STUDIES ON THE OILINESS OF LIQUIDS. I. MEASUREMENTS OF THE STATIC FRICTION COEFFICIENTS.

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When two solid surfaces are brought into contact and made to slide the one on the other, the friction force comes into play. The friction is generally lessened by the presence of a liquid film between the solid surfaces. This effect is expressed by the term "oiliness" of the liquid and is the subject of the present series of investigations.

Now if a solid body of weight W is made just to slide on a horizontal surface by means of a force F whose direction is parallel to the surface, then $\frac{F}{W}$ is known as the coefficient of friction. Thus,

$$\frac{\text{Frictional resistance}}{\text{Normal weight}} = \frac{F}{W} = \mu.$$

The coefficient of friction may differ according to whether motion is imparted to the body at rest or whether the force F is required to keep the body in motion. In the former case the coefficient is known as the static coefficient of friction while in the latter as the kinetic coefficient of friction.

Although a large number of investigators have published data bearing on the subject of lubrication, most of them conducted their experiments on the standpoint of the practical application.(1) Moreover, the variations in their

(1) For example: Wilson and Barnard, *Ind. Eng. Chem.*, **14** (1922), 682, 683; Hersey, *J. Franklin Inst.*, **219** (1935), 677; **220** (1935), 93, 187; Archbutt and Deeley, "Lubrication and Lubricants," (London); Nash and Bowen, "The Principles and Practice of Lubrication," (London).

operating conditions and the indefiniteness of the chemical nature of the liquids used thus prevented any correlation of their results.

In practice, there are two types of lubrication, complete or film lubrication in which the solid faces are completely separated by a thick film of an oil, and incomplete or boundary lubrication in which the faces are separated by a very thin film which may be sometimes only one molecule thick. The theory of complete lubrication is a problem in hydrodynamics, and outside the scope of the present investigation.

The friction coefficients of some chemically definite substances have been measured by W. B. Hardy and his collaborators.(2) It seems necessary, however, to test their results and to extend the measurements to a larger number of substances, with the hope of finding relations between oiliness and other properties, especially molecular constitutions of the liquid.

We measure the boundary lubrications of chemically pure substances as well as mixtures of known compositions. The static and the kinetic coefficients of friction are measured by using several different methods, which have been designed in our laboratory. In the present paper one of the methods for measuring the static coefficient of friction is described.

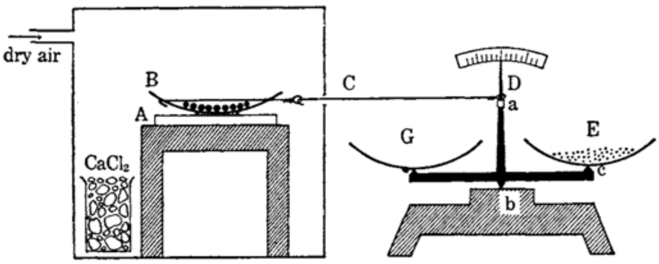

Fig. 1.

Experimental Procedure. The apparatus is shown in Fig. 1. A is an optical glass plate of plane surface which is settled on a suitable stand. B is a slider made of a watch glass, and its weight is adjusted by putting lead shots in it. C is a thin copper wire, one end of which is hitched to the cutting of the watch glass B. The other end of C is connected with the middle part of the pointer D of a prescription balance.

(2) W. B. and J. K. Hardy, *Phil. Mag.*, **38** (1919), 32; W. B. Hardy, *Phil. Mag.*, **40** (1920), 201; *J. Chem. Soc.*, **127** (1925), 1207; Hardy and Doubleday, *Proc. Roy. Soc.* (London), A, **100** (1922), 550; **101** (1922), 487; **104** (1923), 25; Doubleday, *J. Chem. Soc.*, **121** (1922), 2875; *Proc. Roy. Soc.* (London), A, **106** (1924), 341; Hardy and Bircumshaw, *Proc. Roy. Soc.* (London), A, **108** (1925), 1; "Collected Scientific Papers of Sir William Bate Hardy," (Cambridge, 1936).

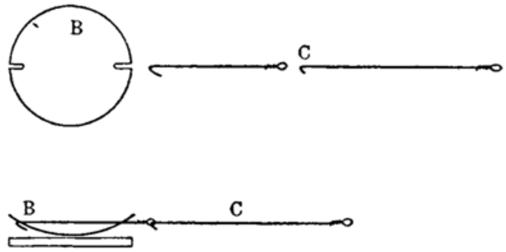

Fig. 2.

Fig. 2 shows the upper and the side views of B and C. C is made of two pieces of wire, short and long, each having a small hook at one end and a small ring at the other. The short piece is hitched to a cutting on the rim of the watch glass, and stretched out through another cutting opposite to the first one. The long piece is hooked to the ring of the short piece and to the pointer of the balance.

A and B are put in a glass case, provided with a vessel containing calcium chloride. A current of dry air is passed through the case during the observation to prevent the effect of moisture on the surfaces and the lubricating liquid. The lubricating liquid is poured on A and then the slider B is put on it. The position of the slider is adjusted so that the pointer D takes the upright position, the right and the left pans being balanced.

Now, fine sand is poured in a thin stream from a reservoir to the right pan E. The quantity of sand gradually increases until finally the right pan goes downward, the pointer inclines to right side, and the slider A moves rightward. Then C is detached from D and the weight of the sand on the right pan E is measured by putting balance weights on the left pan G.

Let the weight of the sand be s, the length between a and b be l, and the distance between b and c be l', then the force acting on the slider is expressed by the following equation :

$$F = s\frac{l'}{l}.$$

So the coefficient of friction μ is obtained by

$$\mu = \frac{F}{W},$$

where W denotes the weight of the slider, i. e. the sum of the weight of watch glass, lead shots, and one half of the wire C.

It is one of the most important conditions that the sliding surfaces are sufficiently clean and free from any greasy matter. The glass plate and the slider are cleaned in the following manner before each observation. They are boiled for half an hour with a chromic acid solution, washed and rubbed with the finger tip under the running tap water, and finally rinsed with distilled water. They are dried in a desiccator containing calcium chloride, a current of dry air being passed. No grease is applied on the ground part of the desiccator, to avoid the contamination of the sliding surfaces.

Measurement. The purest samples available were used in the experiments. Most of the substances were distilled before the tests.

It is already known that the coefficient of friction is not seriously affected by the change of temperature.[3] We conducted, therefore, our experiments at room temperature without special adjustment of the temperature. The temperature was between 17°C. and 24°C. For the measurement, we took the readings of s several times for a definite value of W, and then took their average. The value of l'/l was 1.23 for the balance used in the present measurements, so we get $F = 1.23\ s$. Some of the actual examples are shown in Table 1. The results are summarized in Table 2.

Table 1.

Lubricant	W (g.)	Value of s (g.)		F (g.) (1.23 s)	μ (F/W)
		reading	average		
Ethyl alcohol	33.90	20.00 19.50 19.15 19.30 20.20 20.50	19.78	24.33	0.72
Glycol	22.00	8.10 8.25 9.30 7.20 8.70	8.31	10.22	0.46

(3) Hardy and Doubleday, *Proc. Roy. Soc.* (London), A, **101** (1922), 487.

Table 2.

Lubricant	W (g.)	F (g.)	μ
Methyl alcohol CH_3OH	7.4	4.55	0.62
	14.4	8.28	0.58
	23.95	14.07	0.60
	24.8	14.71	0.60
	24.8	16.05	0.65
	29.9	18.21	0.61
	33.9	21.93	0.65
	33.95	20.86	0.62
		Mean	0.62
Ethyl alcohol C_2H_5OH	16.20	11.50	0.71
	22.8	16.27	0.71
	24.8	18.82	0.75
	33.8	23.03	0.68
	33.9	24.33	0.72
	33.95	23.74	0.70
	34.0	23.25	0.68
		Mean	0.71
Propyl alcohol C_3H_7OH	24.8	15.78	0.64
	33.9	22.28	0.66
	33.95	21.08	0.62
		Mean	0.64
n-Butyl alcohol $CH_3(CH_2)_2OH$	24.85	14.58	0.59
	33.9	21.54	0.64
	33.95	19.29	0.57
		Mean	0.60
n-Amyl alcohol $CH_3(CH_2)_4OH$	19.95	11.54	0.58
	25.0	14.46	0.58
	28.6	15.9	0.56
	29.65	17.26	0.58
	30.0	16.25	0.54
	33.9	19.84	0.59
	34.6	19.28	0.56
	35.5	19.08	0.54
	37.7	21.51	0.57
	45.8	25.4	0.55
		Mean	0.57
Secondary amyl alcohol $CH_3(CH_2)_2CH(OH)CH_3$	29.7	15.12	0.51
	32.0	17.21	0.54
	38.3	19.68	0.51
	40.3	19.33	0.48
		Mean	0.51
Tertiary amyl alcohol $(CH_3)_2C(OH)C_2H_5$	23.3	11.38	0.49
	26.3	13.1	0.50
	30.1	15.38	0.51
	32.7	17.51	0.54
	35.2	16.59	0.47
	44.1	21.04	0.48
	49.4	22.78	0.46
		Mean	0.50
n-Hexyl alcohol $CH_3(CH_2)_5OH$	12.0	9.35	0.78
	16.0	13.40	0.83
	24.6	15.14	0.62
	31.95	22.42	0.70
	38.6	18.77	0.49
		Mean	—
n-Heptyl alcohol $CH_3(CH_2)_6OH$	11.65	7.89	(0.68)
	16.8	10.57	0.63
	21.9	11.59	0.65
	30.0	19.69	0.66
	35.85	21.83	0.61
	38.6	23.36	0.60
		Mean	0.63
n-Octyl alcohol $CH_3(CH_2)_7OH$	12.5	8.04	(0.64)
	17.6	10.51	(0.60)
	22.75	12.02	0.53
	24.6	12.71	0.52
	26.7	14.29	0.53
	36.3	18.02	0.50
	38.6	20.06	0.52
	48.0	27.07	0.56
		Mean	0.53

Table 2.—(*Continued*)

Lubricant	W(g.)	F(g.)	μ
Acetic acid	18.35	12.41	(0.68)
CH_3COOH	21.5	12.80	0.60
	22.8	13.97	0.61
	26.7	15.14	0.57
	32.7	19.03	0.58
	34.2	20.50	0.60
	39.8	23.99	0.60
			Mean 0.59
Propionic acid	7.60	5.72	(0.75)
CH_3CH_2COOH	11.95	7.92	(0.66)
	15.30	9.57	(0.63)
	23.15	13 57	0.59
	23.60	13.46	0.57
	27.7	16.17	0.58
	30.65	16.84	0.55
	37.1	21.39	0.58
			Mean 0.58
Butyric acid	17.6	12.72	(0.73)
$CH_3(CH_2)_2COOH$	18.95	12.49	(0.66)
	24.1	14.24	0.59
	26.15	15.22	0.58
	27.8	15.94	0.57
	35.5	21.14	0.60
	40.0	24.08	0.60
			Mean 0.59
Valeric acid	20.90	13.60	(0.65)
$CH_3(CH_2)_3COOH$	22.95	13.64	0.59
	26.85	16 64	0.62
	31.1	18.04	0.58
	36.6	22.68	0.62
	40.75	24.6	0.60
	43.95	27.52	0.63
			Mean 0.61
Caproic acid	17.6	11.77	(0.67)
$CH_3(CH_2)_4COOH$	23.7	13.70	0.58
	26.3	15.13	0.58
	30.0	18.39	0.61
	33.0	19.46	0.59
	40.0	23.09	0.58
	45.4	27.05	0.60
			Mean 0.59
Heptylic acid	14.2	9.94	(0.70)
$CH_3(CH_2)_5COOH$	17.9	11.93	(0.67)
	23.3	14.15	0.61
	27.75	17.71	0.64
	32 95	20.78	0.63
	34.9	20.49	0.59
	41.5	24.81	0.60
	46.95	30.48	0.64
			Mean 0.62
Caprylic acid	19.8	10.47	0.53
$CH_3(CH_2)_6COOH$	22.25	11.54	0.52
	24.05	12.45	0.52
	27.85	15.48	0.56
	30.0	15.26	0.51
	33.05	18.00	0.54
	35.7	19.09	0.53
	40.4	22.73	0.56
	40.8	19.94	0.49
			Mean 0.53
Nonylic acid	22.25	2.50	0.56
$CH_3(CH_2)_7COOH$	22.5	12.20	0.54
	28.8	16.49	0.57
	29.7	17.54	0.59
	37.3	21.40	0.57
	41.25	23.61	0.57
			Mean 0.57

Table 2.—(*Concluded*)

Lubricant	W(g.)	F(g.)	μ
n-Hexane C_6H_{14}	17.55	12.18	0.69
	21.7	14.59	0.67
	24.55	17.00	0.69
	25.1	17.17	0.68
	34.7	22.3	0.64
	34.7	23.99	0.69
	37.6	25.78	0.69
			Mean 0.68
n-Heptane C_7H_{16}	21.7	15.72	0.72
	22.3	14.93	0.67
	32.6	20.32	0.62
	34.7	25.40	0.73
	41.7	30.18	0.72
	43.5	30.77	0.71
			Mean 0.69
n-Octane C_8H_{18}	22.9	14.49	0.63
	27.0	16.41	0.61
	38.0	24.27	0.64
	42.1	25.45	0.60
			Mean 0.62
n-Nonane C_9H_{20}	23.3	13.82	0.60
	28.0	18.27	0.65
	33.5	21.34	0.64
	37.4	23.94	0.64
	41.9	27.62	0.66
			Mean 0.64
Benzene C_6H_6	15.8	12.29	0.78
	22.0	16.64	0.76
	23.3	19.33	0.83
	26.8	21.37	0.80
	33.1	25.0	0.76
	34.0	27.19	0.80
	41.4	31.15	0.75
			Mean 0.78

Lubricant	W(g.)	F(g.)	μ
Toluene $C_6H_5CH_3$	24.7	19.71	0.80
	24.9	18.45	0.74
	25.7	20.01	0.78
	28.1	22.65	0.81
	33.3	24.7	0.74
	34.7	26.41	0.76
	35.1	25.83	0.74
	38.1	29.26	0.77
	44.7	32.95	0.74
			Mean 0.76
Liquid paraffine	21.9	15.12	(0.69)
	37.1	20.66	0.56
	40.2	22.13	0.55
	45.5	25.70	0.56
	48.3	26.71	0.55
	57.3	29.01	0.51
			Mean 0.55
Glycol $(CH_2OH)_2$	15.2	7.81	(0.51)
	22.0	10.22	0.46
	34.0	15.74	0.46
	41.3	14.75	0.45
	49.2	22.23	0.45
			Mean 0.46
Ethyl acetate $CH_3COOC_2H_5$	19.7	13.76	0.70
	26.2	18.92	0.72
	27.7	18.95	0.68
	36.2	24.89	0.69
			Mean 0.70
Oleic acid $C_{17}H_{33}COOH$	23.1	7.55	(0.33)
	24.3	6.46	0.27
	32.3	9.52	0.29
	40.7	11.36	0.28
	51.1	15.30	0.30
			Mean 0.29
Lubricant oil "Planet-RM medium"	37.4	8.55	0.23
	49.1	10.18	0.21
			Mean 0.22

The values of μ in parentheses are excluded in the calculation of mean values. The tangential force required to move the slider is proportional to the normal force between the surfaces or, in our notation, μ is independent of W. This fact is designated by the name " Amontons's or Coulomb's law." In the region, however, where the value of W is too small, this law does not hold, giving large value of μ. The data in parentheses in Table 2 correspond to this region. Fig. 3 and Fig. 4 show the relations between μ and the number of carbon atoms in the molecule of the substance. Further discussion will be given in later papers.

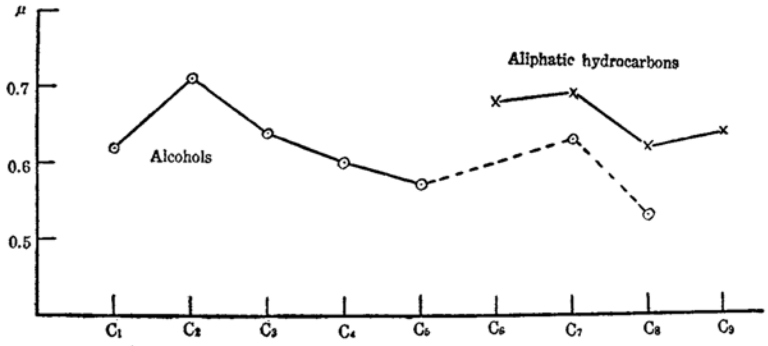

Fig. 3.

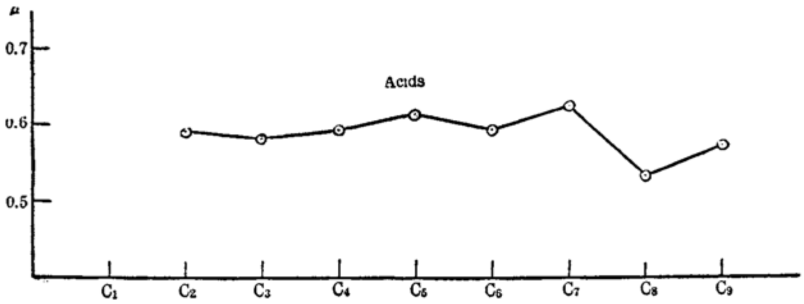

Fig. 4.

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