

EFFECT OF PRESSURE AND TEMPERATURE ON VISCOSITY OF LUBRICATING OILS

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Abstract: Experimental viscosity data are reported for two lubricating oils namely mobile oil and paraffin oil to pressures up to 5.2kbar in the temperature range of 30°C to 90°C with accuracy ± 1 percent. The results of variation of viscosity of these systems with temperature at atmospheric pressure are also reported with estimated accuracy ± 1 percent. The experimental data have been represented by empirical relations for pressure and temperature variation. These data have also been used to determine the activation energy of viscous flow as a function of pressure. At the end, Kiran and Sen observations are also checked. Our analysis shows that with our parameter values, the average modulus of deviation (MD) is less than 2 percent.

Keywords: Viscosity, Activation Energy, Hoppler's Viscometer, Hydrostatic Pressure, Lubricants

INTRODUCTION

The study of variation of viscosity of lubricating oils with pressure and temperature is of great industrial importance. This type of information is needed in order to evaluate the suitability and limitation of various lubricating oils for use in commercial engines and also as hydrostatic pressure transmitting media in high pressure technology. Further, it has become important to characterize new synthetic oils for practical use as lubricants.

A number of workers (1-7) have investigated viscosity of lubricating systems using various techniques. Of these the first significant study of pressure dependence of viscosity is that of Hyde [1] who reported viscosity data for several lubricating oils up to 1.5 k bar. A group led by Bradbury and Mark [2] measured the viscosity of 55 well defined lubricants to 12 kbar at 218°C. Brooks and coworkers [3] have reported viscosity of 5 lubricants base stocks (unformulated) at elevated pressure. The lubricants investigated are a sebacate ester, a TMP ester, SAE20 mineral oil, a 5P4E polyphenyl ether and a methyl chlorophenyl silicon. Abbott and coworkers [4] measured the viscosity of a few lubricants, viz., a synthetic turbine engine oil, a mineral oil, white gasoline and 1:1 mixture of mineral oil and white gasoline at pressure upto 3 kbar and temperature in the range of 20 to 200°C. Scott Bair [5] measured viscosity for pressure to 1.4GPa and temperatures to 165°C for various lubricants including automotive transmission fluids, aerospace lubricants, turbine oil etc. Longfei Li [6] measured the viscosity of lubricating oil by viscometer based on Hele principle. Recently, Oyedeko K.F.K. Akinyemi et al [7] gave a prediction of viscosity of automobile lubricants at different temperatures.

From the foregoing references, it may be noted that the lubricants taken by these authors are either mineral oils or organic based lubricating oils. Further, the purity of these lubricating oils, particularly organic based lubricants depending upon the source from which these are obtained. Therefore, it becomes essential to measure the viscosity of such lubricating oils before their application in technology. We have measured the viscosity of two lubricating oils namely Mobil oil and paraffin oil of industrial importance available in the market as a function of pressure and temperature. It is hoped that these data will be used for the Indian industry.

EXPERIMENTAL

We have used Hoppler's Falling Ball Viscometer for the measurement of viscosity at atmospheric pressure as a function of temperature.

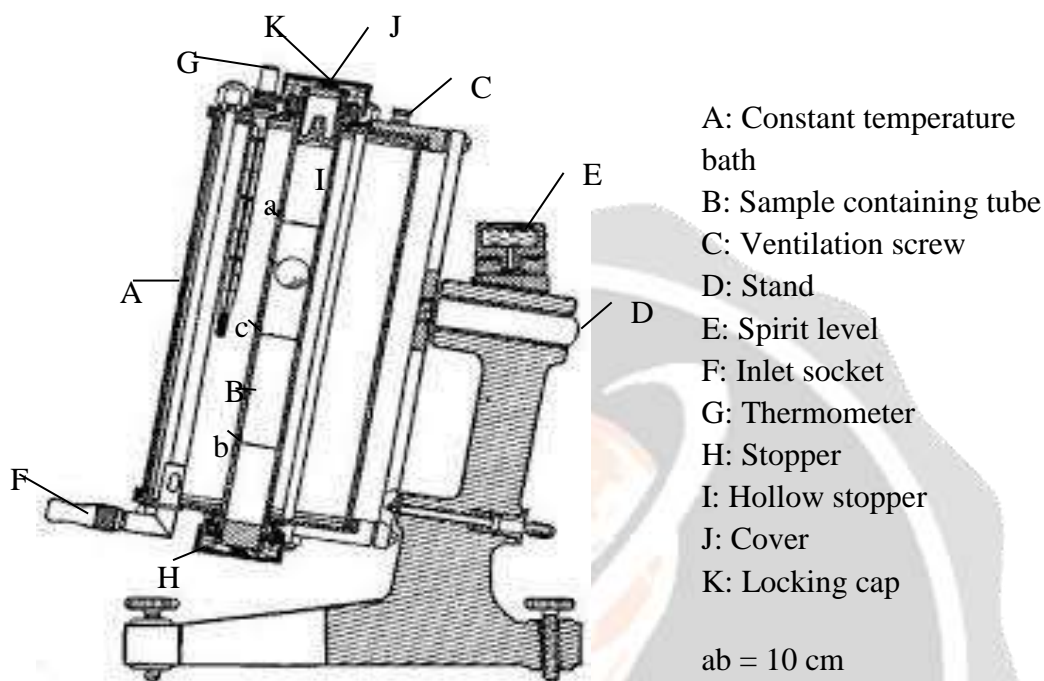


Fig 1: Hoppler's Falling Ball Viscometer

The design of Hoppler's viscometer is shown schematically in Fig.1. It consists of a constant temperature bath A of cylindrical shape through which a suitable liquid at constant temperature is circulated. Tube B containing the sample liquid is housed inside the bath as shown. A ventilation screw C at the top of the constant temperature bath is provided which helps to release the air pressure whenever needed. The bath is clamped to a vertical stand D such that the bath (and hence the sample tube) can be rotated along a horizontal axis. On the top of the stand a spirit level E is provided for leveling the apparatus before the experiment. The regulation of temperature is made by means of constant temperature liquid (water in our case) from the Hakke thermostat which enters through the inlet socket and leaves through outlet socket (not shown in figures). Generally, a temperature constant of about 10 to 15 minutes in the water bath is sufficient to enable the sample liquid to acquire the temperature of the circulating water in the bath. This temperature is measured with the help of thermometer B of accuracy 0.1°C suspended inside the water bath.

The glass tube for the sample liquid, stoppers and the glass-ball are carefully cleaned and then rinsed with the liquid to be studied. The tube is closed by stopper H at the bottom and then filled by a sample about 25 mm below tube brim. The ball is lowered in the liquid by means of the pincette and any air bubbles under the ball are removed by pressing it down with the help of a well cleaned glass rod. The tube is filled completely and then closed by hollow stopper I and cover J on which locking cap K is screwed under a mild pressure. The viscometer tube is manually rotated, so that the ball reaches the top of the tube. The ball is then allowed to fall in the tube. It acquires the terminal velocity before reaching the mark a. The fall time between the marks a and b (a total distance 100 mm) is

measured with the help of stop watch (accurate up to 10^{-2} s). This procedure is repeated a number of times to get the average value of the time of the fall.

The viscosity coefficient η at various temperatures can be determined by using equation

$$\eta = C t (\rho_b - \rho) \quad - (1)$$

where C is calibration constant dependent on the dimensions of the apparatus and t is fall time;

ρ_b and ρ are the densities of the material of the ball (glass in our case) and test liquid respectively. The value of calibration constant is determined by using glycerol as a reference liquid for which viscosity data as a function of temperature at atmospheric pressure are available in the literature [8]. The estimated accuracy of our viscosity measurements is about ± 1 percent.

For viscosity measurement as a function of pressure at various temperatures, the experimental set-up described in [9] is employed. However, the ball used for the present measurements has a lower diameter than in the case of normal Pentane because of higher viscosity of investigated lubricants. Further, the working range of the inclination angle θ , in which calibration coefficient remains constant is determined in each case. Other procedural details have been given in [9]. The average of five to eight rolling-times is used for the calculation of viscosity.

MATERIALS

Relevant information about the lubricating oils (available in the local market) used in this investigation is summarized below

SAMPLE	DENSITY (g/cc) at 20°C	VISCOSITY (cp)
Mobil Oil	0.8946	189.00 (at 30°C)
Paraffin Oil	0.8397	19.00 (at 20°C)

RESULTS AND DISCUSSION

The viscosity of some lubricating oils at atmospheric pressure has been measured at different temperatures in the range starting from 20°C to 90°C.

The results of our measurements for mobil oil and paraffin oil are given in Table 1 and 2 respectively. However, in case of paraffin oil the temperature range does not go above 40°C because the viscosity then becomes so low that the time of fall of the ball comes out to be lower than the critical value of 25s specified for the Hoppler's Viscometer. At atmospheric pressure, the coefficient of viscosity η (cp) could be fitted to the polynomial equation.

$$\ln \eta = \sum_{i=0}^n A_i (1/T)^i \quad - (2)$$

For temperature (K) variation. The values of coefficients for each system are given in Table 3

Table 1: Coefficient of Viscosity η (cp) at atmospheric pressure for Mobil Oil

Temp (°C)	Mobil Oil
30.00	188.57

40.00	108.88
50.00	66.40
60.00	43.67
70.00	30.00
80.00	21.46
90.00	15.97

Table 2: Coefficient of Viscosity η (cp) at atmospheric pressure for Paraffin Oil

Temp (°C)	Paraffin Oil
20.00	19.76
25.00	15.97
30.00	13.25
35.00	11.09
40.00	9.41

Table 3: Values of the coefficients in Eq. (2)

Lubricants	A_0	$A_1 \times 10^{-3}$	$A_2 \times 10^{-5}$	$A_3 \times 10^{-8}$
Mobil Oil	5.32320	-5.600200	17.33100	0.13065
Paraffin Oil	-1.46780	0.931050	6.54940	

The relative viscosity η_r , the ratio of viscosity at elevated pressure to the viscosity at atmospheric pressure, is determined in the pressure range upto 5.2 kbar at various temperatures between 30°C to 90°C. The results of our measurements for above mentioned systems are given in Table 4 and 5 At each temperature our results could be fitted to the polynomial equation.

$$\text{Log } \eta_r = \sum_{n=0}^i a_n b^n \tag{3}$$

Where pressure P measured in the bar. The values of the coefficients for various liquids are given in Table 6. Third to fourth order polynomials are required to give representation of our results within our experimental accuracy of ± 1 percent.

Table 4: Relative viscosity (η_r) of Paraffin Oil as a function of pressure and temperature

	η_r		η_r		η_r		η_r
P (bar)	30°C	P (bar)	50°C	P (bar)	70°C	P (bar)	90°C
1	1.000	1	1.000	1	1.000	1	1.000
450	2.150	398	1.821	405	1.757	421	1.719
696	3.326	634	2.564	775	2.823	717	2.436
850	4.306	1096	4.741	1128	4.244	1124	3.767
1081	6.173	1629	9.202	1620	7.284	1709	6.697
1320	8.634	1835	11.781	2126	12.149	2040	9.055
1611	12.489	2152	16.876	2627	19.702	2654	15.510
1905	17.984	2645	29.476	3154	32.170	3125	23.101
2105	23.671	2951	40.580	3704	52.453	3642	35.178
		3301	58.546	4184	80.353	4101	50.663
				4703	124.189	4609	75.033
						5197	114.732

Table 5: Relative viscosity (η_r) of Mobil Oil as a function of pressure and temperature

	η_r		η_r		η_r		η_r
P (bar)	30°C	P (bar)	50°C	P (bar)	70°C	P (bar)	90°C
1	1.000	1	1.000	1	1.000	1	1.000
394	2.348	407	2.192	390	1.893	421	1.519
620	3.680	660	3.374	634	2.742	781	2.231
1092	9.084	1078	6.524	1052	5.084	1092	3.147
1314	13.347	1365	10.102	1668	11.261	1519	5.091
1629	22.837	1597	14.284	2118	21.105	2184	10.734
1826	32.107	2166	34.249	2596	37.809	2646	17.761
2098	50.918	2620	64.969	3193	77.702	3164	30.536
		3049	111.867	3640	130.023	3708	52.356
				4033	196.788	4101	76.015
						4682	129.584
						5201	207.615

Table 6: Values of coefficients in Eq. (3)

	Temp (0°C)	$a_0 \times 10^3$	$a_1 \times 10^4$	$a_2 \times 10^7$	$a_3 \times 10^{11}$	$a_4 \times 10^{15}$
Mobil Oil	30.00	-1.50380	9.9337	-1.33140	2.2690	-
	50.00	-0.80572	9.2427	-2.48220	10.2730	15.8950
	70.00	-0.52256	7.4693	-0.99129	2.4640	2.7299
	90.00	-0.41741	4.1029	0.59202	-1.7059	1.3424
Paraffin Oil	30.00	-0.70910	8.2916	-1.10450	1.2622	-
	50.00	0.17486	6.7781	-0.61644	0.5632	-
	70.00	0.24406	6.3623	-0.82978	1.3097	-0.8698
	90.00	-0.36395	5.9401	-0.87858	1.5500	-1.1377

From a study of results given in the tables, it is clear that for all systems the viscosity at any temperature increases with pressure. The quantitative variation of viscosity with pressure is represented by Eq. (3). On the other hand, at a given pressure, the data show that in all cases the viscosity decreases with temperature. Such a behavior is to be expected from any rate process and the quantitative variation is most simply represented by the equation

$$\eta = A e^{B/T} \quad - (4)$$

where **A** and **B** are constants. Here the constant $B = E_a/R$ defines the activation energy connected with viscous flow.

We have shown the pressure and temperature variation of viscosity suitably by plotting a number of graphs derived from certain quantitative results of interest shown in Fig 2 to 5.

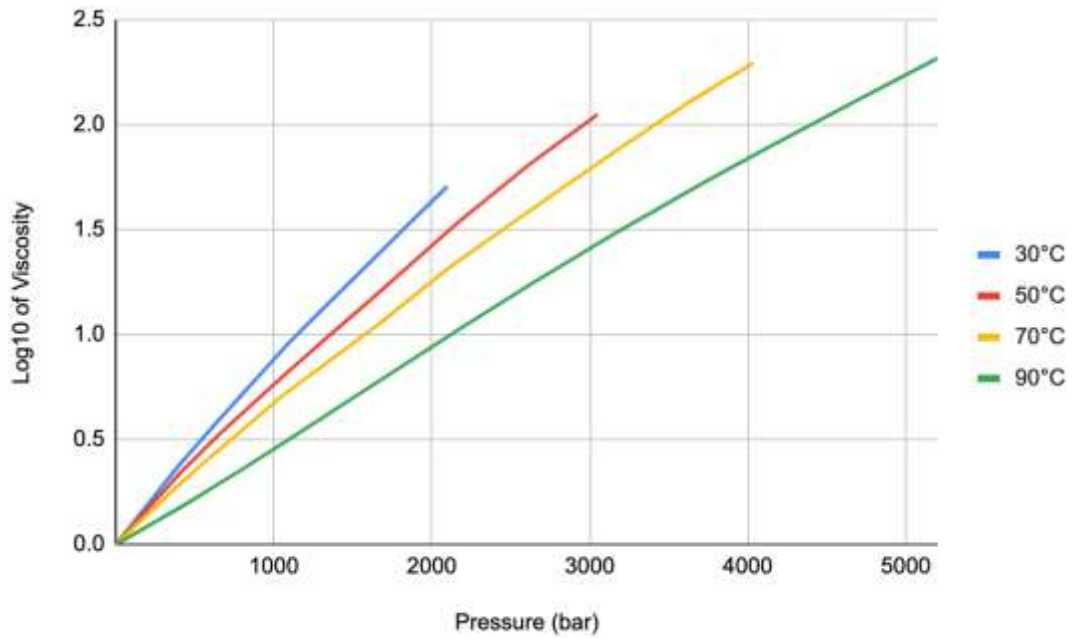


Fig 2: $\text{Log}_{10}(\eta_r)$ Vs Pressure for Mobil Oil at different temperatures

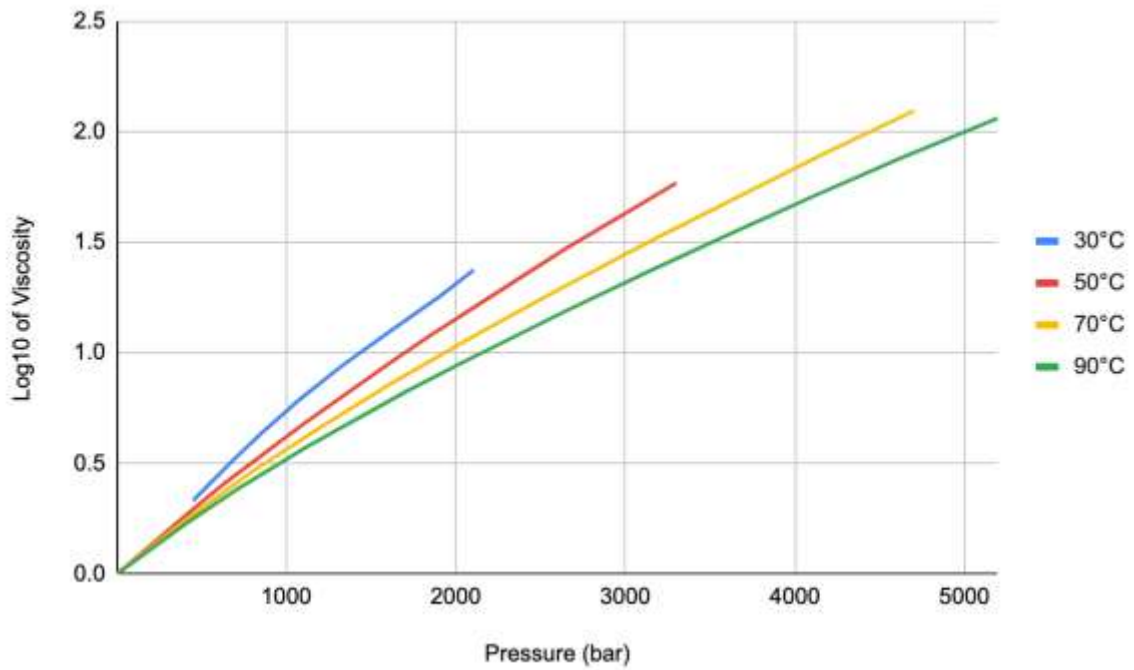


Fig 3: $\text{Log}_{10}(\eta_r)$ Vs Pressure for Paraffin Oil at different temperatures

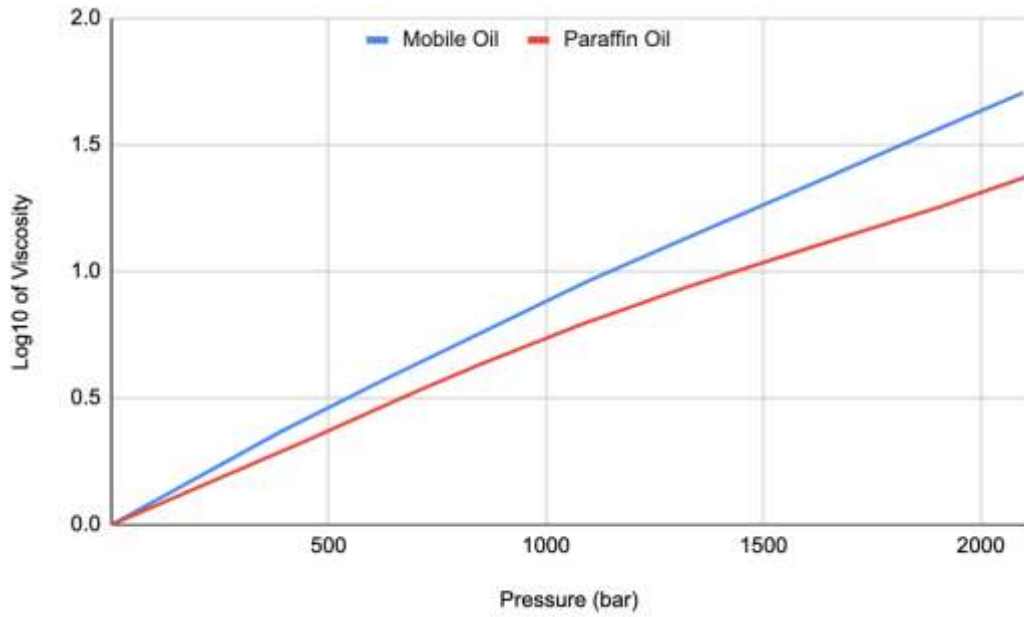


Fig 4: Comparison of $\text{Log}_{10}(\eta_r)$ Vs Pressure at 30°C

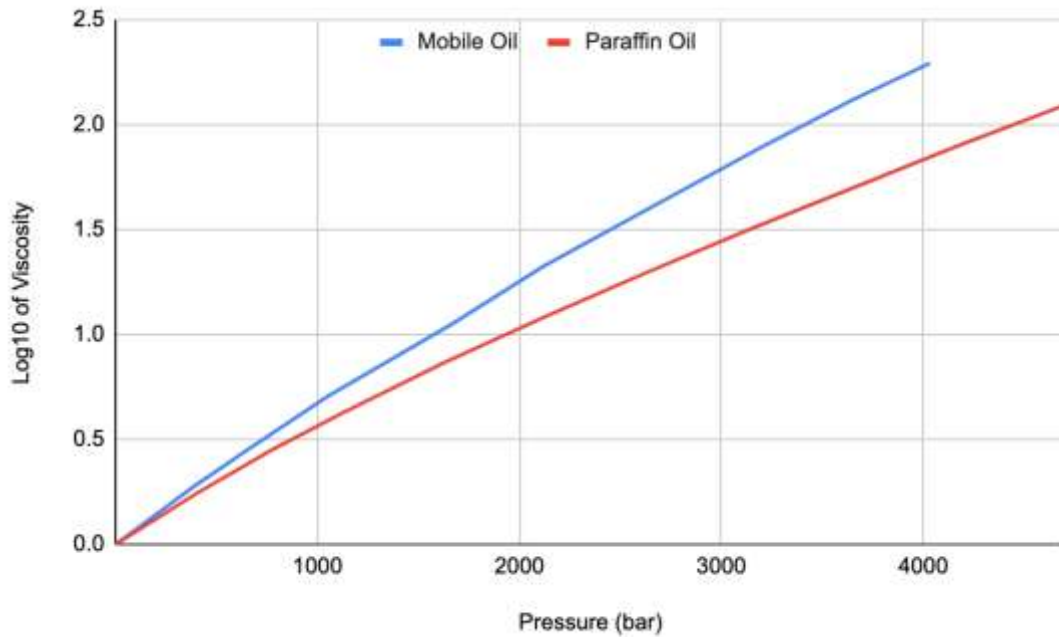


Fig 5: Comparison of $\text{Log}_{10}(\eta_r)$ Vs Pressure at 70°C

CONCLUSION

It may be noted from these figures that at a given temperature, viscosity increases with pressure rapidly at first and then more slowly. The differential pressure coefficient of log of viscosity at 50°C and 90°C for both cases has been determined at 1 and 3 kbar using Eq. (3). The values obtained are given in Table 7.

Table 7: Differential pressure coefficients of $(d \ln \eta/d P) \times 10^4$

	Mobil Oil		Paraffin Oil	
	Pressure in 1 kbar	Pressure in 3 kbar	Pressure in 1 kbar	Pressure in 3 kbar
Temp = 50°C	15.5	11.3	13.2	10.6
Temp = 90°C	11.1	10.4	10.6	8.3

It is observed that the differential pressure coefficients of log η for each system decreases with both pressure and temperature.

The activation energy on the basis of Eq. (4) is determined for each system as a function of pressure using the linear part of the log of viscosity versus the reciprocal of the absolute temperature curves. These values of E_a for all the systems as a function of pressure are given in Table 8. We have plotted activation energy with pressure as shown in Fig.6. It is clear from the graph that E_a increases with increase in the pressure.

Table 8: Activation energy E_a (kJ) as a function of Pressure

System	<----- Pressure in (kbar) ----->			
	1×10^{-3}	1	2	3
Paraffin Oil	27.0	34.9	40.9	47.2
Mobil Oil	41.2	52.5	62.0	

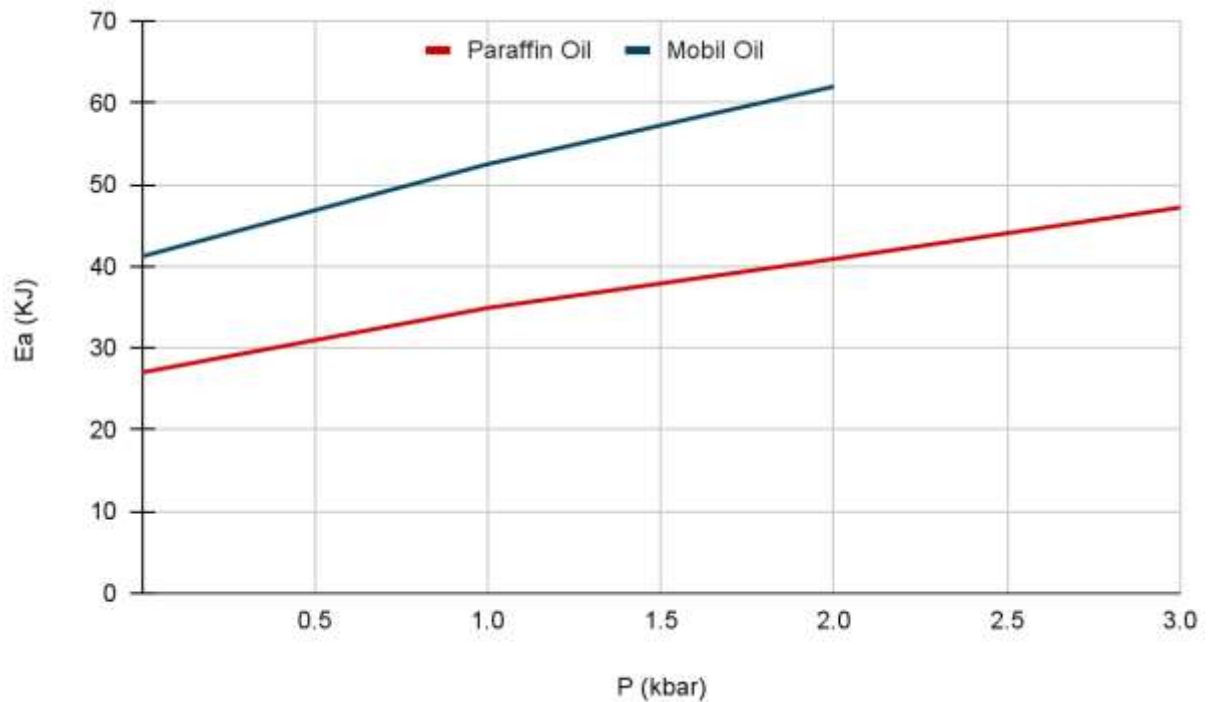


Fig 6: Variation of Activation Energy (E_a) with pressure

We conclude here by representing our viscosity data of both the systems in equation given by Kiran and Sen [10]. The values of parameters B_1 , B_2 and B_3 (along with the pressure limits) for each system are given in Table 9. Average modulus of the deviation (MD) of the values calculated from Equation using these parameters values from our smoothed experimental values are also given in Table 9. Our analysis shows that with our parameter values, MD is less than 2 percent. We hope that this data is useful for Indian Industry.

Table 9: Values of the parameters in Eq by Kiren and Sen

Temp (0°C)	$B_1 \times 10^{10}$	$B_2 \times 10^2$	B_3 (mPa.S)	MD (%)
MOBIL OIL (pressure limit 1.6 kbar)				
50	1.8599	4.5714	21.50	0.7
70	57.4060	4.1379	11.03	1.9
90	3494.2000	3.573	9.72	2.0
PARAFFIN OIL (pressure limit 2.2 kbar)				
30	1.1023	4.6602	4.96	1.6

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