CHAPTER V

THERMAL BALANCE OF THE ENGINE

1. Heat removed by cooling

From the heat released in the cylinder by the combustion of the air-fuel mixture approx. 25 to 30% is converted into mechanical work, 20 to 25% is carried off by cooling, and the balance of 45 to 50% is removed by exhaust gases. Most of the heat drawn off by cooling is transmitted through the walls of the cylinder and head, and only a minor portion is transferred through the piston to lubricating oil, from which it is either transferred directly to air or through the walls of the crankcase or oil-cooler.

The heat removed by cooling represents a loss, and cannot be converted into mechanical work. Further, in order to transfer this heat to air a portion of the effective performance of the engine is consumed. The heat carried off in exhaust gases also represents a loss, but by fitting adequate equipment at least a part of this thermal energy can be recovered and converted into mechanical work.

The purpose of cooling the cylinder is to secure a sliding surface for a piston moving at an average speed of 49 ft/s (15 m/s) and over. This surface is flushed by hot gases, whose maximum temperature at the outset of the expansion stroke reaches over 2000 °C. The conditions for the formation of a lubricating film on the cylinder walls are adverse, and the temperature of the walls must be maintained at a certain level. The maximum temperature on the interior surface of the cylinder wall should not exceed 180 °C for normal operation.

At elevated temperatures lubrication of the cylinder walls becomes irregular and the piston rings suffer from excessive wear.

The purpose of cooling is to carry off heat with the least possible loss in performance, while maintaining the required temperature of the cylinder walls.

The amount of heat transferred from a petrol engine by cooling can be calculated approximately from the following formula:

$$Q_p = 0{\cdot}0949 \,.\, z \,.\, D^{1{\cdot}73} \,.\, L^{0{\cdot}575} \,.\, n^{0{\cdot}71} \,.$$

$$\left[1 + 1{\cdot}5\frac{L}{D}\right](\varepsilon - 1)^{-0{\cdot}286}\,(\text{kcal/h}) \qquad (17)$$

For crude oil engines the formula has been modified as follows:

$$Q_0 = 0{\cdot}0637 \,.\, z\, D^{1{\cdot}73} \,.\, L^{0{\cdot}575} \,.\, n^{0{\cdot}71} \left[1 + 1{\cdot}5 \frac{L}{D}\right] \text{(kcal/h)} \qquad (18)$$

where z denotes the number of cylinders,
D „ „ bore of cylinder in cm
L „ „ stroke of piston in cm
n „ „ rev/min
ε „ „ compression ratio.

From air-cooled engines with a high mean temperature of cylinder walls less heat will be removed through cooling than from water cooled engines. For aircraft petrol engines it is reckoned that cooling will draw off some 0·5 to 0·6 of the amount of heat converted into useful work. For motor vehicle engines the amount is estimated to be 0·6 to 0·7. The heat transferred by way of cooling will therefore amount to

$$Q = 0{\cdot}6 \times \text{(b.h.p.)} \times 632 \text{ (kcal/h)}$$

since 1 h.p. = 632·43 kcal.

Table 7 gives the thermal balance of the mark R-2800 Pratt and Whitney

Table 7

Thermal Balance of the Pratt & Whitney Aircraft Engine

Experimental Single-Cylinder of the Type R-2800

	Operating Performance	Starting Performance
Fuel: Air ratio	0.06	0.11
Mean effective pressure, kg/cm²	8.75	14.0
Engine speed, rev/min	1,800	2,700
Useful work, %	100	240
Burnt fuel, %	98	46
Unburnt fuel (internal cooling), %	2	54
Thermal efficiency, %	28	16
Distribution of heat produced by burnt fuel, % :		
Useful work	29	35
Cooling air	18	12
Exhaust gases	44	45
Oil, radiation, etc.	9	8
Total	100	100
Output consumed by air-cooling system in % of useful work	63	35

aircraft engine, bore 146·1 mm, stroke 152·4 mm [50]. This illustrates the influence of a rich starting mixture on the cooling of the engine. During the starting period no more than 46% of fuel is burnt in the cylinder, the balance is used for cooling. It is thus possible to keep, even at an increased performance, the temperature of the cylinders within satisfactory limits. Owing to such substantial *cooling through fuel* the quantity of heat removed by cooling to air does not undergo any substantial changes. Upon increasing the performance from 100% to 240% the amount of heat removed by cooling increases from 63 to 84 thermal units (Fig. 48).

For internal cooling during starting water may be injected into the induction manifold. Short of using rich mixtures or other type of internal cooling it would not be possible to cool the large cylinders of modern aircraft engines at their very high mean effective pressures.

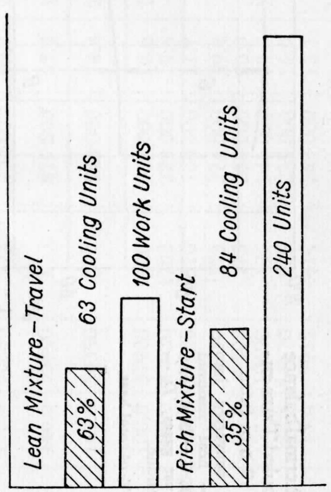

FIG. 48. The thermal balance of an aircraft engine operated with rich and lean mixture respectively.

During travel, out of 100 heat units representing the total input 63 units are used for cooling through fuel. The corresponding total input during starting amounts to 240 units out of which 84 are used for cooling through fuel.

The thermal balance of an air-cooled diesel engine with 110 mm bore and 130 mm stroke is shown in Fig. 49. This diagram makes it apparent how the amount of heat removed through cooling varies with the engine speed.

In a water-cooled engine the removal of heat from the cylinder is more intensive, for the water maintains the walls of the cylinder at a temperature of 80 to 90 °C. In view of a greater temperature difference the heat losses will be greater. The relationship between the distribution of heat in a water-cooled diesel engine with 110 mm bore and 140 mm stroke at 1600 rev/min, and the mean effective pressure p_e, is illustrated in Fig. 50 [46].

2. Thermal stress on the interior surface of a cylinder

Thermal stress on the interior surface of a cylinder differs according to whether the latter is exposed to hot gases constantly, or whether it is periodically sheltered by the piston. Measurements have established thermal stresses of the surface of the combustion chamber amounting to about 400,000 kcal/m²h. The walls of the cylinder and the surface of the exhaust ducts are under thermal stresses of 125,000 kcal/m²h. Average thermal stress of the interior surface of the cylinder for various types of engine is indicated in Table 8. The calculation is based on the assumption that 0·6 Q (b.h.p.) is carried off

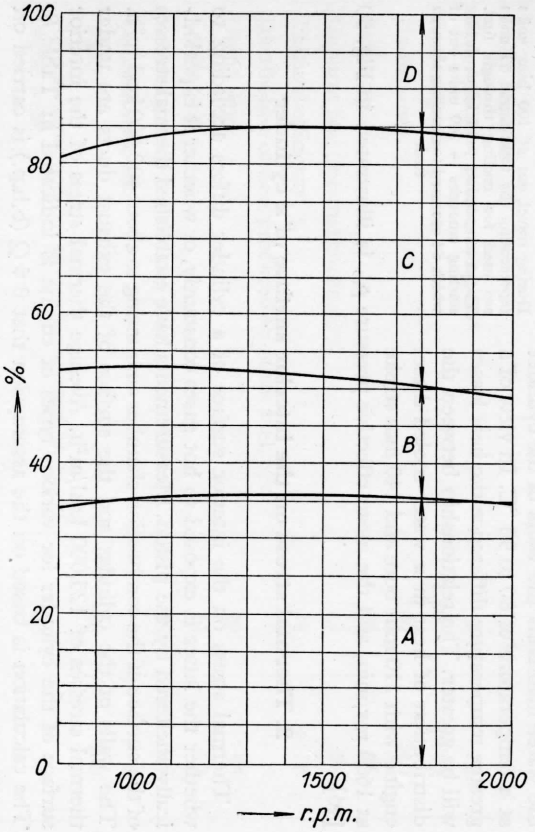

Fig. 49. Thermal balance of an air-cooled Tatra engine of 110 mm bore.
A — heat converted into work, *B* — heat removed by cooling air, *C* — heat taken off by exhaust gases, *D* — residue.
Shown in % of total heat.

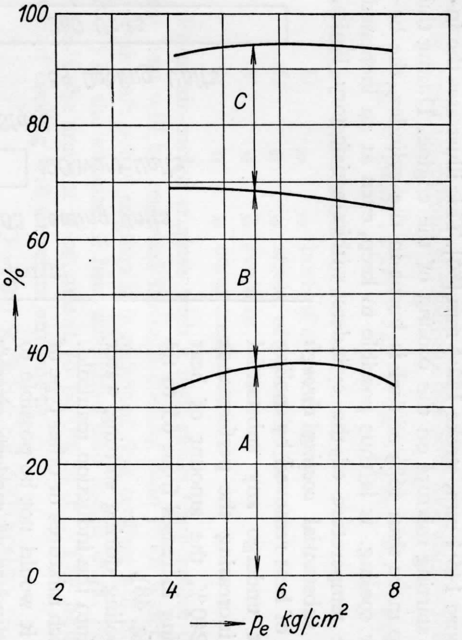

Fig. 50. Thermal balance of an air-cooled compression-ignition engine of 110 mm bore at 1,600 rev/min.
A — useful performance, *B* — loss by cooling, *C* — loss through exhaust gases.
Shown in % of total heat.

Characteristic Data of Internal-Combustion Engines

Table 8

	Mark	Bore, mm	Stroke, mm	Volume of 1 cyl.	Perform., b. h. p.	Speed, rev/min	No. of cylinders	Perf. of 1 cyl.	Heat for cooling, kcal/h	Surface area $2\frac{\pi D^2}{4}+\frac{L}{2\pi}\cdot D$, cm²	Thermal stress in cylinder wall $U\left[\frac{kcal}{m^2\,h}\right]$	Specific output (bhp/l)	Mean eff. pressure, kg/cm²	Type of cooling
aircraft	Continental E 185 - 5	101.6	127	1.03	185	2300	6	30.8	11650	365	320 000	30.0	11.7	air
	Franklin 6AB-225-B7	127	114.3	1.45	225	2600	6	37,5	14230	481	296 000	25.8	8.95	air
	Pratt & Whitney Wasp-Major	146.1	152.4	2.56	3250	2700	28	116.0	44000	685	642 000	45.4	15.1	air
	Ranger SGV-77OD-4	101.6	130.2	1.05	575	3400	12	48.0	18190	370	491 000	45.8	12.1	air
	Wright Cyclone 836 C 18 CA 1	155.6	160.3	3.05	2700	2900	18	150.0	56880	772	738 000	49.2	15.25	air
	Rolls - Royce Merlin	137.0	152.4	2.25	1760	3000	12	146.5	55600	633	879 000	65.2	19.5	water
	Rolls - Royce Eagle	137.0	130.0	1.92	3440	3500	24	143.5	54350	575	948 000	74.8	21.4	water
railway	Maybach MD 650, oil.	185.0	200.0	5.38	1200	1600	12	100.0	37920	1120	339 000	18.6	10.6	water
	GM, 2 stroke	222.0	267.0	6.45	1600	750	16	100.0	37920	1703	223 000	9.6	5.77	water
	Fairbanks 2 str.	206.0	2×254	5.15	2000	810	2×10	100.0	37920	2310	164 000	11.7	6.35	water
car	Tatra T603	75.0	72.0	0.32	100	4800	8	12·5	4750	173	274 000	39.4	7.4	air
	Tatra T602S	75.0	72.0	0.32	200	7500	8	25.0	9500	173	548 000	80.0	9.6	air
	Ferrari 12V	80.0	74.5	0.38	330	6200	12	27.5	10400	191	546 000	73.5	10.7	water
	Simmering, oil	135.0	160.0	2.30	620	2000	16	38.8	14670	625	235 000	16.9	7.6	air
	Tatra 108, oil	110.0	130.0	1.23	125	2000	8	15.6	5915	414	143 000	12.7	5.7	air

through cooling, and the area of the interior surface corresponds to the mid-stroke position of the piston. Thus

$$A = 2\frac{\pi D^2}{4} + \pi . D\frac{L}{2}$$

From the table it is apparent that the thermal stress of the cylinder wall is a function of the mean effective pressure and of engine speed. For small engines greater values of thermal stress can be allowed. The amount of heat transferred through the interior surface of the cylinder must be transferred to the cooling air. If the heat removed through cooling were not to offset the heat introduced into the cylinder by hot gases, the temperature of the cylinder would continue to increase to the point at which the engine would become overheated.

In a properly designed engine the least possible quantity of heat should be carried off by cooling. Hence, it is possible to evaluate the standard of an engine by the number of calories to be removed per b.h.p. If, at a given performance the interior surface of the cylinder is extensive, as is the case with low speed engines, the heat losses are considerable. Conversely, if high performances are attained from small dimensioned cylinders, as is the case with supercharged engines, the heat losses are low. In the latter instance the thermal stress per unit of the interior surface of the cylinder is, however, great.

3. Distribution of heat between head and cylinder

Factors on which depend the amounts of heat introduced into a head and cylinder were discussed in a preceding section. The distribution of heat depends on the design, chiefly on the shape, of the combustion chamber. The surface of the combustion chamber in the cylinder head is always smaller than the surface of the cylinder and piston combined. Even if we take into account only half the surface of the cylinder, seeing that most of the time a varying portion of this surface is cut off by the piston, this surface, including the surface of the piston crown is still greater than the surface of the combustion chamber. On the other hand substantial amounts of heat reach the cylinder head from the surface of the exhaust duct. This is the basic reason that more heat is transferred to the cylinder head than to the cylinder itself.

If the combustion chamber of a petrol engine is of hemispherical design, the surface area of the combustion chamber is small, and only small amounts of heat are transferred to the head. Wedge-shaped and other type combustion chambers have larger surfaces and are exposed to very heavy thermal loads.

If the heat transfer from the walls of the exhaust duct to the head is to be small, the duct must be short, straight and of small diameter. Sometimes the transfer of heat to the head is reduced through inserting a steel tube into the exhaust duct, a small, thermally insulating air-gap being left between the tube and the wall of the cylinder head. At elevated temperatures this un-

cooled portion of the exhaust tubing may be burnt down. Fire-proof material must therefore be used for high-performance engines.

If the cylinder has been screwed into the head, as it is the case with aircraft engines, a portion of the heat from the upper section of the cylinder is transferred to the head. As this effects the portion of the cylinder on which the piston rings rest, the upper dead centre is the area of greatest heat.

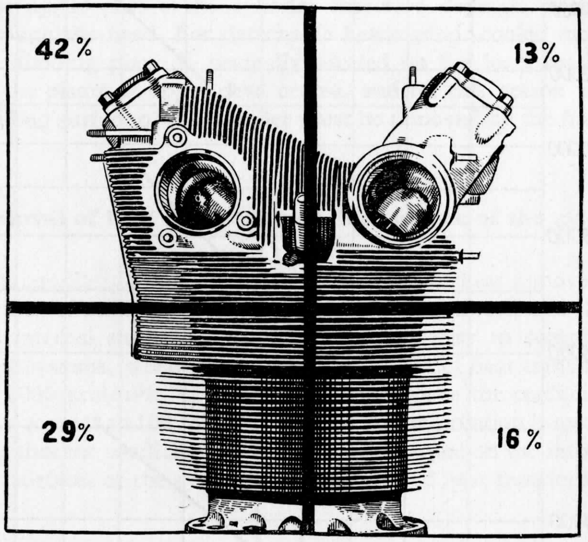

FIG. 51. Distribution of heat shown on a cylinder of a Pratt and Whitney aircraft engine. Note the high percentage of heat removed from the zone of the exhaust valve.

In the course of a test on a cylinder of a Mark R-2800 Pratt Whitney engine the exhaust charge was conveyed from the cylinder through four ducts, and in each of the ducts separate measurements were taken of the amount of the charge and its temperature. It has thus been possible to establish the exact amount of heat removed by cooling. An interesting fact was found: most of the heat was transferred from the quarter of the cylinder housing the exhaust valve. The division of the heat, expressed in percentages of the total, is illustrated in Fig. 51. As 42 % of the total heat is drawn from the area of the exhaust valve, great attention must be devoted to the design of this part of the head.

In a compression-ignition engine with direct fuel injection, where the combustion chamber is formed by the piston crown, the division of the heat between head and cylinder may undergo radical changes. The flat area of the cylinder head will absorb only minimum amounts of heat, and the heat from the piston will be primarily transferred to the cylinder walls. In extreme instances greater amounts of heat may have to be removed from the cylinder than from the head. In engines with a combustion chamber inside the cylinder head, the head of the cylinder is exposed to heavier thermal stresses.

The amount of heat removed through cooling is almost directly proportional to the i.h.p. of the engine. Fig. 52 shows the amount of heat removed by

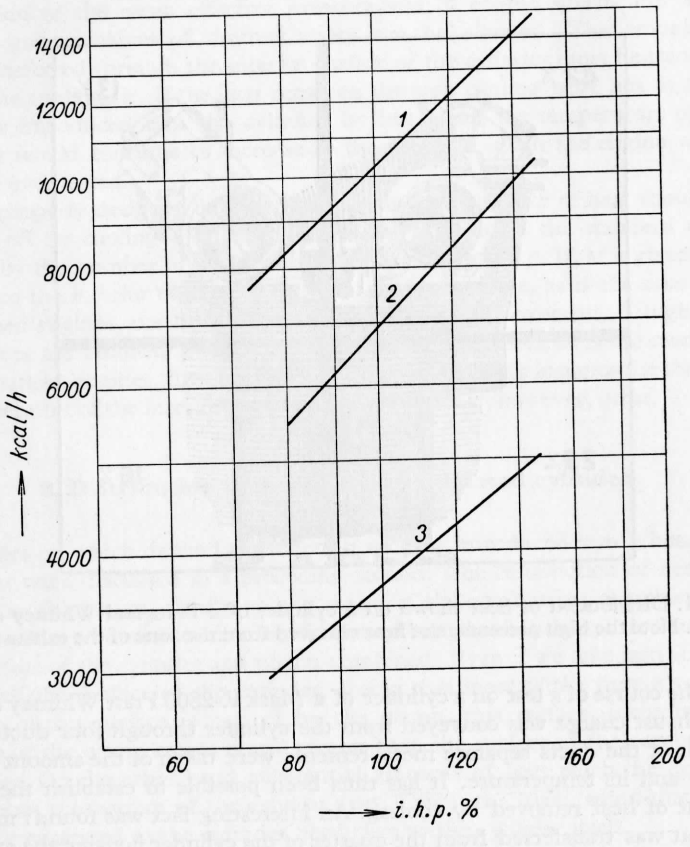

FIG. 52. Distribution of heat in the cylinder and head of an in-line Ranger aircraft engine in dependence on the indicated performance i.h.p. The temperature of the aluminium cylinder was maintained at 145 °C, cylinder head temperature varied between 216—275 °C. Air-fuel ratio and temperature of intake mixture was constant.

1 — total heat, slope 0.95; *2* — cylinder head, slope 1.04; *3* — cylinder, slope 0.8.

cooling from a Ranger series aircraft engine [44]. From this diagram it can be seen that with the thermal load increasing the amount of heat carried off the cylinder increases slowly, but more rapidly from the head.

Total heat transferred is a function of . . . . $(\text{i.h.p.})^{0.95}$

Heat transferred from cylinder head is a function of . . . . . . $(\text{i.h.p.})^{1.04}$

Heat transferred from cylinder is a function of . . . . $(\text{i.h.p.})^{0.8}$

In the case of this particular engine, most of the heat was removed from the cylinder head. It is however to be taken into consideration that for aircraft engines steel cylinders screwed into the cylinder head are frequently used. The hottest upper part of the cylinder therefore depends on the transfer of heat through the head. For detachable heads of air-cooled motor-vehicle engines the dividing plane is normally located on the level reached by the top ring of the piston at upper dead centre, and for this reason all the heat from the sliding surface of the cylinder must be removed by the finning of the cylinder.

4. Removal of heat from the exterior surface of the cylinder

If thermal equilibrium is to be reached, amounts of heat removed from the exterior surface of the cylinder must equal those introduced into the cylinder through its internal surface. This requirement is easy to comply with for water-cooled systems, where the average coefficient of heat transfer amounts to 5000 to 6000 kcal/m²h °C. For air-cooling, where the coefficient of heat transfer is no more than 100 to 200 kcal/m²h °C, the situation is more difficult.

Assuming that the coefficient of heat transfer is equal on the interior and on the exterior surfaces of the cylinder, the amounts of heat transferred through

Table 9

Internal to External Surface Area Ratio in Air-Cooled Aircraft Engines

Mark	Bore mm	Stroke mm	ε	Surface area, m²		Area ratio
				intern.	extern.	
Wright	155.6	174.6	6.7	0.157	2.39	15.4
Wright	155.6	160.3	6.9	0.149	2.29	15.4
Franklin	117.5	101.6	7.0	0.054	0.695	12.9
Franklin	117.5	101.6	7.0	0.054	0.856	16.0
Franklin	117.5	101.6	7.0	0.054	0.910	16.9
Franklin	108.0	108.0	7.0	0.044	0.573	13.1
Franklin	108.0	108.0	7.0	0.044	0.710	16.2
Jupiter 1939	146.1	190.5	5.3	0.123	0.807	6.6
Napier 1939	88.9	88.9	6.0	0.033	0.293	8.9

these surfaces would depend on the temperature difference between gas and wall, and on the area of the surface. The temperature difference inside the cylinder, assuming an average temperature of the interior surface of the wall of the cylinder of 180 °C and an average temperature of gases at the expansion stroke of 1500 °C, would amount to some 1320 °C. On the exterior surface of the cylinder wall however, assuming a temperature of air equal to 50 °C and that of the hot cylinder equalling 200 °C, the temperature difference would amount to only 150 °C. If equilibrium of heat transferred to and from the cylinder is to be attained also in the latter instance, the area of the exterior surface would have to amount to nine times the area of the interior surface, in order to offset the 9 : 1 ratio between the two temperature differences.

Table 9 gives a comparison of the areas of interior and exterior surfaces of the cylinders of certain aircraft engines. The division of the cooling surface to cylinder heads of different types of engines is given in Table 10.

Table 10

Distribution of Cooling Surface Area in Aircraft Engines

	Bore mm	Stroke mm	Area of Head m^2		Cylinder Area m^2		Total Area m^2	Ratio Head to Cyl.	Ratio Area to Volume cm^2/cm^3	Ratio Area to Output cm^2/bhp
			total	fins	total	fins				
1	117.5	101.6	0.433	0.376	0.260	0.222	0.693	1.66	6.3	280
2	117.5	101.6	0.605	0.543	0.260	0.222	0.865	2.31	7.85	283
3	108.0	88.9	0.367	0.334	0.207	0.174	0.574	1.77	7.05	355
4	108.0	88.9	0.708	0.635	cylinder and head made of one piece		0.708	—	8.55	316
5	117.5	101.6	0.901	0.815			0.901	—	8.25	257
6	155.6	174.6	—	1.550	0.845	0.845	2.390	1.82	7.20	180
7	155.6	160.3	—	—	0.755	0.755	2.290	2.05	7.50	190