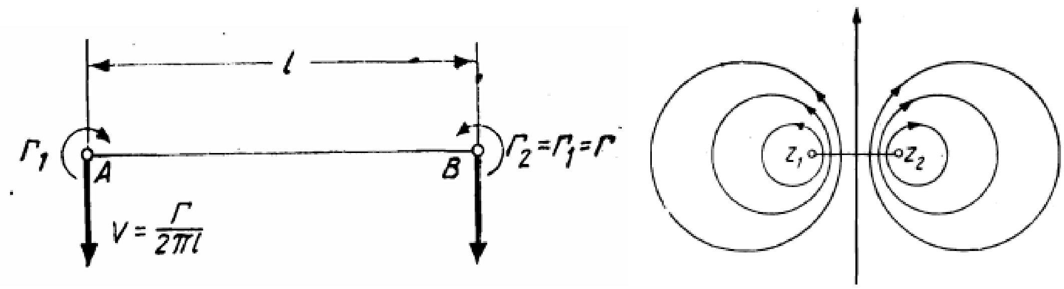

Fig. 1. Parallel, equal and oppositely directed vortices – velocities and streamlines [7]

b) Strings of vortices

The flow between two coaxial cylinders, known as Taylor-Couette flow, is a field of research of particular importance in fluid mechanics. It was initiated by the works of G.I. Taylor and has continuously evolved, being studied both from a fundamental and applied point of view (in chemical engineering, rheometry, tribology, etc.). The phenomenon of Taylor-Couette flow has become essential for understanding hydrodynamic instabilities, especially in the context of vortex flows.

c) Prandtl's Mixing Length Theory and Taylor's Vortex Transport Theory.

In one-dimensional turbulent motion where the mean velocity is parallel to the dominant flow axis Ox , vectors (u = u(y), v=0, w =0), the only apparent non-zero tangential unit stress is according to the paper [8]:

$$\tau_{yx} = -\rho\overline{u'v'} \quad (7)$$

Prandtl establishes the expression for this tension. His theory is based on the idea of conservation of momentum in the direction of the main flow. It is assumed that in turbulent motion there are macroscopic fluid particles that have a proper motion. These macroscopic particles move over a certain length in both the longitudinal and transverse directions, keeping the value of their momentum component on the Ox axis constant. Unlike Prandtl who examined the exchange of momentum (quantity of motion), Taylor examined the exchange of momentum moments (kinetic moments). Taylor's theory of vortex transport or diffusion gives results similar to Prandtl's regarding velocity distributions in a plane jet, but provides better results in other cases [8].

2. Experimental Installation

The experimental installation, as can be seen in Figure 2, consists of the following components:

- rotating inner cylinder with diameter D_1= 216.9 mm, and length L=290 mm.
- transparent outer cylinder with diameter D_2 = 238 mm,
- 250 W electric drive motor, 1360 rpm, which can be driven with a frequency converter
- drive shaft,
- coupling,
- support and end caps,
- two sealing O-rings.

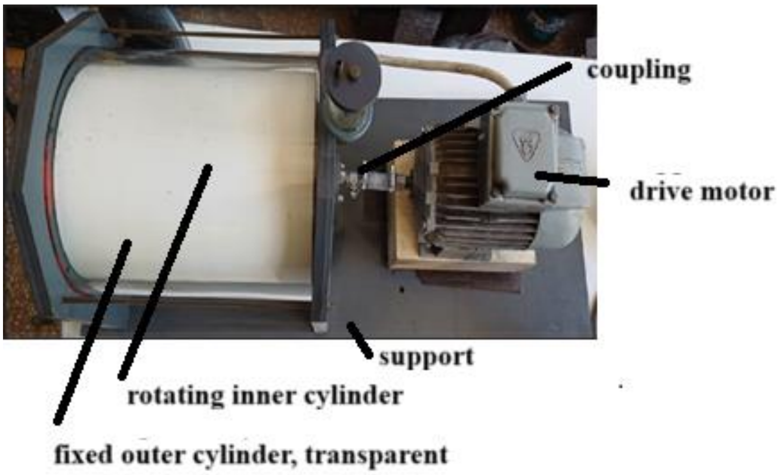

Fig. 2. Experimental setup for studying Taylor vortices

We used two types of oil in the experiments – 80W90 engine oil with kinematic viscosity $158 \cdot 10^{-6}$ m^2/s and TR25 transformer oil, with $8.862 \cdot 10^{-6}$ m^2/s, and with a density of 860 kg/m^3.
As measuring devices, we used a tachometer with accuracy ±0.05%., and visualization / filming techniques, some of them with laser light. In the TR25 oil we also used blue dye for better visualization, the oil being light in color. To change the speed, we drove the electric motor through a frequency converter.

2.1 Visualisations

In our own laboratory setup, with the two types of oils, we obtained the visualizations like in Figures 3-7. The characteristic Reynolds and Taylor numbers were calculated according to the relations (8-9). For the TR25 oil, with low viscosity and light color, we also used a blue dye for better visualization. The large difference in viscosity of the two oils led to different results depending on the speed of the inner cylinder.

Fig. 3. Visualizations with the formation of Taylor vortex layers for TR25 and 80W90 oil respectively

Fig. 4. Strings of vortices at speed n = 136 rot/min, Re =37681, Ta =340438, oil TR25.

Fig. 5. Strings of vortices at speed n = 470 rot/min, Re = 130697, Ta = 4095718, oil TR25

Fig. 6. The formation of Taylor vortices at speed n = 57 rot/ min, Re = 892, Ta = 191, oil 80W90

Fig. 7. The formation of Taylor vortices at speed n =61 rot/ min, Re = 964, Ta = 223, oil 80W90.

2.2 Experimental results

To characterize the fluid flow in the gap created by the two cylinders, the Reynolds and Taylor numbers are used. We used computation relations (8) and (9) to determine the Reynolds and Taylor numbers, according to the paper [9].

$$Re = \frac{uD_1}{\upsilon} = \frac{\Omega \cdot D_1^2}{2\upsilon} \quad (8)$$

$$Ta = \frac{4 \cdot R_1^2 \cdot (R_2 - R_1)^2 \cdot \Omega^2}{\upsilon^2 \cdot (R_2 + R_1)^2} \quad (9)$$

The notations refer to Ω - angular velocity of rotation, υ - kinematic viscosity of the fluid, diameters or radii of the inner and outer cylinders.
In Table 1 we have centralized the results of speed measurements, converter frequencies f (Hz), calculations of tangential velocity u (m/s) and angular velocity Ω (s-1), respectively we have determined the Reynolds and Taylor numbers. The results are very different, influenced by the viscosity of the fluids and implicitly by the speed.

Table 1: Experimental results

n(rpm)	u(m/s)	f (Hz)	Re	$\Omega(s^{-1})$	Ta	80W90
21	0.238	3	328	2.2	26	
32	0.363	4	499	3.3	60	
41	0.466	5	639	4.3	98	
48.6	0.552	6	758	5.1	138	
57.2	0.650	7	892	6.0	191	
61.8	0.702	8	964	6.5	223	
78.4	0.890	10	1223	8.2	359	
93.4	1.061	12	1457	9.8	509	
100	1.136	14	1560	10.5	583	
n(rpm)	**u(m/s)**	**f (Hz)**	**Re**	**$\Omega(s^{-1})$**	**Ta**	**TR25**
46	0.523	1	12806	4.8	39322	
58	0.659	2	16129	6.1	62372	
91	1.031	3	25243	9.5	152790	
96	1.090	4	26695	10.0	170874	
136	1.539	5	37681	14.2	340438	
158	1.793	6	43899	16.5	462080	
200	2.271	8	55616	20.9	741642	
250	2.839	10	69519	26.2	1158816	
360	4.088	15	100108	37.7	2402920	
470	5.337	20	130697	49.2	4095718	

In Figures 8, 9 and 10 we have graphically represented the variation of the speed with the tangential velocity, the Reynolds and Taylor numbers as a function of the tangential velocity for the 80W90 oil in light blue, and for TR25 in dark blue. We used the logarithmic scale, the difference in the values being large. A stabilization of the circular or toroidal vortices was found, depending on the Taylor number.

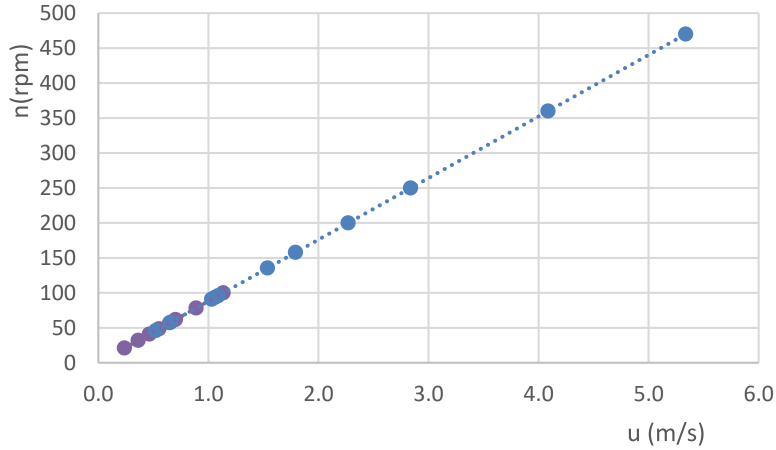

Fig. 8. Speed function of tangential velocities

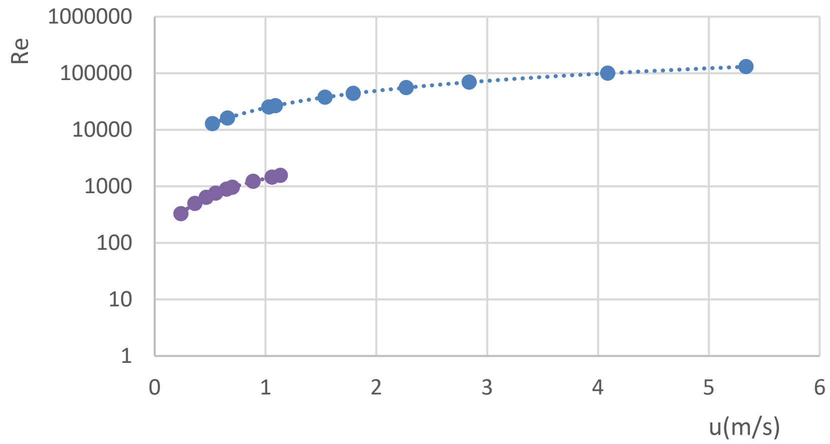

Fig. 9. Reynolds number as a function of tangential velocities

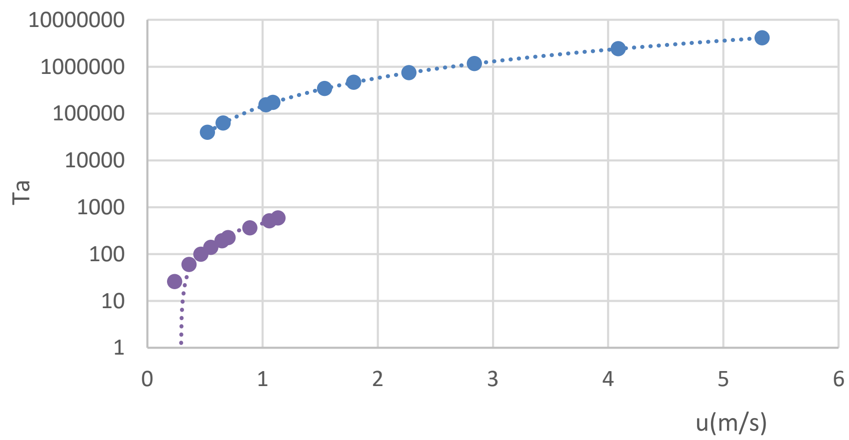

Fig. 10. Taylor number as a function of tangential velocities

3. Applications for Taylor Vortices Flow

Taylor vortices flow has multiple applications, primarily in the field of turbomachinery, in flows through labyrinths or sealing elements, but also in the protection of sliding bearings, ensuring their proper lubrication.
Applications for vortices flow can also be found in the pharmaceutical industry, in mixing different fluids, but also in cooling systems, in avoiding fluid crystallization, in nano fluidics, in chemical engineering, rheometry, tribology, etc.
In specialized literature [10], we can observe the formation of paired Taylor vortices in the study of flow in nano-reactors, as in Figure 11, or the formation of paired vortices of opposite direction in the interstices between rotating cylinders, Figure12, as in the case of labyrinth rings [11].

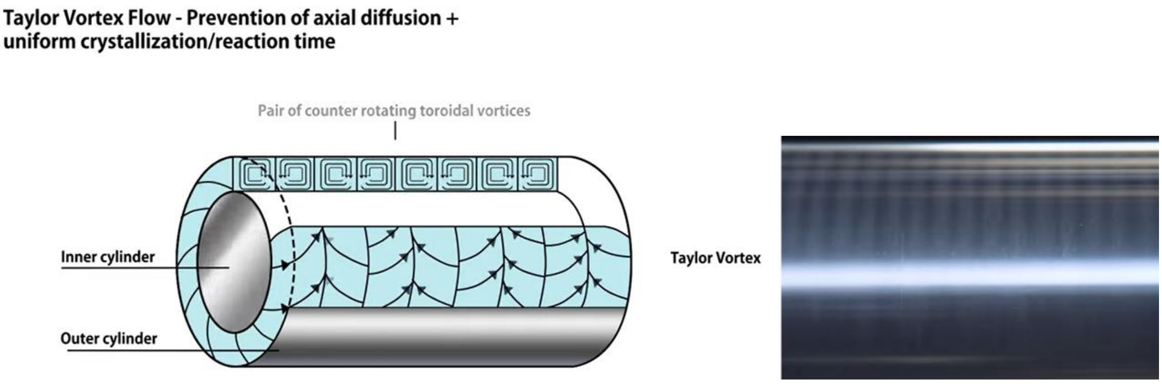

Fig. 11. Taylor Vortex Flow Nano Reactor [10]

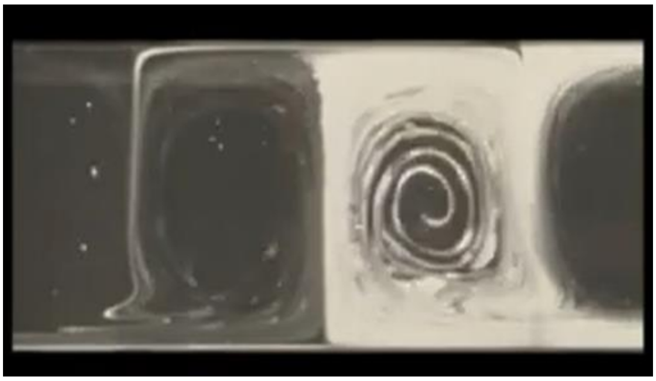

Fig. 12. Taylor vortices between rotating cylinders [11]

3. Conclusions

- Reynolds and Taylor numbers are essential indicators in identifying the behavior of fluids in Taylor–Couette flow.
- Viscosity plays a key role: the higher it is, the greater the stability of the flow.
- Vortex stability is influenced by the drive speed, respectively by the motor frequency.
- The visualizations confirm the theory – the appearance of vortices is dependent on Re, Ta and the time variation of these quantities.
- The results are comparable with the literature, validating both the methods and the interpretations.
- Further developments will analyze more diameters of the moving cylinder, the interior, thus varying the space between the cylinders, and more fluids conveyed. The multiple applications of Taylor vortex flow justify the in-depth analysis of the field.

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