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ON THE SELECTED RHEOLOGICAL PARAMETERS OF EDIBLE VEGETABLE OILS

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Abstract

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The rheological parameters of 5 edible vegetable oils have been determined. In particular: rapeseed oil, corn oil, sunflower oil, olive oil and pumpkin oil. The oils exhibited Newtonian behaviour above about 10 s^{-1}. The lower rates of shear demonstreated non-Newtonian behaviour. The analysed oils were found to be, in accordance with predictions, time-independent. The flow curves of all tested oils have been plotted and fitted in satisfying agreement with simple mathematical model. Received data have been used for numerical simulation of inlet effect in laminar flow between two parallel plates. The simulation of velocities and fluid pressure have been created.

vegetable edible oils, rheology, viscosity, modelling, numerical simulation

Vegetable edible oils are essential ingredient of most of national cuisines. Their physical and chemical properties highly influence the quality of final product as well as the processing procedures. Irreplaceable role is attributed to rheological properties. Rheological properties are very often determined in order to define the behaviour of solutions, suspensions and mixtures. Edible vegetable oils are a typical example of such material. The basic parameter, obtained during rheological study of liquid foods, is viscosity, used to characterise the fluid texture (Alonso et al., 1990; Rao, 1977; Rao, 1992). As an example of application, chemical exchanges in foods frequently occur with time and may be studied by rheological methods. Another important factor is temperature, which frequently occurs in rheological equations (Rosen and Forster, 1978). In the case of vegetable oils, viscosity increases with chain lengths of triglyceride fatty acids and decreases with unsaturation, which menas decreases with hydrogenation. So, viscosity is a function of molecules' dimension and orientation (Moretto and Fett, 1988; Santos et al., 2004). Physical properties (including viscosity) of pure triglycerides of short chain, have been evaluated in preceding studies (Eiteman and Goodrum, 1993; Eiteman and Goodrum, 1994; Goodrum and Eiteman, 1996). These studies have tried to develop models, to the use of oils with triglycerids to substitute as a diesel fuel. Studie about rheological properties of binary mixtures of triglycerides have been published (Goodrum, Geller and Lee, 1998; Valeri and Meirelles, 1997). These investigations have been trying to understand how these compounds interact among them, and how triglyceride chain length affects physical properties of edible oils. Studies related to properties of short chain triglycerides, in pure state and simple mixture, can be very useful in the development of different valuable products. On the other hand, natural vegetable oils are not composed of pure triglycerides or simple binary mixtures of triglycerides. They are complex mixtures of many triglycerides with different chain lengths. Recently, physical properties of short chain triglycerides, obtained from a natural source, were evaluated (Geller, Goodrum and Knapp; 1999). Rheological properties of two complex mixtures of triglycerides of short chain were experimentally determined ina temperature range of 25–80 °C (Geller and Goodrum, 2000). The objective of this work was to evaluate selected rheological properties of commercial edible oils (rapeseed, corn, sunflower, olive and pumpkin), to compare values of their viscosities under different shear rates and describe their flow curves. Indispensable part of this work is creating of simple models to fit the flow curves and finite element models of oil velocity and pressure.

MATERIALS AND EXPERIMENTAL PROCEDURE

The edible vegetable oils (commercially distributed in the Czech Republic) have been monitored. In particular: rapeseed oil, corn oil, sunflower oil, olive oil and pumpkin oil. The oils have been stored in a original producer's containers under room temperature.

The oil density had to be determined first. The standard weight/volume procedure was selected and performed. The density values are listed in Table I.

I: *Densities of the tested oils*

Oil type	Rapeseed	Corn	Sunflower	Olive	Pumpkin
Density [kg.m^{-3}]	924	926	918	922	912

The procedure of sample preparation for viscosity measurements corresponded to a typical sampling procedure. Since the oil was assumed to be a Bingham fluid (Santos et al, 2005) and creating of internal textures was not expected, no special pre-experiment treatment was performed. The adequate volume (10.4 ml) of oil was put into the apparatus cuvette (without previuous mixing or any other kind of preparation) and the experiment was performed.

There are several methods to measure dynamic viscosity of fluid or semi fluid materials and different geometries may be utilized: concentric cylinders, cone and plate, and parallel plates.

Presented data have been obtained from measurements performed on laboratory Anton Paar DV-3 P Digital Viscometer which is designed to measure dynamic viscosity, shear stress (τ), and shear rate ($\dot{\gamma}$). The DV-3 P is a rotational viscometer, based on measuring the torque of a spindle rotating in the sample at a given speed. Shear stress is expressed in [g/(cm.s^2)], shear rate in [s^{-1}] and viscosity in [mPa.s] speed of spindle in revolutions per minute [rpm]. The experiments have been performed with use of a small sample adpter with TR9 spindle. The small sample adpter permits more accurate measurements than standard device equiped with another spidle type. Also the measuring range of viscometer can be extended to lower values. This extension is in particular advantageous when measuring materials where low shear rates data are required. Due to the parallel cylinder geometry shear stress, except other values, can be determined.

RESULTS AND DUSCUSSION

Presented study was done to find the rheological data of examined vegetable oils, to verify or contradict the influence of sharing rate on viscosity of oil under given (21 °C) temperatue, to plot the dependence curves of shear stress on shear strain rate, make a simple suitable model of such dependence and to use obtained information for solution of oil flow between two parallel plates and evaluate the inlet effects in laminar flow.

Each oil was examined in details and selected rheologicsl data are listed in Tab. II. The steps between single shear rates were smaller than it appears in Tab. II and owing to conciseness, only selcted representing values were featured. Individual measurements were repeated 3 times and average values were used for later calculations. It is important to note that measured values exhibited very low variability in single corresponding measurements. In no case the deviation value exceeded relevant limit.

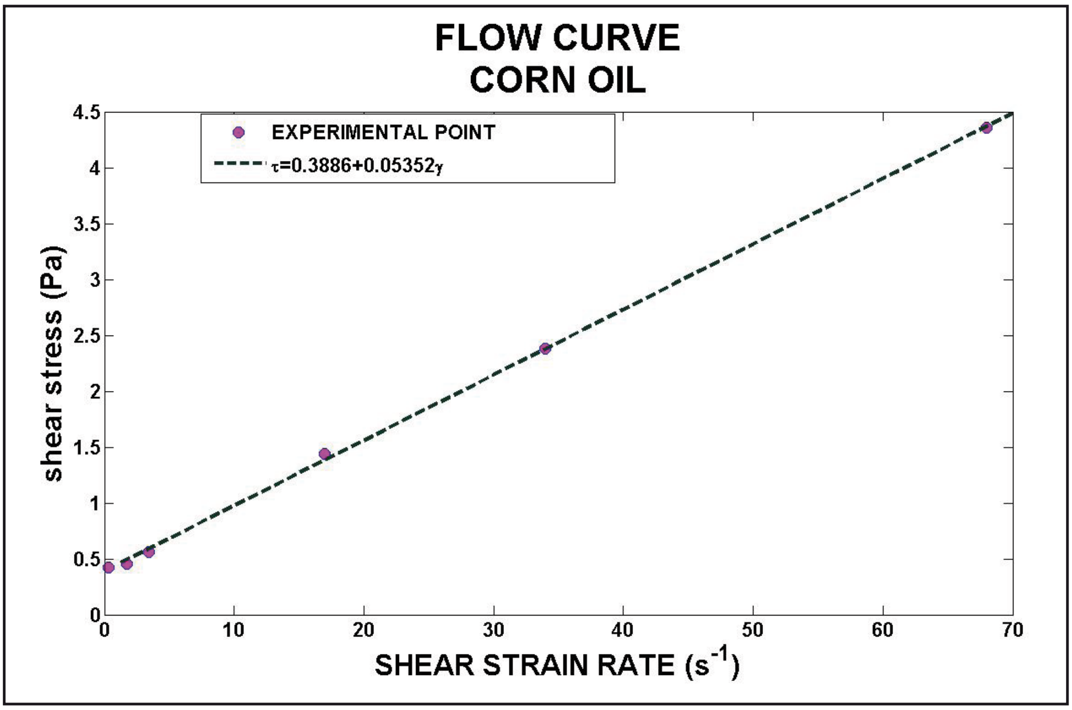
II: *Experimental results*

Oil type	Shear rate [s^{-1}]	Viscosity [mPa.s]*	Shear stress [$g.cm^{-2}$]*
Pumpkin	0.34	952.725	4.637
Pumpkin	1.7	272.751	5.818
Pumpkin	3.4	171.123	14.752
Pumpkin	17	86.777	25.204
Pumpkin	34	74.130	46.552
Pumpkin	68	68.459	17.458
Corn	0.34	1012.978	15.600
Corn	1.7	329.400	4.543
Corn	3.4	166.076	5.647
Corn	17	84.566	14.376
Corn	34	70.241	23.882
Corn	68	64.064	43.563
Olive	0.34	959.609	4.825
Olive	1.7	283.772	4.825
Olive	3.4	183.580	6.242
Olive	17	95.900	16.302
Olive	34	81.908	27.849
Olive	68	76.132	51.770
Rapeseed	0.34	1150426	3.967
Rapeseed	1.7	258.917	4.402
Rapeseed	3.4	170.436	5.800
Rapeseed	17	90.800	15.436
Rapeseed	34	77.471	26.3357
Rapeseed	68	71.695	48.753
Sunflower	0.34	2649.304	7.638
Sunflower	1.7	550.895	7.713
Sunflower	3.4	342.961	9.603
Sunflower	17	159.755	22.566
Sunflower	34	135.166	37.836
Sunflower	68	124.068	69.478

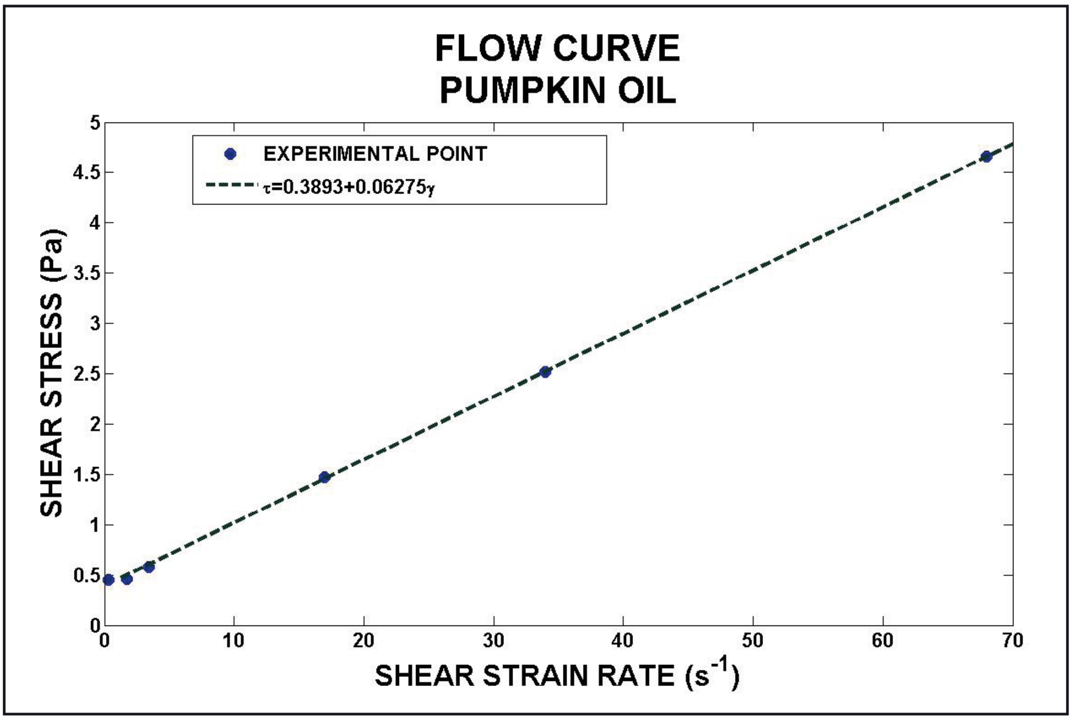
* listed data present average value from three independent measurements

According to Tab. II., it may be observed that oil viscosity depends on shear rates, especially for values below approx. 10 s^{-1}. This indicates a range of non--Newtonian behaviour and oils may be classified as Bingham fluids. Generally, liquid food viscosity depends on its temperature and composition as well as on the the previous treatment applied to the samples (Rao, 1977). This implies that another critical factor influencing oil viscosity is temperature. As stated before, all our experiments were conducted under room temperature (21 °C). It could be assumed that similar flow dependencies would be obtained for different experimental temprature conditions. Obviously in different value levels. The influence of vegetable oil heating and cooling on viscosity values was studied eg. in (Gaspar, 2002; Santos et al., 2005). The sunflower oil viscosity values measured at steady region of shear rates presented in (Santos et al., 2005) range around 75 mPa.s. Our own measurements show a higher values ranging around 130 mPa.s. This difference may be explained by partly different oil composition and as a result of diverse manufacturing methods and following dissimilarities and many other factors. Another researcher referring to oil viscosity is (Steffe et al., 1986). Following oil viscosity values (in comparaable temperature conditions) are stated in his work: corn 65 mPa.s (our measurement 60 mPa.s), olive 85 mPa.s (our measurement 80 mPa.s), rapeseed 163 mPa.s (our measurement 77 mPa.s) and sunflower 60–90 mPa.s (our measurement 130 mPa.s).

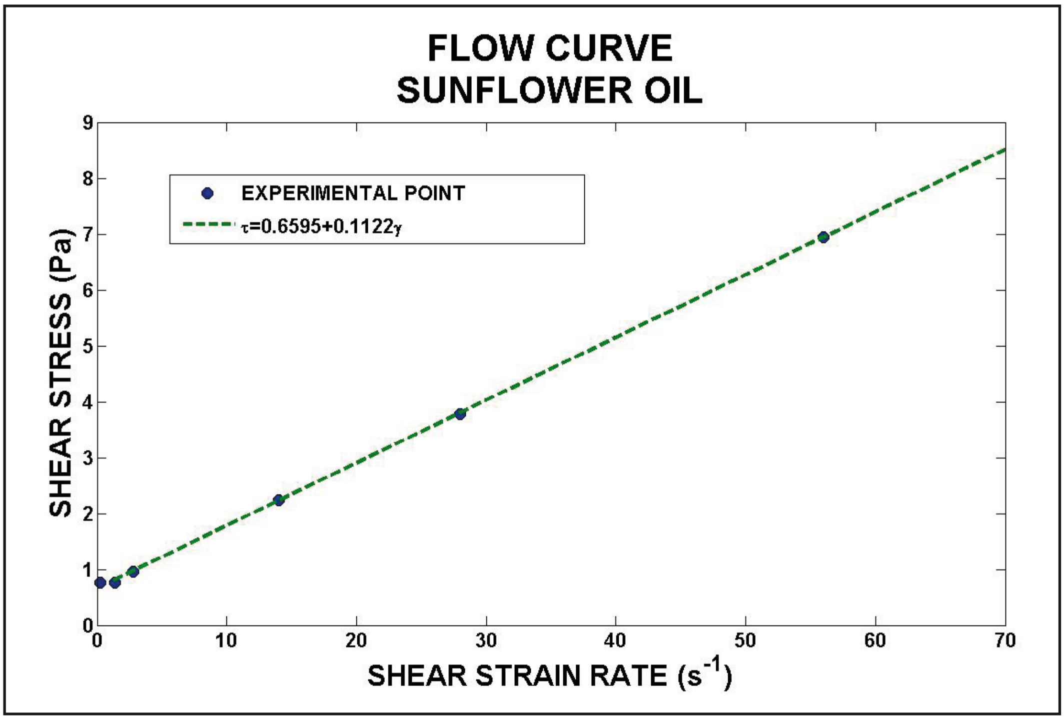
Another part of this paper is dedicated to mathematical modelling of measured rheological data. Modelling provides a means of representing a large quantity of rheological data in terms of simple mathematical expression. Rheograms, summarised in terms of power-law equation represent one example of modelling. Figs. 1–5 show the flow curves of all oils tested and the green dash lines represent model fitting. Fitting exhibited very satisfying results because value of R2 did not decrease under 0.95 in any case.



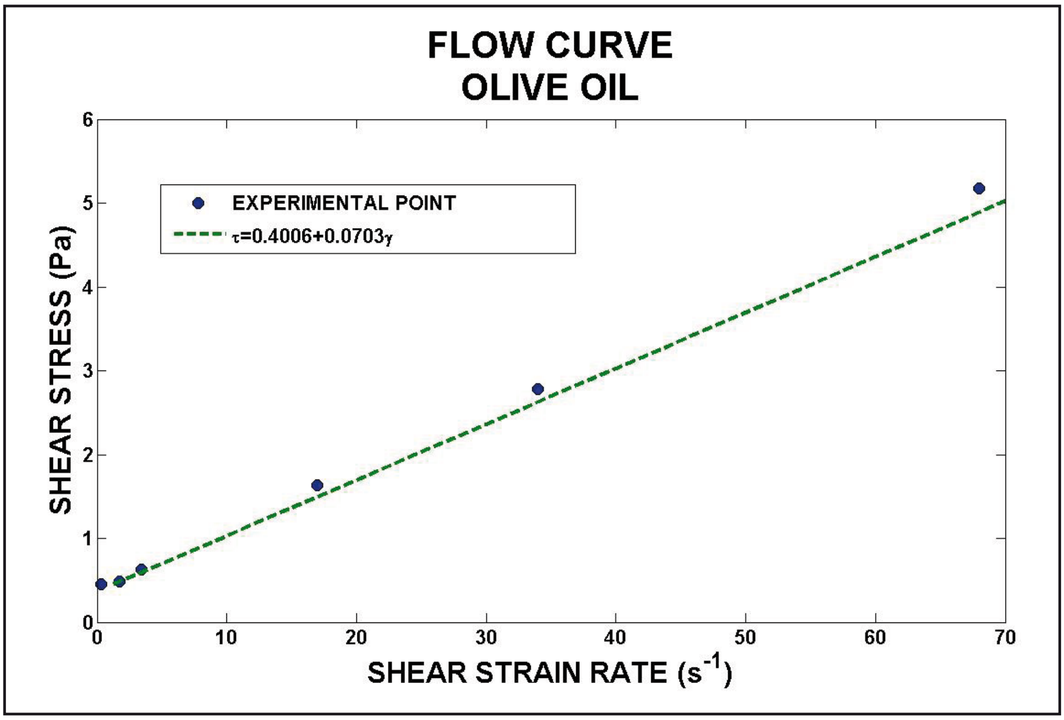
1: *Rheogram of the corn oil fitted with mathematical model*



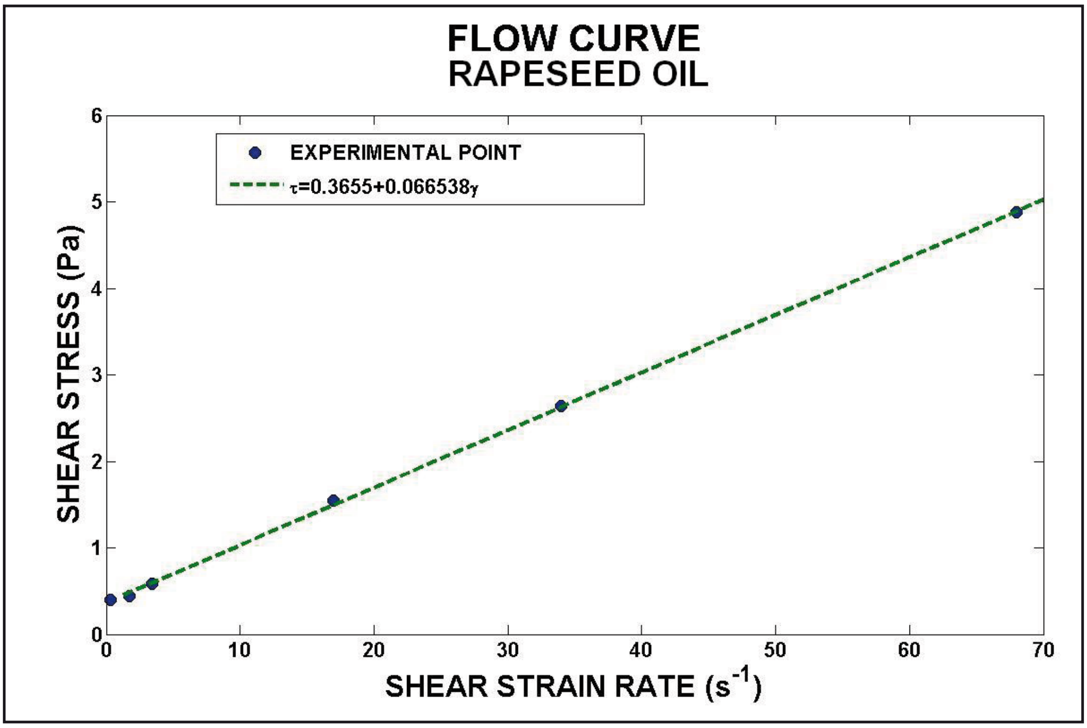
2: *Rheogram of the pumpkin oil fitted with mathematical model*



3: *Rheogram of the sunflower oil fitted with mathematical model*

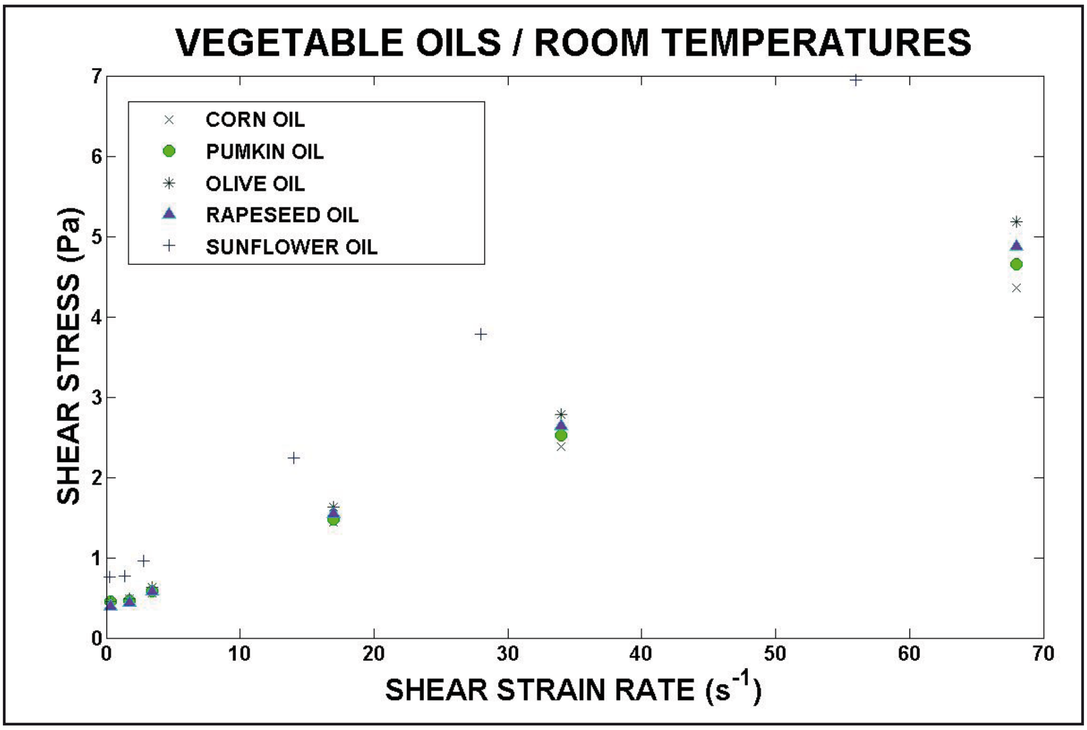


4: *Rheogram of the olive oil fitted with mathematical model*



5: *Rheogram of the rapeseed oil fitted with mathematical model*

Fig. 6 shows an examples of flow curves of all tested oils. The comparison of individual curves indicates a higher values of shear stress in the case of sunflower oil, while the values of other oils are in principle similar. Literature sources (Geller and Boodrum, 2000; Santos et al., 2005) comprise a similar data and therefore almost identical dependences.



6: *Differencies in flow curves of different vegetable oils*

Rheograms shown above reveal that the slope of the line increases with increasing viscosity. Although (Steffe, 1996) classes oils (namely olive oil) among Newtonian fluids, our measurements in accordance with conclusion of (Santos et al, 2005) show non-Newtonian behaviour especially below 5 s^{-1} and classify olive oil as a Bingham fluid.

Comprehensive work dealing with problematic of modelling of rheological behaviour of both Newtonian and non-Newtonian food stufs is (Steffe, 1996).

EXAMPLE OF EXPERIMENTAL RESULTS APPLICATION

The obtained results, i.e. the viscosities can be used for the solution of the oil flow in different pipes etc. Among many possible problems we have focused on the problem of the flow between two parallel plates. The purpose of this study has been to evaluate the inlet effects in laminar flow at fairly moderate Reynolds numbers, in this case about 40. The flow is described by the Navier–Stokes equations :

$$\rho \frac{\partial \vec{u}}{\partial t} - \nabla \cdot \eta [\nabla \vec{u} + (\nabla \vec{u})^T] + \rho (\vec{u} \cdot \nabla) \vec{u} + \nabla p = 0$$

$$\nabla \cdot \vec{u} = 0$$

where ***u*** is the velocity vector, ***ρ*** is the oil density, ***η*** si the dynamic viscosity and ***p*** is pressure.

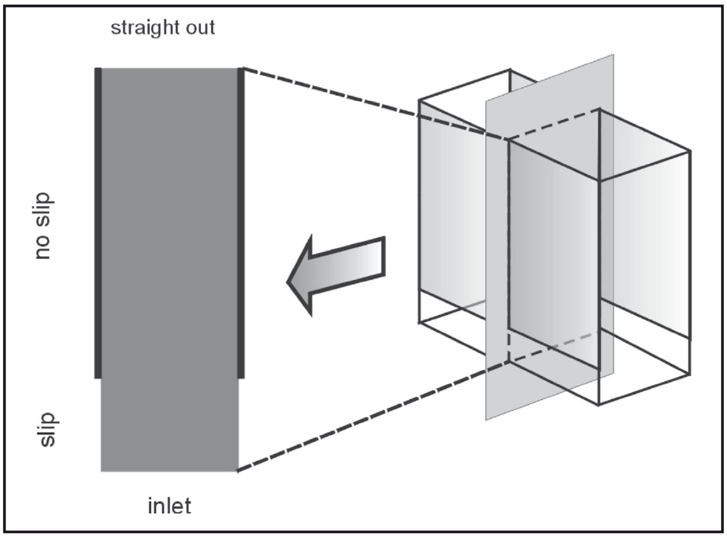
This equation is than applied for the flow of the oil in the domain shown in Fig. 7. Symmetry along the thickness of the domain help to reduce the three – dimensional problem to two-dimensional. In this reduction, the variations of the flow in the direction perpendicular to the figure are neglected. The fluid enters at the inlet which is the lower horizontal boundary. Slip or symmetry conditions describe the flow at the lower vertical boundaries just below the position of plates. The vertical plates impose no – slip conditions on the vertical boundaries. At the horizontal boundary at the top of the domain, straight – out conditions prevail.

The boudary conditions presented in the Fig. 7. are the following:

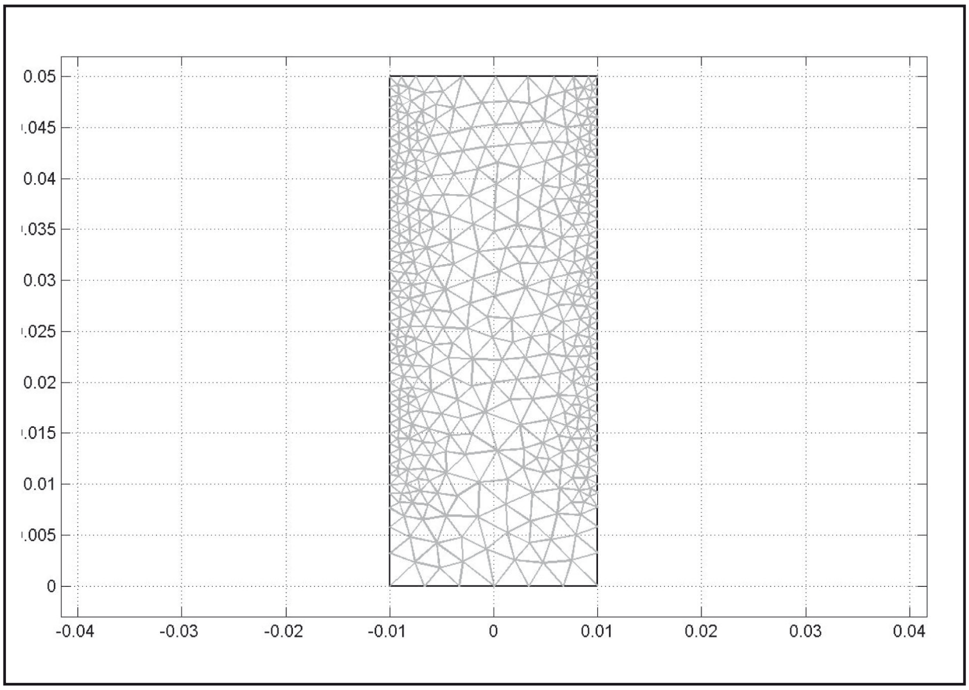
$\vec{u} \cdot \vec{n} = u_o$	inlet
$\vec{u} \cdot \vec{n} = 0$	slip
$\eta [\nabla \vec{u} + (\nabla \vec{u})^T] \cdot \vec{n} = 0$	slip
$\vec{u} = 0$	no – slip
$\vec{u} \cdot \vec{t} = 0$	outlet
$p = 0$	outlet

t and ***n*** are the tangential and normal unit vectors, respectively.The problem described above can be solved only numerically. The numerical solution has been performed by the FEMLAB finite element code. The inlet velocity has been chosen as 0.24 m/s. The fluid parameters, i.e. density and dynamic viscosity were taken for the sunflower oil.The value of the Reynolds number is very closed to 40. The numerical simulation was performed using FEMLAB finite element code. The finite elements are displayed in Fig. 8.

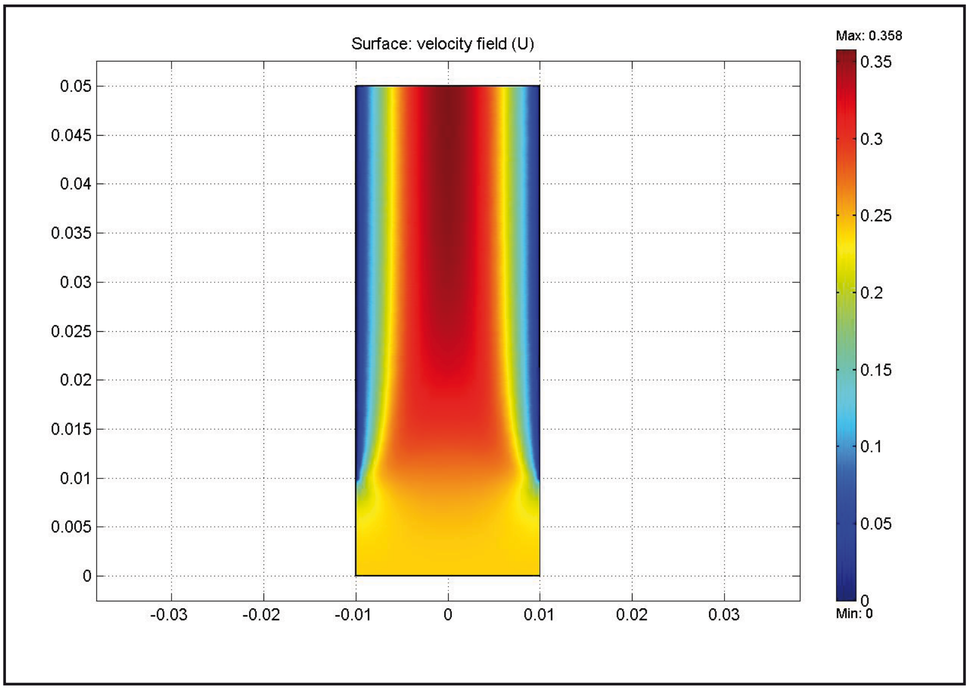
The distribution of the sunflower oil velocity is shown in Fig. 9. The distribution of the pressure is shown in Fig. 10.



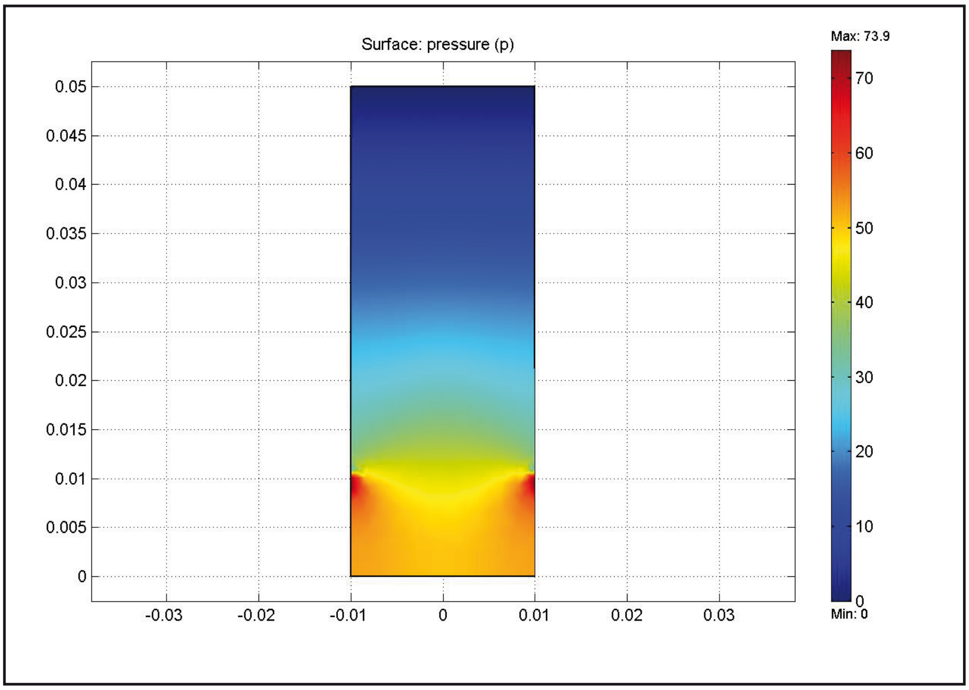
7: *Schematic of the solved problem*



8: *Schematic of the finite elements (928 elements with 465 nodes were used)*

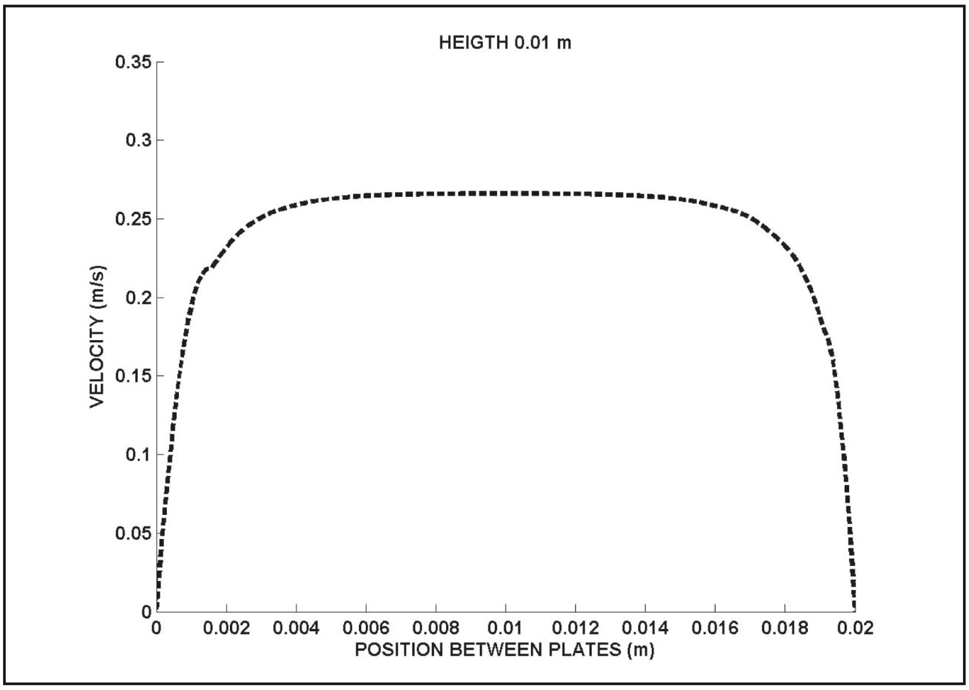


9: *Velocity distribution of the sunflower oil velocity*

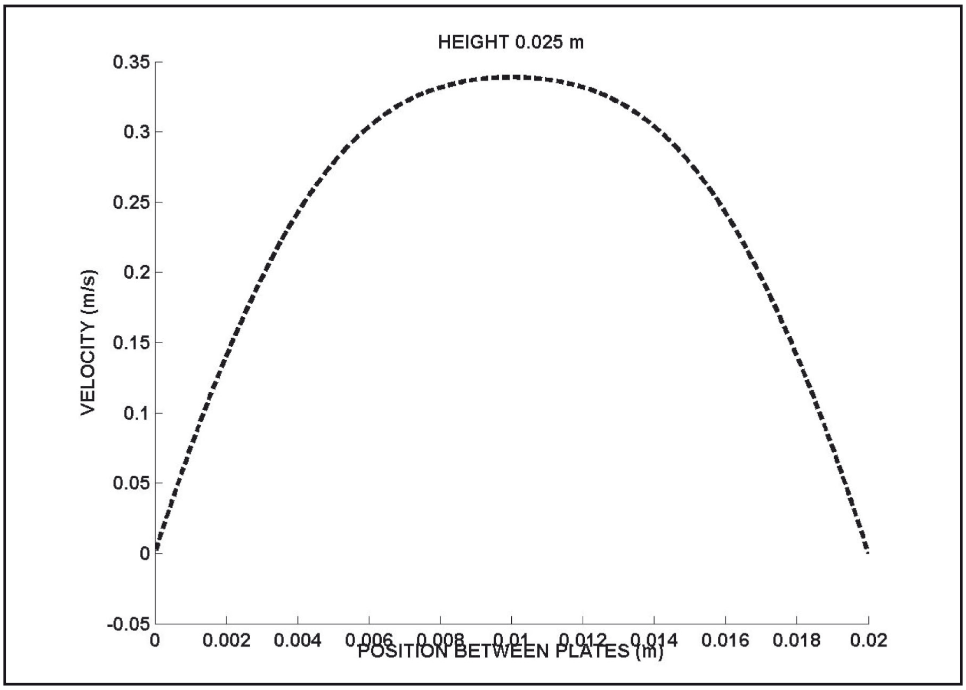


10: *The distribution of the pressure*

The velocity profile across the walls at the different distance (y) from the bottom are shown in Figs. 11–12.



11: *The velocity of the sunflower oil along the width between plates*



12: *The velocity of the sunflower oil along the width between plates*

These examples show how the velocity profile develops along the main direction of the flow. At the outlet the flow is almost fully developed and we obtain a parabolic velocity profile like in the case of oil flow in the circular tube. The same conclusions have been obtained for remaining oils.

CONCLUSIONS

The edible vegetable oils demonstrated similar rheological characteristics as described in literature. The oils exhibited Newtonian behaviour above approx. 10 s^{-1}. Because of the non-Newtonian behaviour at lower shear rates, tested oils may be declared as a Bingham fluids. The analysed oils were found to be, in accordance with predictions, time-independent. Created simple power-law model has fitted very well (R^2 = 0.95 and more) on flow curves of all oils. The experimental results have been also used for solving the problem of oil (sunflower) flow between two parallel plates. The purpose of this study has been to evaluate the inlet effects in laminar flow at fairly moderate Reynolds numbers, in this case about 40. The flow is described by the Navier-Stokes equations. The complicated problem has been reduced from the three – dimensional to two-dimensional. The numerical simulation has been performed by the FEMLAB finite element code. The simulations of velocities and fluid pressures have been created as well as the the velocity profiles between plates. It has been documented that the velocity profiles develop with increasing distance from inlet area.

SOUHRN

O vybraných reologických vlastnostech jedlých rostlinných olejů

Byly stanoveny reologické charakteristiky pěti rostlinných jedlých olejů. Konkrétně se jednalo o řepkový, kukuřičný, slunečnicový, olivový a tykvový olej. Oleje vykazovaly znaky Newtonovské kapaliny nad rychlostmi deformace přibližně 10 s^{-1}. Při nižších rychlostech deformace se oleje chovaly jako ne-

-Newtonovské kapaliny a celkově by tedy podle výsledků našich měření měly být zařazeny mezi Binghamovské kapaliny. Podle očekávání se u olejů neprokázala závislost reologických vlastností na čase. Byly sestrojeny tokové křivky pro všechny oleje a následně proloženy pomocí jednoduchého matematického modelu. Korelační koeficient R^2 mezi experimentálními a vypočtenými hodnotami dosahoval min. 0,95. Získaná data byla také použita pro numerickou simulaci průtoku slunečnicového oleje mezi dvěma rovnoběžnými deskami. Cílem takové simulace bylo zhodnocení efektu vtoku při laminárním proudění a relativně nízkých hodnotách Reynoldsových čísel (v tomto případě asi 40). Proudění bylo popsáno Navier-Stokesovými rovnicemi. Numerická simulace byla provedena pomocí softwearu FEMLAB a metody konečných prvků. Simulovány byly rychlosti a tlaky kapaliny a dále rychlostní profily mezi deskami.

jedlé rostlinné oleje, reologie, viskozita, modelování, numerická simulace

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