

## CHAPTER XI

### THE CYLINDER HEAD

#### 1. The shape of the combustion space in petrol engines

The cylinder head is the most important part of an air-cooled engine and it is also the most difficult one to manufacture. The correct solution of the problems facing the designer in this respect decides to a large degree the qualities of the whole unit. A well designed air-cooled cylinder head must ensure: 1. high volumetric efficiency up to high engine speeds, 2. small heat losses, 3. an even temperature of the combustion chamber, 4. light weight, 5. small dimensions, 6. interchangeability, 7. easy manufacture.

It is far from easy to fulfil all these requirements and the design of a good cylinder head for an air-cooled engine is one of the most exacting tasks facing the designer.

The first decision to be made concerns the shape of the combustion chamber to be used. This shape must not only aid most complete combustion but it must also ensure high volumetric efficiency and effective exhaust valve cooling.

In order to attain a large mean effective pressure and low specific fuel consumption, especially with the engine running on part throttle openings, the use of a high compression ratio is of great importance.

The upper limit to compression ratio is given by the boundary above which detonation occurs. The example shown in Fig. 176 explains how detonation originates.

At the end of the compression stroke the cylinder contains a compressed mixture of air and fuel. This is ignited by the sparking plug under the inlet valve. We shall not be far from the truth in assuming that flame travels on spherical planes. Although it is true that the piston is still in upward motion when the mixture ignites, tests conducted [61] together with thorough mathematical analysis have shown that this

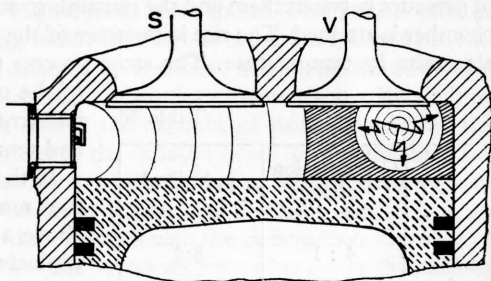


FIG. 176. Origin of detonation in the combustion chamber.

movement may be disregarded. It may be assumed that the piston is at rest at top dead centre during the whole period of combustion.

Between the spark appearing at the sparking plug and the beginning of combustion, which is accompanied by a rise in pressure, a certain period, known as the delay period or "ignition lag", elapses. The duration of this period depends chiefly on the temperature and pressure of the mixture to be

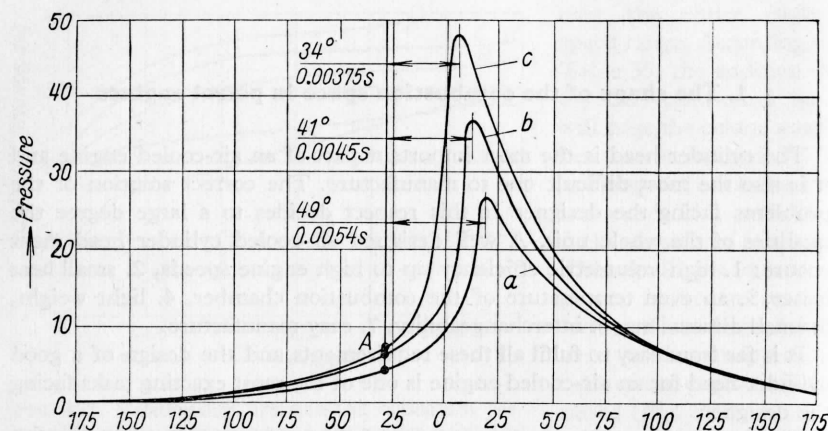


FIG. 177. Effect of compression ratio upon ignition lag at 1,500 rev/min, and constant ignition advance 30 degrees before top dead centre (Table 36).

ignited. The average ignition lag is approximately 0.004 sec. The variation of ignition lag with compression ratio is shown in Fig. 177.

After this delay the mixture begins to burn, the flame front spreading as the surface of a sphere of increasing size. After the burning of the part of the mixture adjacent to the sparking plug, temperature rises expanding the products of combustion. These products of combustion expand until a balance of pressure between them and the remaining unburnt charge in the combustion chamber is attained. The rise in pressure of the unburnt charge must naturally also raise its temperature. The same process takes place as further amounts

of the charge burn. As the remaining unburnt charge decreases, its pressure and temperature continue to rise.

If the temperature and pressure of the remaining unburnt charge rises above a critical point, self-ignition and explosive combustion of the charge residue takes place. This explosive combustion which does not spread from the sparking plug but from its own nucleus

Table 36

|   | Compression ratio | $p_t$ kg/cm <sup>2</sup> |
|---|-------------------|--------------------------|
| a | 4 : 1             | 8.4                      |
| b | 5 : 1             | 9.6                      |
| c | 6 : 1             | 10.3                     |

(shown in Fig. 176) is known as detonation. The velocity of flame travel depends on the crankshaft speed, pressure, the fuel: air ratio, [62] etc. See Fig. 178. The velocity of a detonating wave is many times greater, reaching up to 9840 ft/s (3000 m/s). This extremely rapid combustion-detonation is accompanied by a rapid rise in pressure and is outwardly evident by its unpleasant, high pitched "pinking" or knocking. The very rapid pressure rise is detrimental to long engine life and measures must therefore be taken to eliminate knock.

If the "end gases", which are the last to be ignited, are compressed against the hottest part of the combustion chamber in the vicinity of the exhaust valve, temperature will rise further and the conditions for detonation will arise sooner.

One of the principles of cylinder head design therefore is to place the sparking plug near the exhaust valve in order to compress the end gases into the cool corner around the inlet valve.

The highest engine output can be reached if gas pressure above the piston

is at its highest at about 10° passed top dead centre. With the ignition lag and the velocity of flame travel known, the ignition advance must be greater with a longer distance over which the flame front must travel. This period extends to the compression stroke, during which it brings no gain, but a loss in output. A long combustion period also causes a greater heat loss to the cylinder walls.

For these reasons the design of the combustion chamber must be such as to limit to the smallest possible length the distance of flame travel from the sparking plug to the remotest corner of the cylinder head. This commends the use of compact combustion chambers which have the further advantage of a small volume: surface ratio with its accompanying low heat loss.

These deliberations led Ricardo to concentrate the combustion chamber of side valve engines in a pocket above the valves with the plug above the exhaust valve. The piston crown very closely approaches the cylinder head at top dead centre in this engine and the whole charge is displaced and compressed into the combustion chamber above the valves.

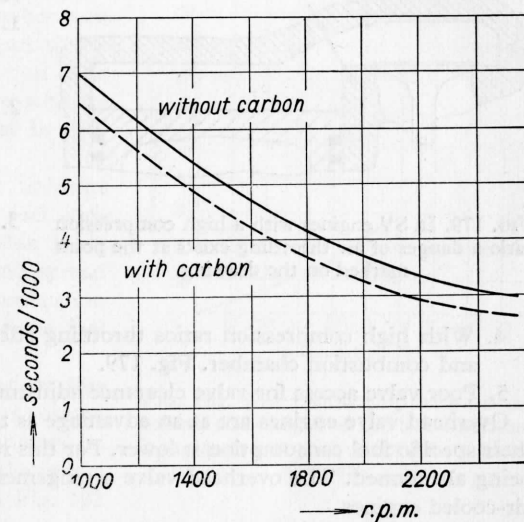


FIG. 178. Influence of engine speed upon rate of combustion in an engine with and without carbon deposits.

The expulsion of the charge before top dead centre produces great turbulence which is typical for a Ricardo type combustion chamber. This turbulence does not permit a sudden local temperature rise which would endanger regular combustion and speed the rate of combustion, thereby making possible a higher compression ratio without the risk of detonation. Side valve engines have

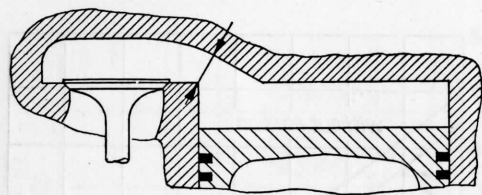


FIG. 179. In SV engines with a high compression ratio a danger of air throttling exists at the point marked on the drawing.

the following inherent disadvantages:

1. The combustion chamber surface is large thus causing large heat losses.
2. A flat combustion chamber is unsuitable from the point of view of a detonation free combustion.
3. Volumetric efficiency is low owing to bends in the mixture flow and the heating of air.

4. With high compression ratios throttling effects occur between cylinder and combustion chamber. Fig. 179.
5. Poor valve access for valve clearance adjustment.

Overhead valve engines are at an advantage as they give higher output and their specific fuel consumption is lower. For this reason side valve layouts are being abandoned. The overhead valve arrangement is particularly suited for air-cooled engines.

Overhead valves may be arranged in the cylinder head in various positions making possible the formation of combustion chambers which are 1. wedge-shaped, 2. hemispherical.

1. With a wedge-shaped combustion chamber the valve operating mechanism can be designed with greater ease. In principle it is beneficial to concentrate maximum volume beneath the exhaust valve and to make the section remote from the plug as small and as well cooled as possible.

Fig. 180 shows an up to date combustion chamber which may be divided into three sections. The first section, adjacent to the sparking plug, exercises the greatest influence on heat losses. The surface of this section is exposed to the longest period of combustion and should therefore not present undue risks for heat loss. For that reason the exhaust valve is placed in this section.

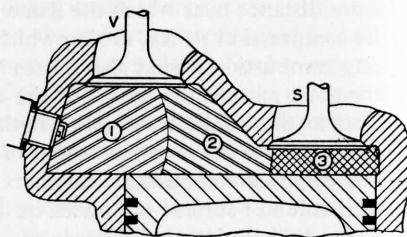


FIG. 180. Illustration of a wedge-shaped combustion chamber.

1 — the first section has a bearing on thermal losses, 2 — the second upon combustion roughness, 3 — and the third upon detonation.

The second section is most important for combustion roughness as when combustion spreads through it, the piston is at top dead centre. A sharp pressure rise must therefore be avoided and the section should be kept as small in volume as possible.

The third section is noted for its influence on detonation. It must therefore be small in volume and well cooled. This part of the compression space is usually formed by the gap between the piston and cylinder head which should not be larger than 8 mm. The cold disc of the inlet valve with its beneficial cooling effect may be positioned here.

During combustion the unburnt charge is compressed and fuel concentration is increased within it. It follows that with the flame spread through one half of the combustion chamber, less than a half of the fuel is burnt.

The ratio of the weight of this burnt part of the charge to its volume has been the subject of studies by numerous authors [49] and the results obtained by them given in Fig. 181

are in agreement. According to the diagram in Fig. 181 it will be noted that with the burnt gases taking up 50% of combustion chamber volume, only 24% of the charge by weight has been burnt.

The elimination of detonation in the combustion chamber is aided by the quench area extending between the cylinder head and pistons. The charge displaced from this space during the compression stroke causes high turbulence inside the combustion chamber thus favourably affecting the process of combustion.

The effect of air swirl caused by air entering the cylinder tangentially during the induction stroke and of squish during the compression stroke is illustrated in Fig. 182. The curves A to D represent the properties of similar combustion chambers with parallel vertical overhead valves. The basic shape of all these spaces is flat and their compression ratio is 9 : 1. With spaces A and B the inlet port is at a tangent to the cylinder circumference, thus causing the air entering the cylinder to swirl rapidly. The inlet port of C and D points towards the axis of the cylinder and no swirl occurs. In the combustion chambers marked B and D, 30% of the piston crown forms a quench area between piston and cylinder head, the aperture being about 1.8 mm high. The plug is located approximately in the axis of the cylinder.

Taking the performance of an engine with a combustion chamber A as a

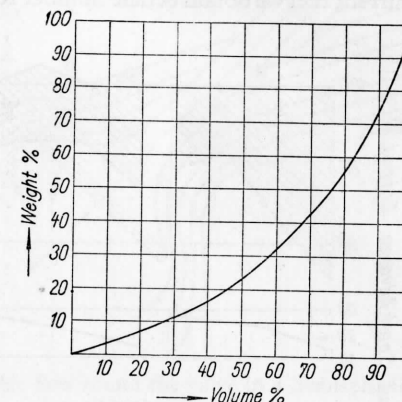


FIG. 181. The relationship between the volume and weight of the burnt mixture is in agreement with different measurements.



basis (100%), the output of engines with the other combustion chambers are approximately the same. The octane requirements on the other hand, differ considerably, the lowest being in chamber *D* without swirl and with a quench area.

Comparing the properties of these types on the verge of detonation with current fuel we obtain octane number requirements shown in Fig. 182 (dashed

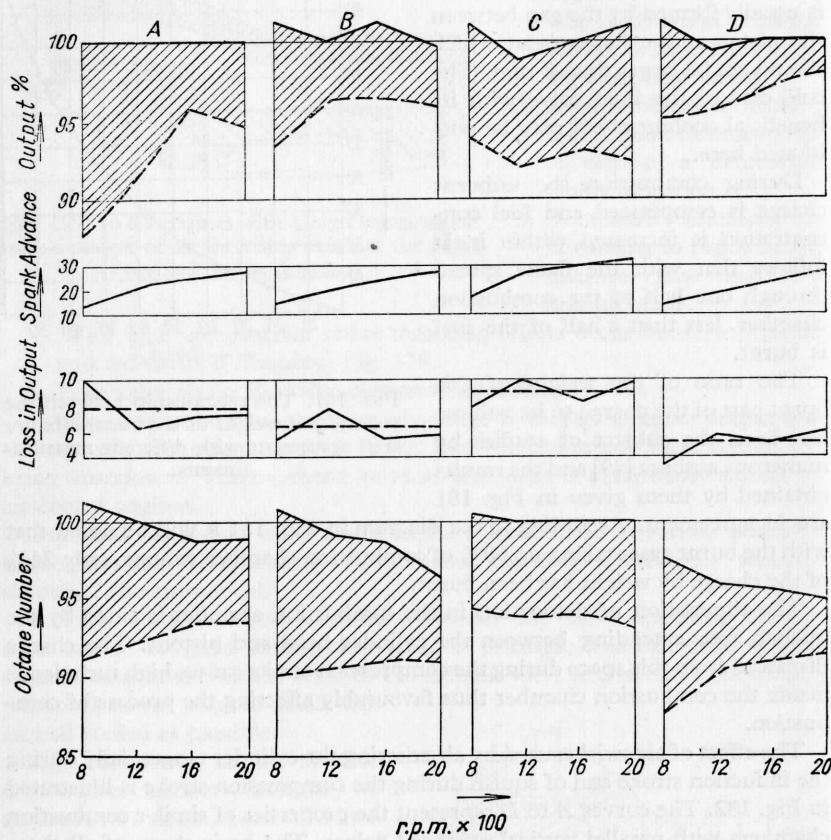


FIG. 182. Comparison of similar combustion chambers of petrol engines.

line), from which it is apparent that types *A* and *C*, without quench area, show the greatest drop in performance and their octane requirement is high. Types *B* and *D* with a quench area show a higher power output and a lower octane number requirement. In this instance, induction swirl does not enhance their properties.

The results given here may not apply in general, but they underline the importance of quench area and the small influence of induction swirl. With other types of combustion chambers, however, swirl does effect a considerable improvement. It is important to direct the stream of mixture entering the cylinder towards the sparking plug.

In another experiment using the same fuel, the compression ratio could be raised from 7.25 to 9:1 following and increase in quench area from 15.8% to 30%. This brought about not only an increase in engine output but also a reduction of specific fuel consumption which is particularly important at reduced load running.

The temperature of the internal surface of the combustion chamber is very important. A lower temperature results in a lower octane requirement and

increased volumetric efficiency. This must be realised all the more by the designer of an air-cooled engine who must pay attention to the best possible heat transfer from regions most remote from the sparking plug.

In wedge-shaped combustion chambers, good cooling of valve seats between the two ports is important and a sufficient cooling air stream must be directed to this region. With cylinder heads of small bore engines this is difficult to arrange. With the choice of a short-stroke layout, more room for the valves becomes available and the flow area between the ports is also larger.

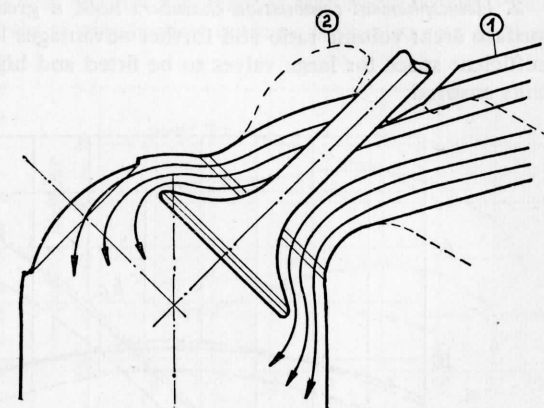


FIG. 183. Air flow round the valve in a hemispherical combustion chamber.

1 - shape preferred in motor cycle engines, 2 - in aircraft engines.

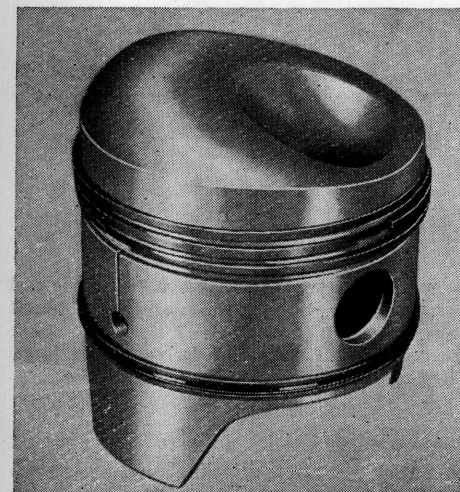


FIG. 184. Experimental piston with well shaped crown for a hemispherical combustion chamber.



Local temperatures of combustion chamber walls can be regulated by proper finning and the direction of cooling air to places which need the most intensive cooling.

2. *Hemispherical combustion chambers* hold a great advantage in their low surface area: volume ratio and further advantages lie in the fact that there is sufficient space for large valves to be fitted and high volumetric efficiency is thus ensured.

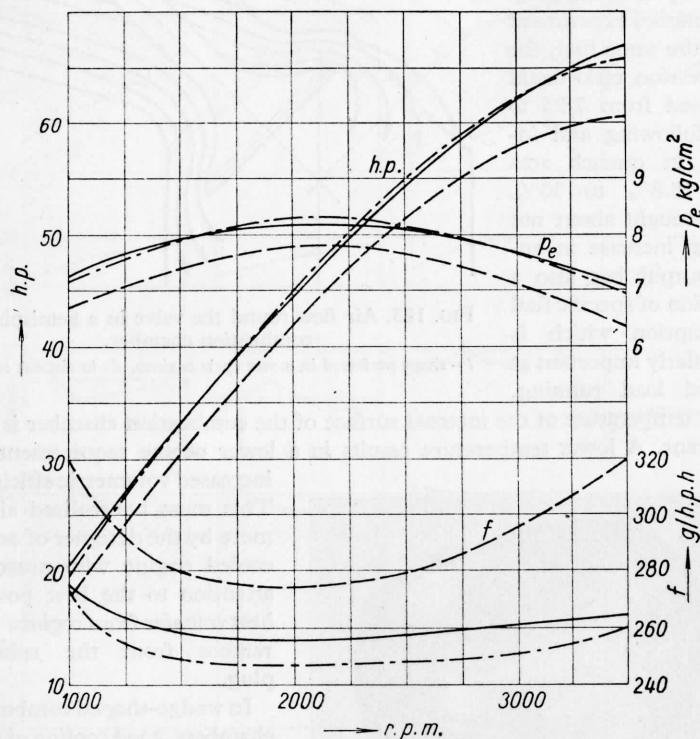


FIG. 185. Comparison of performance and fuel consumption for a hemispherical combustion chamber with a flat piston crown and  $\epsilon = 6$  (dashed line), shaped piston crown and  $\epsilon = 7.2$  (full curve), and shaped piston crown  $\epsilon = 7.2$  and the spark plug shifted towards the centre of the combustion chamber (dash and dot line).

In the latter case ignition advance had to be reduced from 46 to 36 degrees.

A convenient feature of the air-cooled engine is its unobstructed exhaust valve seat periphery, permitting the use of extensive finning on the outside. The cooling of the exhaust valve seat is of great importance.

The direction of air flow past the inlet valve is good and on entering the cylinder, the air stream is continually deflected about the inside wall of the

cylinder. Fig. 183 shows the air flow past the inlet valve into a hemispherical cylinder head. The change of flow area is gradual and there are no abrupt bends.

It is owing to these desirable features that engines with hemispherical combustion chambers are known to give highest outputs. By the correct shaping of the piston crown the combustion process may be regulated, as shown in Figs. 184 and 185.

The distribution of temperatures in the combustion chamber is of great importance. More can often be gained by correct cooling than by the shape of the combustion chamber itself. The combustion of the mixture must proceed toward the coolest part of the combustion chamber.

Cooling efficiency is considerably reduced and

the octane requirement of an engine raised when carbon deposit forms on

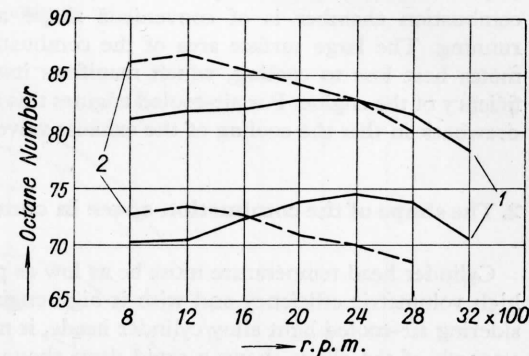


FIG. 186. Octane number requirements of an OHV (1) and SV (2) engine without (bottom lines) and with (top lines) carbon deposit.

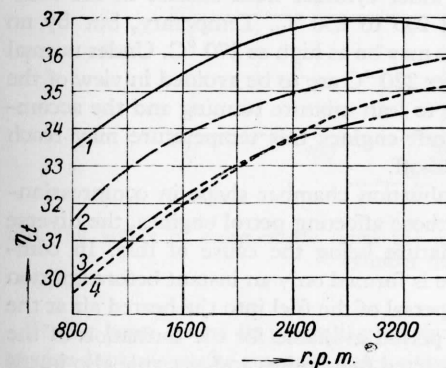


FIG. 187. Comparison of thermal efficiency of different types of combustion chambers plotted against engine speed.

The test was carried out on an experimental single-cylinder engine having a displacement of 770 cu. cm, a stroke: bore ratio 0.94 and  $\epsilon = 7$ . Octane number requirements for all four chambers tested were approximately equal. 1 — inclined valves in the cylinder head, hemispherical combustion chamber, 2 — parallel valves in the cylinder head, 3 — SV valves, 4 — F head.

the combustion chamber walls. A hemispherical space is not so sensitive to carbon deposit and the loss of performance is therefore smaller. Fig. 186 shows the loss of performance caused by carbon deposit in some types of cylinder heads; with a hemispherical head it amounts to only about 2%.

Owing to small heat loss to walls, the thermal efficiency of a hemispherical combustion chamber is high. Fig. 187 compares the thermal efficiencies of several shapes of combustion chambers as tested on an experimental single cylinder engine with a stroke: bore ratio of 0.94 and a compression ratio of 7 : 1. The octane require-

ment of all these types of combustion chambers, at full throttle and uniform engine speed, was identical. The highest indicated thermal efficiency was attained by the hemispherical combustion chamber [15].

A compromise between side valve and overhead valve types is the F head with a side exhaust valve and an overhead inlet valve. The size of the valves, the inlet valve in particular, is not dictated by limitations of space and the combustion chamber is of convenient shape and permits smooth engine running. The large surface area of the combustion chamber, however, promotes heat loss to cooling, which manifests itself in the lower thermal efficiency of the engine. For air-cooled engines this arrangement shows a definite drawback in that the cooling of the exhaust valve presents difficulties.

## 2. The shape of the combustion space in compression-ignition engines

Cylinder head temperature must be as low as possible in order to maintain high volumetric efficiency and with it high engine performance. When considering air-cooled light alloy cylinder heads, it must be remembered that the strength of the alloys shows a rapid drop above 200 °C. Fig. 188 shows the variation of strength of aluminium alloys used for cylinder head construction with temperature [28].

In petrol engines, local overheating of the combustion chamber leading to detonation, must be prevented. Special attention must be paid to the region adjacent to the exhaust valve seat and the sparking plug. According to recent experience, the temperature of the inner cylinder head surface in the combustion chamber should not exceed 235 to 250 °C. Temporary, but by no means continuous, local temperatures may be as high as 270 °C. Under normal running conditions, temperatures over 220 °C are to be avoided in view of the possibility of a temperature rise due to lean mixture running and the accompanying risk of detonation. In aircraft engines this temperature may reach 300 °C for a short period during take-off.

The requirements governing combustion chamber shape in compression-ignition engines differ widely from those affecting petrol engines, the diverse means of preparing the air-fuel mixture being the cause of this. In compression-ignition engines the mixture is formed only an instant before ignition commences by the injection and dispersal of the fuel into the heated air at the end of the compression stroke. The period available for the formation of the mixture is extremely short, for the injected fuel ignites and as a rule also burns before injection is over. For this reason the formation of a homogeneous mixture of air and fuel, and the complete utilization of the amount of air present as in the petrol engine, is impossible and larger amounts of air than needed for the chemically correct mixture must be used.

An overloaded compression ignition engine emits black exhaust smoke which is a sign of insufficient air available for combustion; the oxygen content of exhaust gases may be ascertained by analysis. The trouble is caused by local

air shortages. All the oxygen in the neighbourhood of the fuel jets is used for the combustion of fuel and the remaining fuel in the jet centre cannot find sufficient oxygen for complete combustion. Oxygen is contained in the space separating the jets, but it is too remote from the droplets of atomized fuel. A good combustion chamber must, therefore, ensure the best possible mixing of air and fuel in order to utilize the highest possible percentage of the oxygen present in the cylinder for combustion.

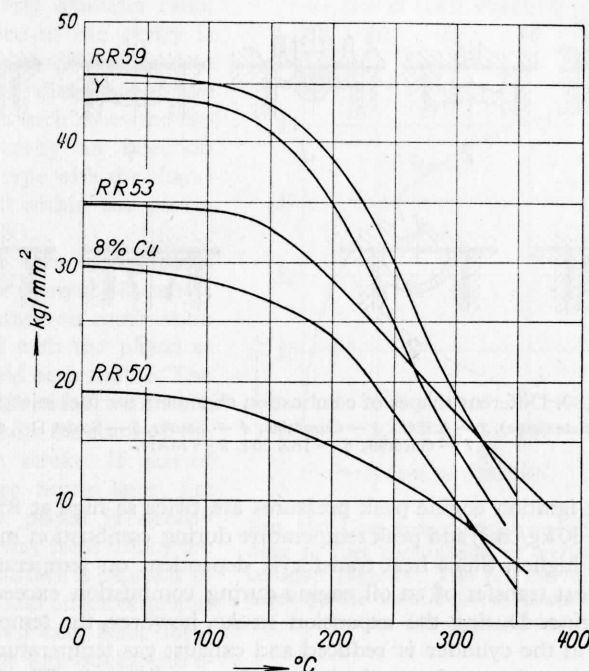


FIG. 188. Effect of temperature upon the strength of aluminium alloys used for cylinder heads.

It has been stated in preceding sections that the performance of a petrol engine depends on the amount of air by weight, which is drawn into the cylinder within a given time.

The same applies to oil engine performance with one difference: the amount of air which takes part in the process of combustion is the deciding factor; much therefore depends on the need for excess air being as small as possible. A compression-ignition engine will, therefore, have a lower output than a petrol engine having the same volumetric efficiency. Lower performance results in a smaller liberation of heat and therefore the heat stress per unit of

the inner surface area is lower. From the point of view of cooling, the compression-ignition engine scores over the petrol engine.

The oil engine, however, works with high compression ratios. For this reason pressures at the end of the compression stroke are high, and so are the peak pressure and combustion temperature. Compared with peak pressures of 491 to 568 lb/in<sup>2</sup> (35 to 40 kg/cm<sup>2</sup>) which are common in petrol engines,

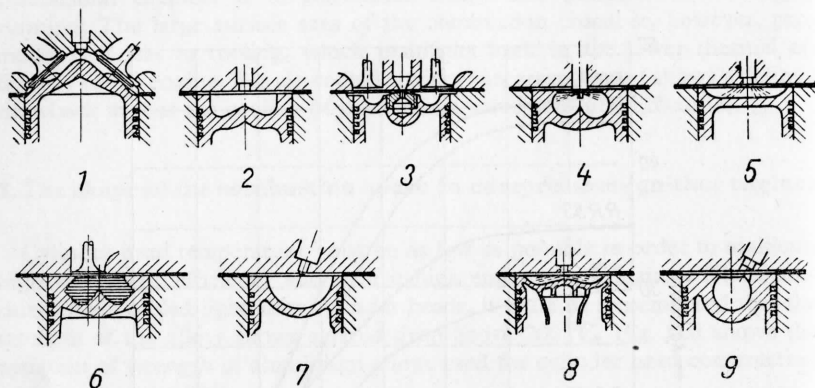


FIG. 189. Different shapes of combustion chambers for fuel injection.  
1 — Tatra (obsolete shape), 2 — A.E.C., 3 — Cummins, 4 — Saurer, 5 — Soviet D 1, 6 — Crossley, 7 — Gardner, 8 — JAZ 204, 9 — MAN.

compression-ignition engine peak pressures are twice as high at 853 to 1137 lb/in<sup>2</sup> (60 to 80 kg/cm<sup>2</sup>) and peak temperature during combustion must therefore also be higher. Since heat transfer is dependent on temperature difference, the heat transfer of an oil engine during combustion exceeds that of a petrol engine. During the expansion stroke, however, the temperature of burnt gases in the cylinder is reduced and exhaust gas temperature is lower than in petrol engines owing to the increased expansion ratio. The heat stress on exhaust port walls is, therefore, lower than that common in the petrol engine.

The mixing of air and fuel can be performed in two ways in an oil engine:

1. direct fuel injection
2. indirect fuel injection.

Direct injection, as the name implies, aims a jet of fuel directly into the combustion chamber and a good mixture is obtained by shaping and arranging the fuel jets in the most suitable way and by creating the required turbulence inside the cylinder. The surface area of the combustion chamber is made as small as possible and thus has the advantage of small heat loss. The following advantages are derived from this:

a) A small amount of heat is lost by cooling. To transfer this heat into the air, only a small share of the effective engine performance is needed.

b) Thermal efficiency is high. Specific fuel consumption is therefore low.

c) Heat losses are low even during the compression stroke. Air temperature at the end of the compression stroke is high and the starting of a cold engine is thus facilitated without the need for auxiliary sources of heat.

Some shapes of direct injection combustion chambers which have found favour are shown in Fig. 189. Turbulence here depends to a large extent on the cylinder bore: piston crown cavity diameter ratio. The orifice of the cavity is sometimes much smaller than the largest diameter of the cavity — in such cases the engine is really an injection chamber type with the chamber or cell within the piston (e.g. MAN).

For the sake of maintaining a high thermal efficiency, the instantaneous combustion of all fuel with the piston at t.d.c. would be desirable. The heat thus liberated could work for the whole duration of the expansion stroke. If part of the charge burns later, i.e. when the piston is already moving away from t.d.c., the cylinder surface is exposed to hot gases and effective piston travel is reduced. Heat liberated in this way would, therefore, be utilized in a less efficient manner. Fig. 190 shows the dependence of thermal efficiency on the percentage of fuel burnt at a constant pressure and constant volume. The thermal efficiency shows a rapid drop if less than 60% of fuel is burnt at constant volume.

The instantaneous combustion of fuel at top dead centre ensures high thermal efficiency, but difficulties arise when trying to achieve silent running. The silent operation of air-cooled engines is of particular importance, since, with no water jackets surrounding the cylinders, it becomes more difficult to subdue the noises of combustion and piston slap. For this reason the geometry of the shapes in question and the means of mixture formation must be chosen in such a way as to ensure as quiet combustion as possible.

High turbulence shortens ignition delay and thereby reduces engine noise. Compact toroidal chambers in the piston promote squish during the compression stroke and aid mixture formation. Swirl, caused by the air entering

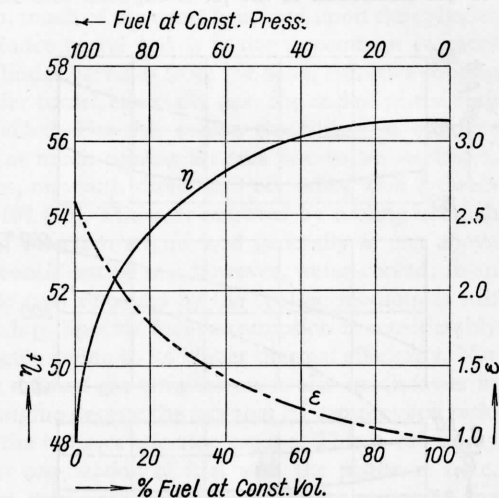


FIG. 190. Comparison of thermal efficiency according to fuel combustion at constant volume or constant pressure. The full curve represents efficiency, the dashed the expansion ratio  $\epsilon_c$  during combustion.



the cylinder at a tangent during the induction stroke is also desirable. The higher the degree of swirl, the fewer jets of fuel are needed for mixing fuel and air. This is a welcome feature especially in small capacity cylinders, for the holes in the injection nozzle may be comparatively few and large with a subsequent reduced likelihood of blockage by carbon or by fuel impurities.

Better mixing of the fuel with air takes place if the axis of the fuel is normal to the airstream. If the jet is exposed to a side blast the distance which the droplets must cover is shorter.

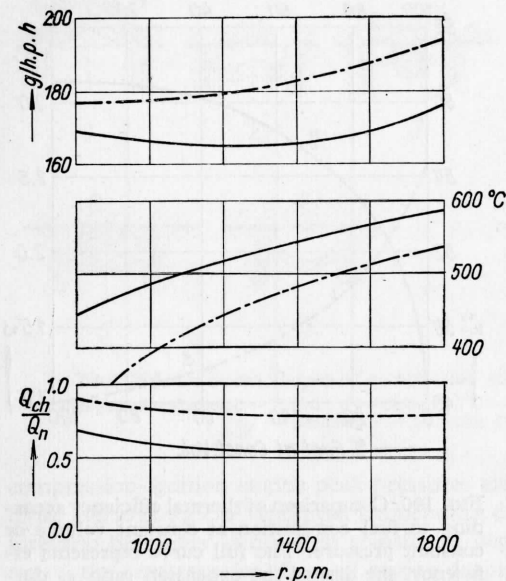


FIG. 191. Characteristic of oil engine with direct and indirect fuel injection. Full curve — direct injection, dashed curve — indirect injection.

$Q_{ch}$  — heat removed by cooling,  $Q_n$  — heat converted to performance.

periphery of the orifice. With an orifice which is too small, the edges are insufficiently cooled and may crack owing to overheating. With the cavity mouth too wide, the circumference will be too cold for drops of fuel in contact with it to evaporate fast enough and carbon will be deposited more rapidly. Both the conditions of turbulence and those of temperature must therefore be met. In extreme cases recourse may be made to cooling the underside of the piston crown by a jet of oil directed against it from below.

It is important to keep the cavity walls at the correct temperature especially where the surface is required to evaporate fuel colliding with it by letting it spread into a continuous film and by preventing droplets from bouncing off

The clearance between the piston crown and cylinder head should be as small as possible (usually 0.75 to 1 mm). The designer must bear in mind the reduction of bearing clearances caused by inertia forces acting upon the piston assembly at top dead centre, and tolerances in the manufacture of connecting rods, crankshaft webs, cylinder length and the distance of the cylinder base from the crankshaft axis.

The clearance chosen must take into account inaccuracies in production, carbon deposit on the cylinder crown and also piston expansion through heat.

The cavity orifice diameter has an influence not only on turbulence, but also on the temperature of the

after the collision. By high turbulence above the surface the fuel and air may be well mixed under these conditions and the amount of surplus air needed is small.

The great advantage afforded by direct injection to air-cooled engines is the simple design of the cylinder head, the cooling of which presents no great problems and can be carried out without high temperature differences and the risk of failure owing to overheating. The problem of placing the glow-plug (which is necessary for easy starting from cold) does not arise either.

In the case of direct injection, much of the usual heat load upon the cylinder head is transferred to the cylinder barrel and it is not uncommon to carry away as much heat from the cylinder barrel as from the head. Effective cooling for the upper part of the cylinder barrel, especially near the end of piston ring travel, must therefore be provided. For this reason the fitting of cylinder heads by flanges is unsuitable as much cooling fin area has to be sacrificed.

A comparison of two engines, one with direct and the other with indirect fuel injection, is given in Fig. 191 [13]. The heat removed by cooling is much lower in the case of the direct injection engine and generally is just above 0.5 b.h.p. Both engines under consideration are, however, water-cooled; in an air-cooled engine the portion of heat removed by the cooling medium is still smaller expressed in terms of e.h.p. Specific fuel consumption is considerably lower in the direct injection engine owing to its higher thermal efficiency. Not without interest is the fact that exhaust gas temperature is also much lower in the case of the direct injection engine despite the fact that its compression ratio is generally lower than that of the indirect injection engine. This is caused by the rapid ignition and efficient combustion of fuel with the piston at t.d.c. In indirect injection heads the combustion process is slower owing to the different manner of mixture formation; part of the fuel therefore is burnt less effectively during the expansion stroke and the exhaust gas temperature is thus raised. Higher combustion temperature in an injection chamber engine may also be caused by a smaller air surplus.

Indirect fuel injection is used in engines with injection chambers, in which case the fuel is injected into a chamber containing only a part of the air of the combustion chamber. Hot burning gas streaming from the injection chamber at high velocity into the combustion chamber carries with it droplets of remaining unburnt fuel into the air in the combustion chamber. Peak pressure is developed inside the injection chamber and does not act upon the piston. Pressure in the combustion chamber is lower and engine running is therefore smoother. At the high velocity with which burning gas sweeps through the connecting duct between the injection chamber and the combustion chamber, much heat is transferred to the cylinder head walls (the connecting duct). This increased heat transfer occurs also during the compression stroke when hot air entering the injection chamber is cooled down by passing the connecting duct. High compression ratios must therefore be used with this type of engine in order to ensure high temperature in the injection chamber at the end of the compression stroke for easy starting from cold.

Injection chambers are of three basic types:

1. the pre-combustion chamber
2. the swirl-chamber
3. the air cell

The air cell type cannot be applied to air-cooled engines owing to its large demands on space and its highly unfavourable effect on engine cooling.

Injection chambers may be formed either directly in the cylinder head, cast-in to aluminium heads or they may be screwed in. Cast-in chambers are

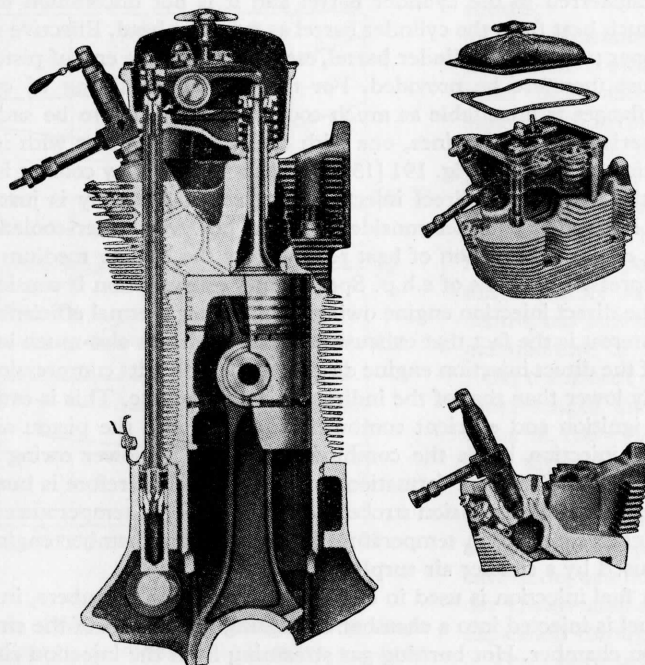


FIG. 192. Cylinder and injection chamber of an air-cooled Deutz engine.

used by Deutz (see Fig. 192) and screwed-in chambers by Caterpillar (see Fig. 193).

Injection chambers with a fairly large orifice in the chamber axis have become popular in recent years. The wide orifice reduces the velocity of the gas flowing into or out of the chamber thereby reducing compression work. As a result of the lower speed of the burning gases, heat transfer to the cylinder head is also reduced, thus lowering heat losses.

The MWM cylinder head shown in Fig. 194 may be demonstrated as a successful example of an air-cooled cylinder head with an injection chamber. The chamber is formed by a separate casting which is screwed on to the

cylinder head. The area of contact with the cylinder head is small and little heat is transferred from the chamber to the cylinder head, thus preventing overheating at this point with its resultant effects which often include cracking of cylinder heads. Surrounding the main orifice of the chamber, a number of smaller apertures are drilled into the chamber parallel to the orifice axis.

The MWM engine is noted for its specific fuel consumption which does not exceed that of a direct injection engine, but which at the same time permits relatively low peak pressures inside the cylinder. The rise in pressure per  $1^\circ$  of crankshaft rotation is also low, the engine being smooth and silent in operation, which is particularly desirable in air-cooled units. Another welcome advantage of this engine is its readiness to run on various fuels. Without modification to the engine, fuel oil may be replaced by petrol, paraffin, jet propulsion fuels, etc. For use with petrol, the pressure of the petrol supply pump must be raised to about 28.5

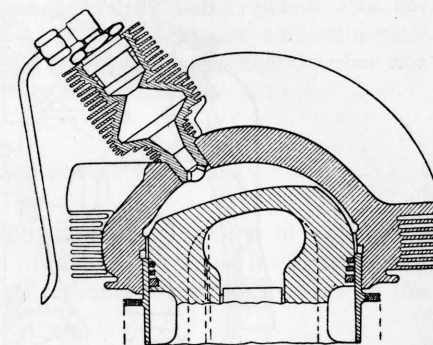


FIG. 193. Injection chamber of an air-cooled oil engine.

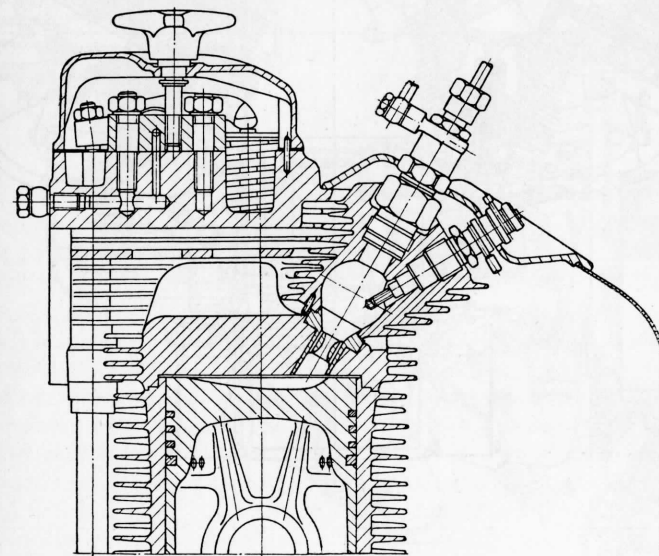


FIG. 194. Sectional view of the cylinder head of an MWM engine.

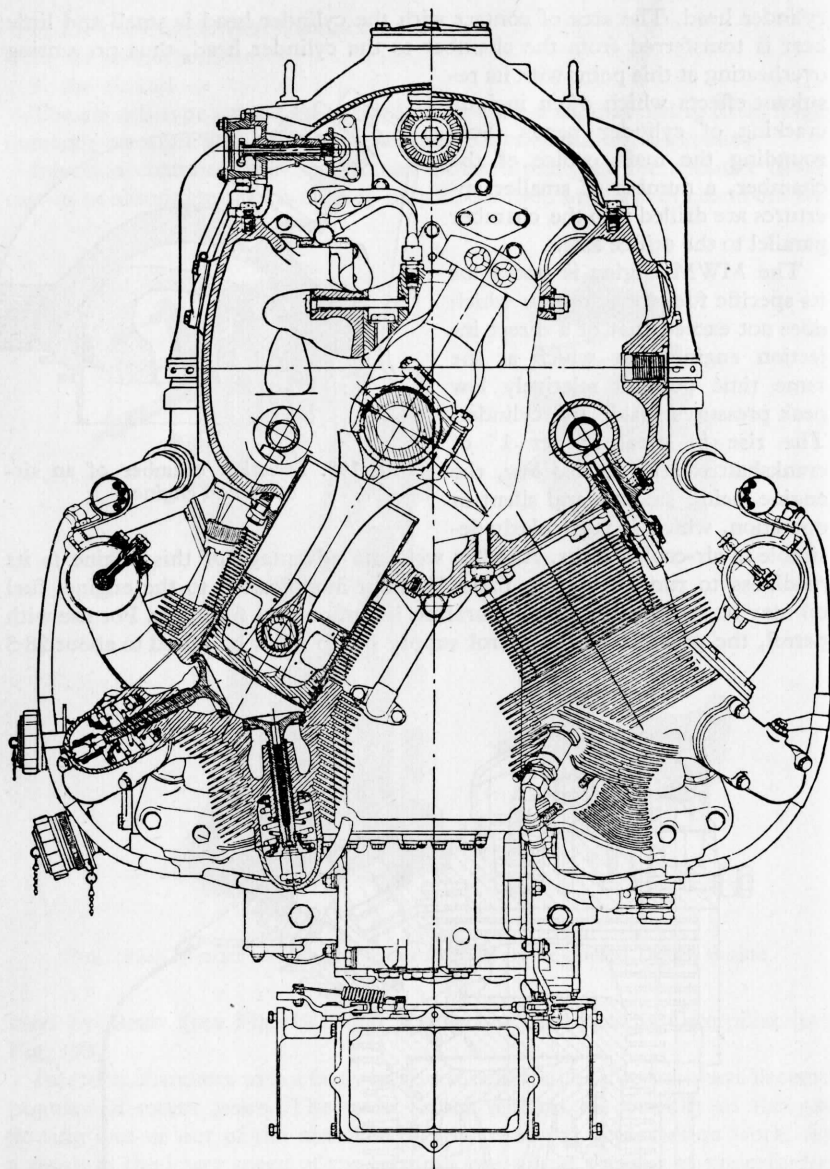


FIG. 195. Sectional view of the Argus As 410 aircraft engine with a well finned cylinder head.

lb/in<sup>2</sup> (2 kg/cm<sup>2</sup>) and the rate of flow must be increased. The excess fuel passes through the injection pump thereby flushing and cooling it in order to prevent the formation of gas locks when using volatile fuels such as petrol. This engine may be started at a temperature of 10 °C below zero without a glow plug, for the fuel spray passes through the orifice of the injection chamber into the cylinder, where the air is sufficiently hot to ignite it.

### 3. Detailed design

Cylinder head temperature is limited by considerations of volumetric efficiency, the requirements of correct combustion (freedom from detonation) and the strength of the material of the cylinder head. With a view to the

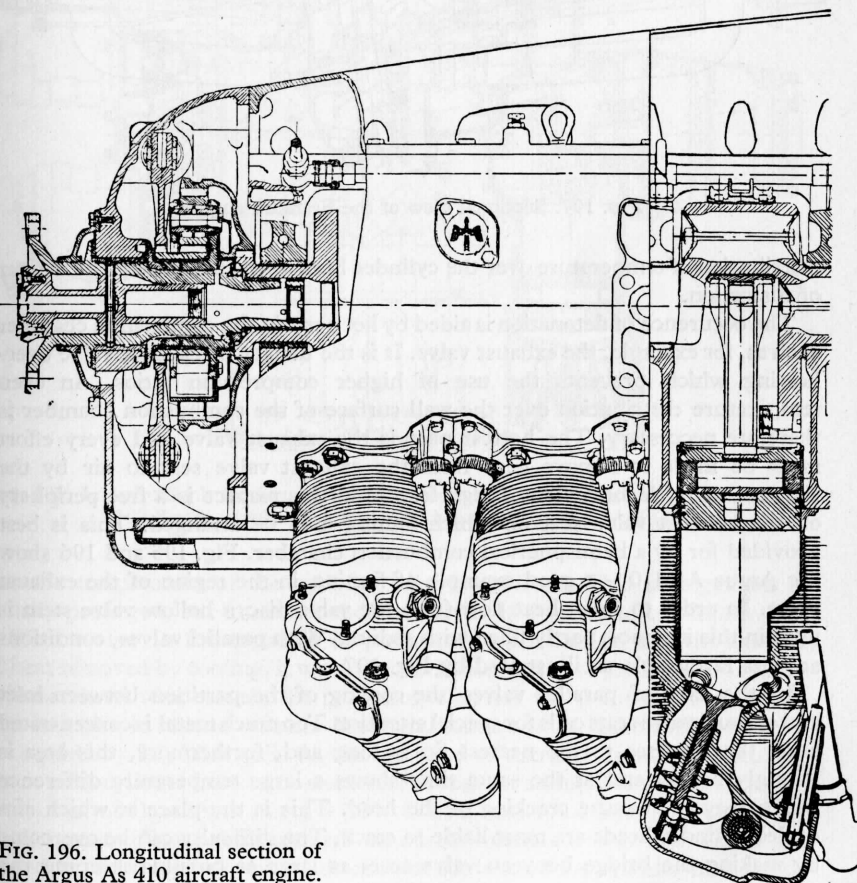


FIG. 196. Longitudinal section of the Argus As 410 aircraft engine.



highest possible volumetric efficiency, cylinder head temperature must be kept as low as possible. The temperature of the inlet valve and its surroundings has considerable influence on the degree of heating of the incoming air and thereby on the volumetric efficiency of the engine. Because of this, it is beneficial to direct cold cooling air to the inlet valve region in the first place. With such an arrangement there is however the possibility of a very uneven

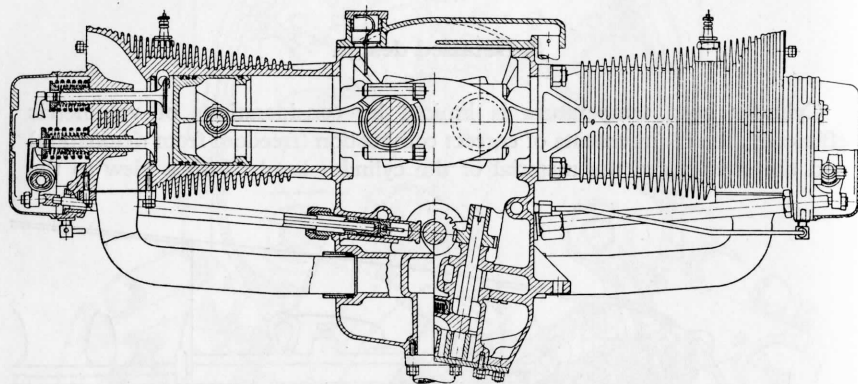


FIG. 197. Sectional view of the Franklin engine.

distribution of temperature over the cylinder head with the subsequent danger of distortion.

The occurrence of detonation is aided by hot parts in the combustion chamber such as, for example, the exhaust valve. It is the danger of exhaust valve overheating which prevents the use of higher compression ratios. An even temperature distribution over the wall surface of the combustion chamber is therefore necessary. The hottest part is the exhaust valve and every effort must be made to remove heat from the exhaust valve seat to air by the shortest route. A convenient design feature in this respect is a free periphery of the exhaust valve seat on which finning may be arranged. This is best provided for by a hemispherical combustion chamber. Fig. 195 and 196 show the Argus As 410 – a good example of finning in the region of the exhaust valve. In order to assist heat flow from the valve disc, a hollow valve stem is used in this instance, partly filled with sodium. With parallel valves, conditions are less favourable as illustrated by Fig. 197.

In the case of parallel valves the cooling of the partition between inlet and exhaust valve seats calls for special attention. Too much metal is concentrated here, the distance to the nearest fin is long and, furthermore, this area is strongly heated and at the same time shows a large temperature difference which may even cause cracking of the head. This is the place at which air-cooled cylinder heads are most liable to crack. The difficulty can be overcome by making the bridge between valve seats as large as possible, keeping the

distance for heat transfer short (thin walls) and by directing a sufficient stream of cooling air to the area (Figs. 198 and 199).

If exhaust valve temperature is to be kept low, cold air should be brought direct to the exhaust valve area. With this arrangement the exhaust valve is the coolest part, whereas the inlet valve region is somewhat hotter, for the heated air coming from exhaust-side fins, has lost some of its cooling ability;

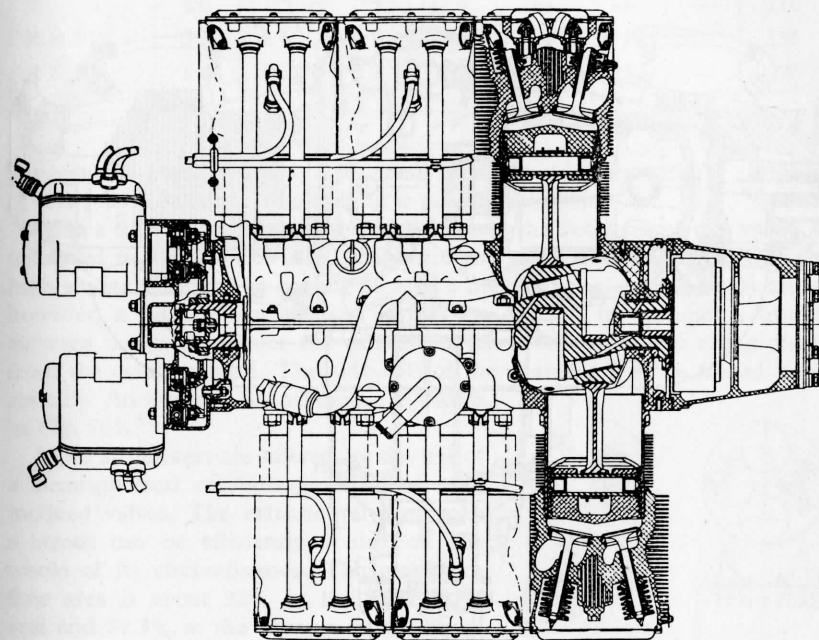


FIG. 198. Longitudinal section of the Lycoming GO-435 aircraft engine. Bore 123.8 mm, stroke 98.4 mm, 260 b.h.p. at 3,400 rev/min.

but the temperature of the cylinder head is uniform. This arrangement is usually preferred, but much depends on details of design and conditions.

With a view to the economy of performance for cooling and the amount of heat removed by cooling, it would be advisable to choose the highest possible cylinder head temperature. In preceding chapters the point has been made that in order to reduce cylinder head temperature by  $10^{\circ}$ , fan input must be multiplied by 2.3. This calls for the exercise of extreme caution in deciding the correct cylinder head temperature. The highest admissible temperature for heads cast of aluminium alloys is  $235^{\circ}\text{C}$  with individual hot spots of  $250^{\circ}\text{C}$  at the most. Higher temperatures cannot be tolerated. Fig. 188 shows the variation of strength of several aluminium alloys used for cylinder heads with

temperature. A considerable reduction of strength of the material is evident at temperatures above 200 °C. The composition of these alloys is given in Table 37. The reduction of strength at high temperatures need not manifest itself through cracks only, but may result in permanent deformation, especially at the pressure gas seal between the cylinder head and cylinder.

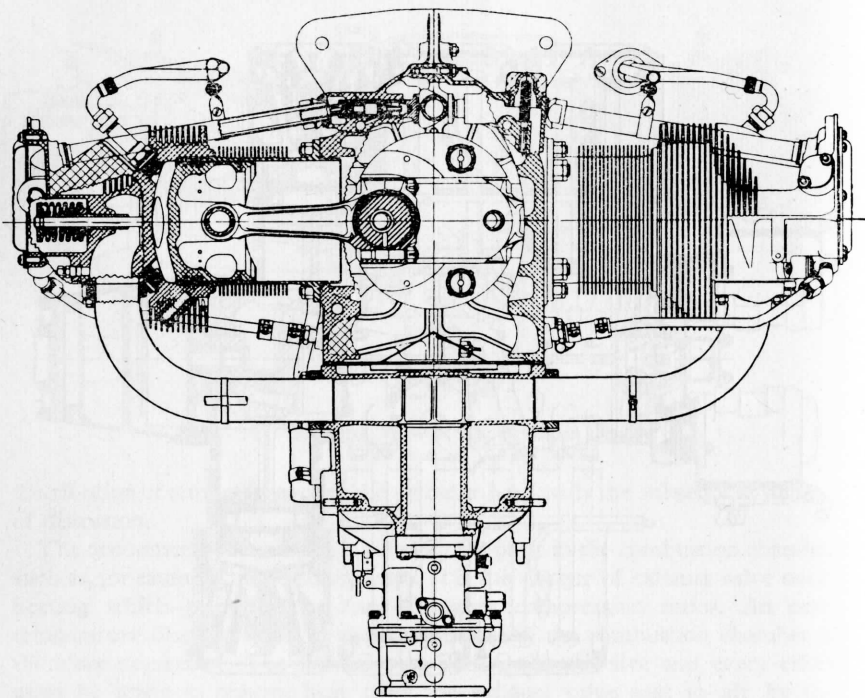


FIG. 199. Transverse section of the Lycoming GO-435 engine weighing 181 kg.

A well designed cylinder head must possess:

1. large and well cooled valves
2. large flow area for cooling air
3. large cooling area with properly located fins
4. easily accessible and oil tight valve mechanism.

The valves in the cylinder head should always be as large as the design permits, since large valves promote high volumetric efficiency and high output even at high engine speeds. Fig. 200 shows four overhead valve layouts. With two parallel valves, the flow area of the inlet port amounts to 18.5% of piston area and that of the exhaust valve to 13.5%. A slight increase in inlet valve size is still possible at the expense of the exhaust valve. The partition

Table 37

Compositions of Aluminium Alloys for Cylinder Heads

|        | Cu  | Mg   | Si  | Ni  | Fe  | Ti   | Zn | Brinell |
|--------|-----|------|-----|-----|-----|------|----|---------|
| RR 59  | 2.0 | 1.7  | 0.3 | 1.3 | 1.3 | 0.05 | —  | 130     |
| Y      | 4.0 | 1.5  | 0.5 | 2.0 | 0.4 | —    | —  | 110     |
| R R 53 | 2.0 | 1.6  | 0.9 | 1.3 | 1.3 | 0.10 | —  | 135     |
| R R 50 | 1.4 | 0.12 | 2.2 | 1.1 | 1.1 | 0.23 | —  | 76      |

between the ports is already very small and may cause fractures of the head at this point. Exhaust valve cooling is poor in this case.

With a four-valve layout with parallel valves the flow area of two valves is increased to 21.6%. The small weights of the two valves are convenient for high engine speeds. The cooling of such a four-valve cylinder head by air is, however, a difficult proposition; it may be effected by forming a trough between the pairs of inlet and exhaust valves with vertical fins rising direct from the cylinder head. The sidewalls of the channels may be finned horizontally. An example of this design is shown in Fig. 201.

More advantages are offered by the use of a hemispherical combustion chamber with inclined valves. The exhaust valve of such a layout can be efficiently cooled on the whole of its circumference. The maximum flow area is about 32% at the inlet valve seat and 22.3% at the exhaust valve. Small changes can still be made by altering the respective sizes of the valves and by constructional details. The conditions prevailing with aluminium alloy heads, in which inserted valve seats are used of necessity, are probably less favourable.

By the use of a "pent roof" four-valve cylinder head layout, the flow area at the exhaust valve seats may also be increased to about 32% of the piston crown area. The coefficient of flow through the ports is however less favourable than in the foregoing case (hemispherical combustion chamber), for flow is restricted by the close proximity of two valves and on the outer side also by the vertical wall.

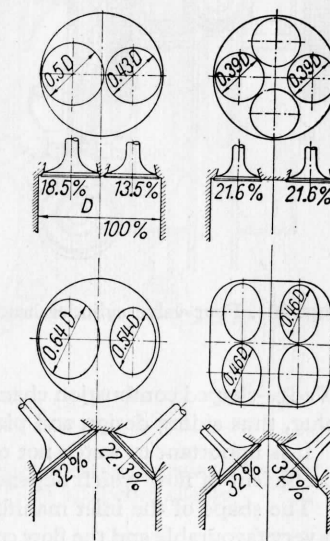


FIG. 200. Comparison of valve flow areas expressed in percentages of the piston crown area for various types of valve gear.

In plan view, some wedge-shaped combustion chambers project outside the cylinder. With such an arrangement much more favourable conditions are created even if parallel valves are used. Sharp and insufficiently cooled edges must however be avoided and good scavenging of the remote corners must be ensured. The inlet valve should not project outside the plan view of the cylinder in order to keep the inlet air stream as straight and as cool as possible.

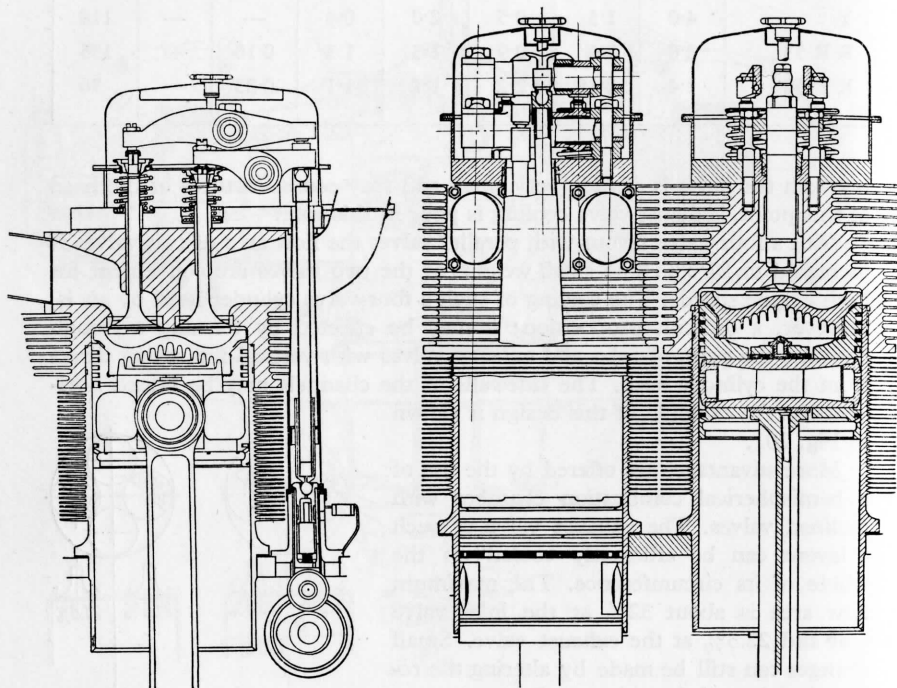


FIG. 201. Four-valve cylinder head of an air-cooled compression-ignition engine of a 140 mm bore.

Wedge-shaped combustion chambers permit a lateral mounting of the sparking plug, thus aiding design and placing the plug in an accessible position.

It is important to watch not only the flow area at the inlet port but also the coefficient of flow which depends on the shape of the inlet manifold.

The shape of the inlet manifold with a hemispherical combustion chamber is very favourable and the flow coefficient is high. Fig. 183 shows the promotion of good air flow characteristics by the hemispherical head layout as the induction elbow behind the valve is well shaped. The cross section varies continuously and bends are slight. This shape of inlet port is favoured by many motor cycle engine designs and makes high mean effective pressures

possible. The dotted line 2 denotes another widely used shape, found in many aircraft engines.

An example of a hemispherical air-cooled head is shown in Fig. 202. Another desirable feature of the hemispherical head is its low rate of carbon deposit resulting in a small performance loss. The valve actuating mechanism is however more complicated and a great deal depends on design details.

The layout shown in Fig. 203 has found widespread application in aircraft engines. The valve rockers are at an angle to the cylinder axis in the plane of the valves, whereas push rods are outside this plane and are disposed radially to the crankshaft axis. The rocker bearings must therefore withstand considerable axial thrust. This disadvantage may be lessened by constructional modifications. The valves are in a plane at right angles to the air stream and their cooling is very good.

Cylinder heads of radial aircraft engines have reached a high degree of perfection and provide excellent cooling for exhaust valves. The finning of the head between both valves is parallel to the cylinder axis, all other fins being at right angles to it. The evolution of an aircraft engine cylinder is shown in Fig. 204. By the constant increase in cylinder fin area the specific output per cylinder has also increased. In the latest Pratt and Whitney 28-cylinder engine the valve gear is arranged in a different manner. (Fig. 205). The massive cylinder head walls and the thin and close finning are worth noting. The removal

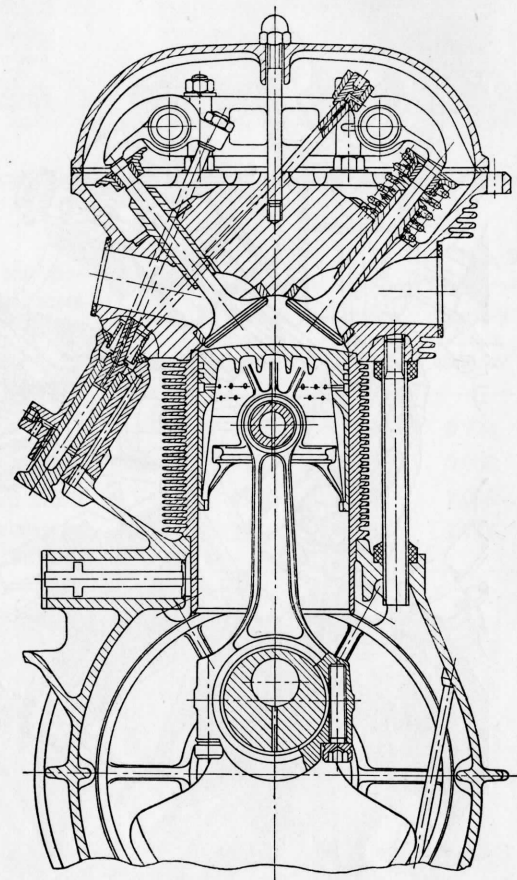


FIG. 202. Hemispherical combustion chamber of the Tatra 910 petrol engine.



of heat from cylinder heads of large aircraft engines is becoming difficult and for considerations of cooling, bore is restricted to 150 to 160 mm. Higher power outputs may therefore be obtained only by increasing the number of cylinders. The Pratt and Whitney Company's 28-cylinder engine supplies 3650 b.h.p. at 2800 rev/min. [50]

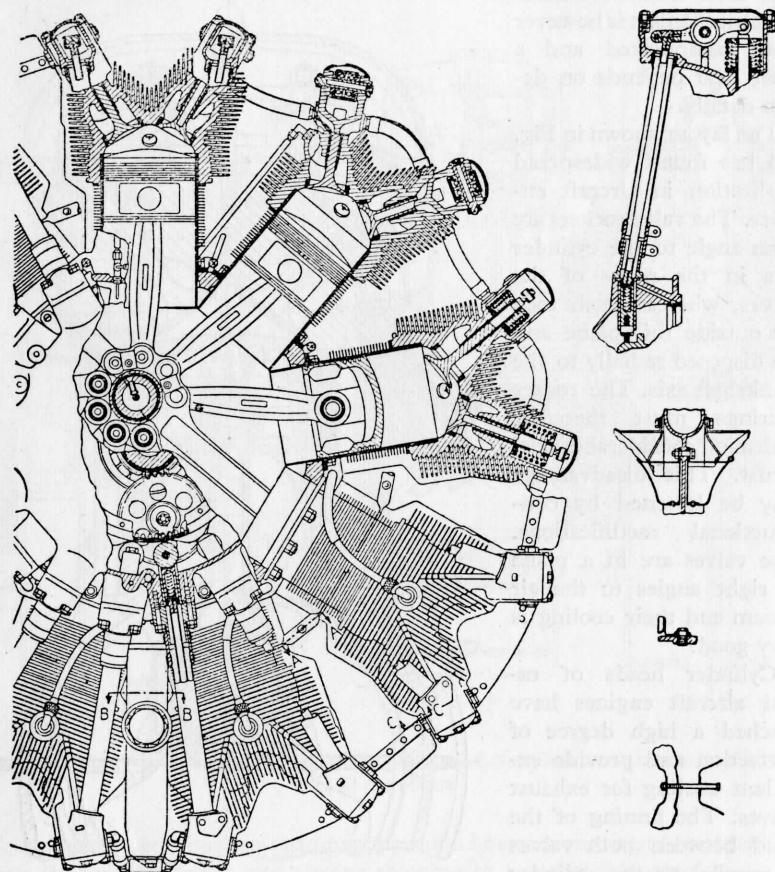


FIG. 203. Transverse section of a radial aircraft engine (Lycoming). Note the valve gear.

The development of an aircraft engine takes from 5 to 8 years; the development of an automobile engine from 3 to 5 years and not even the most painstaking calculations can reduce this period. Various engine parts are exposed to the most complex stresses under operating conditions, e.g. vibrations which

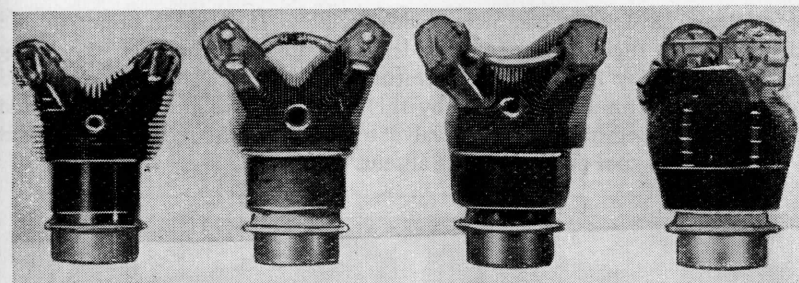


FIG. 204. Development of the cylinder of the Pratt and Whitney engine, bore 146 mm. See Table 38.

cannot be anticipated with any degree of certainty, long-term tests being necessary to show their influence.

In order to reduce the transfer of heat from exhaust gases to the cylinder head, the exhaust port is always kept as short and as straight as possible. Heat transferred from exhaust gases places an unnecessary burden on the cylinder head finning.

Table 38

|   | Year of manufacture | Performance b.h.p. | Cooling surface area, m <sup>2</sup> |
|---|---------------------|--------------------|--------------------------------------|
| 1 | 1927                | 45                 | 0.774                                |
| 2 | 1932                | 67                 | 0.968                                |
| 3 | 1940                | 100                | 2.000                                |
| 4 | 1946                | 125                | 2.770                                |

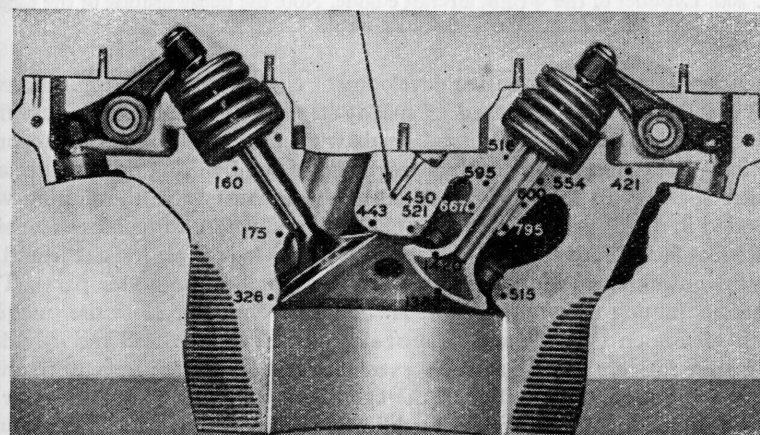


FIG. 205. The new cylinder head of the Pratt and Whitney aircraft engine. Note the wall thickness of the cylinder head. Temperatures in °F.

Experiments have been conducted with stainless steel sheet lining of the exhaust port in such a manner as to leave an air space between the lining and the light alloy head. The temperature of the cylinder head was reduced considerably (as much as 100 °C) by this and the valve guide also operated at a lower temperature. Exhaust valve temperature though, was increased as dissipation to cool port walls was absent.

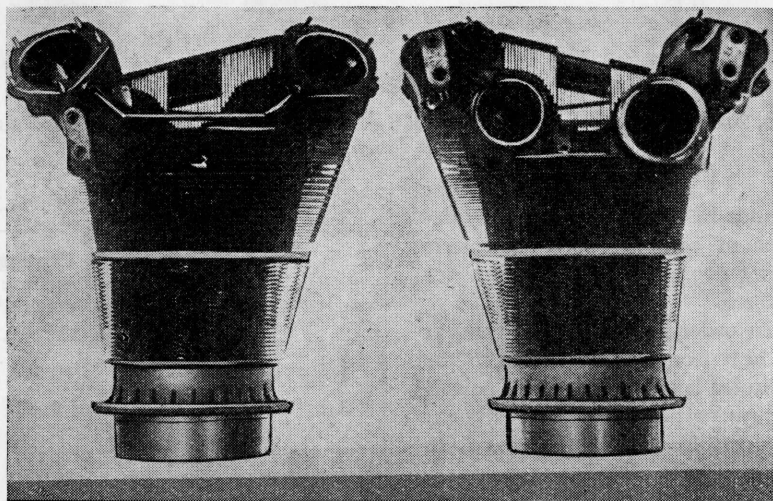


FIG. 206. Cylinder of the Wright aircraft engine. Note the dense finning of the forged cylinder head.

Another example of extensive development is given by the Wright aircraft engine cylinder. With the need of speedy step-up of engine output cast fins no longer filled the bill and forged heads with machined fins went into production. The cooling area was thus greatly increased by using thinner fins and smaller spacing. In the neighbourhood of the exhaust valve the finning was extended in depth without regard to obvious production difficulties. The size of the fins facing forward was reduced in order to reduce air resistance and to prevent unwanted heating of the air before it reaches the hotter parts. The ingenious finning of a forged head is shown in Fig. 206. Note the unequal depth of fins on the inlet and exhaust side of the cylinder head and cylinder. Very thin fins are linked at their extremities in order to prevent fracture through vibration. The outline of the cylinder is without "steps" in order to fit well under a cowling. These modifications brought about a lower power consumption by cooling despite increased performance, the reduced pressure drop over the cylinder resulting in reduced air flow. The power expenditure for cooling of this Wright C 18 engine with a take-off output of 2700 b.h.p.

at 2900 rev/min is shown in Fig. 207 [65] – the values relevant to the cast head being marked in dotted line, those for the forged head and machined fins in full line. The reduction in power consumption for cooling purposes is substantial in this case and proves the importance of finning. The cylinder bore of the engine is 155.6 mm, stroke 160.3 mm, number of cylinders 18.

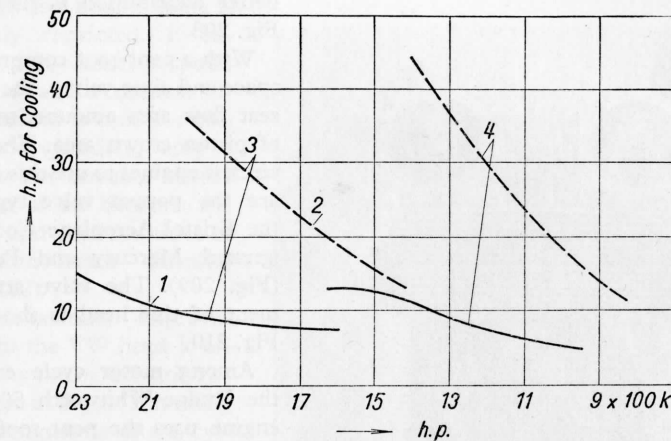


FIG. 207. Cooling input of the Wright aircraft engine with forged (1) and cast (2) cylinder head, operated with rich (3) and lean (4) mixture. Note the considerable reduction of input for cooling the forged cylinder head.

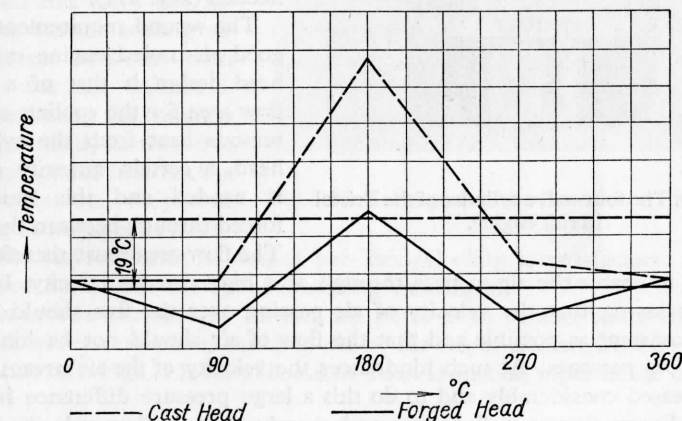


FIG. 208: Reduction of temperature on the circumference of the valve seat in a forged (full line) and cast (dash line) cylinder head of the Wright aircraft engine.



Great difficulty was experienced with the cast cylinder head with exhaust valve leakage caused by uneven temperature distribution over the circumference of its seat. A more even temperature distribution was reached by the use of closer spaced finning on the forged head and by raising the exhaust stub which made possible an increase in the number of fins in the critical position. The resultant reduction of mean valve seat temperature and its better distribution is shown in Fig. 208.

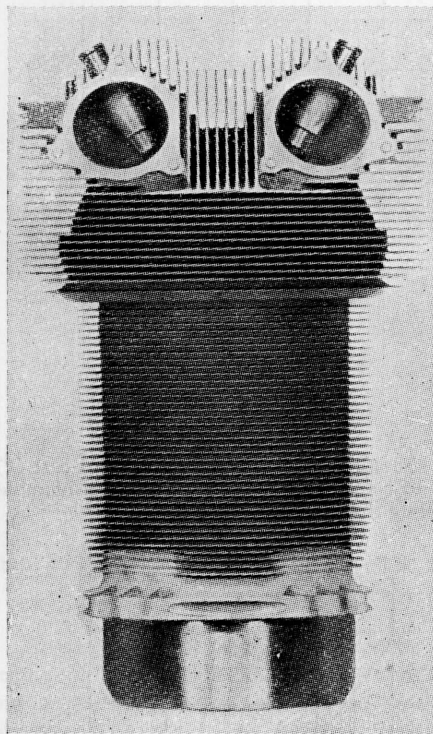


FIG. 209. The four-valve cylinder of the Bristol aircraft engine.

With a pent-roof compression space and four valves, the valve seat flow area amounts to 32% of piston crown area. The only aircraft engines to use this layout are the poppet valve types of the Bristol Aeroplane Co., designated Mercury and Pegasus (Fig. 209). The valve arrangement of this head is shown in Fig. 210.

Among motor cycle engines the Rudge Whitworth 500 c.c. engine uses the pent roof head with four valves. The actuating gear used for the four radially disposed valves of the 250 c.c. engine of Rudge manufacture is interesting; six rockers are needed (Fig. 211).

The second requirement on a good air-cooled engine cylinder head design is that of a large flow area for the cooling air. To remove heat from the cylinder head, a certain quantity of air is needed and this must be forced through between the fins. The flow area must therefore be such as to enable the air to pass through at a high enough velocity. It goes without saying that the velocity of air passing over the fins should be as nearly constant as possible and that the flow of air should not be hindered by narrow passages. At such hindrances the velocity of the air stream must be increased considerably and to do this a large pressure difference is necessary. Every change in flow area and thereby also in flow velocity is the cause of increased pressure loss. The requirement of minimum interstice variation between fins is well met in radial aircraft engines, where all cyl-

inders stand unobstructed and the height of fins is constant over the entire circumference. Conditions are much less favourable in the case of in-line engines where the small centre-to-centre distance between adjacent cylinders limits the height of fins in one direction. The height of lateral finning on both sides of the combustion chamber is particularly restricted.

With parallel valves in a common plane with the crankshaft axis, flow area through the head finning is severely restricted. If exhaust port channels point outwards and a common inlet manifold is used for two adjacent cylinders, only a narrow slot remains for the passage of air between the valves and past the sides of the combustion chamber (Fig. 212).

A substantial improvement to the VW head is effected by the modification illustrated in Fig. 213 showing the arrangement of the cylinder heads on the Porsche sports car engine. By inclination of valves not only was a more favourable combustion chamber geometry obtained and valve size increased, but the cooling air flow area between both valves was also increased. By abandoning the common inlet manifold, further free area was gained between the two cylinders. Improved cooling made possible a considerable improvement in output per litre. Cooling is satisfactory, despite increased bore, with the cylinder spacing unchanged.

Flow area is increased by turning the ports to be parallel to the direction of air flow. An example of this is given by the Argus aircraft engine cylinder head shown in Fig. 214. Notable are its short induction pipes in the cylinder head.

The single vertical rib connecting fins assists in distributing heat into the horizontal fins and also transmits the load of the rocker pivot bearing spindle direct to the cylinder head. The outline of the cylinder head is unsymmetric

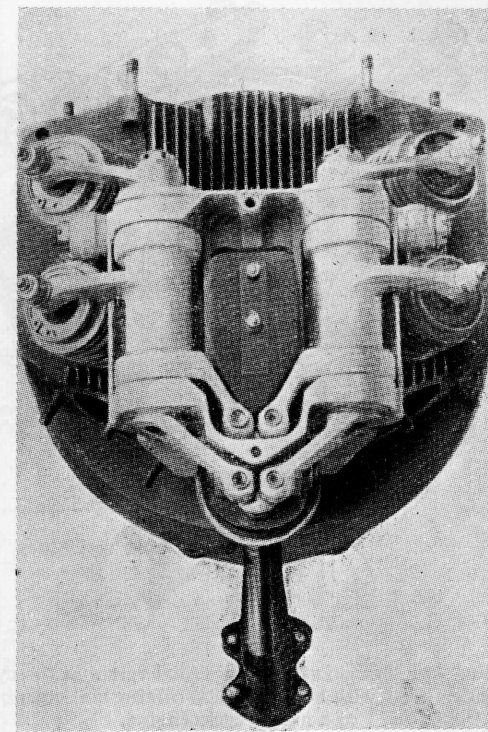


FIG. 210. Valve gear of the Bristol aircraft engine.



and the exhaust side fins are higher. Every second fin in the space between the valves is omitted in order to strengthen the sand core. Fig. 215 shows a similar arrangement of the Walter - Minor aero engine head.

Spacing of cylinders in flat engines is determined by the design of the crankshaft and is therefore relatively large. Nevertheless, it has been found desirable to incline the plane of the valves in relation to the crankshaft

centre plane in order to obtain better cooling air flow and shorter ports. This arrangement has been applied to the Tatra-plan engine, shown in section in Fig. 103. Both valves are, furthermore, inclined making the use of a hemispherical combustion chamber possible. Owing to special rocker layout, the valves may be actuated by push rods leading from a camshaft located in the crankcase. The camshaft being beneath the crankshaft, push rod tunnels can be used as oil return pipes from the far side of the cylinder heads. For the lubrication of rockers, oil is delivered through the hollow push rods. Cylinder heads are fastened direct to the crankcase by four long bolts.

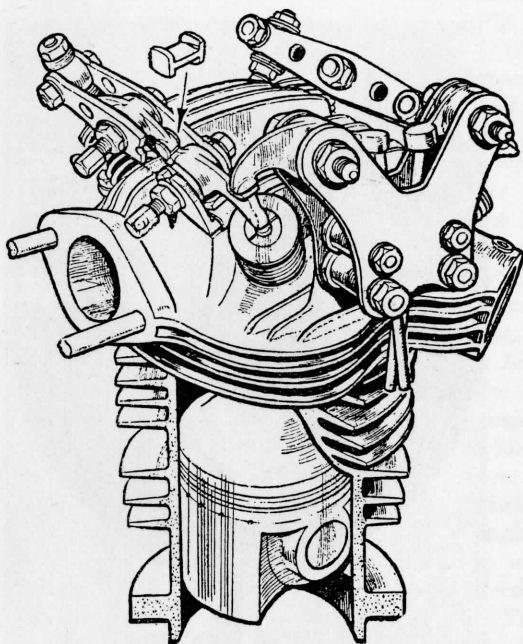


FIG. 211. Actuation of four radial valves in the cylinder head with hemispherical combustion chamber of a motor-cycle engine.

A different finning pattern is used for the in-line Deutz compression-ignition engine with parallel valves (Figs. 216, 217). In order to enable cooling air to penetrate to the centre of the head between valves, both ducts turn to the outside of the head immediately behind the ports thus leaving the middle section free for vertical fins. Both ducts have a vertically placed rectangular cross section in order to provide enough space between manifolds for the passage of air. The opposite side of the head houses an injection chamber so that a space between vertical fins would in fact form a blind passage preventing the flow of air. Vertical finning is therefore retained only for the middle section of the head, the side fins being horizontal (Fig. 192). Fig. 192 is more instructive, as the ingenious solution of the problem of cooling this head can be seen.

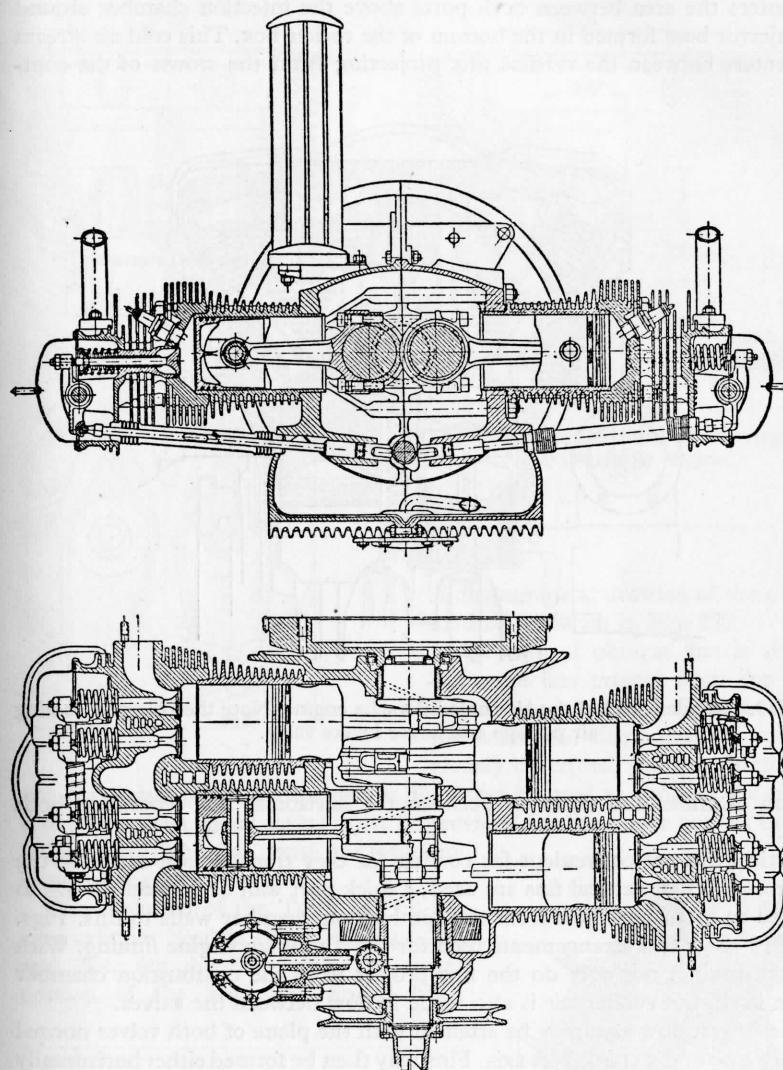


FIG. 212. Transverse and longitudinal section of the VW engine. Note the small air transition area shown in the longitudinal section.

Cold air reaches the head from the injection chamber side and enters between the horizontal fins, between which it streams over both sides of the head past the outer sides of the inlet and exhaust ports to the other side of the engine. Air enters the area between both ports above the injection chamber around the injector boss formed in the bottom of the rocker box. This cold air stream first enters between the vertical fins projecting from the crown of the com-

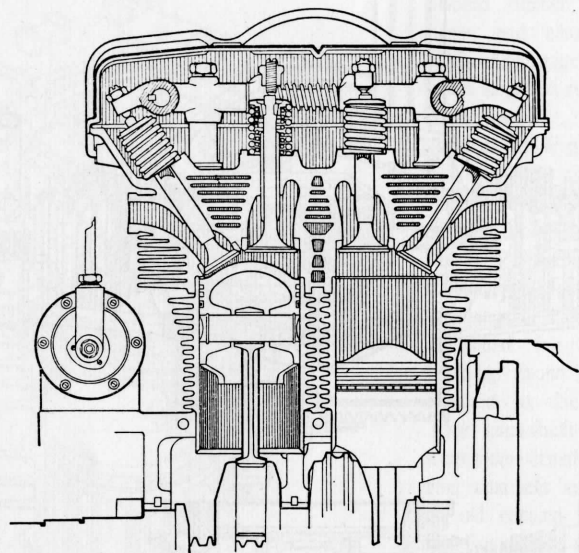


FIG. 213. Cylinder head of the air-cooled Porsche engine. Note the enlarged cooling air passage and larger intake valve.

bustion chamber and flows on between the horizontal fins separating both ports.

Vertical fins are convenient for cooling for they transfer heat direct to the air stream. When vertical fins are used, a thick port wall or vertical rib has to be used to assist heat flow from the combustion chamber walls to fins. Figs. 218, 219 show two arrangements used for the Tatra engine finning. With vertical finning, not only do the fins project from the combustion chamber crown itself, but cooling air is also made to flow between the valves.

The largest flow area may be attained with the plane of both valves normal to the plane of the crankshaft axis. Fins may then be formed either horizontally (Fig. 220), or obliquely (Fig. 221).

With horizontal fins it is beneficial to assist heat flow to all fins by a thick vertical rib in the plane of the ports. This arrangement is very convenient for moulding and such heads can easily be cast into steel moulds. Casting of

heads into steel moulds is highly advantageous, for precise castings with a level and straight surface of the fins are produced. Furthermore casting time including preparation is greatly reduced and compact castings are obtained.

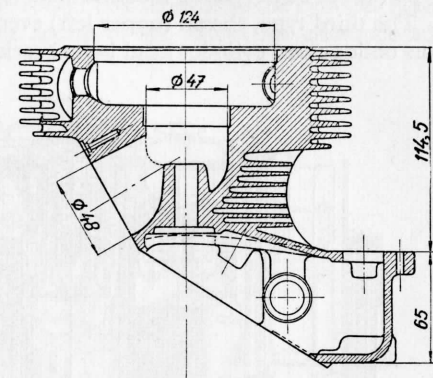
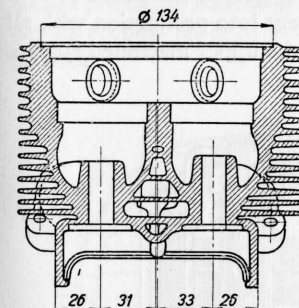
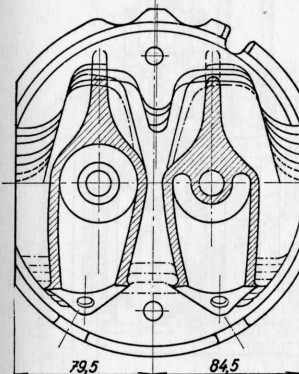


FIG. 214. Cylinder head of the Argus As 10 C aircraft engine.



A diagrammatic drawing of the casting method is shown in Fig. 222.

The case of oblique fins is similar, but more fins project from the combustion chamber wall. Compared with the horizontal disposition of fins previously described, oblique finning has

one disadvantage as the uppermost fin cannot be used to conduct the air and a separate sheet metal casing must be provided for the upper part of the cylinder head. (The fins must not form any blind passages).

The evolution of the Tatra 111 oil engine cylinder head is shown in Figs. 223 and 224. On the first type, the lower portion of the head was finned hori-

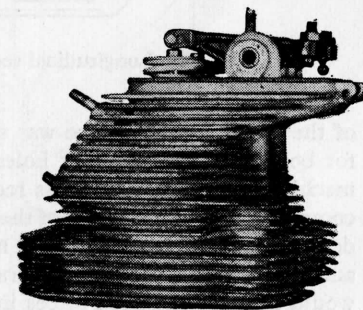


FIG. 215. Cylinder head of the Walter Minor aircraft engine. Note the thick fin for transmitting forces from the rocker arm to the cylinder head.

zontally, the upper obliquely. The cylinder head studs are screwed into threads formed in the lower part of the cylinder head. A large area of fins had to be cut away above the stud holes for access during assembly. The second type (upper right) shows modifications to the upper part of the head.

The third type, shown (upper left) eventually went into production with all fins oblique and cylinder head bolts bearing upon the upper machined surface

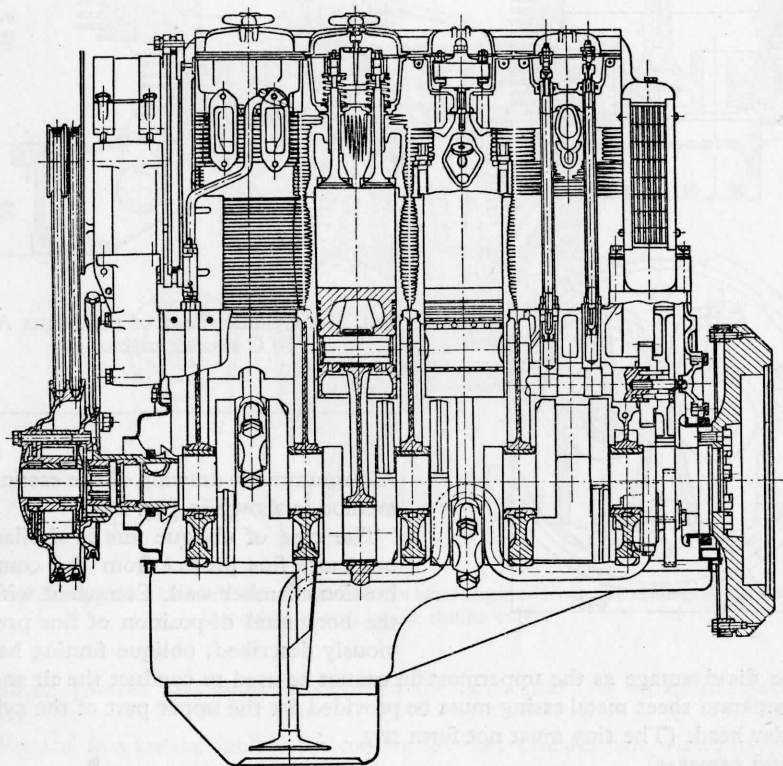


FIG. 216. Longitudinal section of the Deutz F-4-L-514 engine.

of the head. By this, space was saved for finning as no cutaway was needed for box spanners. The bolt holes are drilled in the fins so that no separate machining of the seatings was required. The pressure exerted by the bolts is communicated to the centre of the head by massive fins, thus partly eliminating deformation of the head through mechanical stresses. The bolts must be elastic and reduced in diameter considerably, otherwise thermal expansion of the head would increase the axial forces in the bolts excessively. The injector is in all

these types housed in a boss formed in the thick central fin. The inlet port extends to the upper plane of the head in order to simplify the shape of the cowling. In this instance air flows past the inlet valve to the exhaust. The rocker pivots are housed in a separate rocker box screwed to the cylinder head. An inspection cover is provided for access to the valves for clearance adjustment.

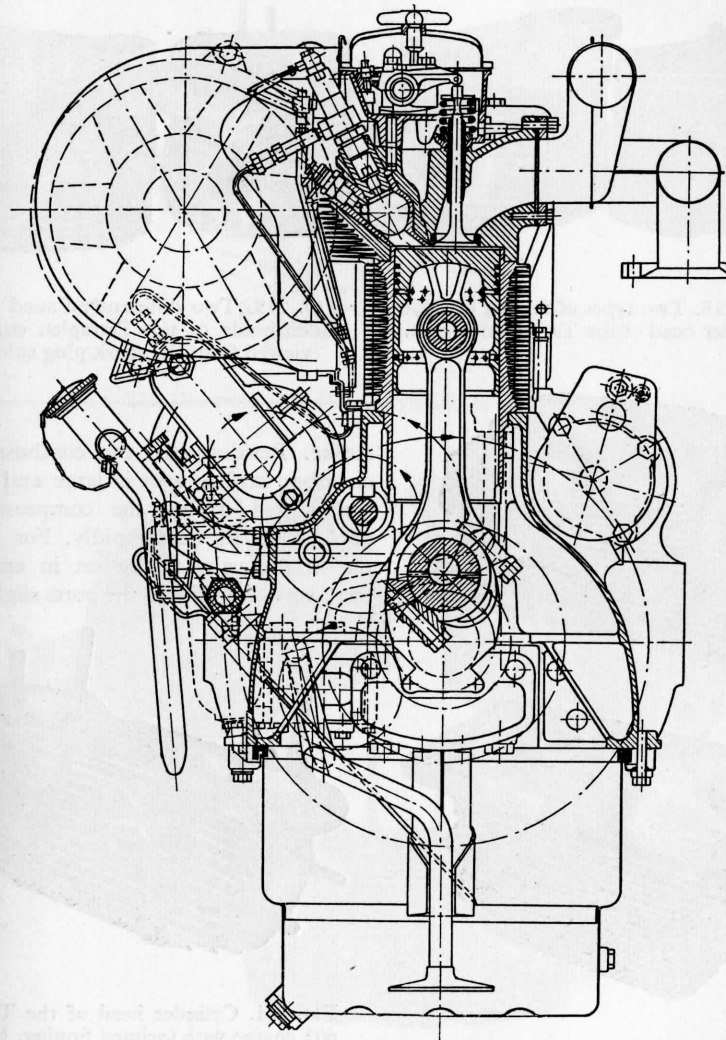


FIG. 217. Transverse section of the Deutz F-4-L-514 engine.



Fig. 225 shows the further development of Tatra compression-ignition engines. The hemispherical combustion chamber does make for high volumetric efficiency but it does not provide sufficient swirl during the induction

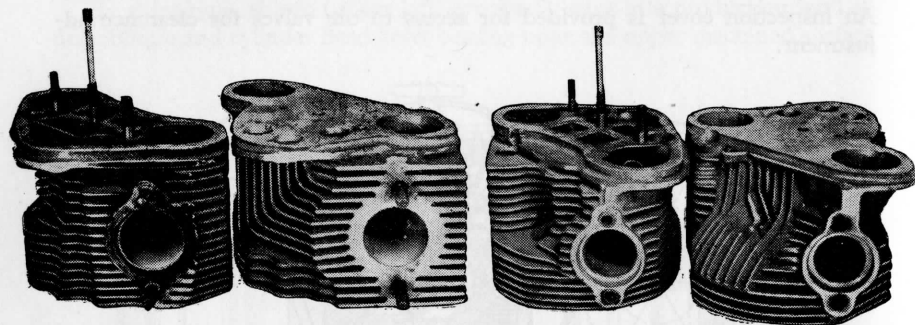


FIG. 218. Two types of finning of the cylinder head of the Tatra 603 engine.

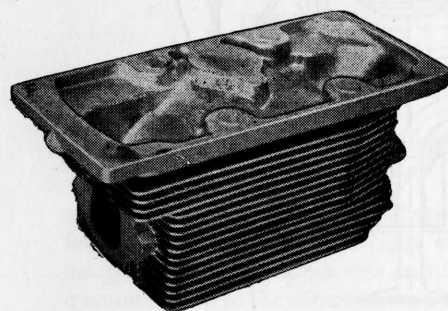
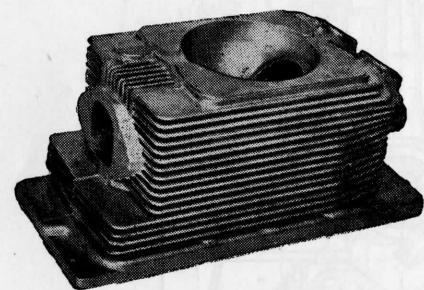


FIG. 220. Iron mould casting of the aluminium cylinder head of the Tatra 603 engine.

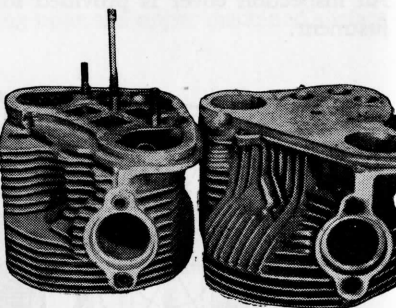


FIG. 219. Two differently finned cylinder heads of the Tatra 603 engine viewed from the spark plug side.

stroke. Besides this, the combustion chamber surface area is large and air compressed during the compression stroke loses its heat rapidly. For this reason the valves were set in an almost vertical position, the ports slightly

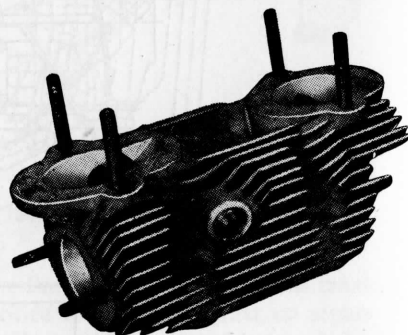


FIG. 221. Cylinder head of the Tatra 603 engine with inclined finning. Note the poorer finning in the region of the spark plug.

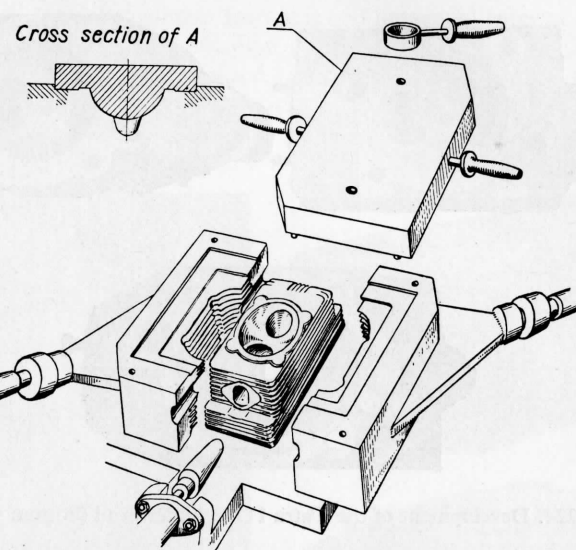


FIG. 222. Illustration of casting cylinder heads into iron moulds.

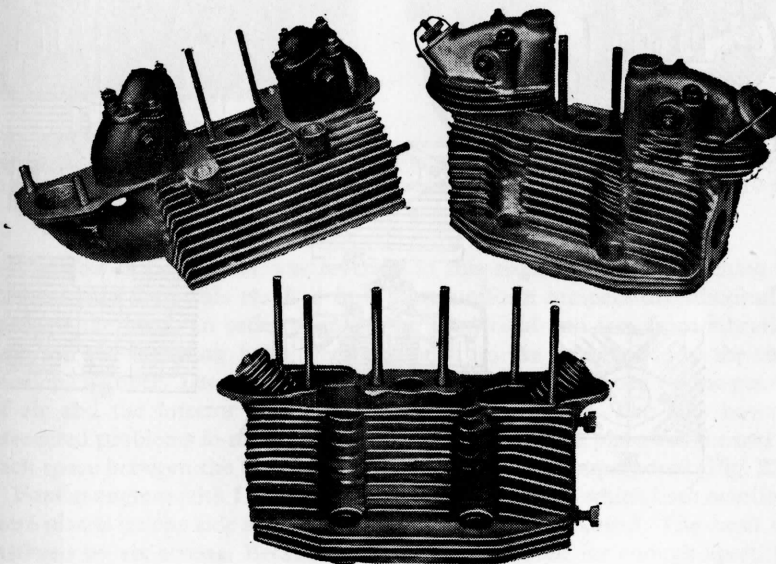


FIG. 223. Development of the Tatra 111 cylinder head (top view).

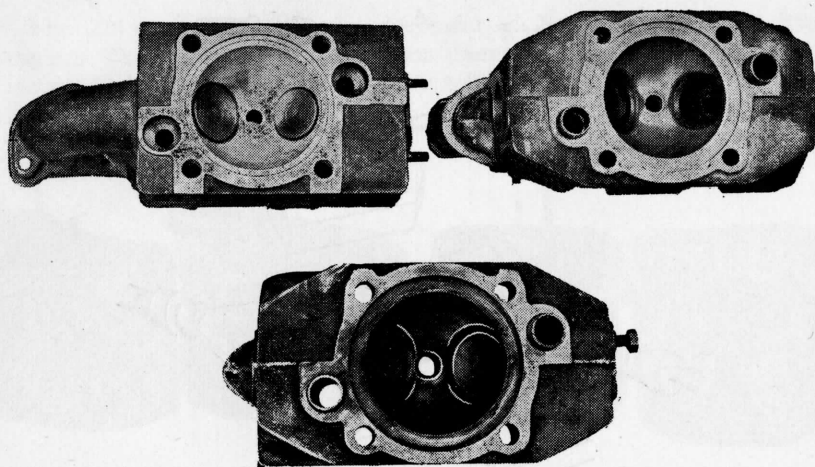


FIG. 224. Development of the Tatra 111 cylinder head (bottom view).

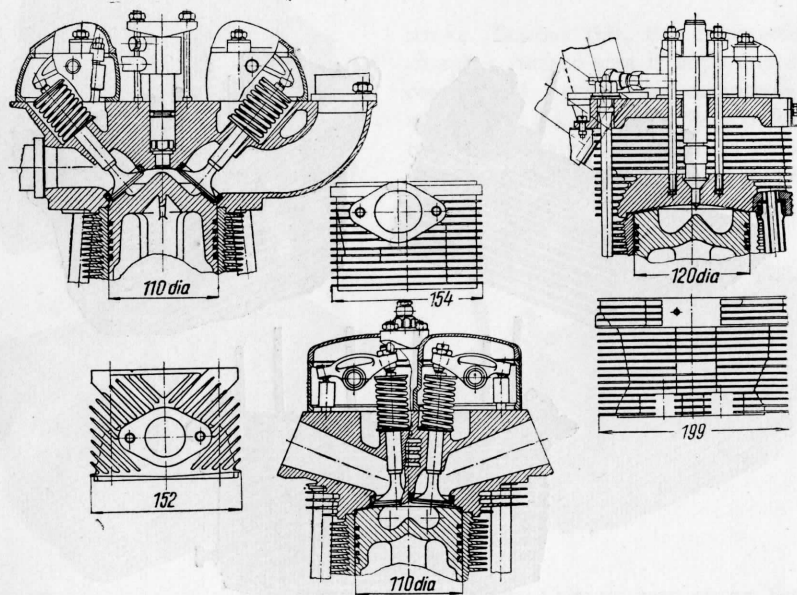


FIG. 225. Development of the cylinder head of the Tatra compression-ignition engine.

inclined away from the cylinder head axis and tangential entry of air was thus ensured. A very compact combustion chamber was formed inside the piston crown and its narrow orifice caused high turbulence during the compression stroke. Traces of varnish provided definite proof of dual turbulence during compression (Fig. 226).

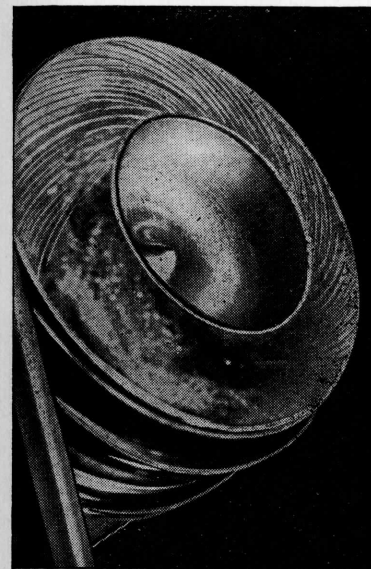


FIG. 226. Double compression turbulence in the toroidal injection chamber in the piston of the Tatra compression-ignition engine.

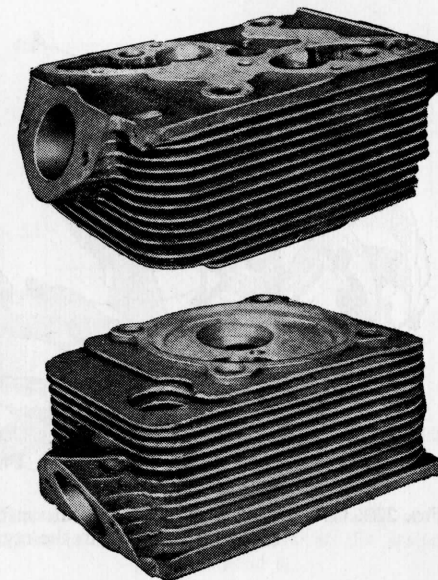


FIG. 227. Cylinder head of the Tatra compression-ignition engines, series of 110 mm bore, new design.

The flow of cooling air was reversed in this engine, fresh air reaching the exhaust side first; this resulted in a more uniform temperature distribution through the head. In order to make the head rigid and free from vibration, lugs for the fastening bolts were cast on from the upper plate to the combustion chamber. The section between the valves was thus freed for the passage of air and the injector was therefore efficiently cooled. The lugs however presented problems in moulding and therefore a separate plate was formed for each space between the fins and these plates were then superposed (Fig. 227).

For flat engines with 120 mm bore a layout was used in which both manifolds were placed on one side and only one camshaft was employed. The head was fastened by six screws. Because cylinders were spaced far enough apart, the provision of sufficient finning with a large enough flow area presented no difficulty.

A problem in the design of air-cooled engines is the disposition of the exhaust pipe in such a manner as to lead it out of the cooling air stream in the shortest and straightest possible way in order to reduce to a minimum the heat exchange between exhaust gases and the cylinder head. With a short exhaust pipe and the usual type of finning, the pipe emerges into the cooling air duct. In order to prevent warming of the air, particularly where it is directed against the

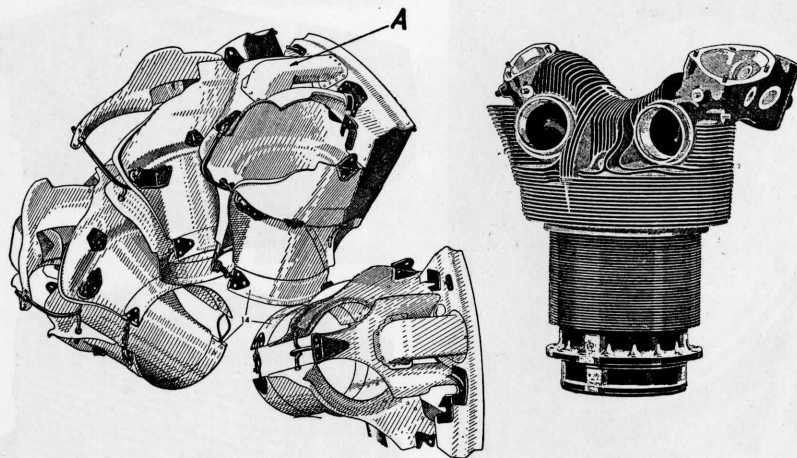


FIG. 228. Cowling of the BMW 801 aircraft engine. Note the special duct A for conveying cool air to the region of the spark plug.

exhaust side of the cylinder head first, the exhaust pipe must leave the duct by the shortest possible route. At the same time the access of cooling air to the cylinder head must not be impaired. This often leads to complex shapes of the cooling air ducts and to difficult assembly.

These difficulties are overcome by the use of a finning layout shown in Fig. 102, in which the exhaust pipe is short and its curvature slight. The upper cooling fin in this design forms a good duct for the air stream and the remaining sheet metal cowling is very simple. Provision is made for extensive finning of the exhaust valve region and the coefficient of heat transmission for this spot is further increased by the curved air stream. The air flowing between the upper cooling fins, which is usually not put to efficient use, comes into direct contact with the exhaust pipe and thus aids in the cooling of the cylinder head. Such a design facilitates the casting of the head in a steel mould.

A separate channel is used to direct a fresh air stream to points subjected to extreme heating in aircraft engine cylinder heads. The illustration of the BMW 801 engine (Fig. 228) shows an example of this. The vertical fins between the valves are interrupted by a fin in the plane of the valves. Air flowing from the front escapes upwards in front of the vertical fin through

sheet metal louvres. A special duct A leads air behind the baffle fin to the sparking plug and between exhaust and inlet valve ports. The illustration also shows the method of attaching the air ducting cowls.

As already stated, a smooth fin surface is desirable. Casting in steel moulds meets this demand by making it possible to produce smooth and thin fins. Fig. 229 shows the influence of the thickness of fins and the quality of their surface upon the amount of air passing between the fins at a given pressure. By reducing fin thickness and polishing their surfaces, the amount of air increased by about 27%.

Aluminium alloys are generally used for air-cooled cylinder manufacture. Cast iron is suitable only for engines working under low loads or for motor cycle engines with separately exposed cylinders of small displacement and a large area of fins. Even motor cycle engines are increasingly being fitted with light alloy heads. The type of finning most used today has a spacing of 6 to 5 mm, height of 40 mm and is 2 to 3 mm thick at the base and 1.2 to 1.5 mm at the top. Aircraft engine cylinders are cast with fins up to 80 mm high, 1.6 to 2 mm thick and up to 2.5 mm apart. The casting of such heads is very laborious and a large percentage of waste occurs. But not even such finning is sufficient for highly stressed aircraft engines and recourse has to be made to the use of forged aluminium heads with milled fins. An example of such a head with machined fins is given in Fig. 206.

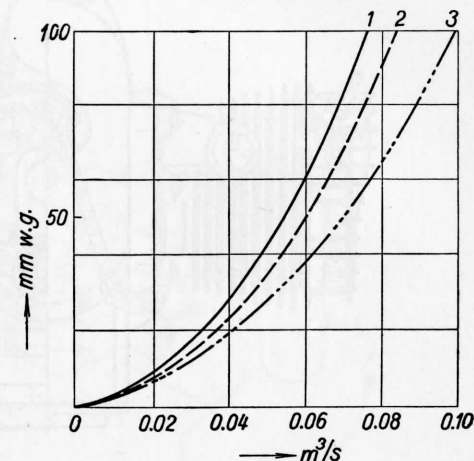


FIG. 229. Influence of surface quality and thickness of fins upon air flow at the static pressure head  $p_{st}$ .

1 — Rough heads, thick fins, 2 — rough heads, thin fins, 3 — rough heads, thin smooth fins.

#### 4. Valve gear arrangement

The simplest form of valve actuation is that used in side-valve designs with the valves disposed beside the cylinder. Such an arrangement is used on the Soviet M-72 motor cycle engine, for instance, a cross section of which is shown in Fig. 230. The valves are slightly inclined to the plane of the cylinder in order to place the camshaft out of the way of the crankshaft and also to obtain a more favourable combustion chamber shape and to facilitate the entry of air. The head of this engine is extremely simple, containing only a plug thread



insert. The valves must be set at a sufficient distance from the cylinder for good access of air to the whole periphery of the exhaust valve seat.

The simplest arrangement of overhead valves is in line with the longitudinal axis of the engine and with the camshaft housed in the crankcase.

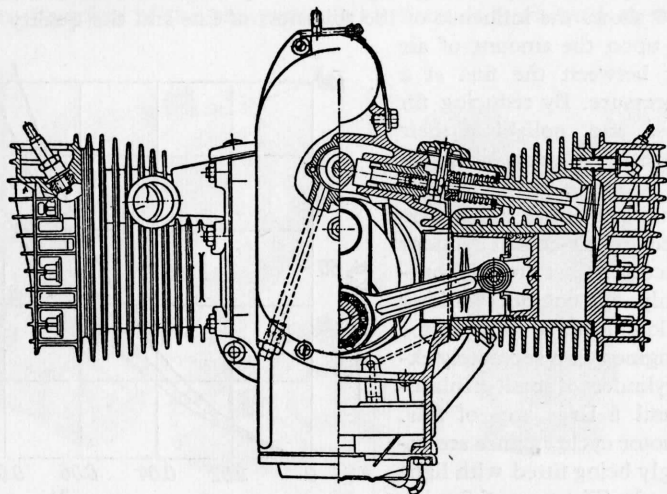


FIG. 230. Transverse section of the Soviet M-72 motor-cycle engine.

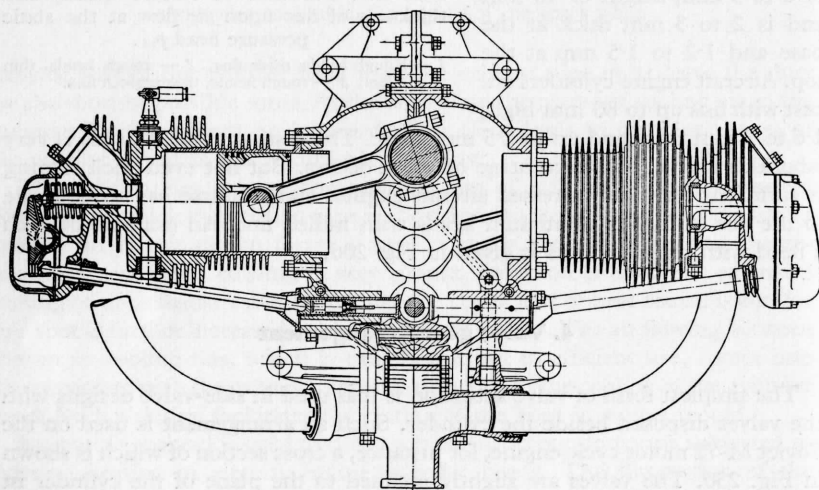


FIG. 231. Transverse section of the four-cylinder Continental aircraft engine, bore 98.4 mm, stroke 95.25 mm. Note the hydraulic tappets for the automatic maintenance of valve clearance.

Such a layout is shown in Fig. 231. Reliable sealing of push rod covers is important in view of the expansion or contraction of the cylinder barrel at varying loads. The seals used must therefore permit a certain amount of movement. The VW design makes use of spring bellows at the ends of the push rod cover tubes. In most designs however, synthetic rubber sealing rings, which permit a certain resiliency of the union and which stand up to high temperatures,

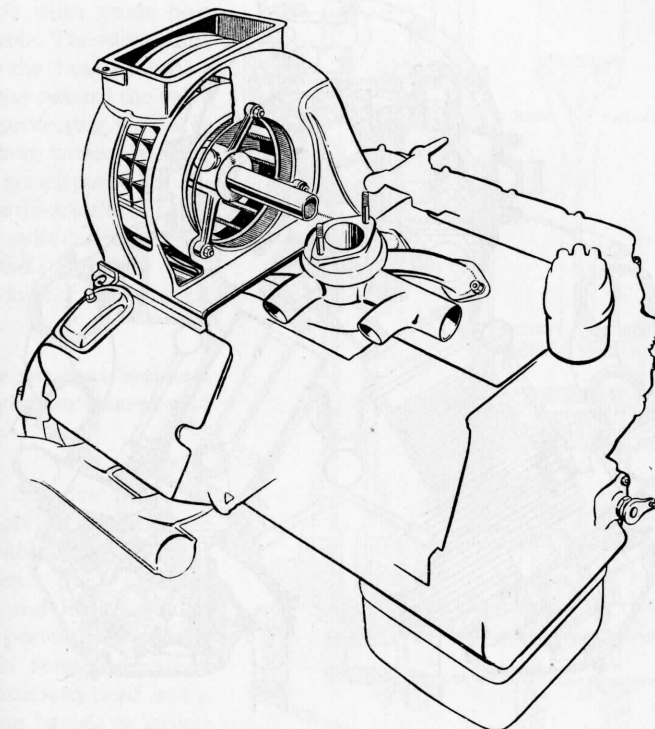


FIG. 232. Arrangement of the radial fan of the air-cooled Steyer engine.

are used. If the temperature of the head is too high for synthetic rubber, the push rod covers may be threaded or pressed into the cylinder head. (Fig. 232.)

Valves positioned in a plane perpendicular to the crankshaft axis require a more complex actuating mechanism. If the plane of the valves is not quite normal to the plane of the crankshaft, the arrangement used in the Tatraiplan engine (Fig. 103) or that of the Argus As 410 (Fig. 195) may be found convenient. The plug position of such a layout is inclined and outside the rocker box. With parallel valves, rockers of unequal arm lengths can be used on a common pivot shaft, such as in the head shown in Fig. 102.

With a hemispherical cylinder head with the plane of the valves at right angles to the crankshaft axis, it is convenient to place the camshaft as high as the design permits. The arrangement shown in Fig. 201 may then be used; it is especially suited for V engines and its weight is low.

With closely spaced cylinder barrels, the design of a cylinder head of such a type needs very diligent attention by the designer. Access to the sparking

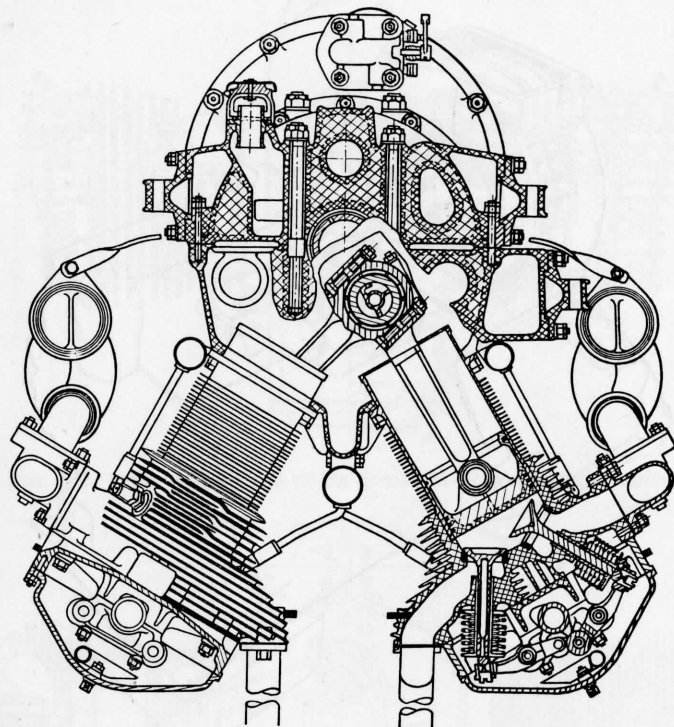


FIG. 233. Transverse section of the inverted Ranger aircraft engine.

plug can be arranged by using a tube threaded into the cylinder head and passing through the cylinder head cover. A separate oil return pipe is needed on the underside of the cylinder.

Overhead camshaft drive eliminates the variation of valve clearance owing to the expansion of heated cylinders. The Tatra 87 arrangement shown in Fig. 384 may be taken as an example of this. The overhead camshaft common for all cylinders of one bank is mounted in its own housing and the drive is transmitted from the crankshaft through a roller chain. The camshaft box mounting on the cylinder heads must be resilient enough to provide for variation in the lengths of individual cylinders which can be caused when one

cylinder misfires (thereby remaining cool) and which would otherwise cause deformation of the camshaft housing or even seizure of the camshaft bearings. The camshaft drive is shown in detail in Fig. 383.

Figs. 233, 234 show the camshaft drive of the Ranger inverted aero engine.

The camshaft case is common for a bank of cylinders. The finning of the exhaust valve guide boss is notable. The valve guide inside the boss extends a long way toward the valve head protecting the valve stem from flame. Sparking plugs are disposed laterally. The dismantling of separate cylinder heads in overhead camshaft engines is less convenient.

#### 5. The gas seal between the cylinder barrel and head

All cylinder heads of automobile engines are detachable but the joint between the cylinder barrel and head must be sealed perfectly. When the joint is formed between an aluminium head and a cast iron barrel, no gasket need be used. For the seal between a cast iron head and a cast iron barrel copper sheet or copperasbestos gasket material is used.

In order to provide a reliable gas seal, the pressure of the surfaces in contact must be sufficient and evenly distributed. Too high a joint pressure leads to permanent deformation and to damage to the seating, the area of which should amount to 20 to 25% of piston crown area in the case of petrol engines and 35 to 40% in the case of compression-ignition engines. Local temperature increases lead to loss of strength in the material and to seating damage.

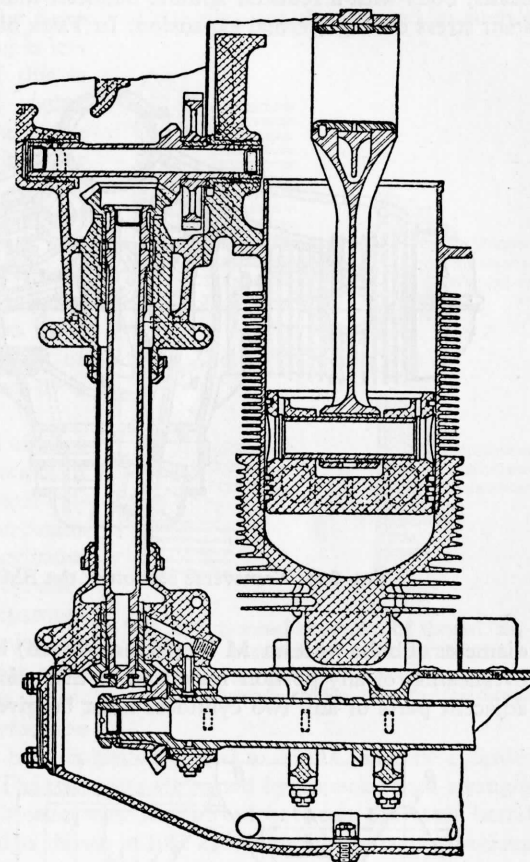


FIG. 234. Camshaft drive of the Ranger aircraft engine.

In order to ensure an even distribution of stress over the whole seating area, the spacing of the retaining bolts on the periphery of the cylinder barrel must be regular. Four bolts are usually sufficient for bores up to 110 to 120 mm. If the cylinders are held in place by bolts from crankcase to the heads, bolts with a reduced spindle diameter must be used to maintain constant stress during thermal expansion. In Tatra oil engines, for example, the

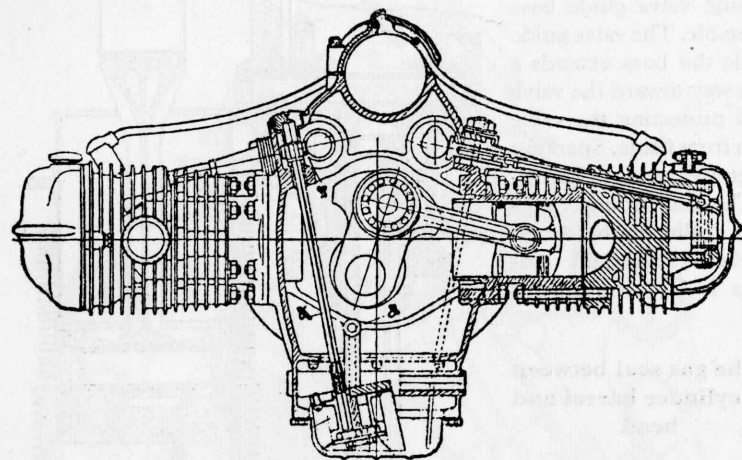


FIG. 235. Transverse section of the BMW R 51 engine.

diameter of bolts with an M 16 (16 mm thread) is reduced to 10 mm. Local overheating of any portion may lead to distortion and blow-by so that the adjacent parts of any two cylinders must be given due attention.

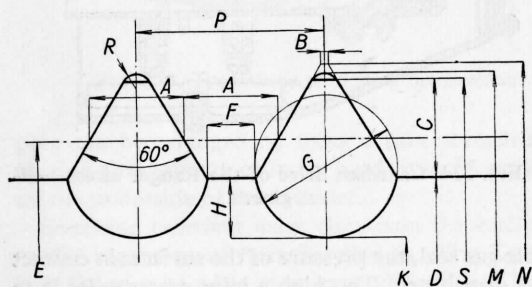


FIG. 236. Special bronze wire for connecting cylinders to heads.

$A = 0.5 P$ ,  $B = P/24$ ,  $R = 0.072 P$ ,  $C = 0.525 P$ ,  $D =$  basic diameter,  $E = D + 0.4 P$ ,  $G = 0.75 P$ ,  $H = 0.3 P$ ,  $S = D + 1.05 P$ ,  $M = D + 1.122 P$ , etc.

Attachment of the cylinder head to the upper cylinder flange by bolts or studs and the transmission of stress from the cylinder head to the crankcase through the cylinder walls carries some disadvantages. Not only is such an arrangement heavier, but upper cylinder cooling is also impaired. It is rarely possible to thread the studs into the cylinder flange and to pass them through

the cylinder head, for they would obstruct the inlet and exhaust ports and general design and moulding are unfavourably affected. With the nuts located under the upper cylinder flange, fins have to be cut away in the very place where they are most needed. The reduced cooling of the upper cylinder can cause gumming of piston rings. In order to prevent this, long bosses are sometimes formed below the flange and the nuts are then placed in such a location, where local cooling is less important. An example of this is given by the BMW R 51 engine (Fig. 235). The cylinder base flange must be of great thickness in order to prevent deformation.

If the cylinder walls of a barrel clamped between the head and crankcase are thin, uneven bolt loads may even cause piston deformation and piston seizure. The bolts must therefore be tightened evenly or their load must be checked by a torque wrench.

The head-to-cylinder seal of large aircraft engines proved a source of trouble and for this reason steel cylinders, screwed onto cylinder heads came into general use. The cylinder is screwed into the heated cylinder head and can never be separated from it again. The bolt holes are drilled into the cylinder flange after threading it into the head as otherwise they would not mate. Before the

cylinder is screwed on, the head is heated to 300 to 350 °C and the cylinder barrel may also be cooled. The two parts are joined by a special high-strength thread or a special coil of bronze wire is inserted between the steel barrel and aluminium head, shaped as shown in Fig. 236. This wire acts as a packing preventing the threads from working loose.

When the cylinder head is heated during running, its pressure on the upper cylinder is relieved and the upper part of the cylinder expands. This had been provided for in the manufacture of the cylinder, the bore of which is not cylindrical, but bevelled by 0.3 to 0.45 mm in its upper reaches. Such a cylinder cannot be rebored and must be replaced by a new one.

The cylinder is machined so as to ensure its true cylindrical shape at operating temperature. The reduction in diameter in the pressed-in part of the cylinder is still apparent some 50 mm below the base of the cylinder head. After heating the bore is exactly cylindrical. The thread in the head must be

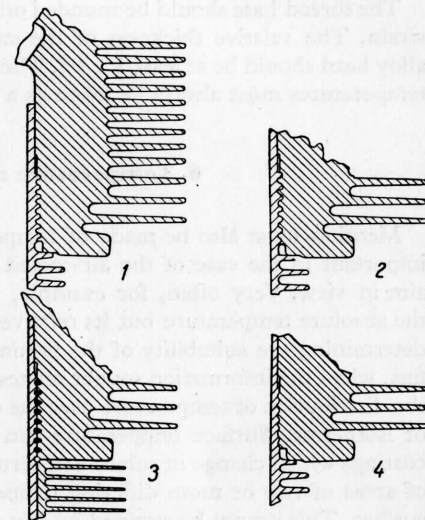


FIG. 237. Several examples of thread connection between cylinder and head.

1 — Thread with 60° angle, 2 — stub thread, 3 — special wire according to Fig. 236, 4 — fine thread.



formed in such a manner as to bed down perfectly with the head hot. Owing to the difference in the rate of expansion of aluminium and steel, the thread pitch at normal temperature must be smaller in the head than in the cylinder. If the thread pitch were the same on both parts, the thread would engage perfectly when hot only in its few upper turns, the middle turns being relieved and the lower turns bearing against the opposite side. Several illustrations of cylinder head to cylinder joints are shown in Fig. 237.

The thread base should be rounded off in order to prevent a concentration of strain. The relative thickness of the steel cylinder wall and the aluminium alloy head should be at least 1 : 4.5. The strength of both materials at working temperatures must always be taken as a basis.

## 6. Temperature measurements

Mention must also be made of temperature measuring which is specially important in the case of the air-cooled engine. Methods used differ with the aim in view. Very often, for example, the aim does not lie in determining the absolute temperature but its relative distribution. Such a case arises when determining the suitability of the finning layout and the utilization of single fins, when the information sought relates to the temperature of individual fins, the distribution of temperature over the cylinder head surface and the plotting of isotherms. Surface temperature can be measured readily by the use of coatings which change in colour at a certain temperature. Thus the boundaries of areas of two or more differing temperatures may be seen over the whole surface. This cannot be attained by any other accurate temperature measuring methods. The use of such means has its advantages for gaining information quickly. "Thermocolor" colours are most widely used and they show the variation of one single or several temperatures by a change in colour. The most used of these colours are given in Fig. 238.

The use of Thermocolor does not give precise results, the variation being  $\pm 5^{\circ}\text{C}$ . If the colour is exposed to temperature for a long time, it begins to change at lower temperatures. According to the change in colour shown in Fig. 238, the given temperatures are arrived at after 30 minutes heating. If heat is applied for 120 minutes, the change of colour will take place at a temperature some  $10^{\circ}\text{C}$  lower and with Thermocolor Nos. 6, 7 and 8 even at temperatures  $25^{\circ}$ ,  $30^{\circ}$  and  $50^{\circ}\text{C}$  lower.

Fig. 238 shows the distribution of temperatures over the surface of an aircraft engine cylinder as shown by Thermocolor. On the exhaust side of the cylinder head Thermocolor No. 7 was applied, on the inlet side Thermocolor No. 30 and on the cylinder barrel Thermocolor No. 4. While not being very exact this method provides a good survey of temperature distribution on the surface.

It will be realized that Thermocolor cannot be used for precision measuring in the same manner as e.g. thermocouples. Its great advantage lies in the

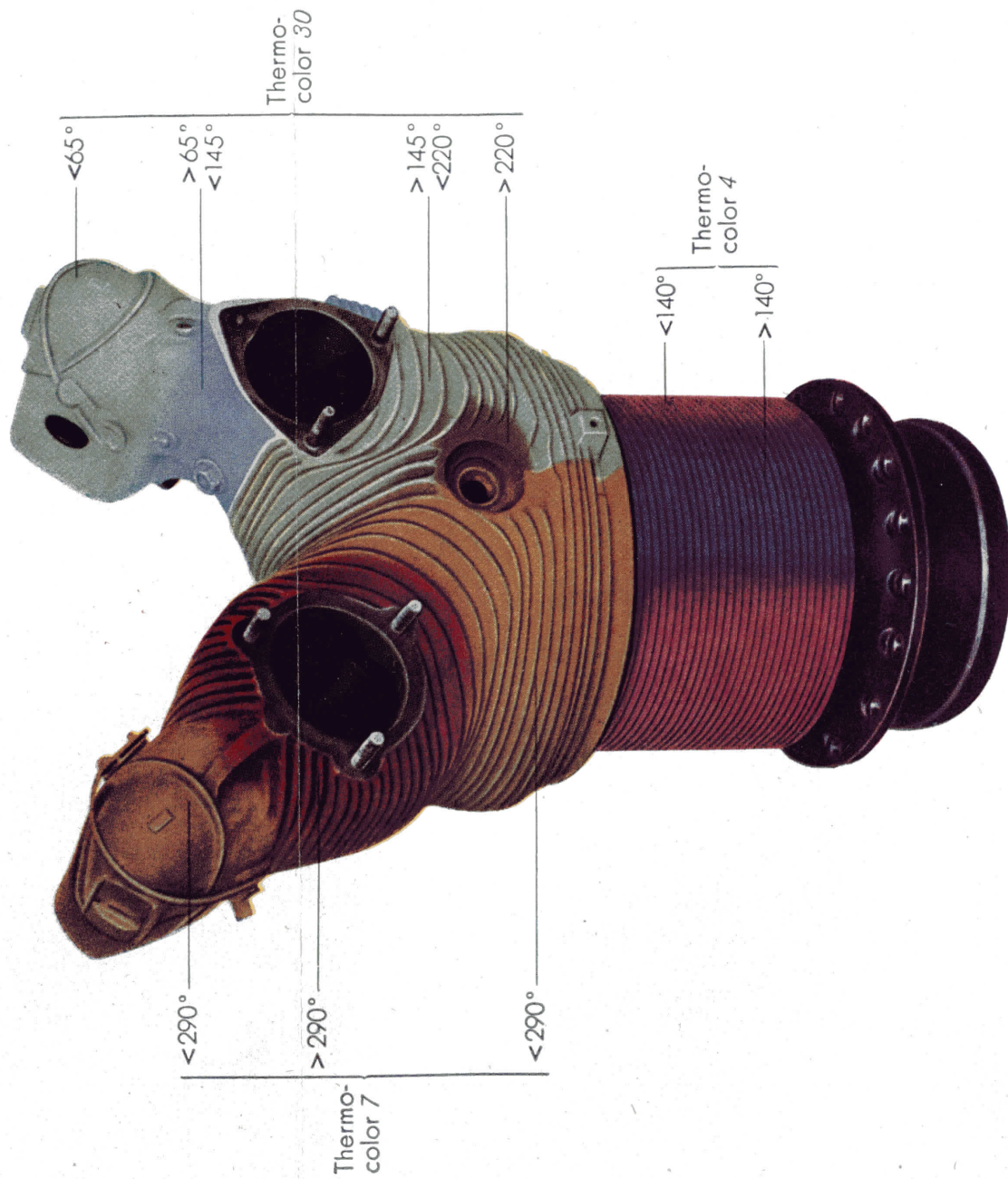
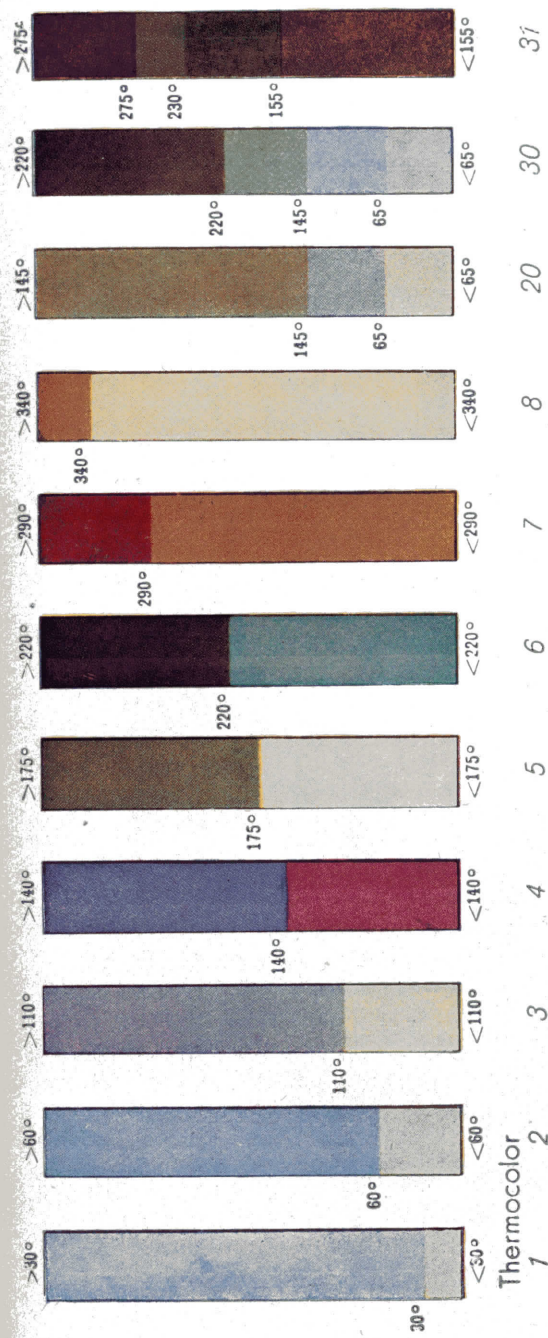


FIG. 238. Example of measuring cylinder temperatures by Thermocolor.

fact that it permits the observation of temperature distribution over a surface and the drawing up of isotherms. To do this a very large number of thermocouples would be required – a condition which cannot be met in practice, as for example, it is very difficult to fix the couples to the thin fins of an air-cooled engine, whereas paint can be spread over the thinnest of them without difficulty. For such reasons this method cannot be overlooked for it offers

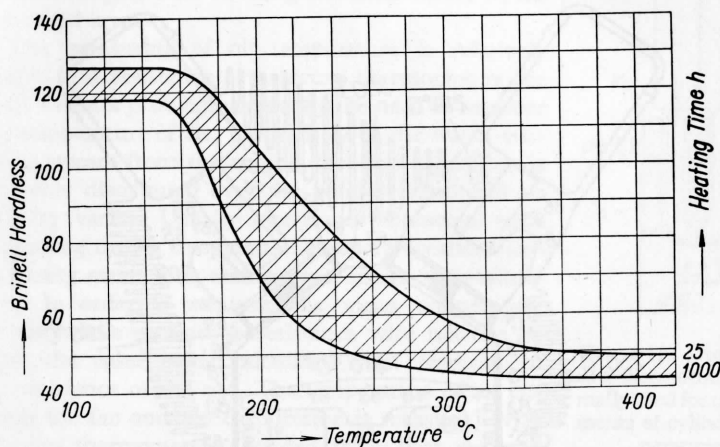


FIG. 239. Reduction of hardness of a typical aluminium alloy for cylinder heads in relation to time and temperature.

great advantages. The designer often needs to determine the degree of utilization of the fins and for this purpose the method is well suited.

Thermocolor paint is supplied in powder form containing also the binder and it is prepared for use by dissolving in alcohol. The paint dries quickly and is impervious to petrol and oil. The thermal insulation effect of a minute layer of the paint is negligible owing to its low coefficient of heat transfer to air. The approximate temperatures prevailing in the area to be painted must be measured before applying Thermocolor in order to select the right grade. Often several grades of paint have to be used. In the example shown in Fig. 238, three grades of paint were used to measure the temperatures of an air-cooled engine cylinder. Thermocolor Nos. 20, 30, 31 are used here to show several temperatures each. A record of the experiments may be made by black-and-white photography, but for greater clarity it is suggested that isotherms be marked on the surface by chalk lines.

In order to gain rough information on the temperatures prevalent inside aluminium cylinder heads and cylinders, use can be made of the property of heat-treated materials which causes a reduction of their hardness after a certain time depending on the temperature and the time during which the part is