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Enhanced turbulence in the Taylor-Couette flow system

Hamid Oualli[a,*], Mahmoud Mekadem[a], Ahcene Bouabdallah[b], Mohamed Gad-El-Hak[c]

[a]*Fluid Mechanics Laboratory, Ecole Militaire Polytechnique, BP17, Bordj El Bahri, 16046, Algiers, Algeria*
[b]*LTSE Laboratory, USTHB University, 16111 Bab Ezzouar, Algiers, Algeria*
[c]*VCU, P. O. Box 843015, Richmond, VA 23284-3015, USA*

Abstract

The Taylor-Couette system keeps making subject to countless studies. It is used in catalytic reactors, electrochemistry, photochemistry, biochemistry and polymerization, as well as in mass transfer operations (extraction, tangential filtration, crystallization and dialysis). This work deals with a numerical study dedicated to a Taylor-Couette flow considering the influence of a pulsatile dynamic superimposed to the rotative inner cylinder. Simulations are implemented on the FLUENT commercial package where a three-dimensional and incompressible flow is considered. It is shown that the suggested controlling technique fundamentally alters the physical flow behavior resulting in substantial turbulence enhancement to which transition is instilled at a Taylor number of $Ta = 17$ instead of $Ta = 41.33$ corresponding to the non-controlled case.

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1. Introduction

The Taylor-Couette system is the typical flow model for the major part of hydrodynamic stability problems and bifurcation studies. More than several thousands of published works are relevant to this kind of problems. This is explained by the physically wealth regimes encountered in this confined flow route to turbulence from laminar stable to fully turbulent regimes. Namely, the Taylor-Couette flow consists in a viscous incompressible fluid evolving between two rigid concentric cylinders. The inner cylinder is rotative while the outer is stationary. This is the most commonly used configuration. The various transient regimes (laminar to turbulent) appearance depend essentially upon the inner cylinder acceleration process but also upon geometrical considerations as the cylinders radii ratio which is determines the toroidal structures scaling. Experimentally, Duvet [1] established that for slow and low inner cylinder speeds a laminar "Couette flow" is the first appearing regime. When the angular velocity of the cylinder is gradually increased and after a certain critical value of the rotating rate, the laminar flow is destabilized, leading to the birth of a family of flow regimes generally accompanied by intricate physical phenomena characterized by periodicity, quasi-periodicity, chaos and turbulence.

* Corresponding author. Tel.: +213 86 34 69 ; fax: +213 86 32 04.
E-mail address: houalli@gmail.com

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Nomenclature

R_1 radius of the inner cylinder [m];
R_2 radius of the outer cylinder [m];
d annular space between the two cylinders [m];
H height of liquid in the gap of the vertical system [m];
Ta Number of Taylor;
Tc_1 Taylor number corresponding to the appearance of the Taylor wave (first instability);
$\eta = R_1/R_2$: ratio of the inner to the outer radius;
$\delta = d/R$: radial gap;
$\Lambda = 2\pi/\lambda$: axial Wavelength;
λ apparent wave number;
a dimensionless axial wave number;
$\Gamma = Hd$: aspect Factor or filling rate;
Ω inner cylinder rotating rate [rad/s];
f Deforming frequency [Hz];
$\varepsilon = \Delta r/R$: deforming amplitude [% of the inner diameter];

Taylor [2] brought order into the plethora Mallock results, sometimes contradictory. He showed theoretically and then confirmed experimentally that a stable laminar flow starts to become unstable over a threshold critical value of the inner cylinder rotational speed corresponding to a critical value of the Taylor number, $Tc_1 = 41.2$, and experimentally $Tc_1 = 41.32$. Subsequently, this result was checked by DiPrima [3] who found $Tc_1 = 41.61$. Using two different calculation methods, Chandrasekhar [4] reported that $Tc_1 = 41.41$. From the value, $Ta = Tc_1$, the fluid is organized in the cylindrical cavity in a stack of superposed counter-rotative structures occupying the width of the annular gap and propagating along the axial direction z, see Fig. 1.

Coles [5] experimentally explored a wide range rotating rates and various observed configurations through visualizations and photographs are described. Bouabdallah [6] elaborated a work devoted to the first two instabilities investigation. He identified conditions for the chaos appearance using spectral evolution of the flow to turbulence. For an infinite geometry, the nonlinear theory of Stuart [7] led to results physically correct in the range $Tc_1 < Ta < 1.2Tc_1$. For numerical simulations and since the 60s, several authors tried to get solutions to the Taylor-Couette problem. Based on the assumption of axial periodicity, Meyer [8] is the first to execute numerical calculations regarding the Taylor-Couette flow. He was able carrying out a comparison of numerical results with experiments elaborated using finite length cylinders. Street and Hussaini [9] developed a numerical program based upon several resolving methods to solve the problem with an inner rotating cylinder.

The different regimes met in Taylor-Couette systems are generally illustrated when increasing the cylinder rate, see Fig. 1.

It is sought in this study to make assessment of the influence of the inner cylinder radial pulsatile motion on the Taylor vortices configuration. Specifically, a special attention is paid to flow criticality in terms of the critical Taylor number evolution characterized by the first instability triggering (Taylor stationary wave). It is worthwhile noting that to our best knowledge no reference can be found in literature dealing with such a presented controlling technique. The problem is solved using FLUENT software where to the computational simulations are implemented. The controlling parameters, namely: amplitude and frequency of the oscillating movement are introduced using an UDF (User Defined Function), a homemade program compiled together with the used software.

2. Problem formulation and system description

The fluid used in this study is benzene-liquid, a viscous, incompressible fluid completely filling the space between the two vertical concentric cylinders (no free surface). The basic system has a height $H = 200mm$, a ratio of the inner to the outer radius, $\eta = 0.9$, an aspect ratio $\Gamma = H/d = 40$ and a radial gap $\delta = d/R_1 = 0.1$. The inner cylinder is subject to a sinusoidal radial deformation controlled using the parameters: frequency (f) and amplitudeset equal