CONTRIBUTION TO THE TAYLOR-COUETTE FLOW CONTROL USING THE INNER CYLINDER CROSS-SECTION VARIATION

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Summary The hydrodynamic stability of a viscous fluid flow evolving in an annular space between a rotating inner cylinder having a periodically variable radius and an outer fixed cylinder is considered. The basic flow is axis-symmetric with two counter-rotating vortices each wavelength along the whole filled system length. A finite-volume CFD code is used to simulate the flow behavior. The study aims to investigating the transition and assessing the flow response to the superimposed boundary motion with increasing amplitude of oscillation.

NUMERICAL APPROACH

Since the seminal paper of Taylor [1], a large number of experimental and theoretical studies of the onset of Taylor Vortex Flow (TVF) have developed. Due to its cellular nature, the Taylor–Couette Flow (TCF) is claimed to be one of the rare flow types combining intense local mixing with a limited axial dispersion, Baron [2]. It allows the enhancement of heat and mass transfer at the cylinder walls, and several possible applications of the unique reactor performance have been proposed covering the fields of turbomachinery, catalytic and biocatalytic, counter-current extraction, tangential filtration, crystallization, and electrochemical, photochemical and polymerization reactions, Muzishina [3]. In the present study, we consider a flow control strategy capable of spatially localizing the Taylor vortices between two concentric rotating cylinders. To this end, we proceed by actuating the geometry of the TCF to affect vortices appearing in the radial direction along the length of the apparatus. Particularly, we are interested in investigating the impact of a pulsatile radial motion of the inner rotating cylinder on the TVF in an infinite length cavity. We conduct numerical simulations using a finite-volume approach. It is found that a destabilization of the TVF results from the interplay of the imposed oscillating radial flow and the flow resulting from the Taylor instability. The applied control significantly destabilizes the flow in such a way that the first instability can be triggered at an enhanced critical Taylor number less than half its natural value.
We briefly describe the numerical procedure used to solve the problem. The grid is generated using the GAMBIT program and saved on a structured quadrilateral grid as shown in Fig. 1. The volume of the annular gap is constructed on 120×120×7 cells. The mesh is uniformly distributed in the axial direction and linearly condensing in the radial direction. The solution is carried out using the computational fluid dynamics package FLUENT. This computer program applies a control-volume method to integrate the equations of motion. An implicit scheme is used to discretize time, and a third-order MUSCL scheme is used to discretize the convective terms in the momentum equations. Pressure implicit with splitting of operators is used as the pressure–velocity coupling scheme. Finally, the time integration of the unsteady momentum equations is performed with a second-order approximation.
The time step is fixed equal to Δt=0.002. Modulation of the inner cylinder diameter is carried out using the “moving mesh” FLUENT program. A short algorithm is used to change the shape of the grid cells, and to create and eliminate the cells to ensure the desired deforming motion. The maximum number of iterations each time step is 1,000. This number is systematically reduced if the solution converges with the residual of the order of 0.001.

Validation and comparison with experiment

The Taylor–Couette device is in its classical configuration; a stationary outer cylinder and a rotating inner cylinder. The flow structure for Tc1=41.33, corresponding to the first instability appearance is given in the Fig. 2. This numerical result is in good agreement with the experimental value of *Tc1*=41.2 reported by Bouabdallah et al. [4], for the same geometrical conditions. In order to characterize the effect of the inner cylinder diameter variation, an influencing parameter ε is defined as: $\varepsilon=(R2-R1)/R1=\Delta r/R1$, where $R1$ and $R2$ are respectively the maximum and minimum radii of the inner cylinder. The natural case corresponds to the non-actuated state, ε=0%.

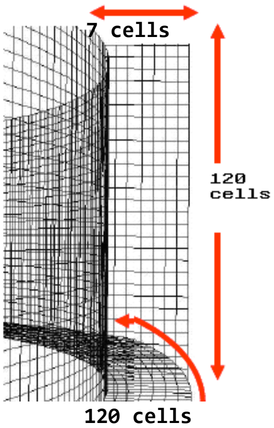

Fig.1: 3-D grid with 2×10^5 quadrilateral cells.

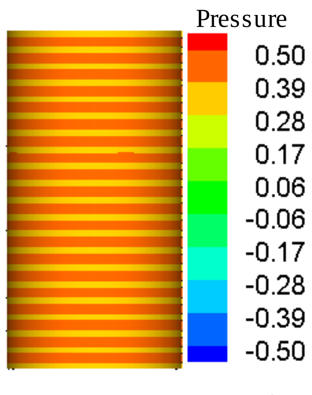

Fig.2: Present results for the first critical Taylor number Tc_1

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The variation of the first critical Taylor number with the amplitude of deformation is seen in Fig. 3. For ε=0.1%, the first critical Taylor number Tc_1 increases from 41.2 to 42. This tendency reverses completely when ε exceeds 0.1% and the critical Taylor number decreases rapidly until Tc_1=17.66 for ε=5%, after which the declining rate moderates.

Fig. 4 depicts the evolution of the axial vorticity as the deforming amplitude increases from 0 to 5%. The boundary layer is clearly discernable in the natural case—no actuation applied. The boundary layers on the inner and outer cylinders are surrounding two rows of structures evolving anti-symmetrically in the gap with a phase shift of π, as shown in Fig. 4a. When the inner cylinder diameter is set to oscillates, the boundary layer on the outer (stationary) cylinder vanishes completely even for the smallest value of the deforming amplitude considered in the present study, ε=0.1%. This behavior is observed for the entire range of the applied deforming amplitudes from 0.1 to 5%. The boundary layer on the inner cylinder, however, shrinks significantly for the small deforming amplitude and resists to the applied perturbation until ε=2%, as shown in Fig. 4c. Over this threshold value, the inner boundary layer completely disappears for all the higher values of the deforming amplitude and the two structure rows are pushed outwardly to be squeezed on the cylinders boundaries. The vortices are of larger scale, axially elongated and closer from each other to be connected. Axial and radial symmetries are thus altered, as shown in Figs. 4c and 4d. The threshold value ε=2% quite surprisingly coincides with the local maximum value of axial vorticity depicted in Fig. 5. Over the value ε=2%, the axial vorticity decreases drastically to reach its lowest value, about 60% lower than that of the natural basic flow, Figs. 4a and 4d. Similar response to the radial perturbation is observed for the radial vorticity as shown in Fig. 5. The maximum radial vorticity significantly diminishes, up to 75% compared to the basic flow value, indicating even higher sensitivity to the radial oscillation. The decrease in the maximum radial vorticity is accompanied by an enhancement of the flow re-organization. The Taylor–Couette structures become axially closer to each other and radially squeezed in a more organized pattern of two axially aligned structure rows leaning against the cylinders surfaces, as depicted in Fig. 4 d.

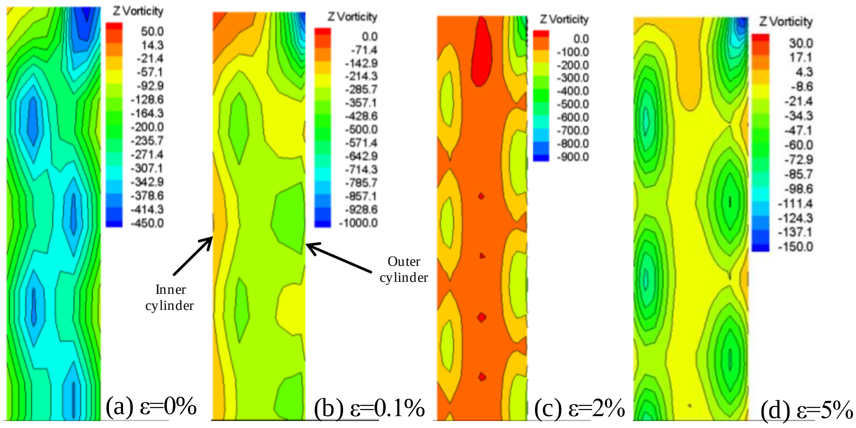

Fig.4: Axial vorticity for the Taylor Couette flow versus deforming amplitude ε%

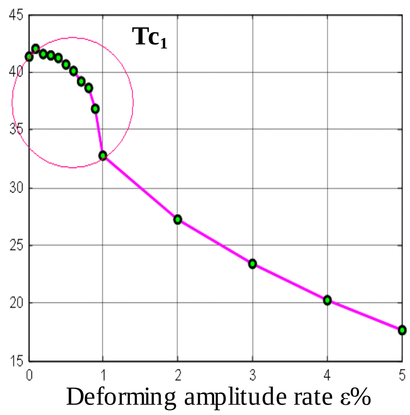

Fig.3: Critical Taylor number Tc_1 versus deforming amplitude ε%

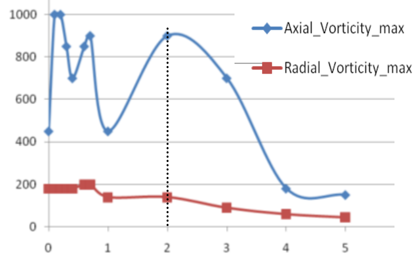

Fig.5: Maximum vorticity versus deforming amplitude ε%

CONCLUSION

We have numerically characterized a novel behavior of the Taylor Vortex Flow by periodically deforming the cross-section of the inner rotating cylinder in a Taylor–Couette apparatus. As a salient result of the oscillations, axial and radial symmetries are broken, significant reduction in the maximum vorticity values is achieved, and substantial enhancement of the transition from the Taylor-Couette basic flow to the Taylor-Couette vortical flow is observed.

References

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