The Effect of Gases, Vapours and Liquids
on Limiting Friction.
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by

JAMES M. MACAULAY, B.Sc., A.R.T.C., A.M.I.E.E.

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THE EFFECT OF GASES, VAPOURS and LIQUIDS on the LIMITING FRICTION between SOLID SURFACES.

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JAMES M. MACAULAY, B.Sc., A.R.T.C., A.M.I.E.E.

If a piece of plate glass is laid on another similar piece and the interface between the plates examined under monochromatic (sodium) light or under white light, a number of parallel interference bands may be observed indicating that a wedge of air, of considerable thickness, has been trapped between the plates. The question arises:- What is the nature of the support of the upper plate?

The colours (if any) observed with white light and the number of the interference bands observed with sodium light enable an esti:mate to be made of the thickness of the wedge between the plates. For example, suppose only a faint rose colour (the last "pale rose" of Newton's colours of thin plates)* is visible at one edge, when white light is used, while about 30 bands are seen with sodium light, then the thickness of the trapped wedge varies from about 0.0002 c.m. to 0.002 cm. By pressing the plates together the angle of the wedge can be readily altered, and, if the glass surfaces are of good opti:cal polish, a uniform colour (under white light) can be got all over the surface, and this colour can, by pressure, be changed finally through red, orange, straw, whitish, grey (when the film thickness is about 0.00001 cm.) to black,* when the glass surfaces may be said to be "in contact". Now molecular forces are usually assumed to have a range of about 10^{-6} cm.; so when two surfaces are placed together they are usually separated by a layer so thick that there can be no direct action of the particles in the one surface on those of the other.

* See S.P. Thompson's "Light Visible and Invisible" p.140.

Fig.1.
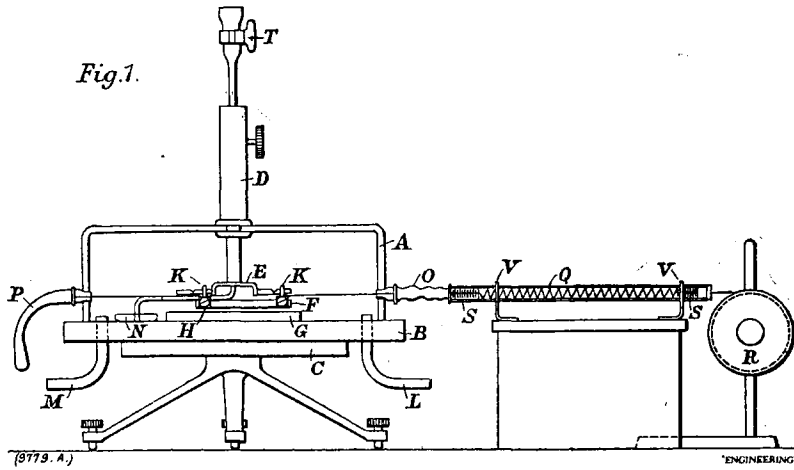
But, in considering the nature of the support of the upper
of two plates separated by an air layer, it must be remembered that
ordinary atmospheric air contains multitudes of large solid particles,
the motes which dance in a sun-beam – [*] and also that it contains water
vapour. The late Lord Rayleigh in a paper "On the theory of Surface
Forces" [†] comments on the fact "that a solid body brought into contact
with vapour at a density which may be much below the so-called point
of saturation will cover itself with a layer of fluid"..."The fluid
composing the layer, though denser than the surrounding atmosphere
of vapour, cannot properly be described as either liquid or gaseous".
Again "In our atmosphere fresh surfaces e.g. of split mica or of
mercury, attract to themselves at once a coating of moisture. In a
few hours this is replaced or supplemented by a layer of grease,which
gives rise to a large variety of curious phenomena. In the case of
mica the fresh surface conducts electricity while an old surface on
which presumably the moisture has been replaced by grease insulates
well".

It was thought that it might be of interest to investigate
how far the friction between solid surfaces was altered by the nature
of the atmosphere in which the surfaces were placed; different surface
layers might be formed and the coefficient of friction between the
surfaces thereby altered. For this purpose an apparatus was designed
to enable plates to be laid together in different gases.

The apparatus employed is illustrated by Fig. I. An inverted
glass vessel A rests in a groove formed in a supporting plate B which
rests on a levelling table C. Mercury poured into the groove gives
a gas-tight joint. D is a tube containing a rack and pinion designed
to be gas-tight but allowing the carrier E to be raised and lowered.
G is the fixed plate and F the sliding one. Two clips H enable the
sliding plate to be lifted by the rack and hooks K, so that the
sliding plate can be brought back to the same initial position without
sliding on the surfaces in the reversed direction.

[*] The naked eye can see 0.001 cm.

[†] Collected papers, Vol.III,p.523.

Any desired gas can be introduced through M, the outlet being by means of the tube L.

The pull was applied by means of a calibrated spring, but (so that the chamber might be kept gas-tight) the spring was fixed to a cork in the end of the tube Q and the latter was moved over V-supports in order to stretch the spring and apply the pull from the friction winch R. Q was connected to the chamber A by means of a flexible rubber connecting piece O. The plate F, after being raised, was adjusted to its fixed starting position on the carrier E by means of a thread passing into the flexible rubber balloon P.

As in all work on friction, the initial trouble is the definition of the surface conditions with respect to "cleanness". It is well known that if two glass surfaces are very clean 'seizing' will take place and erratic values for the coefficient of limiting friction μ - up to as much as unity - will be obtained, accompanied by scratching of the surfaces. * For example, using two glass plates of good optical polish (kindly supplied by Messrs. Barr and Stroud, Ltd.) coefficients of limiting friction as high as 0.8, 0.9, over 1.0 were obtained when the surfaces had been very thoroughly cleaned by prolonged washing with sodium oleate in running hot water, then in hot distilled water, drying being done rapidly before an electric radiator and the surfaces placed together while hot. Slipping when it did occur was with a jerk and a scratching of the glass. If the surfaces, after washing, were rubbed with 'clean' dry linen, co-:efficients of limiting and of kinetic friction as low as 0.2, 0.1, 0.08 were observed, and slipping was then steady and slow (say 1 cm. per minute) suggesting the viscous flow of a fluid.

In the experiments about to be described extreme cleanness of surface was not aimed at and the difficulty introduced by 'seizure' did not therefore arise. The initial condition of surface may be specified as follows:- The plates were thoroughly washed in soap and water, then rinsed in either distilled or clean Loch Katrine water, and allowed to dry in air. The marks which always remained on the dry surfaces were then removed by rubbing with a 'clean' linen cloth.
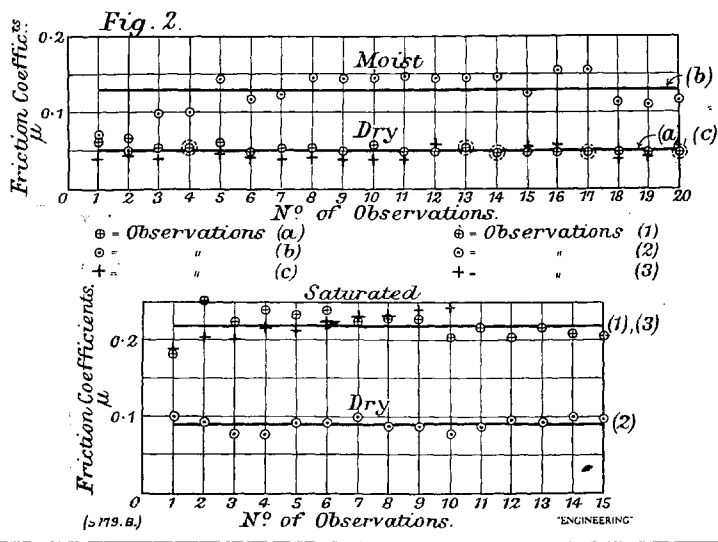
Fig. 2.

$\oplus$ = Observations (a) $\dot\oplus$ = Observations (1)
$\odot$ =   "   (b) $\odot$ =   "   (2)
$+$ =   "   (c) $+$ =   "   (3)

(5179.B.)

The question of the flatness of the glass surfaces was also considered, and two pieces of thick plate glass were selected which showed regular interference bands with sodium light. In view of the fact that Hardy found the coefficient of friction to be sensibly the same for ordinary plate glass as for optically plane glass, the sur-:faces chosen were taken to be satisfactory for the purposes of the experiments.*

The next point to consider was the constancy of conditions when air was used as an atmosphere. It was decided from Hardy's work that no appreciable errors would arise from changes in room temperature, but there remained the question of varying atmospheric humidity.* It was decided to work with the atmosphere as dry as possible, so a dish containing concentrated sulphuric acid and another containing phosphorus pentoxide were inserted in the chamber A. The line marked 'dry' in Fig. 2 (observations a, points ⊕) shows the results of 20 experiments, performed in succession, giving a mean value of 0.05 for μ , the coefficient of limiting friction between the glass surfaces. This value was much lower than was expected, and the observations were again made after removal of the drying agents and with the chamber A containing air of the humidity of the particul-:ar day. An average value for μ of about 0.13 was now obtained, as shown by the upper line marked 'moist' in Fig. 2 (observations b. points ⊙). The drying agents were then reinserted and the apparatus left in the sealed condition for about 24 hours. Observations c, marked +, were next obtained giving again 0.05 as the mean value for μ . These results show that the coefficient of limiting friction had been reduced from 0.13 to 0.05 by the removal of moisture from the atmosphere. The normal reaction between the surfaces (due simply to the weight of the top plate) was 101.3 grams or about 2.01 grams per square cm. It was noted that the readings for the dry condition were much more consistent than for the moist condition.

✸ Hardy, Phil. Mag. p.33 and p.49, Vol. XXXVIII,1919

It was now decided to investigate this effect of water vapour, with different gases and with different surfaces (glass, steel, brass). With the glass surfaces an endeavour was made, but without success, to detect a change in the surface layers by observation of the interference bands produced by sodium light.

In order to save time the gases were drawn through an ordinary chemical drying apparatus, containing calcium chloride and concentrated sulphuric acid, before entering the chamber A. The drying agents in the chamber were then left with little drying to do. The gases were saturated with moisture by bubbling them through water in a vessel which replaced the drying apparatus, the drying agents in the chamber having been removed and replaced by a dish containing water.

The glass plates having been cleaned again and the chamber A filled with saturated air, a series of experiments was performed and the observations indicated by line 1, Fig. 2, obtained. The saturated air was then replaced by dry air and it was found that a period of 2 hours was sufficient to enable the coefficient of limit- :ing friction to be reduced from $\mu = 0.22$, the value for the saturated condition, to 0.09 for dried air. This value increased again to about 0.22 on leaving the air in contact with the water dish over- :night. The large difference (0.05 and 0.09) in the coefficients obtained with dry air, shown by lines a,c, and 2. (the plates having been 'cleaned' between the two sets of observations) may be accounted for by a difference in the surface 'grease' referred to in the quotation given above from the paper by the late Lord Rayleigh on surface forces. Further examples of this variation are shown later in Table II.

Table I summarizes the results obtained with glass plates in atmospheres of air, hydrogen and carbon dioxide, saturated and dry; and also with plates of brass and of steel with surfaces optically polished and kindly supplied by Messrs.Barr & Stroud Ltd.

In the earlier experiments the values of μ were calculated as the mean of 50 successive observations, but as this mean value was found not to differ sensibly from that of about 10 successive observations, the latter number was taken as the minimum from which to obtain the values for μ given in this table.[*]

TABLE I.

	Surfaces.	Normal Reaction		Atmosphere	Average Value of μ		% increase in μ, wet over dry.
		Grams	Gms/cm^2		Dry	Moist	
	Glass on Glass	101.3	2.01	Air	0.05	0.13	160%
(1)	Glass on Glass	101.3	2.01	Air	0.09	Saturated 0.22	145%
	" " "	91(4)	1.80	Flooded with water	-	0.23	155%
	" " "	101.3	2.01	Hydrogen	0.10	over 0.33	over 230% (2)
	" " "	"	"	Carbon di- -oxide	0.11	over 0.33	over 200% (2)
(3)	Brass on Brass	128.8	20.6	Air	0.12	0.14	17%
(3)	Steel on Steel	124.2	19.9	Air	0.13	0.20	54%

(1) Surfaces again cleaned. (2) Spring stretched to fullest extent.
(3) Cleaned with benzol and linen. (4) 10 grams buoyancy correction.

In every case the addition of water vapour to a dry atmosphere is shown to have produced a notable increase in the coefficient of limiting friction; and this increase, when the atmosphere was hydrogen and when it was carbon dioxide, was substantially greater than when the atmosphere was air. The third line of the above table shows that the effect produced by flooding the glass surfaces with water was to produce an even greater increase in friction than that produced by the water vapour.

No appreciable difference is shown in the coefficients obtained with glass in dry atmospheres of air, hydrogen and carbon-dioxide.

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[*] In subsequent work with other vapours, the number of observations was increased again to 50 for each value of μ .

Fig.3.

P   P   W   P

Solid

Surface
Layer

P   p   P   r   r₁   Air

Solid

(9779.C.)   "ENGINEERING"
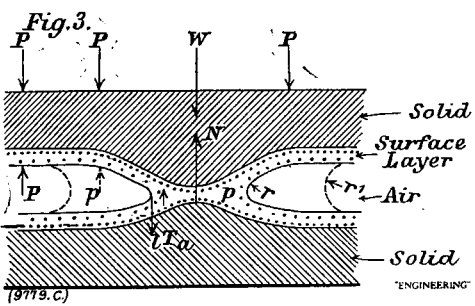
The following method of accounting for the effects due to water and to water vapour may be of interest, since it suggested further experiments to be described later, using other liquids and vapours. Consider two surfaces, in a <u>dry</u> atmosphere, being slowly brought into contact. The surfaces will be coated with layers (of grease, etc.) having more substantial properties on the sides next the solid surfaces than on the sides next the atmosphere. The surfaces, even although of good optical polish, will not be mole-:cularly plane, so that small projections from the surfaces will provide points of 'contact' - whatever 'contact' may mean.

The accompanying diagrammatic sketch (Fig. 3) is meant to represent a single point of contact between the two plates. As the plates were being brought together the surface layers would be thinned down until levels were reached which were substantial enough to give a normal reaction N, sufficiently great to support W, the proportion of the total load to be borne by the point of contact. The surface layers will assume some such form as that illustrated, so that surface tension effects have also to be considered. The surface separating the layer from the surrounding atmosphere may be somewhat indefinite, and may be regarded as of weak surface tension $_{\ell}T_a$. If P represents the pressure of the atmosphere and p the pressure behind the curved surface (radius r) of the layer, then the plates will be pushed together by a force $(P-p)$ multiplied by some small area A, and $W+(P-p)A = N$ Also $(P-p) = {}_{\ell}T_a / r$ so

$$W = N - {}_{\ell}T_a \cdot A/r$$

Now, in order to get the case of surfaces flooded with water, suppose simply that the air between the plates is replaced by water. Then

$$W = N' - {}_{\ell}T_w \cdot A/r$$

where $_{\ell}T_w$ is the surface tension for a water/layer surface. This surface tension will be much greater than that of an air/layer surface, hence N' is greater than N, so that friction is increased without increasing W, by flooding the surfaces with water. Friction forces have the same origin as the normal reactions N.

Next consider the surfaces again in a dry atmosphere and add moisture to the atmosphere. A thin layer of moisture will form on the surfaces of the existing surface layers or may partly replace these layers. When the plates are now brought into contact, the thin water films will touch first, and a flattened water drop will form round some of the points of contact, as illustrated by the dotted curves (of radius r') in the sketch (Fig.3). Such drops form-:ing round the points of contact which first come into action may absorb all the water available in the thin water films, so that many points of contact may be without water surrounding them. Other things being the same as before we have

$$W = N'' - {}_{\varrho}T_w \cdot A/r - {}_wT_a \cdot A'/r'$$

where T_{wa} is the surface tension of a water/air surface T_{wa} will be of similar magnitude to ${}_{\varrho}T_w$. N'' is thus even greater than N', but in the case of flooding, all points of contact have to be considered, whereas with moisture acquired from the atmosphere there may be only a few points surrounded by water. Thus the greater effect shown by the third line of Table I to have been produced by flooding can be readily accounted for.

By way of illustration a numerical calculation will be help-:ful. Consider simply a tiny drop of water flattened between two surfaces, so that the flattened drop is of thickness about 2 wave-:lengths of sodium light 0.0001 cm.($r = 0.00005$ cm), and of radius 0.1 mm. (area $= 0.0003$ sq. cm.),then, the surface tension of water being 73 dynes per cm, the plates (due to surface tension) will be pulled together with a force equal to $73 \times 0.0003/0.00005$ dynes or about half a gram weight; and the surface tension effect of 6 such tiny drops per sq.cm. would suffice to account for the 145 per cent increase in the coefficient of limiting friction shown in the second line of Table I, - the normal reaction of 2 grams per sq.cm.being increased to 5 grams per sq.cm. without altering the load on the top plate. Of course a greater number of smaller drops would have a similar effect.

It should be pointed out that these experiments have been carried out under conditions of low normal reaction, so that it is to be expected that the effect of the water vapour when heavier loads are employed will be relatively smaller, - if the number of water drops per sq.cm. remains the same and the plates remain at sensibly the same distance apart, the surface tension forces will remain constant and so contribute a smaller proportion of the combined normal reaction.

An endeavour was made to detect by direct experiment the amount of water which condensed on glass plates when they were removed from a dry atmosphere into one saturated with water.   Two glass plates (over 88 sq.cm. area and thin so that the total weight - 60 grams-might be kept low) were separated, dried for over 8 hours in the chamber (Fig.I.) laid together, removed and quickly weighed on a chemical balance which could just detect 0.0001 gram.   This was repeated after the plates had been separated, left in saturated air in the chamber and laid together.   No increase in weight could be detected.   A simple calculation then shows that, if the dimen-:sions already assumed for the water droplets formed when the plates were put together in the saturated atmosphere, (viz. 0.01 cm. radius and 0.0001 cm. thick) be taken, then only sufficient moisture could have condensed on the plates to give certainly less than 36 drops per sq.cm. and probably less than 18 drops per sq.cm.   To account for the moisture effect on friction only 6 such droplets are re-:quired.

It may be remarked that this method of regarding the forces between two plates as being of two kinds, 'repulsive' forces N, and forces of attraction (the surface tension effect), is in accord with the known characteristics of 'forces of cohesion', (when molecular motion is ignored); viz to use old phraseology, that they become sensible as forces of attraction at insensible distances and change to forces of repulsion when the distance is still further reduced. And further, the method accounts for the differences in the coeffi-:cients of friction (such as the 0.05 and 0.09 referred to above)

which are due to differences in the layers on surfaces tested in a dry atmosphere. With very clean surfaces (thin films) coefficients of friction are large, since for the same W, N is larger due to r being smaller for thin layers, and probably also because $_\ell T_\alpha$ would naturally be larger for the thinner and more substantial layers.

In order to test the theory further the following experiments were performed. If the theory be true the effect on friction, produced by flooding the surfaces, and by vapour in the atmosphere should hold for any liquid or vapour, provided, of course, there be no chemical or solvent action on the surface layers; and liquids of great surface tension should have a greater effect than liquids of small surface tension.

The first vapour and liquid to be tried was Ethyl Ether (Sp. gr. 0.720). The vapour was first introduced into the chamber (Fig.I) by bubbling dried air through the liquid for a period of three hours. No increase in μ was observed; indeed a small decrease appeared to have occurred. It was thought that possibly the current of air saturated with ether vapour and possibly ether spray had wetted the surface and the ether had evaporated off again leaving a 'greasy' impurity behind. Hardy notes this effect,* and an examination of the surfaces subsequent to observation (3) Table II, revealed, by breathing on the surfaces, streaks in the direction on which the plates had been sliding. The experiment was therefore repeated but the ether was now introduced into the chamber, filled with dry air, by the tube fitted with the tap marked T in Fig. I, so that a free ether surface was formed in the dish N shown in the diagram. Now ten minutes were found sufficient to increase μ to about the mean value (50 observations) of 40 per cent above the dry air value.

Table II gives the results obtained with the vapours of Ethyl Ether, Acetic Anhydride and Bromine, together with the values for μ when the plates were flooded with ether and with acetic acid. The flooded value was not obtained for Bromine because of the chemical action of this vapour on the mercury seal and metal parts of the apparatus necessitating short duration.

* Phil. Mag. p.46 Vol. XXXVIII, 1919.

TABLE II.

SURFACES - GLASS on GLASS.

Vapour or Liquid.	Normal Reaction Grams	Grms/cm²	Average Value of μ Dry Air A	Air saturated with Vapour B	Flooded with Liquid C	% Increase in μ B over A	C over A
Water	101.3	2.01	0.09	0.22		145% (1)	
(2)	91	1.80			0.23		155% (1)
Ethyl Ether	101.3	2.01	0.20	0.28		40%	
(S.G.0.720)	"	"	0.24				(3)
	"	"	0.16				
(2)	90	1.78			0.47		195%
Acetic Anhydride	101.3	2.01	0.18	0.28		56%	
	101.3	2.01	0.10				
(2)	86	1.70			0.38		280%
Bromine	101.3	2.01	0.33	0.51		55%	

(1) Transcribed from Table I. (2) Corrected for buoyancy
(3) The observations for this value were taken to ascertain
whether there were any after effects subsequent to deposition
of ether, i.e., the ether dish was quickly removed and dry
air passed through the chamber for 4 hours 10 minutes.

All the above values of μ are calculated by taking the arithmetic
mean of 50 successive observations with the exception of those for
water vapour (15, 10, and 10, respectively) and of Bromine
(50 and 6 respectively). The plates were cleaned, as already
described before using each vapour, and a period of at least two
hours allowed to elapse for drying the plates with the current
of dry air.

Again, the addition of each vapour to a dry atmosphere has
produced a substantial increase in the coefficient of limiting

friction, and the flooded surfaces show a greater increase still.

It was thought that it might be of interest to try the effect produced by flooding the surfaces with (i) air-free water, (ii) ordinary water saturated with air. Air might come out of solution and alter the layer on the surfaces of the plates, so as to increase the value of the surface tension for a water/layer surface, and so increase the coefficient of limiting friction. The apparatus used for these experiments was quite different from that already described. Clean glass plates were placed in a rectangular glass trough fitted with a water-tight lid provided with inlet and outlet tubes. To enable the plates to be held apart and lowered into contact, threads passed through the outlet tube. Thoroughly boiled water which had never been in contact with air after boiling, was passed through the trough, which was then placed on a tilting table. The plates were lowered into contact and the coefficient of limiting friction found by observ-:ing the angle of friction. Rather erratic values were found for the angle, partly due to the plates tending to grip towards one corner, with resulting rotation. However a mean value, $\mu = 0.31$ was obtained from 50 successive observations, no single observation differing by more than 21 per cent from the mean. The air-free water was then replaced by ordinary tap water from which all the visible air bubbles had been removed, after the water had been standing for four hours. The angle of friction was now found to be distinctly <u>less</u> than had been obtained with air-free water; a decrease of as much as 60 per cent was found in the mean value for μ. But visible air bubbles had still formed and were easily seen trapped between the plates. The pressure inside such bubbles would be <u>greater</u> than the surrounding pressure so, in accordance with the surface tension theory, friction <u>ought</u> to be diminished. The experiment was therefore repeated, using now tap water which had been raised to 40° C. and allowed to cool to room temperature.

No bubbles were now visible on the plates, and the coefficient
of friction was found to have _increased_ in accordance with
expectations. A value $\mu = 0.38$ was obtained as the mean of 50
observations, the greatest departure of a single observation from
the mean being about 20 per cent. This increase in friction was
confirmed by a repetition of the experiments with air-free water
and with the water which had been heated to $40°$ C. Air had come
out of solution to form an air layer on the surfaces of the plates,
which is quite a different thing from a layer of air bubbles.

As a further test it was thought that it might be of interest
to try how nearly the increases in friction, produced by the various
vapours, were proportional to the surface tensions of their
respective liquids.

Table III, column 4, gives the values obtained from the
observations.

If the remarkable assumption be made that the thickness
(t) of the film of liquid (deposited by the vapour) from which the
droplets are obtained is the same for each liquid,* and the probable
assumption that the average distance apart of the plates remains
the same (2r), the theory which is being propounded gives the
surprising result that the values of the coefficients (column 5,
Table III), calculated from the magnitudes of the liquid surface-
tensions, are in exact agreement with those obtained as experimental
values, within the accuracy of the experiments.

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* Since this paper was written it has been found that experiments
by E. Pettijohn described in the Journal of the American Chemical
Society ("Measurement of the Thickness of Film found on Glass and
Sand", 1919, Vol. XLI, p.477), justify this assumption. Thus,
with water and other five liquids "chosen so that the Specific
Gravity, Volatility, Surface Tension, etc., varied" his conclusions
are given in the following words:-
"The method has been applied to sand and to glass, and films
    have been formed with water and with several organic liquids.
    The film thickness is found to be independent of the liquid used
    (and of the size of the solid particle) --- "While these films
    are formed by the addition of liquid to the solid, the inference
    is that the same conclusion may be drawn for a film formed from
    the vapour phase" --"Evidence is presented to show that the
    liquid forming the film does not combine chemically with the
    solid".

If μ_v is the coefficient of friction with vapour (defined by $F = \mu_v W$, where W is the total applied normal load) and μ is the coefficient with dry surfaces then

$$\mu_v W = \mu \left(W + \frac{T}{r} a n \right)$$

where T is the surface tension of the liquid, a the cross-sectional area of a droplet and n the total number of such droplets between the surfaces.

The first assumption made above means that a n is constant and with the second that an/r is constant say = k. Hence

$$\mu_v = \mu \left(1 + \frac{k}{W} \cdot T \right) ------------(A)$$

The values for μ_v in column 5, Table III were calculated from equation (A) using the value for k, viz., an/r $= \pi \times 01^2 \times 6 / 0 \cdot 00005 (=39)$ already found in the water vapour experiments, and from the respect:ive book values for T given in column 2.

TABLE III.

Vapour	Value of Surface Tension T Dynes/cm.	Coefficient (dry)	Experimental value of μ_v (from Table II)	Calculated value of μ_v (from eqn. A)
Water	73	0.09	0.22	0.22
Ethyl Ether	18	0.20	0.28	0.27
Acetic Anhydride	32	0.18	0.28	0.29
Bromine	44	0.33	0.51	0.61

The experimental value for Bromine is, of course, low on account of the short duration of the experiment; only 6 observations could be taken before the action of the Bromine on the apparatus compelled the abandonment of the experiment.

It might be thought that the above calculation should apply equally well to the case of flooded surfaces. But it would be unreasonable to ignore the solvent action of the liquids on the layers of 'grease' (as they are usually called) on the glass surfaces.

In fact the theory receives further support from the <u>extra</u> <u>large</u>
increases in friction, shown by Table II, to have been obtained
by flooding the surfaces.   The liquids would thin down the
surface layers, and, as already pointed out, this ought to mean
further increase in the friction coefficient μ and so of μ_v

- - - - - - - - -

Further corroboration of the surface tension theory from
which equation (A) above has been derived, may be obtained by
applying the theory to the results of the beautiful experiments
(with '<u>clean</u>'flooded surfaces) recorded by Sir William Hardy and
Miss Bircumshaw in their Bakerian Lecture published in the May
issue of the Proceedings of the Royal Society of last year.[*] '<u>Clean</u>'
surfaces are not free from surface layers of condensed gas or other
impurity, so the surface tension effect described above will come
into play with clean surfaces as well as with surfaces coated with a
'grease'layer.   To quote from an earlier paper by Sir William Hardy
and Miss I. Doubleday[†] "'clean' surfaces are not the same as surfaces
freshly produced by fracture.   It is said that when steel is fract-
:ured under mercury the new surfaces amalgamate; 'clean' steel plates
in clean air will not amalgamate".

On page 20 of the Bakerian Lecture for 1925, a diagram is
given summarizing the results of numerous experiments with normal
paraffins and their related acids and alcohols.   From that diagram
values can be obtained for coefficients of friction observed when a
<u>steel</u> sliding plate was used having (1) a spherical shaped face,
(2) a plane face.   Now when a spherical shaped slider rests on a
plane lubricated surface, the area of contact is excessively small,
so the coefficient of friction observed will correspond to a very
high value of W in equation (A) above, that is practically to μ
of that equation; while the observations made with a plane slider
will give μ_v.

[*] Roy. Soc. Proc. Vol. A 108, 1925, p.1.

[†] "   "   "   "   " 100, 1922, p.552

But it is possible to calculate μ_v from μ (by equation (A)) provided the constant K for the plane slider experiments can be determined, and the surface tensions of the various liquids obtained. K depends on the number and area of the 'points of con:tact', that is on the nature of the material of which the surfaces are made and on the degree of polish. To obtain K (for the Bakerian Lecture experiments) it is necessary to take for one chosen liquid both the experimental values μ and μ_v given by the spherical and plane slider respectively. For all other liquids values for μ_v can then be calculated from the experimental values for μ and the surface tensions; and the results compared with the experimental values of μ_v.

Thus, choosing Octyl Alcohol as the lubricant from which to obtain K, for the steel surfaces,

μ (from spherical slider experiments) = 0.307

μ_v (" plane " ") = 0.457

W (the weights of the plane slider) = 20.4 grams.

T (the surface tension of Octyl

Alcohol at $15^{\circ}C$) = 27.9 dynes/cm.

Hence from equation (A)

$$0.457 = 0.307\left(1 + \frac{K \times 27.9}{20.4 \times 980}\right)$$
$$\therefore K = 350$$

For any other liquid, e.g., Pentane which gave μ (spherical slider experiments) = 0.485 and for which T at $15^{\circ}C$ is 22.7 dynes/cm.

$$\mu_v = 0.485\left(1 + \frac{350 \times 22.7}{20.4 \times 980}\right) = 0.67$$

This agrees well with the value 0.68 recorded in the Bakerian Lecture as having been obtained by experiments using the plane faced slider.

Table IV below contains all the lubricants used by Sir W. Hardy and Miss Bircumshaw, for which the author of this paper could obtain the necessary data. Although unfortunately there is

no great variation in the surface tensions of these lubricants,
the close agreement between the calculated and experimental values
of μ_v shown in columns 4 and 5 of Table IV is in satisfactory
agreement with the results recorded in Table III.

TABLE IV.

Lubricant	μ (Spherical Slider Experiments.)	Surface Tension dynes/cm at 15° C.	μ_v Calculated from eqn.(A) and	μ Hardy's Slider experi- :ments.
Pentane	0.48$_5$	(a) 22.7	0.67	0.68
Hexane	0.46$_5$	19.0	0.62	0.65
Octane	0.42	22.3	0.58	0.60
Ethyl Alcohol	0.45	22.2	0.63	0.64
Propyl "	0.43	23.8	0.61	0.62
Butyl "	0.40	24.2	0.57	0.58
Octyl "	0.307	27.9		0.4575
Cetyl " (liquid state)	0.12	(a) 28.4 (b)	0.18	0.24
Hexoic Acid	0.33	(a) 26.8	0.47$_5$	0.45
Caprylic "	0.20$_5$	(a) 27.5	0.30$_5$	0.29

(a) Determined by the author (Jaeger's bubble method)—about

$\pm$ 3% accuracy.

(b) At 51° C. approximately the melting point.

EFFECT OF PRESSURE.

An inspection of equation (A), $\mu_v = \mu \left(1 + \dfrac{kT}{W} \right)$,
indicates that μ_v is not constant for different values of W, but will
decrease as W increases, reaching a limiting value when W is large
compared with k T. This does not really mean a departure from the
law of proportionality of friction to normal reaction. The friction-
al resistance called into play, when a tangential pull is applied,
is the horizontal component of the forces which give rise to the
force N shown in Fig. 3; no horizontal force results from the
presence of liquid drops, so long as there is no motion.

Fig.4.
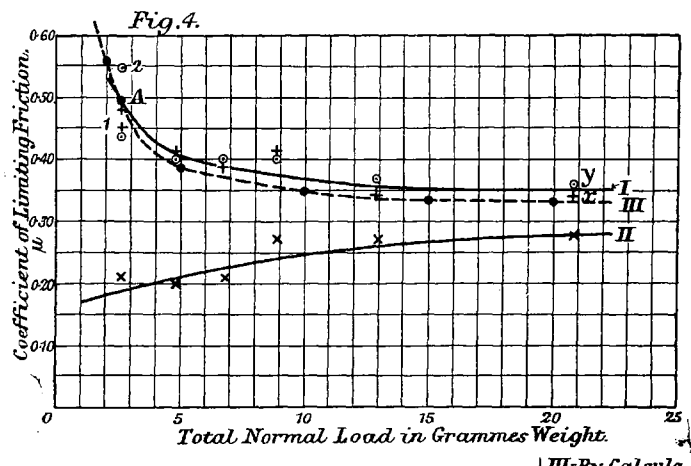
I:-From Experiments in Air Saturated with Moisture.
II:- " " Dry Air.
III:-By Calculation from Equation A.

(9779.D.)

ENGINEERING

When slipping occurs, calculations based on a thickness of film
equal to that already chosen, and bringing in the coefficients
of <u>viscosity</u> of the various liquids, indicate that a satisfactory
explanation of the differences, real or apparent, between limiting
and Kinetic frictions may possibly be obtained.   But this point
requires further investigation.   So far as limiting friction is
concerned $F = \mu N$ is regorously obeyed in all cases, $F = \mu W$ is not.

To test the effect produced by varying the load on the
friction plate, simple devices were designed so that (a) the
normal load could be increased and decreased, (b) the atmosphere
in the chamber could be saturated or dried as desired, without
requiring the chamber to be opened throughout the course of the
experiments.   To avoid changing the spring used to apply pull,
(involving considerable alterations to the apparatus) a much
smaller sliding plate (glass of area about 1 sq.cm.) was chosen.
This increased the difficulties with reference to consistency of
observations, but it is estimated that an accuracy of within ±5
per cent has been attained by taking averages of 20 successive
observations.

The air in the chamber was saturated with water vapour
as in the previous experiments, and points marked + (Fig.4)
obtained.   The air was then dried as before and the points marked
X were plotted.   In order to see that the surfaces had not been
altered by these numerous experiments, the air was again saturated
with moisture and the points marked ⊙ were obtained.

Owing to the large change in μ_r which takes place at the
lowest normal load available (2.6 grams per sq.cm.), the point A
is of special importance, and this point was, therefore, specially
checked - point 1 (10 observations) immediately after point x, and
point 2 (20 observations) immediately after point y.   Curve I,
Fig. 4, represents the change in friction with increasing normal
load for an atmosphere saturated with moisture; curve II the change
for a dry atmosphere.   The two curves approach a common limit at a

high value of the normal load.

To test the surface tension theory, curve III was obtained by calaculation from equation (A) above, the value of the constant being found from the saturated and dry values for μ (0.49 and 0.19) for load 2.60 grams per sq. cm. Using this value for K and the value given by curve II for μ(dry) corresponding to a chosen load, table IV was calculated and curve III plotted from the values for μ_v thus obtained.

Equation (A) is $\mu_v = \mu\left(1 + \frac{K}{W}T\right)$

so $0.49 = 0.19\left(1 + \frac{K \times 73}{2.60 \times 980}\right)$

$\therefore K = 54$

When $W = 5$ grams (say)

$\mu_v = 0.21_5\left(1 + \frac{54 \times 73}{5 \times 980}\right) = 0.39$

TABLE IV.

W (grams)	μ (dry)	μ_v
1	0.17$_5$	0.88
2	0.18$_5$	0.56
5	0.21$_5$	0.39
10	0.25	0.35
15	0.27	0.34$_5$
20	0.28	0.34
50	0.28	0.30
400	0.28	0.28

It has thus been shown that, for low loads, μ_v decreases rapidly with increase in load, to a limiting value when the normal load is of magnitude say about 400 grams per sq.cm. It is interesting to find that the curves I and III (saturated condition) are of the same form as those given (with flooded surfaces) in the Bakerian Lecture published in the May issue of the Proceedings of the Royal Society of last year.[*]

[*] Roy. Soc. Proc. Vol. A108, 1925, p.1.

Curves similar to III could of course be obtained for other vapours used in these experiments by substituting the corresponding values of their surface tensions in equation (A).

The <u>increase</u> in μ with increase in load (dry surfaces) indicated by curve II is interesting. A general explanation for this has already been suggested. It was pointed out above how very clean surfaces gave greater coefficients of limiting friction than less clean ones, due to the thinner and more substantial "grease" layers present on the very clean surfaces. Increase of normal load will tend to make existing layers thinner and more substantial.

<u>The Effect of Temperature.</u> Further, equation (A) shows that, as the Surface Tension of liquids <u>decreases</u> with rise in temperature, μ_v should also <u>decrease</u> with rise in temperature.

Hardy finds that this is the case. He gives the following values (Bakerian Lecture, Table VII) for steel surfaces, under a load of 20.4 grams, flooded with Caprylic Acid:-

At $15.5^{\circ}C., \mu_v = 0.288$

At $100^{\circ}C., \mu_v = 0.267$

His limiting (high load) value for μ, with the same surfaces, (he finds that μ is <u>independent</u> of temperature) is 0.206.

Hence from equation (A), $0.288 = 0.206 \left(1 + \dfrac{K \times 27.5}{20.4 \times 980} \right)$

$$\therefore K = 290$$

The surface tension of Caprylic Acid at 100° C. was found by the author to be 19.1 dynes per cm.

$$\therefore \mu_r = 0.202 \left(1 + \dfrac{290 \times 19.1}{20.4 \times 980} \right) = 0.263$$

as compared with experimental value above of 0.267.

assistance in connection with Surface Tension data; also to Mr.
Malcolm Smith for assistance in the design of, and skill in
constructing, the apparatus required.

SUMMARY.

(1) Reference is made to the manner in which the interference bands observed with monochromatic and with white light enable the thickness of the layer trapped between two glass plates, one laid on the other, to be measured. The problem ~~to be considered~~ is to discover what supports the upper plate and gives rise to friction.

(2) A description is given of two types of apparatus which enabled coefficients of friction to be measured for different surfaces (glass, brass, steel) in different atmospheres (air, hydrogen, carbon-dioxide, and air saturated with the vapours of water, ether, acetic acid and bromine); also for surfaces flooded with ordinary water, air-free water, ether and acetic acid.

(3) Friction coefficients were found to be the same for the different gases when dry, but in each case very much greater when the atmosphere was moist. The increases observed with different vapours (added to dry air) were directly proportional to the surface tensions of the respective liquids.

(4) The results summarized under (3) are accounted for by the fact that the surface tension of a liquid, condensed round "points of contact", would increase the normal reaction between the surfaces. Values for the coefficient of friction in a vapour saturated atmosphere, are calculated from the equation $\mu_r = \mu\left(1 + \dfrac{kT}{W}\right)$, using book values for T, the surface tensions of the various liquids. The calculated values agree with the experimental values exactly, within the limits of accuracy of the latter. It hs also shown that the same equation (with a new value for k) enables the experiment:al values of the apparent friction coefficient for plane steel surfaces (as given in the Bakerian Lecture referred to under (5)) to be calculated from the experimental values of the coefficient for a spherical slider of the same steel.

(5)   The equation give under (4) enables the forecast to be
      made that Amonton's Law (the law of proportionality of
      friction to normal reaction) will appear (though not
      actually) to be departed from for low normal reactions.
      Curves are given showing the relation of μ_v to W which are
      very similar to those given by Sir William Hardy and Miss
      Bircumshaw in their recent Bakerian Lecture to the Royal Society.

(6)   This equation also predicts (with numerical agreement) the
      effect of temperature on the apparent coefficient as first
      reported in the Bakerian Lecture.

THE THEORY OF THE POLISHING OF SOLID SURFACES

by James M. Macaulay, B.Sc., A.M.I.E.E.

In a paper entitled "Polish" (Collected Papers, Vol. IV, p.542, 1901) the late Lord Rayleigh states:

> "In the process of grinding together two glass surfaces,
> "the particles of emery, even the finest, appear to act
> "by pitting the glass, i.e. by breaking out small
> "fragments".

This view receives confirmation by the experiments (with a loaded steel ball) of Dr. J.W. French described in his article on "The working of Optical Parts" (Dictionary of Applied Physics, Vol.IV, p.326.

Lord Rayleigh proceeds to argue that polishing is probably an entirely different process although he quotes Herschel 'whom we may regard as one of the first authorities on such a subject' as follows:-

> "Enc. Met. Art.Light p.447,1830 -----"The intensity and
> "regularity of reflection at the external surface of a
> "medium is found to depend not merely on the nature of
> "the medium, but very essentially on the degree of
> "smoothness and polish of its surface. But it may
> "reasonably be asked how any regular reflection can take
> "place on a surface polished by art, when we recollect
> "that the process of polishing is, in fact, nothing more
> "than grinding down large asperities into smaller ones
> "by the use of hard, gritty powders, which, whatever
> "degree of comminution we may give them are yet vast
> "masses, in comparison with the ultimate molecules of
> "matter and their action can only be considered as an
> "irregular tearing up by the roots of every projection
> "that may occur in the surface. So that, in fact, a
> "surface artificially polished must bear somewhat of the
> "same kind of relation to the surface of a liquid or
> "crystal, that a ploughed field does to the most
> "delicately polished mirror, the work of human hands".

Lord Rayleigh then says:

> "But although perhaps no sure conclusion can be demon-
> ":strated the balance of evidence appears to point in the
> "opposite direction",

and again,

> "Under these (polishing) conditions which preclude more
> "than a moderate pressure, it seems probable that no
> "pits are formed by the breaking out of fragments but
> "that the material is worn away (at first, of course,
> "on the eminences) almost molecularly".

He further quotes experiments (made by weighing the glass removed) to show that the original mean (ground) surface of a glass

plate has to be lowered by 6 to 10 wave lengths of mean light to

get an unimpeachable polish. His final conclusion appears to be

--------"there would be much less difference than Herschel thought

"between the surfaces of a polished solid and of a liquid".

French, in the article referred to above, accepts this

view but remarks:-

> "Although the molecular character of the polishing operation
> "and the similarity of the surface produced to that of a
> "liquid are quite definitely expressed (by Lord Rayleigh)
> "and although Lord Rayleigh has referred in other of his
> "papers to the remarkable pool-like appearance of
> "elementary polished patches of a glass surface, it is not
> "quite clear whether he regarded the result as being due
> "to the removal of the substance molecule by molecule as
> "distinct from the removal of minute aggregates of molecules
> "or as being due to a molecular rearrangement or flow of
> "the surface molecules as in the case of a liquid. The
> "latter conception is attributable --------to Sir Geo.
> "Beilby, who has developed it --------in papers dealing with
> "metal surfaces, the tenacity of which is such that the
> "amorphous layer is capable of bridging over surface
> "cavities even when these are not completely filled with
> "debris. It is very doubtful if any such bridging over of
> "even minute cavities occurs in glass owing to the small
> "cohesion of the silicates as compared with that of metals.
> "According to the molecular-flow theory of polishing,
> "the forces exercised by the polisher upon the surface
> "molecules of the glass suffice to overcome the cohesive
> "forces binding them together, with the result that the
> "molecules re-arrange themselves uniformly under the action
> "of their surface tension forces".

Now it is usually assumed that such polished surfaces are molecularly

plane although there is no real justification in the views of Rayleigh,

Beilby or French for this assumption. It is known (Twyman effect)

that when a piece of optical glass is ground the surfaces are put

into a state of intense compression with the body of the glass in

tension, (F.W.Preston, Transactions of the Optical Society,Vol.

XXVII, p.184, 11th February, 1926) and that this effect disappears

on polishing. Thus before and during the polishing operations the

conditions are favourable to the existence of an undulating surface;

the undulations being unobservable by ordinary methods when not

exceeding, (say) $\frac{1}{2}$ one wave length of light. This view - that a

polished glass surface is not molecularly plane - has been taken in

accounting for the results obtained in the Friction Experiments

described in this Thesis, and has, one ventures to think, proved

satisfactory for that purpose.

But the question is, in fact, considered by French (in the above article) when he considers how the 'pits' etc., might be covered by 'flowed' surface molecules <u>without</u> bridging. He says,

> "A clear distinction must be drawn between a polished
> "surface and one that is at the same time optically
> "regular".

Also (p.326 of the same Article) he states,

> "If rouge is employed in the last stage it is generally
> "possible, by special illumination of the surface, to
> "detect an open net-work of these fine grooves; but if
> "no medium other than a very fine film of water is used
> "for the final polishing operation, the presence of
> "grooves will hardly be observable".

Clearly, these grooves which are "hardly observable" must be <u>enormous</u> when considering the **departure** of a polished surface from the molecularly plane surface of a liquid.

<u>Finally</u>, Dr. French summarises the processes of grinding and polish-:ing as follows:-

1. "The removing of material by the breaking away of splinters,
   "the size of which is reduced in stages by the use of
   "finer grades of abrasives.

2. "The production of an amorphous or surface-flow layer and
   "the gradual removal of these layers by grooving as
   "distinct from the splintering of the first stage, the
   "removal of material being effected by means of a very fine
   "abrasive or polishing material such as minute aggregates of
   "particles of rouge.

3. "The elimination of the grooves produced in stage 2 by the
   "use of a continuous medium such as rouge, there being,
   "during this stage the maximum production of surface flow
   "and practically no removal of the surface layer material
   "and no splintering action whatsoever".

It seems evident, on this presentation of the processes, that the polished surface cannot be molecularly plane.   One has the polished surface which is not "<u>optically regular</u>"; polishing is then continued until optical regularity is obtained and one is then left with a surface, polished but <u>irregular</u> to the extent of the limit of optical detection, i.e. to say (in ordinary observations)$\frac{\lambda}{2}$.[*] This departure from a true plane, is, of course, very large compared with the **range** of molecular attraction.

[*] Lord Rayleigh, by special arrangements, could detect $\frac{\lambda}{10}$

Beilby ("Aggregation and flow of Solids", p.110) states, in reference to the rouge polishing of glass -----"if, however, a "portion of the polished glass surface is lightly etched with "hydrofluoric acid gas mixed with air, --- the smooth surface layer "has been dissolved away, exposing the pits and furrows below, "showing that even in a hard, brittle, and vitreous substance like "glass the pits and furrows are filled up and covered over by the "flowed" surface layer during polishing".

It is here that French and Beilby disagree, at least for glass surfaces. French believes that the process is one of removing layer after layer of 'amorphous' flowed material until the bottomsof the pits are reached with perhaps some welding of material debris which will lessen the number of layers that have to be removed.

Beilby maintains the polishing process is hastened by the bridging of flowed material. Dr. French's difficulty seems to arise from the necessary coherence of the amorphous solid particles. Now, this difficulty would not arise if the surface layers of molecules were considered not to be in any special 'amorphous' condition but simply glass liquefied by heat vibrations. Before considering this suggestion further it may be useful to quote Beilby's detailed conception of how 'surface flow' produces the polished surface.

He states (p.112) that rouge particles are small enough to exhibit Brownian movements - (dimensions from 500 $\mu\mu$ to 800 $\mu\mu$ i.e. 5×10^{-5} cm. to 8×10^{-5} cm. or say 2000 to 4000 molecular diameters)

Further,

"It is due to the almost molecular fineness of rouge
"that the necessary molecular contact over comparative-
"ly large areas simultaneously can occur. The flow
"which is necessarily involved in all true polishing
"is a molecular operation; the layers of the substance
"which are involved are in some cases known to be
"only a few molecules in thickness". Again,

"The rouge particles, it may be supposed, hardly
"penetrate below the surface, but coming into almost
"molecular contact with the sheet of molecules on the
"surface, drag it off like a skin. The fresh molecul-
":ar layer left by the removal of the skin retains
"its mobility for an instant and before solidification
"is smoothed over by the action of surface tension,
"thus producing the liquid-like surface which is the
"necessary condition of a perfect polish".

It is difficult to imagine how the rouge particles which are in "almost molecular contact" with the glass molecules attract the latter so as to exert a greater force than that which the cohesive forces of the underlying glass molecules exert on the glass surface molecules.※   Is it not easier to think of relatively large areas of surface molecules being put into the liquid condition by the com:munication to them of the requisite heat vibrations?   The following calculations indicate that there would probably be sufficient mechan:ical energy available to provide the necessary quantity of heat. The surface molecules having been put into the liquid state would be easily "dragged off" by the rouge particles.

It has to be borne in mind that although the relative velocity of the moving and fixed particles may appear to be hopeless:ly small to produce the heat vibrations, a molecule on the station:ary plate will be acted on by an enormous number of moving molecules per second.

Assume glass to consist of silica (SiO_2)

From the molecular weight of silica (60), density of Hydrogen $[9 \times 10^{-5} \text{ grams/cc, at N.T.P.}]$ and No. of Molecules in 1 c.c. Hydrogen $(= 3 \times 10^{19})$

~~[9×10   grams 1 cc at N.T.P.]~~ & density of silica (say 3) it is easy to calculate that there will be approx. $\frac{1}{3} \times 10^{23}$ molecules of silica in 1 cc.

Hence number of molecules of silica in 1 cm. length of plate $= 3 \times 10^{7}$

Now, from ordinary experience, "friction", i.e. bringing of the molecules of two surfaces 'across' one another produces heat and it remains to show that the mechanical energy expended in such an operation is sufficient to melt (at least) one molecular sheet of the glass surface.

Mass of 1 silica molecule $= \dfrac{60 \times 9 \times 10^{-5}}{2 \times 3 \times 10^{19}} = 9 \times 10^{-23}$ gram.

Taking Specific Heat of glass = 0.16, melting point of glass at 1100° C. and Latent Heat of glass (assumed) = 100 calories per gram.

※   This is the same objection that is raised in "Engineering" to Hardy's theory of scratching (and referred to in this Thesis p.32) I cannot now remember whether I am indebted to Engineering ~~or not~~ for the present argument.

Heat required to melt one layer of molecules on 1 sq.cm.

$$= 3^2 \times 10^{14} \times 9 \times 10^{-23} \{ \cdot 16 \,(1100-20) + 100 \} \text{ calories.}$$

$$= 1000 \text{ ergs}$$

Beilby gives a pressure of 4 lbs./$\square''$, applied by the finger, ds sufficient to produce surface flow with rouge.

At this value, normal force $=$ 280 grams wt./cm^2.

Taking $\mu = 0.3$

Frictional force $=$ 85 grams wt.

∴ work done against friction when moving this force through 1 cm.

$$= 25 \times 480 \text{ ergs} = 83,000 \text{ ergs.}$$

as compared with 1,000 ergs required.

Also, in one 'stroke' of the polisher only the 'eminences' on the square cm. would be acted on so that the energy available at these 'points' would be enormously greater.

In the above, no allowance has been made for heat lost by conduction etc., and further consideration indicates that it is not necessary to do so.

One considers that the heat is produced, not over relatively large areas, but at <u>points</u> of contact of polisher and surface. If these were mathematical points, the rate of production of heat at a point, however small, would suffice to make the temperature at the point infinite - even after the steady state is attained the temperature at distance r from a point in an infinite solid where heat is being supplied at the rate of q calories per sec. is $v = q/4\pi r k$ where k is the thermal conductivity of the material.

The temperature attained by a surface will depend essential-:ly on the manner in which the heat is applied to the surface. This may be illustrated in various ways. An experiment performed by the writer was as follows. A drop of molten tin (melting Point 330° C. and mass about 3 gms.) was allowed to fall on a block of tin (Melting Point 230° C.). The lead drop melted the surface of the tin block and the two metals were fused together. This despite the fact that the tin was only at room temperature and had an enormous heat capacity compared with that of the drop of lead.

If, now, the tin surface be heated by the direct play of a Bunsen Flame upon it there is no melting until a longer time has elapsed than the time interval before the molten drop solidified; also, of course, the temperature of the Bunsen Flame was several times that of the lead.

An analogy to the way in which high temperature vibrations may be set up locally when polishing a surface is suggested when one recollects how a Kundt's Tube may be set into vibration by slowly stroking it by hand, or how a violin string is set vibrating by the slow stroke of the bow.

The above formed the basis of a letter which was published in the issue of 'Nature' dated 4th September, 1926. This letter is appended below.

The Polishing of Surfaces.

THE manner in which an optical polish is produced on glass and metal surfaces has been considered by the late Lord Rayleigh (" Polish," Collected Papers, vol. 4, p. 542, " Interference Bands," vol. 4, p. 54). The amorphous layer theory of the late Sir George Beilby is well known. The article by Dr. J. W. French on " The Working of Optical Parts " (" Dictionary of Applied Physics," vol. 4) summarises and extends these considerations. Reference may also be made to a paper by M. M. Fichter, a notice of which appeared in NATURE, August 2, 1924, p. 173.

The object of this present note is to suggest that, in the process of polishing, surface layers are really melted by the communication of heat vibrations to them. Consider a single surface layer of glass molecules of area 1 sq. cm. If glass consisted wholly of silica there would be approximately 9×10^{14} molecules per unit area, each of mass 9×10^{-23} gram. Taking the specific heat of glass as 0·16, initial temperature 20° C., melting-point 1100° C., and assuming a latent heat of fusion 100 calories per gram, the heat required to melt a single layer of molecules of 1 sq. cm. area would be 900 ergs.

Now Beilby gives a pressure of 4 lb. per sq. inch (280 grams per sq. cm.) as sufficient to produce surface flow with rouge polishing. Taking a coefficient of 0·3, the work done against friction when this force is overcome through 1 cm. is 83,000 ergs.

As one stroke of a polisher will polish only a small proportion of the 1 sq. cm. area considered, there will be available in the ordinary polishing procedure frictional energy of amount many hundreds of times that required to melt one layer of glass molecules.

At first sight it might be thought that any great rise in the temperature of the surface molecules would be prevented by the loss of heat due to conduction, etc. But this is to suppose that conduction would take place across plane interfaces. Is it not more reasonable to consider the heat as being produced at *points* of contact? If these were mathematical points, then no matter how small the rate of production of heat at a point, the temperature at the point would be infinite (the expression for the steady temperature v at distance r from a point in an infinite solid where heat is being supplied at the rate of q calories per sec., is $v = q/4\pi r k$, where k is the thermal conductivity of the material).

That the temperature attained by a surface depends essentially on the manner in which the heat is applied, is illustrated by the fact that a bunsen flame (of high temperature) may be played on a block tin surface without melting it, while a small globule of molten lead (only 100° C. above the melting-point of tin), if dropped on to a tin surface, will melt the tin below.

As an analogy to the manner in which high temperature vibrations may be set up locally, in polishing a surface, reference may be made to the setting of a Kundt's tube into vibration by slowly stroking it by hand, or a violin string by the slow stroke of the bow.

JAMES M. MACAULAY.
Natural Philosophy Dept.,
The Royal Technical College,
Glasgow, C.1, August 4.

This resulted in the publication in 'Nature' of the following

letter from Mr. F.W.Preston (of the Standard Plate Glass Co.,

Butler, Pa., U.S.A.), the author of several papers on the nature

of the polishing operation - papers read to The Optical Society

etc.   His paper of last February (already referred to) came to

the writer's knowledge after the publication of the above letter.

The Polishing of Surfaces.

DR. HAMPTON of West Bromwich has directed my attention to Mr. J. M. Macaulay's letter on " The Polishing of Surfaces " in NATURE of September 4, p. 339.

In conversation with Sir Herbert Jackson, Mr. Twyman, and others, I have once or twice had occasion to point out that the energy available in practice for liquefying the surface layer of glass is many hundreds of times what is theoretically necessary.   It is known that in polishing glass, the amount of glass removed corresponds to a solid layer of the order of ten wavelengths in thickness.   The total quantity of heat necessary to liquefy or even vaporise a layer of this thickness is not great in comparison with the energy expended in the actual process of polishing.   The figure given by Sir George Beilby of four pounds per square inch as a pressure sufficient to start flow has no significance.   In the process of polishing glass on a commercial scale, pressures very much less are the rule.   In the polishing of plate glass, for example, they are of the order of half a pound per square inch ; in the spectacle industry they are commonly of the same order ; in the optical industry the specific pressures used become greater and greater as the surface becomes smaller.

There is every reason to believe that glass will polish with the most insignificant pressures that can be attained in practice ; but of course the lower the pressure the longer the time required.   The coefficient of friction which Mr. Macaulay takes as 0·3 is a long way out.   In polishing with felt and similar materials the coefficient ranges from about 0·85 to 1·1, and is usually taken by designers as from 0·95 to 1·0.   In polishing with pitch the apparent coefficient of friction fluctuates very widely, because the film of moisture between the pitch and the glass renders the interfacial pressure itself either very great or very small according as the quantity of moisture becomes less or greater.   However, whatever assumptions may be made about the pressures and coefficients of friction, it may be taken that in the polishing of large surfaces of glass about ½ kilowatt hour is expended over a square foot of surface polished.   In the optical industry, where surfaces are smaller and preliminary grinding is better, an expenditure of energy of about half this amount suffices.   From this it may be calculated, I think, that the efficiency of the glass polishing operation is (on the assumption that the energy is required for liquefying a thin surface layer) not more than about one-half of one per cent.

I am not a great believer in the surface flow theory. In various papers to the Optical Society of England and elsewhere I have given reasons for believing that

whatever part surface tension effects may play, the process of polishing is at bottom primarily one of abrasion.   F. W. PRESTON.
222 E. Clay St.,
    Butler, Pa., October 26.

_____

THE practical information which Mr. Preston gives is of considerable interest and value.   His observations appear, on the whole, to support the view expressed in my previous letter, that glass surfaces are actually fused in the process of polishing.

One wonders whether the conception may not approximate in some degree to Mr. Preston's belief that " the process of polishing is at bottom primarily one of abrasion."   One can imagine the surface molecules in the liquid state being, so to speak, picked off by the rouge particles, thus giving, so far as the resulting debris would indicate, an abrasion effect.
                    JAMES M. MACAULAY.
Natural Philosophy Department,
    The Royal Technical College,
        Glasgow, C.1,
            November 24.

Addendum.

If the above be accepted as a partial explanation of the nature of the polishing operation it would seem to serve as the basis of an explanation for the fact that clean polished surfaces exhibit such a remarkable tendency to 'seize' and scratch.

Hardy explains this phenomenon in terms of "the 'cohesion' between the molecules of the opposing surfaces and compares the failure when slip occurs to the rupture of a more or less plastic solid", to use the words of a 'Leader' in the issue of "Engineering" dated 23rd Jan. 1925.

This explanation is criticised by "Engineering" the principal grounds of the criticism being that it was difficult to imagine how the cohesion of molecules on opposing surfaces could exceed that of the molecules underlying these surfaces.

"Engineering" then proceeds to express the view that "the forces concerned would be the thrusts and stresses involved, "the same in character as those arising in the collision of the "molecules of a gas and the asperities concerned would either "have to yield, or the load be lifted in some way, before slip "could occur. ------- if there be actual interlocking of the "asperities", this scoring is exactly what we should expect.

Instead of either of these explanations, the following is offered:-

On the theory advanced in this Thesis, when a clean glass plate slides on another clean glass plate, there will be small areas on the sliding plate that come within molecular range of corresponding areas on the fixed plate. When the normal pressure on these areas reaches a certain magnitude, the molecules on the opposing surfaces will be so to speak "jerked" or "whipped" into the liquid state and so the surfaces at these places will be welded together. These welded molecular sheets will require the

continuous action of the sliding molecules to maintain their liquid

condition. Immediately the sliding molecules get outwith the

range of the stationary ones (due to the surfaces not being mole-

:cularly plane) solidification will take place. Thus elementary

solid areas will be welded together with consequent gross rupture

which can be observed by the eye in the form of scratches.

Further, M. Fichter has described experiments ("Comptes

Rendus" No. 23, Tome 178, June 2, 1924) from which he concluded

that metal surfaces specially polished (with alumina under water)

were partially welded together on being more or less heated and

pressed together. He found that the separation of two such metal

surfaces (brass) required the application of a force of as much as

1.5 to 2 kilos per cm.^{2}

It is curious that this should be of the same order as

the pull that would be required if the plates were welded together

on 6 areas per sq.cm; each small area of 0.0003 cm.^{2} (the values

assumed for the water drops in the friction part of this Thesis)

as follows:

Tensile strength of brass $= 35 \times 10^8$ dynes/cm.^{2}

$\therefore$ Pull per cm.^{2} at rupture $= \dfrac{6 \times 0.0003 \times 35 \times 10^8}{980}$ gms. wt.

$= 6.4$ kilos.

SUMMARY.

It is suggested that :

(1) Polished Surfaces, even when apparently optically regular, are not molecularly plane.

(2) In the polishing operation molecular layers on the solid surface have heat vibrations communicated to them by the polishing substance and are thereby liquefied.

(3) It is the removal of these liquefied surface layers of molecules that reduces the 'eminences' sufficiently to give optical regularity and this action together with surface tension forces acting on the liquid layers left on the surface gives the unimpeachable polish effect.

(4) The scratching of clean polished surfaces is due to the welding together of elementary areas of the surface mole-:cules which have been put into the liquid state by the frictional heat generated.

APPENDIX.

(A)   The effect of Ionisation on the Condensation
of Steam at Atmospheric Pressure.

These experiments (carried out on Prof.Muir's
suggestion) were a repetition of C.T.R. Wilson's
experiments using steam at atmospheric pressure;
and ionisation was produced by electrical
spark discharge in the steam. Striking cloud
effects were obtained. This work was done dur-
ing the summer of 1914 and was interrupted by
the course of events.

(B)   On the Preparation of Iron Sheets and Tubes
for Industrial Purposes by Electrolytic
Deposition — a "Surface Layer" problem.

This Research has occupied two Summer Sessions
in the James Watt Engineering Laboratories and
numerous experiments have been made with a Model
Works Plant and with Laboratory Apparatus under
the direction of Professor Cormack C.M.G.,C.B.E.,
D.Sc.

There are many variables and although small
iron sheets and tubes, of good appearance, have
been "grown" adequate control of the process has
has not yet been attained. The physical proper-
ties of the Iron Product also remain to be
definitely ascertained.

Two observations of scientific interest

have been made in the course of the work, viz:-

(a)   It is well known that the mechanical circulation
of the electrolyte affects the quality of the
electrolytic deposit. Experiments on this
factor gave the remarkable result indicated by
the attached photograph.
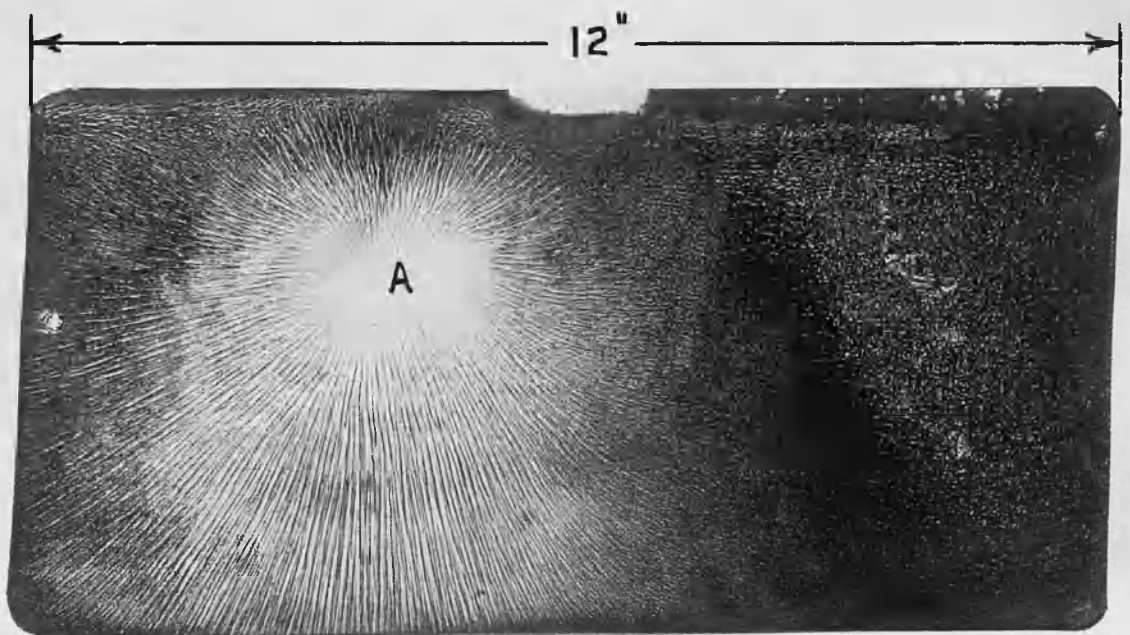
This photograph shows an iron deposit on a tin
cathode when the electrolyte had been caused to
impinge on the cathode (with a certain velocity)
at the point marked 'A' on the photograph.

(b)   Experiments with light-gauge, flexible, cathodes
gave the result that such cathodes were always

bent towards the anode when iron was deposited upon them.   This appears to suggest that the deposition produces a state of tensile stress on the cathode surface.

These two observations seem worth pursuing.

C.
&.   <u>Jaeger's Method of determining Surface Tension.</u>

During the progress of the work on Friction it became necessary to determine the Surface Tensions of a number of Sir Wm. Hardy's lubricants as there were no values available in the Standard Physical Tables. It was decided to use Jaeger's "Bubble Method" for this purpose.

In order to test the reliability of the apparatus used preliminary determinations of the Surface Tension of water were made. It was observed that in every case the value was slightly lower than could be accounted for by the estimated experimental error. [The cleanliness difficulty was, of course, constantly kept in mind]. A large number of experiments, was therefore, made using different samples of tap water and air-free water; also using different diameters of orifices, with circular and elliptical sections and orifices with different shaped "tapers". The cause of the persistent low value has not yet been ascertained.

The simple text-book theory of the method has been elaborated by Dr. Allan Ferguson (Phil. Mag. p.128. July-Dec. 1914) but his theory suggests no explanation of the low results obtained.