CHAPTER XV

THE COOLING FAN

1. The types of fan employed

Fans can be classified into the two basic types of radial (centrifugal) and axial (propeller) fans.

In radial fans, air flows through the wheel in a plane perpendicular to the fan axis in a radial and centrifugal direction, for which reason these fans are also referred to as centrifugal fans. The blades may be curved forwardly or backwardly. A higher efficiency is attained by blades curved backwardly. With blades curved forwardly the outlet velocity of air is higher and its kinetic energy can only be converted into a static pressure head with low efficiency.

The dimensions of a fan with the blades curved forwardly are smaller than those of a fan with blades curved backwardly for equal speed and pressure head. For this reason automobile cooling fans usually use the former. The outlet velocity pressure can be converted into static pressure with low efficiency, particularly if space limitation does not permit the provision of a suitably shaped spiral casing. The efficiency of radial blowers is therefore generally low. In order to prevent air turbulence the outlet velocity should be specified higher than the inlet velocity which is attained by a gradual reduction of the blade width toward the wheel periphery. Basic types of radial fans are shown in Fig. 302.

The use of a radial fan is indicated by low speed, a small volume of air to be delivered and high pressure head.

One advantage of the radial fan is the possibility of using a direct drive from the crankshaft, the obtained pressure head being sufficient for cooling

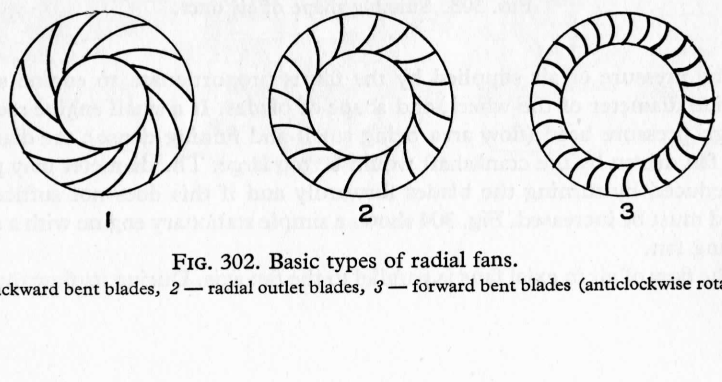

FIG. 302. Basic types of radial fans.
1 — backward bent blades, *2* — radial outlet blades, *3* — forward bent blades (anticlockwise rotation).

purposes. Large bends in the air ducts have to be incorporated immediately behind the fan. With an in-line engine the provision of uniform air supply for all cylinders is difficult. The vanes in the air duct are not equally efficient at varying engine speeds and, therefore, the most suitable shape of air duct must be found experimentally (Fig. 303).

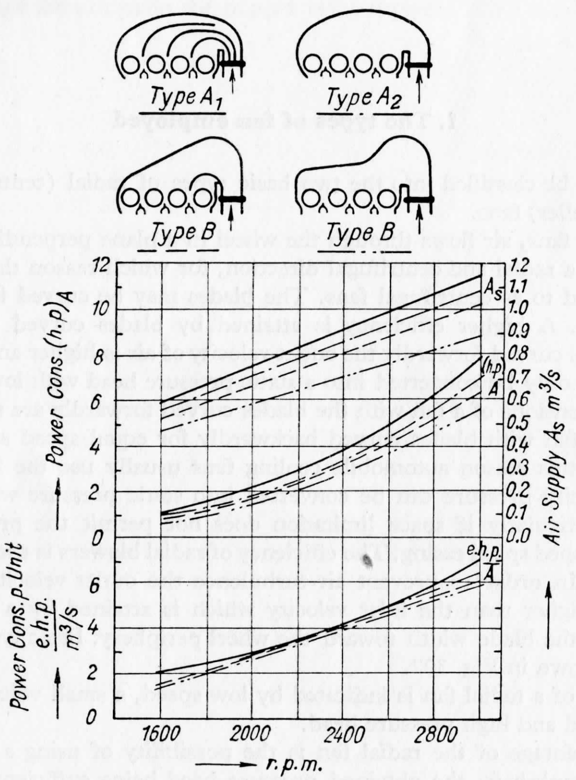

FIG. 303. Suitable shape of air duct.

The pressure of air supplied by the fan is proportionate to engine speed, outside diameter of the wheel, and shape of blades. If a small engine requires a high pressure head (flow area being small and finning dense), the diameter of a fan driven by the crankshaft would be too large. The diameter may partly be reduced by turning the blades forwardly and if this does not suffice, fan speed must be increased. Fig. 304 shows a simple stationary engine with a radial cooling fan.

The flow of air in axial fans is parallel to the fan axis. During its flow through

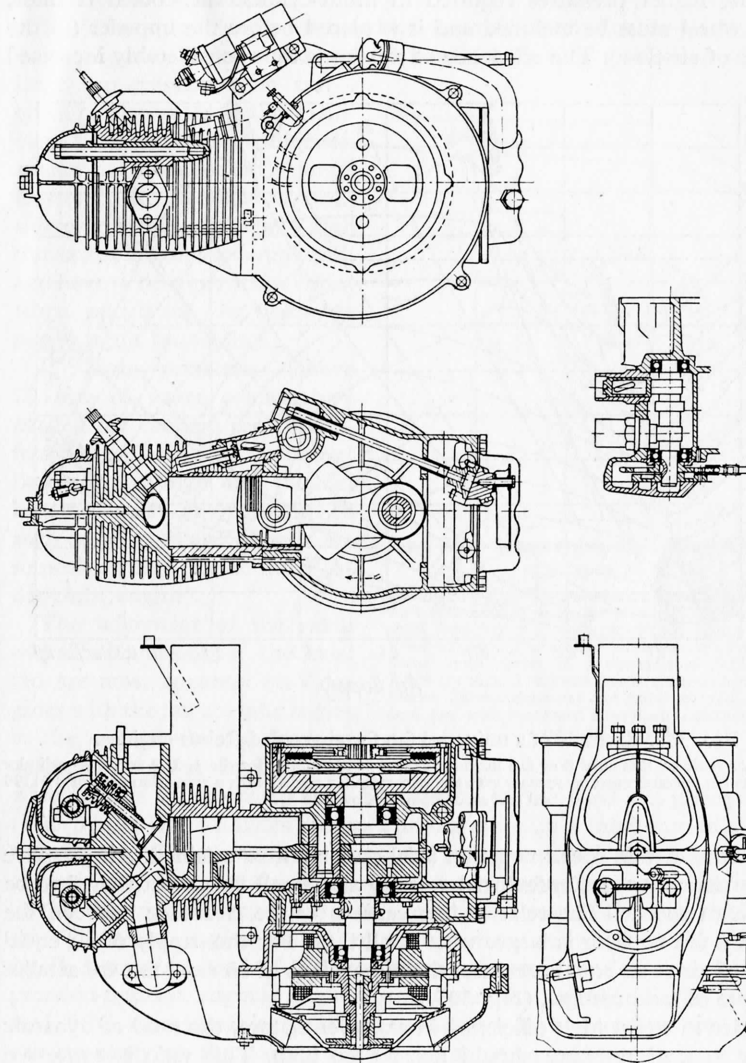

FIG. 304. Sections of an air-cooled BMW engine, bore 72 mm, stroke 73 mm, performance 13 b.h.p. at 5,800 rev/min.

the fan, the air does not change its direction frequently and good efficiency can be attained. With small pressure heads no guide vanes are necessary and the simplest propeller fan is sufficient [29].

For the higher pressures required in multi-cylinder air-cooled engines, a guide wheel must be included and it is placed before the impeller (in the direction of air-flow). The efficiency of the fan is thus considerably increased

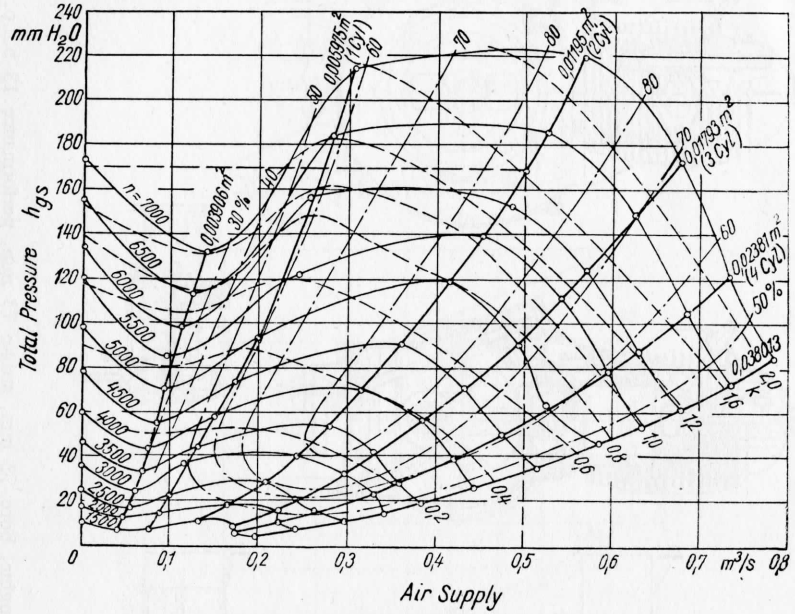

FIG. 305. Example of a universal fan for air-cooled Robur engines.

The characteristic of this axial flow fan includes curves of air supply for the 1, 2, 3 and 4 — cylinder engine. The fan operates most favourably with the two-cylinder engine with a transition area of 0·01195 m² and an efficiency of over 80 %.

and within a certain speed range an axial outlet can be attained. Air pressure is proportionate to circumferential velocity and small fans must therefore be run at high speeds. The relative loss caused by the clearance between the wheel and fan housing is larger with small fans. For the supply of an equal amount of air at an equal pressure, the dimensions of an axial fan are smaller than those of a centrifugal. (Fig. 305.)

In order to attain high efficiency in axial ventilators, the ratio of dynamic pressure to total pressure should not be too high. This ratio is expressed by the dimensionless pressure number [16] which should not exceed 0·6. With higher pressure numbers, e.g. 0·8, the fan diameter is reduced or lower speed may be employed, but the fan is sensitive to resistance variations at the outlet side.

If the outlet velocity of a fan is too high, efficiency is generally reduced, for the dynamic pressure cannot be utilized with any degree of economy. A high dynamic pressure is also usually the cause of uneven air distribution to individual cylinders.

High fan speeds make for a reduction in diameter, but they are often the cause of noise. V belts are usually used for driving axial fans but with a large transmission ratio and a given minimum fan pulley diameter, the crankshaft pulley diameter is inconveniently large. Losses in the belt drive are considerable, especially where high transmission ratios are employed, and have to be taken into account when calculating the necessary power input for cooling.

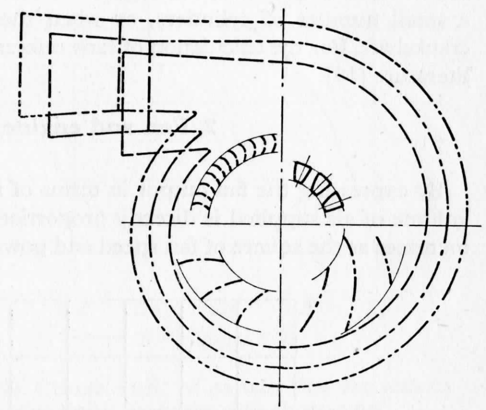

FIG. 306. Comparison of dimensions of different types of fans.

All four types are designed for an equal delivery of 0,7 cu. m/h and delivery head 380 mm w.c. The smallest is an axial flow fan of a diameter of 200 mm operating at 8,900 rev/min. The second larger one is a fan with forward bent blades of a diameter of 275 mm and 3,800 rev/min. The third one is a fan with radial outlet blades 330 mm diameter and 3,800 rev/min. The largest is a fan with backward bent blades, diameter 390 mm and 3,800 rev/min.

If high pressures (above 200 mm of water column) are needed for cooling, the circumferential velocity of the wheel becomes too high and the fan becomes noisy in operation. In such cases, twostage blowers are sometimes used (e.g. in the SLM flat-eight engine).

The advantage of the small overall dimensions of the axial fan are most apparent on V engines with the fan at right angles to the crankshaft axis. Such an example is given in Fig. 393 which shows an air-cooled V 12 Continental engine used as a prime mover in tanks by the United States Army. The fan takes up a minimum of space and the passage of air through the armoured compartment is the shortest possible and without sharp bends. Warm air is drawn from the engine and is forced out of the engine compartment by the shortest route. The two axial fans of this 750 b.h.p. engine are 660 mm in diameter and their axial depth is very small. A pressure head of 150 mm water column is needed to cool this compression-ignition engine, the temperature of the cylinder heads being kept at 175 °C. Considerable resistance to air flow is produced by the entry and exit openings for the cooling air which are protected by louvres, so that total fan input is twice as high as would be normally necessary for cooling the engine. Cooling air passes not only over the cylinders, but also through coolers of engine oil and hydraulic transmission gear oil. Satisfactory cooling is guaranteed up to external temperatures of 52 °C. The power consumed by the fan is 110 b.h.p. i.e. 14·7% of the total b.h.p. performance. For water-cooled engines the fan input under similar conditions would be even greater.

Fig. 306 compares the dimensions of four types of fans of an equal output [18]. The largest is a radial fan with blades curved backwards and the smallest is the axial fan. All three types of radial fan have the same speed of 3800 rev/min whereas the axial fan rotates at 8900 rev/min. Axial fans are generally preferred for automobile air-cooling, radial fans being only used on engines with a small number of cylinders, or when the fan impeller is mounted on the crankshaft. For the calculation of fans reference should be made to specialised literature [16].

2. Fan and engine balance

By expressing the fan output in terms of its speed it will be found that the volume of air supplied is directly proportionate to the fan speed, air pressure increases as the square of fan speed and power consumed as the cube of speed.

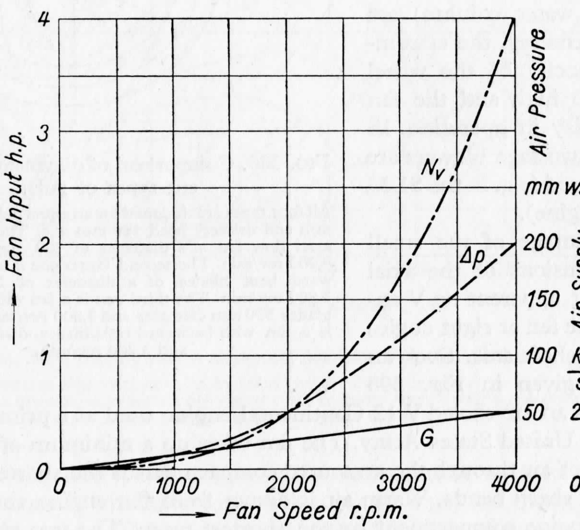

FIG. 307. Air flow, air pressure and fan input plotted against speed.

These correlations are given in Fig. 307 and they apply to an arrangement in which the air is forced through an opening with a constant flow area, this being the case with an air-cooled engine. If twice the amount of air is to be forced through the aperture, air pressure must rise 2^2 times, i.e. four times. These conditions are met by the fan.

The increase in power consumption with the 3rd power of speed is very rapid and must be given due consideration in high speed engines.

The characteristic of the fan which expresses the correlation between the pressure and quantity of air supplied is of utmost importance (Fig. 308). The conditions shown apply to constant fan (engine) speeds. It is apparent from the diagram that if the amount of air supplied is reduced at constant fan speed (e.g. by throttling) air pressure increases according to the curve *a*. If, however, the amount of air supplied is reduced below a certain limit, a sharp drop in pressure ensues as a result of blade overloading. Air velocity through the impeller is then too low and since there is too great a static pressure head in the impeller, air cannot follow the under-pressure side of the blade and "breakaway" occurs, manifesting itself by turbulence and consequent noise.

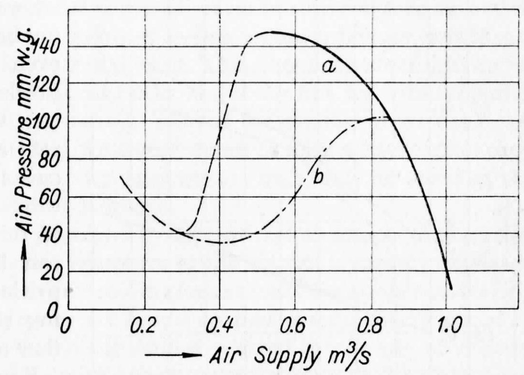

FIG. 308. Characteristic of an axial flow fan and its operational harmony with the engine.

During the design of a fan the conditions under which it will operate in the engine must be considered. If, for example, the engine requires a pressure head of 120 mm water column and a flow of 14·1 ft³/s (0·4 m³/s) at maximum speed and a fan with the characteristic given in Fig. 308 is used, unsatisfactory cooling will result. This fan can supply under a pressure of 120 mm water column a volume flow of 27·5 ft³/s (0·78 m³/s) of air at an efficiency of about 88%. It may therefore be considered to be a very good fan. When used in conjunction with an engine through the cooling ducts of which only 14·1 ft³/s (0·4 m³/s) of air can be forced at 120 mm water column, this fan is completely unsatisfactory. With the amount of air flow reduced below 17,6 ft³/s (0·5 m³/s), breakaway conditions arise and pressure drops to about 40 mm of water column. At this pressure, however, 14·1 ft³/s (0·4 m³/s) will not be forced through, but an amount proportional to pressure, which is 8 ft³/s (0·23 m³/s), which is far below the flow required for satisfactory cooling. The fan under consideration would therefore be satisfactory when used with an engine of double the number of cylinders and hence a double flow area.

This example proves that fan design must be adapted for the requirements of the engine. The fan described is however not even suitable for an engine twice as large with a flow requirement of 28·2 ft³/s (0·8 m³/s). If cooling is regulated by throttling, the rate of flow could under low temperature conditions be below 17·6 ft³/s (0·5 m³/s) with resultant breakaway. This does not seem as dangerous, for with an increase of temperature, the thermostat would open up the regulating louvres and airflow would increase and balance the demand.

But if the amount of air flowing under breakaway conditions is increased, the rise in pressure will not follow the same curve as with throttling, but curve b. In the range between these two curves the fan is unstable, i.e. the same rate of flow can be attained at various pressures. Were the characteristic of the fan as unfavourable as shown in Fig. 308, the fan would not be clear of this unstable range even at full duct opening and breakaway conditions would persist. Only by increasing the flow rate above 29·2 ft³/s (0·83 m³/s) and a reduction in pressure can the fan be made to operate clear of this range of instability. This can be effected in practice by prising up some of the air ducting shrouds thus increasing the flow area.

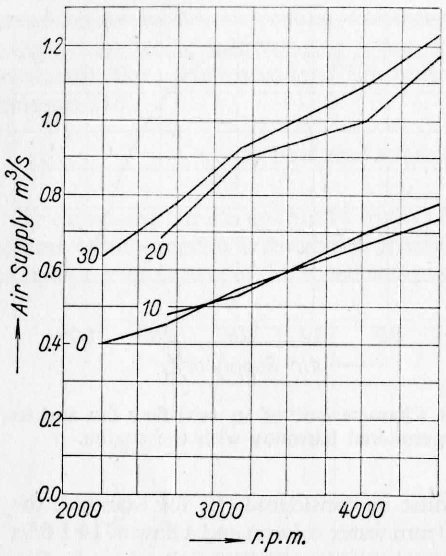

FIG. 309. Influence of an obstacle behind the fan upon the output of the fan. Figures at the curves indicate distances in mm of the obstacle from the fan wheel.

Requirements on a well designed fan are: the absence of breakaway and the narrowest possible range of instability. The fan must be effective down to very small flow rates without breakaway occurring and the two curves should be very close together in the region of instability both during throttling and acceleration.

The breakaway of air from the fan blades manifests itself by increased noise and by pulsating induction. The increase in noise is sometimes difficult to note with the engine running, but if a hand or a strip of paper is placed near the guide wheel the reverberations of inducted air can be clearly felt. This condition may be caused by a reduction of the flow area such as for example occurs when the fins are cast with smaller spacings than required or when some of these spaces are blocked; an immediate temporary cure can be effected by prising off parts of the air ducting to the engine. Some of the air intended for engine cooling does escape unused, but owing to the rise in volume supplied a pressure rise ensues and a greater flow past the engine results.

Shaped (cast) blades can operate under higher load and are not so sensitive to breakaway as sheet metal blades, which also have a reputation of being noisier in operation. On welded sheet metal blades, the welds must be neat. Rough and projecting welds enhance breakaway conditions and the same may

be said of projecting seams or ripples on cast blades or of sharp edges produced by machining, etc. Conversely, a smooth blade and housing surface reduces resistance and promotes laminar air flow and an increased stability of blades. Any turbulence in the inducted air (caused, for example by the interference of an object obstructing the inlet) reduces efficiency and stability. Objects hindering the free outlet of air also reduce fan performance. Fig. 309 shows the reduction in fan output through the approach of an obstacle to free air outlet.

In order to reduce the overall width of in-line engines, fins are sometimes left to protrude into the outlet duct of the fan. This does not reduce fan output if the cylinder is not too near to the air outlet and if the fins are without baffle.

The dynamic air pressure is generally utilized for cooling aircraft engines. On some modern aircraft engines with very dense finning a high pressure is necessary. During take-off, when engine output is high and the speed of the aircraft low, such engines tend to overheat.

If cooling arrangements are governed by take-off requirements then during level flight at high speeds the air resistance to the aircraft is unduly increased by the large air intakes; in such cases cooling fans are used for supplying cooling air. Most unfavourable conditions are found on helicopters, the air speed of which is relatively low. Cooling is sometimes assisted by the use of exhaust gas ejectors, the exit of hot air with exhaust gases adding to the propulsion of the aircraft.

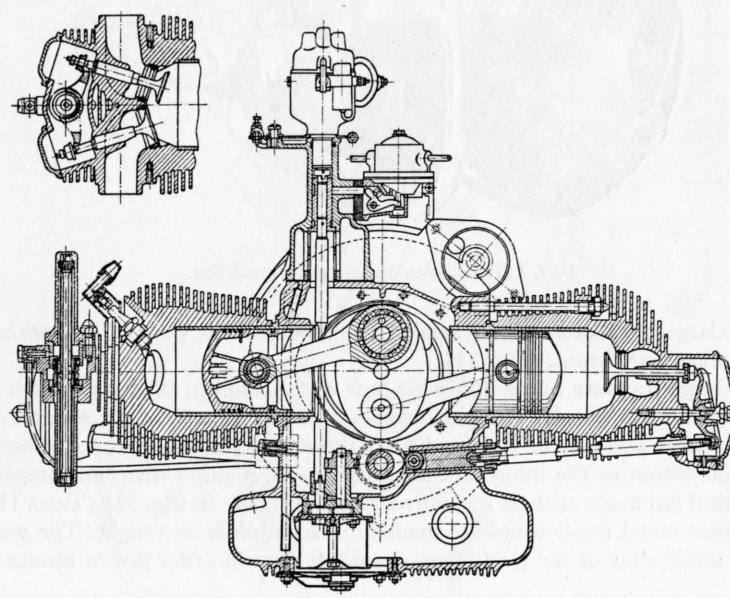

FIG. 310. Sectional view of a two-cylinder Panhard-Dyna car engine. Note aluminium cylinder with liner.

3. Design details of fans

For small pressure heads axial, propeller type fans, without a guide wheel and casing, are employed. These are in general use in water-cooled engines and are rare in air-cooled engines. Fig. 310 shows a propeller fan. In order to reduce noise, the blades are sometimes distributed at irregular intervals around the circumference, care being taken to balance the fan as a whole.

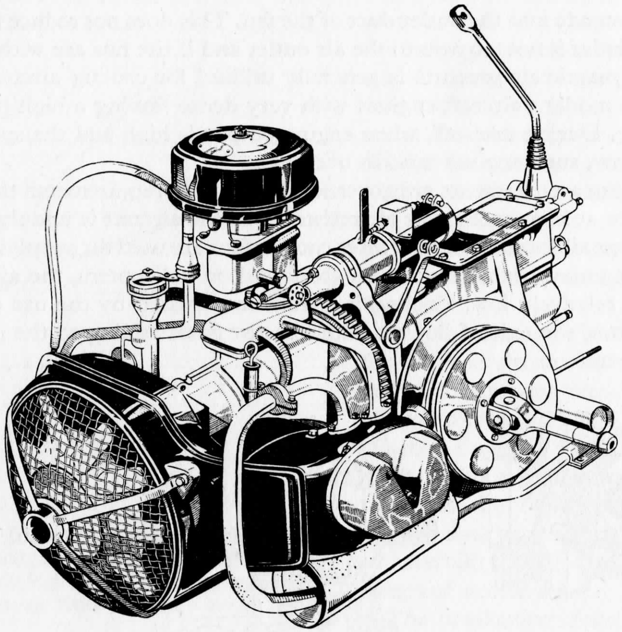

FIG. 311. Citroen engine with axial fan.

For larger pressure heads axial fans, mounted in casings but without guide wheels are used. (Fig. 311.)

For large pressure heads above 80 mm water column, axial ventilators are fitted with guide wheels. The guide wheel vanes are usually of sheet metal and their number and that of the fan blades should be chosen so as not to have a common divisor in the interest of noise reduction. A guide wheel and impeller of an axial fan made of sheet metal pressings are shown in Fig. 312 (Tatra 111). The sheet metal fan is simple to manufacture and light in weight. The welds at the outer ends of the guide vanes must be neat in order not to hinder air flow.

If the fan is fixed by means of a steel band, it must be gripped about the circumference of the guide wheel. Were the unit attached by the circumference

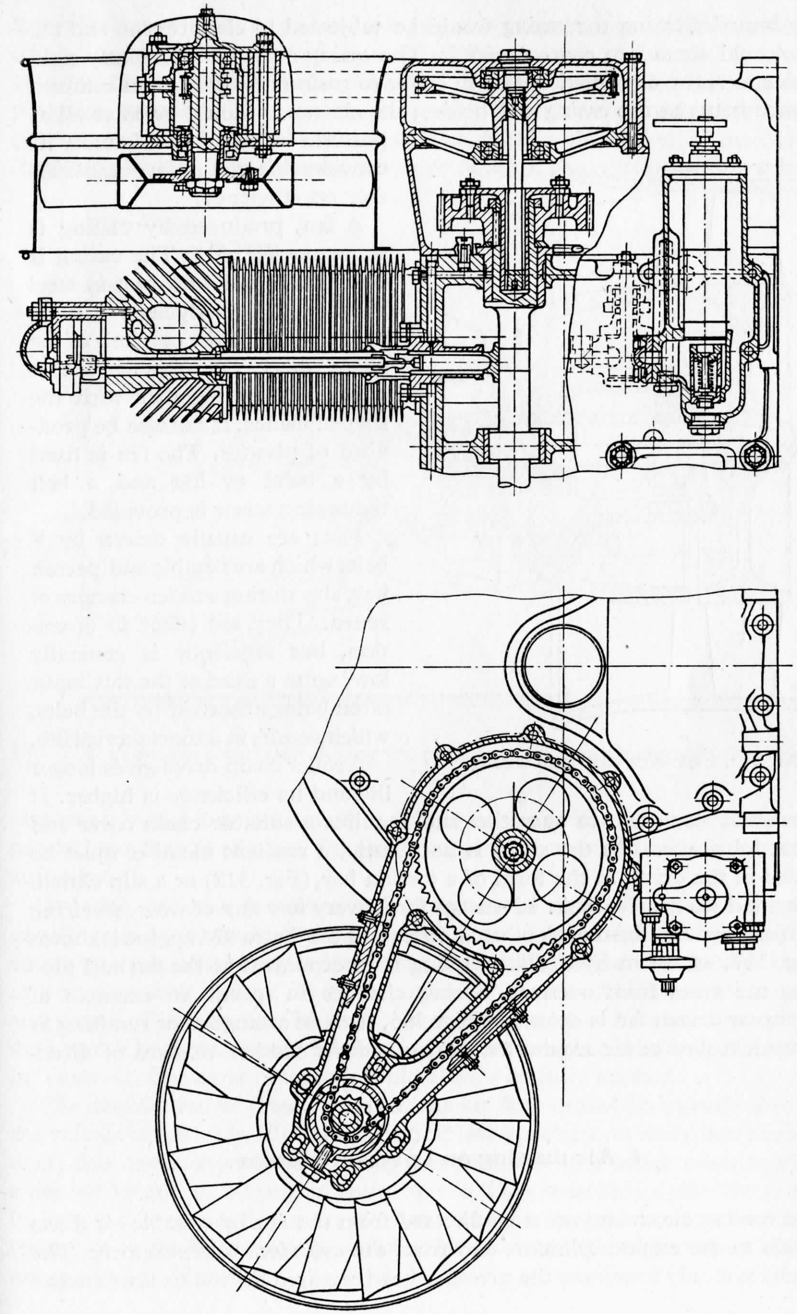

FIG. 312. Propeller fan of the Tatra 111 engine.

of the impeller casing the casing would be subjected to compression and the blades could come into contact with it. The casing must be sufficiently rigid in order to resist deformation and in order to maintain a small and uniform clearance between the casing and blades; the clearance should be as small as possible in order to minimize its considerable and unfavourable effect on efficiency.

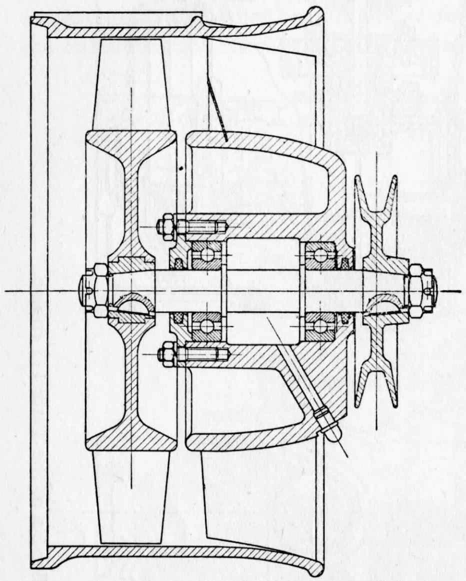

FIG. 313. Fan with cast iron casing.

A fan, produced by casting is shown in Fig. 313. The casing is cast aluminium with cast-in steel sheet blades. A dynamo can be mounted inside the cast hub of the guide wheel. The impeller is cast of aluminium together with the shaped blades. It can also be produced of plastics. The fan is fixed by a band or lug and a belt tightening screw is provided.

Fans are usually driven by V belts which are flexible and permit belt slip during sudden changes of speed. They are silent in operation, but efficiency is generally low, up to a third of the fan input often being absorbed by the belts, which results in a short service life.

A roller chain drive gives longer life and its efficiency is higher. It is, however, less silent in operation and requires a suitable chain cover and efficient lubrication. As the chain is not elastic, a resilient member must be included in the drive, in the form of a torsion bar, (Fig. 312) or a slip clutch.

Gear and shaft drive is an advantage for its very low rate of wear, servicing and efficieney. An illustration of such a drive on the Tatra 924 engine is shown in Fig. 117. where an hydraulic coupling is incorporated at the fan end protecting the gears from overload during changes in speed. An example of a bevel gear driven fan is shown in Fig. 386, such an arrangement resulting in a convenient flow of air around the engine without sudden changes of direction.

4. Air ducting and pressure losses

The cooling air stream must be directed from the fan by suitable air ducts or cowls to the engine cylinders and from the cylinders to atmosphere. The fan must not only overcome the pressure head required for the air flow around

the cylinders, but also the total resistance of the air ducts. The distribution of air pressure about the outer surface of the vehicle should also be investigated as the pressure head thus created can assist or impair the flow of air past the cylinders. The cooling air outlet should be placed in an underpressure region of the body and the inlet duct in the region of the highest dynamic pressure. The dynamic pressure of air in conjunction with a suitably

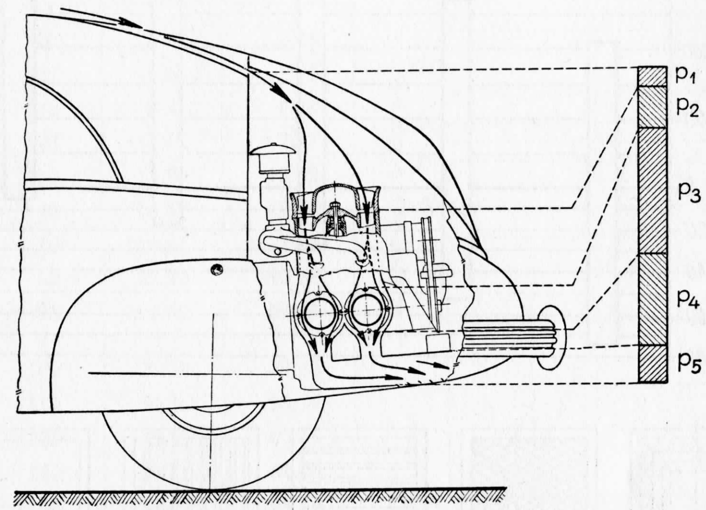

FIG. 314. Pressures developed during the passage of cooling air through the vehicle

chosen air outlet location can often suffice for the good cooling of racing engines without the use of a fan. On aircraft engines dynamic pressure is generally sufficient.

Dynamic pressure increases as the square of speed. Air-cooled engines usually reguire a pressure of 100 mm of water column for cooling purposes and this corresponds to a speed of 92 m.p.h. (145 km/h). For this reason dynamic pressure alone cannot be relied upon for engine cooling, as for instance at a speed of 18·6 m.p.h. (30 km/h) when driving up-hill it amounts only to 4·34 mm. The dependence of dynamic pressure on speed (km/h – m/s) is given in Table 41. Dynamic pressure should always be fully utilized.

The distribution of pressure loss in the air flow during its passage through the vehicle is shown in Fig. 314. The first loss p_1 occurs on entry into the inlet duct, this opening sometimes being too confined. It is either obstructed by a decorative grill or by control shutters, etc. This resistance to air flow should be kept as low as possible under all circumstances. In special purpose vehicles, resistance in the inlet ducts is considerable its values for various duct shapes being given in Fig. 315.

A further pressure loss occurs in the air duct between the fan and cylinder finning, being caused by the conversion of kinetic energy of the air into static pressure and by the changes in flow velocity and direction. These losses are marked p_2 in the diagram.

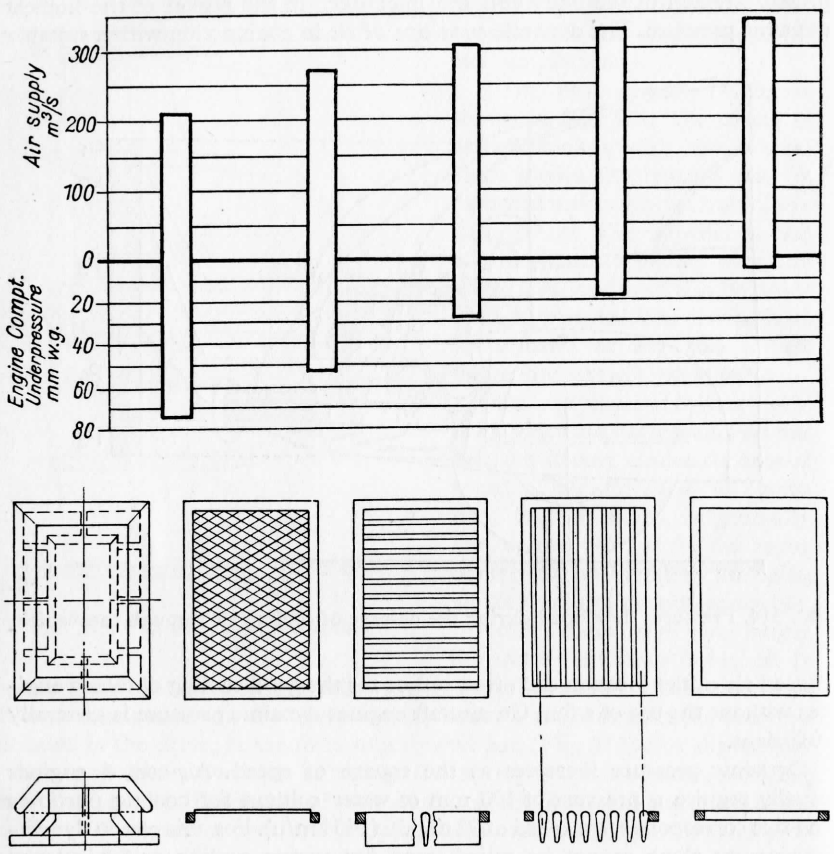

FIG. 315. Air resistance of protective gratings in armoured vehicles.
The streamlined design of grating reduced underpressure to one third with a simultaneous increase of air flow by 50 %.

The greatest pressure loss p_3 occurs in the cylinder finning interspaces. It includes losses through friction, variation in velocity, variations in flow direction, losses through turbulence and at the confluence of two air streams behind the cylinder.

A large pressure loss p_4 occurs at the outlet of air from the engine ducting; this can be reduced only to a small extent by the use of a suitable diffuser.

Table 41

Dynamic Head of Air

Velocity		Dynamic head
km/h	m/s	mm w.g.
10	2.78	0.48
20	5.56	1.93
30	8.33	4.34
40	11.11	7.71
50	13.89	12.05
60	16.67	17.36
70	19.44	23.63
80	22.22	30.86
90	25.00	39.09
100	27.78	48.22
110	30.56	58.34
120	33.33	69.43
130	36.11	81.48
140	38.89	94.50
150	41.67	108.5
160	44.44	123.4
170	47.22	139.3
180	50.00	156.2
190	52.78	174.1
200	55.56	192.9
210	58.33	212.6
220	61.11	233.4
230	63.89	255.1
240	66.67	277.7
250	69.44	301.3
260	72.22	325.9
270	75.00	351.5
280	77.78	378.0
290	80.56	405.5

The last pressure loss p_5 occurs in the remaining duct from the engine to the exterior of the vehicle.

In automobile engines the pressure loss occuring in the flow of air around the cylinders is further increased by

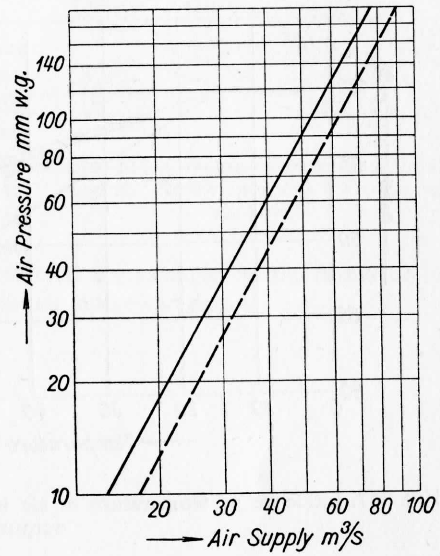

FIG. 316. Effect of cylinder bolts upon the pressure head across the cylinder.
Full line — cylinder with bolts, dash line — cylinder without bolts.

the bolts which obstruct the flow between the fins. This must be taken into account when determining the flow resistance of cylinders. The difference of resistance between cylinders with and without bolts is shown in Fig. 316.

All this provides sufficient proof of the fact that the pressure loss at the cylinder is only part of the total pressure loss which must be taken into account when designing the fan. Furthermore, losses through leakage, which amount to about 20 to 40 % of the quantity of air needed for cooling must be allowed for. If high pressure heads are used for cooling, loss through leakage result in a large increase in fan input. All shrouds therefore should be a leakproof fit to reduce the pressure loss to a minimum.

Air under pressure can also be used for cylinder charging, but as the pressure head is negligible from the point of view of cylinder charging, its in-

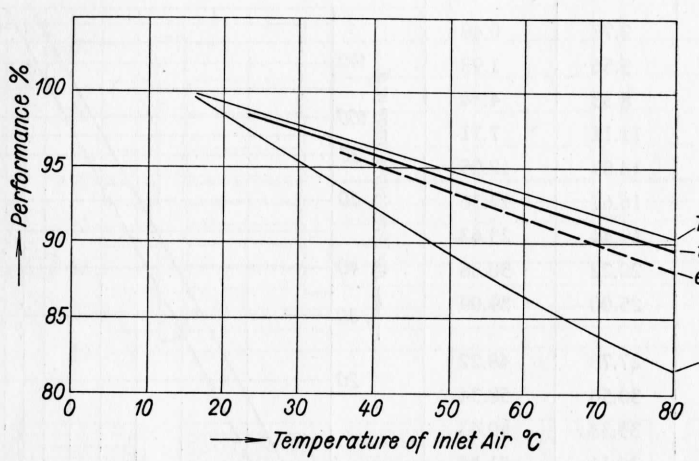

FIG. 317. Influence of temperature of air inducted into the engine upon engine output.

fluence on engine performance is practically nil. There is also the danger of the air in front of the cylinders being warmed by heat radiation and the advantage of increased charging pressure is thus lost. The air entering the cylinders must pass through an air cleaner and the whole layout is more difficult to install. With petrol engines the float chamber must under such conditions be pressure sealed and its breather hole connected to the induction manifold.

The temperature of the inducted air exerts a considerable influence on engine output. The specific gravity of warm air being lower, volumetric efficiency is reduced with the entry of warm air and with it engine performance. The influence of temperature of inducted air on engine performance is shown in Fig. 317. This influence is not equal for petrol and compression-ignition engines. In petrol engines it approaches b.h.p. $\propto T^{-1}$ in oil engines it is closer to b.h.p. $\propto T^{-\frac{1}{2}}$. The diagram shows the results of measurements made on a petrol engine. It follows that it is beneficial to induct air of the lowest possible temperature which does not, in the case of petrol engines, impair the formation of a readily inflammable mixture.

The air ducting must be arranged in such a way as to divert an equal flow

to all cylinders and to ensure uniform cooling over the whole circumference of each cylinder.

Difficulties in uniform air distribution to each cylinder increase with the number of cylinders in one bank but good results can be achieved by the use of suitable baffles. "Suction" cooling is very convenient from the point of view of a regular air flow distribution among cylinders.

A regular distribution of temperature can be attained by the use of deflector baffles on the exit side of the cylinder (see Fig. 98). Difficult conditions prevail with multi-cylinder aircraft engines with a very large number of cylinders.

A diagrammatic drawing of the air ducting of a multi-row radial aircraft engine is shown in Fig. 318. The cylinders are arranged on the crankcase in spiral form and every row has its own air intake and exit.

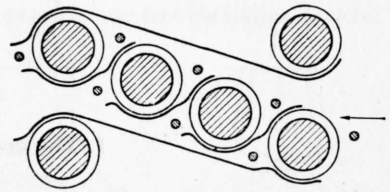

FIG. 318. Cowling of multi-line radial engines. Arrow indicates direction of air flow.