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NUMERICAL SIMULATION OF THE FLUID INSTABILITIES IN THE GAP BETWEEN TWO ROTATING CYLINDERS

NUMERICKÁ SIMULACE NESTABILIT PROUDĚNÍ V MEZEŘE MEZI DVĚMA ROTUJÍCÍMI VÁLCI

Abstrakt

Článek prezentuje výsledky numerické simulace Taylor-Couetteho proudění mezi proti sobě rotujícími válci, které autor získal experimentálním a matematickým výzkumem. Byly simulovány všechny druhy proudění pozorované na fyzikálním experimentu, to znamená nejen časově nezávislé druhy proudění jako je Couetteho proudění a Taylorovy víry, ale také časově závislé typy proudění jako je vlnové proudění, modulované vlnové proudění a dva druhy spirálového proudění. Pro numerickou simulaci byl použit matematický model založený na Navier-Stokesových rovnicích a rovnici kontinuity a metoda konečných objemů

Abstract

The article presents the results of numerical simulation of Taylor-Couette flow at counter-rotating concentric cylinders, which the author dealt with in his experimental and numerical investigation. There were all kinds of flow observed during the physical experiment simulated. That means not only time independent kinds of the flow as Couette flow and Taylor vortices, but also time dependent types of the flow as wavy vortex flow, modulated wavy vortex flow and two kinds of spiral flows. Mathematical model of the flow based on the Navier-Stokes and continuity equations as well as numerical method of finite volumes had been used for those simulations.

1 Introduction to problem and current state

The paper concerns the examining of hydrodynamic instabilities rising at Taylor-Couette flow between two concentric cylinders, where both inner and outer cylinder are rotating, however angle speed of the inner cylinder has to be bigger than the angle speed of the outer cylinder. Under such conditions the flow is instable even when using an ideal liquid. At some circumstances, there can appear secondary flow characterizing this instability [1]. Flow of the real liquid between cylinders is a modification of Couette´s flow caused by rotation of inner cylinder. At the outer standing cylinder the toroid vortices rise. These ones were named after G. I. Taylor, who described this problem in 1923. He also experimentally showed and gave reasons even for their theoretical appearance. There exist other modifications of Taylor´s vortices, which can be seen in the figure. 1.1.

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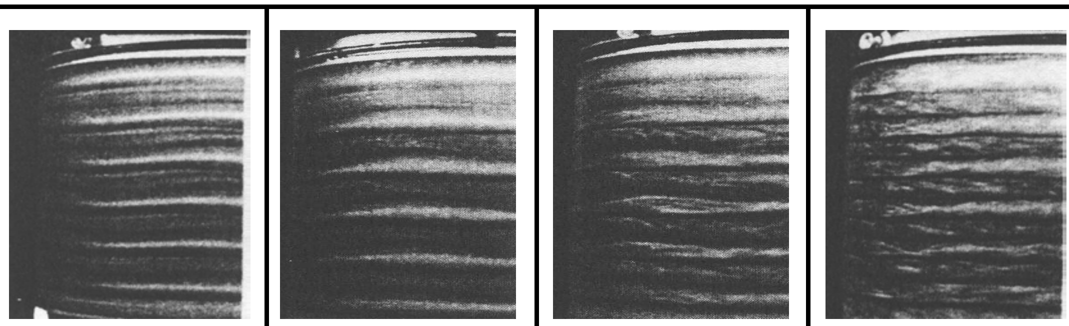

Wavy vortex flow Re = 250	Modulated wavy vortex flow Re = 1100	Chaos Re = 1510	Turbulence Re = 1800

Fig. 1.1 Modification of Taylor vortexes

2 The regimes of Taylor-Couette flow

Generally, most of the authors divide the Taylor-Couette flow into the following flow regimes, where Taylor´s number **T** as a criterion for change from one instable state to another is defined as:

$$T = \frac{\Omega_1 R_1 d}{\nu}\sqrt{\frac{d}{R_1}} \geq T_{c1} = 41{,}3 \qquad [1]$$

where: Ω_1 – angular velocity of the inner cylinder, R_1- radius of the inner cylinder, d-width of the gap, ν – kinematic viscosity

- ❑ Taylor vortices – TVF

The formation of non-periodical instabilities of the toroid axisymmetric Taylor vortex structure is given with a critical value of $\mathbf{T_{c1}}$. This instability will appear, if the following condition is fulfilled: $\mathbf{T > T_{c1} \geq 41.3}$.

- ❑ Wavy vortex flow – WVF

This flow appears after another increasing of rotation speed of inner cylinder that also means T. If the condition $T_{c2}>T_{c1}$ is fulfiled, the new wave moving vortices in a circumferential direction start to rise. Critical number T_{c2} lies approximately in interval $T_{c2} \approx (1{,}1 \div 100).T_{c1}$ and it depends both, on the geometry of the gap and on the properties of the liquid.

- ❑ Modulated wavy vortex flow – MWVF

At this state modulation of wave movement of vortices appears. The new second frequency of azimutal waves modulates the vortices. At this state gradually happens that toroid vortices extend and narrow down in a circumferential direction.

- ❑ Chaos - CHA

The chaotic regime is defined for Taylor number lying in interval $\mathbf{T \approx (100 \div 1000).T_{c_1}}$. It strongly depends on the ratio of radii η and experimental technique (if the rotation speed of the cylinder increases very quickly or very slow and equally, various structure of flow can be obtained). Additional **T** number increasing causes the rising of turbulent effects and disturbing the vortices.

These states of the flow can be observed only when the outer cylinder is standing. In case of counter-rotating or co-rotating two cylinders, different regimes of the flow can appear.

3 Numerical simulation of the flow instabilities [3]

Numerical simulations were based on experimental measuring carried out on the experimental apparatus in a laboratory of the department of hydromechanics and hydraulic systems. Firstly the laboratory conditions had been completed, i.e. the temperature and normal atmospheric pressure were measured. Before starting the experiment measuring it was necessary to mix the oil with aluminum powder. The oil mixing always took 3 minutes with angular velocity 500 min^{-1} of the inner cylinder. Thereafter the experiment was stopped to let the vortices disappear. Then the own measuring was started. The results of experimental measurement as boundary and physical conditions for later numerical simulation of the flow instabilities were used.

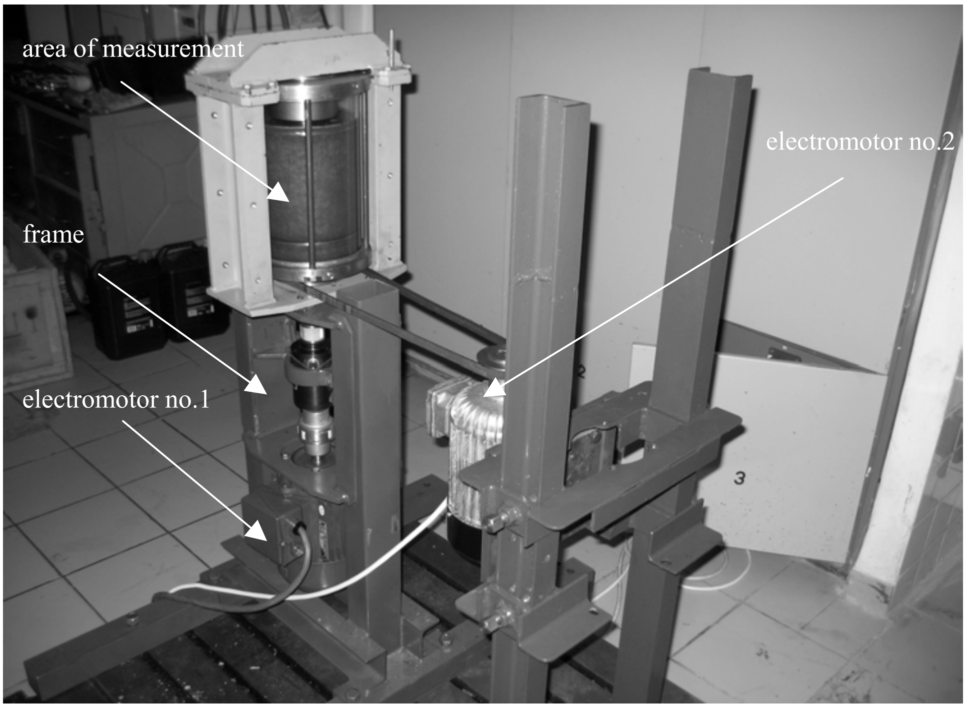

Fig. 3.1 Experimental apparatus

3.1 Physical properties of the used liquid (oil)

- density of oil $\rho = 876\ kg\ m^{-3}$
- temperature of oil T = 22,5 °C
- kinematic viscosity $\nu = 8{,}29 \times 10^{-5}\ m^2 s^{-1}$

3.2 Mathematical model of the flow

The flow between two cylinders has been classified as transitional flow between laminar and turbulent regime. That is why the laminar model of the flow had been applied. The LES model gave similar results, nevertheless it was more time consuming. Classical RANS models, e.g. k-ε model and others, are not suitable because of putting down the vortex structures, additionally the vortices were disappear after getting convergency. In the simulations the method of finite volumes had been applied [4].

3.3 Computational grid

The structured equable grid including 140 000 cells in a preprocessor Gambit had been made. Number of the cells in axial cross-section (see figure. 3.2) in 3D is following: direction i = 8 cells, direction j = 40 cells.

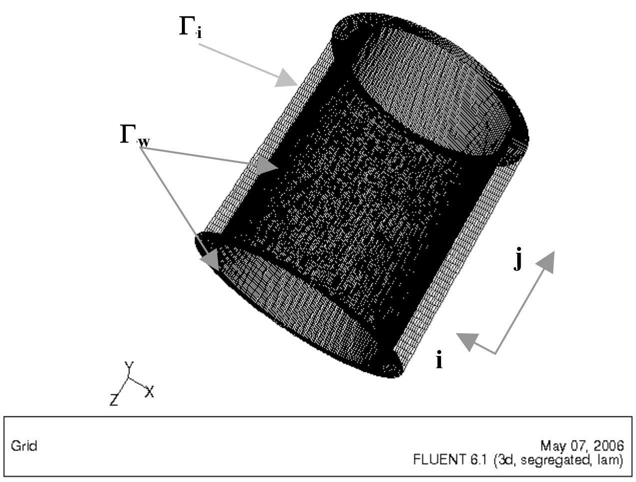

Fig. 3.2 Computational grid

3.4 Boundary conditions of the time dependent problem

The problem was solved as time dependent one with a time step $\Delta t = 0{,}001$s. The whole time of numerical simulations was from 60 to 80 s. The boundary conditions of 3D region were defined as follows (see tab. 3.1):

Boundary description		Description in Fluent 6	Boundary conditions
Endwall	Γ_w	WALL	rotation
Inner cylinder	Γ_w	WALL	rotation
Outer cylinder	Γ_w	WALL	rotation
Cross-section	Γ_i	INTERIOR	-

Tab. 3.1 Boundaries of 3D region

4. Evaluation of 3D numerical simulations

Applying software FLUENT all six kinds of the flow gained by physical experiment were successfully simulated. These kinds of the flow are the basic ones in the Taylor-Couette laminar system. For better understanding of flow vortex structures in the gap between two cylinders all successive pictures are always presented in iso-surfaces of tangential velocity component u_z and contours of axial velocity component u_r in axial cross-section [2].

I Regime of non-periodic flow

First basic regime simulated without any bigger troubles was a Couette flow. The region of this flow existence lies under the stable curve. Therefore there should not exist any vortex structures. This assumption is correct only for infinite cylinder length without endwalls of the cylinders. When running a real experiment or numerical simulation, however, these ideal conditions are not realizable. At first vortices rise near the endwall in the form of toroid vortices named Eckman vortices (see fig. 4.1 right). The middle of the region is free of the vortices structures.

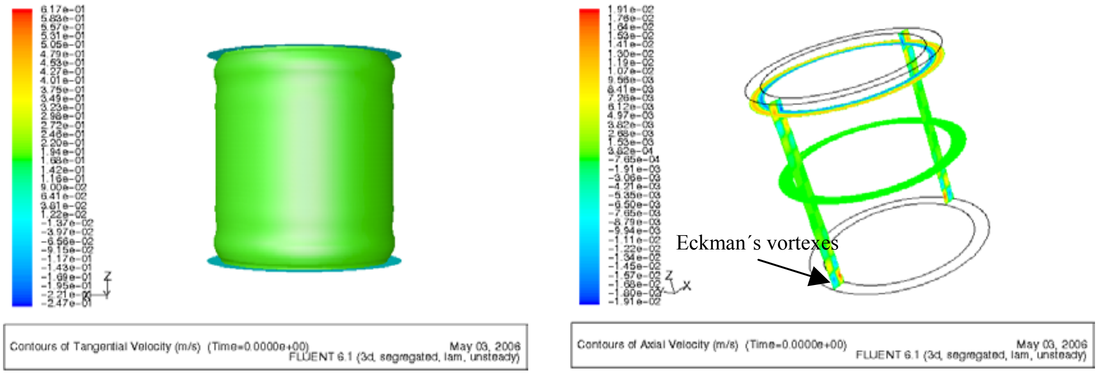

Fig. 4.1 Couette flow

The second case of the non-periodic successfully simulated flow was called Taylor´s vortex flow. In the figure 4.2 there is iso-surface of tangential velocity component is showed for velocity u_z = 0,27 m/s. There it is seen the characteristic shape of the vortex rings in this regime. They never change their shape and position in the region and are time independent. In the right figure 4.2 the behaviour of axial velocity component u_r in radial cross-section can be observed.

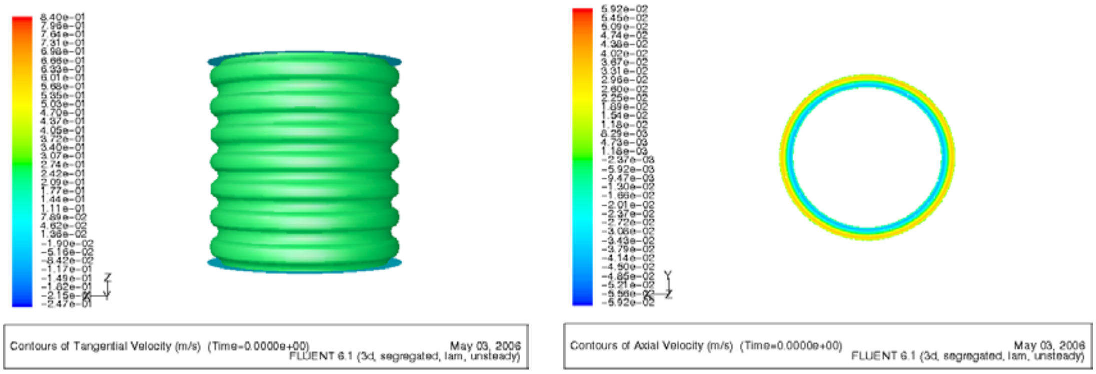

Fig. 4.2 Taylor vortices

II Regimes of the periodic flow

The first periodic flow is so called wavy vortex flow. Iso-surface for u_z = 0,3 m/s (fig. 4.3) displays visible wavy oscillating movement in the circumferential direction. The number of the waves in this direction can be read from the radial cross-section in the right part of the figure 4.3. The number of the floating waves is five. From the evaluation of axial velocity component there is noticed that wavy movement is completely symmetric and there are no irregularities of the flow.

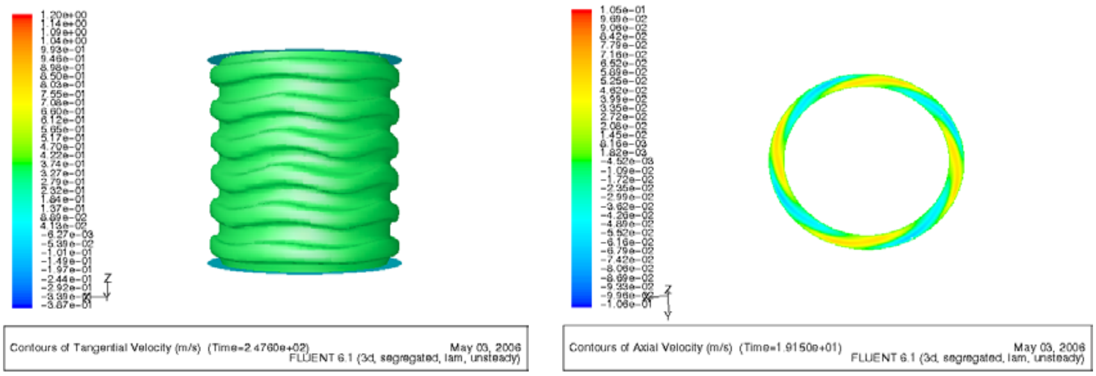

Fig. 4.3 Wavy vortex flow

Modulated wavy vortex flow was with great difficulties numerically simulated. In the fig. 4.4 the characteristic displacement of the circumferential wave peaks can be seen. That is the most important property for second modulation frequency that appears in this flow. For better understanding the picture is filled in arrows placed in the peak wave amplitude. Iso – surface of the flow was created for u_z = 0,1 m/s. In the radial cross-section one can notice the irregular form of the waves. This fact is again caused by second modulation frequency in the system. The number of the circumferential waves is seven.

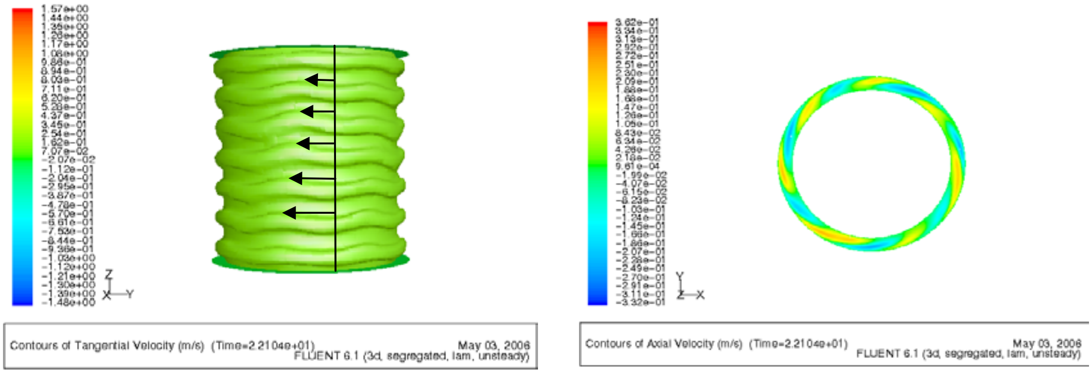

Fig. 4.4 Modulated wavy vortex flow

Finally two kinds of spiral regimes were numerically simulated. First one was named the simple spiral flow SPI characterized by spirals unrolled from bottom endwall. Second flow was created from two independent opposite moving spirals. Iso-surfaces of both spiral flow variants are showed in the figures 4.5 and 4.6. In both cases of the spiral flow the number of the spirals is very easily recognizable and it is two. The spirals are axially symmetrical.

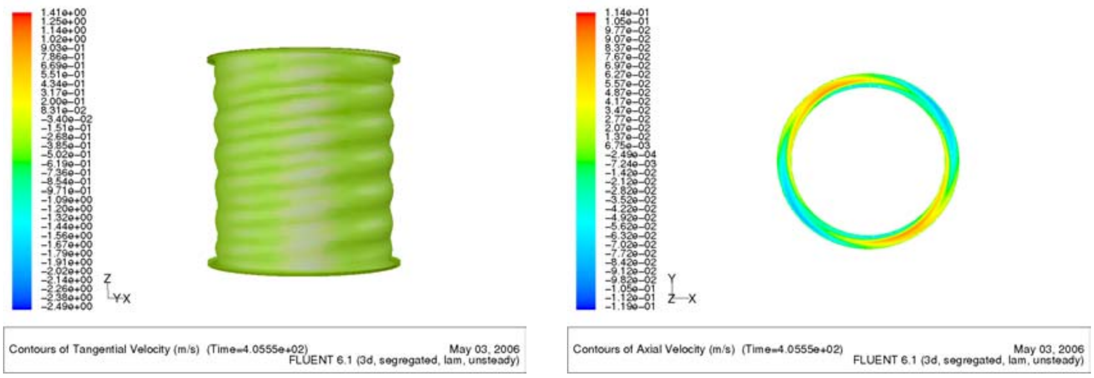

Fig. 4.5 Spiral regime (SPI)

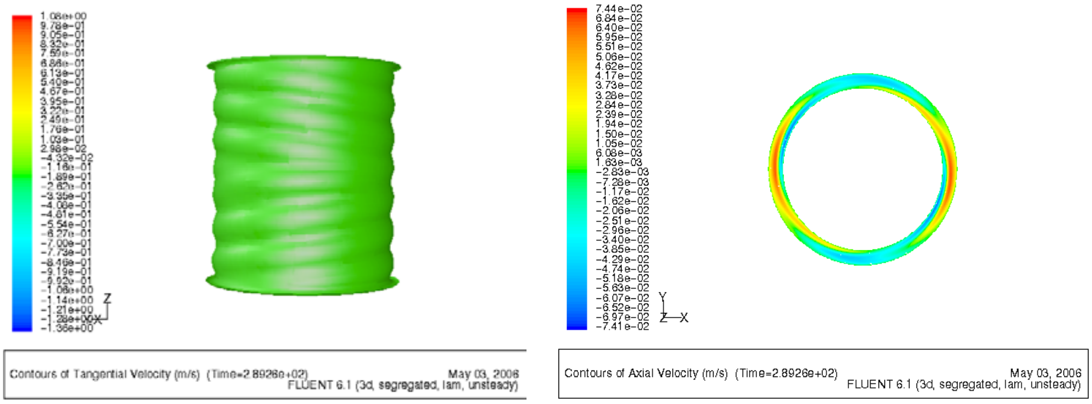

Fig. 4.6 Spiral regime (SSPI)

Summary

The results of the numerical simulation, thanks to a model of DNS, proved the possibility of solving even for such difficult nonlinear cases as for Taylor´s vortices and their higher modifications. As for the numerical calculation generally the flow structure reaching was influenced by choice of grid. From the visual point of view the excellent correspondence between simulations and experiment was reached.

Re**viewer:** Prof. Ing. Jaroslav Janalík, CSc.

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