VISCOUS FLUID MIXING IN AN ANNULAR SLOT

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1. Introduction

The problem of viscous fluid mixing is important for chemical technology and food industry. Molecular mixing (diffusion) takes too long, placing paddles of other bodies into the mixing area can lead to large mechanical torque due to drag force. We consider flows of a viscous fluid with admixtures in an annular slot and liquid is moved by rotation of the slot boundary. Such flows also take place in bearings [1]. Our aim is to observe and model different types of flow in an annular slot and analyze the impact of the flow type on admixtures transport.

2. Experiments

Our setup consists of two transparent coaxial vertical cylinders with a small gap between them. The inner cylinder is connected to a DC motor, the outer one is fixed (figure 1). We change the rotation rate varying the supplying voltage of the motor. Different liquids are placed into the gap to change viscosity. We examine glycerol, silicone oils, water. Particles visualize the flow and show its mixing ability.
For very viscous liquid, the flow is laminar. We placed particles in the middle of the gap. The particles move along circles. The inner cylinder rotates by several revolutions (2-3 times), and then we change the polarity of the motor and make the cylinder return to initial position. A similar experiment is described in [3]. We change the rotation rate, the number of revolutions. We capture the final position of the particles and measure their displacement.
If the liquid viscosity is not very high, the laminar flow is unstable and toroidal vortices appear. We observe this instability keeping constant rotation rate of the inner cylinder. For this experiment we put aluminum powder at the bottom before the rotation starts. The admixtures gradually go up and after some time fill the whole gap.
We draw some black and white stripes at the surface of the inner cylinder. While the gap gets filled with admixtures both types of stripes turn gray as seen from exterior. We take pictures and find the upper border of mixed liquid.

3. Simulations

We derived an equation to laminar flow between the cylinders. We found the similarity parameter α which is shoes the flow regime:

$$\alpha = \frac{\nu T}{R^2} \qquad (1)$$

where R is the inner cylinder radius, ν is the liquid kinematic viscosity, and T is a reference time.
We proved that for $\alpha >> 1$ the flow is quasi-steady, so it is can be returned to initial state applying proper boundary conditions.
We simulated non-steady laminar flow and checked our conclusions from the dimension analysis. Simulations showed that for finite values of α the flow never comes to the initial state.

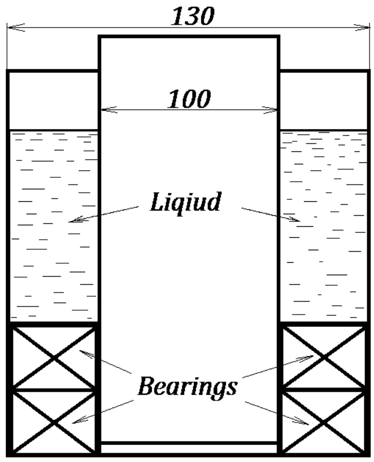

Figure 1 – The scheme of the setup.

For flow with vortices we simulated admixtures transport only, taking velocity field from literature [2]. We assumed that any particle has its own velocity and interacts with liquid by Stokes drag force. Due to inertia of the particles they travel toward vortex periphery and can jump from one vortex to the other. We estimated the probability of this jump and simulated particles migration from the lowest vortex upwards.

4. Conclusions

Three different regimes of fluid flow were detected: reversible, which is observed for slow rotation of the cylinders and a smooth change in the direction of rotation, an irreversible laminar one when viscous forces dominating over inertial, but with sharp accelerations, and vortex with dominance of inertial forces over viscous ones. The value of the parameter α determines the flow regime. We summarize them and their properties in Table 1.

Table 1 – Types of the flow and their properties

Regime	α	Mixing
Reversible	$>> 1$	No
Irreversible laminar	~ 1	Within thin layer
With vortices	$< \alpha_{crit}$	Quick within vortex cell, slow migration through the whole gap

5. References

[1] Peter R. N. Childs «Rotating Flow» Elsevier, 2010

[2] Taylor, G. I. (1923). «Stability of a Viscous Liquid contained between Two Rotating Cylinders». Phil. Trans. Royal Society A223 (605—615): 289—343.

[3] https://www.youtube.com/watch?v=_dbnH-BBSNo