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The spherical Taylor–Couette flow

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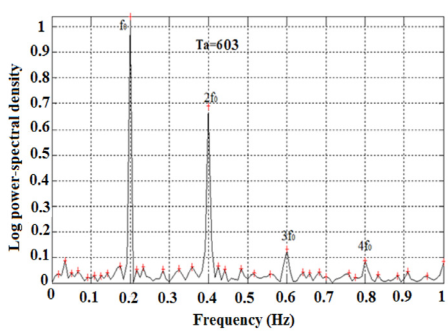
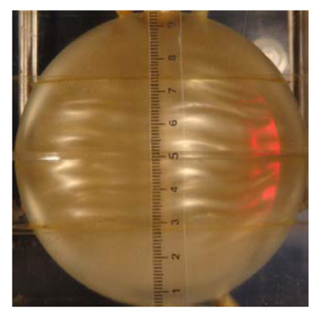
HIGHLIGHTS

- The electrodiffusion method was applied for the first time in the flow between two concentric spheres in rotation.
- The evolution of the flow patterns was illustrated by the wall velocity gradients and their fluctuations.
- The visualization of each flow state was quantified by the power spectra of wall velocity gradients.

GRAPHICAL ABSTRACT



Azimuthal waves at Ta= 603.



Spiral Wavy Mode visualization, Ta=126.

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ABSTRACT

The instability modes that lead to turbulence between two concentric spheres, the inner one rotating while the outer is at rest, are investigated through visualization and using the electrodiffusion (ED) method. The wall velocity gradients are measured for the first time in a spherical shell by ED method. The exploration of the flow regimes is carried out for a dimensionless gap width $\delta = (R_2 - R_1)/R_1$ of 0.107, an aspect ratio $\Gamma = H/d$ over the interval (17–21) and a Taylor number in the range (22–1500). The influence of these parameters on the apparition of instabilities is elucidated. The evolution of the flow patterns is visualized and also quantified by the wall velocity gradients and their fluctuations. Using the fast Fourier transform, the time series of velocity gradient obtained by the ED method permitted analysis and identification of the fundamental frequencies and their evolution associated with each flow state.

1. Introduction

The spherical Taylor–Couette flow has been an important research topic for several years. Its scientific relevance lies not only in the simplicity of the system but also in its applicability to astrophysical objects and geophysical motions such as atmospheres, oceans, and planetary cores.

The first instability of the basic flow leads to the formation of Taylor vortices in the equatorial region, as reported by Khlebutin [1], Sawatzki and Zierep [2], Menguturk and Munson [3], Yavorskaya et al. [4], Wimmer [5,6], Bühler and Zierep [7,8], Bühler [8], Schrauf, [9], Egbers and Rath [10] and Hollerbach [11].

Khlebutin [1] was the first who carried out flow visualization experiments and torque measurements using six dimensionless gaps ($0.037 \leq \delta \leq 1.515$). He observed the Taylor vortices for $\delta \leq 0.19$ but no such structures existed for $\delta \geq 0.44$. Egbers and Rath [10] experimentally investigated the existence of Taylor vortices and instabilities in spherical Couette flow. In accordance

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Nomenclature

R_1	Radius of inner sphere (m)
R_2	Radius of outer sphere (m)
d	Gap width $= (R_2 - R_1)$ (m)
f_0	Fundamental frequency
H	Height of liquid (m)
Γ	Aspect ratio $= H/d$
δ	Gap/radius ratio $= d/R_1$
Ω	Angular velocity (rad s^{-1})
υ	Kinematic viscosity (m^2 s^{-1})
θ_i	Angle measured from the sphere axis (°)
S	Wall velocity gradient (s^{-1})
s'	Fluctuation intensity of S (s^{-1})
Tc_1	Critical value of start-up of Taylor vortices
Tc_2	Critical value of spiral mode
Tc_3	Onset of spiral mode & wavy mode
Tc_4	Critical value of spiral wavy mode
Tc_5	Critical value of azimuthal waves
Tc_6	The near-turbulence regime
Tc_7	Onset of chaos
Tc_8	Developed turbulence

with Khlebutin [1], they did not observe the Taylor vortices in wider gaps ($0.330 \leq \delta \leq 0.500$). Wimmer [12] showed that the flow modes could be produced by different acceleration histories of the inner sphere. Another study on torque measurements as a function of flow regimes was done by Menguturk and Munson [3]. They found a good agreement between the experiment and perturbation theory for narrow gap values.

Schmitt et al. [13] studied experimentally spherical Couette flow in a dipolar magnetic field. They focused on the time dependence of the electric potential differences between electrodes located on the outer sphere and on the time correlations between these differences.

On the other hand, several numerical studies were carried out. Nakabayashi et al. [14] plotted the evolution of non-dimensional root mean square (RMS) values of V_φ/U_0 and V_θ/U_0 ratios. V_φ and V_θ are the fluctuations of azimuthal and meridian velocity components, respectively and U_0 is the peripheral velocity of the rotating inner sphere. Bar-Yoseph et al. [15,16] considered both concentric and eccentric spherical gaps for two different radii ratios of medium size gap by means of finite-element method. Mamun and Tuckerman [17] examined asymmetry and Hopf bifurcation in spherical Couette flow of Newtonian fluids. They presented bifurcation diagrams along with torque characteristics. Yang [18] simulated fictitious symmetric boundary conditions to find all possible flow modes. Yuan [19] discussed the wavy and spiral Taylor–Görtler vortices in medium spherical gaps ($\delta = 0.14$ and 0.18). Kelly et al. [20] studied linear wave modes restored by the Coriolis force and proposed selection mechanisms to explain the presence of the particular observed modes.

This paper aims to experimentally explore the spherical Taylor–Couette flow. The ultimate goal is the evolution of flow structures during the laminar–turbulent transition. We present the evolution of the velocity gradient (S) and the fluctuating rate s'/S as a function of the Taylor number for different values of the aspect ratio Γ. The hydrodynamic instabilities are investigated by spectral analysis of time series recorded for different flow regimes.

2. Experimental conditions

The experimental setup consists of two concentric spheres made of transparent Plexiglas, with the inner sphere rotating and

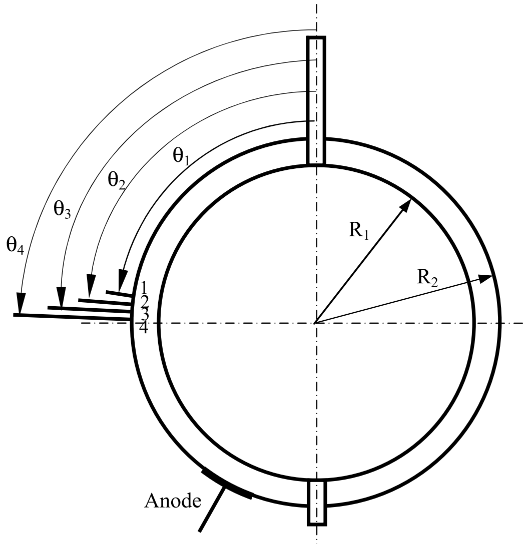

Fig. 1. Experimental setup. Numbers 1, 2, 3, 4 denote position of measuring electrodes.

the outer one stationary (Fig. 1). The outer and inner spheres have a radius of $R_2 = 54.9$ mm and $R_1 = 49.6$ mm, respectively. The corresponding non-dimensional gap width $\delta = d/R_1$ is equal to 0.107. The definitions of geometrical parameters are similar to those used in the cylindrical Taylor–Couette systems, i.e. the gap width $d = R_2 - R_1 = 5.3$ mm and the aspect ratio $\Gamma = H/d$ where H is the height of liquid varying in the spherical gap. Another important control parameter which must be taken into account is the acceleration rate of the inner sphere. The flow patterns are also determined by the flow history depending on the rate of Taylor number variation.

The inner sphere is driven by a dc motor whose speed varies between 0.01 and 3.01 rev/s. The fluid temperature is measured by a digital thermometer and maintained constant within ±0.1 °C. The working fluid is an aqueous solution of ferri–ferro-potassium cyanide in an equimolar concentration of 2 mol/m^3 with an excess of potassium chloride (300 kg/m^3).

Four platinum probes of 0.5 mm diameter serves as cathodes, they are flush mounted with the inner wall of the outer sphere at angles of $\theta_1 = 82.5°$, $\theta_2 = 84°$, $\theta_3 = 85.5°$ and $\theta_4 = 88.5°$ measured from the axis (Fig. 1). The anode is a platinum sheet with dimensions of 50 × 20 mm fixed at the bottom of the outer sphere.

The electrodiffusion method was applied for the study of Taylor–Couette system at the early 1970s by Cognet [21]. This method makes use of the mass transfer in the vicinity of the working electrode—probe. The principle of this method is to impose a potential between cathode and anode which is different from the equilibrium one. In this way, an electrochemical reaction takes place and the probe active surface in contact with the solution becomes the site of ion exchange. The motion of ions is the result of the convection by the fluid flow, molecular diffusion due to the concentrations gradient and migration due to the electrical field. The migration is suppressed by addition of a supporting electrolyte (KC1). In the quasi-steady boundary layer approximation (Leveque [22]), the velocity gradient S at the probe is related to the limiting diffusion current by the relation:

$$S = 0.0996 \frac{I^3}{(nFc)^3 D^2 R^5}, \quad (1)$$

where I is the measured electric current, D the diffusion coefficient, R the electrode radius, F the Faraday constant, n the number of electrons involved in the electrochemical reaction and c the concentration of active species in the bulk.