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THE INFLUENCE OF WORKING CONDITIONS ON PISTON TEMPERATURE.

by Glaser.

The process for measuring piston temperature on a running engine was developed at DVL in the first place for better supervision of the operating temperatures in the fuel endurance test (investigation of the tendency of fuels to deposit formation, piston-ring sticking). It is therefore fitting to investigate how far external conditions influence the processes inside the engine - especially piston temperature. Therefore the individual factors influencing piston temperature were investigated in those engines which were previously used at DVL for ring-sticking tests; comparison with earlier test results confirms that ring-sticking depends first and foremost on the temperature in the ring-groove.

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I. OBJECT OF THE TESTS.

The use of a suitable measuring technique for observing the piston temperature of a running engine was discussed in a recently published report (1). Since reliable measurements were made even during long periods of working, the prospect arises of using this method for the permanent observation of the conditions in the engine during long duration fuel test runs - the so-called ring-sticking runs. It is necessary to investigate how far the piston temperature is influenced by changes in the individual working conditions. The result of these investigations would be a valuable guide as to which working conditions must receive special attention, if the temperature of the piston is to be kept constant.

II. METHOD OF MEASURING PISTON TEMPERATURE.

The method of measuring the piston temperature has been described in detail in a specisl report. It will therefore only be discussed briefly here:

The wires of a thermo-couple which is built into a piston are insulated and led to contacts at the lower edge of the piston, where they rub against contact springs in the neighbourhood of bottom dead centre. These contacts are connected with a second thermo-couple by way of a sensitive mirror galvanometer. This second thermo-couple can be brought to any required temperature by heating it electrically. The temperature of this counter couple is measured in the usual manner by another thermo-couple, so that it can be read off directly on a calibrated instrument. If the temperature at the point of measurement in the piston is the same as that of the counter-couple, then there is no current flowing between the two points. Therefore the temperature of the counter thermo couple needs only to be regulated so that the galvanometer registers a zero current. If this is done, the temperature can be read off directly on the graduated dial. To make this clear, Fig.1 shows the whole installation.

The method of installing the thermo-couple in the piston, the design of the contacts and contact springs, and the method of constructing the equipment for matching up the counter thermo couple, are described in detail in the above report, so that there is no need to discuss this further here.

III. WORKING CONDITIONS AND TEST METHOD.

Since the process for measuring the piston temperature is primarily intended for use in tests on the formation of deposit in the piston ring groove, the influence of the working conditions was investigated on those engines which are used for ring-sticking tests. It should be mentioned that in the tests about to be described all the working conditions were kept as constant as possible, and only that quantity was altered whose influence on piston temperature, was to be determined. Of course, a change in one quantity often brings about a rise or fall in another working condition.

This was corrected as far as possible in individual cases, so that where possible only one factor was investigated at a time. For example, in the investigations on the influence of ignition timing, the cylinder wall temperature was kept constant by cooling to the required extent. Again, a change in engine speed produces a corresponding change in the power output; therefore the throttle setting must be altered accordingly if the power is to be kept constant. This again results in an alteration in the quantity of cylinder charge and the intake conditions. Therefore, to investigate the influence of the engine speed, it is necessary to carry out two tests: one at constant throttle with various power outputs, and the other at constant power with various throttle openings. Similar instances of inter-dependence of condition occurred in several other cases; they will be discussed in more detail later. Very often the fuel consumption had to be regulated for each measurement; this generally made it necessary to re-set the initial temperature. This interdependence of the individual conditions made it very difficult to carry out accurate tests, and the initial conditions could only be kept constant within certain limits, which were, however, quite narrow. The course of the individual investigations can be seen in the graphs, so that it is unnecessary to go into the conditions in detail. The following fuels were used for all the tests:-

Fuel : VT 702 + 0.12 Vol.% tetra-ethyl lead.

Lubricant: : Rotring D-reference oil

1. <u>BMW 132-Oil Test Engine.</u>

The tests on the BMW 132 oil test engine had the most important bearing on all later engine tests. It is a single cylinder engine constructed from a unit of a BMW 132 aero-engine, which is used for testing the ring-sticking tendency of aero-engine lubricants. The data of this engine are given in <u>Table 1</u>. As the experiments are primarily intended to improve the technique of testing engine lubricants, the initial conditions are selected according to the working conditions in the ring-sticking test runs (2). These are also set out in <u>Table 1</u>.

In order to keep the cylinder wall temperatures as steady as possible, the temperature of a test point was observed throughout the tests and was held as constant as possible. The test point temperature selected was that of a sparking plug ring, which was on the sheltered side of the injection nozzle bore, and was installed as a packing ring for a DVL combustion chamber thermo-couple (3). This position was chosen because initial tests had shown that the thermal load on the cylinder could best be observed from there. The initial temperature at this measuring point was kept considerably lower than in the ring-sticking runs (220°C instead of 265°C), so as not to prejudice the result by inducing premature ring-sticking. (The temperature measured above is hereafter known as the cylinder control temperature).

The variation of the individual factors is seen in Figs.2 to 10. How far the piston temperature was influenced by these or other factors will be discussed in each individual case. As already stated, the effect of engine speed was investigated with reference to two other factors.

When the influence of ignition timing and cylinder wall temperature was investigated, the power fluctuated by about ± 1 HP. Since the piston temperature would vary by ± 1.4°C at constant power (see dependence of piston temperature on power in Figs. 2 and 33), a corrected curve was plotted in Figs.5 and 7 which takes into account the change in power. The fuel consumption (cf Fig.6) also results in a slight fluctuation in power, which is, however, too small to alter the piston temperature curve to any extent.

The influence of the oil temperature could only be determined over comparatively small range. To undertake investigations at lower or higher temperatures it would have been necessary to have additional heating or cooling installations on the test bed, which was impossible because time and material were lacking. Nevertheless, the piston temperature can be clearly observed, so that we may assume that outside the region which was investigated the prolongation of the curve was linear.

The influence of oil pressure and volume of oil circulation has been investigated in connection with other tests; for this reason the engine speed and the cylinder control temperature are higher than in the other tests. Fig.9 shows that at the very low oil-pressure of 1.2 atü the power falls sharply; an attempt to keep it constant by opening the throttle was unsuccessful. It is therefore unnecessary to correct the piston temperature.

The oil circulation rate was varied by altering the oil pressure. Fig.10 is, therefore, on the same footing as Fig.9 as regards experimental technique. It is only intended to show the relation between the effects of oil circulation rate and oil pressure.

2. N.S.U. engine.

For research in the small four-stroke engine field, the engine used was the air-cooled 500 c.c. motor-cycle engine of "Vereinigte Fahrzeugwerke A.-G.", Neckarsulm, Type NSU 501/OS. The engine data, and the working conditions under which the measurements, to be discussed later, were made, are set out in Table 2.

Although the engine generates its maximum power at 3500 r.p.m., all the investigations were made at 2000 r.p.m., since this was the engine speed used in the ring-sticking tests (it has been proved (4) that at high engine speed the piston ring grooves were gummed too rapidly, so that the side play of the piston rings, which has a great influence on ring-sticking, altered during the test, and so could not be controlled. At low engine speeds this trouble was absent).

The cylinder head is detachable in this engine, with the result that the heat flow between cylinder and head alters from run to run. Therefore the cylinder control temperature was measured on the tappet side (perpendicular to the direction of flow of the cooling air) between the first (upper) and second cooling fins. Earlier tests, in which 4 thermo-couples were distributed evenly over the circumference of the cylinder, in the direction of flow of the cooling air and perpendicular to it, showed that the point selected for measurement on the tappet side is the one most influenced by the working conditions, and thus offers the best opportunity for controlling the thermal condition of the cylinder. The measurement at this stage was made by three thermo-couples, in close proximity to each other, whose average value was kept constant throughout the tests.

Figs. 11-21 show the course of the individual tests. The procedure adopted was as far as possible the same as that for the BMW 132 oil test engine. In the investigations on the influence of the engine speed (Figs. 12 and 13), the variation of the piston temperature was at first very difficult to understand. The same tests were repeated at an ignition advance of 32°, in order to establish if the above was connected with the comparatively high ignition advance (cf figs. 14 and 15). The significance of the ignition advance will be discussed in detail later on, in the discussion on the test results (Section IV, 2).

The tests with altered ignition (Fig.16) were made at a somewhat higher cylinder wall temperature. Just as in the other tests it was kept constant, so that this fault had an insignificant effect on the result. In this investigation the power fluctuated by 0.2 b.h.p.; but according to Fig.11 this alters the piston temperatures only very slightly. Therefore it is unnecessary to correct the piston temperature curve.

The same is true of the influence of the cylinder wall temperature. Here too it is unnecessary to alter the curve which was obtained. In order that this result can be compared with that in other engines, the variation of the plug-ring temperature is shown in Fig.18. As in this test bed the heat flow from the cylinder head to the cylinder itself is very unsatisfactory, temperatures at this measuring point are very high.

The influence of the oil temperature was examined by heating the oil as it entered the engine (Fig.19).

The volume of the oil circulation (cf Fig.20) was altered by adjusting the oil pressure regulator. The oil pressure only fluctuated very slightly in the process, so that this value, which was already very low (0.15 atü) hardly altered during these investigations.

The influence of lateral ring-play was also investigated on this engine; the first ring had to fit into its groove with a different amount of play in each test, and so this test was made in connection with various ring-sticking runs. The ring-sticking time was determined at the same piston temperature in each case. To this end, a different cylinder wall temperature had to be set for each degree of play (cf Fig.21). The result, that is, the fact that the heat flow between the cylinder and the piston is affected by the lateral play has already been noted and explained elsewhere (5); it will be discussed more fully in Section IV. 8.

It is also interesting to observe that the power rises linearly with the ring-play. This fact is possibly connected with the piston ring friction and the resulting heat loss; but for the present a satisfactory explanation of this is impossible. It is obvious that the linear curve is only possible within the limits shown; if the ring-play is large the line must develop into a curve, or there must be a sudden sharp fall, for above a certain degree of play the oil-film will no longer fill the space between the ring and the groove; it will no longer act as a packing, so that gas blowby will be permitted in large volume, and the power will fall in consequence. Whether we have here a method of testing the film adhesion of various oils in the engine remains to be seen.

To determine the influence of lateral ring-play on piston temperature at constant cylinder wall temperature and constant power, the values for the piston temperature require correction: the figures below show the individual steps required for this purpose.

<u>Ring-play</u>	m.m.	0.05	0.08	0.10	0.13
<u>Initial values</u>					
Power	b.h.p.	8.54	8.86	9.11	9.41
Cylinder wall temperature	°C	283	268	271	275
Piston temperature	"	273	274	273.5	274
Piston temperature at constant power	°C	273	273.5	272.5	272.5
Cylinder wall temperature	°C	273	285	282.5	280.5
Power and cylinder wall temperature	°C	273	284.5	281.5	279.5

This result is presented graphically in Fig. 45, and will be discussed in detail later on.

3. The DKW engine.

Since ring-sticking tests have already been made on a small two-stroke engine, both at DVL (6) and elsewhere (7), the individual factors were investigated on a DKW engine EW 301. This is a liquid-cooled single cylinder unit of 300 c.c. capacity, with mixture lubrication and crank-case charging (reverse-scavenging). It was constructed by Auto-Union asa stationary engine. The working data are seen in Table 3. The coolant used was tri-ethylene-glycol, which has a boiling point of 240°C.; the object of this was to make the thermal load on the engine in the ring-sticking tests as high as possible. In spite of this the cooling temperature was in most cases kept fairly low, so as to avoid ring-sticking, which occurs easily on two-stroke engines.

The previous tests were made at constant coolant outlet temperature, so that this value could serve as a standard. The plug ring temperature was measured in every case, but was not used to keep the thermal load on the engine constant, since according to investigations made so far the connection between the cooland temperature and the plug ring temperature is still completely obscure. The tests now about to follow will show that so far the correct temperature at which to conduct the tests has not been found.

The fuel consumption could not be controlled, sharp fluctuations had therefore to be allowed for. It appears from Fig.27 there is no great effect on the piston temperature, so that it was not necessary to correct the curves accordingly. The relationship with power, shown in Fig. 22, shows that if the coolant temperature was constant the plug ring temperature rose as the power. It follows that the thermal condition of the engine cannot be controlled by watching the temperature of the coolant. Nevertheless, the coolant outlet temperature was kept as the initial value, as the intention was to determine the dependence of piston temperature on the conditions maintained up to the present in the ring-sticking tests.

The same fact was observed in the investigation of the influence of engine speed (cf Fig.23). The course of the piston temperature was not very clear at first, and appeared to be masked by the sparking plug-ring temperature, so this influence was investigated again. From the knowledge acquired from the previous tests about the temperature distribution over the engine, two thermo-couples were fitted, one on the exhaust side and one on the ignition side of the cylinder at the level of the upper point of reversal of the first piston ring, in such a way that the point for measuring was about 1.6 mm behind the cylinder wall. The corrections of the relationship as already determined is clear from Fig. 24: the piston temperature remains unchanged while the cylinder wall temperature is constant, while the coolant outlet temperature which is necessary to maintain a constant cylinder wall temperature actually rises as the engine speed, only to fall again. This means that at constant coolant temperature the piston temperature will first fall and then rise again as the engine speed increases further. This has already been established by Fig.23. If the throttle is reset at constant power, this tendency is still apparent, even though the cylinder wall temperature remains the same.

These tests also show that the plug-ring temperature varies in a manner similar to the coolant temperature rather than the piston temperature. Therefore, to control the temperature distribution of the DKW engine it is essential to measure the temperature at the cylinder wall.

The relationship with ignition advance, illustrated in Fig.26, likewise shows that the plug-ring temperature is influenced more than the piston temperature. This is understandable if one takes into account the fact that the cylinder head is separated from the cylinder by a heat-insulating gasket, and that the head encloses the greater part of the combustion chamber. It is also remarkable that in the two-stroke engine power is nothing like so strongly influenced by the ignition setting as in the four-stroke engine. Since two-stroke engines of the type used in this case are very prone to fluctuations in power when the consumption is altered, the throttle had to be changed to a considerable extent when investigating the influence of fuel consumption, if constant power was to be maintained (cf Fig.27).

In order to investigate the importance of the temperature of the parts surrounding the combustion chamber, a variety of variables was plotted: Fig.28 shows the effect of the coolant outlet temperature with a circulatory cooling system, Fig.29 that with thermo-syphon cooling. The latter was taken from Fig.30, which shows the effect of cylinder wall temperature on the temperature of the piston. To throw more light on the significance of the plug-ring temperature, Fig.31 shows the corresponding relationship with a circulatory cooling system. Finally, measurements were made at various intake air temperatures (cf Fig.32). It is quite clear from these that as the temperature of the air rises, the cylinder charge and thus also the power, fall. Whether the fall in plug-ring temperature is connected with this, is another question. At any rate, this illustration makes it clear that measuring at the plug-ring gives no clue to the piston temperature.

IV. RESULTS

So far we have discussed the course and nature of the tests on individual engines; we shall now discuss in general terms the behaviour of the piston temperature under the various working conditions. An attempt will be made to correlate the results achieved in the three engines, or where this is not possible, then to explain the differences. For purposes of comparison, the individual curves are reproduced to the same scale in Figs. 33 to 45. As the engines in certain cases work in quite different regions (e.g. consumption in the two-stroke engine, power), a scale was chosen for the abscissa which made comparison possible.

1. Power.

Fig. 33 shows that the BMW 132 and the DKW show the same relationship between piston temperature and power. The slight bend in the curve of the BMW 132 cannot, however, be fully explained; perhaps it is due to the fact that the position at which the cylinder control temperature was measured in this engine did not make it possible to control the cylinder wall temperature with complete reliability.

Because the NSU was run at an engine speed which is far below its optimum power, the temperature rise is not so steep as with the two other engines.

To sum up, it can be stated that the piston temperature rises in linear relationship with the power, by 3/4°C per 1/100 full power.

2. Engine speed.

Figs. 34 and 35 show the influence of engine speed on individual engines. Unfortunately there is no similar relationship for all three engines. Engine speed is undoubtedly that factor, alterations in which influence most the conbustion process and thereby the temperature distribution of the parts surrounding the combustion chamber. Since the value timing, the valve overlap, and the volumetric efficiency are in direct relationship to the engine speed, optimum power is only reached in each engine at a certain definite engine speed. Engine speeds above or below this must cause an increase in the engine temperatures. This was most in evidence in the BMW 132. At constant throttle the power rises as the engine speed in accordance with the torque curve (cf Fig.3); as was established in the foregoing section, the piston temperature rises as the power. But this is only true within comparatively narrow limits; beyond this region, the valve-timing and overlap contribute to a further increase in piston temperature independent of engine speed. Fig. 34 shows that in the BMW 132 the piston temperature actually reaches a minimum at about 1900 r.p.m. At higher engine speeds the rise in power becomes apparent, while the rise in temperature at low engine speeds might be attributable to the unfavourable valve timing.

The fact that the piston temperature also rises as the engine speed in the BMW, although the power remains constant (cf Fig. 35), cannot be explained at this stage, but perhaps the volumetric efficiency rises with the engine speed in a greater degree than can be compensated for by closing the throttle. The fact that at 2200 r.p.m. the engine speed at which maximum power is reached (cf Fig. 3), the piston temperature appears to reach a maximum, confirms this assumption.

The ring-sticking tests in the NSU engine were made at an ignition advance of 38°, and therefore the piston temperature was also first investigated at this ignition timing. At constant throttle the rather surprising result was obtained that although the power rose as the engine speed the piston temperature fell. Considering that this engine was constructed for an optimum engine speed of about 3600 r.p.m., the ignition advance of 38° before top dead centre at 2000 r.p.m. must be considered to be far too high; but, as Fig. 36 shows, a high ignition advance means a high piston temperature. As the engine speed rises the unfavourable effect of the ignition advance of 38° becomes less and less, that is to say that the effect is the same as if the ignition were gradually retarded at constant engine speed. But a reduction in ignition advance results in a fall in piston temperature.

To confirm this assumption, the piston temperature was investigated again as a function of engine speed at an ignition advance of 32° before top dead centre. At this figure the engine has its optimum power at 2000 r.p.m.(cf Fig.16). As this ignition timing was no longer too high for the range of engine speed which was investigated, the gain in power (at constant throttle) must cause a rise in piston temperature. As Fig. 34 shows, this is actually the case.

At constant power (Fig. 35) there was a fall in piston temperature, corresponding to the throttle setting, with rising engine speed, at both 32° and 38° ignition advance. The fall is steeper at 38° than at 32°, which can be explained in terms of the foregoing.

The volumetric efficiency, the scavenging, the times of inflow and outflow and other factors are influenced just as much by the engine speed in the two-stroke engine as in the four-stroke engine. It is interesting that the piston temperature does not change at engine speeds between 2500 and 3000 r.p.m. and at constant throttle (cf Fig.34). If the power is kept constant, the piston temperature first falls as the engine speed increases, and then rises again from 2800 r.p.m. onwards (cf Fig. 35). This also proves that where greatest volumetric efficiency and scavenging effect coincide with maximum power, the lowest piston temperatures result.

3. Ignition.

It has already been established in an earlier work (8) that the combustion chamber temperatures rise linearly with the ignition advance. It is therefore quite understandable that this should also be found when the piston temperature variation was investigated (cf Fig. 36). The fact that the curve for the NSU engine is slightly humped and at a low ignition advance resembles the curve for the DKW, while at high ignition advance it runs parallel with the curve of the BMW 132, leads to the conclusion that the curve at low engine temperatures is less steep than when the engine is not (this phenomenon may be connected with the higher temperatures on the cylinder head of the NSU, which was mentioned at the end of Section 5).

4. Fuel consumption.

Fig. 37 shows the piston temperature as a function of fuel consumption for the three engines investigated. In order to bring the two-stroke engine with mixture lubrication into the comparison, the consumption was entered as a percentage, 100% being that consumption at which the optimum power was achieved. The result confirms what was generally expected: the piston temperature behaves in the same way as the previously investigated combustion chamber temperature (8). As consumption falls the piston temperature first rises, and then falls again from a certain limiting value onwards.

5. Cooling- or cylinder wall temperatures.

To supervise the thermal behaviour of the engines, the plug-ring temperatures, and, in liquid-cooled engines, the coolant temperatures, were measured and kept constant. Fig. 38 shows, however, that only with the BMW 132 and the DKW with circulatory cooling is there a linear relationship between piston and plug-ring temperature. This is connected with the fact that in the NSU and DKW the cylinder-head is detachable, and so there is no continual heat flow between the cylinder head and cylinder wall. Also the coolant outlet temperature as a function of piston temperature is not linear in the DKW, whether with circulatory or thermo-syphon cooling. Fig. 39 shows that the two methods of cooling take effect in very different ways: whereas with circulatory cooling the piston temperature rises by about 0.4°C per °C of cooling temperature, with thermo-syphon cooling there is no observable influence in the normal region of working; here a large rise in piston temperature only occurs at very high coolant outlet temperatures.

In engines with a detachable cylinder head it is therefore impossible to observe the piston temperature by measuring the temperature at the sparking plug ring or the temperature of the coolant. Therefore, with these two engines (NSU and DKW) the cylinder wall temperature was observed in the neighbourhood of the upper reversing point of the first piston ring. Fig. 40 shows that it is possible to control the piston temperature very well from this measuring point.

The somewhat steeper climb of the curve with the NSU at high cylinder temperatures is due to the construction of the engine: since the cylinder head becomes considerably hotter than the cylinder itself (cf Fig. 38), the higher temperature of this part of the combustion chamber also affects the top of the piston, so that its temperature must rise faster than the cylinder wall temperature.

6. Oil temperature.

Fig. 41 shows the influence of oil temperature. In the BMW 132 the piston temperature rises by about 0.3° per ° of oil temperature. In the NSU engine, the speed of oil circulation is too slow($\sim$20 l/h), so that one cannot assume that the piston is cooled by the oil. The slight bend in the curve is due to the alteration in power (cf Fig. 19).

7. Volume of oil in circulation and oil pressure.

As Fig. 42 shows, the oil circulation in the BMW 132 can be reduced to about half the normal figure without any effect on the piston temperature. The piston temperature only falls when the colume is about 40% of normal. This is because only a certain volume of oil can pass between the piston and cylinder in consequence of the effect of the oil scraper ring, so that an increase in the volume in circulation has no effect. (Of course it is possible to cool the piston further, if care is taken that more oil is thrown onto the piston). But if the volume in circulation falls below a certain value (40%), the volume which passes between the piston and the cylinder is less than normal, so that the heat loss, and at even lower values lubrication also, are impaired. Consequently the piston temperature rises.

The range investigated with the NSU was not so wide; but it can be assumed that the same thing happens here.

Since the volume of oil circulation is a function of oil pressure, and vice-versa, an alteration in oil pressure has the same results (x). The normal oil pressure is very low to begin with in the NSU engine (0.15 atü), so that its alteration at different volumes was too small and could not be accurately measured.

8. Intake air temperature.

The investigations made on a DKW engine as to the influence of the intake air show that there is a linear rise in piston temperature of 0.07°C per °C of intake air (cf Fig. 44).

9. Ring Side-Play.

The investigation of the ring side-play brought an interesting fact to light. Fig. 45 shows that this has a great influence on the heat transfer: at very low clearances there is almost metallic contact between the ring and the piston groove; the heat transfer must therefore be good. If the play increases, the oil between the ring and the groove acts as an insulator, so that the heat is less efficiently conducted; therefore if the cylinder wall temperature is kept constant the temperature of the piston rises. If the play is still greater, the free space becomes so large that the oil no longer adheres to the surfaces, but begins to flow through between the ring and the groove. The oil, in flowing past, can transfer some of the heat from the piston, so that as the lateral ring-play increases the piston temperature falls once more.

V. CONCLUSIONS

The investigations described here show that although external working conditions are unchanged the piston temperature can vary greatly; above all, it was established that it can only be controlled by watching the cylinder throughout one and the same run, if the measurement is taken at a point from which it can be assumed that there is a continual loss of heat to the cylinder walls. However, in the course of time the conditions inside the engine may change considerably, especially after interruptions, so that it is impossible to form an opinion about the piston temperature which occurs, merely by measuring

(x) See Fig. 43.

certain cylinder temperatures. This is also the reason why the piston temperature as a whole is higher in some tests than in others, although the external conditions are constant (cf the piston temperature as a function of power and as a function of consumption in the BMW 132). The question: which factors play a part here, has been fully discussed elsewhere (5), so that it is unnecessary to go into the subject again here.

After earlier investigations into the influence of working conditions on the process of piston ring-sticking (9), the suggestion was put forward that the running time up to ring-sticking when the same fuel was used in every case was merely a function of the temperature in the piston rings. For simplicity the results of these earlier tests are reproduced in Fig. 46. The tests described in the present report on the piston temperature confirm this assumption: all those influences which in those tests resulted in a shortening of ring-sticking times cause a corresponding increase in piston temperature. The effect of lateral ring-play on ring-sticking depends on two factors: 1. On the space which must be filled by deposits; 2. On the effect of heat transfer from the piston to the ring. As was only recently established (5), at constant piston temperature the running time up to ring-sticking bears an almost linear relationship to the lateral ring-play (cf Fig.47). If the piston temperature is not watched during ring-sticking tests, but only a constant cylinder wall temperature maintained, then the steepness of the curve "Ring-sticking time as a function of lateral ring-play" is influenced only by the nature of the heat transfer between the piston and the ring, according as the piston temperature would rise or fall with increasing play as in Fig. 45. The same is true of the oil pressure: in the earlier tests the oil pressure had a great effect on the ring-sticking time, while the later tests indicate a different influence on piston temperature. The explanation of this difference is to be sought in the fact that the piston is of completely different design: in the earlier slipper piston (BMW VI) the oil scraper ring was above the sliding surface of the piston, in the BMW 132 one ring was above and one was at the lower edge of the piston. Also, the sliding surface of the BMW VI piston was only half the size of the one used in the present engine. Since at that time considerably less heat passed from the piston skirt to the cylinder wall, the piston had to be cooled in an increasing degree by the oil, so that the influence of the oil pressure was also greater.

The increase in the ring-sticking time which is apparent in some of the curves in Fig. 46 when the load is further increased is not due to a corresponding reversal of piston temperature, but to the behaviour of the lubricant as regards the formation of deposit.

Unfortunately, for reasons which are discussed in another report (1), it has so far proved impossible to measure the temperature actually in the piston ring groove. This is a task which is indicated for the future, if lubricants are to be properly tested and evaluated in the engine - no matter what model. The dependence on piston temperature which was discussed here may be a considerable advance in the direction of solving this problem.

VI. SUMMARY.

With the aid of the measuring process adopted by the DVL, investigations were made of the dependence of piston temperature on individual working conditions in three engines, a BMW 132 single-cylinder, a 500 c.c. NSU engine and a two-stroke engine at 300 c.c. capacity. On page 11 is a survey of the various test results. It appears that the individual influences coincide in part, and that the piston temperature can only be controlled in certain cases by watching the external conditions very closely. Finally the results are

connected up with facts which were established earlier about the dependence of ring-sticking times on the individual working conditions. This confirmed what was already believed viz. that if the same fuel is used the running time up to ring-sticking depends only on the temperature in the piston rings.

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Survey of the effect of individual working conditions on piston temperature.

Power: Linear function; rise of $^3/_4$°C per $^1/_{100}$ of full power.

Engine speed: Different in individual engines. As the best values for valve-timing, ignition advance and, in consequence, power and volumetric efficiency are reached by altering the engine speed, the piston temperature approaches a minimum.

Ignition: Linear increase as the ignition advance; at low thermal load (DKW) about 0.8°C per ° of ignition advance, at high load (BMW) about 1.75°C per ° of ignition advance. The NSU is intermediate, varying with the thermal load.

Fuel Consumption : The curve corresponds to the dependence of combustion chamber temperature on consumption; as consumption falls the piston temperature rises, falling again after a certain maximum is reached.

Coolant temperature : Does not allow of definite conclusions about the piston temperature. Large changes in coolant temperature only change the piston temperature by a few °C.

Plug-ring temperature : Linear relationship, as long as the heat flow between the cylinder head and the cylinder is not destroyed; about 0.9°C per °C of plug-ring temperature.

Cylinder wall temperature : Linear relationship. The best place for measuring the piston temperature. About 0.5°C per °C of cylinder wall temperature.

Oil temperature: If the volume of oil in circulation is high, the piston temperature rises linearly by about 0.3°C per °C of oil temperature.

Volume of oil in circulation : As the circulation increases in volume, the piston temperature falls. No further effect after a certain minimum value is reached.

Oil pressure : Corresponds to the volume of oil in circulation.

Ring side-play: At very low values the piston temperature rises as the play, reaches a maximum as the play increases, and then falls again beyond this limit.

Table 1.

Engine data and working conditions for the investigations on the BMW 132 N-oil test engine.

Cylinder	BMW 132 Series N
Piston	" " " "
Bore	155.5 mm.
Stroke	162 "
Capacity	3076 ccm.
Compression	1:6.5
Power	59 ± 1 H.P.
Engine speed	2050 ± 10 r.p.m.
Fuel consumption	210 ± 2 g/b.h.p. per hour
Ignition timing	40° ± 0.5 before top dead centre
Oil pressure	5.4 ± 0.1 atü
Oil temperature inlet:	114 ± 3°C
outlet:	116 ± 3°C
Plug ring temperature (control temperature)	220 ± 2°C

Table 2.

Engine data and working conditions for the investigations on the NSU engine.

Engine	NSU 501/OS.
Bore	80 mm.
Thrust	99 mm.
Capacity	494 ccm.
Compression	1:6
Power	8.6 ± 0.2 b.h.p.
Engine speed	2000 ± 20 r.p.m.
Fuel consumption	225 ± 5 g/b.h.p./hour
Ignition timing	38° ± 0.5 before top dead centre
Oil pressure	0.12 ± 0.01 atü
Oil temperature inlet:	90 ± 1°C (pre-heating)
outlet:	77 ± 2°C
Cylinder wall temperature (control temperature) 1)	252 ± 1 and 264 ± 1°C 2)

1) Point of measurement see page 3.

2) cf Fig. 16.

Table 3.

Engine data and working conditions for the investigations of the DKW engine.

Engine	DKW EW 301
Bore	74 mm.
Thrust	68 mm.
Capacity	292.5 ccm.
Compression	1:5.65
Power	4.5 ± 0.1 b.h.p.
Engine speed	3000 ± 30 r.p.m.
Fuel-oil ratio	20 : 1
Fuel consumption	380 ± 20 g/ b.h.p./hour
Ignition timing	30° before top dead centre
Coolant outlet temperature (control temperature)	90 (100)°C
Cylinder wall temperature (control temperature) 1)	213°C
Coolant	Tri-ethylene glycol.

1) This is the control temperature used in the determination of the number of revolutions.

Fig. 1

Diagram of the installation for measuring the piston temperature.

Fig. 2

BMW 132. Influence of power.

Fig. 3

Influence of engine speed at constant throttle.

Fig. 4

BMW 132 Influence of engine speed at constant power.

Fig. 5

BMW 132. Influence of ignition.

Fig. 6

BMW 132. Influence of fuel consumption.

Fig. 7

BMW 132. Influence of cylinder wall temperature.

Fig. 8

BMW 132. Influence of oil temperature.

Fig. 9

BMW 132. Influence of oil pressure.

Fig. 10

BMW 132. Influence of oil volume in circulation.

Fig. 11

NSU. Influence of power.

Fig. 12

NSU. Influence of engine speed at constant throttle and 38° ignition advance.

Fig. 13

NSU. Influence of engine speed at constant power and 38° ignition advance.

Fig. 14

NSU. Influence of engine speed at constant throttle and 32° ignition advance.

Fig. 15

NSU. Influence of engine speed at constant power and 32° ignition advance.

Fig. 16

NSU. Influence of ignition timing.

Fig. 17

NSU. Influence of fuel consumption.

Fig. 18

NSU. Influence of cylinder wall temperature.

Fig. 19

NSU. Influence of oil temperature.

Fig. 20

NSU. Influence of oil volume in circulation.

Fig. 21

NSU. Influence of ring side-play.

Fig. 22

DKW. Influence of power.

Fig. 23

DKW. Influence of engine speed at constant coolant temperature.

Fig. 24

DKW. Influence of engine speed at constant throttle and cylinder wall temperature.

Fig. 25

DKW. Influence of engine speed at constant power and cylinder wall temperature.

Fig. 26

DKW. Influence of ignition.

Fig. 27

DKW. Influence of fuel consumption.

Fig. 28

DKW. Influence of coolant temperature with circulatory cooling.

Fig. 29

DKW. Influence of coolant temperature with thermo-syphon cooling.

Fig. 30

DKW. Influence of cylindor wall temperature.

Fig. 31

DKW. Influence of plug ring temperature.

Fig. 32

DKW. Influence of intake air temperature.

Fig. 33

Piston temperature as a function of power.

Fig. 34

Piston temperature as a function of engine speed at constant throttle (cf Figs. 3,12,14 and 24).

Fig. 35

Piston temperature as a function of engine speed (cf Figs. 4, 13, 15, 23 and 25).

Fig. 36

Piston temperature as a function of ignition advance (cf Figs. 5, 16 and 26).

Fig. 37

Piston temperature as a function of fuel consumption.

Fig. 38

Piston temperature as a function of plug ring temperature.

Fig. 39

Piston temperature as a function of coolant outlet temperature. (cf Figs. 28 and 29).

Fig. 40

Piston temperature as a function of cylinder wall temperature (cf Figs. 7, 18 and 30).

Fig. 41

Piston temperature as a function of oil inlet temperature.

Fig. 42

Piston temperature as a function of the volume of oil circulation.

Fig. 43

Piston temperature as a function of oil pressure.

Fig. 44

Piston temperature as a function of intake air temperature (cf Fig. 32).

Fig. 45

Piston temperature as a function of ring side-play (cf Fig. 21).

Fig. 46

Ring-sticking time as a function of various working conditions in the BMW.VI (Normal value = 9 hours = 100%)

Fig. 47

Running time up to ring-sticking as a function of lateral ring play at constant piston temperature.