Studies on the Oiliness of Liquids. III. Measurements of the Kinetic Friction Coefficients.

By Jitsusaburo SAMESHIMA and Moriji MIYAKE.

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We shall describe, in the present paper, the measurements of the kinetic friction coefficients of liquids. There are already many a types of machine which are used for the measurement of the kinetic friction in the industrial purpose. They measure, usually, the power of complete or film lubrication of oil. Recently, Beare and Bowden have published a paper on this subject and described an apparatus for the measurement of kinetic boundary lubrication which was constructed by Hardy.(1)

We have measured the kinetic friction coefficients by the apparatus described in the following lines.

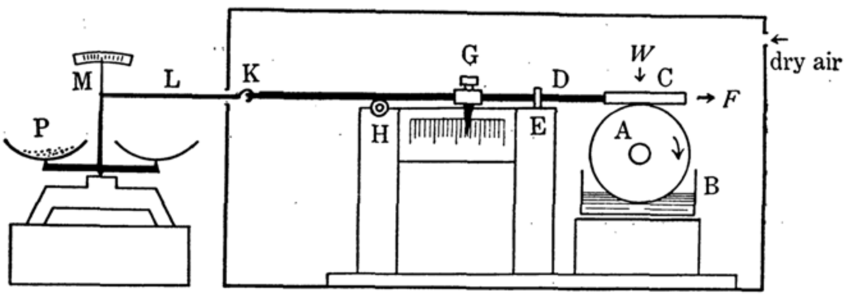

Fig. 1.

Fig. 1 is the schematic view of the whole apparatus. In this figure, A is a steel cylinder of 5 cm. diameter and 3 cm. length, the surface being highly polished. B is a vessel containing the liquid to be tested. The lower part of the cylinder A is dipped in the liquid. By rotating A in the direction shown in the figure, the surface of cylinder is covered with the film of the liquid. C is a small piece of steel plate of the dimension $4 \times 1 \times 0.3$ cm., the lower surface of which being polished. D is the elongation of C and has a pointer G at its middle part, and a loop of wire K at the end. The system CDGK is mounted on the rotating cylinder A

(1) Beare and Bowden, *Trans. Roy. Soc.* (London), A, **234** (1935), 329.

and a small wheel H. Fig. 2 is the plan of this part. H is a small pulley which can rotate with little friction, so as to move the rod D to right or left. E is the guide to keep from the movement in the direction of fore and aft. At the loop K one end of the wire L is hooked, the other end of which being attached to the pointer M of a balance as shown in Fig. 1. The pointer G is adjusted so as to come to zero reading on the scale when the balance pointer M is in the perpendicular position. The function of the balance is quite the same with that in the measurement of the static friction coefficient which has already been explained in the first paper.(2) The apparatus, excepting the balance, is put in a glass case in which the dry air is passed.

A few grams of liquid is put in B, and let the cylinder A start to rotate. Then the plate C will be pulled rightward and accordingly the pointer M will incline rightward. Now fine sand is poured on the balance pan P in a fine stream until the pointer M returns to the perpendicular position. In such a state, the friction force F is in equilibrium with the weight in P. So the friction force can be obtained by a simple calculation as described in the former paper.

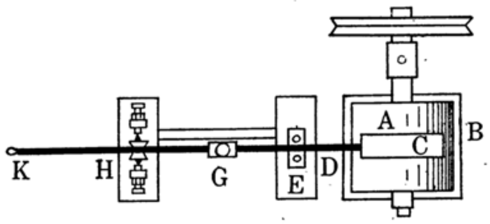

Fig. 2.

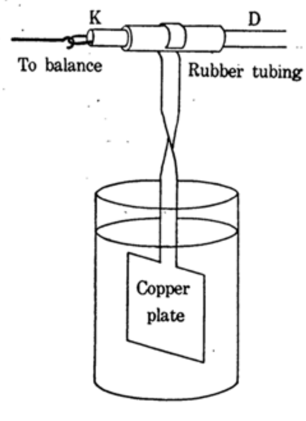

Fig. 3.

The contact line between A and C must be in the same height with the joint between L and M. The load W is measured by replacing the cylinder A with a balance.

(2) Sameshima, Kidokoro and Akamatu, this Bulletin, **11** (1936), 659.

When the sample is a nonpolar and low viscosity liquid, then the equilibrium point can hardly be determined owing to the movement of G to and fro. This is probably caused by the seizure between the solid surface A and C without the film of liquid. In this case a damper, shown in Fig. 3, is attached to D. This consists simply of dipping a copper plate in a viscous liquid made of the liquid paraffin and vaselin.

The surface of the steel cylinder A and the steel plate C have been cleaned, at first, by washing with benzene, with soap solution rubbing by finger tip, and finally with alcohol. The cleaning is satisfactory, by this treatment, in the measurements of the friction coefficients of alcohols. In the case of hydrocarbons and of water, however, the surfaces are not sufficiently cleaned by this method, for the values of friction coefficient fluctuate considerably in each observation. So, at last, the surfaces have been cleaned by the electrolytic method described in the followings.

The electrolytic solution is the mixture of the equal volume of 1% NaCl solution and alcohol. The electrolytic cell consists of the platinum anode and the steel cathode. The electrolysis is conducted at 4–6 volts and less than 0.1 ampere, being continued for 10–30 seconds. The surface of the cathode is cleaned by the discharge of hydrogen on it. After this treatment, the surface is rinsed with distilled water and dried in a desiccator passing a current of dry air. The steel surface cleaned by such a manner is readily wetted with water or alcohols, and gives fairly concordant value of friction coefficient in each liquid.

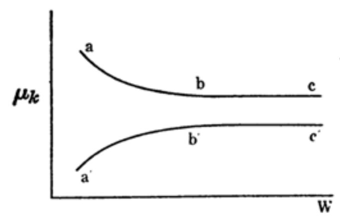

Fig. 4.

The friction coefficients are measured for the varying values of the load W. The relations are shown by the two curves of Fig. 4. In the region where W is large the friction coefficient becomes constant, while in the region where W is small the coefficient is not constant and changes with W. The former is represented by the portion of the curves bc or b′c′, and the latter ab or a′b′. The portion bc or b′c′ corresponds to the boundary lubrication while ab or a′b′ to the film one. In the present report the friction coefficient for the boundary lubrication will be given.

The rotation velocity of the cylinder A was, in the present experiment, 0.80 second for one rotation. The diameter of the cylinder is 5 cm., so the velocity of the sliding surface is calculated to be 19.6 cm. per second. Diverse results were obtained by numerous authors on the relation between the friction coefficient and the moving velocity of the sliding surfaces.(3) It seems so far probable that the kinetic friction is smaller than the static friction unless the sliding velocity is extremely small. The quantitative relations on this subject will be studied in the further experiments.

Care must be taken on the moisture of the air, which considerably affects the friction of some liquids. The air in the glass case of sliding machine is kept dry by inserting a considerable quantity of anhydrous calcium chloride, and moreover, a current of dried air is passed during the measurement.

The experimental results are given in Table 1. In this table, W shows the load and F the tangential force, both in gram unit. The kinetic friction coefficient μ_k are calculated as the ratio of F and W. The values of μ_k in parenthesis are excluded in the calculation of mean value, for these correspond to the portion ab or a′b′ in the μ_k-W curves shown in Fig. 4.

The value of μ_k of water fluctuate considerably in repeating the measurements. Hardy and Doubleday described as follows(4): "Water, considered as a lubricant, is of a remarkable character. It is neutral to clean surfaces of glass or steel in that it neither lowers nor raises the friction." The value of μ_k for water obtained in our experiments may or may not be the friction coefficient between steel surfaces of no lubricant. Further experiments are necessary to decide this question. We take, however, $\mu_k = 0.255$ as a provisional value for the kinetic friction coefficient of steel surfaces lubricated with water.

Fig. 5 and Fig. 6 show the relation between the kinetic friction coefficient and the number of carbon atom in the chemical formula of the lubricant liquid.

Measurements have been done on the mixture of water and alcohol, the results of which are given in Table 2. The relations between the kinetic friction coefficient and the composition of the mixture are depicted in Fig. 7.

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(3) Jacob, *Ann. Physik*, [4], **38** (1912), 126. More literatures are given in Bear and Bowden's paper, *loc. cit.*

(4) Hardy and Doubleday, *Proc. Roy. Soc.* (London), A, **104** (1923), 34.

Table 1.

Lubricant	W (g.)	F (g.)	μ_k
Methyl alcohol	35.5	6.06	0.171
CH_3OH	65.5	11.64	0.178
(b.p. 64.2–64.5°C.)	92.7	15.94	0.172
	115.5	19.84	0.172
			Mean 0.173
Ethyl alcohol	26.7	4.64	0.174
C_2H_5OH	36.7	6.39	0.174
(b.p. 78.3–78.4°C.)	66.7	12.28	0.184
			Mean 0.177
n-Propyl alcohol	65.5	10.41	0.159
C_3H_7OH	65.5	10.26	0.157
(b.p. 97.0–97.5°C.)	92.7	14.70	0.159
	92.7	15.06	0.163
	115.5	18.64	0.161
			Mean 0.160
n-Butyl alcohol	92.7	13.14	0.142
$CH_3(CH_2)_3OH$	115.5	16.90	0.146
(b.p. 116.5–117.0°C.)	115.5	15.60	0.135
	160.5	22.73	0.142
	160.5	22.14	0.138
			Mean 0.141
n-Amyl alcohol	65.5	4.08	(0.062)
$CH_3(CH_2)_4OH$	115.5	11.10	(0.096)
	173.5	19.92	(0.115)
	223.5	28.02	0.125
	273.5	34.96	0.128
			Mean 0.127

Lubricant	W (g.)	F (g.)	μ_k
n-Hexyl alcohol	318.5	32.28	(0.101)
$CH_3(CH_2)_5OH$	418.5	46.60	(0.111)
(b.p. 154–155.5°C.)	553.9	64.44	0.116
	653.9	75.24	0.115
	653.9	76.50	0.117
	753.9	88.14	0.117
	753.9	87.86	0.117
			Mean 0.116
n-Heptyl alcohol	173.5	11.88	(0.069)
$CH_3(CH_2)_6OH$	318.5	31.32	(0.098)
	368.5	38.50	0.105
	418.5	45.22	0.108
	462.0	49.56	0.107
			Mean 0.107
n-Octyl alcohol	173.5	6.78	(0.039)
$CH_3(CH_2)_7OH$	318.5	26.88	(0.084)
	418.5	38.34	(0.092)
	489.1	45.36	0.093
	539.1	50.86	0.094
	553.9	52.08	0.094
	589.1	55.44	0.094
	653.9	60.46	0.093
	753.9	71.70	0.095
			Mean 0.094
Primary isoamyl alcohol	115.5	9.48	(0.082)
$\genfrac{}{}{0pt}{}{CH_3}{CH_3}{>}CH\cdot CH_2CH_2OH$	223.3	24.48	(0.109)
(b.p. 130.0–130.2°C.)	418.5	47.88	(0.114)
	489.1	63.84	0.130
	553.9	72.24	0.130
	653.9	81.84	0.125
	653.9	86.80	0.133
	753.9	94.80	0.126
	753.9	100.30	0.133
			Mean 0.130

Table 1.—(*Continued*)

Lubricant	W(g.)	F(g.)	μ_k
n-Hexane $CH_3(CH_2)_4CH_3$ (b.p. 68–69°C.)	65.5	13.42	0.205
	92.7	19.86	0.214
	115.5	25.66	0.222
	173.5	41.22	0.238
			Mean 0.220
	35.5	10.80	0.304
	65.5	19.84	0.303
	115.5	36.72	0.318
			Mean 0.308[5]
n-Heptane $CH_3(CH_2)_5CH_3$ (b.p. 98.4–99.2°C.)	65.5	12.10	0.185
	92.7	16.72	0.180
	115.5	20.28	0.176
	173.5	30.18	0.174
	215.5	37.98	0.176
			Mean 0.178
n-Octane $CH_3(CH_2)_6CH_3$ (b.p. 124–125°C.)	65.5	13.26	0.203
	92.7	18.94	0.204
	115.5	22.80	0.206
	173.5	35.70	0.206
	215.5	44.10	0.205
			Mean 0.205
n-Nonane $CH_3(CH_2)_7CH_3$ (b.p. 147.0–147.8°C.)	65.5	15.34	0.234
	92.7	21.28	0.229
	115.5	27.46	0.238
	173.5	41.15	0.237
			Mean 0.235

Lubricant	W(g.)	F(g.)	μ_k
n-Valeric acid $CH_3(CH_2)_3COOH$	115.5	12.06	(0.104)
	215.5	27.48	(0.127)
	318.5	42.24	0.133
	418.5	54.72	0.131
	563.8	73.32	0.130
	663.8	86.82	0.131
			Mean 0.131
n-Caproic acid $CH_3(CH_2)_4COOH$ (b.p. 194–195°C.)	215.5	17.94	(0.083)
	563.8	67.52	0.120
	563.8	64.62	0.113
	663.8	80.40	0.121
	663.8	76.04	0.115
	763.8	91.55	0.120
	763.8	87.16	0.114
			Mean 0.117
n-Heptylic acid $CH_3(CH_2)_5COOH$	698.5	66.66	0.095
	848.1	82.94	0.098
	948.1	93.10	0.098
	948.1	85.14	0.090
	1093.8	102.90	0.094
	1193.8	108.42	0.091
			Mean 0.094
n-Caprylic acid $CH_3(CH_2)_6COOH$	598.5	36.30	(0.061)
	848.1	65.14	0.077
	948.1	75.18	0.079
	948.1	68.06	0.072
	1083.8	79.40	0.073
	1183.8	87.88	0.074
	1343.4	101.34	0.075
			Mean 0.075

(5) Hexane gives two different values of μ_k, 0.220 and 0.308, the reason of which is yet unknown.

Table 1.—(*Concluded*)

Lubricant	W(g.)	F(g.)	μ_k	Lubricant	W(g.)	F(g.)	μ_k
n-Nonylic acid $CH_3(CH_2)_7COOH$	598.5	25.20	(0.042)	Water	35.5	9.40	0.265
	948.1	50.34	(0.053)		65.5	17.26	0.264
	1083.8	62.40	0.058		92.7	25.20	0.272
	1183.8	68.64	0.058		115.5	31.96	0.277
	1343.4	77.78	0.058		173.5	48.34	0.279
	1443.4	84.64	0.059		35.5	8.74	0.246
			Mean 0.058		65.5	16.30	0.249
Water	25.5	6.24	0.245		92.7	24.66	0.266
	35.5	8.76	0.247		115.5	29.74	0.258
	65.5	15.66	0.239		173.5	45.42	0.262
	92.7	23.02	0.248		35.5	9.94	0.280
	35.5	8.4	0.237		65.5	17.68	0.270
	65.5	14.16	0.216		92.7	28.84	0.311
	92.7	21.76	0.235		115.5	33.82	0.293
	115.5	26.28	0.228		173.5	51.10	0.294
	173.5	39.86	0.230				Mean 0.255

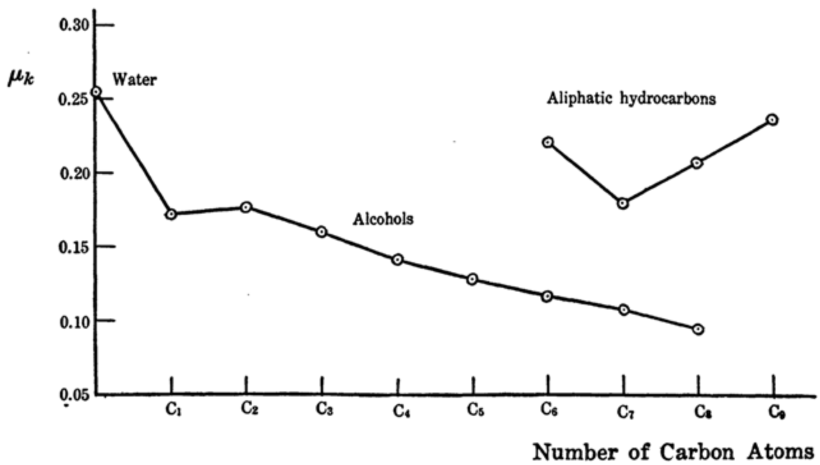

Fig. 5.

Table 2. Mixture of Water and Ethyl Alcohol.

Lubricant	W(g.)	F(g.)	μ_k
water 90% alcohol 10%	65.5	13.86	0.212
	65.5	13.44	0.205
	92.7	19.32	0.209
	115.5	21.88	0.189
		Mean	0.204
water 74.9% alcohol 25.1%	65.5	13.26	0.202
	65.5	11.70	0.179
	92.7	20.46	0.221
	92.7	16.14	0.174
	115.5	20.40	0.177
	173.5	31.18	0.180
		Mean	0.189
water 50.1% alcohol 49.9%	65.5	11.76	0.180
	92.7	16.92	0.183
	92.7	16.83	0.182
	115.5	20.40	0.177
	115.5	21.78	0.189
	173.5	33.82	0.195
		Mean	0.184
water 25% alcohol 75%	65.5	11.52	0.176
	92.7	16.50	0.178
	115.5	20.49	0.177
		Mean	0.177

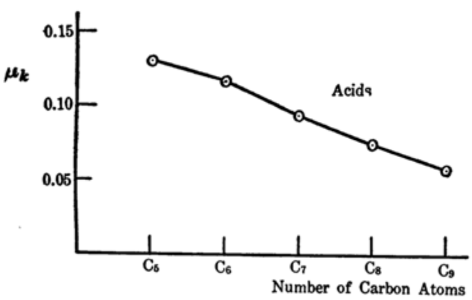

Fig. 6.

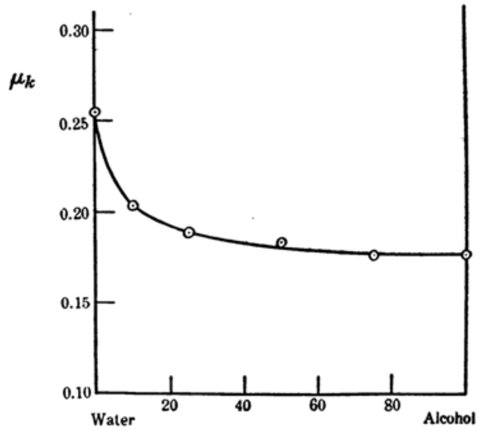

Fig. 7.

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Chemical Institute, Faculty of Science,
Imperial University of Tokyo,
Tokyo.