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A Flow Visualization Study of Acceleration Effect on the Taylor-Couette Flow

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ABSTRACT

The acceleration effect on the Taylor-vortex and later developed wavy vortices was investigated from flow visualization techniques in circular Couette system (with the inner cylinder rotating and outer cylinder at rest) as a function of Reynolds number Re. Our results show that when the acceleration is higher than a critical value of about 2.2 s^{-1}, there exists a new flow regime in which the flow pattern shows remarkable resemblance to the regular Taylor vortex flow with shorter axial wavelength. One of the most surprising aspects of this flow is that it occurs in the range of Reynolds number in which the wavy vortex flow is supposed to occur.

INTRODUCTION

The flow of a fluid between inner-rotating and outer-stationary cylinders is a classical hydrodynamics instability problem. A great deal of theoretical and experimental work has been published in the last few decades on the flow transition pattern for this problem. (for example, see review articles of Chossat (1992), and Koschmieder (1993)). For the case of a *long* cylinder and *narrow* gap, (usually $\Gamma > 40$, and $\eta > 0.85$) it is well established that when Re is ***gradually*** increased to a critical value Rec, the spatially uniform circular Couette flow (CCF) changes to the axially periodic Taylor vortex flow (TVF). When $1.1<Re/Re_c<1.4$ (depending on aspect ratio) a wavy vortex flow (WVF) is formed. If Re is increased further, the flow will pass through a weakly turbulent region before it reaches the turbulent wavy vortex flow (TWVF). In 1965, Coles (1965) was the first to report the non-uniqueness of the wavy flow in the Taylor-Couette flow. He noted that for a given Reynolds number, as many as 20 to 25 different states (characterized by axial wavelength and azimuthal wave number) were seen, and these states were found to be a function of the initial conditions as well as the manner in which the inner cylinder was accelerated to the final speed. Although numerous studies (see Ahlers et al. (1983), Coles (1965), Park et al. (1983), and Burkhalter and Koschmieder (1973, 1974) have shown the importance of acceleration in determining the final state of the flow, these investigations were somewhat limited in scopes. For example, in Coles (1965) and Ahlers et al. (1983), no quantitative values of the acceleration used in their investigations were given. Therefore, the path to which the flow is subjected to is not accurately known. On the other hand, although Park (1983) had provided quantitative values of the acceleration, his investigation was limited only to the onset of Taylor vortex flow (TVF). Similarly, in the investigation by Burkhalter and Koschmieder (1973, 1974) on the axial wavelength of supercritical axisymmetric Taylor vortex flow, the accelerations used were restricted to only two extreme conditions (ie "sudden start" and "quasi-steady").

In this paper, a systematically experimental investigation of acceleration effect on Taylor-couette flow was carried out by using flow visualization technics. The acceleration values were changed from sudden start to quasi-steady, and the flow states experience Taylor vortex flow to wavy vortex flow.

EXPERIMENTAL APPARATUS AND METHOD

The experiments were carried out in an apparatus consisting of an inner aluminium cylinder and a stationary outer precision perplex cylinder with radius R_2 = 94.0 mm. The radius of inner cylinder was R_1 = 75.5 mm resulting in the radius ratio $\eta = R_1/R_2$ of 0.8032, The Reynolds number is defined as $Re = R_1\Omega\, d/\nu$, where Ω is the angular frequency of the inner cylinder, and d is the gap size between two cylinders, ν is the kinematics viscosity. The acceleration is defined as the rate of change of Reynolds number: $a = dRe/dt = (R_1 d/\nu)\, d\Omega/dt$. The axial average wavelength λ is defined as 2H/Nd, where H is the height of the fluid column, and N is the number of axial vortices.

The working fluid is the mixture of 66% glycerine and 34% water with the kinematic viscosity 10.516cS at the room temperature $27^{O}C$. To visualize the flow, Kalliroscope AQ-100 reflective flakes were added to the solution, and the resulting motions were monitored and captured with the aids of a 5-Watt Argon ion laser and a CCD video camera.

In this study, the motion of the inner cylinder is controlled by a PC through a micro-stepping motor. For all cases, the inner cylinder is accelerated linearly from rest to a predetermined speed, and the time-interval between the initial and the final speed is adjusted to achieve the acceleration required. With the present set-up, the maximum acceleration which could be achieved is $dRe/dt \cong 500\ s^{-1}$, and the minimum acceleration is $dRe/dt = 0.01 s^{-1}$ (i.e. quasi-steady condition)

RESULTS AND DISCUSSIONS

Figure 1 is a chart summarising the effect of acceleration on the state of the Taylor-Couette flow. Each point in the chart represents an experimental data taken at least two hours after the inner cylinder has reached the final speed. The figure clearly shows that when the acceleration (dRe/dt) is less than a critical value of $2.2\ s^{-1}$, the state of the flow when the Reynolds number increases follows well known sequence of circular Couette flow, followed by regular Taylor vortex flow and finally by wavy vortex flow. The first sign of the wavy mode in this experiment occurs at $Re/Re_c \approx 1.15$. Here, the flow pattern appears as a slight rocking of the boundaries between adjacent vortex cells, in a fashion which could be accounted for by the presence of a single travelling circumferential wave occupying the entire circumference. This rocking behaviour is found to occur only within a very narrow range of Re. When $Re/Re_c \approx 1.2$, the number of azimuthal waves is increased to two (or m=2 mode), and beyond $Re/Re_c \approx 1.8$, the m=3 mode is observed and remains throughout the entire range of Reynolds numbers tested.

However, it can be seen in Fig. 1 that when $dRe/dt > 2.2\ s^{-1}$, there exists a new flow regime which to our knowledge has not been seen before. In this regime, which is bounded by a parabolic-shaped curve (see shaded curve in Fig. 1), the flow pattern is remarkably similar to the Taylor vortex flow (TVF) normally seen at Re_C. Here, the vortices are stable and regular, except that their average axial wavelength is much shorter than that in TVF. Moreover, the flow occurs in the Reynolds number range where the wavy vortex flow would normally occur. To ascertain that the vortices have stabilized after two hours, a few points (indicated by 1,2 and 3 in Fig. 1) were selected for observation 8-12 hours after the final speed is reached, and the results were found to be the same as for the case of 2 hours. Because of its similarity to the TVF, and also for ease of reference, we shall refer to the new flow as a Second Taylor Vortex Flow (STVF) (see Figure 2(c)). For the purpose of comparison, different states of the flow for other Reynolds numbers are also shown in Fig. 2. One should keep in mind that they are all subjected to the same acceleration. For the wavy flow, we must stress that the number of azimuthal wave in Fig. 2. (b) is two (mode m=2) whereas in Fig 2. (d), the number of the waves is three (mode m=3). On first appearance, the picture in Fig. 2. (b) may not convey the impression that the flow is in a wavy state, however, a real-time visualization shows that the vortices are undoubtedly undulating around the circumference of the cylinder. In fact, if one examines Fig. 2. (b) closely, one can see that the boundaries between neighbouring vortices are slightly inclined to the horizontal axis. This is caused by the presence of azimuthal waves.

It is noted to stress that the formation of Taylor vortex flow at Reynolds number higher than Re_c has been observed previously by Burkhalter and Koschmieder (1974). In fact they reported that for a radius ratio (η) of less than 0.727, Taylor vortex flow is found to exist up to $9Re_c$ for sudden start and quasi-steady conditions. They referred to the flow as supercritical Taylor vortex flow. However, they did not report seeing the same flow phenomenon depicted in figure 1. Moreover, the STVF observed in the present study (η=0.8032) occupies a narrower range of Reynolds number, and occurs only when the acceleration is higher than $2.2\ s^{-1}$. Although STVF may well be the same as the supercritical Taylor vortex flow reported by Burkhalter and Koschmieder (1973, 1974), it is not possible to make any meaningful comparison because our setup is quite different from theirs, particularly in the radius ratio which has previously been shown to affect the stability of the flow.

As mentioned earlier, the averaged axial wavelength for the second Taylor vortex flow is found to be much shorter than that for the first Taylor Vortex flow. The above observation led one to suspect that the vortices in the new flow regime may be a function of both the Reynolds number and the "history effect" of acceleration. A thorough investigation by the authors confirms this to be the case (see Figure 3). In this figure, note that for a constant acceleration, the axial wavelength of the vortices at first decreases sharply and then approaches a constant value as the Reynolds number increases. The sharp drop in the wavelength is found to occur near the left-hand boundary of the second Taylor vortex stability curve. Similarly, the figure also shows that for a given Reynolds number, decreasing the acceleration would lead to an increase in the axial wavelength.

For completeness, we also examined the effect of acceleration on the wavelength of the first Taylor vortex flow, and the result shows that irrespective of acceleration, the average axial wavelength remains relatively constant at about 2.0.

CONCLUSION

The experimental investigation of acceleration effect on the Taylor-Couette flow was conducted by flow visualization techniques. We have shown that the state of Taylor Couette flow is a function of not only the Taylor number, but also the acceleration of the inner cylinder. An important outcome of this investigation implies that it is possible for two distinct flow states (either STVF or wavy flow) to co-exist at the same Reynolds number, with acceleration as a controlling factor.

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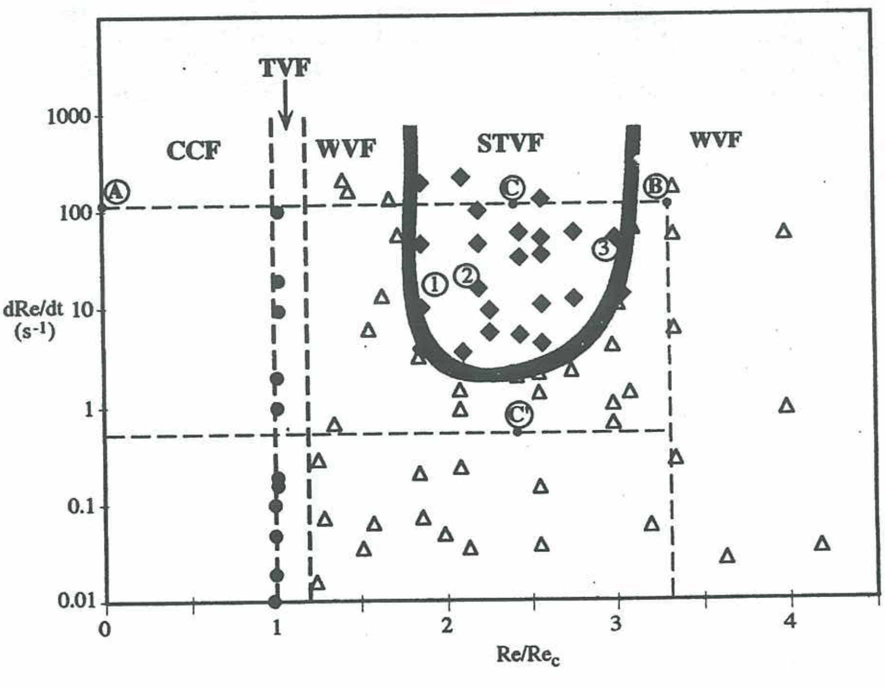

FIG. 1. A chart showing the effect of acceleration on the state of a Taylor-Couette Flow. CCF: Circular Coutte Flow; TVF: First Taylor Vortex Flow; STVF: Second Taylor Vortex Flow; WVF: Wavy Vortex Flow. The shaded curve indicates the approximate transition boundary between the wavy vortex flow and the second Taylor vortex flow. •: First Taylor vortex flow; Δ: Wavy vortex flow; ♦: Second Taylor vortex flow.

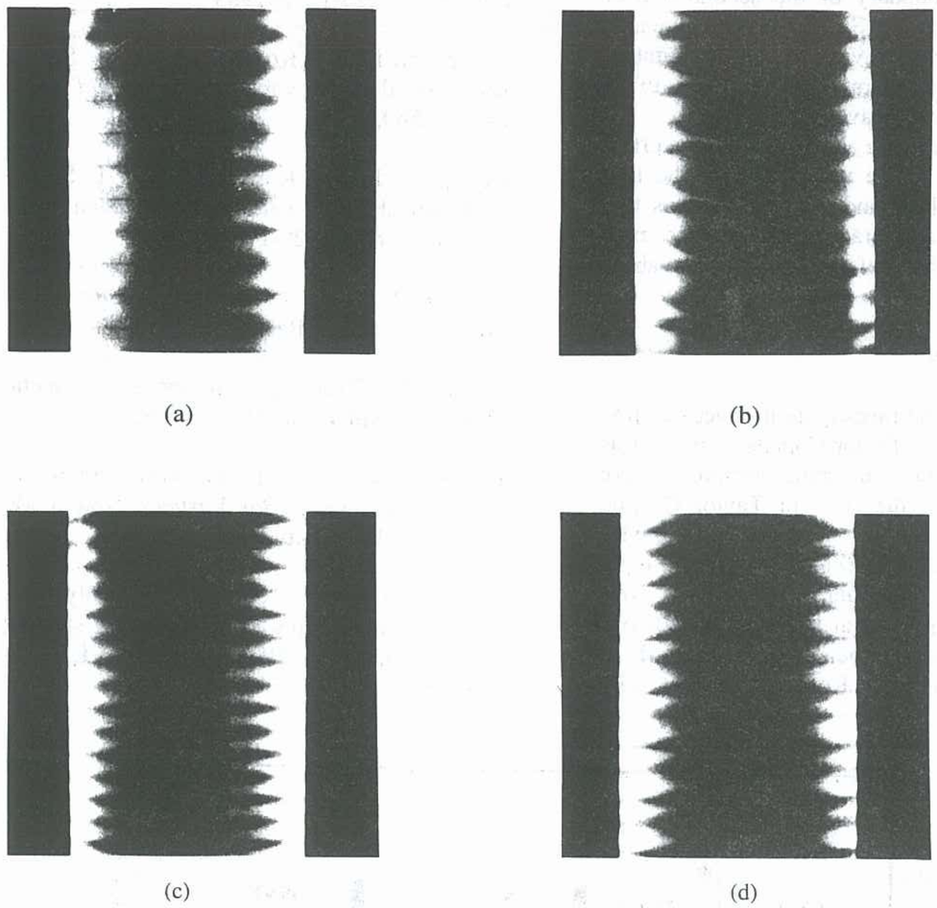

FIG. 2. Pictures of different flow states. (a) TVF Re/Rec=1.0, λ=2.0, dRe/dt=110.01 (s^{-1}); (b) WVF (m=2) Re/Rec=1.5, λ=2.0, dRe/dt=110.01 (s^{-1}); (c) STVF Re/Rec=2.5, λ=1.58, dRe/dt=110.01 (s^{-1}); (d) WVF (m=3) Re/Rec=2.5, λ=1.98, dRe/dt=110.01 (s^{-1}).

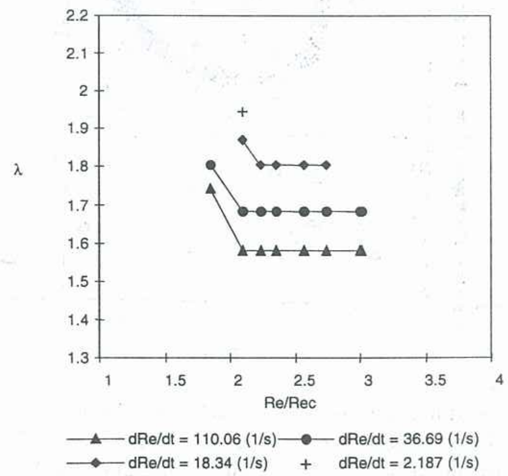

FIG. 3. Axial wavelength of STVF versus Re/Rec for different acceleration. Note: the axial wavelength of Taylor vortices is approximately equal to 2.0.