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To cite this article: S Fialová *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **240** 062013

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Journal bearing with non-Newtonian fluid in the area of Taylor vortices

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Abstract: The constitutive relation for tension tensor of a non-Newtonian liquid is defined in the first part of the article. The solution will focus on identifying the interaction of the fluid with the rotating shaft. Journal bearing theory is well developed for Newtonian fluid and outside the area of Taylor vortices. In this work, the matrices of mass M, stiffness K and damping B will be determined outside and in the region of Taylor vortices. It turns out that the bearing properties can significantly differ in the area of Taylor vortices, where the M, B, K matrices are different from the area outside of Taylor vortices. However, the greatest importance of this work lies in the computational modelling of the flow of non-Newtonian liquid in the region of Taylor vortices and comparison with the results of the solution outside of this area. The solution will also be used for modelling of ferromagnetic and magnetorheological fluids, where their viscosity significantly changes depending on the value of the magnetic induction. Matrices M, K, B will therefore include the dependence on magnetic induction. Controlling the value of magnetic induction can significantly affect the dynamics of the pump rotors and water turbines.

1. Introduction

The study of instability in thin gaps containing magnetic fluid is presented in the work. The solution is done without considering the occurrence of cavitation, as there is no knowledge of cavitation in magnetic fluids. Based on the results obtained, experiment will be prepared for monitoring the occurrence of cavitation and the possibility of its computational modeling. In these liquids, both the viscosity and the initial voltage can be varied by the magnitude of magnetic induction. The flow in centric or eccentric gaps between the cylinders with no axial head, of which the internal cylinder rotates, is characterized by the transition from laminar to turbulent flow and the existence of different vortex structures. Their properties depend on boundary conditions (speed), geometry, network quality in numerical calculations and the choice of a mathematical model of flow. Another important parameters are the physical properties of liquids that predestine the behavior of the vortex structures.
The work is focused on vortex structures in thin gap with assumed application on journal bearings and seals. Particular attention is paid to the generation of Taylor vortices in a magnetic liquid. Its constitutive relations are based on a Bingham model of an incompressible liquid.

2. Constitutive equations of magnetic liquids

The basic issue of constitutive relations for ferromagnetic and magnetoreological liquids is elaborated particularly in works [11], [12], [13].
Other contexts are given in the literature review. Constitutive equations may include diffusion, chemical reactions, magnetization, polarization, rotation of magnetic particles and temperature. In summary, these phenomena are characterized by entropy production [14]. Technical applications can be carried out at

temperatures in the range (-500C, 2000C). However, it is necessary to take into account the value of the Curie temperature, which results in the loss of magnetic properties of the liquid.

Furthermore, it is necessary to consider the use of magnetic liquids for structural elements working under unsteady loads [2]. Time-dependent heating of the liquid occurs and thus there is a significant change of viscosity. These changes need to be taken into account in mathematical and computational modeling. These phenomena can occur especially in the design of hydrodynamic dampers but also of seals operating in unsteady load, where large volume of magnetic liquid is deformed without cooling.

To derive a mathematical model of magnetic liquid flow, it is necessary to know the final tensor of irreversible stresses Π_{ij} and the magnetic power F, which is applied by the magnetic field to the liquid. It is necessary to include this power in the Navier Stokes equations.

For a Newtonian incompressible liquid, the tensor of irreversible stresses is defined by:

$$\Pi_{ij} = \eta \left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} \right) = 2\eta v_{ij} \tag{1}$$

An analogous model to Bingham liquid is used for the magnetic liquid (Odenbach [11], [12], [13]):
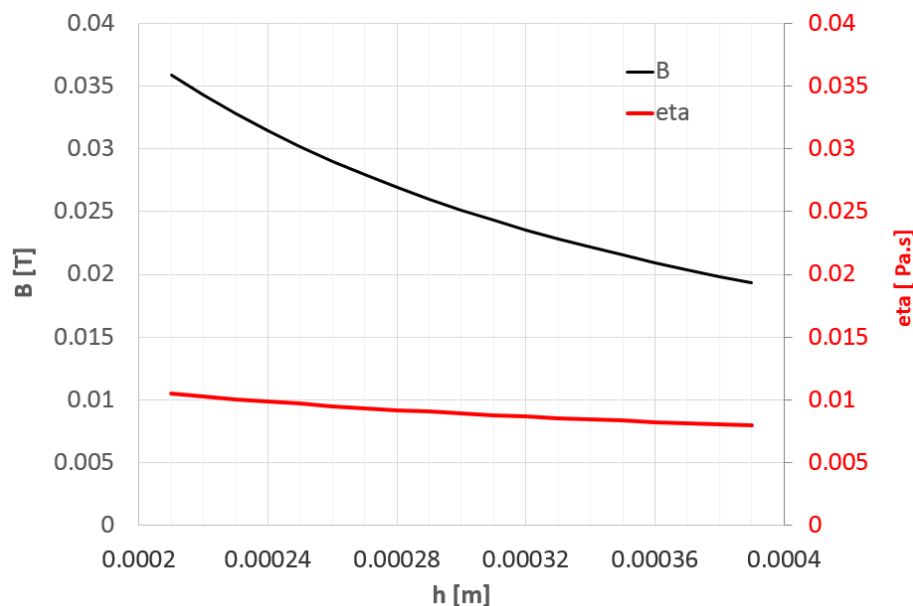
$$\Pi_{ij} = \Pi_{ij}^0 + 2\eta v_{ij} \tag{2}$$

Where the stress tensor Π_{ij}^0 and dynamic viscosity η depends on magnetic induction B. For the solution of liquid flow in thin films, the following material constants can be used:

$$B = k_B \mu_0 \mu_r \frac{I}{h(t)} \tag{3}$$

where k_B is a constant, depending on the type of magnetic liquid and the thin gap geometry, μ_0 is the vacuum permeability ($4\pi \cdot 10^{-7}$ Hm^{-1}), μ_r is the relative permeability of the magnetic liquid, I is the current, h is the width of the liquid layer gap, generaly dependent on time t. According to Radionov [15], the following simplified relationship for the viscosity of the magnetic liquid can be used:

$$\eta = \eta_0 \left(1 + 50\sqrt{B} \right) \tag{4}$$

B is entered in Tesla units. For constant gap width, the magnetic induction is constant $B = k_B \mu_0 \mu_r I$, the constant k_B is dependent on the type of magnetic liquid. If the width of the gap varies in the order of eccentricity, which is a tenth of the width of the gap, it is possible to determine the changes of the magnetic induction and consequently the viscosity, see Fig. 1:

Figure 1. Dependence of magnetic induction and viscosity on gap width for water

When dealing with a simplified task for thin gaps, it is:

$$\Pi_{ij} = \Pi_{ij}^0 + 2\eta v_{ij}$$

$$\Pi_{ij}^0 = \tau\delta_{ij}; \tau = kB^n \tag{5}$$

where $K = 1000$ and $n = 2$ are the material constants of the magnetic fluid that we will be dealing with.

3. Flow modes between cylinders

Most authors divide the Taylor-Couette flow in the gap between the cylinders from which the internal rotates into different current structures [1], [3], [4]. Here the criterion of transition from one unstable state to another when increasing the speed of the internal cylinder is the Taylor number that according to Schlichting can be expressed as:

$$Ta = \frac{\Omega R_i s}{v} \sqrt{\frac{s}{R_i}} \geq Ta_{C1} = 41{,}3 \tag{6}$$

where R_i is the radius of the internal rotating cylinder, v is the kinematic viscosity, Ω the angular velocity and s is the radial gap. For $Ta \geq 41{,}3$, Taylor vortices occur, which can be both stationary and non-stationary. This is represented not only in the radial but also in the axial component of the velocity, , see the so-called wave mode in Fig. 2c.

a) Couette flow   b) Taylor vortices   c) Wave mode
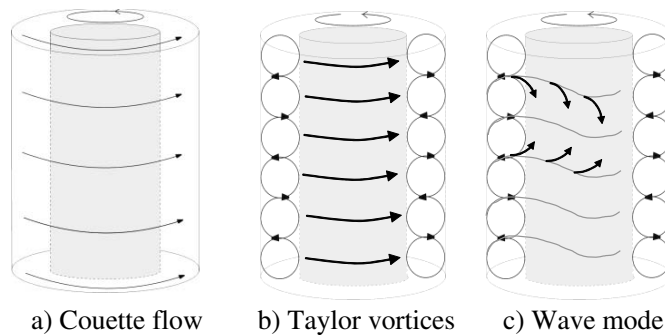
**Figure 2.**   Vortex structures between two cylinders

The vortex structures can be characterized as follows:

Couette flow - the liquid circulates in a tangential direction around the rotating cylinder, see Fig. 2 a)

Taylor vortices (TVF) – basic stationary flow is generated in the form of a circular, axially symmetric Taylor vortex of a stable character and is given by $Ta > Ta_{c1} \geq 41{,}3$ where Ta_{c1} is a critical value, see Fig. 2 b)

Wave Mode (WVF) - this flow begins to appear after a further increase in the speed of the inner cylinder and concomitantly the Taylor number, and for $Ta_{c2} > Ta_{c1}$ leads to waveforms of the vortices in circumferential direction. The critical number Ta_{c2} is approximately in the range $Ta_{c2} \approx (1{,}1 \div 100) * Ta_{c1}$, see Fig. 2 c). Another more complicated structure is a Modulated Wave Mode (MWVF). In this state, there is a modulation of the wave movement of the vortices in the circumferential direction, which is difficult to deal with and very unstable.

Turbulence (TURB) - Another increase in revolutions leads to turbulent effects which disturb the vortices, see Fig. 3.

| a) Couette flow | b) Taylor vortices | c) Wave mode | d) Turbulence |
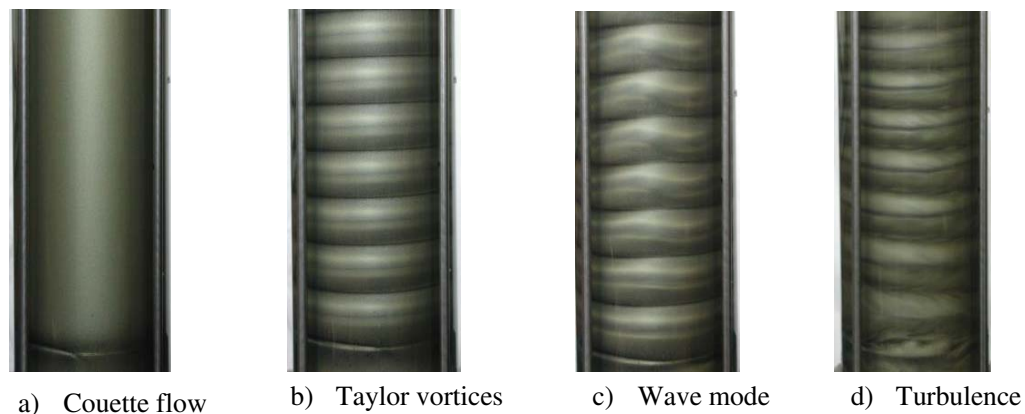
Figure 3. Physical experiment of vortex structures [5]

The Ta_{c1} value is theoretically determined for an infinitely long cylinder. Neither the physical experiment nor the numerical experiment can fulfill this assumption, so the value of the critical Taylor number slightly deviates. Experimentally and numerically, all possible vortex structures were solved in the workplace of TU Ostrava, see Fig. 3, [5], [6], [7], [8]. The above mentioned values apply to the center-mounted rotor and the cylindrical gap. With an eccentric rotor, the critical value of the Taylor number changes [9], [10].

4. Mathematical model

The mathematical model consists of the continuity equation and the equation of equilibrium. In the case of turbulent flow, it consists of Reynolds equations and equations for turbulent quantities. The physical properties of the liquid are considered as the following:

Option 1 - water with constant physical properties, Navier Stokes equations
Option 2 - magnetic fluid based on water with ferromagnetic particles, Bingham character.

The numerical calculation is only focused on the area of stable Taylor vortices corresponding to the scheme in Figure 3 b). The numerical simulation area was defined by the gap between the cylinders of the given geometry:

Inner radius r=0.025 m
Gap width s=0.0003 m
Length of cylinder l=0.003 m
Speed of the inner cylinder n=200, 400, 500, 600, 1000, 9000 rev.min^{-1}

The length of the cylinder was chosen with respect to a reasonable number of grid elements, the limiting surfaces were then fixed as symmetrical.
For the experiment, water (option 1) and water in a magnetic field (option 2) were selected as the flow medium.

4.1 Grid

A structured uniform grid was created, see Fig. 4. The number of elements was chosen so that each vortex was captured by at least 10 elements in each direction of the coordinate system. The number of grid points was around 600,000.
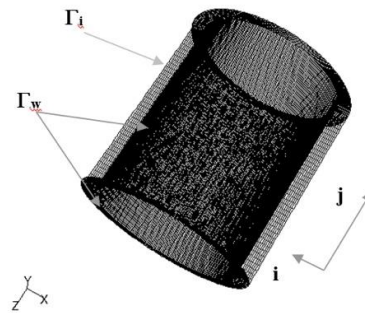
Figure 4. Computational grid

4.2 Numerical results

The Taylor number for the given speed ranged $Ta \in \langle 0; 775 \rangle$ and Reynolds number $Re \in \langle 200; 9000 \rangle$. This number characterizes flow as laminar, transitional between laminar and turbulent or turbulent. Based on the Reynolds number and based on the physical and numerical experiment performed at the workplace [6], a laminar model was chosen. This was because the classical two-equation models $k - \varepsilon$ undervalue the vortex structures down to complete zero. Only the LES model would be suitable for this calculation, but due to the time consuming simulations and the number of testing calculations, a laminar flow model was chosen.

Table 1 Taylor vortices - Option 1(laminar flow model)

r = 0.025 m; s = 0.0003m; l=0.003 m; ρ=1000 kgm^{-3} ; $\eta_{\text{ option 1}}$=0.001 Pa.s

n	*Ω*	*Ta*	*Re*	*N*	*$u_{tang\text{-}max}$*	*Mx*	*My*	*Mz*
[rev.min⁻¹]	[rad.s⁻¹]	[1]	[1]	[1]	[ms⁻¹]	[Nm⁻¹]	[Nm⁻¹]	[Nm⁻¹]
200	20,94	17,21	157,08	0	0,52	1,67E-11	1,67E-11	-2,11E-05
400	41,89	34,41	314,16	2	1,05	-1,31E-11	4,16E-11	-4,21E-05
500	52,36	43,02	392,70	4	1,31	-6,11E-11	1,93E-11	-5,25E-05
600	62,83	51,62	471,24	5	1,57	6,92E-10	-8,91E-10	-9,82E-05
1000	104,72	86,04	785,40	6	2,62	-1,55E-09	-2,54E-09	-2,20E-04
9000	942,48	774,32	7068,58	6	23,56	3,19E-07	5,71E-07	-7,49E-03

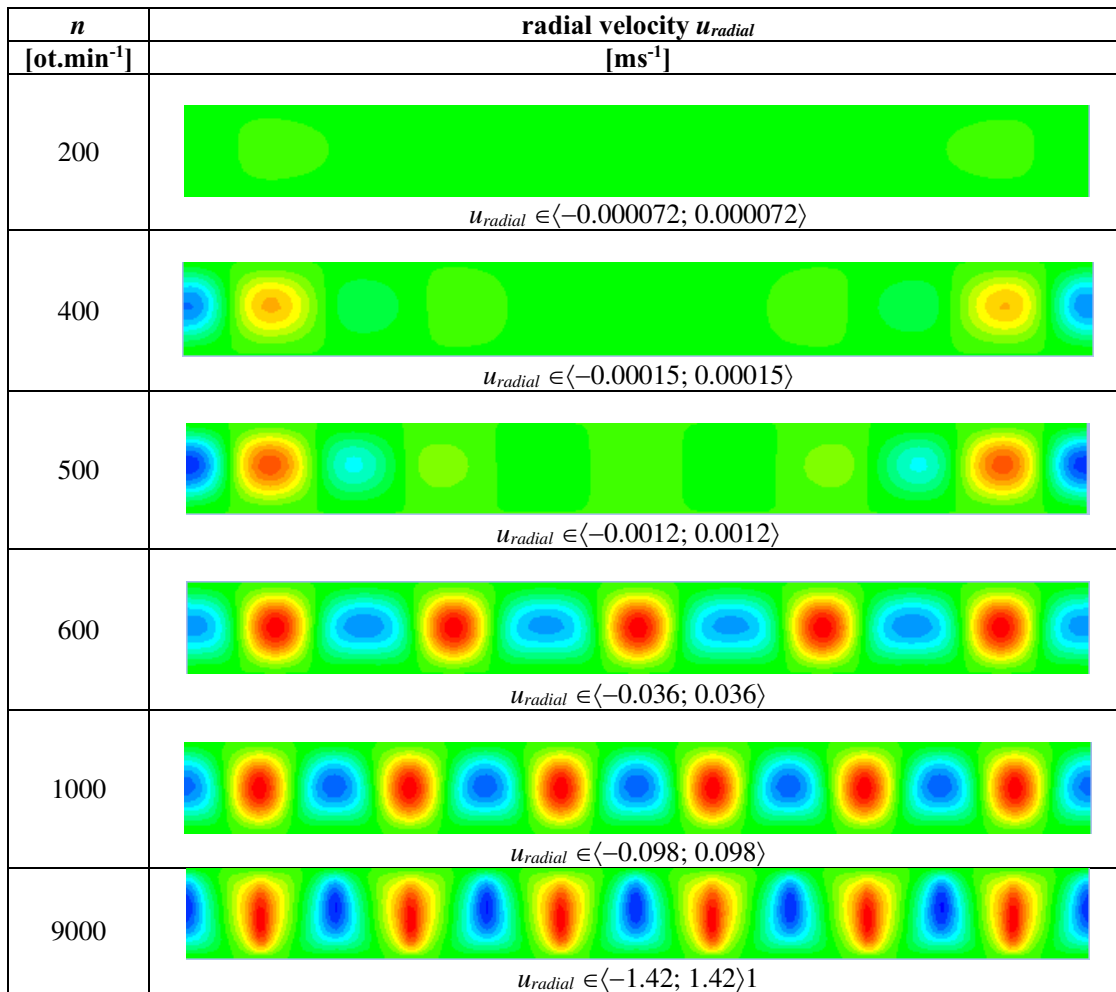Table 1 defines: *n* - internal cylinder speed, *Ω* - angular velocity, *Ta* - Taylor number, *N* - number of vortices, *Re* - Reynolds number, *$u_{tang\text{-}max}$* - tangential velocity, *Mx, My, Mz* are moments evaluated in the rotor axis with respect to the axes coordinate system and point as shown in Table 1. The number of vortices changes at different speeds, as shown in Fig. 5.

Table 2 Taylor vortices - Option 2

r = 0.025 m; s = 0.0003m; l=0.003 m; ρ=1000 kgm^{-3} η $_{\text{option2}}$=0.00903 Pa.s

n	*Ω*	*Ta*	*Re*	*N*	*$u_{tang\text{-}max}$*	*Mx*	*My*	*Mz*
[ot.min⁻¹]	[rad.s⁻¹]	[1]	[1]	[1]	[ms⁻¹]	[Nm⁻¹]	[Nm⁻¹]	[Nm⁻¹]
200	20,94	1,91	17,39	0	0,52	1,60E-10	1,74E-11	-2,11E-05
400	41,89	3,81	34,79	0	1,05	-1,12E-11	2,17E-10	-0,00045
500	52,36	4,76	43,49	0	1,31	6,26E-11	1,21E-10	-0,00055
600	62,83	5,72	52,18	0	1,57	2,71E-09	1,26E-09	-0,00064
1000	104,72	9,53	86,97	0	2,62	3,71E-09	2,40E-09	-0,00103
9000	942,48	85,75	782,76	5	23,56	-5,36E-07	7,19E-07	-0,02116

Figure 5. illustrates the number of vortices in case of option 1. The calculation converged well, as it is evident from the even distribution of the vortices. The same calculation was made for option 2, i.e. magnetic liquid. Above all, Taylor numbers are subcritical, and thus there is no Taylor vortex, only at 9,000 rpm Taylor vortices begin to form, see Table. 2.

n	radial velocity u_{radial}
[ot.min⁻¹]	[ms⁻¹]

| n [ot.min^{-1}]	radial velocity u_{radial} [ms^{-1}]
200	 $u_{radial} \in \langle -0.000072; 0.000072 \rangle$
400	 $u_{radial} \in \langle -0.00015; 0.00015 \rangle$
500	 $u_{radial} \in \langle -0.0012; 0.0012 \rangle$
600	 $u_{radial} \in \langle -0.036; 0.036 \rangle$
1000	 $u_{radial} \in \langle -0.098; 0.098 \rangle$
9000	 $u_{radial} \in \langle -1.42; 1.42 \rangle 1$

Figure 5. Vortex structures of option 1 evaluated by the contours of the radial velocity in the gap (red colour is maximum and blue colour is minimum)

The pressures, radial velocities and tangential velocities along the line in the center of the gap and parallel to the axis of rotation are shown in the following figures 6, 7, 8. In each case the first picture evaluates all the results, the values of the evaluated quantities are significantly higher for 9000 rpm and the other results are not visible. Therefore, in the other two figures, the same dependencies are displayed without values for 9000 rpm and values for option 1 and option 2 are separated.

It can be seen that the magnetic fluid significantly suppresses the vortex structures due to the significantly higher viscosity and increases the pressure drop across the gap. Except for 9000 rpm (see Fig. 6), a periodic pressure behavior occurs along the gap. Also, moments in the z direction order exceed the moments for a common liquid, i.e. water.

Radial velocity values are significantly smaller for magnetic fluid and Taylor vortices are negligible.

The tangential velocity exhibits periodic behavior for Newtonian fluid, with a non-Newtonian fluid showing a marked periodicity up to 9000 rpm.
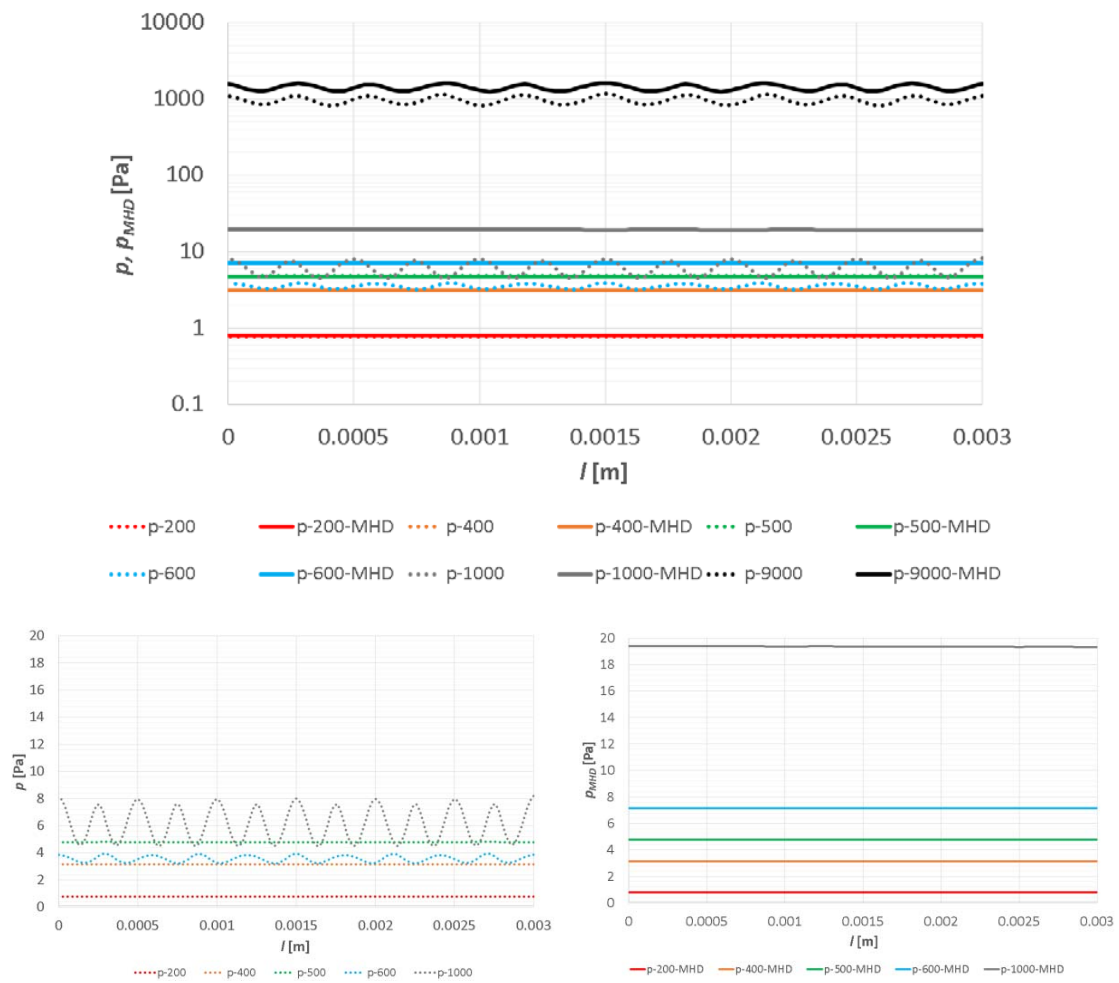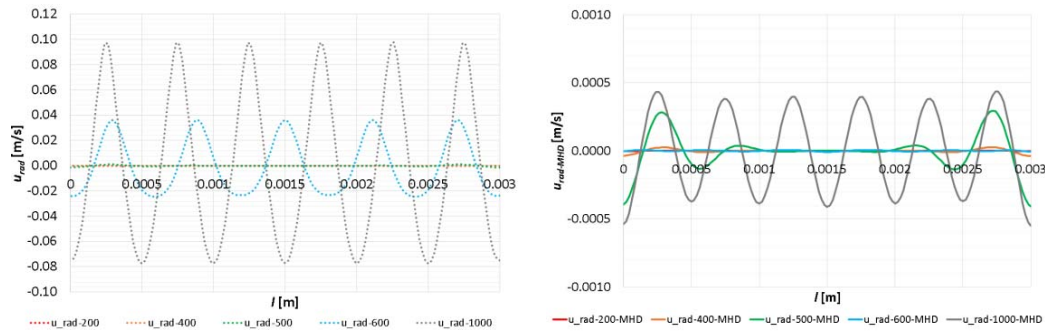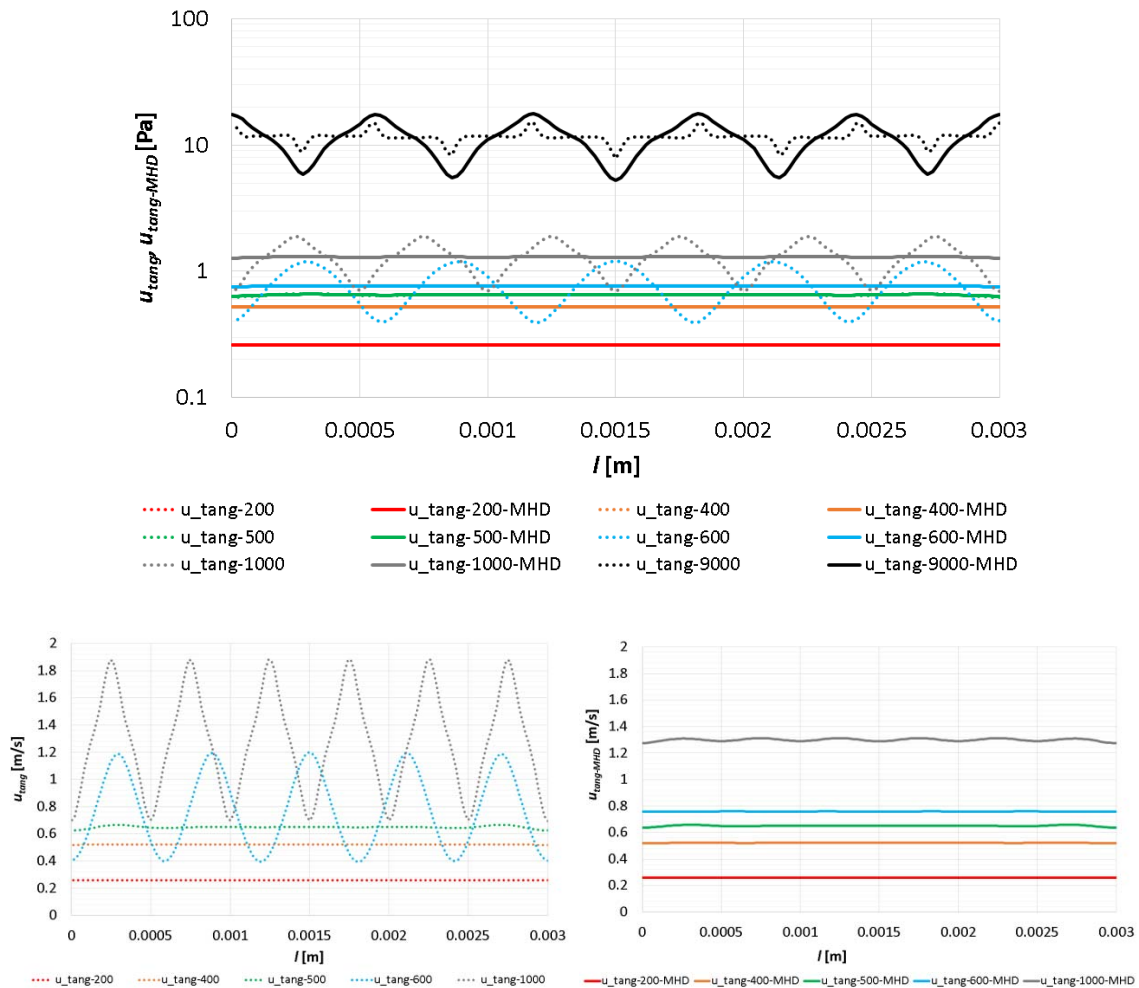
Figure 6. Pressure values in the center of the gap for option 1 and option 2.
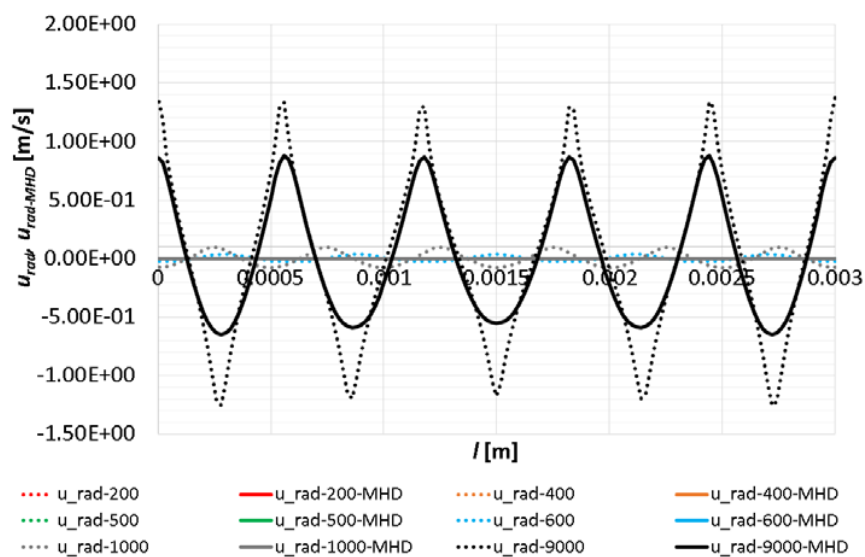
Figure 7. Radial velocity values in the center of the gap for option 1 and option 2

Figure 8. Tangential velocity values at the center of the gap for option 1 and option 2

5. Conclusion

Numerical modeling for geometries defined in accordance with the gaps on the journal bearings has shown that the stable region of the Taylor vortices exists for a wide range of speeds, only at the highest speed convergence problems occur. The number of vortices increases to a speed of 2000-3000 rpm. Then there is a decrease in the number of vortices, which may be due to poor convergence, since the

length of the cylinders is not an approximate integral of the number of vortices. For the transient flow between the laminar and the turbulent flow, it is convenient to use the laminar model. Turbulent two-equations models underestimate the curl and vortices are not created. Also the values of forces and moments are wrong. Vortex structures have a major influence on the dynamics of the rotor based on the principle of Taylor vortices.

Acknowledgement

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