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Characterization of patterns in rimming flow

R. Chicharro [a,*], A. Vazquez [a], R. Manasseh [b,c,d]

[a] Universidad Nacional Autónoma de México – Facultad de Ciencias, Laboratorio de Fluidos, Av. Universidad 3000, Delegación Coyoacán C.P. 04510, México D.F, Mexico
[b] Faculty of Engineering & Industrial Sciences, Swinburne University of Technology, Hawthorn, VIC 3122, Melbourne, Australia
[c] Department of Mechanical Engineering, University of Melbourne, VIC 3010, Melbourne, Australia
[d] Fluid Dynamics Group, CSIRO Materials Science and Engineering, PO Box 56, Highett, VIC 3190, Melbourne, Australia

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ABSTRACT

Patterns were generated inside a horizontal cylinder rotating at low speeds. The cylinder was filled with a very low volume liquid fraction of 1.8% of Newtonian fluid and the rotation speed ranged between 0.08 and 5.2 s^{-1}. A novel laser-plane technique was utilized to obtain time series from each pattern. This enabled the characterization of fluid patterns using Fourier spectral (*FS*) and dynamical-systems (chaotic) techniques such as the recurrence map, correlation dimension (D_2) and Hurst exponent (H). Four patterns were found (fingers, furrows, waterfall and smooth tooth) before annular flow was reached. The results indicate that the *FS* technique not is suitable for flow pattern characterization; and *H* only has the ability to indicate a possible pattern change. The best tool for indicating the pattern transitions and the inner coat liquid evolution was found to be recurrence maps and D_2.

1. Introduction

The evolution of a thin liquid coating on or inside a right circular cylinder that is undergoing rotation about a horizontal axis is called rimming flow [1]. A cylinder undergoing uniform rotation is able to hold a thin coating of liquid, due to the combined effects of liquid viscosity and cylinder rotation. In general, however, the coating on a long right circular cylinder may be subject to instability due to the action of surface tension at the liquid–air interface and centripetal acceleration [2]. The analysis of this problem requires an understanding of the interplay between gravitational, rotational and surface tension effects on the coating.

This type of flow has many industrial applications: in the paper industry (the Fourdrinier machine), the roller-coating industry (photographic films, aluminum foils), and in liquid degassers, liquid cooling of turbine shafts, etc. Further numerous topics in applied engineering science are noted by Karapantsios et al. [3], Benkreira et al. [4], and Wilhelmsson et al. [5]. In industry the low liquid volume fractions (1–5%) are very important, especially in the pharmaceutical industry in which the coating provides a sustained release barrier for drug transport. In these systems the coating variability has a strong dependency on surface velocity of a rotating drum, and recent studies reveled that a uniform flow is reached for high rotation speeds Sandadi et al. [6]. In the present paper, we focus on the flow patterns observed at low liquid volume fraction and using a Newtonian fluid. In this regime, Vallette et al. [7] realized experiments using a glass cylinder of radius $R_0 = 5$ cm, length $L = 50$ cm and partially filled with silicone oil ($\mu = 10$ cS) using filling fractions of $A = 1–4\%$ (where $A = 100V_L/V_T$, with V_L,V_T being the fluid and cylinder volume respectively). They investigated the bifurcations to time-dependent and chaotic one-dimensional fluid fronts inside the horizontal rotating tube. A primary cellular pattern undergoes a variety of secondary transitions, depending on the filling fraction. Chen et al. [8] indicated that no information was available for rimming flow for liquid volume fractions less than 2%, despite its industrial importance. Chen et al. [8] used Newtonian solutions of glycerol and polyvinyl alcohol (PVA) of low viscosity (28.4–4.8 cP) and observed the existence a certain critical volume fraction (V_C) for each solution, where the rotational speed required to achieve uniform rimming flow takes a minimum value. For $V > V_C$ the patterns are mainly the "shark-tooth" and turbulent regimes, while for $V < V_C$, "fingers" and "rings" are formed. In addition, they found a critical rotational speed (Ω_c) for the annular flow to exist; for water this is $\approx 6\ s^{-1}$ with a filling fraction $\approx 2\%$, and for $A < 0.5\%$ the rotation speed for annular flow to exist is inversely proportional to the volume fraction.

Numerical and experimental work was realized by Evans [9] in who presented three-dimensional numerical simulations for filling fraction of ~1.9% and silicone oil with $\mu = 48$ cP. The liquid motion was described using a lubrication model and the results exhibit similar fingering to that observed in laboratory experiments for

* Corresponding author.
E-mail address: RMANASSEH@groupwise.swin.edu.au (R. Chicharro).

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