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Secondary Waves in Ribbing Instability

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Abstract. Many natural and technological processes involve phenomena dominated by interfacial mechanics, i.e., occurring within regions of intersection between several fluid and/or solid phases. In addition to capillary and gravitational effects, interfacial phenomena typically involve the interplay of complex processes such as dynamic contact lines, surface active materials, adhesion, temperature and/or compositional gradients, evaporation, etc. The aim of this work is to analyze the answer of the coating system with one cylinder, when viscoelastic polymers are used. We report new experimental results concerning different dynamical regimes, including traveling waves, obtained in that simple configuration and with free boundary conditions.

In the experiments with a non-Newtonian fluid (viscoelastic) with high molecular weight polymer (PIB_H), propagative modes have been observed for \( Ca > Ca^* \). In this case, as the distance to the threshold increases, the digitations standard, initially stationary, presents propagative modes only in some of the regions over the cylinder, and finally the traveling wave is established throughout the whole cylinder without showing any preferential direction. Propagative states have already been observed in the case of two rigid cylinders rotating with opposed surface speeds. However, in that case, the presence of defects does not produce a well-defined traveling wave and the system shows a rapid transition to chaos. Analyzing the space-temporal diagrams, the wave phase velocity could be measured with a methodology that allows calculating systematically this value, and we find a linear correlation between the capillary number \( Ca \) and the phase velocity \( V_f \). Besides, a detailed description of bifurcations has been made until reaching a chaotic state where it is possible observes the coexistence of traveling wave zones.

Keywords: Hydrodynamics instability, traveling waves.
PACS: 4720.k, 8310.ji

INTRODUCTION

The aim of this work is to study the dynamical behavior of the directional viscous fingering (ribbing instability) in the nonlinear regime. Many natural and technological processes involve phenomena dominated by interfacial mechanics that is, occurring within regions of intersection between several fluid and/or solid phases. In addition to capillary and gravitational effects, interfacial phenomena typically involve the interplay of complex processes such as dynamic contact lines, surface active materials, adhesion, temperature and/or compositional gradients, evaporation, etc.

The exact mechanics governing these processes, such as the hydrodynamic that controls wetting, or the macroscopic action of surfactants in the evolution of films or coatings, is still not fully understood. Basically, there is a strong interest to know the non linear aspect of the evolution of the interface previous (and during) to coating. Moreover, is necessary to predict the flow behavior during application and the drying process. Basic question involve the wetting and spreading of thin liquid layers as they flow on geometrically complex surfaces. At the same time, some physical properties of a liquid, such as viscosity and surface tension, are continually changing, as it dries. The problem can be represented by a set of coupled non linear partial differential equations in space and time that can be solved numerically.

Final coating defects, such as sagging, blisters and ribs, can be visualized, as they develop in the simulation output, and their origin can be related to rheology, processing and geometric parameters. Rheology plays a major role in the development and onset of such hydrodynamics instability. In the case of viscoelastic fluids, it has been noticed [1] that the presence of elastic effects has a dramatic influence on the instabilities and change new purely elastic interfacial behaviours due to the influence of normal stress [2].

From a critical value of the Capillary Number \( Ca^* = \frac{\mu v}{\sigma} \) where \( \mu \) is the dynamical viscosity \( \sigma \) the surface tension and \( v \) the mean roll speed, instability develops on the air-fluid interface (ribbing instability). These configurations are similar to the ones observed in experiments of directional-solidification in liquid crystals and eutectic alloys. Our interest is to understand the particular behaviour that appears when the system is far away from the onset of this ribbing instability. In the Fig.1 we can observe the wave pattern corresponding to a system of two cylinders where,
when the critical condition \((C_a^*)\) is reached the formed structure is transmitted over a second cylinder.

**EXPERIMENTAL SETUP**

In the Fig.2 (plane-cylinder system) there is a schema of the experimental system where the instability was studied. This journal bearing geometry is adequate to study the instability threshold and the posterior evolution. The system consist on a steel roller \((R = 37.5 \text{ mm}, L = 380 \text{ mm})\) and a 10-mm thick glass plate mounted on top. The temperature was controlled via a thermostat zed bath. The gap \(h\) was varied between 0.2 mm to 0.45 mm. So, the geometrical parameter, aspect relation \(\gamma = h/R\) varied from \(1.2 \times 10^2\) to \(9 \times 10^{-3}\). When \(C_a = C_a^*\), there appears what we call primary instability. We have an example of the evolution with \(C_a\) of this primary structure for a Newtonian fluid in Fig. 3. As we can observe, change the wave length, yet they continue being stationary; \(\varepsilon\) is the distance to threshold \(\varepsilon = \frac{C_a - C_a^*}{C_a^*}\) and is controlled by modifying thr cylindr rotation velocity.
FIGURE 3. Ribbing instability evolution obtained with the same experimental set-up for a Newtonian fluid (vaseline) is a measures of the threshold distance.

TRAVELING WAVES

The experiment was carrying out with non Newtonian fluid, a viscoelastic polymer with high molecular weight, constant viscosity in our range of work, and strong elastic properties. The PIB polymer (6500 wppm), has a molecular weight of $4.70 \times 10^6$ g/mol, the apparent viscosity is 68 mPa.s, the surface tension 29.6 mN/m.

As it can be seen in Fig.4, we find the unexpected appearance of traveling waves. Such appearance, when the system moves away from the threshold, has been observed with Newtonian fluids in experiments [3] made with an eccentrically cylinder system, in which the external cylinder velocity $v_e$ is fixed at a small value, and the internal cylinder velocity $v_i$ in counter-rotation, is varied. Thus, after the first sub-critical bifurcation towards a stationary cell
pattern (primary instability) is overcome, there appears a secondary bifurcation corresponding to a state in which a uniform traveling cell movement exists.

Fig.4, show the evolution of the system when $C_a$ increases above $C_a^*$ until the chaotic regions appear to later give rise to the establishment of the traveling waves. As we can observe, initially the digitations pattern is stable and
**PHASE VELOCITY**

It is possible visualize a parity symmetry breaking in the images shown above. In the space time graphs the oblique lines indicate the presence of observed traveling waves (images 7 and 8 of Fig.4) and they allow us to calculate the phase velocity. We verified that the pattern wave number decreases linearly with increasing asymmetry. For \( \lambda > 1.60 \), it is difficult to measure a defined \( \lambda \).

In Fig.5 a linear correlation between phase velocity \( v_f \) and \( \varepsilon \) may be observed (the lower limit is \( \varepsilon = 1.7 \)). Furthermore, the bifurcation threshold towards the propagative regime for two geometric conditions is visualized.

**DISCUSSION OF THE OBTAINED RESULTS**

This work presented the development of a study made on the nonlinear regimes of the ribbing instability. In the same system, in the case of Newtonian fluids, the digitations pattern is stable for every \( C_a > C_a^* \). And, as already remarked, two control parameters are necessary to observe traveling waves with this kind of fluid.

For visco-elastic polymeric solutions, the pattern of primary instability becomes non stationary for values over \( C_a^* \), and the subsequent evolution, shows a different behavior before to arrive to fully chaotic state. An approach to analyze the mechanisms that lead to these propagative structures is the method followed by Fauve et al. [4] that uses Ginzburg-Landau’s equations formalism.

Some authors propose considered the asymmetry parameter to correlate phase velocity with pattern asymmetry (proportional to amplitude) where the variation in wave numbers, can arise due to the coupling between amplitude and phase. The behavior of these traveling waves can be analyzed using a breaking of parity model where a \( k \) and \( 2k \) modes interact [5]. Propagative behaviors have been observed in other one-dimensional hydrodynamic systems [6]. For the first time, in this work, a bifurcation for secondary instabilities is observed in the plane-cylinder system with free boundary conditions where the cylinder rotation is the sole control parameter.
REFERENCES