EXPERIMENTAL INVESTIGATIONS OF A MODIFIED TAYLOR-COUETTE FLOW

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Abstract: In this study the instability problem of a modified Taylor-Couette flow between two vertical coaxial cylinders of radius \( R_1, R_2 \) is considered. The modification is based on the wavy shape of the inner cylinder surface, where inner cylinders with different surface amplitude and wavelength are used. The study aims to discover the effect of the inner surface geometry on the instability phenomenon that undergoes Taylor-Couette flow. The study reveals that the transition processes depend strongly on the amplitude and wavelength of the inner cylinder surface and resulting in flow instabilities that are strongly different from that encountered in the case of the classical Taylor-Couette flow.

Key Words: Modified Taylor-Couette Flow, Hydrodynamic Instability

1) Introduction

Flow instabilities affect many industrial and engineering applications that involve fluid flow phenomena. The understandings of physical mechanisms that lead to such instabilities are of great interest. Taylor-Couette flow problem was one of the most flow configurations studied to understand the hydrodynamic instability phenomenon. It gives a simple and clear flow configuration that involves many instability stages which ends by a turbulent flow regime. But there are still several issues to be addressed such as the effect of flow geometry on these instabilities. Applying a little geometrical modification on this flow can lead to flow behaviors that are completely different from the transition procedures that undergo a classical Taylor-Couette flow. The modified Taylor-Couette consists of two coaxial cylinders of which the outer cylinder is smooth and fixed and the inner cylinder is rotating and has a wavy surface with a specified amplitude and wavelength. Such flow configuration has been studied by [1], where they have used measuring techniques based on the particle imaging velocimetry (PIV) and shear force on the wall to localize transition stages and study the interaction between Taylor vortex and that imposed by the inner cylinder surface geometry. The radial and axial velocity components strongly influence the generation of vortices. They depend on the axial position, amplitude, and wavelength of the wavy surface. By increasing the rotational speed of the inner cylinder, the flow becomes unstable at a certain critical point. This instability is manifested in the form of a generation of additional vortex cells induced by the inner cylinder surface geometry. As rotational speed increases beyond some critical velocity, the flow bifurcate [2] (Hopf bifurcation) to an asymmetric solution where each vortex pair is formed by two vortex of different size, in which the large vortex becoming larger, up to 1.5 times the size of small vortex, which can be explained by the presence of an azimuthal wave of axial pressure that affects the whole flow [2].

In this study the hydrodynamic instability problem of Taylor–Couette flow using a wavy shape inner cylinder surface have been considered. The study will explain the effect of inner cylinder surface shape on the flow behavior during instability stages that undergoes this flow configuration. Also it will permit more understanding to the mechanisms that led to the described instability stages.

2) Experimental Apparatus

The experimental apparatus used is the same as that used by [3], where it consists of two coaxial cylinders. A transparent outer cylinder of Plexiglass with radius \( R = 65.3 \text{ mm} \), thickness of \( 5 \text{ mm} \) and height \( H = 287 \text{ mm} \) is used. Inner coaxial rotating cylinder is fitted inside the outer cylinder. The geometry of the different wavy surface inner cylinders are given in the Table 1, where \( a \) is the amplitude, \( \lambda \) is the wavelength, \( K \) is the wave number and \( d = R_2 - (R_{\text{max}} + R_{\text{min}})/2 \).

| Table 1. Geometry of The inner cylinder |
|---|---|---|---|---|---|
| Cyl | \( R_{\text{max}} \) | \( R_{\text{min}} \) | \( a \) | \( \lambda \) | \( K \) | \( d \) |
| C₁ | 55.20 | 47.39 | 31.30 | 3.91 | 35.88 | 8 | 14 |
| C₂ | 59.12 | 43.52 | 31.30 | 7.83 | 35.88 | 8 | 14 |
| C₃ | 55.20 | 47.39 | 31.30 | 3.91 | 71.75 | 4 | 14 |
| C₄ | 59.12 | 43.52 | 31.30 | 7.83 | 71.75 | 4 | 14 |

The entire device is mounted vertically on two Plexiglas plates of \( 25 \text{ mm} \) thickness and a dimension of \( (250 \times 250) \text{ mm}^2 \). Therefore a removable enclosure lid containing an O-ring sealing is added with a necessary bearing for the centering and guiding of the inner cylinder. The fluid used in the experiments is an aqueous solution of PLuracol (EMCAROX, ICI product). The fluid exhibits temperature-dependent Newtonian fluid characteristics in the range of the experiments. The axial velocity profile has been measured using a Pulsed emission Ultrasound Velocimeter. The UVP device measures the axial velocity component in 128 points distributed along the measuring window.

3) Analysis and investigation of the results

Four cases have been studied as shown in the table (1) depending on the geometry of the wavy inner cylinder surface. The first case \( C₁ \), corresponds to an inner cylinder surface with short wavelength and low amplitude, \( C₂ \) corresponds to an inner cylinder surface with short wavelength and big amplitude, \( C₃ \) corresponds to an inner cylinder surface with a long wavelength and low amplitude and \( C₄ \) uses an inner cylinder with long wavelength and big amplitude. The forgoing instability analysis will be based on the study of flow behavior for each case in the range of Taylor number begins from \( Ta = 50 \) to \( Ta = 600 \). The
evolution of velocity fields as well as the spectral analysis of the flows will be discussed in details.

![Fig.1](image1)

**Fig.1 Evolution of the frequency ratio \(\frac{f_1}{f_0}\) vs. Ta case \(C_1\)**

**Case \(C_1\):** At low Taylor numbers the flow is stable and there is no main frequency in the Spectral diagram Figure (1). The first transition is located at \(Ta = 370\), where the main frequency drops rapidly above the value \(f_0\). It must be noted that in this case, the spectral diagram exhibits random perturbations which are much greater than that appeared in the case of smooth cylinder [3]. At this Taylor number the wavelength does not change and remains the same as that imposed by the geometry of the inner cylinder surface. The analysis of the axial velocity field show a steady flow at \(Ta = 53\). The contours of the axial velocity profile Figure (2) show a difference between the relative instability of source and sink zones within the flow, where sink zones appear to be more disturbed compared to the sources zones. At \(Ta = 174\) the flow becomes disturbed over time and the axial flow velocity become five times greater. Velocity contours show an amplification of the difference between the sizes of the source and sink zones. By increasing Taylor number to \(Ta = 529\), the axial velocity becomes twice its value in the previous case. The positive and negative cells are now asymmetrical. Small and large Taylor cells appear clearly in this stage Figure (3) and here also sink zones appear to be more perturbed in time than the source zones.

![Fig.2](image2)

**Fig.2 Contours of axial velocity profile at Ta = 53, case \(C_1\)**

**Case \(C_2\):** As shown by Figure (4), the flow does not exhibit any main frequency in the period \(Ta < 242\). As Taylor number increases beyond this limit the flow oscillates at a relative frequency \(\frac{f_1}{f_0} < 1\). For \(325 < Ta < 463\) the flow becomes steady with two asymmetric Taylor cells per cylinder wavelength. Beyond \(Ta > 463\), the flow has a spectrum of decreasing frequency which begins to increase again beyond \(Ta > 530\). The analysis of the axial velocity profile shows a stable flow with no perturbations. By increasing Taylor number beyond 276, azimuthal waves superimpose on the Taylor cells and the velocity become 5 times greater. For \(Ta = 377\) Figure (5) the flow passes by a Hopf bifurcation [3] and continues in steady state. The velocity contours make evident the change in size of the Taylor cells, where one of them becomes larger than the other. As Taylor number increases beyond \(Ta = 571\) the flow goes to a modulated oscillatory state with source zones that are more stable in time than the sink zones.

![Fig.3](image3)

**Fig.3 Contours of axial velocity profile at Ta = 529.**

**Fig.4 Evolution of the frequency ratio \(\frac{f_1}{f_0}\) vs. Ta case \(C_2\)**

**Case \(C_3\):** The flow in this case is very different from the previous cases where it contains initially 4 cells per wavelength. At \(Ta = 160\) the flow oscillates at frequency ratio \(\frac{f_1}{f_0} = 0.9\) with azimuthal waves which superimpose on the Taylor cells. Then immediately after, the flow becomes stable with two Taylor cells per wavelength. Beyond \(Ta = 370\) the flow transits back from the steady state to an oscillatory state of low frequency. This behavior appears clearly in the Figure (6), where the wavelength presents an intermittent behavior varying from two Taylor vortices to four vortices per wavelength and vice versa. Note that among the four vortices there are two inner vortices rotating in the same direction as
the cylinder geometric vortex and the other two rotate in the opposite directions Figure (7). At T=157 the flow becomes wavy with the appearance of azimuthal waves, but it does not stay long time. By increasing Taylor number the flow transits to chaotic states with two incommensurate frequencies, where one can clearly see the doubling of vortices in the axial velocity profile.

Fig.5 Contours of axial velocity profile at Ta = 377

Fig.6 Evolution of the wave length vs. Ta case C

Case C : The flow in this case is stable until Ta=444 Figure (8). As Taylor number passes this value the spectrum of the flow present a new behavior which differs from the preceding cases where three high frequencies appear. Early instability stages consist of a stable flat velocity profile with two cells per wavelength and characterized also by the presence of a small perturbation between each pair of cylinder geometric vortex Figure (9)

Fig.7 Contours of axial velocity profile at Ta = 83

Fig.8 Evolution of the frequency ratio (f/f_o) vs. Ta case C

Fig.9 Contours of axial velocity profile at Ta = 77

Conclusion
As it clear from the results, the different flow regimes and transitions depend strongly on the length and amplitude of the wavy inner cylinder surface. The main contribution of this work is the analysis of the axial velocity fields in space and time using the ultrasonic approach. This analysis allowed during different transition stages to follow the evolution of the frequency and wavelength of the flow. The direct exploitation of the axial velocity profile permitted to specify clearly the topology and in particular the number and size of vortex cells and the relative stability of source and sink zones of the flow. Indeed, when there are oscillations in the flow, source zones appear to be less stable over time than sink zones. When the flow structure switches from vortex arrangement of 4 cells / λ to 2 cells / λ in the case C, the oscillations of the flow mainly concern the small vortex cells (sink zones) which likely disappear.

References