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The effect of viscosity on the rotating waves and polygonal patterns within a hollow vortex core

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A B S T R A C T

The question of how viscosity influences the development of instabilities within a rotating shallow layer of liquid, which gives rise to polygonal patterns, has been investigated experimentally. A phase diagram of the existence regions of these polygonal patterns is constructed in (Fr, Ta) plane, where Fr is the Froude number and Ta is the Taylor number. The results show that the effect of the viscosity on the domain of existence of the patterns depends on the initial fluid height above the rotating disc. The results also show that the variation of viscosity does not affect the locking ratio between the rotational frequencies of the pattern to the disc; the two frequencies remain locked at approximately 1/3.

1. Introduction

When water is placed in an open stationary cylindrical container and set in rotation by a rotating disc located at the bottom of the container, coherent structures are generated. These resemble to a large extent to the ones often observed in nature. This type of flows are used as a laboratory model to study complex geophysical and astrophysical phenomena [1–3]. In general, the dynamics and stability of such fluid motion involve a solid body rotation and a shear layer flow. The shear layer flow occurs in the outer region, because of the cylindrical confining walls, while the solid body rotation evolves in the inner region.

When the layer of water, above the disc, is shallow and the disc's speed is relatively high, a circular hollow-vortex core is formed. This devoid of liquid region can undergo series of spontaneous symmetry-breaking, which have the form of rotating polygons. The existence of these shapes, reported first by Vatistas [4], became recently the subject of growing interests. Indeed, several experimental studies were conducted to understand the mechanism behind their formation and dynamics [7,6,5,10,11]. In addition, several theoretical studies have also been conducted recently with the aim to explain the mechanism behind the rotating polygonal patterns [13,16,8,9]. In these studies the stability of the rotating hollow-core vortex was investigated. Assuming the base flow as potential, Tophøj et al. [13] identified resonance between gravity and centrifugal waves to be the cause of the polygonal patterns formation. The model by Tophøj et al. was found quite appropriate when the disc's speed is high. However, when the disc's speed is moderate, the central region of the rotating flow is nearly in a solid-body rotation. In this situation, the suitable swirling flow model might be of the Rankine's type, which combines a solid body rotation of the inner region with the potential flow of the outer region [8]. Using Rankine's vortex model for the base rotating flow, a new instability mechanism was proposed [9]. This mechanism involves the interaction between gravity and "Kelvin-centrifugal" waves. The rotating wave patterns were also described as traveling cnoidal waves, solutions of a Kortewege-de Vries equation [16].

The theoretical models mentioned above assumed that the fluid is inviscid; which is attractive because it allows for significant simplifications to the problem. However, the experiments indicated that the fluid viscosity could affect the phenomenon of the polygonal patterns formation and its role is intriguing. Recently, a simple experiment was conducted with liquid Nitrogen in a hot kitchen pot at temperature of 20 °C [13]. In this case, the Leidenfrost condition could be reached and a thin boiling film was formed around the solid walls. The Nitrogen liquid was brought to rotation by stirring it rapidly with a spoon. A cascade of polygons starting from 6-*gon* to 2-*gon* were observed within the hollow-core during the spin down process until the liquid Nitrogen reached its quiescent state filling the entire bottom. In the experiment the thin boiling film

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reduced the friction between the walls and the rotating liquid Nitrogen. Other experiments, conducted with relatively high viscosity fluids showed that viscosity could affect significantly the shape of the rotating patterns [15]. In these experiments, patterns up to 11-*gon* were observed and found able to travel in opposite direction to the disc rotation. Moreover, higher N-*gon* patterns were observed at lower disc's speed, while the lower N-*gon* ones were observed at higher disc's speed. The phenomenon was also found to exhibit strong hysteresis. In fact, it was discovered that completely different patterns formed during the disc spin-up and spin-down procedure. Experiments with fluids of moderate viscosities are very few. Jansson et al. [14] conducted experiments with ethylene glycol (its viscosity is approximately seven times than that of water); they found that viscosity reduces the number of observable N-*gon*. They also revealed that viscosity appears to have weak influence on the rotating frequency of the polygonal pattern.

In the present paper, we reexamine the role of the working fluid viscosity in the formation and the dynamics of the polygonal patterns. We investigate the role of moderate values of viscosity on the existence of polygonal pattern in Taylor and Froude numbers space. We also examine the influence of the viscosity on the frequency locking between the wave speed, at which the polygonal patterns propagate around the hollow-core vortex, and rotational frequency of the driving disc.

2. Experimental details and image processing

The experiments were conducted in a 284-mm diameter stationary cylindrical container with a rotating 280-mm diameter disc near its bottom. The shape of the vortex core was imaged from above as shown in Fig. 1.

The disc's speed was controlled using a controller and incremented slowly. Sufficient time was given to the fluid flow to stabilize between increments. The disc's rotational speed ranges from 75 to 267 rpms. Experiments with tap water and aqueous glycerol mixtures, as the working fluids, were conducted with three different initial liquid heights of 20, 30 and 40 mm above the rotating disc. Eight different aqueous glycerol mixtures were used in the experiments; the viscosities of these mixtures are 1, 2, 4, 6, 8, 11, 15 and 22 times the water's dynamic viscosity, μ, ($\mu = 1.002 \times 10^{-3}$ Pa s at 20 °C). The swirling flow and its instabilities were imaged from above at 30 frames per second, using a CMOS high-speed pco.1200hs camera. The typical polygonal patterns observed with water are shown in Fig. 1.

The rotating frequency of the pattern was obtained using Fast Fourier Transform (FFT) of the time series of the radial displacement for a given point on the polygonal pattern contour, defined by its radius and its angle in polar coordinates with origin at the center of the disc; see Ait Abderrahmane et al. [12,17] for further details. The patterns contours were obtained using image processing algorithm which consists of a sequence of classical image processing operations namely segmentation, noise filtration and edge detection summarized below in Fig. 2.

3. Results and analysis

3.1. Phase diagram

The experiments indicate that the pattern phenomenon involves the pattern wavenumber, N, the pattern rotational speed, ω, the fluid kinematic viscosity, ν, the initial water height above the disc, h, the disc's rotational speed, Ω, and the disc's and tank radius, R and R_t. The two latter parameters are constant in our experiment. Based on the Buckingham π theorem, the variables

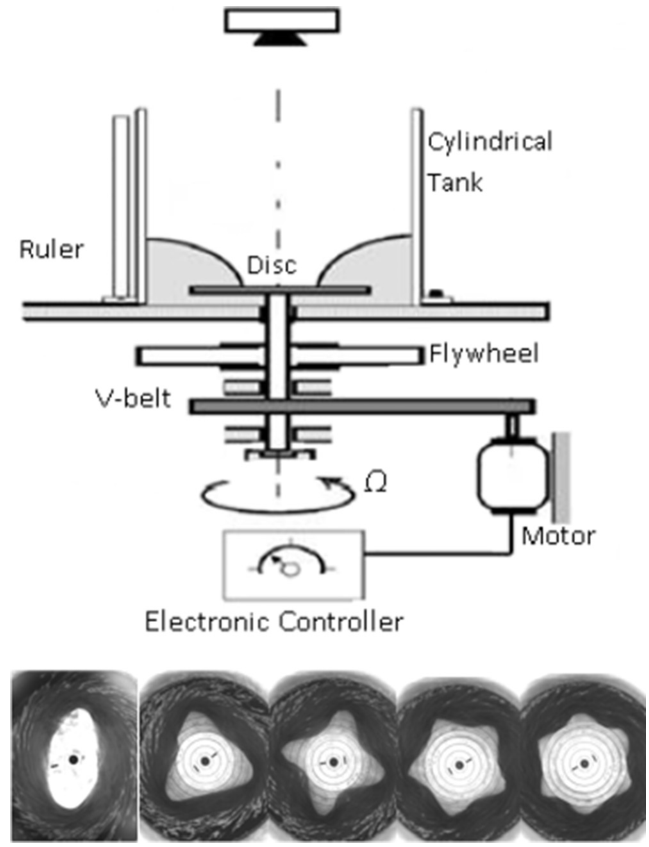

Fig. 1. Schematic of the experimental setup and typical polygonal patterns following the symmetry-breaking of the circular hollow-core vortex.

of the problem can be grouped in three dimensionless numbers, namely Taylor ($Ta = \frac{h^4\Omega^2}{\nu^2}$), Froude ($Fr = \frac{R\Omega}{\sqrt{gh}}$) and aspect ratio ($h/R$). g stands for the gravity. The Taylor number characterizes the importance of centrifugal force or inertial force due to the rotation of a fluid about a vertical axis, relative to viscous force. The Froude number describes the significance of the centrifugal force relative to gravitational force. The aspect ratio characterizes the shallow water conditions. The goal of our experiments is to investigate the role of a moderate fluid viscosity on the formation and the dynamics of the patterns. Hence, we varied the working fluid viscosity, the disc's speed and the initial fluid height above the disc. The two latter parameters were varied in the ranges where all polygonal patterns were observed. In contrast, with other experiments [14,10], the aspect ratio in our experiments is limited to three values only (0.14, 0.21, 0.28). These values ensure the shallow water condition and the observation of all possible polygonal patterns (up to hexagon).

A parametric study of the effects of the viscosity on patterns formation and their stability has been carried out. Fig. 3 shows the phase diagram in (Fr, Ta) plane, when the initial fluid height is h = 20 mm. With water we observed triangular, square, pentagonal and hexagonal patterns. Increasing the viscosity of the water, by adding gradually a controlled amount of glycerol, resulted on the gradual shrinking of the interval of the Froude number within which the patterns occur. Increasing the fluid viscosity triggers the transitions between unstable modes and disappearance of higher N-*gon* at low Froude numbers or low disc's speeds.

At fluid height h = 30 mm, we observed oval, triangular, square and pentagonal patterns with water as the working fluid; see Fig. 4. Similar to the previous experiments, increasing the viscosity of the