Liquid fuels viscosity (non-Newtonian fluids)

Introduction

Viscosity is an important parameter when preparing liquid fuels for combustion as it determines how much drag the fuel experiences when passing through the pipelines, elements of the burner or the injection system in a Diesel engine. Increase of the viscosity may cause a reduction in the range of the fuel stream, excessive leaning of the fuel mixture and power losses. Also, fuel viscosity controls droplets size distribution during the spraying process.

Fluids can be categorised as Newtonian and non-Newtonian. A relationship between shear stresses τ and the shear rate $\dot{\gamma}$ can be described using the exponential rheologic model proposed by Ostwald de Waele [2]:

$$\tau = k\dot{\gamma}^n \tag{1}$$

where k [$N \cdot s^n/m^2$] is a rheologic parameter called a flow consistency index, which is a measure of the apparent viscosity (the greater the k, the more viscous the liquid). The dimensionless parameter n is a flow behaviour index which quantifies deviation of the fluid from its Newtonian representation. If $n=1$, the function given by the equation 1 is linear and the liquid can be classified as Newtonian. In this case, the Ostwald equation becomes the Newton equation and the consistency index becomes the dynamic viscosity η. Viscosity of Newtonian fluids depends on the pressure and temperature but is independent of the shear rate or duration of the process. This is different in the case of non-Newtonian fluids, for which the apparent viscosity at a given temperature and pressure is a function of the velocity gradient, flow direction and the type of processes the fluid was previously subjected to. The non-newtonian fluids can be divided into two groups, 1) fluids for which the shear stress changes in time (thixotropic and rheopectic fluids), 2) fluids for which the shear stress for a given velocity gradient remains constant in time. Furthermore, the latter can be subdivided into pseudoplastic fluids (shear thinning, i.e. their viscosity decreases under the shear strain), dilatant fluids (shear thickening, i.e. their viscosity increases when the stress is applied) and Bingham fluids (i.e. they behave like Newtonian fluids after a certain magnitude of the stress, the so called yield stress is applied) [1]. Shear stress as a function of shear rate for the aforementioned fluid types is shown in figure 1. Gases and liquids having low specific weight behave like Newtonian fluids. It was experimentally confirmed that liquid fuels behave either like Newtonian or shear thinning fluids.

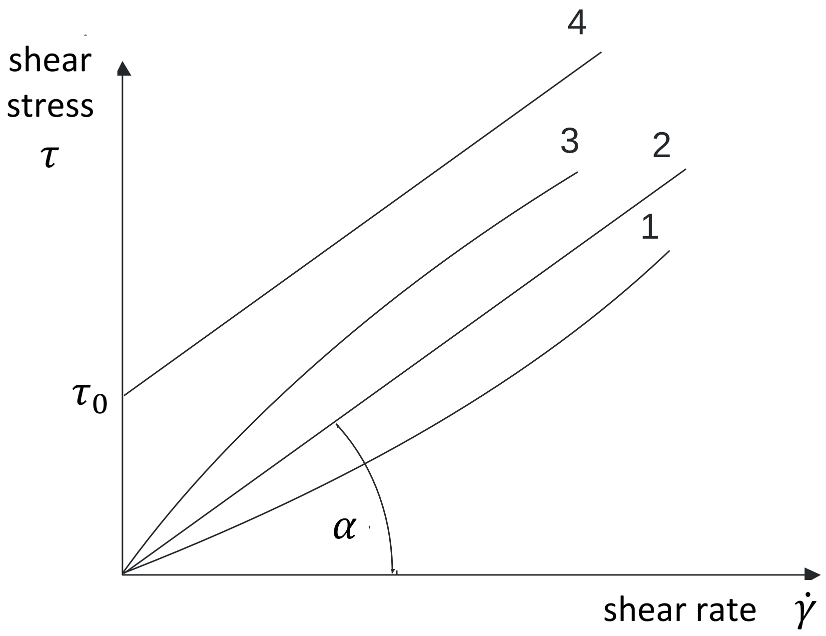

Fig.1. Relationship between the shear rate and shear stresses for different types of fluid; 1, shear thickening fluid ($n > 1$), 2, Newtonian fluid ($n = 1$, $\mathrm{tg}\,\alpha = \eta$), 3, shear thinning fluid ($n < 1$), 4, Bingham plastic (τ_0 indicates the yield stress)

Parameters k and n can be calculated using theoretical models. However, these models are only approximate. This is why k and n are usually determined experimentally. The most popular experimental methods are the ones based on the Stokes and the Hagen-Poisseuille laws or the ones utilizing rotational viscometer [3]. Rheotest 2, which you will use during classes, is an example of the rotational viscometer. The fluid inside the viscometer is enclosed between the external stationary cylinder and the internal rotating one, which is driven by a shaft. Due to the cylinder rotation, the fluid is sheared. The resulting flow velocity distribution is shown in figure 2. In order to relate the shear rate with shear stresses, the torque, M, is measured as a function of the velocity gradient. If the cylinder of a radius R_1 and height h has an angular velocity ω then the shear stress can be expressed as:

$$\tau = \frac{M}{2\pi R_1^2 h} \tag{2}$$

and the velocity gradient is given by:

$$\dot{\gamma} = \frac{2\omega R_2^2}{R_2^2 - R_1^2} \tag{3}$$

where R_2 is an internal radius of the stationary cylinder. The above relationship is strictly true only for Newtonian fluids. However, if the distance between cylinders is sufficiently small, only a minor error is introduced when applied to non-Newtonian fluids. By measuring the torque M for given angular velocities ω the relationship $\tau = \tau(\dot{\gamma})$ can be found and the type of the examined fluid as well as the rheologic parameters k and n (equation 1) can be determined. The rest of the parameters present in equations 1-3 are characteristics of the given measurement system.

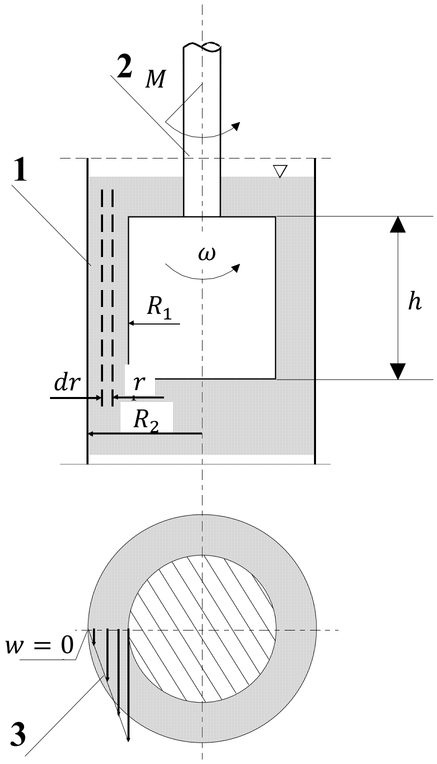

Fig.2. Scheme of the rotational viscometer 1, external cylinder filled with the examined fluid; 2, internal cylinder with a drive shaft; 3, velocity distribution

The aim of the exercise

The aim of this exercise is to familiarize students with rheologic properties of liquid fuels and find $\tau = \tau(\dot{\gamma})$ relationship for the selected fluid for a range of temperatures. Based on that, the character of the examined fluid should be determined.

Experimental setup

The test stand is schematically shown in figure 3. Rheotest 2 is composed of two elements – a viscometer and a gauge, that are connected with a thermostat. Inside the viscometer body, there are two asynchronous engines (750 and 1500 rpm) that are turned on and off with a switch. The engines drive the shaft allowing the internal cylinder to rotate. A lever mounted on the viscometer body is used for adjusting the speed of the shaft rotation (and thus the shear rate). Twelve speeds can be selected that are numbered from 1 to 12 and the current set-up is indicated by the arrow located on the scale next to the lever. In the upper part of the apparatus there is a dynamometer connected with a transducer. The dynamometer is used for measuring the torque of the shaft connected to the internal cylinder. The external cylinder is filled with the examined fluid and is enclosed by a thermostatic tank. There is a thermometer inside the tank, and the tank is connected with the thermostat. On the gauge scale, parameter α represents the torque and the range of the scale can be adjusted using the switch located in the upper part of the viscometer body. Switching from the position I to the position II means that the range is changed as 1/10. The gauge is also equipped with frequency counter, showing the current frequency in the network. Two screws on the gauge desktop are used for resetting the system. A combination of two engines and 12 lever positions allows for obtaining 24 different rotation speeds of the internal cylinder.

Five measuring systems are available, they are named with the following symbols: S/S_1, S/S_2, S/S_3, S/N, S/H. Table 1 presents magnitudes of the parameters characterizing each system, while the shear rate corresponding to each lever position is shown in table 2. The following relationship exists between α and the shear stress:

$$\tau = K\alpha \tag{4}$$

where K is a constant characteristic for a given measuring system and its values are listed in table 3.

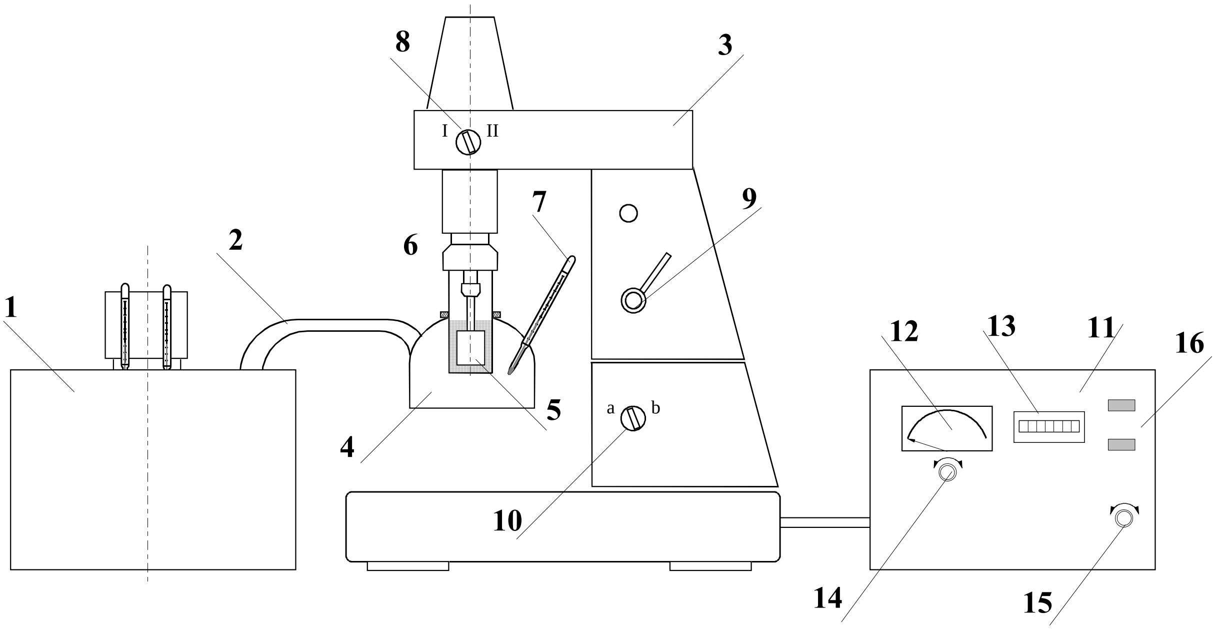

Fig.3. Scheme of the test rig for measuring rheologic properties of fluids. 1, thermostat; 2, connections between the thermostat and Rheotest 2; 3, Rheotest 2; 4, thermostatic tank; 5, cylinder with the examined fluid; 6, internal cylinder with a drive shaft; 7, termometer; 8, switch of tha gauge scale ranges; 9, lever controlling the shaft rotation; 10, engines switch; 11, recorder; 12, torque magnitude indicator; 13, current frequency indicator; 14, mechanical reset screw; 15, electrical reset screw; 16, switches for turning on the apparatus

Table1. Characteristic parameters for analysed measurement systems

Measurement system	Fluid volume V, cm^3 (±5%)	R_1/R_2	$D_1 = 2R_1$, mm	$D_2 = 2R_2$, mm
N	10	0,98	39,2	40
H	17	0,81	21	26
S_1	25	0,98	39,2	40

S_2	30	0,94	37,6	40
S_3	50	0,81	32,4	40

The experimental procedure

After revising the measurement system and checking its condition, follow the steps below:

1) Before turning the apparatus on, perform a mechanical reset of the system. Then, turn on the viscometer and the gauge. Place the lever at the position 8a and perform an electrical reset when the cylinder is rotating.

2) Fill in the external cylinder with the selected liquid. The required volume of available fluids (at the temperature of measurement) is given in table 1. Mount the cylinders.

3) Set up the temperature specified by your instructor and turn on the thermostat. When the required temperature is reached wait around 15 minutes (let the cylinder to rotate all this time). This is needed to for the temperature distribution to be uniform.

4) Read α for increasing rotation speeds, beginning from the lever positioned at 1b and changing its position in the order given by table 2. When the hand on the scale is close to 100%, change the range by turning the switch to the position II.

5) Repeat the measurements, but now let the speed to decrease (the order opposite to that given in table 2). Remember about changing the range of the scale (switch back to the position I) so that the same ranges are used for the same lever positions.

6) Repeat points 2-5 for various temperatures specified by your instructor.

7) When the measurements are finished, remove the fluid from cylinders and wash them using solvent.

Table 2. Shear rate $\dot{\gamma}$ (s^{-1}) for given measurement systems

Symbol of the lever position	S/S_1 S/N	S/S_2	S/S_3 S/H	Symbol of the lever position	S/S_1 S/N	S/S_2	S/S_3 S/H
1b	1,5	0,5	0,1667	6a	48,6	16,2	5,40
2b	2,7	0,9	0,300	8b	72,9	24,3	8,10
1a	3,0	1,0	0,333	7a	81,0	27,0	9,00
3b	4,5	1,5	0,500	9b	121,5	40,5	13,50
2a	5,4	1,8	0,600	8a	145,8	48,6	16,20
4b	8,1	2,7	0,900	10b	218,7	72,9	24,30

3a	9,0	3,0	1,000	9a	243,0	81,0	27,00
5b	13,5	4,5	1,500	11b	364,5	121,5	40,50
4a	16,2	5,4	1,800	10a	437,4	145,8	48,60
6b	24,3	8,1	2,700	12b	656,0	218,7	72,90
5a	27,0	9,0	3,000	11a	729,0	243,0	81,00
7b	40,5	13,5	4,500	12a	1312,2	437,4	145,80

Analysis of the results

Note down the shear rate and the corresponding α and prepare a table similar to table 4. Based on your results calculate the shear stress and plot the relationship $\tau = \tau(\dot{\gamma})$ for studied temperatures. Use the linear regression method to compute rheologic parameters k and n. For this purpose rearrange equation 1 to a linear form so that the independent variable becomes $\ln \dot{\gamma}$ and the dependent variable is $\ln\tau$:

$$\ln\tau = n \ln \dot{\gamma} + \ln k \tag{5}$$

Based on your plot, assess the character of the examined fluid and explain the influence of temperature on the shear stress and viscosity. Calculate the correlation coefficient and assess correctness of the performed approximation.

Table 3. Values of K, N/(m^2·%) for given gauge scale ranges

Measurement system	Gauge scale range	
	I	II
N	0,312	3,40
S_1	0,580	5,56
S_2	0,594	5,83
S_3	0,789	7,73
H	2,900	2,89

Table 4. Viscosity of liquid fuels - results of the measurements

Examined liquid:
Measurement system:
Measurement system constants $K_\mathrm{I} =$
$K_\mathrm{II} =$
Temperature $t =$

No.	Symbol of the lever position	Shear rate $\dot{\gamma}$, s^{-1}	Gauge value α, % for rotation speed			Shear stress τ, N/m^2	Viscosity $\eta = \tau/\dot{\gamma}$ $N \cdot s/m^2$
			Increasing speed	Decreasing speed	Average		
1							
2							

Literature

[1] Kembłowski Z.: Reomtria płynów nienewtonowskich, WNT, Warszawa, 1973

[2] Paliwa i ich spalanie. Część V Laboratorium (Petela R. - red.), Skrypt Politechniki Śląskiej Nr 1191, Gliwice, 1984

[3] Wilkinson W.L.: Ciecze nienewtonowskie, WNT, Warszawa, 1963