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Supervision of piston temperature during endurance testing.

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A great part of the element of ubcertainty which is caused in lubricating oil tests by the method of ring-sticking, arises from the fact that it has been impossible up to now to keep the temperature at the decisive figure with sufficient certainty. This is particularly true of the piston ring section. We will therefore first deal with certain sources of error which occur when, as up to the present, the temperature is measured outside the engine. We will then pass to the processes going on inside the engine which will, in certain circumstances, alter the piston temperature in spite of constant external conditions. To conclude, we shall make an exhaustive report on the process for measuring piston temperatures of running engines which was worked out by D.V.L.

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I. Introduction.

Experience gained so far in ring-sticking tests has shown that besides fuel and lubricant the decisive factor in the result is the piston temperature. While in general the degree of uniformity in the results of these tests was thoroughly satisfactory, it still often happened that in different cases, despite constant initial conditions and the most careful execution, the same oil gave running times which varied over wide limits. Also the individual engines gave widely divergent results, when they were used by different testing authorities, although the same conditions were observed throughout; we had therefore to make the arbitrary provision that conditions in each engine should be so adjusted as to give a running time of 8 to 8½ hours on the reference oil Rotring. These inaccuracies can be traced to the fact that the processes going on in the piston ring section could not be sufficiently controlled, although external conditions were constant. The object of this paper is therefore to elucidate more clearly the methods of supervision used up to now, to indicate the processes which influence the temperature of the rings - and hence ring-sticking - and finally to report on the process for measuring the temperature of the piston in a running engine.

II. Influence of external processes on the combustion temperature.

The mechanical conditions, i.e., speed and power, can in general be so exactly maintained and adhered to, if the measuring instruments are in order, that they do not cause irregularities. The same may be said of fuel consumption and ignition. As regards supervision of cylinder temperatures, the case is different. How little individual measurements may be depended on can be seen in the fact that one authority selected the sparking plug gasket temperature on the down-stream side as a criterion, another a point at the top of the cylinder head, and another the mean value of various cylinder-wall and -head temperatures. I should therefore like to refer here to the main sources of trouble.

1. Faulty installation of the thermo-couple.

Generally speaking, the thermo-couples are peened in. The bush can work loose, so that layers of oxide or sediment can form between the thermo elements, causing a considerable reduction in output. It is suggested that, to test the quality of the installation, the electrical resistance between cylinder material and couple wire be measured from time to time.

As we shall report later, this method of supervision has proved excellent, especially for measuring piston temperatures. Loosening of the couple wire, of which there was no mechanical evidence, or the formation of some layer of disturbance, resulted in observable changes in resistance.

2. Faulty contact at the connections and change-over switch.

Here too layers of oxide and wobbly contacts may give rise to considerable errors in measurement.

3. Faulty insulation of the wires running along the cooling fins.

A disturbance only occurs here if the wires come into contact with each other, or if the same wirs makes contact at several points with different metal parts.

The plug gasket temperature is used as the standard in many engines. According to tests made by D.V.L. on a small engine, the type of sparking plug and the method of leading off the cooling air play a very important part; in these investigations, the temperature of the cylinder wall at about the place where the topmost piston ring reaches its highest point was kept constant, and the plug ring temperature was measured with different types of sparking plug. It appeared that the heat value and the length of the screw-thread - i.e., the position of the ignition point within the bore, have no noticeable influence, while variations in the length of the plug housing caused the temperature to vary by as much as 35oC. Plugs which can be dismantled should have an even greater effect. Also, the cooling air exhaust was throttled in varying degrees, with the other conditions constant. The result was that at the same cylinder wall temperature, the temperature of the plug gasket varied by more than 20^{o}.

It is possible that at another point or with the sparking plug in a different position, the results of measuring the cylinder wall temperature would be quite different; this is only intended to show the importance of the place chosen for measuring the temperature, and explains the different values obtained for the same running time with the same fuel.

In addition, the oil entry and exit temperatures were chosen differently for the different engines. It is obvious that the temperature of the oil will influence the piston temperature and thus the ring-sticking time. Thus at different oil temperatures, the same running time requires different control temperatures.

But the influence of oil temperature is overshadowed by the volume of oil fling on to the piston. Tests carried out elsewhere have shown that the piston temperatures could be lowered by more than 40^{o}C. if the volume of oil which is directed at the enterior of the piston is correspondingly increased. This surprising result led us to record the volume of oil thrown on to the cylinder walls and piston of a BMW 132 oil-testing engine; a window was fitted in place of the cylinder flange, and it was revealed that the oil volumes thrown from the connecting rod vary very greatly. The greatest volume appears to be flung from the oil supply side of the big end; in the middle it is comparatively small; at the far side the volume rises again. This shows clearly that the lateral and radial play of the big end is very important. The quantitative study of the volume of oil fling has not yet been concluded; we shall report on this later.

Influence of internal processes on the piston temperature.

The volume of oil thrown is not in itself sufficient indication of the thermal load on the piston. Therefore, in what follows we shall enumerate the different factors which influence the temperature of the rings :-

(1) The clearance between piston and cylinder.

The piston clearance should be kept as small as possible (but should of course be large enough toprevent the piston from seizing), as the temperature of the piston skirt can best be controlled through the cylinder wall temperature, that is, through cooling. If the clearance is greater, that proportion of the heat which is absorbed by the oil between the piston and cylinder increases, so that supervision from outside becomes even harder, as it is impossible to measure continuously the heat absorbed by the oil. If the play is greater still, the oil film no longer forms a seal, but gives way in places, so that the continuity of heat flow to this part of the piston suffers considerable interruption. Another possible result of the impaired sealing is that combustion gases pass the piston rings, which not only interferes with the uniform cooling of the piston, but may actually cause local overheating. As this causes the cylinder wall to become heated, greater cooling is necessary - the cylinder wall temperatures (control temperatures) being kept constant throughout the run. Even with a high blow-by gas flow the running time is only slightly affected, which proves that the increase in cooling to a great extent cancels out the influence of the blow-by gases. But the results of such runs are less uniform than with a small blow-by.

(2) Side clearance of the rings.

The side clearance of the rings is very important, as many authorities have observed. But the extent of this influence depends very largely on the way in which the piston distributes the heat: pistons with a large sliding surface on the skirt of course conduct much more heat to the lower part than to the ring section, while pistons with a small sliding surface - e.g., slipper pistons - act quite differently; here the ring section is loaded to a considerably greater extent, so that the influence of the ring clearance is much greater than in the first type of piston. If the piston clearance increases, the heat is conducted even more to the ring section, so that lateral ring side clearance becomes increasingly important.

The influence of ring clearance on the time that elapses before ring sticking begins must be considered from two points of view :-

(a) The greater the side clearance, the greater will be the space which must be filled with deposits ~~in order~~ to bring about sticking, and thus the longer the running time. Given even temperature, the running time should rise linearly with the side clearance. This was proved by measurements with a piston temperature measuring device, which will be described later, Fig.1. The fact that the results of these tests did not completely bear out the linear relationship, could have been due to the fact that the temperature could not be measured in the ring groove, but only in the piston, at a point near the ring section.

(b) Heat transfer from the piston to the cylinder is influenced by the ring clearance: if this is small, the heat transfer is good, and the ring takes roughly the temperature of the part of the piston near it. If the play is large, the heat transfer is worse, as the oil between the ring and the groove acts as a heat insulator. In order to maintain an even piston temperature, therefore, considerably more cooling is necessary to begin with, see Fig.2. If the clearance between the ring and the piston is still larger, the oil there begins to flow, and may thus conduct away part of the heat. Thus it is no longer necessary to have such low cylinder wall temperatures in order to keep piston temperature at the same level as before.

(3) The sealing of the rings.

It is obvious that the temperature is also influenced by faulty sealing between the piston and the cylinder. It makes no difference whether this is caused by the oval or badly run in rings, by inadequate ring-tension, or by the ovality of the cylinder. The consequent blow-by of gas will in any event lead to local heating. Admittedly, this disturbance can largely be eliminated, as has already been mentioned.

(Fig.1. Effect of ring side clearance on running time at constant piston temperature)

(Fig.2. Effect of ring side clearance on cylinder wall temperature at constant piston temperature)

(4) Formation and adhesion of film.

It is well-known that by chamfering the lower edge of the piston it is possible to influence the oil-scraping effect to a pronounced degree. In the same way the condition of the oil-scraper rings will have a great effect on the quality of the oil-film between the piston and the cylinder. If the scraper ring works too efficiently, the oil film will be repeatedly broken - the more so, the greater the irregularity in shape of the cylinder - and so it will be impossible to guarantee an even flow of heat from the piston to the cylinder wall.

Many oils whose adhesive properties are poor, give fairly short running times - which often vary a good deal - although their tendency to form deposits is not unfavourable. The short running time is therefore only due to the fact that, although the standard temperature was the same, the poor adhesion caused the piston temperature to be higher than in the case of the reference oil with its superior adhesion. The heavier thermal load, however, often leads to a greater formation of deposit, and thus to shorter running times up to the moment of ring-sticking.

(5) Friction.

The results of the ring-sticking test runs frequently show that burring occurs on the running surfaces of the piston rings. This indicates that in certain cases the temperatures at the sliding surface are so high that part of the material becomes plastic, or that particles which have been broken away from the structure have become welded to the rings owing to the high temperatures. Therefore, it seems that we cannot speak of the rings as conducting heat. On the contrary, the high friction is a source of heat which might influence the distribution of temperature in the cylinder. We have no test data on this point; it is merely referred to in the hope of interesting others in making corresponding tests.

(6) The Deposits.

We must finally refer to the formation of deposits. It is quite possible that the carbon deposits could in time cause alteration in the heat flow. This explains much of the variation which occurs, especially when an oil which is very sensitive to temperature is being tested.

Measuring the piston temperature of a running engine.

All these considerations make it clear that it would be very useful if we could carefully supervise the temperature of the rings during a run. For this reason D.V.L. have attempted to develop a suitable process for making such measurements, and on this we shall now report.

The basis was the piston temperature measurement process which was first published in the U.S.A. by Keyser and Miller some years ago; a thermo-couple is built in at the place on the piston where the temperature is to be measured, with its two wires led to contact pieces at the lower edge of the piston. While the piston is at bottom dead centre, these contacts touch corresponding contacts, through which the thermo-current is conducted.

As the time during which they touch is very short, a millivoltmeter connected to the fixed contacts via a cold junction would only record a small portion of the actual thermal power output, because of its inertia; also, the continually fluctuating contact resistance has some effect here, so that even an indicator which had no inertia - e.g. an oscillograph - would not record the actual thermo-current.

Therefore we measure the thermo-current by the so-called null method. If an E.M.F. is applied equal and opposite to the thermo-couple voltage, no current will flow throughout the circuit. To determine the temperature, the counter - which can easily be measured - must be of such magnitude that there is no current flowing through the circuit. The magnitude of the current then corresponds to the temperature at the measuring point.

It is clear that with this method the circuit resistance is of no importance, as the current is always at zero. The higher the circuit resistance, the more sensitive must be the zero instrument, if the accuracy of the measurements is not to suffer; for otherwise, owing to the fall in voltage, slight differences between the thermo-current and the counter-current can no longer be observed.

In America the Counter-current was drawn from a Wheatstone bridge fed by a battery; this was controlled by a variable resistance in the bridge. The whole installation was so calibrated that the magnitude of the bridge current, that is, the temperature to be measured, could be obtained from the setting of the variable resistance. Such a bridge circuit will only guarantee a dependable measurement of the counter-current if the resistance of the control circuit is constant and very small. Also, the wire must not become worn through repeated control movements, or its resistance will alter, and the instrument would require frequent re-calibration. Fluctuations in the current source are of course also to be avoided. Since the fulfilment of these requirements might prove difficult, D.V.L. went to work in another way to obtain a counter-current, see Fig.3. The counter-current here is delivered by a thermo-couple, which is brought to the same temperature as that at the measuring point on the piston by an electrical heating installation. The temperature of the counter-couple is measured by another thermo-couple. While the two wires from the counter-current lead via the zero instrument to the contacts in the engine, the wires of the indicator couple pass via a cold junction to a millivoltmeter. A measuring device which indicates the temperature directly, and is calibrated exactly for the material of the element, proved specially efficient.

(Fig.3. Diagram of the piston temperature measuring apparatus.)

(Fig.4. Heating element for generating counter-current.)

(Fig.5. Heating element for generating counter-current(complete view))

(Fig.6. Piston temperature apparatus (front view))

(Fig.7. Piston temperature apparatus (rear view))

To avoid errors and inaccuracies as far as possible, the indicator- and counter-thermo-couples are welded into one junction, Fig.4. This is surrounded by a wire coil which can be heated electrically, and the junction can thus be brough to any required temperature. Of course, the coil is wound round loosely, so that the junction and leads are not touched by it. For protected against air currents, which would cause heat loss with consequent fluctuations in the temperature of the thermo junction, a glass bell covers the whole unit. This only fits loosely, so that the heated air in the internal space can escape without delay (Fig.5.)

The heating coil is fed from the mains via a transformer. Several resistances arranged in stages provide accurate control. The whole installation is shown in Fig.6. At top left is the instrument for reading off the temperature directly; the switch to the left of the ammeter is for disconnecting. This short-circuits the instrument, thus protecting it during transport. The apparatus terminals below it serve to short-circuit the fixed resistances for coarse control. Right at the bottom are three knobs for fine control.

On the right, close to the switch box is the zero instrument, a light spot galvanometer of the firm of Hartmann and Braun. The rear view, Fig.7. shows in the right foreground the container with the melting ice for the cold junction, and close to it on its left the transformer; between them and behind is the heating element for generating the counter-current. The other parts are easily recognised, and there is no need to describe them further.

With this installation, the temperature of the thermo junction can be quickly and accurately adjusted. Tests have shown that temperatures ranging from 20° to about 850° can be set in the shortest time - about two to three minutes.

At this point we should mention that the counter-current installation proved extremely suitable for calibrating the most varied types of thermo installation. For this reason the instrument has been so constructed that the heating element for generating the counter-current at the thermo junction are interchangeable. To calibrate a given thermocouple, we have to use a heating element such that the counter-current couple is replaced by the couple to be calibrated. If a millivoltmeter is connected to the couple via a cold junction, then a calibration curve can be plotted very quickly, since any required temperature can be set in a short time with the counter-current instrument.

An indicator or a thermal measuring installation can of course be tested in the same way. A large number of heating elements were produced by D.V.L., in which different thermal materials were built in. To test the measuring installations on the test-beds, for instance, in a quick and reliable way, it was only necessary to connect the heating element to the corresponding thermal material; the test could then be completed in a very short time - about 10 minutes.

For accurate measuring, the zero instrument must indicate clearly EMM.F.s of less than 0.01 millivolts. This condition was very satisfactorily fulfilled by a light spot galvanometer of the firm of Hartmann and Braun (cf. also Fig.6.).

But since at present such instruments are in short supply (the time for delivery is at least 18 months), D.V.L. determined the zero current in another way: the current flowing between the measuring point in the piston and that in the thermo-couple is interrupted at intervals which vary as the engine speed. A direct current interrupted in this way can be transformed. The alternating current generated in the secondary winding can be amplified by a suitable valve circuit. Measurements were carried out with an experimental installation on these lines, which indicates that, given sufficient amplification, this method would be successful.

Great difficulty was experienced, both here and in America, with the installation of the thermo wires in the piston: since all the engines on which measurements were taken had light metal pistons, it was impossible to solder or weld the thermo-couple to the material of the piston. An attempt to fit a small piece of iron or copper, with the wires hard soldered into it, into a drilling in the piston-ring groove, was unsuccessful, as heat expansion during working always caused small cracks to form, through which the combustion gases could pass. The deposits which formed in the cracks caused fluctuations in heat transfer, and thereby errors in measuring. For this reason we dispensed with a measuring point in the ring groove.

There were considerable technical and mechanical difficulties in the way of installing the couple from the interior of the cylinder outwards, especially as regards insulating each wire right up to the measuring point, which was behind the groove and as close to it as possible. Therefore, in the case of the two small engines - the NSU-engine 50/501 OS (500 cm3) and the DKW-engine EW 301 (300 cm^3) - we did not measure near the groove, and inserted the wires, close to each other, in the interior of the piston, behind the rings. This arrangement withstood all the strains of running in the small engines, as it was impossible for any gases to blow through. Also, we may assume that the temperatures at the point of insertion are roughly in proportion to those in the groove; so that from them we could draw conclusions as to the temperatures of the piston rings.

Fig.8. shows the type of installation in use in the N.S.U. piston. The contacts at the lower edge of the piston show clearly. The wires are passed through the actual contacts in a small drilling, and secured by a grub screw from the inside. The insulating material was Igamid A, a synthetic resin produced by I.G.Farben, which is completely stable up to 250°C. The tests referred to later were all made using this type of contact. Lately we have used, for high thermal loads, contacts of the same type, insulated in the piston by mica.

We measured the resistance at the insertion point before and after every test, in order to make sure that the insertion was secure. The slightest loosening of the wires leads to alterations in resistance.

While this type of insertion stood up to every strain in small engines, even at high engine speeds and for long periods of working - 20 to 40 hours - extraordinary difficulties were encountered with a BMW 132 single-cylinder engine; the reason is undoubtedly to be sought in the considerably higher piston speeds (11 to 12 m/s at 2000 r.p.m. as against 7 to 8 m/s in small engines), that is, in the higher acceleration. Wires, whether introduced into the piston in an exposed condition or secured with clips and insulating tubes, tore loose after a very short operating time. We then covered the wire in asbestos, and passed it through holes in the cooling fins, without avail. If the wire was stretched too tight, it snapped, owing to the heat expansion of the piston, if less tightly stretched, it sheared through the holes in a very short time. The method in use in the U.S.A. of laying the wires inside or on top of a suitable carrier (steel wire of tube) was also unsuccessful.

We next decided to introduce the wires to the interior of the piston. Drillings of 3mm. were made, into the piston crown from the groove, and into the body of the piston from the crown. Into these the wire was introduced, embedded in a thin asbestos covering (lately we have used glass fabric as a substitute). The auxiliary drillings are closed off with a plug of piston material. To make the wires absolutely fast, a suitable cement was pressed in until it came out at the other end of the drilling.

With this type of insertion the wire never broke loose. But since the wire ends were laid as far as the first groove and were there inserted into the piston material, failures such as have already been referred to were observed. We tried several methods to eliminate this fault, but tiny cracks continued to appear between the couple and the body of the piston. Certain deposits formed in these, which affected the measurements.

These difficulties made it necessary to transfer the measuring point to the interior of the piston.

Fig.9. shows the latest type of installation. A groove is milled into the top of the piston, in which is placed a narrow thin iron plate. The two thermo wires are hard soldered on, one at each end of this plate. The exposed part above the groove is covered by a chamfered strip of piston material, which is fitted in very tightly. The two wires are led as before through suitable drillings in the piston skirt to the contacts at the lower edge. The contact pieces are insulated by mica, as already mentioned.

In this type we no longer measure the temperature at a definite place, but take an average between the temperatures at the two connections between the wire and the iron plate. But since these two points are close to the top ring groove, perhaps such an average figure is better than a measurement at a single point for the purpose of checking up on the temperatures prevailing in the ring groove. Also the large area of contact between the plate and the piston material gives more reliable figures than measurement at a single point, because the degree of contact would fluctuate considerably on account of the varying heat expansion of the material.

(Fig.10. Types of contact spring.)

The material used for the contacts was phosphor bronze. The contact springs were made of the same material, so that no additional thermal forces are created.

The choice of a suitable type of spring was also a difficult matter. Fig.10. shows all the types tried by D.V.L. Types 1 and 3 were made of steel with a coating of German silver (of course the piston contacts are also of German silver). But the coating wore off very quickly, for when it was fixed more securely the spring was less efficient.

As a result of the high speed at which the contacts touch the springs, vibrations always occurred, leading quickly to breakage. Only types 8 and 9 in Fig.10. were really effective. As the springs in the crank case are always wet with oil, it was possible, by having two blades, separated from each other at the lower end, to use oil damping. On the B.M.W. 132 a piece placed behind the inner spring prevented the deviation from becoming excessive, so that there was further damping here.

We show an illustration of the actual device in Fig.11. This is the contact spring of a N.S.U. engine, and the method of installing the two springs is shown in Fig.12. Naturally the method of installing is rather different on the DKW and BMW 132 engines, but for all that the spring has the form described above.

Finally it must be mentioned that accurate measurement is only a certainty if the contacts and springs are of the same material; for the temperatures at the connections of the wire and contact and the wire and spring are not quite the same, so that a small thermal force is created. But we may assume that this source of interference is generally of the same magnitude, so that there is no influence on the relative temperature.

V. Results of the measurements.

To conclude, we give a few results of tests: Fig.13. shows the dependence of piston temperature on the operating conditions in a small liquid-cooled two-stroke engine.

(Fig.11. Contact spring for N.S.U. engine)

(Fig.12. Method of installing contact springs in a N.S.U. engine)

It is interesting to note here that the coolant temperature has little influence on the temperature of the piston. In the normal range, increase in engine speed causes a slow fall in piston ring temperature, and at very high speeds a rapid rise; but we must check this curve, as its course appears somewhat obscure. Apart from power, other influences are slight.

The results with the small air-cooled engine (N.S.U.) Fig.14. show that the temperature of the cylinder walls has a great influence on that of the piston. The ignition advance has slightly less effect, while changes in the other conditions only affect the piston temperatures very slightly. (The fall in piston temperature consequent on increased engine speed may perhaps be explained by the fact that in these tests, as for ring-sticking runs, we used a high ignition advance (40° before T.D.C.)). This raises the temperature at a low engine speed still more than at a high engine speed.

The result was the same, only to an increased degree, when measurements were made on the B.M.W.132, Fig.15. The surprising thing here is the small influence of oil pressure; we may of course assume here that the big end clearance has itself a much greater effect, while the oil pressure only slightly alters the oil fling volume. Owing to lack of time, we could not examine all the factors. (We also established the dependence of piston temperature on the plug gasket temperature with a piston having the thermo-couple inserted in the first ring groove. The disturbances described above occurred here, leading to the variations as they appear in the picture).

It should be emphasised here that when taking these measurements only one value was altered, other conditions remaining constant. For example, the influence of ignition was established on a BMW 132 at constant cylinder wall or plug gasket temperature.

(Fig.13. Influence of various operating conditions on the piston temperature of a DKW engine)

In a liquid-cooled two-stroke engine the piston temperature is mainly influenced by power, the remaining influences, including that of the coolant temperature, are slight.

(Fig.14 Influence of various operating conditions on the piston temperature of a N.S.U. engine).

In an air-cooled engine the piston temperature is mainly dependent on the cylinder wall temperature and ignition advance. Other influences are slight.

(Fig.15. Influence of various operating conditions on the piston temperature of a BMW 132 oil testing engine).

The results lead us to suppose that the great differences in control temperature for the same running time, with the same oil, may perhaps be due to the fact that practically every test station used a different ignition advance for its ~~tests.~~

Investigations show that the use of the piston temperature apparatus has in the past given valuable results. It is certainly desirable to introduce it into general use, but first more experience is needed, especially as regards the installation of thermo-couples and springs.