FOR AERONAUTICS

JAN 31 1923
MAILED

Mr. Faucett

TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 135.

RESULTS OF EXPERIMENTAL FLIGHTS AT HIGH ALTITUDES WITH DAIMLER, BENZ, AND MAYBACH ENGINES TO DETERMINE MIXTURE FORMATION AND HEAT UTILIZATION OF FUEL.

By K. Kutzbach.

From Technische Berichte, Volume III, Part I.

January, 1923.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL NOTE NO. 125.

RESULTS OF EXPERIMENTAL FLIGHTS AT HIGH ALTITUDES WITH DAIMLER, BENZ, AND MAYBACH ENGINES TO DETERMINE MIXTURE FORMATION AND HEAT UTILIZATION OF FUEL.

By K. Kutzbach.

The experimental flights described herein were made with the object of obtaining information regarding the following two questions, which as yet have not been sufficiently elucidated. These are:

1 What effect has altitude upon the formation of the mixture?

2 What alteration takes place, with increasing altitude, in the utilization of the heat contained in the fuel?

The following observations must be borne in mind, in order that the results of the tests may be correctly interpreted.

1. <u>Alteration in mixture with increased altitude</u>.- The quantity of fuel introduced into the engine cylinder in the form of an air-fuel mixture, depends (1) upon the pumping efficiency (η_l) of the engine, i.e. its efficiency as an air pump, and (2) upon the temperature and pressure of the outer atmosphere. This efficiency is further dependent upon:

(A) Volumetric efficiency, η_f, influenced by the valve setting and resistance encountered in the induction system, and, generally, by the difference between the exhaust and the induction pressures in the cylinder.

---

* From Technische Berichte, Volume III, Part I.

2. The Temperature rise η_T of the mixture, produced by contact with the internal walls and surfaces of the carburetor, the intake manifold, and the interior of the cylinder (cylinder walls, piston head, valves) during the period between admission and at the beginning of compression. In so-far as the temperature of the admitted air is lowered by the vaporization of the liquid fuel, this has a favorable effect on the value of η_T

$$\eta_l = \eta_f \, \eta_T \qquad (1)$$

With the carburetor fully open, owing to the flow of the mixture due to its inertia, η_f may even reach 0.95 as the inlet valve is often open until the crank is between 40° to 70° past the dead center. The temperature rise is difficult to determine, as any estimate based upon temperature measurements in the cylinder will give an erroneous impression. The heating of the incoming mixture by the residual products of the preceding combustion has no effect on η_T, as the residual products of combustion are themselves subject to cooling action and their influence on the volume admitted, is, therefore, neutralized. Hence the mixture being cooled through vaporization of the fuel by some 20 - 25°, must undergo a temperature rise of only about 30° (up to 50°). In relation to T_a, the temperature of the atmosphere at admission to the carburetor, the value for η_T is, therefore,

$$\frac{T_a}{T_a + 30^\circ}$$

approximately 0.9 (to 0.85), so that in the most favorable case

$\eta_l = \eta_f \times \eta_T$ = 0.95 × 0.9 = approximately 0.85 (to 0.8), hence for well-designed engines with mechanically operated inlet valves, η_l = 0.3 to 0.85, at standard temperature t_a and standard pressure b of the atmosphere.

With charging taking place at the standard atmospheric pressure of 760 mm and an air temperature of 15°, the volume admitted is further affected by

$$\mu = \frac{273 + 15}{273 + t_a} \; \frac{b}{760} = 0.379 \, \frac{b}{T_a} \text{ approximately}$$

Assuming that

H_u = the lower calorific value of the fuel in kcal/kg (light gasoline is about 10000 kcal/kg)

B = Fuel consumption of the engine in kgs per hour

V_h = Total stroke volume of the engine in cubic meters so that at "N" R.P.M. the engine piston has an hourly working displacement volume of $\frac{N}{2}\, 60\, V_h$ cubic meters. Then the heat capacity of the fuel in units of working volume of the cylinder

$$\frac{H_u \, B}{30 \, N \, V_h} \text{ kcal/m}^3 \text{ or gcal/lit.}$$

If H_o in kcal/m³ of gcal/liter is the heat value of the fuel-air mixture at a temperature of 15° and a barometric pressure of 760 mm, then the heat capacity of the fuel per unit volume of the cylinder is, also $= H_o \, \eta \;\; \mu_l$

Therefore

$$H_o \, \eta_l = \frac{H_u B}{30 \, N \, V_h \, \mu} \tag{2}$$

This figure $H_o \eta_l$ which can be called the specific heat value of the working stroke volume, or, in short, the "liter-heat" of the engine, gives a very convenient basis for judging the performance of the carburetor and its operation during flight. What is then the value of $H_o \eta_l$ with complete combustion and perfect fuel utilization?

If gasoline with approximately 10000 kcal/kg lower calorific value and requiring theoretically 12.5 m³ of air for complete combustion is taken, the heat units contained in the mixture, $H_o = \frac{10000}{12.5} = 800$ kcal/m³, assuming complete combustion, and the presence of the exact quantity of air required to effect this - no excess or deficiency.

If $\eta_l = 0.8$ to 0.85, $H_o \eta_l = 640$ to 680 kcal.

As about 10% extra air is necessary in practice for the complete combustion of fuel in the cylinder, $H_o \eta_l$ will then become 580 to 620. Thus the values of $H_o \eta_l$ according to the efficiency of the engine, lie somewhat between 580 and 680 for the best utilization of heat in the fuel. Outside these limits only imperfect combustion will result, owing to insufficient air, i.e. part of the fuel will pass unburnt through the engine, and, on meeting the outside atmosphere will continue in combustion as a visible flame from the exhaust.

1. The Result of the High Altitude Tests.

Figs. 1 and 2 show in curve 1 the values of $H_o \eta_l$. During a flight with a 260 HP Daimler engine without supercharger, the carburetors were fully open from the beginning, η_l having thus a maximum value for the given number of revolutions. It will be seen that the value $H_o \eta_l$ constantly increases with increasing altitude, and always far exceeds the value associated with the best utilization of heat in the fuel. In the test with a 200 HP Benz engine fitted with supercharger, the throttle could not be fully opened until a considerable altitude was reached (altitude regulation) and η_l only attained its maximum above this. Here also the value of $H_o \eta_l$ rose above permissible limits. It should moreover, be noted that $H_o \eta_l$ in passing from throttling to altitude control, does not increase very much, showing that the opening of the throttle does not increase η_l much further. The contrary was the case with the Maybach engine No. 1224, where full opening of the throttle at 3500 m (11500 ft) altitude had the effect of considerably increasing η_l and, therefore, also $H_o \eta_l$. All three engines seemed, however, to be running with much too heavy fuel consumption, the value of $H_o \eta_l$ rose considerably above 680, so that some means had to be found to correct this.

Fig. 2 shows on the right the effect of one such means adopted with Maybach engine No. 1389, and which consisted in reducing the cross-section of the fuel jet on changing to the "altitude position" of the throttle. As the diagram shows, the throttle was put to altitude position intermittently at a fairly low altitude, and the throttle fully opened at a height of 2200 (7220 ft). With this improved carburetor, the value of $H_o \eta_l$, and thus the fuel consumption remained within permissible limits.

The fact that with all carburetors the value of H_0 increased with diminishing air density, is especially remarkable.

Devices for automatically regulating the quality of the mixture (by means of a barometer) have hitherto only been seen in periodicals and patent specifications; but many carburetors already possess devices to prevent fuel waste, as, for example, by means of a "compensator" (as it is called on the Hispano-Suiza engine) or a "fuel economizer", actuated by the pilot.

One of the simplest arrangements for this purpose, especially in supercharged engines, consists in placing within the air intake in front of the carburetor, or parallel to it, some form of throttle device or, supplementary air valve, which remains quite or nearly closed at low altitudes, and which is only fully opened at the higher altitudes. The fuel jet is then so regulated that, at low altitudes, the engine knocks (owing to excess of air) if the supplementary air valve or throttle is open, and runs smoothly with this intake throttled. For a more precise idea of the behavior of such devices in flight, it is sufficient to measure the fuel consumption and revolution speed of the engine.

3. Variation in fuel utilization with altitude.

The best idea of the fuel utilization at high altitudes, in addition to measuring the fuel consumption, is obtained by the careful determination of the speed of revolution of the engine. in horizontal flight in still air, unless, of course, a dynamometer can be fitted to the engine. Conclusions from this should, however, be drawn cautiously, as the revolution speed is dependent on several variable factors.

The revolutions per minute are influenced by the equilibrium maintained between the engine torque Q and the resistance D offered by the airscrew. The torque Q, depends on the heat, in the form of fuel, supplied to the engine, and the efficiency η_e of its transformation into work in the engine; it is thus proportional to the heat per unit volume of working stroke supplied by the fuel.

$$Q = c\ (H_o \eta_l\ \mu)\eta_e \qquad (3)$$

The efficiency η_e of the transformation of heat into work is composed of:-

1 The chemical or combustion efficiency (η_c) of the mixture, showing what portion of the chemical heat value of the fuel liberated by its ignition has really gone to develop heat in the engine.

2 The thermal efficiency (η_t) of the working cycle, the ratio of the heat developed in the cylinder to the indicated work done inside the cylinder on the piston, including, besides exhaust losses, also the losses of heat through the cylinder walls, and in "after" combustion.

3 The mechanical efficiency (η_m) of the transmission of work on the piston into torque at the crankshaft, including all losses due to friction, power absorbed by pumps, etc.

$$\eta_e = \eta_c\ \eta_t\ \eta_m \qquad (4)$$

The resistance D of the airscrew increases as the square of the revolutions, and as the air density (expressed by μ) and decreases when the speed V, of the airscrew relative to the air increases; this factor can be expressed by $f(V) = V^k$

$$D = c_1 \frac{N^2 \mu}{V^k} \qquad (5)$$

Equilibrium is obtained when $Q = D$ and, therefore, -

$$c \quad H_o \eta_l \quad \mu \quad \eta_e = c_1 \frac{N^2 \mu}{V}$$

or,

$$N^2 = c_2 \ (H_o \ \eta_l) \ \eta_e \ V^k \qquad (6)$$

V^k can be disregarded, as having little influence, V varying but little during the tests, and k approximating to unity. The ratio of the thermal efficiency for two flights at different altitudes is then

$$\frac{\eta_e}{\eta'_e} = \left(\frac{N}{N'}\right)^2 \frac{H'_o \ \eta'_l}{H_o \ \eta_l} \qquad (7)$$

These values are calculated from the values of N (curves 2) and $H_o \ \eta_l$ (curves 1), and are represented by curves 3. The values of η_e correspond in all engines to the altitude (point a) at which the throttle was fully opened (altitude position), and with the Benz engine, and Maybach engine No. 1224 also to the altitude (point b) at which the first reading was taken. In the two latter cases, it assumed that the value of η_e has not been altered by the movement of the throttle lever, that the curves 3 can, therefore, be continued to points c. This assumption is, however, only approximately correct (In the flight with Maybach engines No. 1224 the values were read at 2500 m (8200 ft) altitude, with the airplane descending, in which case, the thermal condition of the engine would be different, and, therefore, this point shows a marked divergence in all three curves).

It is, however, perfectly clear that in all engines the transformation of the heat of the fuel into useful work falls off very considerably with increasing altitude.

The chief reason for the great drop in η_e lies in the value of η_c. η_c becomes less than 1 as soon as the extra air taken in by the engine becomes insufficient (less than 10%), and thus the complete mixing of air and fuel, each molecule of fuel at once finding its molecule of oxygen, becomes impossible. Thus, if $\eta_c = 1$ up to the most efficient mixture of $(H_o\ \eta_l)_{opt} = 600$, then, for mixtures in which $H_o\ \eta_l$ is more than 600:-

$$\eta_c \sim \frac{(H_o\ \eta_l)_{opt}}{H_o\ \eta_l} \sim \frac{600}{H_o\ \eta_l} \qquad (8)$$

So long as combustion is complete, and $H_o\,\eta_l$ is below the value at which complete combustion of the mixture still takes place (here taken as 600), η_c remains equal to unity, and, using equation (4)

$$\left(\frac{N}{N'}\right)^2 = \frac{H_o\ \eta_l}{H_o'\ \eta_l'}\ \ \frac{\eta_t\ \eta_m}{\eta_t'\ \eta_m'} \qquad (9)$$

In other words: The revolution speed increases (if η_t and η_m do not decrease too rapidly) at first as $\sqrt{H_o\ \eta_l}$, until the best value for complete combustion $(H_o\ \eta_l)_{opt}$ is attained. This, seemingly was, at first, the case in the test with the Daimler engine.

As soon, however, as $(H_o \eta_l)_{opt}$, or N_{opt} is exceeded, it is clear that according to equation (8), when the supply of fuel to the engine is increased η_c alone decreases correspondingly.

$$\left(\frac{N_{opt}}{N'}\right)^2 = \frac{(\eta_t \eta_m)_{opt}}{\eta_t' \eta_m'} \qquad (10)$$

This equation permits us to conclude that, for values of $(H_o \eta_l)$ exceeding about 600, $(\eta_t \eta_m)$ must decrease as the square of the revolutions. The curves for N and $(H_o \eta_l)$ are very informative in this respect.

There can be no doubt that according to the above tests the product $(\eta_t \eta_m)$ decreased at high altitudes, even in the case of the last test with Maybach engine No. 1389. η_m would decrease, because part of the frictional losses (due to inertia and friction of auxiliaries) remain unaltered; while η_t decreases owing to slower combustion when $(H_o \eta_l)$ increases above a certain value, possibly also because the combustion takes place at lower pressure, and because the absolute heat capacity of the cylinder is small in comparison with the external cooling surface. In any case the R.P.M. of the Maybach engine No. 1389 with economizer jet, with which $(H_o \eta_l)$ remains in the neighborhood of 600, decreases far less at the outset than with the other engines. The conclusions to be drawn from these experiments regarding the design of the carburetor are obvious.

CONCLUSION.

1 All carburetors tested worked defectively, as the "liter-heat" increases with altitude, instead of remaining constant.

2 The efficiency of combustion, η_c, becomes considerably less than unity at high altitudes, owing to excessive fuel consumption, which, however, is avoidable.

The success of one of the numerous devices which can be incorporated with a view to increasing η_c is shown in a flight with Maybach engine No. 1389.

3 In the engines tested, the product $(\eta_t \eta_m)$ also decreases with altitude, in proportion to the square of the R.P.M. While the decrease of η_m can only be avoided by keeping the engine power constant at all altitudes, the decrease in η_t can certainly be put down, to some extent, to insufficient air in the mixture and can be reduced by the construction of proper "high altitude" carburetors.

Translated by the National Advisory Committee for Aeronautics.

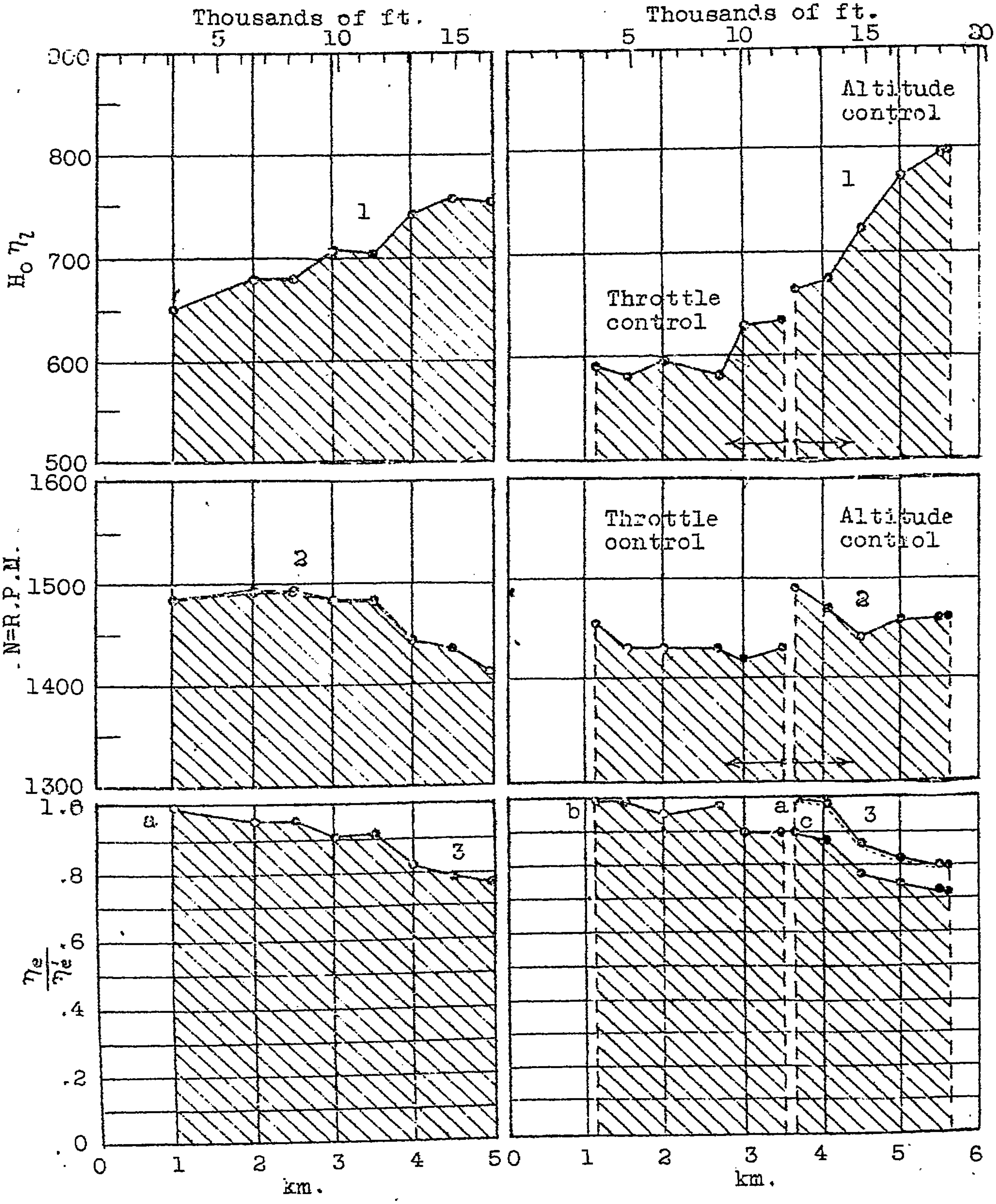

Fig. 1 Daimler D IVa Benz Bz IV

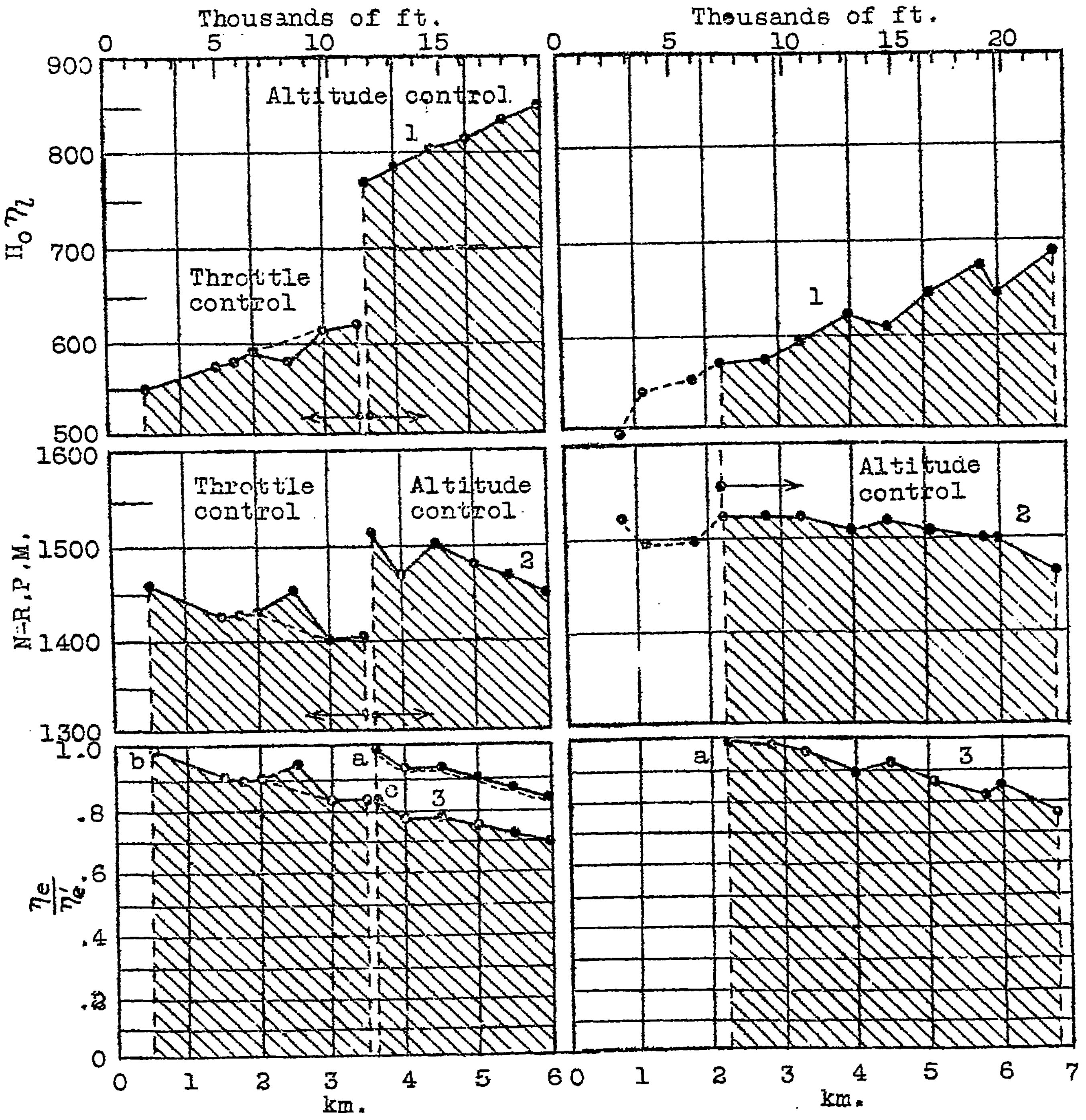

Fig. 2 Maybach Mb IV No. 1224 Maybach Mb IV No. 1389