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MATHEMATICAL AND EXPERIMENTAL INVESTIGATION OF HEAT CONTROL AND POWER INCREASE IN AIR-COOLED AIRCRAFT ENGINES

By F. Gosslau

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MATHEMATICAL AND EXPERIMENTAL INVESTIGATION OF HEAT CONTROL AND POWER INCREASE IN AIR-COOLED AIRCRAFT ENGINES.*

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For more than a decade the vertical water-cooled engine was the German standard aircraft engine. It did not seem possible for its fuel consumption, power output per unit volume, length of life and reliability to be surpassed or even equaled by an air-cooled engine. In the last few years, however, there has been active competition between air-cooled and water-cooled engines and it can now be confidently asserted that, up to 600 hp, the advantage lies with the radial air-cooled engine.** This is indicated by the fact that nowadays hardly an engine within this range is designed for water cooling, while a new radial air-cooled engine appears almost every month. In Germany and elsewhere well-known firms, which had formerly made vertical water-cooled engines exclusively, have turned their attention to the manufacture of radial air-cooled engines.

The first high-powered radial air-cooled engine was the Bristol "Jupiter" which was designed in 1918. The latest airplanes of the German Lufthansa are equipped with this engine,

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*"Rechnerische und experimentelle Untersuchungen über Warmebeherrschung und Leistungssteigerung in luftgekühlten Flugmotorenzylindern" from Zeitschrift für Flugtechnik und Motorluftschiffahrt, Oct. 7, 1928, pp. 461-466.

**Cf. V.D.I., 1925, p.1329; 1926, p.1672; Z.F.M., 1927, p.63.

which now furnishes over 500 hp. The three-engine Junkers airplane "Hermann Kohl" and the four-engine "Superwal" are also equipped with this engine.

Although the mechanical requirements of crank shafts, connecting rods, piston pins and bearings can be calculated for the highest engine powers, the designer could not answer the question as to whether a cylinder exceeding the customary dimensions could be satisfactorily cooled by air, because he did not know the numerical relations between the air velocity, temperature of the cylinder walls, heat dissipation, cylinder dimensions and type of construction.

Experimental Plant

In order to determine these relations, I had an experimental plant (Fig. 1) installed on behalf of the Siemens and Halske Company in their laboratory. The experimental cylinder was exposed to the air stream of a wind tunnel. The compression chamber was heated by an electrically heated oil bath kept constantly in motion by a stirrer (Fig. 2). The wall temperatures were measured by thermocouples. The air stream was produced by a seven-kilowatt blower. The air flowed through a current rectifier (honeycomb), diffuser, air chamber with quieting sieves and a nozzle. By varying the heating current with the aid of resistances and by varying the velocity of the air stream with the aid of throttling disks in the suction nipple of the blower, the mutual relations of the air velocity, wall temperature and heat could be determined.

At the beginning of the experiments in 1925, there were still many different types of cylinders in use. For our experiments we selected a few typical cylinders which are shown in Figures 3-10. These were used as test cylinders in our experimental plant. With them we determined the values required for the law of similarity of heat transmission, in order to be able to judge cylinders of larger dimensions. These values were then plotted as characteristic curves (Fig. 11), which are here straight lines, as in many other heat-transfer problems with logarithmic coordinates, enabling simple extrapolation. Figure 12 shows the characteristic curves for several cylinders of 100 mm (3.94 in.) diameter at a mean temperature difference of 150°C (270°F) between the cylinder wall and the air stream. The curves represent the quantities of heat carried away per hour from one square meter for every degree centigrade (1.8°F) of temperature difference for a variable velocity of the air stream. The bottom curve applies to a steel cylinder closed at the top, while the top curve applies to a cylinder with an aluminum head. The latter, for example, has a cooling effect three times as great at an air velocity of 50 m/s (164 ft./sec.) as the formerly used steel cylinder.

Discussion of the Cylinder Types

The causes of the great differences in the heat given off by the different types of cylinders were then investigated. The temperature distribution along the walls of the different cylinders was determined for the same temperature of the compression chamber and the same air-stream velocity (Figs. 13-17). Obstructions to the heat flow produced sudden temperature variations, while good heat conduction was indicated by the very gradual variation of the temperature curve.

The clearest example was furnished by the cylinder with the removable cast-iron head (Figs. 5-6). Between the cylinder and the cylinder head there was a thin copper-asbestos gasket, which offered a very high resistance to the downward flow of the heat. This obstruction had a decided effect on the temperature curve and threw the burden of heat dissipation almost entirely on the cylinder head. With the deep aluminum head (Figs. 7-8) the equalization of the temperatures is assured by the active flow of heat in the thick walls. Particularly evident is the downward flow of heat in the aluminum head without fins (Figs. 9-10). In the experiments it was found that an aluminum head without fins always dispersed somewhat more heat than a removable cast-iron head. The fins on the aluminum head increased the heat dispersion threefold and reduced the mean temperature correspondingly.

Inferences by Analogy

Figure 19 shows the logarithmic curves which characterize this type of cylinder. It shows the specific heat dissipation for all practical air velocities, temperatures and cylinder diameters. It also illustrates two important general laws:

1. The specific heat dissipation increases with the air velocity rapidly at first and then more slowly.

2. Other conditions remaining the same, the specific heat dissipation decreases with increasing cylinder diameter.

Verification of the Experimental Results

Knowledge of the specific heat dissipation enables one to determine beforehand the heat characteristics of a projected cylinder. The heat calculations of a cylinder involve three steps:

1. Calculation of the heat load. Figures 20-22 show the results obtained with three different cylinders.

2. Determination of the specific heat dissipation α of a given cylinder type (Fig. 19).

3. Calculation of the temperature from the temperature difference between the cylinder wall and cooling air required for a balance between the heat load and the heat dissipation.

The heat load in the cylinder of the small Siemens radial engine is 226,700 kcal/m²/h. The temperature reached by the cylinder in cooling air at 0°C (32°F) and 45 m/s (148 ft./sec.) velocity is obtained by dividing this number by the corresponding value of α, which is 1200 kcal/m²/h/°C in the present case. It is 189°C (372.2°F). Measurements with this cylinder at 1°C (33.8°F) gave a mean temperature of 177°C (350.6°F), making the discrepancy between the calculated and measured mean temperatures only 12°C (21.6°F). This is a very satisfactory result, as compared with the former complete uncertainty of the temperature of a newly designed cylinder.

In order to test further the range of applicability of the measurements, we made advance calculations for a newly designed cylinder with $3\frac{1}{2}$ times the volumetric capacity of the small cylinder tested in the wind tunnel. It was some months before the large cylinder was tested. It was then found that the previously calculated temperature differed only a few degrees from that measured in the middle of the cylinder head while in operation.

Maximum Power of Present-Day Cylinders

Figure 23 shows that the heat loads increase with increasing cylinder diameter for the same stroke-bore ratio. On the other hand the experiments show that the amount of heat dissipated decreases under the same conditions. Hence it follows that, under otherwise similar conditions, the wall temperatures increase with increasing cylinder dimensions.

Efficiency tests by Professor Gibson show, however, that the temperature of a cylinder cannot be indefinitely increased without finally having an unfavorable effect on its efficiency (Gibson, "Aero-Engine Efficiencies," The Aeronautical Society, London). For example, the volumetric efficiency decreases with increasing cylinder temperature (Fig. 24), and the fuel consumption increases with decreasing mean piston pressure (Fig. 25). Hence with increasing cylinder diameter temperatures are approached which greatly reduce the power and economy. In this connection either the cylinder temperature or the degree of cooling is the limiting factor for the cylinder power. The maximum running temperature cannot be definitely prescribed. Just as in the designing of machinery, however, certain stresses are designated as admissible, about 300°C (572°F) may be considered an admissible temperature for an air-cooled cylinder head. With this limiting temperature the maximum power of a single air-cooled cylinder without supercharging is about 70 horsepower.

Increasing the Power by Supercharging

The maximum cylinder power will not remain long at the above figure, however. Any decrease in efficiency may be prevented by supercharging. The turbo-blowers now commonly used with radial engines may be regarded as a development of the rotary mixture distributer originally used by Armstrong for air-cooled radial engines. While the mixture distributer revolves at the speed of the crank shaft, the speed of the supercharger rotor has already been increased to 15,000 r.p.m. An essential task of the supercharger is always to assure an adequate charge even at a high cylinder temperature. Hence it enables the increasing of the admissible temperature of air-cooled cylinders. Since it is driven, however, by gears from the crank shaft, the power required to operate it is lost to the propeller. The mechanical efficiency of the engine is therefore reduced and its fuel consumption increased.

It is more economical to operate the supercharger by turbines utilizing the heat of the exhaust gases (Fig. 26). Such superchargers have been used principally for high-altitude flying. Their speed ranges from 20,000 to 40,000 r.p.m. and adapts itself automatically to the atmospheric pressure. They considerably reduce the noise of the exhaust. In order to avoid injury to the engines, these high-altitude superchargers can be used for only brief periods of time to increase the engine power near the ground.

Longer Strokes Rather than Larger Bores

Supposing the power of a short-stroke cylinder has been increased to the temperature limit, then, due to the decreasing coefficient of heat dissipation, any further increase of the bore would result in still higher temperatures and uneconomical operation. On the other hand, lengthening the stroke would not affect the coefficient of heat dissipation nor the economy of operation, even at a higher power.

In this connection, if we compare the results obtained with two air-cooled radial engines, as given in the accompanying table, we find that engine A reached the temperature limit and even exceeded it as a fuel consumption of 248 g/hp/hr (0.547

lb./hp/hr.). It appears hardly possible to increase the power further with economy of operation. Engine B had the same bore as A, but a longer stroke. It attained the same output of 425 hp at a considerably lower speed (1590 as against 1900 r.p.m.). Its temperature was therefore lower, as shown by the fuel consumption. While engine A attained the maximum output of 450 hp at 2100 r.p.m., the output of engine B could be increased to 580 hp at 2200 r.p.m., at which point, however, the specific fuel consumption began to increase. In order to increase the power at the temperature limit, it is therefore better to lengthen the stroke than to enlarge the bore.

Lower Speed and Larger Displacement Indicated for Commercial Aircraft Engines of the Future

A long stroke is better for an aircraft engine for the further reason that it enables a lower revolution speed for the same piston speed and also because the lower revolution speed thus yields the same weight per horsepower, provided the piston speed remains the same, since in my opinion the piston speed (not the revolution speed) is the determining factor for the power and weight of an engine.

The low-speed, long-stroke Beardmore engine (See table) is but little heavier than the high-speed Fiat engine. In their constant endeavor to obtain higher engine speeds, aircraft engine designers are apparently still under the influence of automobile engine designers. The high speeds may be justified for small water-cooled automobile engines, but they necessitate reduction gears on aircraft engines. A low-speed long-stroke aircraft engine, on the contrary, can dispense with reducing gears, thus enabling a greater output with a more economical fuel consumption. Its design is simpler, its production and upkeep cheaper and, above all, its operation more reliable. Its smaller fuel consumption enables it to run several hours longer than a high-speed engine with the same weight of fuel. It is now represented by only a few types, but is likely to play an important role in the future in commercial aviation and perhaps in a few military applications. It is not so suitable for combat airplanes because of its larger space requirements. Unfortunately, aircraft engine designers of the whole world are too greatly influenced by military requirements, much to the detriment of commercial aviation, which is now compelled to use very light high-powered engines whose structural parts are too highly stressed. Such military aircraft engines cannot continue to be used much longer on commercial aircraft. In Germany at least there is no reason for joining in this pursuit after extreme lightness, which leads to more forced landings than commercial aviation can continue to tolerate. We should rather consider it our task to furnish the universally famed German commercial airplanes with absolutely reliable engines.

Racing Engines

In contrast with this still lacking type the Bristol Mercury is a very highly perfected engine for racing airplanes and at the same time the most powerful air-cooled 9-cylinder engine in the world. It is a good demonstration of what high powers can be developed by air-cooled cylinders. It became known at the 1927 international seaplane races in Venice (Zeitschrift des Vereines deutscher Ingenieure, 1927, p.1740). All the means known to us today were employed to increase its power.

1. The cylinders had shrunk-on light-metal heads, each with four valves and push-rod balance.
2. The crank-shaft speed was increased to 2800 r.p.m.
3. A bevel reduction gear reduced the speed of the propeller shaft to 1400 r.p.m.
4. A mechanically driven turbo-blower of 65 hp at 22,000 r.p.m. was built into the rear end of the crank case.

This engine developed not less than 920 hp, or more than 100 hp for each air-cooled cylinder.

Results Obtained with Different Engines

Engine	d	s	$\frac{s}{d}$	N	n	c_m	b	N_{max}	n_{max}	b_{max}
Radial engine A	146	146	1	425	1900	9.25	248	450	2100	250
" " B	146	190	1.3	425	1590	10.1	228	580	2200	240

Engine	d	s	$\frac{s}{d}$	N_{cyl}	n	c_m	b	N_l	E_g	G_{f4h}
Fiat 980 hp	170	200	1.17	81.6	2000	13.3	265	13	0.91	1.97
Beardmore 900 hp	219	317.5	1.45	150	1350	14.3	220	17.6	1.0	1.89

d, cylinder bore (mm)

s, piston stroke (mm)

N, total engine output (hp)

N_{cyl}, output per cylinder (hp)

n, revolution speed (r.p.m.)

p_m, mean pressure (atm.)

c_m, mean piston speed (m/s)

b, fuel consumption (g/hp/h)

N_l, output per liter of fuel (hp)

E_g, empty weight per horsepower (kg/hp)

G_f, flying weight per horsepower (kg/hp)

Translation by Dwight M. Miner,
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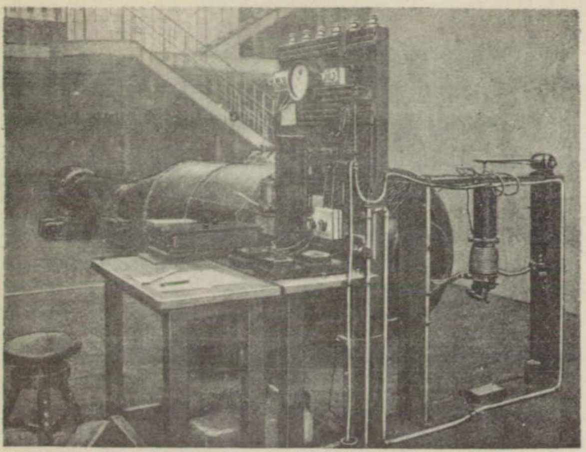


Fig.1 Experimental equipment

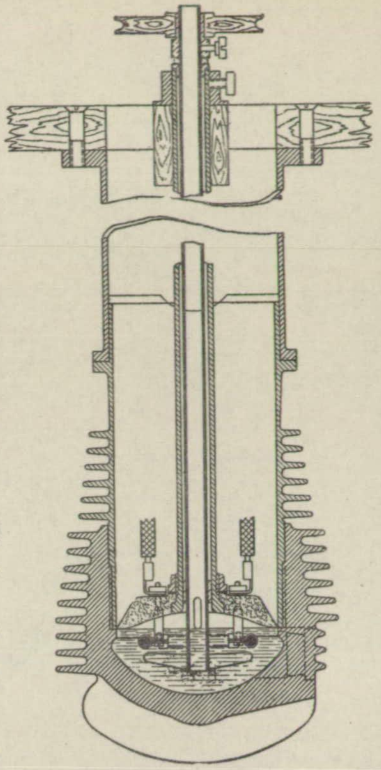


Fig.2 Heating apparatus in cylinder head. Electrically heated oil bath with stirer and vapor outlet.

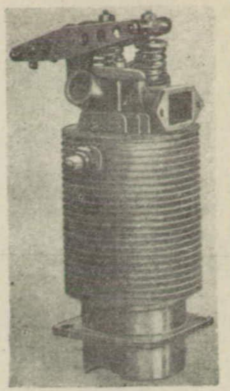


Fig.4 Cylinder type, 1918(Fig.3) Steel cylinder, closed at top, with cast-on aluminum sleeve with fins. Comp. ratio ϵ = 4.7

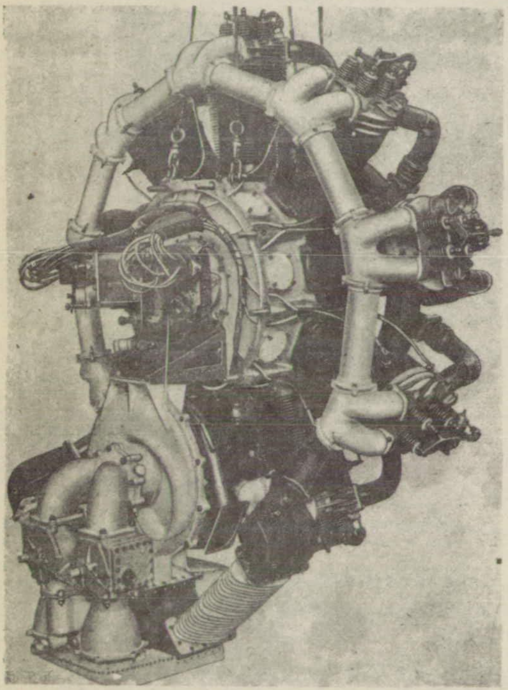
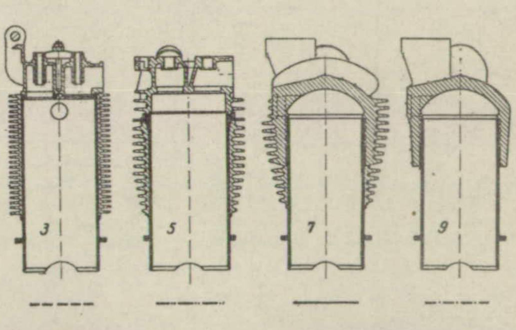


Fig. 26 A 450 hp Bristol "Jupiter" engine with exhaust-gas turboblower for high-altitudes.



Figs.3, 5, 7, 9. Cross section of cylinders investigated.

Fig. 6 One-piece removable cast-iron head with valve housing. Aluminum sleeve with fins.(Fig.5)

Fig. 8 Cylinder types of 1924-1928. Open steel cylinder (Fig.7). Screwed-on aluminum head with valves side by side. $\epsilon = 5.6$ to 7.

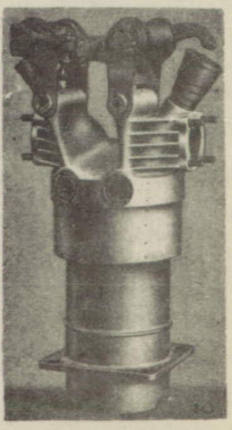
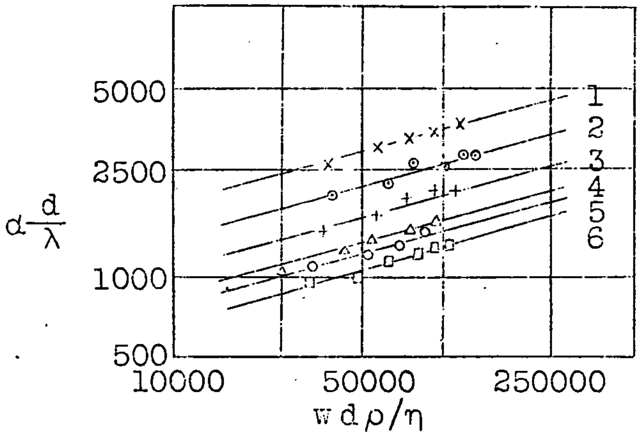


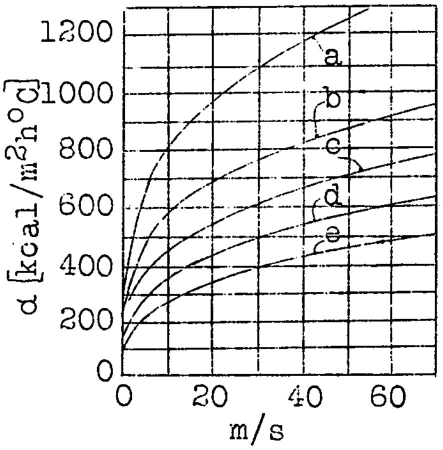
Fig.10 Experimental cylinder like Fig. 8, but without fin sleeve (Fig.9)



d,cyl. dia; w,air velocity; α,coef.of heat transmission; λ,coef.of heat flow; ρ,density; η,viscosity.

1. Cylinder like Fig.7-8,depth of fins 22 mm (0.87 in.)
2. " " " " ,but with fins 10 mm deep.
3. " " " " , " " " 2 mm " .
4. " " " 9-10.
5. " " " 5-6.
6. " " " 3-4.

Fig.11 Characteristic curves.



a, Aluminium head with ribs 22 mm deep.
b, Aluminum head with ribs 10 mm deep.
c, Aluminum head with ribs 2 mm deep.
d, Aluminum head without ribs.
e, Closed steel cylinder.

Fig.12 Specific heat dissipation plotted against air velocity for cylinder diameter, d=100 mm and a mean temperature difference of 150°C between cylinder wall and air stream.

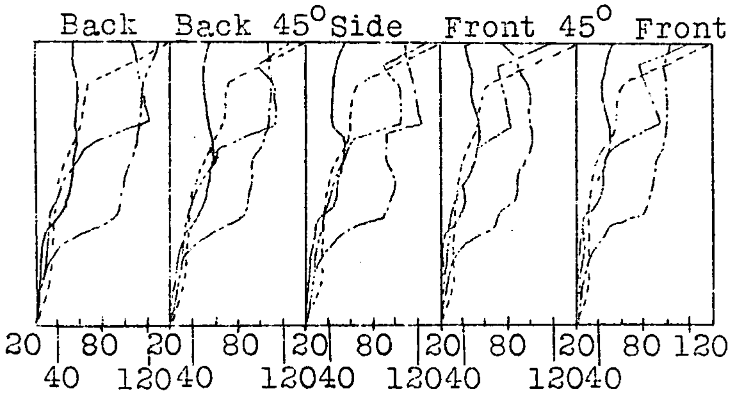


Fig.	---- 3 ---	—— 5 - - ——	7 ————	— 9 - — - -
Cylinder	Closed	Open	Open	Open
Head	Steel	Cast iron	Aluminum	Aluminum
Fins	Cast-on fin sleeve			No fins

Figs.13-17 Temperature distribution from middle of cylinder head to flange for cylinders in Figs.3-10 with like heating of compression chamber and like air velocity

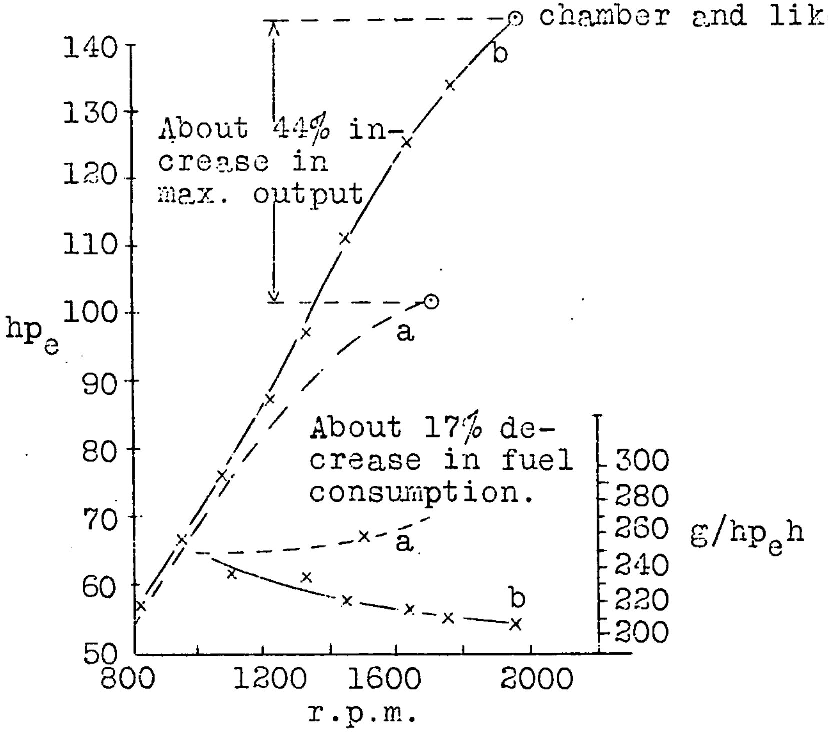


Fig.18 Power output and fuel consumption of Siemens radial engine with cylinders like Figs.3-4(a) and like Figs. 7-8 (b).

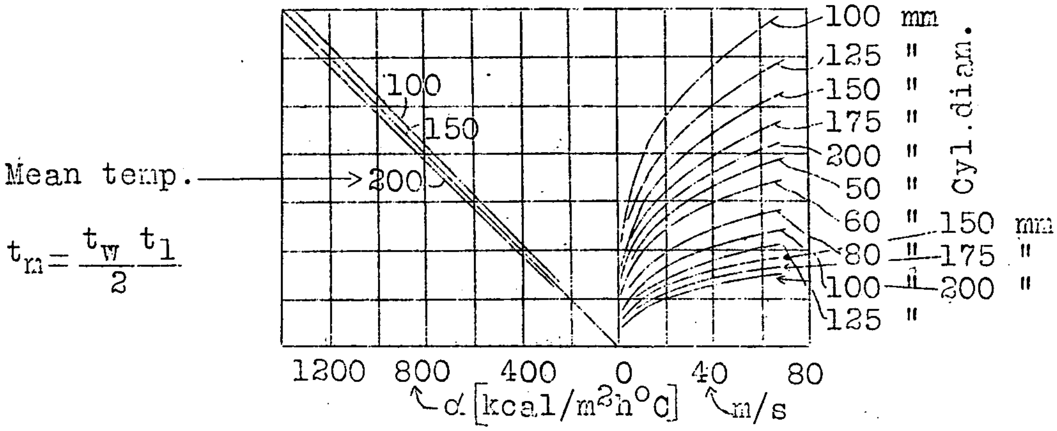
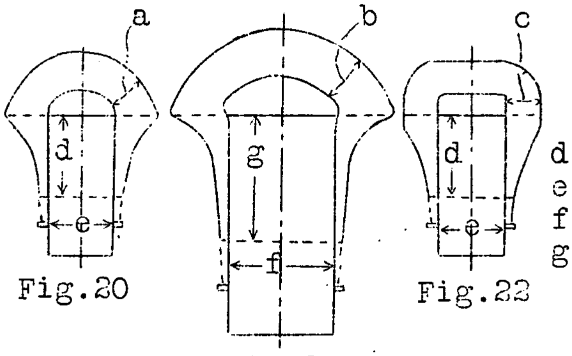


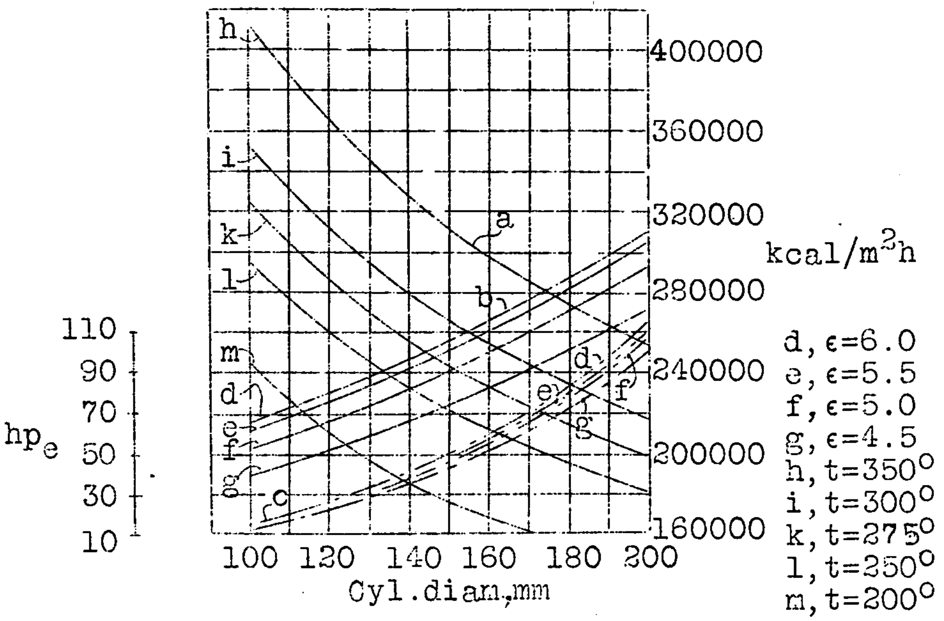
Fig.19 Specific heat dissipation plotted against mean temperature and air velocity for various cylinder diameters. Lower group of curves is for cylinders shown in Figs.3-4, upper group for cylinders in Figs.7-8.

a, Q=226700 kcal/m²h
b, Q=278000 "
c, Q=204300 "



d, 120mm
e, 100 "
f, 154 "
g, 188 "

Fig.20-22 Heat loads of different cylinders.



a,Heat dissipation at different wall temp. b,Mean heat transmission at head.c,Output,hp_e.

Fig.23 Heat dissipation plotted against cyl.diam.at different compression ratios and wall temp.for cyl.like Figs.7-8 for $^s/d$=1.2, w=180 km/h and n=1500r.p.m.

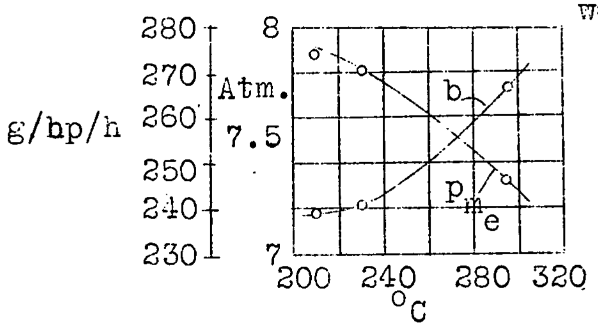


Fig.24 Decreasing volumetric efficiency with increasing cylinder temperature.

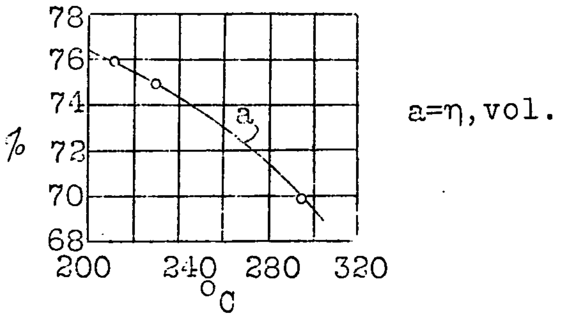


Fig.25 Mean working pressure and fuel consumption plotted against cylinder temperature.