CHAPTER IV

HEAT TRANSFER THROUGH CYLINDER WALLS

Heat transferred from the combustion products to the cylinder walls is conveyed to the exterior cylinder surface, and then either directly to air or to the cooling liquid. The temperature difference in the cylinder wall depends on the thermal conductivity of the material of which the cylinder or the cylinder head is made.

The propagation of heat in the wall of the cylinder does not take place only in the radial, but also in the axial and tangential, directions. The direction of the heat flow depends on the thickness of the cylinder wall, on the thermal conductivity of the material of the cylinder wall, and on the degree of unevenness of distribution of heat in the cylinder. In a large aluminium cylinder head this tangential propagation may be rather considerable and welcome, since it relieves the thermally overloaded regions. In principle, heat flows from the hottest to the coolest point.

Thermal conductivity is expressed by the coefficient determining heat transmission in a substance as follows:

$$\lambda = \frac{Q}{A \frac{\Delta t}{l}} \text{ (kcal/m h°C)}$$

Hence, thermal conductivity indicates the amount of heat which is transmitted in a unit of time through a unit of area at a temperature difference of 1 °C per unit of wall thickness of 1 m. Thermal conductivity and other physical properties of some substances are given in Table 6.

The amount of heat transferred through a simple wall will equal

$$Q = \frac{\lambda}{\delta} \cdot \Delta t \cdot A \text{ (kcal/h)} \tag{13}$$

where A denotes the area of the flat wall (m²);
δ „ „ wall thickness (m)
$t_1 - t_2 = \Delta t$ — temperature difference in the wall (°C)
t_1, t_2 temperatures of exterior surfaces (°C)

Table 6

Thermal Properties of Some Substances

	t [°C]	γ $\left[\frac{kg}{m^3}\right]$	λ $\left[\frac{kcal}{m\ h\ °C}\right]$	C_p $\left[\frac{kcal}{kg\ °C}\right]$	$a \cdot 10^4$ $\left[\frac{m^2}{h}\right]$
Air	20	1.20	0.0219	0.240	758
Air	100	0.94	0.0267	0.241	1210
Water	80	972	0.575	1.003	5.91
Glycol	80	1070	0.225	0.663	3.32
Glycol	130	1028	0.228	0.710	3.12
Methanol	60	774	0.160	0.645	3.20
Motor oil	80	876	0.120	0.499	2.81
Petrol	50	900	0.095	0.44	2.4
Aluminium		2670	175.0	0.22	3280
Bronze	20	8000	55.0	0.091	750
Copper		8800	330.0	0.091	4120
Silver		10500	394.0	0.056	6700
Steel	20	7900	39.0	0.11	450
Cast iron	20	7220	54.0	0.12	625
Boiler scale	60	—	0.5—1.0	—	—
Coke, pulver.	100	449	0.164	0.29	1.26
Carbon black	40	190	0.027	—	—
Rubber		1200	0.14	0.33	3.53
Mica		290	0.5	0.21	820
Glass	20	2500	0.64	0.16	16

For a cylindrical wall the relationship [42] holds true:

$$Q = \frac{2\pi \cdot \lambda \cdot l}{\ln \frac{r_2}{r_1}} \Delta t \text{ (kcal/h)}$$

where l denotes the length of the cylinder,
r_1 „ „ inner radius,
r_2 „ „ outer radius.

Calculations based on this formula are not easy, for the formula contains a logarithmic value; a simplified formula may, therefore, be used:

$$Q = \frac{\lambda}{\delta} \frac{\pi \cdot d_m \cdot l}{\varphi} \Delta t \text{ (kcal/h)} \tag{14}$$

where $d_m = r_1 + r_2 = 2\,r_1 + \delta$
φ = coefficient of shape.

For thin walls of engine cylinders φ can be assumed as being equal to 1, and the heat transfer can be calculated similarly to areas of flat walls.

For a known Q the temperature difference in the wall will equal

$$\Delta t = \frac{Q \cdot \delta}{\lambda \cdot A} \ (^\circ\mathrm{C}) \tag{15}$$

In order to calculate a temperature difference, the thermal load of the wall Q/A must be known. For an approximative calculation it may be assumed that all the heat will be transferred through the surfaces of the cylinder head, piston crown and cylinder wall, when the piston is situated in the mid-stroke position. Leaving the height of the compression chamber out of account, the area of the surface is:

$$A = \frac{2\pi D^2}{4} + \pi D \frac{L}{2} \ (\mathrm{cm}^2)$$

If we assume, for example, a petrol engine with a 75 mm bore and 72 mm stroke, with a performance of 12·5 b.h.p. at 4800 rev/min, from which the cooling will transfer 60% of the heat converted into work, this heat will equal:

$$Q = 12{\cdot}5 \times 632 \times 0{\cdot}6 = 4575 \ (\mathrm{kcal})$$

and the area will amount to

$$A = \frac{2 \cdot \pi \cdot 7{\cdot}5^2}{4} + \pi \cdot 7{\cdot}5 \frac{7{\cdot}2}{2} = 173{\cdot}8 \ (\mathrm{cm}^2)$$

The thermal load of the cylinder wall will equal:

$$Q_1 = \frac{Q}{A} = \frac{4575}{0{\cdot}01738} = 263{,}000 \ (\mathrm{kcal/m^2\ h})$$

The temperature difference in the wall of a 5 mm thick cast-iron cylinder will be:

$$\Delta t_c = \frac{Q_1 \delta}{\lambda} = \frac{263{,}000 \times 0{\cdot}005}{54} = 24{\cdot}4 \ (^\circ\mathrm{C})$$

Similarly the temperature difference in the wall of a 15 mm thick aluminium cylinder will be:

$$\Delta t_a = \frac{263{,}000 \times 0{\cdot}015}{175} = 22{\cdot}6 \ (^\circ\mathrm{C})$$

Hence, the temperature difference indicates the magnitude of the heat flow. Knowing the temperature difference, we can, for a known material, calculate the flow of the heat along the temperature gradient. If isotherms were traced on the surface of the piston crown, the direction of maximum heat-flow could be established, and this would be the zone of the densest isotherms. The amount of heat can be established from the temperature difference and thermal conductivity of the respective materials. A similar conclusion could be reached from the course of the isotherms in the cross-section through the cylinder head. From the differences in the temperatures at various points of the surface of the cylinder head we can estimate the magnitude of the tangential heat flow under certain conditions (e.g., even thermal load of the internal surface of the cylinder, etc.).

The conditions governing the heat transfer through cylinder walls are, however, more involved [4].

From Fig. 46 it may be noted that heat must first pass through a film of carbon or oil on the inner surface of the cylinder wall, and be conveyed thereafter through the cylinder wall, and eventually, on the exterior side of a water-cooled engine, it must be transferred through a layer of scale or through a layer of outer varnish in the case of an air-cooled engine, before it is transferred to the coolant.

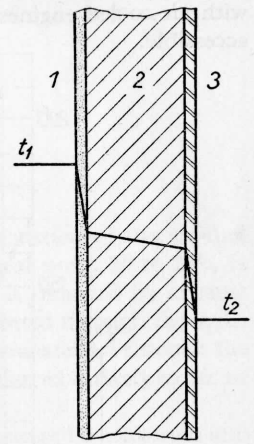

FIG. 46. Heat flow through cylinder wall.
1 — oil film, *2* — metal wall, *3* — outside layer of scale or varnish.

For this reason the transfer of heat is slowed down by the wall and the resulting coefficient of transfer q_x can be calculated from the equation:

$$q_x = \frac{1}{\dfrac{1}{q_g} + \dfrac{\delta_1}{\lambda_1} + \dfrac{\delta_2}{\lambda_2} + \dfrac{\delta_3}{\lambda_3} + \dfrac{1}{q_a}} \ (\mathrm{kcal/m^2\ h\ ^\circ C}) \tag{16}$$

The symbols employed in this formula signify:

q_g — coefficient of heat transfer from gases to wall,
δ_1 — thickness of film of carbon or oil,
λ_1 — coefficient of thermal conductivity of carbon or oil,
δ_2 — thickness of cylinder wall,
λ_2 — coefficient of thermal conductivity of the material of the cylinder wall,
δ_3 — thickness of layer of scale (varnish),
λ_3 — coefficient of thermal conductivity of scale (coating),
q_a — coefficient of heat transfer from wall to water or air.

From this equation the resultant coefficient of heat transfer through the cylinder wall q_x can be calculated, or according to equation (15) from a known external temperature (temperature of water in the cylinder block) and a known temperature difference the temperature of the inner surface of the cylinder wall can be calculated.

It is evident that the thicker the layers of carbon and of scale the higher will be the temperature on the inner surface of the cylinder wall. As carbon, oil and scale are poor heat conductors, the temperature of the inner surface of the wall will rise rapidly till it reaches a point at which it causes pre-combustion. It will then be necessary to dismantle the engine and remove the carbon layer. Greater difficulty is involved in cleaning the exterior surface of a water-cooled cylinder which, as a rule, is inaccessible. For this reason it is essential to fill the radiator with clean, if possible soft water, so as to reduce the deposits of scale to a minimum. This difficulty does not arise with air-cooled engines, where the exterior surface of the cylinder is readily accessible.

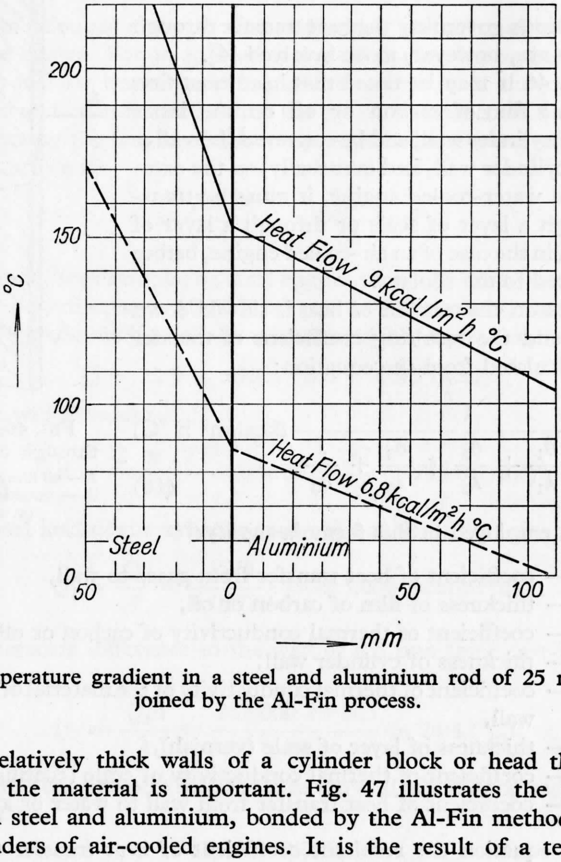

FIG. 47. Temperature gradient in a steel and aluminium rod of 25 mm diameter joined by the Al-Fin process.

For the relatively thick walls of a cylinder block or head thermal conductivity of the material is important. Fig. 47 illustrates the temperature difference in steel and aluminium, bonded by the Al-Fin method, employed for the cylinders of air-cooled engines. It is the result of a test to which a steel and aluminium bar, 25 mm in dia., had been subjected.

During testing one end (steel) of the rod was electrically heated, while the other (aluminium) was immersed into water or, at a lower temperature gradient, into ice. The thermal load of the rod section was about the same as that of the cylinder wall.

The temperature difference in a 20 mm thick aluminium wall is about 9 °C, whereas in a steel wall of equal thickness it reaches 64 °C. The temperature difference in an aluminium cylinder with a 2·5 mm thick wall and a cast-in steel sleeve with a 2 mm thick wall is no more than 5·7 °C.