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FIXED AIR-COOLED ENGINES

By A. H. Fedden
Bristol Aeroplane Company

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FIXED AIR-COOLED ENGINES.*

By A. H. Fedden.

The fixed air-cooled engine is no innovation in the history of aviation. Several types were created before the war, the best known being the Anzani and the Robert Esnault Pelterie fan-shaped engine.

These engines, especially the former, were built and used in considerable numbers. Nevertheless, their mean pressure and efficiency were relatively small and their weight was from 4 to 5 pounds per HP. In 1914, rotary air-cooled engines, in spite of their weaker couple and greater fuel consumption, had supplanted fixed engines for military purposes, on account of their smaller weight per HP.

In the latter part of the war, the practical limits of the rotary air-cooled engine had been reached. The need was felt of an engine with the same characteristics, of facility of maneuver and of as small weight per HP, but of greater power and comparable with water-cooled engines in efficiency and consumption of oil and fuel. The only type which appeared to answer these requirements was a fixed radial air-cooled engine of 300-400 HP.

It is proposed to analyze the advantages and disadvantages of large fixed air-cooled radial engines and to explain how the problems have been solved by the Bristol Aeroplane Company.

I. - Advantages of Fixed Air-Cooled Radial Engines.

In a radial engine, the arrangement of each group of cylinders around a central crank shaft gives remarkable facilities for

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* From "Premier Congres International de la Navigation Aerienne," Paris, November, 1921. Vol. IV, pp. 494-502.

economy of space and weight. Aside from this, there are certain advantages over the vertical or V water-cooled types, of which the following are the most important.

a) Elimination of the couple of inertia.- The couple of inertia due to the accelerations (positive or negative) of the piston and connecting-rod in alternating motion, with the resulting rapid reversals of the stresses in the shaft, is one of the principal faults of the vertical or V type of engine. In polycylinder radial engines with a single group, due to the attachment of all the rods to a single shaft, this very serious defect is practically eliminated.

b) Radial engines can be directly coupled with the propeller gears without encountering the following difficulties inherent in gears. As stated in a), long shafts with multiple couples vibrate from the couples of inertia. This vibration coincides with the periodic vibration of the shaft proper and the maximum moment of the periodic couple may become infinitely greater than the engine couples. This is one of the causes of failure of airplane engine gears. It is known that, during the war, this was such a frequent cause of engine trouble that certain slipping clutch devices were employed in the attempt to eliminate this serious disadvantage. The couple of inertia does not exist in the polycylinder radial engine. The problem of coupling a propeller, of which the fly-wheel effect is considerable, is much simplified.

c) The fixed air-cooled radial engine dispenses with the radiator and water pipes. Aside from the saving in weight, difficulties due to the water circulation are avoided. Such troubles have not yet been eliminated in water-cooled engines and have caused breakdowns in recent contests and exhibition flights. The elimination of water is very important for the Army and Navy. In some regions it is very difficult to obtain water. With some airplanes, one may have to take off within a few seconds after starting the engine, in which event air cooling is much preferable to water cooling.

d) In very warm climates, air-cooled engines have given much better results than those cooled with water. An air-cooled cylinder will always give the total power expected, if the mean temperature of the cooling fins does not exceed 175°C (347°F).

With a radiator, on the contrary, if the mean temperature of the cooling surface exceeds 80°C, (176°F) the losses by evaporation become considerable. In warm climates, where the temperature of the air may vary between 0 and 45°C (113°F) the available temperature difference for cooling may diminish 56% in the case of a radiator. This decrease is only 25% in the case of an air-cooled cylinder.

This difference can cause no damage to air-cooled cylinders, but in the radiator of a water-cooled engine the water would be lost by boiling. When the same conditions occur in connection with great changes in altitude, the advantages of air cooling would be still greater.

e) A fixed air-cooled engine can be built so as to constitute the shortest and most compact power unit possible for an internal

combustion engine running with a four-stroke cycle.

The Bristol Company has built a good 380 HP engine with a total length of 1.32 m (4.33 ft), the greatest width being 0.6 m (1.97 ft). The advantages for maneuvering and the economy of space thus obtained are evident. Moreover, the rear plate of this engine facilitates the arrangement of the auxiliary controls.

f) A preliminary study of a high-powered fixed radial engine from the structural point of view will demonstrate the following advantages. Almost all its parts are symmetrical or round. There are no large parts difficult to manage. A considerable portion of the machinery consists of large interchangeable parts. There are fewer separate parts than in a vertical or V engine of similar power. The actual number of separate parts of a 380 HP radial engine designed by the writer is 370, or 25% less than any other engine of equal power. There are no complicated parts which involve much waste in casting and machining.

g) Air-cooled radial engines can be taken down and set up again more quickly than any other type of equal power, excepting rotary engines. A point of considerable importance, for both military and commercial use, is that there are no water pipes to be disconnected and reassembled. There are no heavy parts to be handled and no difficult and delicate adjustments to be made.

h) With a suitably designed fuselage, the radial engine is ideal for setting up. It may be placed in such a way as to be readily removed from the airplane and put back again in much less time than is possible with a vertical or V engine.

II. - Some Disadvantages of Air-Cooled Radial Engines and Suggestions for Remedying Them.

a) Large cylinders for air-cooling.- On the whole, the designs of large cylinders for air-cooling on radial engines have not been well established. They were entirely incapable of withstanding the required pressures. We think it will be possible, by a careful study of details and well-conducted experiments, to make large cylinders for air-cooling which will run at as low temperatures as water-cooled cylinders of the same capacity. It is admitted that, when the bore is increased, the problem of cooling becomes more difficult. But a cylinder of large bore will retain its full power at higher temperatures than a small cylinder. The writer's experiments were performed with air-cooled cylinders of 146.05 mm (5.75 in) bore and 190.05 mm (7.48 in) stroke, with a stroke volume of 3191 cm^3 (194.5 cu.in). All figures contained in the following paragraphs refer to cylinders of the above dimensions. Not enough attention has been paid in the past to the cooling of the cylinder head. It is necessary to have valves in the upper part, but the vertical type is preferable for the gear control, since with inclined valves the control mechanism becomes too complicated. Excellent mean pressures may also be obtained with vertical valves.

Multiple valves are necessary for the cylinders in question. We recommend two intake and two exhaust valves. We think more than two valves should be used when the bore is greater than 118 mm (4.65 in).

The designing and construction of an air-cooled cylinder head with four valves requires careful experimenting. The air circulation is obstructed by the intake and exhaust orifices and some ingenious device is required, in order to prevent parts back of the latter from getting too warm.

The figures generally accepted for the velocity of the gases, the diameter of the valves, etc. are not the same as for water-cooled cylinders of similar dimensions. We have found that higher mean pressures and colder cylinders are obtained by abandoning the current theories for obtaining the best air circulation on the cylinder head, in order to prevent the formation of points of too high temperature and to so arrange the parts of the cylinder head as to have the maximum width of metal between the valves. Eight types of cylinders have been subjected to the severest tests by the Bristol Company.

The best solution was found to be a steel cylinder closed at both ends and cast in a single piece with the fins. A cylinder head of cast aluminum contains the intake and exhaust orifices.

The tests showed that, for a given bore, a quite well defined pressure ratio gave the minimum temperature for the walls. This ratio was 5 : 1 for the cylinder tested.

Considering that the weight of a circular fin varies as the square of its projection, it is important to keep these fins as short as possible. On a steel cylinder, fins with a triangular cross-section, with a pitch of 7.5 cm (2.95 in), gave the best results. These cylinders were made of carbon steel under 40 tons

pressure.

The aluminum heads are cast from a copper alloy and suitably annealed before machining, in order to prevent distortion. The difficulties of casting the fins in a single piece limits their employment and the correction of their shape. A pitch of 10 cm (3.94 in) was found more practical for cylinder heads.

For large air-cooled cylinders, of the above-indicated capacity, the maximum temperature of the cylinder head must not exceed 300°C (572°F) in order to maintain a good mean pressure and a suitable fuel consumption. The cooling surface should not be less than 2.1 m^2 (22.60 sq.ft) per HP.

Tungsten steel gave the best results for the exhaust valves. The maximum temperature must not exceed 680°C (1256°F). A cylinder 146.05 (5.75 in) by 190.05 mm (7.48 in) will give continuously 50 HP at 1600 R.P.M. and 8.05 kg/cm (114.5 lbs/sq.in) of mean pressure, or 58 HP at 1800 R.P.M. and 8.26 kg/cm^2 (117.5 lbs/sq.in) of mean pressure, in a wind of 120 km/hr (74.56 mi/hr) with a fuel consumption of 0.33 liter (.087 gal) per HP. The working parts of the cylinder were still in good condition after running a long time. Much greater mean pressures can be obtained with this cylinder in its present state of development, but they are of little importance, since we have retained only one figure, which admits of absolute security, together with long service for the cylinder, valves and piston.

b) The bushing of the piston end of the connecting-rod of a fixed radial engine requires much attention, most of the types in

use not allowing sufficient bearing surface to insure long service Such bushings have recently been made to withstand a total load of 3200 (7054.8 lbs) to 3500 kg (7716.2 lbs). If account is taken of the pressure from the explosion, the load on these bushings is increased nearly as the cube of the speed. It is therefore very important to keep the maximum number of revolutions as nearly normal as possible. Much attention must also be given the weight of the parts in alternating motion.

At first thought, it would seem that roller bearings would constitute a satisfactory solution, especially as such bearings present lubrication advantages. In practice, however, it is found that the peripheral velocity of the rollers is very great and that the weight of the piston and of the connecting-rod is excessive. This type requires a special crank shaft. The writer recommends a plain crank shaft with a master connecting-rod and connecting-rod bushings of white metal. This solution facilitates the arrangement of the accessories. The master connecting-rod must not be too heavy, but it must be very rigid, in order to obtain the greatest advantage from the whole surface of the piston-pin bushing. Abrupt changes in cross-section must be carefully avoided. The master connecting-rod is subjected to great alternating stresses and should have a safety coefficient of 5.5 for the rod and 3.4 for the crank end. Oil grooves should be avoided in the bushings. The desire to reduce the pressure on the bushings should not lead the designer into the error of adopting too large a crank pin.

Without regarding the torsional stresses, we cannot insist too strongly on the importance of rigidity in the assembly of the connecting-rod, in order to avoid deformation and breaks in the bushings. Naturally, questions of the oil pump, the filters and, in a general way, the whole problem of lubrication are exceedingly important and must receive the most careful attention. It is necessary to have sufficient pressure for maintaining the oil film and causing enough oil to pass around the piston-pin bearings of connecting-rod, in order to prevent overheating.

With such a connecting-rod as has just been indicated, giving a load factor of 12000 pounds per square inch per foot per second and with an oil pressure of 34.83 pounds per square inch, the bearings wear well and compare favorably with those of vertical or V engines.

The ratio of the length of the connecting-rod to the length of the crank arm must not be less than 3.5. Short connecting-rods considerably increase the oblique component of the pressure on the cylinder walls and their mean temperature.

c) The valve control in fixed radial engines has been a constant source of trouble and the larger the cylinder, the more difficult this problem becomes. The writer has spent considerable time and energy in endeavoring to improve the valve control in general use, but believes, however, that the present method is the most satisfactory for cylinders with a bore not exceeding 150 mm (5.94 in).

With larger cylinders, it will probably be necessary to have

oblique controls for each cylinder. We assume that the present system is the best up to 55 HP per unit and we intend to investigate thoroughly the possibilities of eliminating its weak points.

The weight of the parts in alternating motion and the valve play must be reduced to a minimum. The cross-section of the cam must receive particular attention, as also the positive and especially the negative accelerations of the cams. Cams made by hand and finished by filing according to a pattern, although well designed on paper, may produce very high stresses at certain points.

Any excessive lift or play of the valves must be avoided. The latter is especially important on large cylinders with fins, where the rocker supports rest on the cylinder head. As the cylinder becomes heated at the top, the cylinder head lifts the rockers farther from the tappet stem. On a cylinder of 190 mm (7.48 in) stroke, this play may reach 1.6 (.063 in) or 1.7 mm (.067 in). With such plays, ruptures of valve springs must be expected. In order to remove this danger, the writer considers it absolutely necessary to introduce some means for regulating the valve play automatically, as the temperature of the top of the engine increases. The loading of the valve springs is very high in most cases. The shearing stresses should not exceed 31.5 kg/mm^2 (44800 lbs/sq.in).

d) In all polycylinder engines, the uniform distribution of the fuel mixture is a problem which has naturally received attention. In fixed air-cooled radial engines, this problem has been neglected, however, because it is much more difficult than in vertical engines. The results of unequal distribution are a low volumetric efficiency, excessive fuel consumption and the burning of the exhaust valves.

e) Aluminum is the best metal for the pistons. It would be well to use the same alloy as for the cylinder heads and it should be allowed to "age" before machining. With pistons for fixed radial engine cylinders of over 130 mm (5.12 in) bore, the problem of reconciling a small weight with a sufficient quantity of metal for absorbing the heat can only be solved by long experience. The Bristol company made and subjected to the severest tests seven different types of pistons, before arriving at an entirely satisfactory result. A judicious disposition must be made of the mass of metal used in the piston. 30 grams (1.06 oz) of metal, added to a piston of 150 mm (5.94 in) bore, represents an additional weight of only 28 grams (0.99 oz) with an alternating motion, but an additional load of 35 kilograms (77.16 lbs) on the piston end of the connecting-rod. A piston for a cylinder of 150 mm (5.94 in) bore should not weigh more than 1.253 kg (2.76 lbs). Sharp edges should be eliminated as much as possible.

III. - Characteristics of the Bristol 380 HP Fixed Radial Engine "Jupiter."

Total weight			330.7 kg (729.1 lb)
Weight per HP	330.7/380	=	0.871 kg (1.92 lb)
Average fuel consumption during 54-hour official test			0.2429 kg (.536 lb)/HP-hour
Average oil consumption during same test			0.0258 kg (.057 lb)/HP-hour

The official test here referred to is the test required by the British Air Ministry and was very severe. The accompanying figure gives the official power curves. A is the power curve before starting the 54-hour test and B after finishing this test. The engine being dismantled and found in excellent condition, was then reassembled and a new power curve C was obtained. The maximum power obtained was 462 HP at 1840 R.P.M. The powers indicated by these curves are not those which the engine could attain for a very short time, but those which it could maintain for a certain longer period of time

The engine was then run for two hours under the following conditions:

440 HP at 1775 R.P.M.

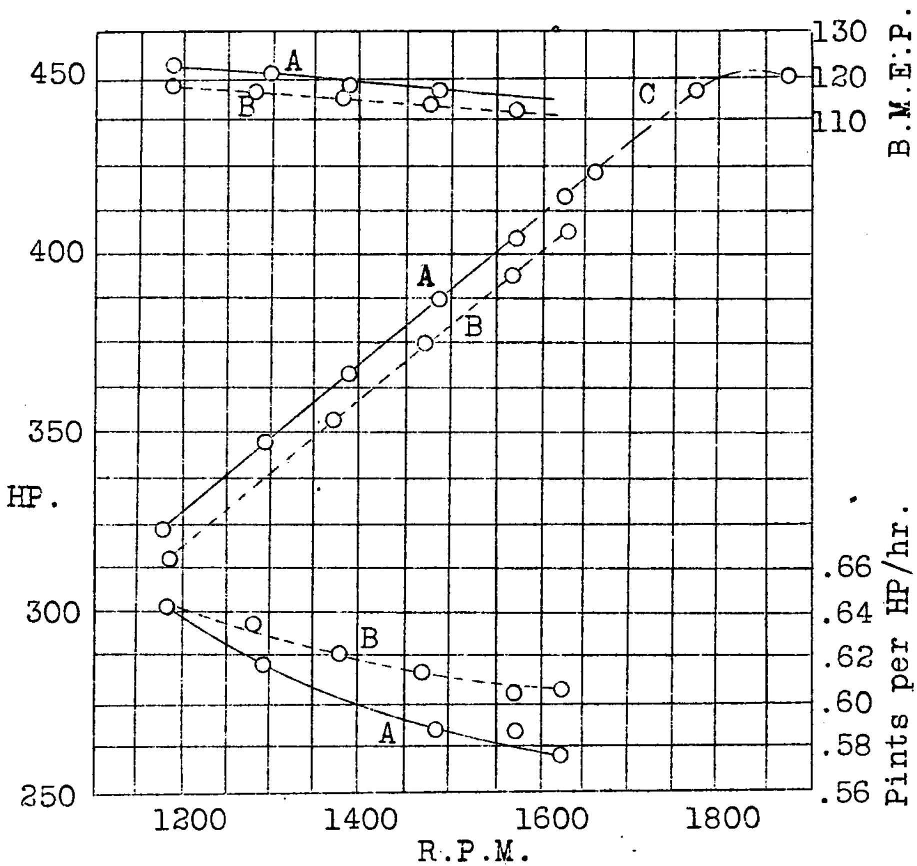
450 HP at 1840 R.P.M.

These figures show that the engine has an ample margin of power and that the principal parts are not subjected to too great stresses, although the R.P.M. was excessive for long periods of time, its normal output being 380 HP at 1575 R.P.M.

The required test also included a half-hour test at the idling speed of 393 R.P.M. with a sudden increase to the normal R.P.M. within five seconds.

The writer finishes his communication with views of various parts of the engine, as also of engine-testing installations (not reproduced in this article) of the Bristol Company, rendering it possible, on the one hand, to test a polycylinder engine, which can attain 600 HP and, on the other hand, to test a single cylinder capable of attaining 65 HP. 45 HP has not yet been exceeded as the unit power for a suitable R.P.M. The tests, however, indicate the probability that it will be possible to construct a fixed air-cooled radial engine of as much as 1000 HP with weight of less than one kilogram (2.2 lbs) per HP.

Translated by the National Advisory Committee for Aeronautics.



A - Readings before starting test.
B - " after completion of test.
C - " " reassembling of engine.
Average fuel consumption .594 pts. per HP/hr.