NUMERICAL SIMULATIONS OF CONSTANT VELOCITY SQUEEZE FLOW

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The paper is dedicated to the investigations of purely viscous fluids in constant velocity squeeze flow, between two parallel disks. The influence of fluid rheological properties on normal force distribution and the interpretation of the obtained results is investigated. The analysis includes both experimental and numerical investigations. All results are being compared with theoretical predictions in order to establish a procedure to determine fluid viscosity by using an inverse approach of the theoretical formulation of the normal force. A good correlation between theoretical, numerical and experimental values proves the validity of this study.

Keywords: Fluid mechanics, squeeze flow, newtonian fluids, rheology , numerical simulations

1. Introduction

Squeezing phenomenon describes the large deformation (or a flow) of a soft material (or a viscous fluid) between two solid surfaces approaching one to each other. During squeezing the gap between surfaces is changing in time and the sample is ejected from the gap. In many applications the gap is small in comparison to the other dimensions of the surfaces, in particular discs diameters (see Fig. 1) so squeezing flow is mainly associated to thin film hydrodynamics, lubrication and rheology of complex fluids. Its application can be found in various domains like engineering, lubrication, thin films, biofluids dynamics and rheometry [2].

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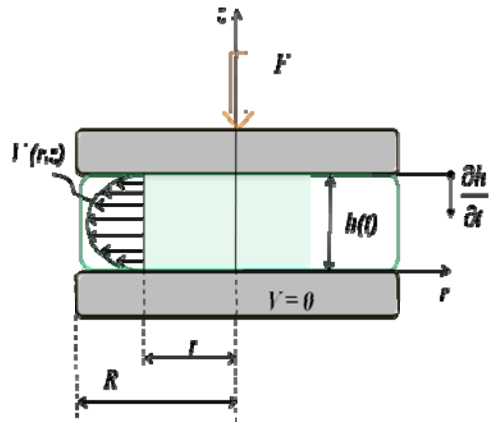

Fig. 1. Simple squeeze of a pure viscous fluid between parallel surfaces.

The motion has both extensional and shears components, but in the limit of small gap and low relative velocity the shear is considered dominant. For a given axial-symmetric geometry, the approaching velocity, $V = - \partial h/\partial t$ and the thrust force F are the only parameters to be determined and controlled (Fig. 1).

Therefore, squeezing flow is often used for the determination of rheological proprieties of different types of materials, from pure viscous fluids to perfect elastic bodies and between, visco-elastic and visco-plastic (yield stress fluids) samples. The thrust force is being given by the following expression, derived from Navier-Stokes system of equations [1-4]:

$$F(t) = -\frac{3\pi\eta_0 R^4}{2h^3}\frac{\partial h}{\partial t}. \tag{1}$$

The present study is dedicated to the analysis of pure viscous fluids behavior during simple squeeze flow and the possibility to extract information about material behavior from the obtained data.

Investigations were carried out on three different Newtonian fluids with different testing temperatures and squeezing velocities. The experiments were carried out on a stress controlled *Physica MCR 301 Rheometer* and numerical simulations are performed with the numerical solver implemented in the Fluent CFD software, using two numerical solutions.

2. Experimental setup

The study was performed on a ***Physica Anton Paar MCR 301*** using parallel plate geometry. The experimental setup allows free surface visualization during experiments and a temperature control trough an incorporated Peltier system that assures the lower plate temperature (only on the lower plate).

The upper plate diameter (43 and 50 *mm*) gives the active contact surface with the sample. The rheometer is controlled trough dedicated software, Rheoplus [10]. The sample is placed on the lower plate which is fixed. The upper plate is descended to a position of 1 mm (mineral oil, glycerin) or 2 *mm* (honey) giving the initial film thickness.

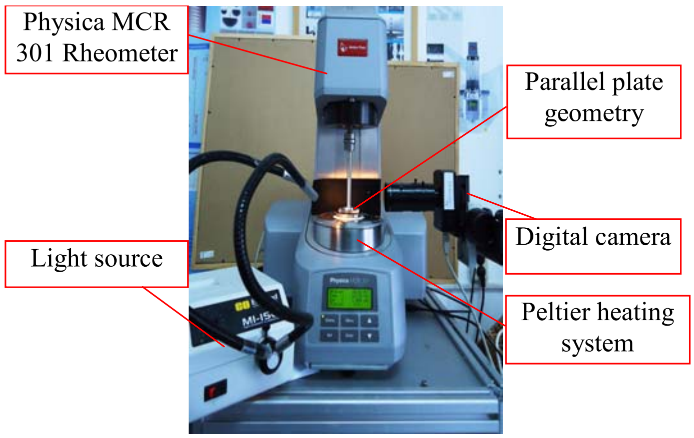

Fig. 2. Experimental setup.

The test starts when the upper plate descends with a given velocity and the fluid film starts deforming and being squeezed out of the initial gap. Normal force is measured on the upper plate, with a precision of 0.02 *N*, as a response of the fluid at the applied strain.

Table 1

Testing parameters for the analyzed Newtonian samples

Fluid Sample	**h [mm]**	**V [mm/s]**	**T [^{o}C]**
Mineral Oil	1	{0.01; 0,1; 1}	{1, 10, 20, 30}
Glycerin	1	{0.01; 0,1; 1}	{10, 20}
Honey	2	{0.001; 0.01; 0.1}	{5, 10, 20, 30}

The investigations were performed for three Newtonian fluids with different viscosity coefficients: a mineral oil sample, a glycerin solution and honey. Testing parameters like initial film thickness *h*, upper plate velocity *V* and temperature *T* are presented in Table 1 for each type of fluid.

Viscosity coefficient plays a very important role for the determination of analytical predictions and the interpretation of experimental results. Hence, multiple dynamic and simple shear tests were performed in order to determine samples viscosity coefficients and their temperature dependence. A small variation of viscosity at constant temperature was found for all the samples. For example, in the case of the mineral oil, at 20 degrees, the viscosity coefficient varies on a domain between 0.09 and 0.15 *Pa s* (see Fig. 3).

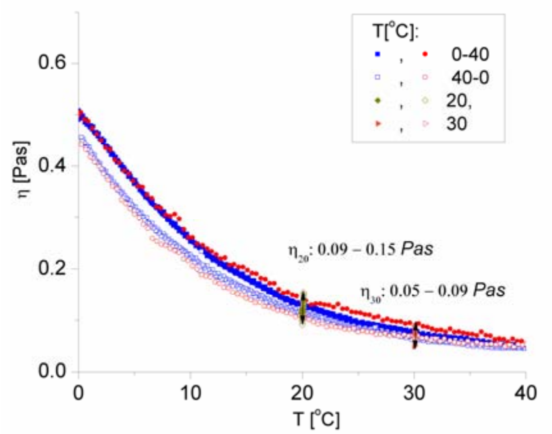

Fig. 3. The dependence of viscosity coefficient on the temperature variation.

This behavior is accentuated once the temperature value descends and it may due to a temperature gradient which may appear in the gap, between rheometers plate. Even though film thickness is small a temperature gradient may occur since the temperature is controlled only on the lower plate.

3. Numerical Simulations

The motion was modeled numerically using CFD commercial code *Ansys Fluent,* for *Newtonian* incompressible fluids using different approach: either a unsteady quasi-static approximation either a unsteady solution with deformable mesh option (by imposing a displacement profile for the upper wall, corresponding to the upper disk of real geometry). The flow is considered homogeneous, laminar, isothermal, isochoric and developed in a 2D axial-symmetric configuration. A dedicated pre-processor, *Gambit*, is used for geometry construction and meshing.

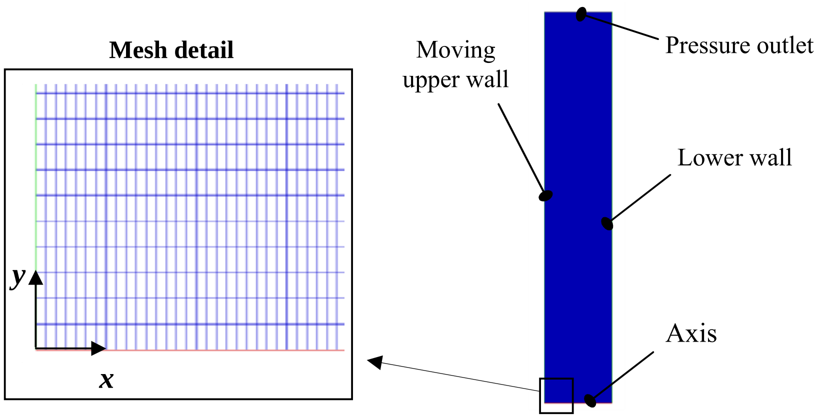

Fig. 4. 2D axial-symmetric squeeze flow geometry used for the numerical simulations.

The quasi-static approximation imposes the construction of a single geometry for every film height. Computational domains are meshed using quad elements, and in the case of second numerical solution the option of deformable mesh is being applied for the whole domain (see Fig. 4). In order to decrease computational time geometry dimensions were reduced by comparison with the real one (R_{real} = 21.5 *mm* and $R_{simulation}$ = 5 *mm*), hence, a corresponding scale factor was applied for the force distribution.

4. Results and discussions

In the case of numerical simulations, a good correlation has been found between the two numerical solutions (i.e. quasi-static and unsteady deformable mesh respectively), for three different squeezing velocities: 0.01, 0.1 and 1 *mm/s* (See Fig. 5). The computational time is longer in the case of using the deforming mesh solution.

The experimental results were compared with both theoretical predictions and numerical force distributions. Taking into account force sensor limits, we have established a validity domain of the experimental values depending on film thickness. The maximum and minimum film thickness for which we obtain a linear coherent force distribution are different for each sample accordingly to the force magnitude (dependent on viscosity).

For example, in the case of mineral oil, for an upper plate velocity of 0.01 *mm/s* and different temperature values 5- 30 ^oC, the maximum film thickens for which force values can be measured is 0.1 *mm*. Also, force size is limited at the range of 0.01÷ 50 *N* due to the force transducer measuring domain (see Fig. 6)

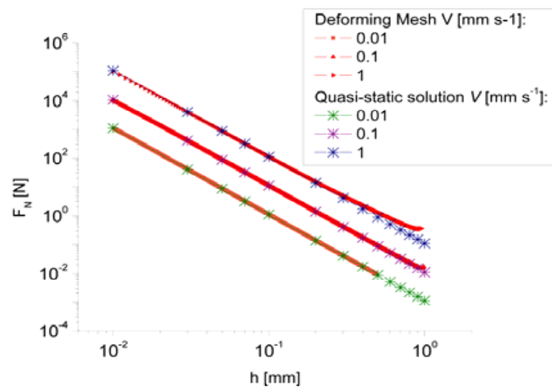

Fig. 5. Normal force distribution for mineral oil sample obtained from numerical simulation of the real flow at different squeezing velocities.

The inferior limit of the measuring domain (small film thickness) may be influenced by many factors like: fluid viscosity, upper plate velocity and displacement, temperature and parallelism nonconformity [2, 5, 8, 9].

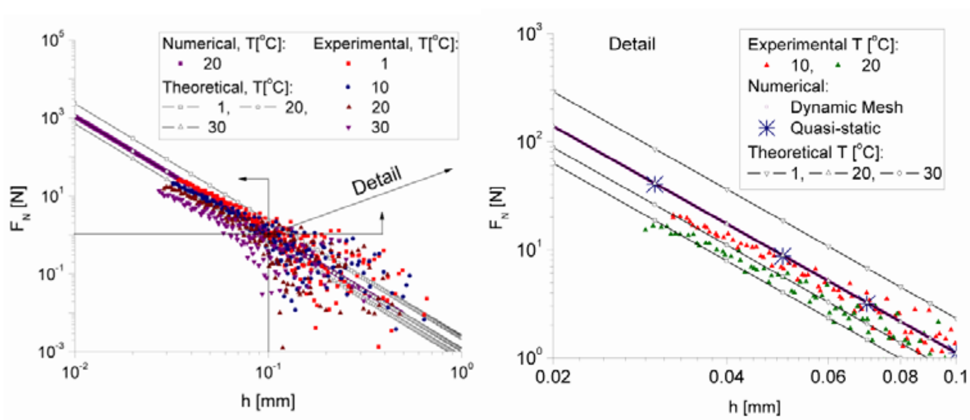

Fig. 6. Experimental, numerical and theoretical distributions for mineral oil sample with different temperature values and V = 0.01 *mm/s*.

However, the inferior limit of measuring domain decreases with velocity.

For a temperature of 10 and 20 ^{o} *C*, experimental values are smaller than theoretical and numerical predictions, but their distribution is linear as expected in the case of Newtonian fluids. Even at higher velocities (*V* = 0.1 and 1 *mm/s)* the results present the same linear distribution and are well correlated to the theoretical predictions.

Dimensionless representations

The dimensioneless expression of thrust force is given by:

$$\overline{F} = \frac{\left|\overline{F}\right|}{\eta R V} = -\frac{3\pi}{2} \cdot \overline{h}^{-3} \tag{2}$$

where

$$\overline{h} = \frac{h}{R^2} \tag{3}$$

One has to notice that the variation of viscosity coefficient (Fig. 3) at constant temperature brings an intriguing question about the value which may be used when processing experimental values. Experimental results were processed using different values of viscosity (in the range indicated in Fig. 3), proving the dependence of dimensionless force on the viscosity value. Consequently, the experimental values were corrected using an average value of viscosity in this range, this procedure being applied for all the samples (Fig. 8 and Fig. 9).

For a small squeezing velocity the difference between experimental and theoretical prediction is still present, yet for bigger velocities a good correlation is observed. In addition the experimental and theoretical predictions are corresponding for a certain thickness domain (Fig. 9).

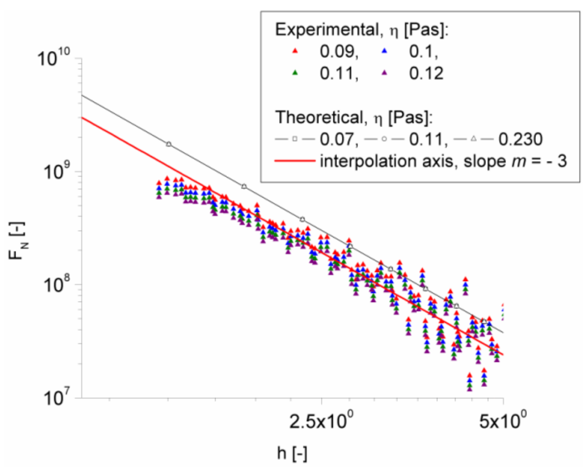

Fig. 7. Dimensionless force variation along with film height for constant velocity (V = 0.01 mm/s) squeeze flow of mineral oil at a constant temperature T =20°C. Plotted values are obtained for diferent values of viscosity coeficient in a range of 0.09 and 0.15 Pas (See fig 3).

At small film thickness a non-linear force distribution is been observed especially in the case of glycerin and honey samples. For the glycerin sample this non-linear behavior is accentuated for a squeezing velocity of 0.01 *mm/s*.

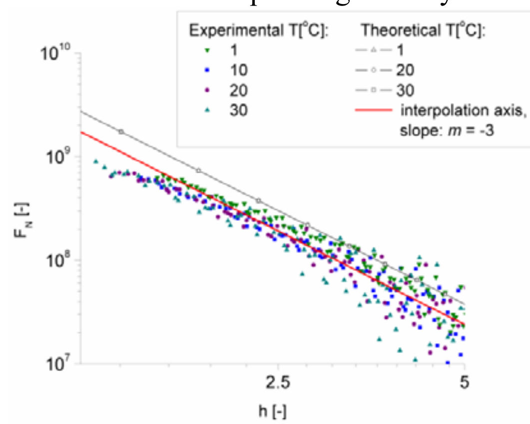

Fig. 8. Dimensionless force variation along with film height for constant velocity (V = 0.01 mm/s) squeeze flow of mineral oil for various testing temperatures.

Once with increasing velocity value the non-linear behavior diminishes and experimental values are bigger than theoretical ones probably due to inertial effects and free surface evolution during the test.

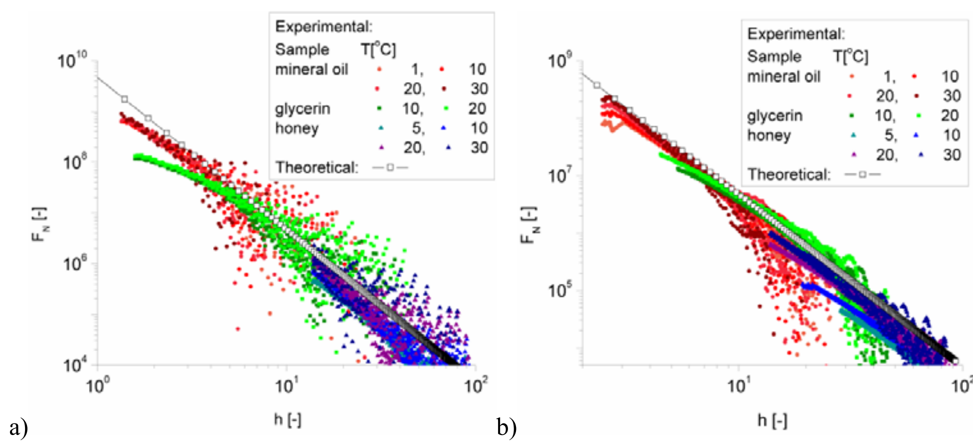

Fig.9. Dimensionless normal force distribution: oil, glycerin and honey samples, theoretical and experimental results for different temperatures and squeezing velocities of 0.1 *mm /s* (a) and 0.1 *mm/s* (b).

Experimental results coincide with the analytical expression at medium gaps. For a small film thickness range one observes a noticeable deviation of experimental values from the analytical force distribution. This deviation can be explained by the influence of plate's deviation from parallelism [2, 6, 8], the influence of inertial effects [2, 6, 9] and free surface evolution [2, 5] during the tests. At large gaps the spreading of measured data is generated by the low sensitivity of the normal force transducer. Free surface evolution was observed during experimental investigations for all analyzed samples. Considering that the samples are pure viscous fluids it is interesting to notice that the free surface differs even from the initial position, before starting the squeezing motion. The free surface has different initial shapes and different evolution during the squeeze for each fluid (see Fig. 10) as a function of wetting angle and the magnitude of surface tension.

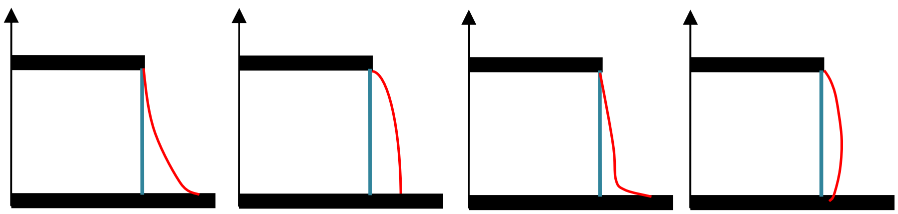

Fig. 10. Different forms of free surface observed during experiments.

The accumulation of material at the edge of the gap is present for all analyzed samples. This behavior is accentuated for higher squeeze velocities and it can lead to a pressure drop near by the end of the gap. Hence, the deviation of experimental force distribution from the theoretical one, in the range of small film thickness may be due to the free surface evolution and the so called “end effects”.

In order to improve modeling of squeeze motion it is necessary to take into account particular fluid properties like surface tension and contact angle and also the wettability properties of the solid surfaces defining the gap.

5. Conclusions

This paper is dedicated to the investigation of constant velocity squeeze flow motion of pure viscous samples. The study includes a complex analysis of the phenomenon trough analytical, numerical and experimental methods. For all analyzed samples (mineral oil, glycerin and honey) experimental measurements have been performed at different temperatures and squeezing velocities. The study was completed trough numerical simulations and a correlation between theoretical formulation and experimental data (dimensionless formulation) was shown.

The study proves the value of numerical solutions for the analyzed constant velocity squeeze flow in the case of viscous fluids. Due to the correlation of the two numerical solutions (fixed mesh, respectively dynamic deforming mesh) we conclude that a quasi-static approximation is more appropriate when analyzing this type of motion by taking into account the reduced computational time of this numerical solution. A good correlation has been found between analytical, numerical and experimental force distributions with the exception of small film thickness range, where a deviation of experimental values from the analytical force distribution was found. This deviation can be explained by the influence of plate's lack of parallelism, the presence of inertial effects and free surface evolution during the tests. The influence of viscosity coefficient is analyzed and its influence on processing experimental data is emphasized.

Free surface shape evolution during the motion also influences force distribution in the range of small film thickness, is limited by the force transducer sensitivity and the working range gap. In conclusion a complete description of the real flow takes into account particular fluid properties (surface tension, contact angle), the wettability properties of the solid surfaces, inertial and temperature effects. All this influences can be investigated numerically so it is expected to obtain the correction coefficients of analytical expression.

Acknowledgements

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