

THOMAS HAWKSLEY LECTURE.

POWER TRANSMISSION BY OIL.
(ELAULIC GEAR.)BY DR. H. S. HELESHAW, F.R.S., *Vice-President*.CAPTAIN H. RIAL SANKEY, C.B., C.B.E. R.E., *RET.*, *President*,
IN THE CHAIR.*Friday, 4th November, 1921.*

The business of a Mechanical Engineer consists in devising and constructing machines by means of which sources of power in nature, otherwise not under the control of man, may be available for various purposes in the arts and manufactures. Thus, in the words of a well-known electrical engineer: "Transmission of energy and its transformation is the fundamental problem of mechanical engineering." Perhaps this statement would have been better expressed in the plural, namely, that "the transmission of energy and its transformation *are* the fundamental problems of mechanical engineering," for the two things are really different.

Power may be transmitted without change to a distance, which is generally what the engineer means when he speaks of power transmission, although as a matter of fact the term is just as applicable in the use of a train of tooth-gearing, or a pair of pulleys, however close together, connected by a belt, or of the short shaft of a motor-car by which the power is conveyed from the petrol motor to the road wheels, as of water transmitted under pressure from a waterfall to a generating station, or of electricity transmitted from the generating station to a distributing centre of power 100 miles or more away.

[THE I.MECH.E.]

The subject of my Lecture is not that of simple power transmission, as in the foregoing examples; but only the special case when it is accompanied with its transformation also, and where oil is employed as the working agent. The use of oil for power is chiefly known in its use as a fuel, and the term was used in this sense at the recent Oil Conference at the Shipping, Engineering and Machinery Exhibition at Olympia. The use of oil for power purposes, which I shall deal with to-night, is not so well known; otherwise a better title for the Lecture would have been "Oil Variable Gear," or better still "Elaulic Gear." *

Both in the use of oil as fuel and the use of oil for variable gear the transformation of power takes place, but there is this vital difference between the two cases, that when used as a fuel the oil is chemically transformed and is destroyed; whereas in the use of oil in variable gear the transformation of power that takes place is merely a change of one of the two factors of which power consists, namely force and movement. Not only is the oil not destroyed, but with proper treatment it does not depreciate, even after years of use.

Oil-variable-gear is the newest change-speed gear, and has only been made commercially possible in recent years by the progress in the mechanical arts. The most familiar gear of this class is the ordinary change-speed gear of a motor-car, which consists in various trains of wheels of different ratios. Notwithstanding its surprising convenience and admirable operation, this gear is very imperfect as regards its changes of speed, which at best is only a step-by-step change. Belting and friction gear have their own defects, and no electrical change-speed gear has yet reached the commercial stage of being cheap and compact. Just as all these have their special uses notwithstanding their defects, so, notwithstanding the defects of elaulic gear, it has gradually and surely found employment in a number of important purposes, which will be described later on.

All other change-speed gears are built up of solid parts, whereas elaulic gear employs a liquid (namely, oil) as the transmitting agency

* I do not employ the word "hydraulic" variable gear, which for want of a better word is often employed. This word is a misnomer for such gear. The word "hydraulic" comes from two Greek words signifying water in a pipe, and it is not water but *oil* which it has been found possible to use in such gear. It was agreed at the Conference on Petroleum, which I have mentioned, that the word "elaulic" should be recognized, and the adoption of this word is being discussed by the Institution of Petroleum Technologists. The word itself simply substitutes the Greek word *ελαιον* meaning oil, for the Greek word for water, and until a better word than "elaulic" is found I shall venture to use it.

for effecting a change of speed. This is done by using a pump to impart pressure to the working oil and a motor of some kind to transmit the power as required. In the only systems which have attained practical success, both pump and motor are of the piston or plunger type, and the pump itself is actuated by a crank or cam so devised as to impart a variable stroke at will to the plunger. The object of the variable stroke is to enable the pressure imparted to the oil to be increased as required, in order to overcome any opposed resistance without an additional effort from the source of power. For instance, if the motive power is an electric motor, by reducing the stroke of the pump to a small amount, any required pressure can be obtained without raising the speed or the amperes of electric current to the motor. This, of course, can only be done with a corresponding loss of volume delivered by the pump, and therefore of the speed of the driven ram, if a ram is used, or revolutions of the driven oil-motor, if an oil-motor is used. Although (as I shall indicate), there are variations in the available oil speed-gears, the above simple principle underlies all such gears.

The object in view of the engineer in designing a variable gear is to produce such a machine (taking this word to cover the complete system of pump, oil, and motor), as will, with the smallest bulk and weight and at the lowest cost, transform power in any required ratio of force and movement with the least possible loss of useful energy; in other words, produce a maximum of work under the conditions required with the least possible loss.

It would require not merely one, but a good many Lectures to deal fully with the subject, and all I can hope to do in the time at my disposal is to deal with the main factors of the problem, which I propose to do in the following order:—

(1) The mechanism of the variable-stroke pump and a brief description of various systems of oil variable-gear, dealing chiefly with two chief systems in commercial use.

(2) The various causes which militate against a successful use of any working fluid, and the properties which oil possesses which make it the best fluid available for use in this type of variable gear.

(3) Various commercial applications of clauic gear.

THE VARIABLE STROKE.

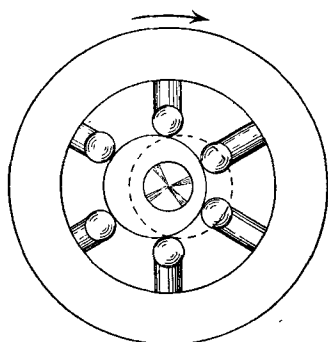
There are two chief systems by which a reciprocating motion can be given to pistons and plungers, one in which a crank or eccentric is used, and the other a swash-plate. Fig. 1 is a

diagrammatic view of these two types, A being the radial and B the parallel type.

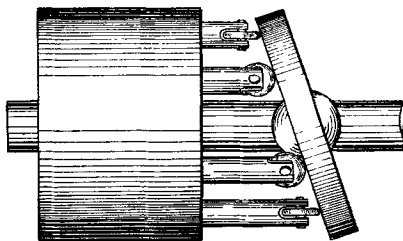
Although by analysis the motion given by both of these can be proved to be identical, that is the displacement is $R(1 - \cos \theta)$ where θ is the angle of the crank and " R " is the crank radius, the mechanical details involved in their use are entirely different: thus, with the eccentric the pistons or plungers surrounding the crank have a movement perpendicular to the axis of the shaft round which they are placed—that is, have their axes in a plane normal to the shaft; in the swash-plate the pistons move parallel to each other and to the axis of the driving shaft. There are various ways, of course, in which both A and B can operate. Thus in the former the eccentric can

FIG. 1.—*Variable-Stroke Pumps.*

A. Eccentric—Radial.



B. Swash-Plate—Parallel.

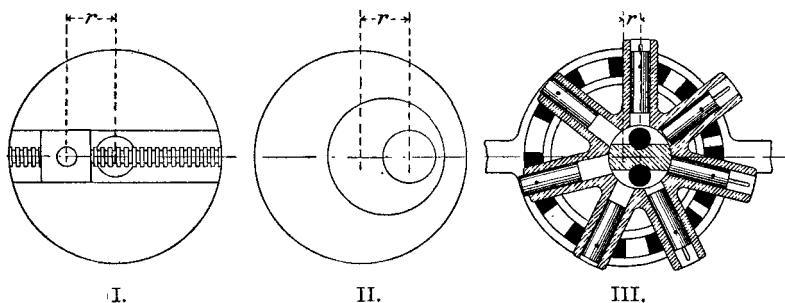


be rotated and the piston merely move to and fro, or the pistons can move round a fixed eccentric.

So exactly in the same way in the swash-plate type, the pistons can merely reciprocate with the swash-plate turning, or the swash-plate can be fixed and the cylindrical body containing the pistons rotate. The kinematics of all these varieties are identical, but the practical mechanics are very different, and in each of the cases A and B what has been found most practical is to have the movement of the pistons round the fixed eccentric or swash-plate. There are very good reasons for this survival, for not only balance of working parts is secured (which is not the case when the eccentric is the moving part), but the variations of stroke are much more easily made when the eccentric or swash-plate do not themselves revolve.

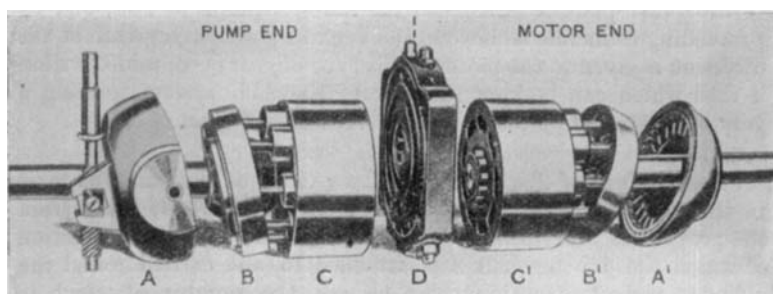
Fig. 2 shows various ways in which the stroke of the crank or eccentric can be changed. I and II both represent forms which have been put into practice, and are quite satisfactory when only small pressures are employed. But it must be remembered that in oil variable-gear, where, in order to obtain moderate dimensions

FIG. 2.—Three methods for varying the Stroke of Crank or Eccentric.



at all comparable with the ordinary gear-box having trains of wheels, the pressures are very high indeed and the difficulties of systems I and II are obvious. System III, however, in which the eccentric or crank does not rotate has proved quite satisfactory; all that is necessary being to move the cylindrical surface carrying the guide-

FIG. 3.—Swash-Plate Type of Oil Gear.



blocks for the piston-heads to and fro on strong guides. This movement can be conveniently effected from the outside. By these means not only any variation of stroke from zero to maximum can be obtained, but also reversal of flow.

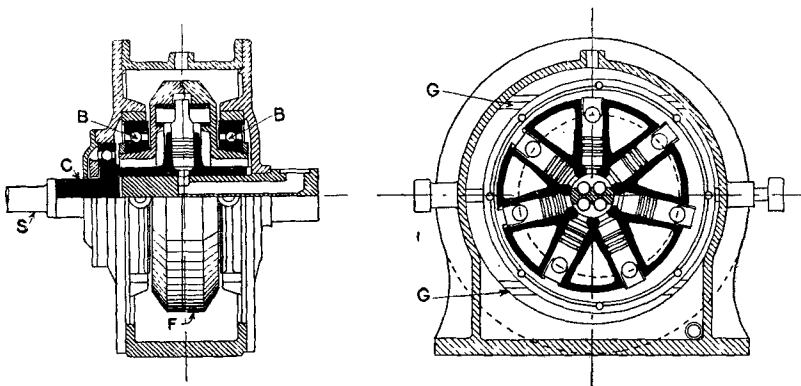
Swash-plate Type of Transmission.—The working details of the swash-plate type of transmission are to be seen in Fig. 3, which is

taken from the prospectus of the Variable Speed Gear, Ltd. On the left-hand side is the pump portion and on the right-hand side the motor portion which, except for the former being variable in stroke and the latter of invariable or fixed stroke, are practically identical. A and A' are respectively the non-rotating swash-plates of the pump and motor. Each of these contains a ring on roller bearings, against which the respective disk members B and B' work. These disk members carry with them the spherical connecting-rod ends which rotate bodily with the cylinder bodies C C'. On the end of the cylinder body C' of the motor can be seen the ports of each cylinder, nine in number, which work in contact with the valve face on the fixed central piece D. The extremely ingenious action of the whole mechanism can thus be easily understood. Assuming all the parts to be closed together and to be full of oil, the rotation of the pump-shaft on the left-hand side causes the cylinder body to rotate and the trunk pistons to move in and out, owing to the swash-plate action. This rotation can, however, only take place by a corresponding motion being imparted to the cylinder body C' of the motor, since the oil contained is incompressible. The vertical shaft on the left-hand side of A is the control spindle by means of which any required stroke can be given to the pump pistons. Inasmuch as the stroke of the motor is constant owing to the angle A' being fixed, the reduction of stroke of the pump side increases the possible torque on the motor side and its revolutions relative to those of the pump decrease in exactly the same ratio. When the vertical position of the swash-plate A is reached the motor remains at rest, and by proceeding to incline it beyond the vertical position reversal of the direction is given to the motor. This type of gear is contained within a case which can be kept full of oil, the whole system forming a very compact and powerful type of transmission gear.

Radial Type of Transmission.—Two views of the pump as used in the radial type of transmission are shown in Fig. 4, taken from the prospectus of Hydraulic Gears, Ltd. On the left side is a section of which the driving-shaft S is attached to, and carried round the cylinder body C containing the pistons, the number of which is generally seven. The cylinder body is carried upon the central valve-spindle which has ports, shown on the right hand view, through which the working oil is admitted to and discharged from the cylinders by the reciprocating movement of the pistons. This reciprocating movement is obtained by moving the eccentric to and fro on the guides G.G., so that just as with the pump previously described, any variation in stroke can be obtained as well as reversal

of flow. One important cause of the successful action of this particular pump is what is called the "floating ring" F, which contains the eccentric. If it were not for this floating ring the slippers would be carried round in the guides under conditions that would soon destroy the pump by friction, and in any case would result in very low efficiency. By the device of allowing the floating ring to rotate on the ball bearings BB while the reciprocating movement of the pistons is not interfered with, the actual movement of the slippers in the guides is reduced to that of the stroke itself (which in the case of very high pressures is correspondingly small), and the friction is thereby correspondingly reduced.

FIG. 4.



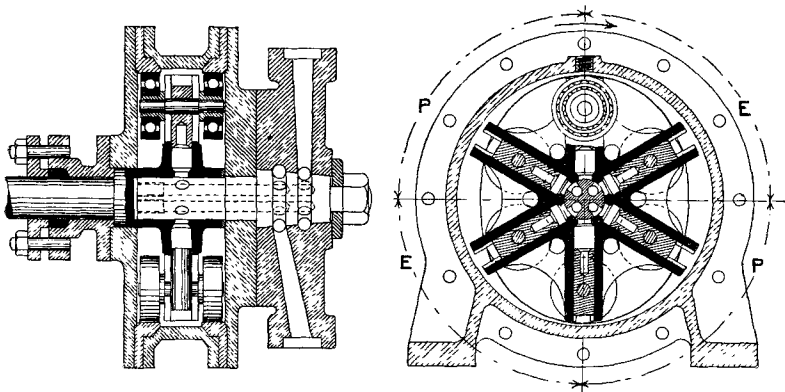
Radial Type Motor.—Fig. 5 shows two views of a radial type of motor, which in this particular system of oil transmission, unlike the previous one, differs radically in design from the pump. The pump is practically balanced by having both the centres of the eccentric and of the central valve at rest, when the parts respectively carried by them, namely, the guide ring and the cylinder, are rotating. In order to balance the motor the path of the piston-head in the motor is not eccentric, but a symmetrical curve somewhat resembling an ellipse. This curve, which will be seen from the figure really differs from an ellipse, is the result of much investigation carried out to ensure a constant flow so that there shall be no shock between the pump and the motor working together with an incompressible fluid. The valve parts, with the exception of being duplicated, are similar to those of the pump, the principle of the valve action being identical in both pump and motor. The

piston-heads are guided in their movement by ball bearings carried on the cross-heads, the outer surface of the ball-bearing race running on steel roller paths. It will be seen from the Figure that PP are two quadrants of pressure: EE the two quadrants of exhaust. These motors work well and silently and give a very high efficiency, which reaches, under the best conditions, 97 per cent, and should not fall below 95 per cent.

THE PROPERTIES OF OIL.

It may be assumed, then, that we have at our command a mechanical contrivance by which the circulation of a liquid under pressure can transmit and transform power. We shall now proceed

FIG. 5.



to consider why it is that oil is not only the most valuable liquid for this purpose, but why it is that it alone has made this kind of variable-gear possible.

Absence of Rust and Chemical Action.—Before we consider the physical properties of oil, which are of great scientific interest and importance, it should be pointed out that oil, unlike water, can be used with working parts of iron and steel not only without itself causing rust and corrosion, but acting as an absolute preventive from the rusting effect of the atmosphere. In hydraulic pumps and motors special provision has to be made for the protection of metal surfaces, and expensive metals such as brass and gun-metal have to be used, or a soapy fluid provided by treating water in

various ways. The use of oil entirely solves this difficulty of corrosion, and ensures unlimited life from this point of view to the different parts of the gear. But there is another reason why oil is so suitable, and that is that in recent years the enormous increase in the production of mineral oils and the improvements in the manufacture of mineral oil lubricants, places in the hands of the engineer an unlimited quantity of a material which is absolutely stable as far as chemical changes are concerned, since mineral oil itself is immune from the organic changes to which animal and vegetable oils are subject.

Efficiency of Oil.—The properties of oil have now to be considered from the point of view of its working efficiency; not only its own working efficiency, but the efficiency it confers upon the variable-gear machine; that is to say, its use in elaulic gear. No transmission or transformation of energy can take place in a machine without loss, and the value of any machine depends partly upon the amount of such loss.

In a change-speed gear this question is the prime factor, because it is a question of the cost of using it, taken in terms of energy. This factor is expressed as the *efficiency* of the machine, that is, of the ratio of useful work coming out of the machine to the total work put into the gear. In this kind of change-speed gear there are two kinds of loss, the loss of actual *motion* or of actual *force*. In the tooth-wheel gear of a motor-car, which is positive, the loss is entirely due to friction; no motion is lost, and what is lost in friction is lost in effort or force. In pairs of belt-driven pulleys, whether step-by-step or coned, the loss may be chiefly in motion, that is in slip of the belt. That is also the case in the variable friction-gear, such as the disk and roller friction-gear. In oil variable-gear, the loss may be in three ways:

- (1) Slip.
- (2) Loss of incompressibility.
- (3) Friction of the working parts, and viscosity of the working fluid.

SLIP.

In counteracting slip caused by leakage, there must be a compromise. Obviously leakage can be practically prevented by a sufficiently viscous lubricant, that is by a thick oil; but in this case the loss of energy in viscosity would be very great. Even with thin oil, if cup washers, made of a suitable substance such as dermatine or dexine, were used with the pistons or plungers, no leakage past

the pistons would take place, but the loss of power again might, under high pressure, be too great. As a matter of fact, owing to the high-speed motion of the pistons in actual practice, a series of small grooves cut in the pistons is quite sufficient to prevent leakage past the pistons, even with a moderately thin oil, since before the oil has crept along the pistons during the stroke, the stroke itself is reversed ; thus, with the high speed of such pumps—say,

TABLE 1.

Densities of Lubricating Oil at Various Pressures.
The Values of Densities (ρ) are taken at 104° F.

Pressure. Tons/in ² .	Castor Oil.	Sperm Oil.	Trotter Oil.	Rape Oil.	FFF Cydr.	Mobiloil.	
						A.	BB.
0	0.9415	0.866	0.898	0.898	0.877	0.894	0.899
1	0.949	0.8745	0.905	0.906	0.884	0.901	0.906
2	0.956	0.882	0.9135	0.913	0.891	0.908	0.9135
3	0.9625	0.890	0.921	0.920	0.8975	0.916	0.920
4	0.9685	0.896	0.9275	—	0.904	0.9225	0.9265
5	0.975	0.9025	0.9345	0.933	0.910	0.9275	0.9325
6	0.981	0.909	0.940	0.938	0.916	0.9325	0.938
7	0.986	0.9135	0.9455	0.944	0.921	0.940	0.9435
8	0.9905	0.9195	0.951	0.9495	0.926	0.945	0.949
9	0.996	0.925	0.956	0.9545	0.931	0.950	0.954
10	1.001	—	—	—	—	—	—

1,000 r.p.m.—the stroke itself is performed in less than one-thirtieth of a second.

INCOMPRESSIBILITY.

If an elaulic gear were perfect, the working fluid should be incompressible. This is so for two reasons : first of all and obviously because any compression would be naturally accompanied by a generation of heat, most of which, whatever attempts are made at

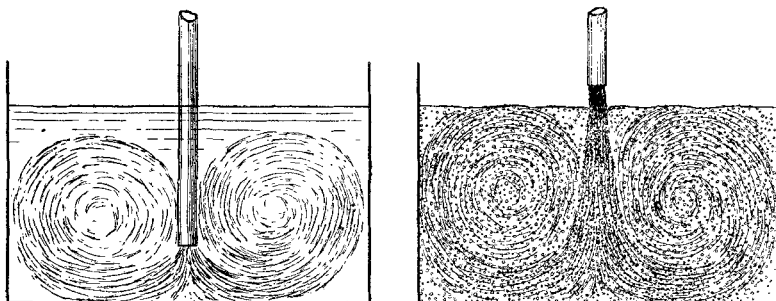
re-generation, could not possibly be restored, and therefore would represent loss of energy. But far more serious than this would be the mechanical difficulties which would result from contraction and expansion. One reason for this is the fact that only by the use of a practically incompressible fluid can the dimensions of a gear be got down to a reasonable working size, since with an incompressible fluid very high pressures can be used and therefore a small gear can transmit high power. As a matter of fact it is well known that liquids (including oil) are themselves practically incompressible.

Table 1 shows a Table of Densities of Lubricating Oil of various kinds taken from a recent Report of the Department of Scientific and Industrial Research.* It is clear that, like water,

FIG. 6.—*Effect of carrying Air into Oil.*

A. Correct arrangement of pipe.

B. Wrong arrangement.



which is for engineering purposes practically incompressible, the oils in use may be regarded as themselves incompressible. Unfortunately in practice lubricating oils often lose this valuable property by the entanglement of air when the oil is in rapid motion and churned up in the presence of air. Bubbles of air, at first very minute, get entangled in the mass; the presence of these minute air-bubbles, which can only rise slowly, prevents the escape of larger bubbles of air, and at last the whole mass becomes saturated with air.

A lantern experiment was then shown, Fig. 6, in which it was seen that as long as the oil circulates without discontinuity, none of this

* Report of the Lubricants and Lubrication Inquiry Committee, H.M. Stationery Office. Reprinted by permission of the Controller.

trouble occurs. It will be realized that if the discharge of oil takes place beneath the surface, the oil retains its incompressibility (A, Fig. 6).

If the discharge-pipe is raised above the surface (B, Fig. 6), it will be seen that after a little time the mass has become filled with bubbles carried into the mass of oil by the descending stream. This shows that the circulation of the oil through the gear must be so designed that this injurious effect cannot take place, which is effected by carrying the discharge pipes under the surface of the oil and never above it. This may seem a simple matter, but the difference between the right and wrong discharge really amounts to success or failure in the working of the oil-gear. I have emphasized this matter because in hydraulic gear with water the effect does not occur to a serious extent owing to the low viscosity of water. This you can see from an experiment with water in the tank. The bubbles do not collect but rise to the surface and escape.

FRICTION AND VISCOSITY.

I now come to by far the most interesting question in regard to the use of oil, namely, its effect in reducing resistance of the working parts by partially or entirely eliminating friction. I make no excuse for dealing at length with this question, as upon it the success of any transmission gear chiefly depends.

It may be at once said that if a film of oil, however thin, can be maintained between all the solid moving parts in any machine, including, of course, elastic gear, not only would there be no wear whatever in working parts of the machine itself, but the resistance to motion would become largely a question of the viscosity of the oil. This viscosity would act in two ways: (1) as resistance of a film between the working surfaces, and (2) as the resistance caused in the passage of the working fluid from one part of the machine to the other, and in passing in and out of the cylinders, through the valves and along the pipes and containing passages.

Everyone, of course, understands in a general way what is meant by viscosity, but one has only to read books on lubrication and discussions on the subject to see that there is a great deal of confusion not merely as to what viscosity is, but as to what part it plays as a lubricant. Everybody knows that pitch is more viscous than treacle, and treacle is more viscous than glycerine, and glycerine is more viscous than water, and water is more viscous than petrol or ether. This quality is due to the resistance to internal motion of the fluid and may be measured by the "shear" or

resistance to moving one portion of liquid over another. A perfect fluid, then, would have no shearing resistance or tangential stress. No known fluids are perfect, and the viscosity of a fluid is measured in terms of the shearing stress or tangential resistance. The coefficient of viscosity is equal to the shearing stress divided by the rate at which distortion takes place. The factor used is called the Coefficient of Viscosity, and can be found thus :—

$$fs = V \times \frac{v}{d}.$$

$$V = \frac{fs \times d}{v}.$$

V = Coefficient of Viscosity or resistance to distortional motion.

d = distance between two layers.

v = velocity of shear at distance d .

fs = shearing force over unit area between the two layers.

Thus, without knowing exactly what viscosity is, we can measure its effect and study its influence as affecting the efficiency of clauic gear. That is fortunate, because, like electricity, it is something the nature of which we have some idea about, but no certain knowledge.

It is generally agreed that resistance between two lubricated solid surfaces may be of two kinds, one in which it is entirely due to the viscosity of the film between them, and the other in which the surfaces themselves play a very important part. It will be useful to illustrate these two kinds of resistance by some experiments, as it is always a good thing for the audience to understand exactly what a lecturer means to convey by the terms he is using. (The Lecturer here showed the result of rubbing two plates of glass first with oil and then with water between them, and was able with the lantern to indicate on the screen when the lubrication changed from one kind to the other as the film between was rubbed away.)

These experiments make quite clear the two different kinds of friction. When there is a film completely separating the two surfaces, it is quite easy to see that the film itself travels between the two surfaces and they move over one another. If the surfaces are of identical material, as in the present case, the speed is exactly half the relative speed of the two surfaces—that is, of course, if both surfaces are wetted by the experiment. This is the case whatever the lubrication used, which may be water or oil.

As long as a substantial film is between the surface, the case is clearly that in which viscosity of the fluid is a measure of the

resistance between the two surfaces. Many writers take this to be all that need be considered, as, for instance, Mr. G. R. Rowland, in an article on "Lubrication and Lubricants." *

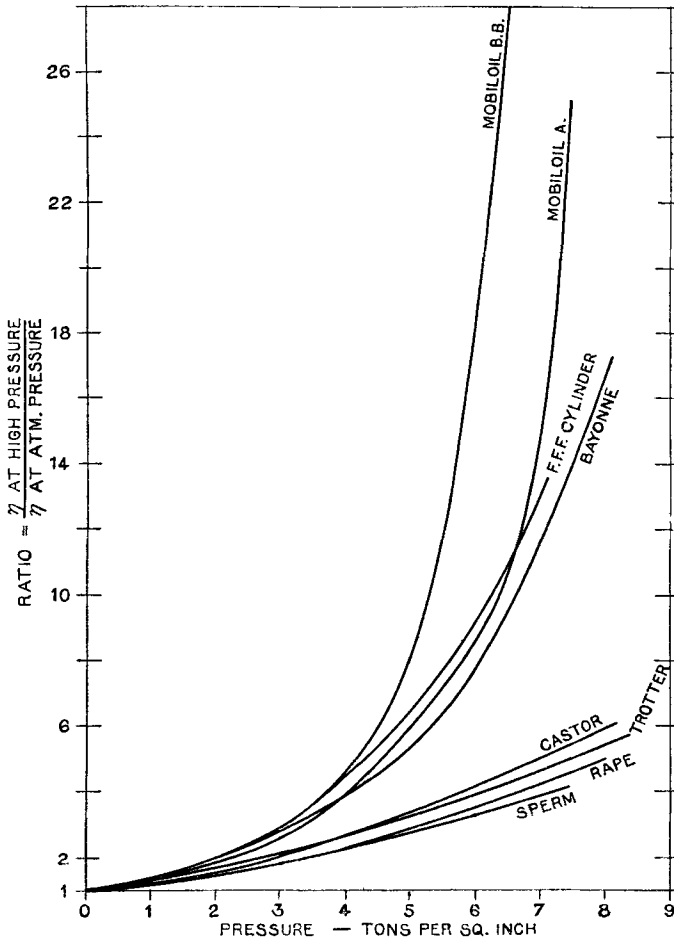
When the pressure between the surfaces is small or even moderate, the foregoing definition is correct and the resistance is easily measured for the temperature at which sliding takes place. But when we come to high pressures, then we get into difficulties, first because in such an experiment the lubricant is squeezed out and seizing takes place between the solid surfaces themselves; and even if it were not squeezed out, the experiments by Mr. Hyde given in the Lubrication Report previously referred to (page 853), show that at high pressure there is an enormous increase in resistance to flow which, no doubt, is due in part to viscosity. The experiments of Mr. Hyde gave such remarkable results—increase in apparent viscosity for an increase of pressure from zero to 6 or 7 tons per square inch, rising from three or four times as great in vegetable and animal oils to twelve, sixteen, or thirty times as great in the case of mineral oils. Water showed practically no increase in viscosity on a rise of pressure from zero to 10 tons per square inch. These remarkable results are best shown for the curves in Fig. 7 taken from the foregoing Report.

I have only time to consider the very interesting and in many ways perplexing problem of what happens when lubrication is more or less squeezed out; but I may call attention to the fact that if there be this great increase in viscosity of lubricants under high pressure, it would be a very serious bar to the extension of elaulic gears in certain directions. At very high working pressures, such as 10 tons on the inch, which would be quite feasible apart from the lubrication question, it would seriously affect the circulation of the working fluid itself between the pump and the motor at high speed, and the consequent use of this gear. While the experiments of Mr. Hyde were conducted admirably with every care, I have a feeling that in the particular form of apparatus used, the surfaces through which the escaping liquid was measured may have played a part which obscured the real increase of the viscosity. This will be alluded to later.

* Journal, American Society of Naval Engineers, 1919, vol. xxxi, page 97, says: "Lubrication and lubricants may be defined as follows: good lubricants are substances semi-fluid or fluid, capable of forming and maintaining films of sufficient thickness between two rubbing surfaces to prevent actual friction between the surfaces, substituting for it the fluid friction (meaning viscosity) of the lubricant itself."

The case of practical importance in elaulic gear and indeed of most engineering problems, is where thickness of the film of lubricant is very small. There we have the case in which under high pressures

FIG. 7.— $\eta = \text{Viscosity}$.



on one hand the influence of the surfaces between which it is desired to obviate actual metallic contact prevents the escape of the lubricant which keeps them apart. It is only necessary to read

numerous utterances, especially of those who are now working at the question to realize that the real explanation of what occurs is at present quite unknown. In the experiment with the two glass plates, it is clear that rubbing them backwards and forwards gradually leads to the removal of the liquid and the approach of the two surfaces together. When they come within range of molecular attraction, which Laplace on various grounds estimated for a liquid to be in the order of 5×10^{-7} cm., which, put into inches, means somewhere about the quarter of a millionth of an inch, then we have what is probably the real cause of solid friction of two bodies. In the case of glass plates, this attraction causes the particles to cohere, and they absolutely tear one another from the surface and what is called seizing or abrasion takes place. This, whether it takes place with pistons, the revolving shaft, or revolving valve surfaces of elaulic gear, at once destroys the machine, and therefore must at all costs be prevented.

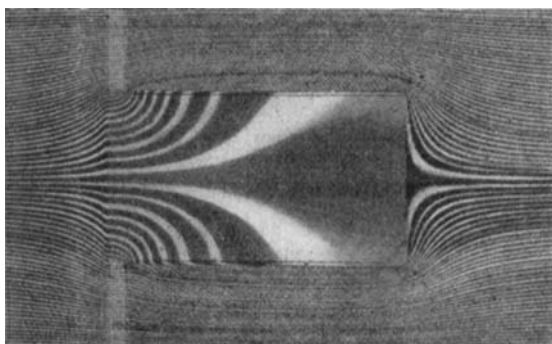
Long before the modern theories of lubrication were propounded, all good engineers thoroughly understood how to provide and protect their machines against such seizing. Not only had they provided metal surfaces which, if the lubricant by chance were removed, would not seize, but they arranged a supply of lubricant so that if one part of the lubricant was squeezed out fresh lubricant was carried in to take its place, which could not escape sufficiently fast to allow the surfaces to get into contact and seize together. This is really what occurs in all properly lubricated surfaces, but one of the most interesting of modern appliances—the Michell bearing—has not merely solved a very difficult and troublesome problem, but illustrates in a beautiful way exactly how this occurs. In this case the thrust-bearing of ships, in which formerly a long line of collars was used, absorbed much power because the lubricant could not be satisfactorily carried in for working purposes, as is the case with a shaft which does not fit the journal, or a piston which reciprocates, or a guide-block. The difficulty was overcome in a simple manner, and as this matter seems to throw light on the secret of lubrication, I will show an experiment in which stream lines are made to tell the tale. This experiment with my own method of stream lines gives when photographed the distribution shown in Fig. 8, another Figure by the same method being given in the Paper by Mr. Hamilton Gibson.*

This experiment shows what occurs not only between flat surfaces with an inclined plane, but in a circular bearing as the film of liquid

* Trans. Liverpool Engineering Society. 1917.

reaches the part of closer contact between the metal surfaces. The chief experiments of the Lubrication Committee at the National Physical Laboratory were carried out with a Lanchester worm-gear, and the great success in the running of that gear, as doubtless of all other successful lubrication, was the automatic and continuous supply of lubrication, which, like that in the Michell bearing, could not escape. The result was that in certain cases the efficiency of this gear reached 97 per cent; that is to say, a loss of only 3 per cent in transmission. In order to illustrate what efficient lubrication and design really mean, it is interesting to recall a case (quoted in my Cantor Lectures on "Friction" at the Society of Arts in 1886), which had been cited by our former President, the late Mr

FIG. 8.—*Distribution of Lubricant flowing over Michell Bearing.*



Wicksteed, of a raw cast-iron worm and worm-wheel, in which the total efficiency was exactly equal to the Lanchester loss of efficiency, that is to say 3 per cent; in other words, 97 per cent of the power was lost in transmission. To bring this home to the imagination, let us suppose this was used in a motor-car driven by petrol-motor. In one case (with a car running 15 miles to the gallon) with the Lanchester worm-wheel gear you might, for a tank containing 12 gallons, be able to run 174 miles, and in the other case less than $5\frac{1}{2}$ miles.

Returning to the stream-line experiment, if the viscosity is increased at the rate at which the experiments of Mr. Hyde are supposed to indicate, the pressure where the bands in Fig. 8 are wide would show (since the pressure increases in proportion to the increase in width of the band) that there is an enormous increase of viscosity at this point, and this would possibly account

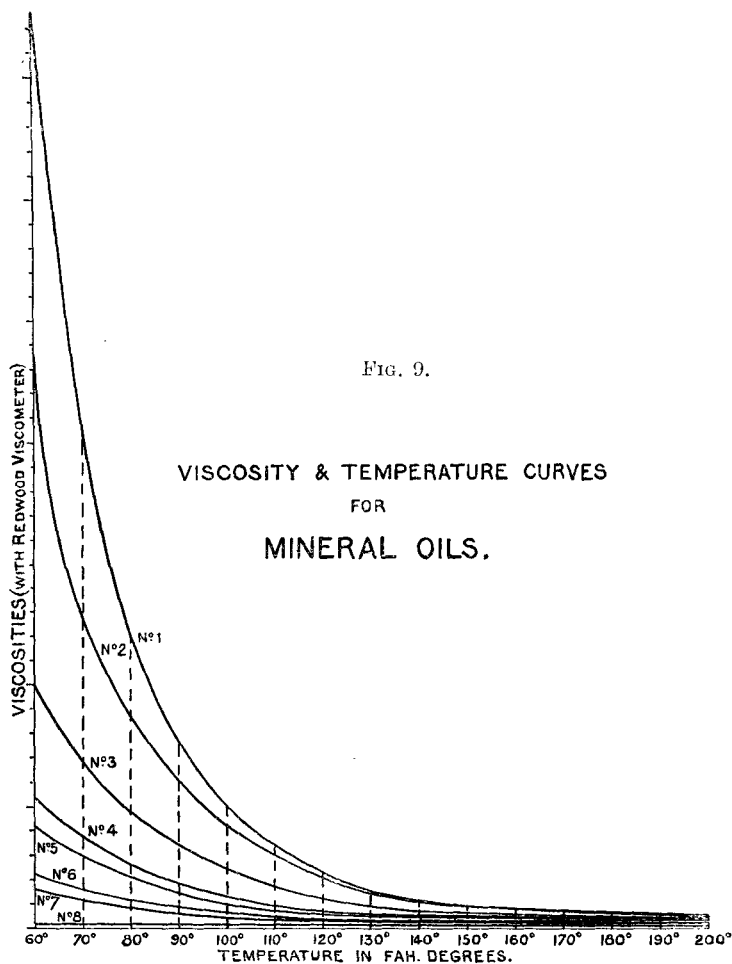
for the fact that this film of liquid cannot escape, and therefore supports the whole load on the bearing. I have shown this diagram because I believe that the explanation of the Michell bearing is really the explanation of the action of cylindrical journals, indeed of all bearings that are successfully lubricated. It is very obvious that the reason why the liquid does not escape from between the surfaces in a journal, even under high pressure, is one of the greatest practical interest.

Temperature is an important factor in the action of the lubricant and very much affects the working of elaulic gear. Without exception, temperature diminishes the viscosity of a lubricant. While, however, the viscous resistance is diminished owing to rise of temperature the value of the lubricant is correspondingly decreased for reasons which will at once be obvious from inspection of Fig. 8, and from what has been said in connexion with it. It is evident that if viscosity is diminished the resisting power of the lubricant to being squeezed between two surfaces is also diminished. Fig. 9 shows the curves of relationship between temperature and viscosity which I have plotted from results taken with a Redwood viscometer of various grades of oil supplied by the Vacuum Oil Co., Ltd. These curves indicate the futility of adopting very viscous oils for lubricating purposes in order to prevent the loss by slip if the working of the gear is going to produce any considerable rise of temperature. It will be seen that as the temperature rises the benefit derived from the viscous nature of the lubricant rapidly diminishes and at 200° F. is little better for the heaviest than the thinnest oil. Thus it is evident that the proper method of dealing with the question is to use a medium or thin oil and, by proper workmanship and design, to provide against slip, thereby ensuring the more equable effect of the operation of the lubricant. If the gear is working, as it should be, cool and not hot, there will be a great loss of resistance and loss of power in the circulation of a very viscous lubricant.

The action which enables some liquids to act with more effect than others on the surfaces between which they are interposed ; why for instance, oil is a better lubricant than water, notwithstanding its greater viscosity, has been called the property of *oiliness* or *greasiness* ; but this does not really bring us nearer to the explanation unless we know what oiliness is. Mr. Deeley, to whom we owe much on the subject of lubrication, writes as follows :—

“Oiliness would appear to be an effect produced by the lubricant upon the metallic surfaces with which it is in contact, rather than a property

dependent upon any particular physical property of the lubricant. It would appear that the unsaturated molecules of the lubricant enter into firm physico-chemical union with the metallic surfaces, thus forming a friction surface, which is a compound of oil and metal. This solid surface would also



appear in the case of metallic surfaces to be much more than one molecule thick, the oil penetrating some little distance into the metal, and altering its physical properties or, as a result of abrasion, forming a paste of metal plus oil between surfaces covered by oil layers one molecule thick.

Other workers on the subject disagree entirely with this, and consider that there is always a film of the lubricant itself between the two surfaces, the lubricant being unchanged in form. Researches appear to show that lubrication is quite possible with even a molecule or two of thickness, and as it would take about a million and a half of molecules to reach an inch, the thickness of the film may be exceedingly small. Mr. Hardy, in the discussion on Lubrication held at the Imperial College of Science and Technology, said: "the property known as 'oiliness' is due to the influence of the lubricant upon the surface energy of the solid. It is to be expected, therefore, that lubrication can be defined only in terms of the chemical constitution of the lubricant and of the solid to which it is applied." If by "chemical constitution" is meant structure, then there may be something in this. But this surface action may not be necessarily anything of a chemical nature, even though Messrs. Wells and Southcomb and others seem to have proved that fatty acids added to mineral oils do improve their lubricating effect. Pumps that have been worked continuously for 7 years at high pressures, revolving at a speed of 700 to 1,000 r.p.m., have not shown the slightest sign of loss or change of surface, even when examined microscopically. When, after many years, the central valve on which the whole pump rotates is examined, it is found that the parts which were originally ground fit one another as accurately as on the day they were made, notwithstanding the constant change of lubrication over the surface through the whole of that period, and it seems impossible to imagine that any abrasion has occurred or any action which would result in a loss of material at the surface. The question may be asked: Is it necessary to invoke chemical action when surfaces are as close to one another as they are in properly fitting bearings under pressure?

During recent years wonderful advances have been made in our knowledge of the molecular structure of metals, and one of the great factors in this advance has been the progress in photomicrography. By means of such photographs we can form a good idea of the differences in molecular structure of different metals and alloys, and it is difficult, in spite of such photographs, to avoid the conviction that even the hardest materials brought to the greatest degree of polish have not innumerable lurking places for molecules of a lubricant.

In speaking on this subject with a skilled metallurgist, I found that his view was that there were not actually pores or crevices in the material, notwithstanding the appearances of the photo-

micrographs. He seemed to hold a totally different view from others. For instance, Deeley, in the foregoing quotation, talks of penetration some little distance into the metal. There was an experiment, hundreds of years old, in which a gold sphere containing water was compressed so that the water passed through the apparently solid metal and formed a dew on the surface, just in the same way as happens in the case of an obviously porous organic material.

Now there are very strong reasons in support of the view that lubricants can penetrate into metallic surfaces, and I can give two examples of this. One is the electro-deposition for the purpose of building up the part of a steel shafting worn by acting as a journal. It is well known to engineers doing such work that this deposition is in some cases difficult, if not impossible, because the lubricant has penetrated into the metal. Another case actually occurred in connexion with this Lecture. Mr. Taverner, of the Imperial College of Science, and to whom I sent the phosphor-bronze, manganese-bronze, steel and cast-iron used in the manufacture of some of the pumps previously described for the purpose of securing photo-micrographs, found that the phosphor-bronze would not retain its polished surface, and after a few hours became dull; whereas the manganese-bronze retained a perfect surface. On inquiry at the works I ascertained that the phosphor-bronze was actually part of a slipper which had been wearing under great pressure for some years on a lubricated surface, while the manganese-bronze was new material; and there is no doubt that the difficulty with the surface was caused by the presence of the lubricant which had exuded from the newly-polished surface, possibly with some change of temperature, and may not have been subject to any chemical change whatever.

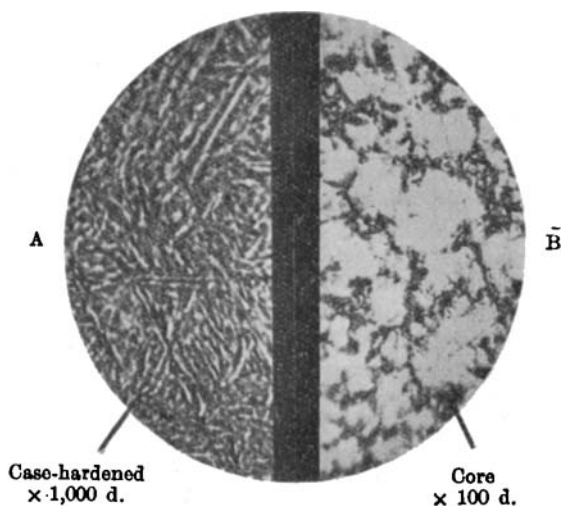
These facts, and others, seem to show that the lubricant may be mechanically entangled in the metallic surface; and a study of the photo-micrographs of the foregoing four different metals, all of which are used in the working surfaces in different parts of the oil pressure pump, make one feel that these surfaces, however polished (of course, all photo-micrographs are from highly-polished surfaces), afford abundant opportunity for entanglement of the minute molecules of lubricants. When we come to consider the number of molecules which, if we could see them, would present themselves to view on such a surface, this view does not seem to be unreasonable.

I have made a calculation, and had it checked, on data taken from recent researches in molecular structure, of the number of such molecules. Fig 10 is a photo-micrograph which you see represented by a lantern slide on a 12-foot screen. This is taken from a

polished area of metal about 3 millimetres in diameter, or about $\frac{1}{8}$ inch. On that area in the case of steel there would be approximately 2,000 million million molecules. This would be the number on the surface of a layer probably less than one quarter of a millionth of an inch in thickness. The actual size of a molecule is estimated as 2×10^{-8} cm., that is, one hundred and twenty-fifth part of a millionth of an inch, so that even with this enormous swarm of molecules in such a small volume, there must be spaces between them. As the foregoing number is utterly beyond our comprehension, I have reduced it in the same

FIG. 10.—*Photo-Micrograph of Steel used in Radial Pump.* (Fig. 4, p. 849).

A being case-hardened portion and B being core.



proportion as the lantern slide itself to the 12-foot screen, namely, $1/1200$ in diameter (or $(1/1200)^2$ in area), as the $\frac{1}{8}$ inch would be to the 12-foot screen. This would give us on one of these minute spaces, not visible to my audience, somewhere about 13,000 million molecules, or a number approximately equal to the population of the world.

It is, of course, hard to believe that there would be room for the penetration into such a vast mass of small particles by a lubricant forced against them; but it must be remembered that the solid particles are built up into crystalline form, and the irregularity of their distribution is obvious.

There is yet another possible explanation of the difference of behaviour of good lubricants and poor lubricants in the persistence of a film between two surfaces moving over each other, which separates them from molecular cohesion; and that is best illustrated by a quotation from one of the recent masterly contributions by Sir J. J. Thomson to the Molecular Theory (*Phil. Mag.*, May 1919): "If the atom is a mixture of negative electrified corpuscles and positive electricity it will produce in its neighbourhood a field of electric forces"—and later on; "These forces will be exerted by the atom not merely on the atoms which are associated with it in the molecules of a chemical compound, but also on the atoms in other molecules giving rise to forces between the molecules and producing thereby the intrinsic pressure and surface tension of liquids, latent heat of evaporation, cohesion of solids and liquids, the rigidity of solids, and so on."

Therefore, having support from such a high authority on molecular action we can quite well believe that this enormous army of molecules, in order to constitute a good lubricant, is held in the surface by electrical forces, without chemical change or even mechanical entanglement, and that for some reason such forces do not operate so effectively to hold bad lubricants, such as water, which would otherwise be equally good or better lubricants than oil.

When the molecular theory is more developed, and the nature of molecular structure and of lubrication are better understood, we may be able to explain the nature of oiliness and greasiness, and to know the reason why one lubricant is better than another, which at present is a matter of speculation and conjecture.

Whatever be the ultimate explanation it is obvious from the diagram, Fig. 8, illustrating the action of the Michell bearing that it is owing to the inability of the molecules to be squeezed out under pressure from the surface, that it is from (a) entanglement, or (b) electrical or (c) chemical attraction of the lubricant at the surfaces which prevents the two metals coming into contact and cohering with each other, destroying, of course at once, the action of the pump or machine. This, I think, justifies the idea that solid friction is what ultimately occurs when molecules get within range of molecular action of each other, ultimately causing cohesion, the distance when this molecular attraction begins to operate being somewhere about one quarter of a millionth of an inch.

Engineers are much concerned in the theory of the subject, and it is of such vital importance in their work that they must take their

part, together with the chemist and physicist in solving problems of lubrication. It is a question whether the time has not come for us to take up again the work by which Beauchamp Tower brought great and never-to-be-forgotten lustre on the annals of our Institution by his work on their Committee nearly forty years ago, and with a fresh committee taking full cognizance of the excellent work reported on by the Lubricants and Lubrication Enquiry Committee, which was made under the able chairmanship of our member, Mr. S. B. Donkin, and possibly in co-operation with the National Physical Laboratory, invite a number of engineers in practice to assist in further researches concerning a matter of such vital importance in mechanical engineering.

APPLICATIONS.

I will conclude my lecture with a certain number of examples of the practical application of elaulic transmission. There is no doubt that what led various inventors to grapple with the subject of variable transmission by the use of oil was the need of variable change gear for motor vehicles. About twenty years ago this need was felt very acutely when the steel tooth-wheels of the change-speed gear-boxes were very different from what they are at the present day. Nickel steel and chrome-nickel steel had not been brought into use for this purpose, if indeed these materials were known at the time, and gearing was not only very expensive, but lasted a very short time; hence oil gear, imperfect as it was, seemed to have a great future. The practical failure of the Hall gear led to other attempts to supply elaulic gear for motor vehicles, and a number of vehicles which worked entirely satisfactorily have been constructed with this kind of gear, the operation being beautifully smooth and silent. Whilst, however, this gear has always been expensive, the change-speed gear, using toothed wheels, has been so improved and reduced in price as to put the elaulic gear out of running in commercial competition with it. For a number of purposes not originally contemplated by the inventors, elaulic gear has been found to be so convenient and so effective in operation that it has superseded other methods of mechanical transformation and has in such cases become a recognized commercial proposition.

As I have stated, a variable stroke pump is employed in every case as the basis of such transmission, but an important distinction in use lies in the kind of motor by which the power is applied. For convenience we will take examples under the following three heads :—

- (1) A simple rectilinear movement, that is by the use of a ram.
- (2) Circular movement, that is, the use of a rotary hydraulic motor.
- (3) Examples with a combination of these two kinds of movement.

THE USE OF A RAM IN ELAULIC GEAR.

The most obvious use of this is an ordinary press. The rival of its use is, of course, either an accumulator or a supply of water from a water-pressure main; and the rapid advance of the elaulic transmission is in those cases where a great range of pressure is required; that is to say, where, at the commencement of the process, the material to be pressed is in a soft, diffused state, while ultimately great effort is required. It is obvious that the use of a hydraulic accumulator or high pressure from hydraulic mains for this purpose is a very wasteful process, owing to the fact that the fluid is incompressible and does not expand like steam or gas. Fig. 11 shows an elaulic press which has been very successful for making "Atora" suet, and a description will be interesting as it is being applied for many purposes where a soft material has to be compressed. The sectional view shows the suet in lumps in a container C, at the bottom of which there are a number of fine holes $\frac{1}{32}$ of an inch in diameter. Above the suet is seen a ram R, and above the pump which is shown at P is the tank T. Let us suppose the container to be full of suet and the operator pulls the pump-lever L to the left and the pump goes the full stroke. The ram R falls automatically at gravity speed, the pump following up. When the ram reaches the suet it first consolidates it at about 200 lb. per square inch on the ram. Further pressure causes the suet to be squeezed through the holes in the die plate, and the pressure rises to about 1 ton on the inch. This pressure causes the spring on the lever-spindle L to collapse and the stroke to be reduced, so that the suet is now compressed at a higher pressure and slower speed. As this is being done the oil flows through the tank to the casing, passes through the lower check valve shown in the section and into the pump section, and is then forced under pressure through the top flange of the pump, the shuttle valve S, which should be shown on its top position, closing the side passage in the valve casing. The oil flows up through the centre of the sleeve, which is held up by a slight spring, lifts the mushroom valve and flows into the top of the press. To lift the ram at the end of the operation the working lever is reversed and the oil is forced into the

lower or smaller side of the ram, thus forcing the piston upwards causing the oil to be forced through the large end of the cylinder. This oil goes to the top of the mushroom valve at S, closes it, pushes the shuttle sleeve down and covers the side passage leaving the surplus oil free to find its way back to the tank.

Fig. 12. This is a baling-press and shows an addition to the previous application in the form of an automatic intensifier. M is

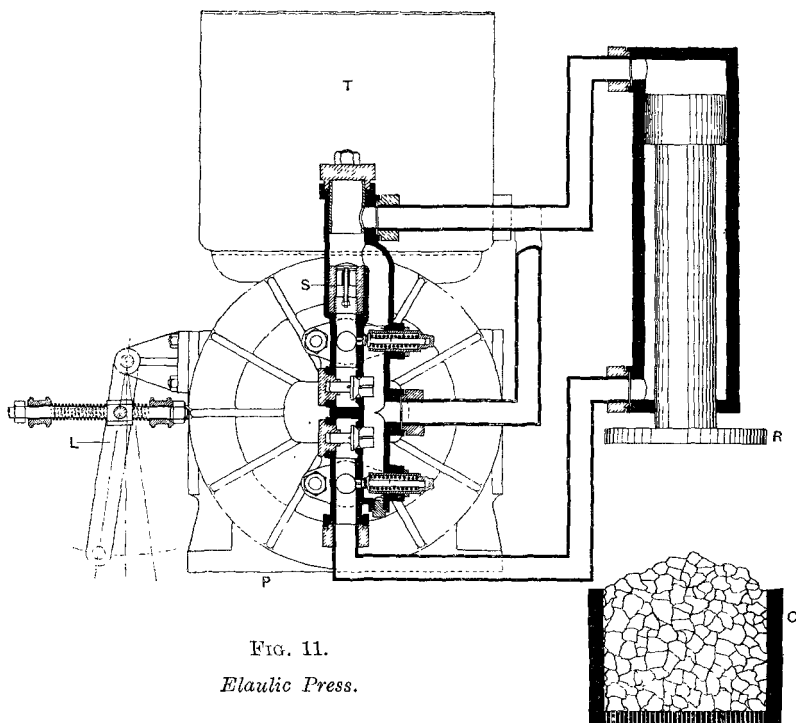
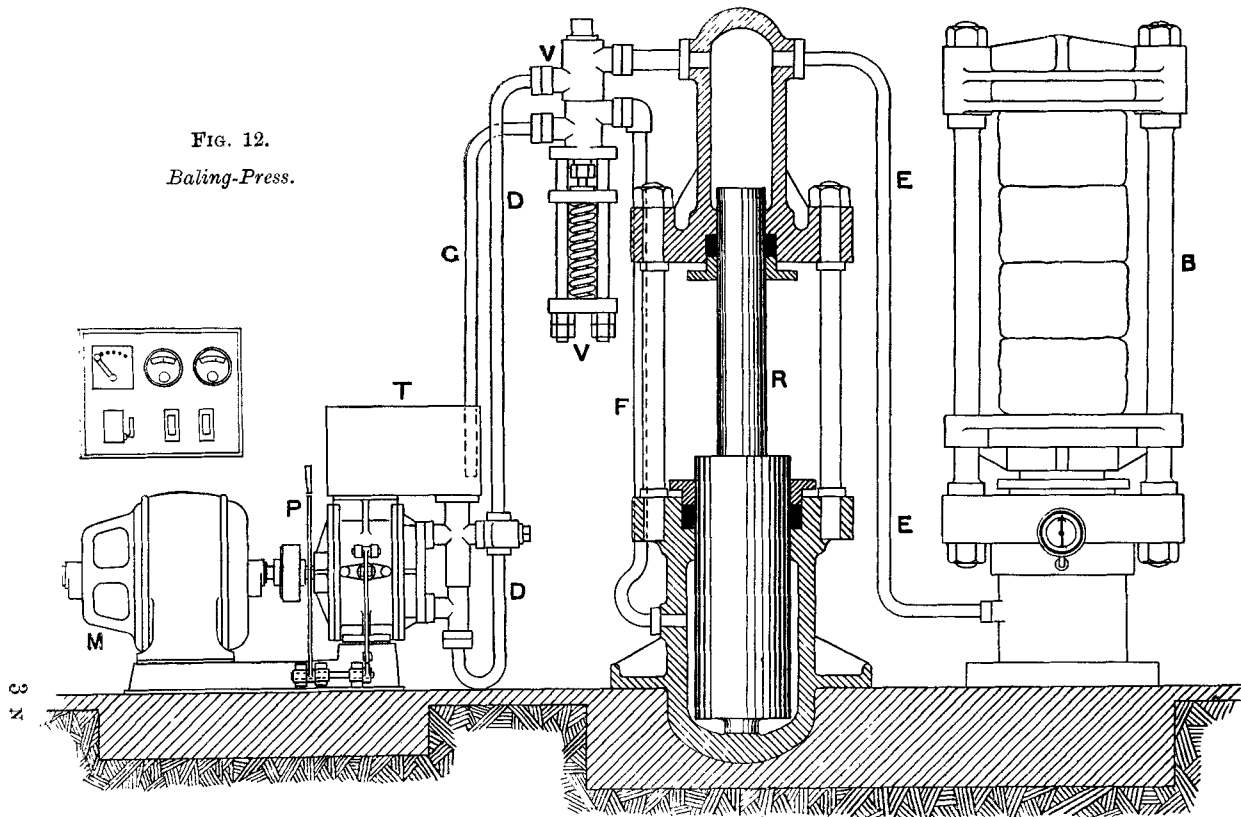


FIG. 11.

Hydraulic Press.

the electric motor, P the pump. The oil passes under pressure up the pipe DD through the valve seating V, over the top of the combined ram R and down the pipe E to the baling-press B. When the pressure reaches a certain point, say one ton, the spring of the valve V is compressed and the oil, instead of flowing direct by the pipe E to the press B now flows by the pipe F to the larger

FIG. 12.
Baling-Press.



end of the ram, which is twice the diameter of the smaller and therefore four times the total area of the smaller end of the ram. The pressure per square inch from the pump is now increased by exactly the difference in square inches between the large and small end of the ram.

The reversal of the pump reduces the pressure, releases the spring V, and reverses the action of the press. The oil now flows by the pipe G into the supply-tank T.

The last four examples, Figs. 13-16, are shown on the opposite page, and the nature of these will be easily understood. The first one of these, Fig. 13, is a swarfing press, the pump being driven by a belt, an intensifier being also used in this case. The material to be pressed consists of the lathe turnings, which, after great compression, can be reconverted into steel bars, otherwise the loose separated shavings are merely ignited in a furnace and burnt away. The effort produced by the belt using a full stroke of the pump is sufficient to enable the material to be rapidly brought into compact form, and the stroke then varied so to bring a pressure of many tons on an inch by the ram to form compressed blocks. From the Figure will be seen the spring arrangement by which the stroke of the pump is automatically varied; and it should be noted that the radial rotary pump described tends to set itself automatically into the lower stroke as the pressure increases, although one of the refinements of the pump is a further automatic arrangement by which this variation of stroke is ensured. Between the pump and the ram can be seen the intensifier, which is a still further refinement, by which almost unlimited pressure can be obtained from the pump. When a convenient pressure, say 1 ton or $1\frac{1}{2}$ tons, is reached the intensifier automatically comes into operation and a total pressure of hundreds of tons can be obtained if required.

Among the most interesting applications of this system, and one which has proved very successful, is the application to steering-gear. This device is well known to engineers and need not be described at length, but the various lantern diagrams show different types of steering-gear, in the operation of all of which is the direct operation of the rams and rudder head. The first steering-gear of this kind was that put upon the steam yacht "Albion," and a full account of the trials of the "Albion" was read before the Institution of Naval Architects.* These experiments show conclusively that

* Steering Gear Experiments on the Turbine Yacht "Albion." Trans., I.N.A., 7 April, 1911.

FIG. 13. — *Swarfing Press.*

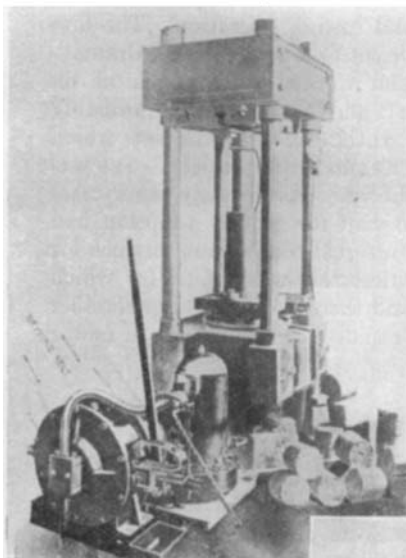


FIG. 16. — *Testing-Machine (Denison).*

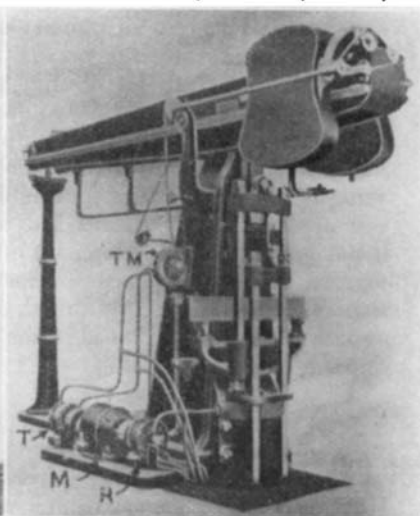


FIG. 14.

Ship's Deck-Winch.

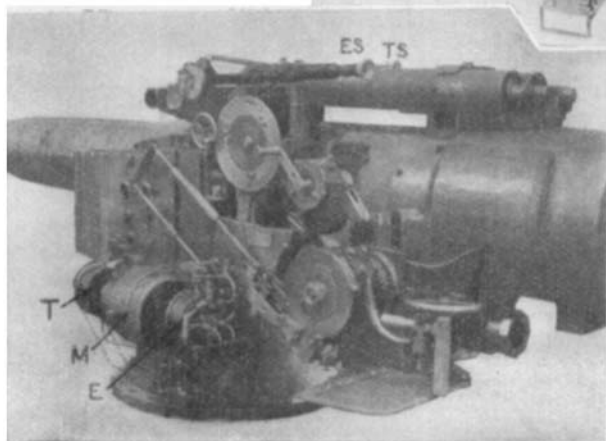
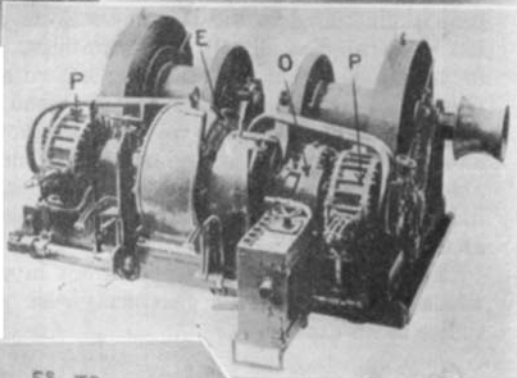


FIG. 15.

Application of Elastie Gears to 6-inch Gun.

the operation of the elaulic gear is superior in many respects to steam steering-gear, such as in rapidity and ease of operation. The first large instalment was made on the Orient Company's S.S. "Orama," of 13,000 tons, and this steering-gear worked without a hitch on the long runs between this country and Australia, and probably was running quite satisfactorily up to the time she was lost, which was after being converted into an auxiliary war cruiser. She was sunk by a German cruiser during the war. As in many other cases this application might have had to wait for general adoption had it not been for the development of internal-combustion engines for modern purposes. It was obvious that this was a field for which elaulic gear was eminently suited, and there is a very large number of such gears being installed in the rapidly increasing fleet of motor ships.

ROTARY MOTOR.

Illustrations have already been given of rotary motors (*see* Figs. 3 and 5). An important application of the rotary elaulic gear is illustrated in Fig. 14, in the form of a deck-winch, which has been applied largely in steamships, but more particularly in motor ships; it combines the known advantages of hydraulic power in dealing easily with any load with the convenience of electrical power. The illustration shows an electric motor E co-axial with which are shown the pumps PP, so as to be able to work independently the winches, and one of the two independent oil-motors directly operating the hollow drums is shown at O.

There are many other applications in various manufactures to which the rotary elaulic gear has been put, but the above will suffice as an example.

COMBINED RECIPROCATING AND ROTARY MOTION.

One of the examples of the combination of reciprocating and rotary motors is a crane in which the load is raised and lowered from the ram while the derricking and traversing of the crane is done by rotary motion. A most interesting application is the operation of guns, and Fig. 15 shows the way in which this is done. Until the introduction of elaulic gear for this purpose, 6-inch guns on warships were operated entirely by hand. In a sea-way it was a most exhausting process for one man to keep a gun trained

on an object on the quarter, owing to the rolling of the ship. The introduction of this gear was found possible, without any increase of dimensions in the shield of the gun. When installed it enabled both elevating and training processes to be performed for an indefinite time with one man for each operation. From Fig. 15 it will be easily understood how the gear was operated. The electric motor M being placed between the two pumps E and T, the former dealing with the elevation and depression of the gun, and the latter dealing with the operation of traversing, TS and ES being the training and elevating sights.

A recent application of elaulic gear is the Denison testing-machine. Fig. 16 shows such a machine. Such testing-machines were previously operated with either a purely mechanical means of operating a pump to obtain pressure on the ram or with an accumulator. The movement of the jocky or floating weight was obtained by a screw worked by a hand-wheel. In the Denison machine this is now done by means which are made clear by the illustration. The electric motor M is situated on the base of the machine operating two pumps T and R, that on the right, R, operating the ram and that on the left operating the rotary motor TM and thus the floating weight on the beam.

The applications of elaulic gear are constantly increasing, and probably it is the real solution of an infinitely variable and easily worked gear which can be operated where there is electric power available, enabling at once the combined advantages to be realized of the electrical transmission of power and its hydraulic operation.

The Lecture is illustrated by 16 Figs.

NOTE.—In the Lecture a tribute was paid to the pioneer work of Mr. Hall, but space does not permit of an account of the Hall Gear which was fully described with illustrations by the Lecturer in the *Commercial Motor*, 17th January 1907.

The attendance was 133 Members and 88 Visitors.

The LECTURE was repeated by Dr. HELE-SHAW in Manchester, Birmingham, and Glasgow:—

MANCHESTER, in the Memorial Hall, Albert Square, on Thursday, 10th November. Mr. CHARLES DAY, *Chairman of the North Western Branch*, presided, and about 280 were present.

BIRMINGHAM, in the University, Edmund Street, on Thursday, 17th November. Mr. E. C. R. MARKS, *Chairman of the Midland Branch*, presided, and about 130 Members and Visitors were present.

GLASGOW, in the Royal Technical College, on Thursday, 24th November. *Chairman*: The Right Hon. Lord WEIR, P.C., D.Sc., *Honorary Life Member*. The attendance was about 200.
