THE USE OF THE TURBO-COMPRESSOR FOR ATTAINING
THE GREATEST SPEEDS IN AVIATION.

*Specific Pressures and Weights of Air
under Normal Atmospheric Conditions.*

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[*Translated from the French.*]

The object of this Paper is to show what must be done in order to obtain the greatest possible speed from an aeroplane ; and, while avoiding prophecies in regard to the distant future, the Author limits himself to that which appears to be realizable at the present time, namely, by making use of the latest improvements that have been thoroughly tested. It will be shown that it is certainly possible to exceed speeds of 400 km. (250 miles) per hour provided that the flight is made at a great height and that the power of the motor is maintained by means of a supercharging arrangement.

It is evident that the future of aviation, whether for commerce or war, depends on high speeds, and consequently in obtaining a high ceiling. The present speeds, which range from 150 to 160 km (94 to 100 miles) per hour for commercial aeroplanes, are insufficient to give a marked advantage over railway transport. I

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the speed could be doubled, without prejudicing that safety which it is hoped to secure shortly, long distance transport by aeroplane would become essential for important travel and for the postal services.

In the first place it should be noted that the aeroplane is the only vehicle in which the resistance to travel is independent of speed. This is directly proportional to the weight of the apparatus for the same angle of incidence, whereas in all other classes of transport the resistance increases with the speed—more rapidly than the square of the speed in the case of boats, less rapidly than the square of the speed in the case of railway trains and automobiles—on account of frictional losses, both independent of the speed and proportional to it, which form a part of the expression for the total resistance to movement. In rising through the air the aeroplane can select a medium of the density which suits it best, whereas the boat or the wheeled vehicle is unable to change its conditions of resistance.

Human possibility is, however, necessarily limited by conditions. It is certain that the aeroplane, like the boat and the wheeled vehicle, will find a practical commercial limiting speed. At the present moment it is not possible to determine this limit with any exactitude, because much still remains to be ascertained. It does not, however, appear unreasonable to expect a speed of at least 250 km. (155 miles) per hour, whereas at the present time the steam passenger boats run at 22 knots (40 km. per hour) and railway trains and automobiles at 80 km. (50 miles) per hour for long distances.

The following Table gives a survey of the figures for resistance per ton weight of vehicle :—

—	Speed.		Resistance.	
	Km. per hour.	Miles per hour.	Kg. per ton.	Per cent.
Cargo steamers up to .	20	12·5	2·5	0·25
Large Trans - Atlantic steamers up to . . }	40	25	6·0	0·6
Battle cruiser . .	65	40	25	2·5
Railway train . .	100	62·5	10	1·0
Automobile . . .	100	62·5	70	7·0

If these vehicles were capable of running at 400 km. (250 miles) per hour, then, by extrapolation from the formulæ for resistance, the following figures would be obtained :—

	Speed.		Resistance.	
	Km. per hour.	Miles per hour.	Kg. per ton.	Per cent.
Large trans - Atlantic steamers at least . . .	400	250	600	60·0
Railway train . . .	400	250	150	15·0
Automobile . . .	400	250	500	50·0

whereas, as will be seen, the aeroplane would only require 150 kg. (15 per cent) and perhaps as little as 120 or even 100 kg. per ton (12 or 10 per cent). At these high speeds, therefore, the aeroplane assumes superiority over other methods of transport from the point of view of the motive power required.

Normal Atmospheric Condition.—In design problems concerning aeroplanes, propellers and engines, it is the specific weight ρ (in kg. per m³.) of the air in which the aeroplane is flying that is the essential factor. On the other hand, the working of a centrifugal compressor depends on the pressure p (in kg. per m².). It is therefore necessary as a basis of calculation to ascertain as accurately as possible the laws for the decrease of p and of ρ with altitude, at least in the ordinary atmosphere of these countries.

Numerous observations made by means of sounding balloons during the last fifteen years have enabled these laws to be determined very satisfactorily. In particular there exist two extensive series of experiments, the results of which have been published by M. Soreau* on the one hand, for forty observations made during the first half of 1912 at Trappes, Pavia, Uccle, Strasbourg, Vienna, etc., and on the other hand by M. Lapresle,† for 215 observations made from the Lindenberg observatory near Berlin between 1906 and 1916.

At first sight the two series appear somewhat divergent, but

* Proc. of the Académie des Sciences. 1 Dec. 1919, and *Aérophile* 1-1 Dec. 1919.

† *Aérophile*. 1-15 March 1920.

careful analysis has shown, on the other hand, that they agree as perfectly as could be expected. The Author proceeds to give the result of this analysis.

The variation dp in the barometric pressure is necessarily dependent upon corresponding variation dZ in the altitude Z , reckoned from sea level, and to the specific weight ρ of the air at this altitude, by the differential equation :

$$dp = - \rho dZ \quad . \quad . \quad . \quad . \quad (1)$$

If the temperature of the air were constant, ρ would be proportional to p , and we should have

$$\rho = \rho_o \frac{p}{p_o} ;$$

hence

$$dZ = - \frac{p_o}{\rho_o} \cdot \frac{dp}{p} \quad . \quad . \quad . \quad . \quad (2)$$

whence by integration,

$$Z = \frac{p_o}{\rho_o} \log_e \frac{p_o}{p} = \frac{1}{M} \cdot \frac{p_o}{\rho_o} \log \frac{p_o}{p} \quad . \quad . \quad . \quad (3)$$

this last logarithm being to the base 10, and M the modulus.

Putting :

$$\frac{p}{p_o} = \mu \quad . \quad . \quad . \quad . \quad (4)$$

we also have

$$Z = - A \log \mu \quad . \quad . \quad . \quad . \quad (5)$$

where A is a coefficient, which, for the normal air pressure of 760 mm. of mercury (10,330 kg. per m².) and the specific weight 1.2932 times that of air at 0° C. is equal to 18,400 ; or more simply 18.4, reckoning Z in kilometres.

This is the well-known Halley formula ; it is not applicable to the lower strata of the atmosphere on account of the fall of temperature of the air with increased altitude ; but it applies to the stratosphere, at heights over 11 km. (7 miles), where the temperature remains practically constant up to the greatest heights attained by the sounding balloons ; it is therefore necessary to take the coefficient A such as to correspond to this temperature, which is - 54° C.

$$A = 18.4 \cdot \frac{219}{273} = 14.76.$$

FIG. 1.—Normal Atmosphere, Altitudes Z .

$$Z = -A \log \frac{p}{p_0}.$$

$$Z = -B \log \frac{\rho}{\rho_0}.$$

In the stratosphere, consequently, between the altitudes Z_1 and Z_2 and the pressures p_1 and p_2 the conditions are

$$Z_2 - Z_1 = 14.76 \log \frac{p_1}{p_2} \quad . \quad . \quad . \quad (6)$$

We shall now examine from the means of the observations how the coefficient A in formula 5 varies with the altitude.

On the diagram, Fig. 1 (page 799), where Z is the abscissa and A the ordinate, corresponding points are plotted for :—

1. The Soreau figures in curve 1.
2. The Lindenberg figures in curve 2.

Up to values of $Z = 11$ km. the points obtained by experiment fall very closely on straight lines, which are moreover convergent, as would be expected, to a point on the axis of the abscissæ Z at 87 km. The divergencies between the points obtained by experiment and the straight lines do not exceed 0.14 per cent in relative value for the Soreau observations and 0.17 per cent for those made at Lindenberg.

If these differences are plotted as ordinates to a much larger scale, the diagram shown in Fig. 2 is obtained. This shows the remarkable agreement between the two series of figures, an agreement which cannot be accidental and which points to complete reliability in the results obtained from the observations. The actual curves deviate in wave-form from the mean lines.

Above 11 km., that is, in the stratosphere, the straight lines of Fig. 1 become hyperbolic arcs, asymptotic to the straight line $A = 14.76$ and parallel to the axis of Z .

The small difference, amounting to 1.3 per cent, between the Soreau and Lindenberg curves is evidently due to a small difference (amounting to about 3.6°C.) between the mean ground temperatures for the two series of observations.*

Up to $Z = 11$, or even $Z = 11.5$, it is therefore possible, with a degree of approximation of less than 0.17 per cent, for normal atmospheric conditions, to have

$$Z = -A' \left(1 - \frac{Z}{87}\right) \log \mu, \quad . \quad . \quad . \quad (7)$$

where A' is a coefficient having a value about 19 and varying

* The observations adopted by Mr. Soreau in his calculations were all made in winter or in the spring.

slightly, according to the ground temperature: 19.215 for the Lindenberg series of experiments and 18.965 for those of Soreau.

From this very simple formula, which is linear in relation to Z , it may be deduced that the pressure is reduced to one-half when $Z = 5.393$ km. and to one-fourth when $Z = 10.157$ km.; in the stratosphere the steps for reducing the pressure by one-half do not exceed 4.443 km.

The next step is the investigation of the specific weights. From equation (1), they are the derivatives of opposite sign to the pressure

FIG. 2.—Curves of Differences from Fig. 1.

referred to Z . Using equation (7), the value of the ratio $\lambda = \frac{\rho}{\rho_0}$ for the specific weights of air at the altitude Z (up to 11 km.) and at sea-level are easily found.

$$\lambda = \mu (1 - b \log \mu)^2 \quad . \quad . \quad . \quad (8)$$

b being equal to $\frac{A}{87}$.

Making, as in the Halley formula,

$$Z = -B \log \lambda \quad . \quad . \quad . \quad (9)$$

This formula enables the coefficient B to be deduced from the coefficient A. Thus expanding the series, and starting from the coefficient $A' = 18.965$ corresponding to the Soreau figures,

$$B = 23.4 (1 - 1.12 x + 0.1 x^2) \quad . \quad . \quad (10)$$

with $x = \frac{Z}{87}$.

The theoretical curve for this coefficient B is shown at 3 on Fig. 1. It is a parabolic arc differing very slightly from the straight line

$$B = 23.4 \left(1 - \frac{Z}{78}\right) \quad . \quad . \quad . \quad (11)$$

And, since the actual curve of the coefficient A of the formula for the pressure deviates in wave-form from the mean straight line, the same should apply to the true curve for the coefficient B, with greater variations; the maxima of the variations correspond to the points of inflexion of the curve of variation, shown in Fig. 2, and the points at which they meet the mean theoretical straight line correspond to the summits of the same curve in Fig. 2. This is what is shown in Fig. 1.

The points marked as round dots and the curve 4 have been deduced from figures given by the Lindenberg observations up to $Z = 12$ km.; the curve has been continued as a hyperbolic arc because, beyond this altitude in the stratosphere, the temperature is almost constant.

The points marked by crosses correspond to the figures for pressure given by Soreau up to 17 km. They were obtained by calculation from finite differences for successive kilometres. It will be seen that, notwithstanding the necessarily large variations due to this method of calculation, the agreement with the Lindenberg results is satisfactory, except for altitudes greater than 12 km.

The pressures and specific weights for normal atmospheric conditions are therefore accurately given. Until further observations introduce some corrections, which apparently can only be of small magnitude, the law for the variation of ρ with altitude can be taken as that which corresponds to curve 4 of Fig. 1, which, for an approximate calculation, can be taken as a straight line, or better still, for altitudes varying between 3 and 6.5 km., by the horizontal line $B = 21.8$, and, for altitudes between 6.5 and 15 km., by the straight line

$$B = 24.3 - 0.385 Z \quad . \quad . \quad . \quad (12)$$

The specific weight of air at normal atmospheric pressure, according to the curve, is reduced to one-half of that at ground-level at 6,530 m. altitude, and to one-fourth at 11,830 m. altitude; beyond this, in the stratosphere, the steps to reduce the specific weight by one-half are equal to 4,443 m., as in the case of the pressure.

With regard to the temperature of the air, this decreases from 5 deg. to 7 deg. C. per km., according to the altitude and the season of the year, until the stratosphere is approached. This decrease in a stable atmosphere can in no case exceed 10 deg. C. per km., which is the figure that corresponds to the adiabatic expansion of air in the upper strata; if this were not the case, a body of air which had begun to rise would continue in motion, because, at each successive level, it would have a specific weight less than that of the surrounding air.

THE AEROPLANE. INVESTIGATION OF THE CONDITIONS FOR HIGH SPEED.

The supporting surface is given almost entirely by the wings, a little by the fuselage of the aeroplane, and a small amount also by the tail-plane; on the other hand, the resistance R to forward movement is not only due to the wings, but also to the fuselage, the tail and all the accessories: struts, stays, wires, etc. These forces are proportional to the specific weight ρ of the surrounding air, on the one hand, and to v^2 on the other hand, v being the velocity of the aeroplane in metres per second.

For horizontal flight it may be taken that

$$\begin{aligned} R &= X\rho v^2 \\ W &= Y\rho v^2 \end{aligned} \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (13)$$

W being the total weight of the aeroplane in kg., X and Y two functions of the incidence of the wings alone, characteristic for the particular aeroplane. The ratio $\frac{R}{W}$, equal to $\frac{X}{Y}$ is therefore also a function of the incidence alone. The term "relative resistance" will be used for this and be denoted by f . The minimum value of f , usually obtained for angles of incidence approximating to 4 degrees for existing types of aeroplanes, will be called the "finess" of the aeroplane. Attention may be drawn to the fact that the fineness of the best aeroplanes flying is about 0.12; that in the types now being designed it is hoped to reduce it to 0.10 and even less, perhaps even to 0.08; and that the flight at ceiling height is obtained when

the incidence is exactly equal to that for this minimum value of f , or more accurately, as the Author has shown elsewhere, slightly greater on account of the increase of the slip of the airscrew with the incidence, an increase which allows the motor to revolve a little faster and consequently to give more power.

Let S be the area of the wings in square metres ; the coefficient Y is proportionate to it and

$$Y = K_y S \quad . \quad . \quad . \quad . \quad (14)$$

similarly for the portion X_a of the coefficient X , which corresponds to the resistance of the wings only

$$X_a = K_x S \quad . \quad . \quad . \quad . \quad (15)$$

It should be noted that the coefficients K_x and K_y are here referred to the specific weight ρ equal to unity, whereas ordinarily they are made to correspond to the arbitrary specific weight 1.225. The change can therefore be made from one to the other by dividing by 1.225.*

With regard to the portion X_c of X , which corresponds to the resistance of the fuselage of the aeroplane and to the various accessories, it is approximately independent of the incidence and of the area S of the wings. It will be assumed that it is quite independent of these, and, with a view to simplification of notation, X_c will be replaced by C giving

$$X = C + K_x S \quad . \quad . \quad . \quad . \quad (16)$$

The power P (in kg. m. per second) developed by the motor multiplied by the propelling efficiency η of the airscrew is equal to the resistance Rv of the aeroplane.

$$Rv = \eta P$$

Substituting $X\rho v^2$ for R and replacing ρv^2 by $\frac{W}{Y}$.

$$v = \frac{\eta P}{fW} \quad . \quad . \quad . \quad . \quad (17)$$

is obtained, an equation which is very simple and gives v as a function of the useful work ηP of the propelling mechanism, of the total

* It is to be regretted that from the commencement of laboratory work the coefficients were not systematically referred to $\rho = 1$, instead of to $\rho = 1.225$.

weight W of the aeroplane and of its total relative resistance f . But it does not show clearly the influence of a change in the supporting surface S . One would be tempted to introduce the minimum value for f , or the fineness of the aeroplane. This would not be correct because aeroplanes normally fly with angles of incidence much smaller than those of the ceiling. It is better therefore to treat the terms relating to the wings and those relating to the fuselage of the aeroplane separately. Then from equation (16) is obtained :

$$C\rho v^3 + Wf_a v = \eta P \quad (17A)$$

where C is the coefficient of resistance of the fuselage and f_a is the relative resistance of the wings alone.

This equation shows at once that the useful propelling power ηP being given (it is actually assumed that the motor is revolving at its maximum speed) and the fuselage of the aeroplane and its weight, the maximum speed of the aeroplane is obtained when the incidence of flight, in air having the specific weight that has been determined, is such that f_a , the relative resistance of the wings alone, is a minimum, and it is known that this optimum incidence of the wings is, for the usual form of profile, approximately $1^\circ 30'$.

Nevertheless an attempt to obtain this condition exactly would lead, as will be shown by an example, to extremely small, and consequently dangerous, wing area if flight had to be effected near the ground.

Even in theory, the maximum speed corresponds to a slightly greater incidence, and consequently to a still smaller wing area, because, as the latter is reduced, the weight can obviously also be reduced, so that the total weight of the aeroplane, instead of being constant, as had been assumed, is slightly diminished, and this acts in the same direction as the reduction in f_a .

But it must be noted that the relative resistance of the wing does not vary appreciably if a value for the angle of incidence is taken appreciably inferior to that which gives the minimum. It will therefore be of advantage to do this, in order that the area of the wings may be as large as possible.

Applying these formulæ to a concrete example, such as the Nieuport aeroplane, confirmed by the success with which Mr. Sadi-Lecointe obtained a speed of as much as 330 km. per hour (over 200 miles per hour) or 91.7 m. per second.

The particulars of this aeroplane are :

$$W = 980 \text{ kg.}, S = 11 \text{ sq. m.}, P = 320 \times 75, \eta = 0.8, \eta P = 19,200.$$

From these figures it can be deduced in the first place from the second formula (13) that :

$$K_{\eta\rho} = 0.0106,$$

which corresponds, according to the characteristics of the wings, to an incidence of flight approximating to -2° .

Then, from the first of the equations (13) and (16) it is found that :

$$(C + K_x S)\rho = 0.0249.$$

Now, the coefficient of resistance C of the fuselage of the aeroplane is, as has been stated, equal to 1.6 times that of the wings. Hence :

$$C\rho = 0.0153 \text{ and } K_{x\rho} = 0.00087,$$

whence $f_a = 0.082$. The relative resistance of the aeroplane as a whole is $f = 0.213$. We are therefore far from such fineness as 0.12 obtained by aeroplanes having large wings, and for which the resistance of the fuselage is about equal to that of the wings at the angle of incidence at the ceiling.

The next step is to find the maximum speed which would have been obtained if the constructor, while keeping the fuselage the same, had attempted to reduce the wing-surface still further so as to allow of flight under the optimum angle of incidence of about $1^\circ 30'$, assuming that the weight was not altered. In equation (17A) $C\rho$, W and ηP are not altered; but f_a will have been diminished; it will probably have a value of 0.05 instead of 0.082.

The equation then becomes :

$$0.0153v^3 + 49v = 19,200;$$

whence $v = 98$ metres per second, that is, 352 instead of 330 km. per hour.

The advantage is appreciable; but whereas the $K_{\eta\rho}$ at this incidence had increased to approximately 0.025 the area S of the wings would have been reduced to

$$\frac{W}{K_{\eta\rho} v^2} = \frac{980}{0.025 (98)^2} = 3.9 \text{ sq. m. only.}$$

The relative resistance of the aeroplane would have fallen to 0.184, instead of to 0.213, notwithstanding the great reduction in wing area.

This example shows conclusively that it is very difficult to exceed speeds of the order of 350 km. per hour near the ground ; the density of the air there is too great ; this requires the wings to be reduced to very small dimensions, which renders the manipulation of the aeroplane difficult and necessitates speeds of taking-off and landing that are extremely dangerous ; it diminishes the fineness of the aeroplane and causes an excessive load on the wings per square metre.

To overcome these difficulties, the only method is to find layers of the atmosphere of less density by rising to high altitudes. With the same fuselage, the coefficient C remaining constant, it will be seen that in equation (17A), which gives v , the coefficient C_ρ of v^3 diminishes proportionately to ρ ; but, the power P of the motor would fall still more rapidly, so that the speed would diminish if it were not for the method of restoring the power P of the motor by means of the turbo-compressor.

Going back to the aeroplane of Sadi-Lecointe, suppose it to be flown at a height of 6,500 m., for example, where the specific weight ρ is reduced to one-half of that at ground-level, and with the same incidence. The wing area will be greatly increased : 18 instead of 11 sq. m. The aeroplane becomes more like the normal type. But the weight will increase appreciably, not only on this account, but particularly because of the whole arrangement of the turbo-compressor, the weight of which is about 65 kg. A total weight of 1,100 instead of 980 kg. is therefore taken.

Equation (17A) then gives $v = 108$ m. per sec., that is 390 km. (242 miles) per hour. The relative resistance falls to 0.161.

Now flying the aeroplane at 11,800 m., where the specific weight of the air is only one-fourth of that at ground level, and giving it a wing area such that $f_a = 0.06$, and supposing the load to be increased to 1,200 kg., equation (17A) then gives $v = 135$ m. per sec., or 486 km. (302 miles) per hour. The wing area will still be about 18 sq. m. and the relative resistance will fall to 0.118.

But at this very great altitude, the lives of the pilot and of the passengers could not be guaranteed, except in air-tight cabins in which an air-pressure approximately equal to that at the ground would be maintained. This would cause an appreciable increase in the total weight of the aeroplane and moreover it could only be obtained with appliances of much greater size than that which has been taken as an example of the application of the formulæ. It is, however, in this direction that an attempt must be made to obtain very high speeds, of the order of 400 to 500 km. per hour (250

to 310 miles per hour). The matter is being considered from various sides. The problem is very difficult; it will certainly be solved, as many others have been, in a period of a few years if sufficient pains are taken and the necessary funds are forthcoming. So far as the turbo-compressor, which should be capable of compressing air from 0.2 up to 1.0 atmospheres, is concerned, there is no serious difficulty.

While waiting for the air-tight cabin it is possible to remain at altitudes of about 6,000 m., where the conditions for life are made possible by the use of oxygen apparatus for respiration, or even without this help.

The progress actually in sight will doubtless allow an appreciable reduction in the weight of the fuselage and of the wings, even though nothing can be done for the motor; an improvement in the dynamic qualities of the wings and a reduction of the passive resistance of all the "dead" portions of the aeroplane will be obtained, and this will enable the coefficient $\frac{R}{W}$ for normal flight, to be reduced to less than 0.12. It has also been proposed to flatten the fuselage considerably by placing the motors and the petrol and oil reservoirs, and even the men in the wings. This would not be possible except in the case of very large aeroplanes and of very thick wings. It might thus be possible to reduce $\frac{R}{W}$ in normal flight to considerably less than 0.12, even to 0.10. But, in order that too great a demand should not be made on the possibilities of the future, the value of 0.12 will be taken.

If, on the other hand, a mean weight of 6 kg. per horse-power is taken, which can now be obtained for a long distance flight, equation (17) then gives a mean speed of 300 km. per hour; it would be sufficient to reduce the mean weight per horse-power to 4.5 kg. in order to attain 400 km. per hour. This is doubtless not possible for long-distance machines, but it is certainly attainable for military aeroplanes which do not have to carry a heavy load of fuel. This is the order of magnitude of the speeds that it is to be hoped will be attained shortly by the assistance of the turbo-compressor.

It would be advisable, it appears, to encourage the invention of apparatus capable of giving these speeds by means of suitable competitions. Flights near ground level have given almost all that could be expected. As high speeds can only be obtained at great altitudes the time has come to abandon flight near the ground and to introduce regulations for competitions which will involve long distance flights at any height.

The Turbo-Compressor.—The indicated power of an aviation motor is roughly proportional to the weight of air that enters the cylinder in unit time, always supposing that the carburation is regulated in the same manner; but it is not this power that is of importance; it is the net power at the airscrew shaft, which is less than the indicated power by the total expended in piston friction, the friction in the connecting-rod ends and of the shaft in its bearings, losses due to vibration, losses in valve actuation, and in operating the oil and water pumps and driving the magnetos.

So many factors influence these losses that it is impossible to produce a simple and exact formula connecting the effective power with the air consumption. At best, therefore, it can be said that the present motors give about one horse-power per gramme of air introduced per second when working at normal atmospheric pressure; a little more (or, rather, a little less) than one horse-power, according to whether the motor is above or below the average, whether the lubrication is better effected or no, whether the pressure at the end of the compression is higher or lower, etc.

The torque Q is approximately independent of the speed of rotation within practical working limits, at least for non-rotary motors, and may roughly be given by the very simple formula:

$$Q = A (\rho - \gamma) \quad . \quad . \quad . \quad (18)$$

A being a coefficient peculiar to the individual motor, ρ the specific weight of the induction air, γ a constant, characteristic for each motor, differing little from 0.12.

It will be seen at once from this that, as the aeroplane rises, and the density of the air diminishes, the torque and the power decrease more rapidly than ρ . At 6,500 m., where ρ is reduced to one-half the torque falls to 44 per cent of the value at ground level. It would fall to zero if the formula remained true when ρ fell to 0.12, that is to say, when Z is approximately 18 km.

It is this rapid fall in the torque which causes the drop in speed on the level and in climbing, and which limits the height of the ceiling. At constant torque the incidence of flight would remain the same as also would the outflow and the power absorbed by the airscrew; speeds for horizontal flight would increase inversely as the square root of the density, and in theory the ceiling would cease to exist. The limit would be attained by the maximum speed permissible for the revolutions of the motor.

From the first days of aviation many ingenious inventors had thoroughly foreseen and shown that it would be possible to overcome

this serious difficulty by compressing atmospheric air in the first place in such manner as to feed the motor at a higher pressure, and thus to enable it to draw in a greater charge of air ; but no one, so far as is known to the Author, had yet endeavoured to find a practical solution, until in 1915 the question was put to him by the Lorraine-Dietrich Company. They thought that a solution might be obtained by the use of a centrifugal fan driven by the motor itself through a speed-increasing gear, and they sought the assistance of the Author because of his experience in this class of machinery.

After considering this problem, as well as several others, the Author recommended that no trials should be made. It appeared in fact, that the gearing and the fan, which should in this case be formed of several revolving wheels, would be too heavy and would take up too much space ; moreover, the permanent connexions of the fan to the motor would overload the latter uselessly at starting and would introduce an element of risk. Finally, as will be seen later, in order to re-establish in a suitable manner the initial pressure found at ground level, it is necessary that, as the aeroplane rises, the speed of rotation of the fan should increase progressively in the ratio of 1 to 2.5 at least, a ratio which is much greater than that of the speeds of rotation of the motor. It would therefore be necessary, in order to make good, to insert a change-speed gear, as on automobiles, and this is not practicable on an aeroplane. This arrangement did not appear to the Author to be acceptable. It was this method, however, that was tried later by the British Aeronautical Service, the Author believes without success, and by the Germans, who, towards the end of the war, began to turn out some appliances of this class. It may be presumed that, except perhaps in special cases, this solution will be abandoned in favour of that which has been perfected in France.

The Author had set the problem aside until, in August, 1916, Mr. Bastiou, the pilot, came to ask his help in following up some investigations which he had commenced. He had clearly seen, from his own work, the advantages to be obtained from supercharging and from running the motor at constant torque ; but he also sought for a combination of a compressor driven by the motor.

On further investigation the Author found that the objection would be avoided by a different combination consisting of the coupling of the fan not to the motor itself, but to a turbine driven by the exhaust gases. Provided that the rotor could be caused to revolve at very high speed, the appliance would be small and light, a single wheel being sufficient, both for the compressor-fan and for the turbine. Moreover, this would give complete independence

of the motor and of the supplementary turbo-compressor, because an ordinary exhaust cut-out capable of being operated by the pilot would enable him to turn the gases through the turbine or to exhaust direct to the atmosphere and even to regulate the action progressively.

In any event, the scheme would not be practical unless sufficient power were available in the exhaust gases to compensate for all the losses in the fan on the one hand, and in the turbine on the other hand, without causing excessive back-pressure on the motor. Fortunately, by a lucky chance, the compensation is found with a back-pressure on the motor approximately equal to or slightly higher than the pressure at which the fan must deliver, so that it is possible in practice at any altitude, to restore the motor to almost the same conditions as when running at ground-level; the energy obtained by the expansion of the exhaust gases, between the pressure at the ground and the pressure at the altitude at which the aeroplane is flying is, in fact, sufficient to compress the air-supply to the higher pressure from the lower. That this is the case can be easily shown in the following manner.

To begin with, it is well to note that if there is no leakage, the weight of the gases leaving the motor is slightly greater than the weight of the air that enters it, because, to the air taken into the carburettor must be added 5 to 6 per cent of petrol; next it must be noted that the gases, which leave by the exhaust from a motor running under normal conditions at ground-level, are at a temperature of 800°C ., or at about 750°C . (or $1,023^{\circ}$ absolute C.) after being cooled in the exhaust manifold between the motor and the turbine. If the aeroplane is at an altitude at which the atmospheric air is at a temperature of -20°C ., for example, that is 253° absolute C., the volume of gas leaving will be greater than $\frac{1023}{253}$ or equal to four times the volume of the air entering, measured at the same pressure, and, consequently, working between the same pressures, the gas that is exhausted should theoretically be able to give four times the work strictly necessary for the compression of the air. Hence it will suffice if the turbo-compressor unit has an efficiency equal to the inverse of 4, that is, of 25 per cent, in order that the appliance may work in practice within the given conditions.

Now, it is very easy to make, even without going to the most perfect forms, a fan and a turbine in which the losses of energy of every kind are less than the actual useful work done. The turbine and the fan having each individually an efficiency of over 50 per cent, the combination has an efficiency equal to the product, or an

overall efficiency of 25 per cent. The actual apparatus has 27 per cent; and given a slight increase in weight and space, the Author thinks that it should be possible to obtain rather over 30 per cent. The solution therefore appears quite hopeful.

The above brief description does not take into account, it is true, the variations of temperature which necessarily occur during the expansion of the exhaust gases in the turbine and during the

FIG. 3.—Ratio $\frac{p_1}{p_0}$ plotted for various values of τ in equation $\tau = \eta \frac{T_1}{T}$.

compression of the air in the fan. A perfectly correct theory, which can easily be proved, leads to a formula which is translated graphically in Fig. 3. The ratio of the pressure p_0 of compression of the fan (which is also very closely the pressure of the induction of the motor) to the actual atmospheric pressure p at the actual apparatus, is plotted as abscissæ; and the ratio of the exhaust pressure p_1 of the motor to the pressure p_0 of the supply is plotted

as ordinates. The corresponding curves at various values of the coefficient $\tau = \eta \frac{T_1}{T}$ which governs this ratio $\frac{p_1}{p_0}$ where

η is the overall efficiency of the turbo-compressor,

T_1 the absolute temperature of the exhaust gases on entering the turbine,

T the temperature of the air drawn in through the compressor fan.

From this curve, it will be seen, for instance, that if at the altitude of 5,400 m. it is desired to re-establish the pressure at ground-level, that is to say, to obtain a ratio $\frac{p_0}{p}$ of compression equal to 2, with $\eta = 0.27$, $T_1 = 1,023^\circ$ absolute C, $T = 253^\circ$ absolute C, which gives to τ the value 1.1, it would be necessary that $\frac{p_1}{p_0} = 1.09$ in order that the turbo-fan should fulfil the required conditions, and this without taking account of the 5 to 6 per cent of petrol introduced in carburation. It follows from this that there is a back-pressure on the motor of 0.09 kg. per cm.² over and above that when running at ground-level. This is hardly appreciable.

The curves drawn on the diagram, up to $\tau = 1.3$ rise for values of $\frac{p_0}{p}$ greater than 1.7. It appears therefore that, if it were desired, at altitudes above 10 km. to restore the atmospheric pressure at the ground, that is to say, if the ratio of compression were to be greater than 4, instead of 2 which has just been considered, it would be necessary to allow for a greater back-pressure on the engine. With regard to this it should be noted :—

1. That with increased altitude, the temperature T of the air will fall, whereas T_1 will remain sensibly constant ; from this arises a considerable increase in τ .

2. That two-stage compression will give improved efficiency to the compressor if provided with an intermediate cooling radiator.

The general formula shows, for example, that for a ratio of compression of 4, with $T_1 = 1,023^\circ$ absolute C, $T = 220^\circ$ absolute C, which exists on the average for $Z = 11$ km., then, if the overall efficiency of the turbo-compressor attains 0.316, this will be sufficient, and it is a figure which can be obtained when the back-pressure p_1 at the motor is exactly equal to the pressure p_0 of compression by the turbine. The coefficient τ then rises to 1.47.

From this it will be seen that it is quite possible at any altitude to restore the working conditions of the motor to those existing at the ground-level.

But the actual designing of the machine presented peculiar

difficulties. Even with the large amount of data and experience obtained by previous work in this field it was not possible to attempt a solution without some fear as to the result.

In order to re-establish the air-pressure at ground-level at an altitude of 5,400 m., that is to say, to double the air-pressure, which was the object in view, it was necessary to obtain, at the periphery of the compressing turbine, a tangential speed of 380 m. per second, that is, taking a diameter of 24 cm. as suitable, a speed of rotation of 30,000 r.p.m. This greatly exceeded anything that had been previously achieved.

The action of centrifugal force is very great at this speed. The portions of the metal that are furthest from the axis, for example, exert a pull in the direction of the radius equal to 123,000 times their weight; a gramme of matter gives rise to a tensile force of 123 kg. Moreover, the turbine is required to revolve in gas at $750^{\circ}\text{C}.$, or more accurately rather less, say 650° , on account of the expansion in the distributor—that is to say, it is almost at a red heat; and, at this temperature, all metals lose a great proportion of their tensile strength; whereas the wheel of the turbo-compressor would be subjected to very low temperatures, ranging down to $-55^{\circ}\text{C}.$ at high altitudes, when the usual metals of construction become extremely brittle.

The shaft is subjected to other conditions; at the one end it is heated to redness and at the other it is chilled; and there is the further question of dangerous critical speeds should the rotors not be perfectly balanced.

All these difficulties and many others that need not be mentioned, were, however, overcome. Thanks to the data previously obtained on these questions, and thanks to the special steels that the metallurgical experts had already produced, it was possible, without going through a process of trial and error, to supply the aviation apparatus in a very reliable form, in fact much more reliable than the Author had anticipated.

The arrangement possesses perfect flexibility; it is merely necessary for the pilot to close the exhaust cut-out gradually in order to accelerate the compressor and the motor to a greater or less degree from the minimum, which corresponds to the cut-out completely opened (the motor then runs as though there were no turbo-compressor), up to the maximum speed when the cut-out is completely closed. In the latter position a sort of automatic regulation of speed takes place.

The diagram shown in Fig. 4 gives the speeds of rotation of a turbo-compressor, of the 175 h.p. type, which are necessary for

FIG. 4.—*Speeds of Rotation of Turbo-Compressor for Restoring Pressure of Admission Air to Normal 760 mm. of Mercury.*

Z = Altitude in km.

restoring the ground-level atmospheric pressure at various altitudes.

The output of the turbo-compressor is plotted as abscissæ, in grammes per second; the power of the motor is directly proportional to this output as also is the speed of the aeroplane for flight at constant altitude.

The fall of atmospheric pressure is plotted as ordinates, in mm. of mercury at the various altitudes. The horizontal lines correspond to altitudes of 1, 2, up to 8 km. for normal barometric height, and the temperatures are marked alongside. The chain-dotted line corresponds to the maximum output of the turbo-compressor.

From this curve it will be seen that in order to obtain the same pressure as at ground-level, for a motor of nominal 200 h.p. :—

For Z = 1 km. the speed required is 13,300 revs. per minute.			
Z = 2	"	"	18,500
Z = 3	"	"	22,200
Z = 4	"	"	25,400
Z = 5	"	"	29,400
Z = 6	"	"	33,100

It would not be prudent to exceed the speed of 30,000 r.p.m. appreciably; the coefficient of safety would then fall to too low a value.

If, at low altitudes, the exhaust cut-out were closed the turbo-compressor would give too high a pressure, a pressure which the actual aeroplane motor is not capable of withstanding. This is to be regretted, because it would have afforded a means for obtaining an appreciable increase in the initial power.

Designed in the first instance, for a motor of 175 h.p., at the beginning of 1917, the turbo-compressor was tested thoroughly in the works, systematically, by means of an experimental arrangement enabling the running conditions to be varied far outside the range of those that would be met with in practice on the aeroplanes.

Thus, in trials at overload, the turbo-compressor was made to revolve at speeds up to 53,000 r.p.m., giving a peripheral speed of 670 m. per second at the tips of the compressor. The turbo-compressor drawing from a reservoir and compressing to the atmospheric pressure, produced a vacuum of about 60 cm. of mercury; that is to say, it had a compression ratio greater than 4.5.

After these trials at the works, the turbo-compressor was handed over to the Aeronautical Technical Section, which took charge of it. Under the direction of Commanders Caquot and Martinot-Lagarde, to whom the Author wishes to express his particular thanks, the

trials were first made at ground level (at the high-level station at Galibier, 2,500 m.) in August 1917, and then on board a trial aeroplane, by Lieutenants Sadi-Lecointe and Canivet. The manufacture in quantity had been already commenced in a works that had been specially built for the object by the Company engaged in the manufacture of the Rateau turbines, when the war came to an end.

Since the armistice the investigations and applications have been continued steadily. Various details required perfecting, particularly the exhaust-pipes which, at the commencement, were not of sufficient strength to avoid leakage; the petrol-pumps also had not been designed to supply petrol at a pressure exceeding

FIG. 5.—Rotor of Turbo-Compressor for Supercharging 300 H.P. Motor.

one-half atmosphere. Now, however, the engineers and pilots of the Technical Section, Mr. J. Weiss in particular—who worked for a long while in 1919 on a military Breguet aeroplane—whose assistance has thrown much light on the subject, and more recently the devoted pilots of Le Bourget Aerodrome, who kept in regular use a squadron of Breguet aeroplanes, have succeeded in freeing the installations on board the aeroplane from all those inconveniences that had made themselves apparent in practical working. So far as the main feature is concerned, that is the turbo-compressor itself, no modification was required.

In Fig. 5 is shown the rotor of a turbo-compressor designed for

supercharging motors of 300 h.p.; this rotor has a total weight of 3 kg. The turbine wheel, 18 cm. in diameter, is made of tungsten steel, the tool steel discovered by F. W. Taylor; notwithstanding its small dimensions this turbine develops nearly 50 h.p. with the exhaust gas of a 300 h.p. motor. The compressor wheel or fan, 24.2 cm. in diameter machined from the solid, is made of nickel-steel, as also is the shaft. The blades, nine in number, are exactly radial and machined to the calculated form of a solid of equal strength so that they may undergo no deformation by centrifugal force.

FIG. 6.—*Turbo-Compressor for Supercharging Aero-Engine.*

The shaft, which is 33 cm. long between bearings, appears relatively strong, yet its first critical speed is as low as 8,000 r.p.m., and its second is at 27,000. The machine runs normally at 25,000 to 30,000 r.p.m. hence in the zone of this critical speed.

In Fig. 6 is shown a photograph of the turbo-compressor, and in Fig. 7 the general arrangement with a section of the turbo-compressor. The casing of the compressor is in aluminium and that of the turbine in steel plate. The whole machine weighs only 23 kg.

A radiator is shown for cooling the compressed air from the

compressor before its arrival at the carburettor. It is well known that air becomes heated when compressed; if, for example, air is drawn in at 250° absolute C., the heating for a ratio of compression of 2, and an efficiency of 55 per cent, is 90° C.; the air therefore leaves the compressor at a temperature of 340° absolute C., that is 67° C. It must be cooled if power is not to be lost in the motor. This is very important, not only from this point of view, but also for avoiding any kind of unsteadiness of running which may be caused by this heating.

The whole arrangement, including all accessories, weighs about

FIG. 7.

Arrangement of Turbo-Compressor Supercharger. (Rateau.)

80 kg., under the actual conditions of adapting it to old aeroplanes. It would be possible to reduce this weight very considerably if it were decided to design the motors specially with a view to their use in combination with the turbo-compressor.

The advantage is shown clearly by the figure given above. With an added weight of 80 kg. the power is doubled at high altitudes for a motor giving 300 h.p. at ground-level; on the other hand an ordinary 600 h.p. motor would weigh an extra 350 kg. at least. It must be noted also that the 300 h.p. motor, continuing to run under the same conditions as exist at ground-level, maintains its efficiency, whereas, on account of passive resistance (engine friction, etc.) the

600 h.p. motor, without the turbo-compressor, shows appreciable falling off in power at high altitudes.

What are the results that may be expected from the new arrangement? Taking into consideration only those appliances that have been actually tested, and give double the induction pressure (and there would be no difficulty, if required, in making these appliances capable of compressing the air to a much greater ratio), the formulæ which the Author has established, and which are given in the Appendix, show that, for equal weight of aeroplane, there is an increase of about 4,000 m. in the height of ceiling. And actually on a Breguet aeroplane having its ceiling at about 6,000 m., Lieutenant J. Weiss, after a turbo-compressor had been fitted, flew, in July 1919, with his mechanic, to a height of over 9,000 m., and he was still far from the new ceiling. This is the record for height with a passenger. The absolute record for height is held by the American, Lieutenant J. A. MacReady, who flew, on 28th September 1921, from the Cookfield Aerodrome, near Dayton, Ohio, to a height of rather over 10,500 m. on an aeroplane fitted with a 450 h.p. motor and a turbo-compressor modelled on the Author's design, so far as concerns the essential features.*

With regard to speed, there is a loss at ground-level, because it is necessary to change the airscrew and to substitute for it one of larger diameter in order to be able to maintain the speed of the motor at high altitudes within the permissible range of speed. But above 2,000 m. the turbo-compressor rapidly makes up for this. A few figures will serve to explain. The Breguet aeroplanes in question, fitted with 300 h.p. motors, without turbo-compressors, have a normal speed at ground-level of 180 km. per hour; near the ceiling this speed falls to 145 km. per hour. With the addition of the turbo-compressor a speed is obtained, at the former ceiling height of 6,000 m., which from many measurements has been found to be from 215 to 220 km. per hour. At this speed many flights have been made with these aeroplanes from Paris to Lyons, to Tours, to Nancy, to Metz, etc.

The diagram shown in Fig. 8 gives a clear idea of the comparison of the speeds at constant altitude and in climbing for the particular

* This notwithstanding, the engineers of the General Electric Company have endeavoured to spread the belief that they had invented the apparatus themselves. Proof exists that their designs were only commenced after the French trials at Galibier in August 1917, and that they were in possession of the information contained in the first working drawings and of the results of all the trials made at the Villacoublay Aerodrome.

case under consideration. The broken lines relate to the normal aeroplane and the full lines to the aeroplane fitted with the turbo-compressor.

The reduction of speed near the ground is due to the airscrew having a greater pitch than that for the normal aeroplane and that the motor consequently runs at an appreciably slower speed. This disadvantage could be avoided by the use of an airscrew of variable

FIG. 8.—*Comparison of Climbing and Flying Speeds.*

pitch so as to enable the motor to be run under all conditions at its proper speed. But it will be seen from the curves that the advantage to be obtained from this is not important.

On the other hand, it would not be possible to avoid the use of an airscrew of this type if the turbo-compressor group were arranged for running so as to give the ground pressure at an altitude of 10 to 12 km. instead of at 5 or 6 km. With an airscrew of constant

pitch too much speed would be lost near the ground level and taking off would be difficult, if not impossible.

There is no difficulty in designing turbo-compressors for these great altitudes, for which it would be necessary to raise the pressure four, or even five-fold, either by means of a multicellular compressor with two or three wheels, or better still by arranging in series two turbines similar to those described.

It has sometimes been stated that the distributor of the turbine, having convergent nozzles, is not adapted for a drop of pressure of more than one-half the initial pressure, and that, for this reason, the apparatus has not the same efficiency at high altitudes, above 5 or 6 km. This is an error due entirely to a want of appreciation of the properties of turbines working in an elastic fluid. In the first place it would be very simple to make distributors with convergo-divergent nozzles, as is done for steam-turbines when necessary. But then it must be borne in mind that nozzles which are only convergent give good efficiency when the pressure on entering is much more than double the pressure of delivery; the efficiency even increases as the expansion ratio increases, up to a certain limit, because the turbine then works partly by reaction and the losses in the nozzles and those due to shock on entering the rotating wheel are lower. It has appeared to the Author advisable to deal somewhat fully with this point, which is so frequently misunderstood.

One other point, which is very important, merits examination; it might be thought to be of small interest, so far as it affects the over-all efficiency of the motor group, and that is the question whether the compressor should be direct-driven by the motor or driven by means of a turbine using the exhaust gas. The Author can prove that the second combination is considerably more advantageous; briefly, this results from the fact that the turbine enables the exhaust gases to be expanded right down to the pressure of the surrounding atmosphere, whereas in the motor cylinders the expansion is necessarily very incomplete.

Let it be assumed that, in one case or the other, the turbo-compressor supplies the motor at exactly the same pressure as at ground-level, and that the diagram of the working of the motor is represented by the line GCDEF CG, Fig. 9, which is the diagram for the engine working as a 4-cycle engine. The volumes are plotted as abscissæ on OX and pressures as ordinates on OY. The line EG CJ corresponds to atmospheric pressure at ground-level. AB represents the total useful volume of the cylinders, OA that of the clearance spaces, which are generally about one-fourth of the cylinder capacity.

The diagram is somewhat distorted for want of space. Actually the point E should be much higher because the pressure, during the explosion of the mixture, rises to about 25 kg. per cm.².

If, instead of working at the ground-level, the motor ran, for example, at the height of 5,400 m., where the atmospheric pressure is reduced to one-half, then in the case in which it exhausts direct to the atmosphere, the diagram would be increased by the rectangle GCIH of one-half the height. But the useful work on the shaft is appreciably smaller than the area of this rectangle, firstly, on account of the passive resistance, and secondly, because of the losses

FIG. 9.

Diagram of Aero-Engine showing Energy available in Exhaust for driving Turbo-Compressor.

of pressure by wire-drawing the gases through the exhaust-valves, which losses are greater as the pressure is reduced. Moreover, the multiplying-gear causes a still further loss of power and consequently only 85 per cent of the work represented by the area of the rectangle is actually delivered to the turbo-compressor.

With the exhaust-turbine the case is altered. The gas begins by falling to the pressure in the piping between the motor and the delivery-pipe from the turbine, a pressure which is assumed to be equal to the pressure of one atmosphere at ground level. Contrary to what is sometimes supposed, the energy corresponding to the total pressure BF of the gas in the cylinders is not and cannot be

utilized completely. In the first place there is rapid exhaust without performance of work, following a portion of the hyperbola FJ, because in this class of expansion the temperature of the gas does not vary appreciably; and as usually the final pressure BF in the cylinders is approximately 4.5 kg. per cm.², the point J is so placed that $LJ = 4.5 LC$, that is, $GJ = 5.4 GC$. Then expansion with work in the turbine occurs following the polytropic line JK, the point K is found a long way to the right, on the line HI produced, at a distance from H slightly less than 2 GJ.

The theoretical work done in the turbine is represented by the trapezoid, the area of which is about equal to seven times that of the rectangle GCIH. But the useful work transmitted to the compressor-shaft is less. If the efficiency of the turbine is only 50 per cent, and, actually it is rather more, this is nevertheless 3.5 times GCIH, whereas in the first case considered it was about 0.85.

It will be seen that this solution gives available power for the compressor while leaving the utilizable power of the motor unchanged, and it gives at least four times as much power as would be obtained by a direct drive from the motor itself through multiplying gears. It has therefore a very great advantage.

CONCLUSIONS.

To sum up, it has been shown that speeds of 300 km. per hour are already attainable with commercial long-distance aeroplanes, and about 400 km. per hour with war or sport machines, flying ordinarily at an altitude of 5 or 6 km.

In order to obtain still higher speeds, greater progress must be made as follows :—

The construction must be made still lighter.

The form of the wings and of the dead-wood must be improved as to reduce the fineness to less than 0.10; this is obviously possible, because the fineness of the wings alone can be reduced to less than 0.045; the experimental laboratories can give the greatest assistance in these investigations.

The production of a thoroughly reliable variable pitch airscrew.

The construction of an air-tight chamber, in the first place, for the passengers, and secondly, for the crew, which must combine sufficiently lightness with perfect safety.

In addition to these, improvement is necessary in the motors, particularly with regard to the length of time they will run and their ability to sustain uniform running speed.

When these improvements have been effected, and when the aerial ways have been organized, it will be possible to travel round the world at speeds of over 400 km. per hour, and by stages of 1,500 to 3,000 km. it will be possible to fly from Paris to Tokyo, for example, in three days with eight stages; Paris to Buenos Aires in two days with five stages, of which one—the Atlantic crossing from Dakar to Pernambuco, 3,300 km.—is unfortunately rather long. M. Breguet has already led us to hope for a fairly early realization of these schemes, and this statement has the weight which his word usually carries.

Progress is being made rapidly. In a few years the stratosphere will doubtless have become the great International route of travel.

The Paper is illustrated by 9 Figs. and is accompanied by an Appendix.

APPENDIX.

Note on the Calculation of Ceiling Height.—The raising of the ceiling, which can be obtained by the use of the turbo-compressor, can be calculated with accuracy by the following method.

In the first place, it should be noted that the incidence of flight α_p at the ceiling is that which gives the minimum for the total resistance R for the aeroplane, that is to say that also gives $\frac{X}{Y} = f$ minimum, about 4° with modern types of machines, or slightly more, say about 5° , because the slip of the airscrew, which increases with the incidence, raises the maximum still further; the slip outflow of the airscrew at the ceiling is then determined in this manner as also is its efficiency η .

Where n is the number of revolutions of the motor per second and Q its torque, the useful propelling-power is expressed by $2\pi nQ\eta$ which is equal to the resistance of the aeroplane $X\rho v^3$, and replacing v by its value obtained from the second equation (13) the equation gives:

$$2\pi nQ\eta = \frac{X}{Y^{\frac{3}{2}}} \cdot \frac{W^{\frac{3}{2}}}{\rho^{\frac{1}{2}}} \quad . \quad . \quad . \quad (19)$$

For a given aeroplane, X , Y , and η being also determined at the ceiling, let:

$$2\pi\eta \frac{Y^{\frac{3}{2}}}{X} = \psi, \quad . \quad . \quad . \quad (20)$$

from which:

$$\psi nQ\rho^{\frac{1}{2}} = W^{\frac{3}{2}} \quad . \quad . \quad . \quad (21)$$

3 I

It is this simple equation that shows clearly how the ceiling-height varies when the total weight W or the torque Q of the engine is varied.

Investigating in the first place the influence of variation of weight. If it is supposed that, for relatively small variations the torque Q of the motor is proportional to the specific weight of the air, let :

$$Q = A\rho.$$

then (21) becomes :

$$\psi n A \rho^{\frac{3}{2}} = W^{\frac{3}{2}} \quad . \quad . \quad . \quad (22)$$

Moreover (19), under the same assumption, gives :

$$2 \pi A n \eta = X v^3 \quad . \quad . \quad . \quad (23)$$

As, at the ceiling, n is proportional to v (because the slip of airscrew is known), it will be seen from this equation that *the speed V at the ceiling is independent of the total weight W of the aeroplane as also is n , the speed of rotation of the motor* ; and (22) then shows that ρ is directly proportional to W ; hence, if the ceilings Z_1 and Z_2 are compared, that correspond to two different weights W_1 and W_2 of the same aeroplane :

$$\frac{\rho_2}{\rho_1} = \frac{W_2}{W_1},$$

and, taking logarithms and using equation (9),

$$\frac{Z_1}{B_1} - \frac{Z_2}{B_2} = \log \frac{W_2}{W_1} \quad . \quad . \quad . \quad (24)$$

In particular, if the coefficient B can be considered as constant, as is the case in the stratosphere, or of altitudes comprised between 3 and 6 km. :

$$Z_1 - Z_2 = B \log \frac{W_2}{W_1} \quad . \quad . \quad . \quad (24A)$$

The following is an example of a calculation which will serve later. Taking the case of the Breguet aeroplane, weighing in the first instance 1,600 kg. in running order, to which the turbo-compressor has been added, which, with its accessories, increases the total weight by 80 kg. At the former ceiling of 6 km. the coefficient B , according to curve 4 of Fig. 1 is appreciably constant and equal to 21.7.

Then from (24A) :

$$Z_1 - Z_2 = 21.7 \log \frac{1680}{1600} = 0.460.$$

Thus this extra weight of 80 kg. lowers the original ceiling by 460 m.

On the other hand, with the turbo-compressor, the new ceiling is raised to about 10 km., as will be seen; at this altitude the coefficient B varies rapidly. Taking the tangent to the curve 4 to the abscissa $Z = 10$, this portion of the curve can be replaced by the straight line $B = 25.1 - 0.45 Z = a - bZ$.

Now by treating the increase of $\frac{Z}{B}$ as a differential the equation 24) gives :

$$\Delta \frac{Z}{a-bZ} = \frac{a\Delta Z}{(a-bZ)^2} = \log \frac{1680}{1600} = 0.0212;$$

whence

$$\Delta Z = 0.0212 \frac{(20.6)^2}{25.1} = 0.358 \text{ km.}$$

or only 358 m. instead of 460 m. as in the previous case.

Passing to the investigation of the increase of the torque due to the use of the turbo-compressor, it is necessary to obtain as great exactitude as possible, to take account of the constant term γ of formula (18) for the torque. It is supposed necessarily that when the turbo-compressor is fitted the airscrew is altered in such manner as to bring the speed of rotation n of the motor to the same figure as before. It is then necessary to increase the pitch appreciably, and, although to a smaller extent, to increase the diameter, because the speed of the aeroplane is itself considerably increased. The efficiency of the propeller is improved. Neglecting this advantage, it is found that the factor ψn of equation (21) should be considered as being the same in both cases. Assuming, in the first instance, that the total weight W has not been altered; the correction corresponding to the added weight will be made subsequently.

For the aeroplane without the turbo-compressor, according to (21) :

$$\psi n A (\rho_1 - \gamma) \rho_1^{\frac{1}{2}} = W^{\frac{1}{2}} \quad . \quad . \quad . \quad (25)$$

For an aeroplane fitted with a turbo-compressor two main hypotheses must be considered.

1. The turbo-compressor is designed so as to deliver air of

3 1 2

exactly the same specific weight as at ground-level when the aeroplane is flying at the new ceiling. Then (21) gives :

$$\psi n A (\rho_o - \gamma) \rho_2^{\frac{1}{2}} = W^{\frac{1}{2}} \quad . \quad . \quad . \quad (26)$$

Comparison of (25) and (26) gives :

$$\rho_2 = \rho_1 \left[\frac{\rho_1 - \gamma}{\rho_o - \gamma} \right]^2 \quad . \quad . \quad . \quad (27)$$

Whence the altitude Z_2 corresponding to it can be found by using curve 4 of Fig. 1.

For example, taking the Breguet aeroplane weighing 1,600 kg., with a ceiling at 6 km., whence $\rho_1 = 0.661$, and assuming $\gamma = 0.12$; and, moreover, $\rho_o = 1.248$.

The equation above gives $\rho_2 = 0.152$, whence

$$\frac{Z}{B} = \log \frac{1.248}{0.152} = 0.914,$$

and from curve 4, Fig. 1, by successive close approximations,

$$Z = 16.4 \text{ km.}$$

The new ceiling will therefore be rather less than three times the height of the first.

At lower altitudes the contrary will occur; the new ceiling will be at a little more than three times the old height.

2. The turbo-compressor is calculated on such basis as to increase the specific weight of the air always in the same ratio m from the altitude at which it runs at its maximum speed.

Then equation (25) becomes :

$$\psi n A (m\rho_2 - \gamma) \rho_2^{\frac{1}{2}} = W^{\frac{1}{2}} \quad . \quad . \quad . \quad (28)$$

Whence, comparing (25) and (28),

$$(m\rho_2 - \gamma)^2 \rho_2 = (\rho_1 - \gamma)^2 \rho_1 \quad . \quad . \quad . \quad (29)$$

Now suppose $m = 2$, which is approximately obtained from the existing turbo-compressors in work, provided that the air is cooled sufficiently by the radiators, $\gamma = 0.12$ and $\rho_1 = 0.661$, which corresponds to $Z = 6$ km., as above; the equation of the third degree above becomes :

$$(\rho_2 - 0.06)^2 \rho_2 = 0.0484,$$

which can be solved easily with the help of a slide-rule. It is thus found that :

$$\rho_2 = 0.4055,$$

to which corresponds, according to curve 4, Fig. 1,

$$Z = 10.045 \text{ km.}$$

The ceiling, for equal total weight of aeroplane, will therefore be raised by 4.045 m., and, taking account of the drop, already calculated, of 358 m., due to the added weight of 80 kg., it is actually 4.045 - 358, or, in round figures, 3,690 m.

If the constant were treated as negligible in the expression for the torque, the formulæ would be simplified, and (29) would become :

$$\rho_2 = \frac{\rho_1}{m^{\frac{2}{3}}} \quad . \quad . \quad . \quad (30)$$

Whence, taking logarithms and using equation (9) :

$$\frac{Z_2}{B_2} - \frac{Z_1}{B_1} = \frac{2}{3} \log m \quad . \quad . \quad . \quad (31)$$

It would thus have been found that for the preceding numerical example $\rho_2 = 0.4164$ and $Z_2 = 9.853$ km.; the error would have been 192 m. less, which is appreciable. It should also be noted, that, at this altitude, the effect of the passive resistances of the motor compensate in greater part for the effect of the added weight of the supercharging apparatus.

The coefficient B varies with the altitude, and it diminishes continually with increase of altitude; but between 3 and 6.5 km. it is sensibly constant. Then, if Z_2 and Z_1 remain within these limits, the formula (31) becomes :

$$Z_2 - Z_1 = \frac{2}{3} B \log m, \text{ with } B = 21.8. \quad . \quad (31A)$$

And it will be seen that, under these conditions, the raising of the ceiling, due to the use of a turbo-compressor which increases m -fold the specific weight of the induction air of the motor, is constant.

But in more general terms this is not exactly true. Since B_2 is less than B_1 , it necessarily follows from (31) that :

$$Z_2 - Z_1 < \frac{2}{3} B \log m \quad . \quad . \quad . \quad (32)$$

where B is given a value equal to or greater than B_2 , for example B_1 , which corresponds to the altitude Z_1 of the comparison; and as B is a diminishing quantity, the same applies to the raising of the ceiling. If, for example, the aeroplane previously considered had had a ceiling of 10 km. instead of 6 km., it would have been found, by making the exact calculations according to the complete formula (29), that the raising of the ceiling was 3,400 m. instead 4,045, for equal weights of aeroplanes, and a reduction of 310 m. instead of 358 m. for the same proportional added weight, that is to say, a net increase of elevation of 3,090 m. instead of 3,690 m.

For the sake of completeness, the increased heights of ceiling calculated by formula (29) for an aeroplane having a ceiling in the first instance, of 2,000 m., of 4,000 m., etc., are shown in the Table below (column 1) for equal weights of aeroplane after the addition of a turbo-compressor increasing the specific weight of the air to double (column 2), or four-fold (column 3), in the normal atmosphere.

Z_1	$Z_2 - Z_1$	
	$m=2$	$m=4$
Metres.	Metres.	Metres.
2,000	4,480	8,325
4,000	4,370	7,870
6,000	4,045	7,280
8,000	3,685	6,825
10,000	3,400	6,520

These values of $Z_2 - Z_1$ are, in accordance with equation (32), much less than $\frac{2}{3} B_2 \log m$, except the two first of each column; this is due to the influence of the passive resistances of the motor, which are omitted in the simplified equations (31) and (32).

TABLE OF SYMBOLS DIFFERING IN FRENCH AND
ENGLISH NOTATION.

FRENCH.	ENGLISH.
P Poids.	W Weight.
II Puissance.	P Power.
$\tilde{\omega}$ Poids spécifique.	ρ Density.
ρ Rendement.	η Efficiency.
I' Couple moteur.	Q Torque.
Log. nep, Log Néperien.	Log _e , Napierian log.

Discussion on 15th June 1922.

The PRESIDENT said the Author had expressed his belief that a solution would be reached of the great remaining commercial problems by travelling at high speed in the air. The difficulty in the way had largely to do with the compression of air to meet the fact that it was necessary under such conditions to get up into an atmosphere miles in height, where there was at least one-quarter of the density of the atmospheric conditions on earth. If that was done it was quite easy to see that a resistance of only one-tenth of the resistance on earth would be obtained, thereby enabling the enormous speed of 300 miles an hour to be reached without increase of power, the resistance being reduced to such an extent that extra weight could be carried to obtain the desired result. The point of interest to engineers was the beautiful combination of mathematical reasoning between pressure density, the atmosphere of the air and the problems of the compressor which was necessary to obtain those results, first of all for the machine and then for the human beings who accompanied the machine to live in it.

Mr. WILLIAM REAVELL (Member of Council) said he desired to say how much pleasure it gave him to meet Professor Rateau, because in 1907 they both took part in the Institution of Civil Engineers' Congress in London and contributed Papers on Air-Compression. On that occasion his share was to deal with the question only of reciprocating compressors, while Professor Rateau dealt with the development he had already accomplished in turbo-compression, and explained in a most interesting way the lines on which he anticipated the turbo-compressor would develop.

Discussion in London on 27th October 1922.

The PRESIDENT said that the Meeting had met with two misfortunes. First, Professor Rateau was unable to be present, which was a great disappointment. He had intended to come, but illness had prevented his attendance. The President felt sure that the Meeting would wish to express its regret at the Author's enforced absence. The other disappointment related to the Air Ministry, which had only recently decided, no doubt for good and excellent reasons, that they could not allow their officers to take any part in the discussion. His personal regrets were very much tempered—he was sure the Meeting shared the sentiment—by the wish that military secrets or discoveries, for which the taxpayers had paid, should not be given to any prospective enemies. He was confident that the Meeting would agree that the Institution should not feel resentment at what was probably a wise and judicious action on the part of the Air Ministry. He had, however, succeeded in inducing Professor L. Bairstow of the Aeronautical Research Department to open the discussion. As he could not very well ask Professor Bairstow to introduce the Paper and then discuss it, he (The President) himself would undertake the former duty.

From the title of the Paper it would be seen that speed was the main question, and how the turbo-compressor filled this aim would be seen later. At the outset Professor Rateau remarked: "It is evident that the future of aviation, whether for commerce or war, depends on high speeds, and consequently in obtaining a high ceiling." "Ceiling" meant limiting height, for just as a bird could not fly above a certain height, so an aeroplane was limited by its ceiling, and the raising of that ceiling conveyed the purpose of the turbo-compressor. All practical men would realize that the aeroplane was impossible as a commercial proposition unless it had superior speed. It was, however, so important to cover long distances in a short time—getting to Constantinople in a day or two, or to Japan in two or three days—that, time being money, if the aeroplane achieved this it did become a commercial proposition. As a military proposition, its vast importance would be recognized, but its civil value rested simply and solely on speed. An important aspect of this speed was the price paid for it, and engineers would admit that it was paid for dearly. The Author had given (page 796)

a comparison of the percentage of power required for speed in different modes of transport. This comparison showed that in the case of cargo steamers travelling at $12\frac{1}{2}$ miles an hour, 0.25 per cent of the power was absorbed by resistance; while with large trans-Atlantic steamers travelling at 25 miles per hour resistance absorbed 0.6 per cent, and in the case of battle cruisers having a speed of 40 miles per hour the figure was 2.5 per cent, the corresponding percentages for railway trains and automobiles, each at speeds of $62\frac{1}{2}$ miles an hour, being 1 per cent and 7 per cent respectively. In the case of the aeroplane the speed to be aimed at was 250 miles an hour, at which speed the relative figures for the modes of transport mentioned would be 60 per cent for resistance in the case of the trans-Atlantic steamer, 15 per cent for the railway train and 50 per cent for the automobile.

Professor Rateau had made a statement which the speaker considered required qualification; namely, that the aeroplane was the only vehicle in which the resistance to travel was independent of speed. What was meant was that, whereas all the other methods of locomotion were limited to the surface of the earth, the aeroplane could become independent of resistance by rising into the upper atmosphere, where resistance became less and less. If the aeroplane could rise high enough, the speed might become practically independent of the resistance to travel. That was the real meaning of the sentence quoted. This question of rising to high altitudes was the whole problem. He would remind the Meeting that the alarming results obtained over a range of 70 miles, with "Big Bertha" during the War, were entirely due to the high elevation obtained. The Germans had put down enormous emplacements to bring effective gun-fire within the range of 20 miles, and the sole aim was to get an elevation high enough to carry over that distance. In the case of "Big Bertha" the work done to carry 70 miles was vastly greater. At the altitudes attained, resistance became a negligible factor; it was possible to imagine a shell from a "Big Bertha" travelling for a long period round the world.

The turbo-compressor was necessary, because at very high altitudes the engine could not function. Members might have read the account recently published of the ascent of Mount Everest, where a remarkable thing occurred. Captain George Finch had with him a native, who had never climbed before. They went within measurable distance of the top, and were only defeated by the native collapsing. Captain Finch took an oxygen bottle and sucked it vigorously, in order to get the necessary powers of the high altitudes reached. This was exactly the physiological problem of the

aero-motor, which it was proposed that the turbo-compressor should solve.

The Author, dealing with normal atmospheric conditions, had observed: "In design problems concerning aeroplanes, propellers, and engines, it is the specific weight ρ (in lb. per cubic foot) of the air in which the aeroplane is flying that is the essential factor. On the other hand, the working of a centrifugal compressor depends on the pressure p (in lb. per square inch). It is therefore necessary, as a basis of calculation, to ascertain as accurately as possible the laws for the decrease of p and of ρ with altitude, at least in the ordinary atmosphere of these countries." Following that, Professor Rateau gave the results obtained by scientific men as shown in Fig. 1 (page 799). He showed, in terms of altitude, the way to get the relative factors. The upper equation of that figure gave the relation of the pressure and the lower one of density. He (the President) drew attention to Fig. 2, showing a comparison of the two. Soreau's curve and the Lindenburg curve there compared showed how remarkably well the differences agreed with each other. The whole matter turned on a study of those quantities.

The Author had also, under the heading of "The Aeroplane. Investigation of the Conditions for High Speed" (page 803), followed up his equations by a practical example. A little later Professor Rateau remarked (page 807): "Now flying the aeroplane at 11,800 m."—call it six miles—"where the specific weight of the air is only one-fourth of that at ground level, etc.," and had proceeded to show that the speed produced was 302 miles an hour, concluding the paragraph by observing that "the wing area will still be about 18 sq. m. and the relative resistance will fall to 0.118."

"But at this very great altitude," Professor Rateau had continued, "the lives of the pilot and the passengers could not be guaranteed, except in air-tight cabins in which an air pressure approximately equal to that at the ground would be maintained. This would cause an appreciable increase in the total weight of the aeroplane, and, moreover, it could only be obtained with appliances of much greater size than that which has been taken as an example of the application of the formula. It is, however, in this direction that an attempt must be made to obtain very high speeds, of the order of 400 to 500 km. per hour (250 to 310 miles per hour)."

He desired to draw attention to the Appendix to the Paper, for the sake of those who wished to study the mathematics a little further. What the Author aimed at was to get the value of the torque Q ; an approximate assumption was made which, while not strictly correct, greatly simplified the problem.

The PRESIDENT then called upon Professor Bairstow to open the discussion.

Professor L. BAIRSTOW, C.B.E., F.R.S., remarked that before entering upon a critical survey of the aerodynamical problem, he wished to congratulate the Institution upon obtaining from Professor Rateau such a clear statement on his turbo-generator. So far as the speaker was aware, it was the best published statement of the construction of that instrument that had been presented. Professor Bairstow had first become interested in the subject in 1915, when aerial fighting began and when the Germans had just produced the "Fokker," which was causing trouble among our own aeroplanes. The question of how to deal with that difficulty was one of the problems, on the aerodynamic side, which had been put to the speaker, and it was a matter of commonplace to all who were working on aeronautics that it was scarcely practicable to discuss one side of such a problem without being really interested in the others. Amongst the suggestions put forward at that time for producing better qualities and performance for our own aircraft was that of supercharging the engine by the centrifugal fan. It was realized that the operation would be difficult and that time would be necessary to develop apparatus. One of the other suggestions, not equally good, was that liquid oxygen should be carried instead of the compressor. As the President had pointed out, the trouble with the engine at high altitude was that it did not get enough food; the difficulty with the oxygen suggestion was that it raised the temperature of explosion, and would lead to a marked tendency to burn out valves. He remembered quite well many of the difficulties we had gone through in this country, and consequently he appreciated to a considerable extent the success achieved by Professor Rateau. The fact that the Professor's turbo-compressor was separate from the engine—mechanically separate—and therefore did not have to take up inertia changes due to misfiring, was definitely an asset. The speaker did not, however, propose to deal with the engine or the turbo-compressor side of the problem, on which point others were better qualified to speak. What he desired to do was to assume, on what he believed to be quite good grounds, that Professor Rateau, with his great skill and experience, had produced what he was asked to produce, and see where this led. He did not think that it would be found to lead so far as had been anticipated, although he did not feel that the claims made by the Author would be unjustified. The criticisms—so far as they were criticisms—of Professor Rateau's work, applied

rather to what had been left unsaid than to what had been said. Professor Rateau had remarked that the future of aviation depended on high speeds. That was correct and, indeed, a fundamental commonplace of discussions on civil aviation; but it was not sufficient to rely on such a simple criterion for success. Bitter experience had shown that speed was of commercial value, but it was not an unlimitedly high one; people would only pay a certain price for extra speed. There were other ways of putting up the average speed of flying which were more immediately promising, and with some aspects of that problem he would deal a little later.

Taking the paragraph already referred to by the President, in which Professor Rateau had said: "In the first place it should be noted that the aeroplane is the only vehicle in which the resistance to travel is independent of speed," it must be pointed out that it was only a half truth.

At this point Professor Bairstow exhibited two slides prepared from Figs. 202 and 203 of his book, "Applied Aerodynamics," the first of which (from Fig. 202) he stated showed for a normal aeroplane—practically any aeroplane doing service at the moment—what was the relation between speed and power, not only at ground level, but at various heights up to 20,000 feet. This diagram applied strictly to an aeroplane not fitted with the first of Professor Rateau's devices, but, nevertheless, showed the point which the speaker wished to make, namely, that the resistance of an aeroplane did depend very much on the speed. Taking the upper curve, he would examine its meaning. Along the base was the quantity which he called "standard horse-power," the horse-power which would be measured for an engine on a test bench, at ordinary ground level in a laboratory. The speaker had taken as a convenient variable the horse-power necessary to carry 1,000 lb. of load; this variable was the most important of those which affected aeroplane performance. The vertical scale showed as a dependent variable the speed which might be expected from a modern aeroplane provided with a stated amount of horse-power per 1,000 lb. of gross weight. For instance, assuming an aeroplane fitted with an engine of 100 h.p. for each 1,000 lb. of its load, a speed of about 120 miles an hour might be expected. Confining remarks for the moment to flight near the ground, the diagram led to several conclusions.

At high speeds they would see that the horse-power was increasing very rapidly with increase of speed; in fact, the horse-power tended to increase as the cube of the speed at the highest speeds of flight, and the resistance of the square. With 40 h.p. provided for each 1,000 lb. of gross load the speed would be about

80 m.p.h., and the horse-power then increased much less rapidly than the cube of the speed. Close to the slowest possible speed of steady horizontal flight, only 25 h.p. per 1,000 lb. was needed, and there was a region in which speed was independent of change in horse-power. A curious reversal of effect accompanied an attempt to go more slowly, for it took more horse-power to go slower. The region of flight in which Professor Rateau was particularly interested was that near to the point of contact of the curve and a tangent from the origin. They would see that it gave the highest speed for a given horse-power devoted to carrying 1,000 lb. of load.

It would be seen, therefore, that the way in which resistance and power varied with speed was extremely complex. It would presently be found that Professor Rateau's arguments were based on a constant angle of incidence. If an attempt were made to interpret the diagram in terms of angle incidence it would be found that, at very high speeds, the wing might be inclined at 0° , or it might have its nose slightly dipping down. As the speed decreased the angle of incidence increased until, at a speed of 50 m.p.h.—60 m.p.h., they might have, in most of the ordinary aeroplanes, a greater angle of incidence than the 4° quoted by Professor Rateau, perhaps as much as 8° to 10° . When flying at very high speeds the resistance would be one quarter (25 per cent) of the total tractive effort. If flying in the region marked by the contact of the tangent from the origin, the tractive effort went down to one-ninth (about 11 per cent), and that is the best that could be done now and probably for some little time to come. Professor Rateau had indicated the same ratio for existing machines, but expressed the hope that the tractive effort would presently come down to 8 per cent of the weight. In justice to him it should be said that his detailed argument, later in the Paper, did not depend upon his early general statement.

What happened if one went to a considerable height? It should be borne in mind that the engine in the aeroplane taken as an example had not a Rateau turbine on it. At about 20,000 feet they would notice a considerable loss of speed. The loss of speed did not get very great until 10,000 feet had been exceeded (in a fast aeroplane), but at 20,000 it became very serious. The whole of that loss—rather more than was apparent on the diagram—was due to lack of oxygen, lack of supply to the engine, and it was that lack that Professor Rateau had remedied by his compressor.

Professor Bairstow then exhibited a second slide, from Fig. 203 of "Applied Aerodynamics," showing a diagram of the climbing capacity of an aeroplane corresponding to the first slide, the abscissa,

as before, representing the horse-power necessary to carry 1,000 lb. of load. The ordinate of this second diagram showed the rate of climb of the aeroplane. When the rate of climb became zero, the aeroplane had reached its ceiling. It would be seen that the rate of climb fell from a very considerable quantity near the ground, to zero just a little above 20,000 feet for a horse-power rating of 80 per 1,000 lb. It was on such a diagram that the addition of Professor Rateau's turbo-compressor to an engine would show the greatest effect. There would, within the limits between which the engine could function completely, be very little difference between the curves for the ground and for 20,000 feet, were it not that Professor Rateau's apparatus weighed an appreciable amount.

This led the speaker to Professor Rateau's argument as to economy. The Author had provided a means of keeping up engine power, so that, if desired, heights of 30,000 to 40,000 feet or more could be obtained. The Paper referred to one or two difficulties, such as keeping alive, but had not mentioned keeping warm; it was extremely cold at altitudes of 20,000 feet, and colder still at greater heights. The slide shown by the speaker had not really indicated how the Author attacked his problem. As he had said, the problem was not a new one, nor was Rateau's the only method that had been proposed for overcoming it, but the solution could not be obtained by such devices as, say, the new Handley-Page wing, although assistance might be obtained from them by modifying the aerodynamic qualities of an aircraft.

Professor Bairstow then proceeded to indicate briefly the general theory of the subject, which was not very complicated. He wished to point out the limitations, and how Professor Rateau's theory of flying at great heights fitted in. It was necessary to consider two essential criteria of flight. First, wherever one was in the atmosphere, whether the density of the air was normal or small, it was necessary to fly at such a speed that the weight of the machine was carried. The second consideration was to provide such power that when flying at that speed the resistance to the machine was overcome. The two criteria were not wholly independent. It was known on general aeronautical grounds, from formulæ familiar in aeronautics, that the weight was proportional in the first place to a lift coefficient, a quantity depending on the angle of incidence. It was not equal to the angle of incidence, but knowing the angle of incidence, the lift coefficient was known experimentally; it was denoted by the symbol k_L . The weight carried also depended on the density of the air—the quantity which Rateau called “specific weight”—on

the area of the wings, and on the square of the speed. The formula was

$$\text{Weight} = W = k_L \rho S V^2 \quad . \quad . \quad . \quad (1)$$

The speaker had already mentioned that there only one angle of incidence could correspond with the least tractive effort for carrying a given weight, and it now followed that there was only one best value of k_L . Reversing his equation, he would suppose that he had determined the best value of k_L from experiment, say, in a wind tunnel in any of the aerodynamics laboratories. That was fixed for him? In what else was a choice left to him? It would be seen that

$$k_L = \frac{W}{S} \cdot \frac{1}{\rho V^2} \quad . \quad . \quad . \quad (2)$$

left still a considerable amount of choice. All he had fixed was the whole of the right hand side of (2), which contained four quantities with only one relation between them.

The quantity $\frac{W}{S}$ was weight of the aeroplane per unit area of wing, usually written as w , while the reciprocal of the second quantity, that is, ρV^2 was a very important quantity in aeronautics, known as the square of the air speed; it was not the real speed of the aeroplane at all, but was a quantity appearing on the airman's speed indicator. It might be seen from (2) that k_L could be kept constant if the two quantities ρ and V were varied in opposite directions. It could be varied by changing w . When flying at very high speeds the angle of incidence of a normal aeroplane was too small for greatest economy, and a greater angle of incidence meant an increased value for k_L . One way of doing that was to increase the loading on the wings, a possibility allowing for considerable variation in design; it was here that the Handley-Page wing offered advantages. The standard "Scout" averaged about 7 lb. per square foot, while the gliders now making history averaged about $1\frac{1}{2}$ lb. per square foot. When it was necessary to consider long bombing raids, increasing the wing-load was one of the ways adopted for getting greater efficiency. The quantity at the right-hand side of (2) required that w should be put up to increase k_L , and when starting on a bombing raid, w has been as high as 13. Every advantage got from an aeroplane had its corresponding disadvantage. In the case under consideration, the great difficulty introduced was that of landing. Under the best conditions, and whatever was done to the wing, k_L could not be made bigger than a certain amount. It was not possible to fly steadily at less than a

certain speed, even when it was desired to land, and the conditions of landing might be made very difficult by putting up w too greatly. If ρV^2 were maintained constant for a given aeroplane, it appeared from (2) that it was possible to go on flying at the best angle of incidence; to keep ρV^2 constant by choosing one's position in the atmosphere meant that the greater the height, the greater the velocity. The chief reason why the extreme heights of 40,000 feet and over could not previously be attained was due to lack of supercharging, and by his turbo-compressor Rateau had produced a means of getting increase of speed by going higher. So far that was a clear gain; the higher the machine could go, the faster it would go, without extra ground horse-power.

Resistance, Professor Bairstow continued, was governed by a formula almost precisely similar to that for weight; instead of a lift coefficient there was a drag coefficient. The formula is

$$\text{Resistance} = R = k_D \rho S V^2 \quad . \quad . \quad (3)$$

The drag coefficient of an aeroplane, like its lift coefficient, was dependent only on the angle of incidence, so that by limiting flight to the best angle of incidence we were led to the interesting rule that no matter what the height, whether 1,000 or 40,000 feet above ground, the same resistance must be experienced when carrying a prescribed weight. In going from London to Paris, the work done was measured by the product of the distance and the resistance or more roughly by the consumption of petrol. It did not matter whether the journey was done at the rate of 100 miles or 200 miles an hour, it would cost just as much in petrol. The Author did not claim any economy of fuel, simply economy of speed.

The problem was complicated in many ways. If it was proposed to fly at 40,000 feet, it was first necessary to get there and finally to come down from that height; on the other hand it was not possible both to climb and to fly at the fastest speed. If therefore a Rateau machine were to leave London for Paris it would have to climb comparatively slowly to 40,000 feet, and taking a favourable estimate, from Prof. Rateau's point of view, it would occupy an hour's time to do this. The machine would then have to fly horizontally at the highest speed, and take nearly an hour to come down, although conceivably at high speed. The journey from London to Paris did not appear to be long enough for the use of a turbo-compressor. It seemed, therefore, that Rateau's proposal should have its greatest commercial value on longer journeys. But journeys of 1,000 miles or more were not practicable at the

present time for several reasons, some of which were quite unconnected with the engine. The pilot, for instance, was a human being, and suffered fatigue. It was true that the medical services did their utmost to choose the best available specimens of humanity as pilots, but the aeroplane was itself a tricky thing to deal with. If all went well, it gave no trouble at all, but when it went wrong it went badly wrong, and the pilot was constantly watching his instruments for signs of trouble, particularly any signs of misfiring in his engine. As a matter of fact it had been found that three hours' flying was quite trying enough for any pilot at any one time. The Rateau turbo-compressor was hitting the engine rather hard in the sense that it was keeping it up to its maximum duty for very long periods. In flying at 10,000 feet in an ordinary aeroplane, the engine would not be seriously overworked, and this fact had probably affected design; aero engines were so light that harder working due to supercharging would almost certainly increase the risk of breakdown.

The speaker wished to point out, however, that speeds of 200 m.p.h. were not necessary to make aerial navigation a success. He believed aerial transport to be nearer to success than most people realized. Many of the troubles and difficulties due to thinking in a war spirit were now being thrown off. Traffic had become steadier, and problems were being attacked in much greater detail. Already the speed of commercial aeroplanes was something like 100 miles an hour; and therefore when compared with the journey from London to Paris, where there was a sea passage, the velocity was approximately two and a half times that of the mail train and mail steamer. A particular disadvantage—apart from cost—was that at present the aeroplane could only fly in the hours of daylight; whereas letters sent to Paris from London were posted at night, travelled overnight to Paris, and were delivered there earlier than would be practicable if sent by aeroplane. There was, however, some time advantage in the aerial service, even before the Daimler Co. started their Manchester to London service, as it was possible to post letters from the provinces to London, to be delivered in Paris by air mail, thereby saving a considerable amount of time. If, however, the air service could supply, not an eight-hour winter day or a sixteen-hour summer day, but a twenty-four-hour day and night service, then immediately, in a populous part of the world like Europe, the aeroplane could hold its own against other forms of transport; on long journeys there seemed to be every prospect that air transport would materially reduce the time of transit.

Summing up his conclusions, he would like to say that supposing

all that had been done, and done so splendidly, by Professor Rateau in the development of his turbo-generator could be applied to aeroplanes, the only asset would be the possible saving of time on long journeys, which was offset, to some extent, by having to carry an extra weight of mechanism. That was the only advantage the speaker could see, so far as civil aviation was concerned.

The military advantage of Rateau's proposal was perfectly clear, but with that the Meeting was not much concerned. For fighting purposes, the man who had a supercharged engine and could get 10,000 feet above his opponent was in a much better position than he would be without that engine.

MR. WILLIAM REAVELL (Member of Council) thought the principal interest in this most important Paper was to solve a new problem by the introduction of a mechanical appliance such as the turbo-compressor. The problem the Author had set out to solve, namely, to construct a compressor to give the high ratio of compression he required at extreme altitudes with such a large volume of air as he must supply, limited as he was to extreme lightness in weight, was one of those problems that always fascinated engineers. He thought engineers were at their best when they were encountering the greatest difficulties, because it brought out the best that was in them, and he was sure that point of view had appealed to the Author.

In the Paper which he (Mr. Reavell) presented to the Institution at Paris, and which he was to have the honour of presenting again in London shortly for discussion, he referred, in the section dealing with turbo-compressors, to the great influence which high peripheral speed of the impeller had on the weight and cost not only of the turbine but of the prime mover which drove it, and Fig. 13 (page 849) gave the ratio which the peripheral velocity in feet per second bore to the compression ratio, that is, the ratio of the absolute inlet pressure to the absolute outlet pressure. He there suggested that if figures could be reached in large machines, such as 1,000 feet per second as the impeller velocity at the periphery, it would be about as high a velocity as present knowledge of metallurgy would enable them to reach for large size rotors in commercial machines. A glance at Fig. 13 would convince anyone of the great importance of high peripheral velocity for obtaining a large pressure rise at a relatively low cost, assuming that the metallurgist provided very high tensile materials at a low cost. The Author had at once jumped ahead of the velocity of 1,000 feet per second which he (Mr. Reavell) outlined as the extreme of present practice, and he

gave on page 814 a figure which it would be seen worked out at 1,250 feet per second. The rotor of his compressing turbine was 24 cm. ($9\frac{1}{2}$ inches) diameter, and running at 30,000 r.p.m. it had a peripheral speed of 1,250 feet per second. In the last paragraph but one on page 816 the Author stated that he had actually reached a speed of 53,000 r.p.m. with the $9\frac{1}{2}$ inch diameter impeller, and a peripheral speed of 670 metres (or 2,200 feet approximately) per second. Of course that was only possible by the choice of the materials the Author had used and his method of manufacturing the rotor, but the effect upon the compression ratio, that is, the amount of increased pressure which could be obtained in one stage or wheel of the turbo-compressor, was enormous. At a peripheral speed of 1,000 feet per second he (Mr. Reavell) gave a figure of 1.65 as the compression ratio. The Author stated that at 1,250 feet per second he obtained a compression ratio of 2 to 1; and at 670 metres, that is, 2,200 feet per second, he reached a compression ratio of $4\frac{1}{2}$ to 1. In other words, when the Author was dealing with an altitude of, say, 18,000 or 19,000 feet where the sea-level pressure of the atmosphere was halved, then running at 30,000 revolutions, that is, 1,250 feet of peripheral speed with the $9\frac{1}{2}$ inches diameter rotor, he obtained a compression ratio of 2 to 1, and he compressed that rarefied air from $7\frac{1}{2}$ lb. pressure absolute to 15 lb. absolute. Evidently, the Author's experiments, which he presumed were laboratory experiments and not conducted at an altitude, showed him that if he ran that machine in an aeroplane at 53,000 revolutions, he had a possible compression ratio of $4\frac{1}{2}$, in other words he could deal with an altitude of practically 40,000 feet, if the pilot of the aeroplane could live in it. That was a great triumph for the mechanical engineer, and something which it was desirable should be pointed out on the present occasion. He thought that the makers of turbo-compressors had never had in their wildest dreams a conception of reaching $4\frac{1}{2}$ compressions in one such impeller of a multi-cellular turbo-compressor. Of course, it was a "tour de force." He meant by this that no one would design a commercial machine of large volume for it, but it only showed what could be done by persistence in the proper heat treatment and the right selection of materials for the purpose the Author had in view.

He desired in the next place to draw attention to Fig. 9 (page 823), because that also was very interesting to the engineer. The Author dealt on page 822 with his earlier ideals of having a fan or turbo-machine driven by some power means, through gearing or otherwise from the engine, and he referred to what he deemed the inevitable losses which such an arrangement would give. He then turned to

the amount of energy which was available in the exhaust gas from the aero-engine and showed how when using it in a gas-turbine, as indicated so graphically by the President, he could do the work he required and have energy to spare. It would be interesting to see how that worked out at extreme altitudes such as mechanically the rotor of his turbine would enable him to reach.

He showed in a diagram the importance of what he was referring to. In Fig. 10 the weight of air which the aeroplane engine required at sea level was represented by the line AB. If the machine was running at 5,000-feet altitude where the absolute pressure was about $2\frac{1}{2}$ lb. lower than at sea level, the compressor had to be made large enough to aspire a volume corresponding to length CD. The power required to compress the air to sea level pressure

FIG. 10.

Diagram showing Supercharger Capacity at Various Altitudes.

was represented by the area ABCD, and this work was relatively small and the compressor was not big, but assuming that the supercharger was intended to work at an altitude of 18,000 feet, at which altitude the absolute pressure was about $7\frac{1}{2}$ lb., it would be seen at once that the Author's turbine machine, running at 30,000 revolutions, must be capable of dealing with a volume corresponding to the length EF, which was roughly twice the volume corresponding to the length AB. The energy to compress the air would be the area ABEF, which had to be taken out of the exhaust gases.

As the engine was running at constant speed whatever the altitude, because the supercharger was giving it enough air, therefore enabling it to maintain its ground level speed, it followed that at the higher

altitude a correspondingly larger amount of energy had to be taken out of the exhaust gases.

Taking finally the case where the aspired pressure was only one-quarter of the atmospheric, in that case the volumetric capacity of the compressor had to be equal to the length HG, and the work required to compress the air was represented by the area ABGH. The slope of the curve clearly showed that there must be limitations to an extreme altitude, because of the question of the rapid increase which was required in the air compressor volume and the power required to raise the pressure to ordinary atmospheric conditions at sea level. The curve BG was not an isothermal line, but represented to scale the actual variation in density at the various altitudes.

There was another point which also greatly interested mechanical engineers; certainly it had appealed to him in studying the Paper, namely, the paragraph on page 814, in which the Author set out the actual difficulties to be surmounted when running a machine under those conditions with the extremely hot gases coming from the engine. The statement was there made that the exhaust turbine end of the supercharger was exposed to the temperature of the exhaust gases which caused almost red heat, whereas the compressor end was cooled down practically to the extremely low temperature of the aspired air at high altitudes. So that they were dealing with a very compact and very light machine at one end of which the materials had to rotate under extremely high temperatures, while immediately adjacent to it, a few inches away, the other part of the machine, the business end of the machine which absorbed the energy, had to work under extremely low conditions of temperature. He thought the Author and his coadjutors were greatly to be complimented upon the patience and skill with which they had finally produced such a machine when working under such difficult practical conditions. All the same he wondered how such a machine, which, of course, was the life of the aeroplane on long flights through the stratosphere which the President had pictured in his opening remarks, would perform day after day.

It was clear that, to get the highest economy, the Author contemplated altitudes of much more than 18,000 feet, and it was clear also that he contemplated that the supercharger must run hour after hour at rotational speeds much higher than 30,000, and at extremely differing conditions of temperature at one end compared with the other. He would like to know whether such a supercharging machine had actually run on bench tests in which the conditions of running were made to imitate those extreme altitudes,

and whether it had run even for twenty-four hours, and what the machine was like at the end of the trial.

The claims which the Author justified in Fig. 9 (page 823), with regard to the surplus energy he had available, would make it appear possible to cool by air cooling the exhaust gases to some extent before they passed to the turbo-compressor; and that seemed to him one practical way of ensuring that the materials on a long-distance run such as contemplated would not be too unduly stressed. Although the Author had pointed out that it would involve a series of gear changing, as in a motor-car, he desired to say that if he attempted to drive mechanically from an aeroplane engine to his turbo-compressor instead of by the gas-turbine, a solution had been found possible in England in a machine which could run at a constant speed and yet could have its volume varying from practically zero to the full volume. He believed there were possibilities in that direction on parallel lines to the turbine, and he desired to point out that the Author's premises in that respect, namely, that such a construction was impossible, were not actually borne out in fact.

It was, of course, clear that to obtain the best results from the principle of supercharging, that is, to fly at extremely high altitudes, the designers and constructors of aeroplanes also had some fresh ground to break. The construction of the aeroplane, particularly its wings, would evidently have to be re-studied from the point of view of seeing whether a varying area could be obtained so as to suit the conditions of ground level as well as of extreme altitude; and it would appear, as the Author said, that a propeller of varying pitch was essential. The picture of the air-tight cabin rather appalled him when one thought what might occur, even if the aeroplane and the supercharger worked well, if anything happened to interfere with the air-tightness of the cabin during the voyage from London to Japan when the passengers were inside. He supposed it would not be beyond the skill of designers of coach-work and aeroplane body work to solve it, but in view of the extreme differences of temperature and the stresses on the plane he could not help thinking that there was a practical risk involved in the problem of the air-tight cabin if the high altitude aeroplane was to be used for passenger work.

There was one other practical point he desired to refer to before concluding his remarks. Those interested in turbine construction would be surprised to find that the illustration which the Author gave of the rotor on his turbine in Fig. 5 (page 817), took the form of a star wheel without any shrouding and without any curving of the blades. He would like to ask why in Fig. 7 (page 819) there

did not appear to be any arrangement for guide-blades for the admission of the suction air at high velocity. The hubs of the rotating star blades would strike the entering air with great force at right angles, and he thought that guide-blades would have improved the efficiency. He had no doubt that the Author's answer would be the very practical one that he had so much energy available altogether in the exhaust gases from the engine, as shown in Fig. 9, that as long as he got a total over-all efficiency of 25 per cent in his exhaust turbine and his turbo-compressor, that was all he required. If that were the case, the other points were only refinements and might add extra weight. He would be glad to know, however, what the Author thought about that question, as it would have to be faced when still higher altitudes were dealt with, because the volume swept by the turbine must be still greater and the amount of energy available to do the work in the engine remained the same.

When he read through the Author's conclusions (pp. 824-5), he could not help drawing another "conclusion" of his own. A good many of the members would remember meeting the Author in Paris. He was not in his early youth, and he had already been the Author of many fine contributions to science; but the conclusion that he (Mr. Reavell) came to was that the Author was still one of the young men who saw visions of the future and not one of the old men who dreamed dreams of the past. The Author reminded him of his famous compatriot, Jules Verne, whose works all the members read with such avidity in their youth. They had seen Jules Verne's stories come true. They all enjoyed reading about the "Nautilus" in "Twenty Thousand Leagues under the Sea," and some of the members during the War had a great deal to do with voyages under the sea. And now another of France's famous sons, not in a story, but in a scientific treatise, had shown the way in which their children, or perhaps their children's children perchance some day might move with incredible speed in the stratosphere.

Mr. A. E. L. CHORLTON, C.B.E. (Member of Council), said that, as the subject had been dealt with so thoroughly by the previous speakers, he would only deal with it from a purely mechanical point of view, and not particularly as referring to aircraft. It seemed to him that this point of view could be divided into two parts. First, it meant that a compound internal-combustion engine had been devised and used in practice. So many people had tried in the past to make a compound engine and had not succeeded, that it was most interesting to notice that the Paper gave particulars of such an engine, in which the exhaust pressure of the engine was

effectively used for the purpose of generating power. It naturally occurred to the ordinary engineer when he realized this, to inquire whether it could be used for other purposes than supplying the engine with extra air, as Professor Rateau had done, and, if more time were available for discussion, probably several views on this point would have been given.

The exhaust pressure of an engine averaged about 40 lb. It had always been the opinion of internal-combustion engineers that practically this indicated a big waste of power, and consequently represented that point from which the greatest gain in efficiency might be secured. This pressure of exhaust, used through a turbine, as in the Paper, was probably the easiest way in which exhaust gas could be used; certainly it did not introduce the complications of the old compound engines in which a transfer valve was used, and in which much heat was lost, but it had the disadvantage that the speeds were so high that it was very difficult to apply them actually to any useful work, say by connexion with the crank-shaft of the engine itself. For auxiliary purposes, as in the Paper, it did seem that something useful might be accomplished. At any rate, it was quite well worth while some of the ardent members of the Institution directing their attention to the use of the exhaust of engines, either for the purpose of scavenging and charging, as in the two-cycle engine, or for driving auxiliaries, or for other purposes connected with the installation. It had to be borne in mind, however, that the turbo must be fixed absolutely right next to the internal-combustion engine itself, otherwise there would be great loss of heat, and that would be found to be one of the difficulties. That was what might be called the ordinary engineering view of the subject.

Coming to the purely supercharging side of the question, many of the members knew that supercharging was rather a wide subject, and that it had been done in many different ways. It was first invented as a means of reducing the flame temperatures in the normal engine cylinder, rather than for any purpose connected with high flying. This was stratified supercharging. It was found, of course, that, by adding the extra air, increased power could also be obtained. He would like to state here that Professor Rateau's system suffered fundamentally in efficiency, in the sense that it gave no stratification and all the air was pumped, that is, had power expended on it. The power generated in the cylinder depended purely on the amount of air that could be put in. If the air could be put in economically and efficiently, then big powers could be obtained, that is, high mean cylinder pressures, but as the efficiency of the turbo-compressor was

only 25 per cent—and he thought in actual practice it would be less—there was not very much to play with. If the efficiency could be raised, an improvement naturally would take place; so that apart from providing for the loss of power due to the thinning of the atmosphere, increased power could be provided for the motor itself in lower strata.

He thought it might be useful to direct attention to the different ways in which supercharging had been done. The first way was to use the other side of the engine piston as an air-pump. That principle, that is, stratified supercharging, was invented at the beginning by Sir Dugald Clerk. It was a very simple way, and he doubted whether it had been beaten in actual efficiency and reliability of running by any other method. It possessed, of course a difficulty, namely, that for aerial purposes it might tend to put up the engine weight. On the other hand, the efficiency of the engine could be increased by its use. So that an engineer could combine this method of dealing with the thin air with one in which the efficiency of the engine might be increased, and that it could be used together with that providing for the loss of density.

The PRESIDENT, interposing, inquired if Mr. Chorlton would call that a two-cycle.

Mr. CHORLTON replied in the negative; it was on the line of Sir Dugald Clerk's original work.

The PRESIDENT said he understood that Mr. Chorlton did not refer to the modern two-cycle engine.

Mr. CHORLTON said he did not do so. The next way of dealing with the subject was to employ a blower. Instead of using a piston, different forms of rotary blowers were sometimes employed. The use of a rotary blower, as a pressure pump, as against the use of a piston, was a method which was being employed not only on the Continent but also in this country, Mr. Reavell having done some very wonderful work in connexion with it. It was really a simple type of mechanical device, so that it was unnecessary to explain it further. As well as the rotary type put forward by the Author, the fan method was also used at Farnborough, where they first began by gearing direct to the engine; this was before the Author began his work. If Captain Green had been present, he could no doubt have related a good deal about this side of the subject.

Another question that was worth considering was whether it was not possible to use the fluid pressure of the exhaust of the engine itself without interposing any rotational or reciprocal mechanism, that is, through some form of injector or displacement apparatus. He had given a little time to the subject some years ago, but he had had no opportunity of continuing the work since; it was a method that appealed to him largely on the score that there was nothing in it which was likely to go wrong. It was also light, which was a very necessary qualification for aircraft and aerial work in general. He had noticed in the Paper the point that had been referred to by Mr. Reavell in his remarks about the apparent inefficient design of the rotor of the compressor—the bad entrance and the shape of the blade. He could not help thinking that it was designed purely on the score of strength for the purpose of allowing it to run at huge speeds, and that if the Author attempted to do anything except keep the vanes straight the impeller would fly to pieces. Although with a straight blade efficiency would be lost, the delivery pressure would be increased. The form of the exhaust gas turbine-end was interesting, but the Author did not refer to that point. As an engineer and particularly as a power user, it was a part of the subject upon which he would like to have heard more, especially in regard to its efficiency, quite apart from the fan. The Author also mentioned certain difficulties that had been experienced in keeping the exhaust-pipe tight. Those difficulties might be successfully overcome, but it seemed to him they all tended to reduce the value of this high-speed machine against the normal piston type or the rotary blower type. The difficulties of high flying due to the provision of the closed cabin had also been dealt with; they struck one as being almost, if not insurmountable, then uncommercial. He felt that the search for the path of least density, as it were, brought more difficulties in its train than it escaped, and personally he could hardly feel that it was a commercial proposition from the somewhat limited survey he had given to the subject. From a military point of view, however, it had a great advantage, and it was worthy of increased attention from that point of view alone. But, after all, it was mechanical construction, and the mechanical engineer would have to conquer it in the end. With all respect to the scientist and the physicist who produced graphs and such-like things, it had to be borne in mind that the hard work came afterwards.

He had omitted to mention one interesting form of supercharger that was put on the large German machines that were made just at the end of the War. Those machines contained four engines,

each of about 200 or 300 h.p., all geared to a common shaft through clutches, whilst a fifth engine driving a centrifugal fan provided for the superinduction for high flying. He thought it was the most astounding accumulation of machinery for an aeroplane he had ever seen. It was really wonderful; and only a German would have done it.

The PRESIDENT said that the Author had already been accorded a most hearty vote of thanks, but he felt it would only be just that, on the present occasion, a vote of thanks should also be accorded to Professor Bairstow, Mr. Reavell, and Mr. Chorlton for their excellent remarks. They had spoken out of the fullness of their knowledge and had made the evening a most interesting one. The attention with which the remarks of the speakers had been followed indicated that the Institution need not be afraid of securing the discussion of difficult and abstruse, up-to-date subjects dealing with the latest researches, because they would always command an interested and appreciative audience. He asked the members to accord a hearty vote of thanks to the members who had taken part in the discussion.

The resolution of thanks was carried by acclamation, and the Meeting terminated.

Communications.

Professor P. M. BAKER wrote that paragraph 2 (page 797) needed enlarging. In its present form it was misleading—possibly due to difficulties in translation. As he read the Author's statement there was no reason why an infinite speed of flight should not be attained, the tractive force being independent of speed, and that was obviously incorrect. Possibly the Author might amplify the statement.

Professor Rateau's turbo-compressor was a marvellous achievement. He had accomplished a much more remarkable feat than that involved in the De Laval Turbine—one of the previous outstanding examples of rapidly rotating machinery—and in these circumstances one was tempted to wonder how long his machine would "stand the racket." Could he give the Institution the benefit of his experience in that direction.

With regard to the compressor end of the combination, it would seem at first sight that the straight-bladed centrifugal fan would

be so inefficient at the speed at which the machine operated, that curved vanes would be of great advantage. It was, however, clear that curved vanes could only be used if suitably shrouded (the vanes would otherwise straighten), and that the air friction loss of the shrouding would be very great, possibly considerably outweighing any advantage which might be derived from curved vanes. Guide-vanes in the inlet would seem to possess some advantages. Possibly Professor Rateau would be good enough to give his reasons for dispensing with them.

It was not clear why the curves of Fig. 8 (page 821) were not smooth, unless the compressor was only *started* at the knee in each curve. It would be of interest if this point could be explained. The combined diagram, Fig. 9 (page 823), seemed to call for comment, not that it was a matter of much importance. Without knowing how it was obtained (it was probably a theoretical estimate), it was difficult to see why line LGJ was straight. Unless the exhaust-pipe capacity was considerable, or the number of cylinders great (and only one cycle was indicated), there would surely be a hump in that line near to the point G for each cylinder, but doubtless the succession of humps would only produce a wavy line—how wavy it was difficult to estimate—and it was not inconceivable that the actual back-pressure in the cylinder might be constant at the mean of the humps owing to the inertia of the gases and friction through the valves.

The main interest of the Paper to those who were not connected with the aeronautical side of internal-combustion engine work lay in the fact that it afforded the first practical example of the *compounding* of such engines. To one who had tried various methods of utilizing the exhaust energy of gas and oil engines, it afforded a vision of a possible line along which improvement of the least efficient part of the cycle might be effected—a line which seemed much more promising than that “will o’ the wisp,” the gas-turbine, on which so many inventors were spending their time.

Lieut.-Colonel L. F. R. FELL, D.S.O., O.B.E., R.A.F. (Research Directorate, Air Ministry), wrote that the supercharger in some form had now become a necessity for aircraft engines. The difficulty, however, in adapting Professor Rateau’s system, was that in order to make a satisfactory engine to give reasonable reliability, the engine must be specially designed to suit the supercharger. The heat conditions with the Rateau system were extremely severe on the cylinder, piston and valves, as the exhaust-valves and cylinder-heads were never relieved from the hot exhaust-

gases. The air-cooled cylinder, which was now so popular in aircraft engine design, it was not thought would be able satisfactorily to cope with this, as the valves and cylinder heads under the best conditions were somewhere near the safe limit of temperature. The pistons were, of course, affected in the same way, and would have to be specially designed with a view to heat conductivity.

Unless the engine were designed to accommodate the exhaust-pipes and air-ducts, the result was a very clumsy arrangement. The exhaust-pipes, which in any case required to be heavy in order to withstand the gas-pressure at the high temperatures at which they were required to run, became extremely cumbersome in a normal design.

Tests which had been carried out showed that 1 per cent drop in power was obtained for every pound per sq. in. back-pressure on the exhaust. It would appear that, when the increased weight due to the causes mentioned above was added, and the reduction in reliability, which, at the present time, it would appear would be suffered, it had not yet been definitely established that the exhaust supercharger had a marked advantage, if any gain at all over the blower driven direct off the crank-shaft through gearing. In an engine designed to run on this latter principle, the addition of a supercharger had meant only about 10 lb. additional weight without the sacrifice of reliability due to exhaust-valve and exhaust-piping troubles.

Sir HENRY FOWLER, K.B.E. (Vice-President), wrote that he noticed in the discussion on Professor Rateau's most interesting Paper that no mention was made of the work carried out at the Royal Aircraft Factory on this point. He had hoped that the British Air Force Authorities would have contributed a *résumé* of the interesting work which the writer found being carried on there when he became Superintendent in September 1916, and which, but for the great pressure at that time, he thought would have been brought to a successful conclusion. Professor Rateau mentioned also the question of the variable pitch air-screw, and he (Sir Henry) thought it was generally recognized that one of the next greatest advances in aircraft work was in a combination of this with the turbo-compressor.

Mr. W. HAMILTON MARTIN wrote that, with regard to the centrifugal forces present in the rotor, to which Professor Rateau referred (page 814), it would be interesting to know if the Author could give some idea as to the degree of accuracy of statical balance obtained

on such a turbo-rotor. The Author said that even 1 gramme of matter at the rotor's periphery gave rise to a tensile force of 123 kg. or 123,000 times its own weight when running at 30,000 r.p.m. Apart from the fact that very special steels would certainly be required, it would seem that the safety of operation of such a rotor, and for that matter, its actual life, would depend largely on the degree of perfection of its ultimate balance.

Dynamical balance of such a rotor need, he thought, not be considered as its diskular shape would not likely tend to give rise to noticeable disturbing couples. The writer was of the opinion, if statical balance were more accurately obtained in larger sized turbo-compressors, such as those referred to by Mr. Reavell, much higher speeds could in all probability be safely attained, and consequently the compression ratio per stage might appreciably be increased for a same material used. He knew many engineers connected with the building of high-speed machinery who shared this view: that it was largely the quality of the statical balance which counted when trying to obtain vibrationless running and long life of bearings of such machinery.

Dr. SANFORD A. MOSS (Engineer, General Electric Co., Lynn, Mass., U.S.A.) wrote that the Author presented the American supercharger work in a rather unfavourable light. American engineers had the greatest respect for Professor Rateau's ability, and there was no reason for any misunderstanding. It was quite true that the work of the General Electric Engineers was begun after knowledge of the work in France. This had always been freely stated, and no attempt whatever, had been made to conceal it. The fundamental idea of the use of a gas-turbine wheel in series with an internal-combustion engine, was, of course, quite old. The idea of using a compressor of some kind to supercharge an internal-combustion engine at high altitude, was also quite old, and the General Electric Engineers had never made any claims to invention of these features.

They had for many years been engaged in research and commercial work, on gas-turbines, steam-turbines, and high-speed centrifugal air-compressors, and they had produced great numbers of commercial machines of the two latter classes. Having the benefit of the experience thus accumulated, having knowledge of work which had been done in compounding an internal-combustion engine with a gas-turbine, and in precompressing air for internal-combustion engines at high altitudes in mountainous regions, or on aeroplanes, and having, as Professor Rateau stated, knowledge

of what had been done in France, they set out to design a turbo-supercharger. They used throughout the actual details which had been perfected in their years of previous work on gas-turbines, steam-turbines and centrifugal compressors, and this resulted in a final design in nowise resembling Professor Rateau's design. They had, as Professor Rateau stated, been able to supercharge larger engines at higher altitudes than had previously been possible.

Mr. JAMES D. ROOTS wrote that the subject of supercharging in internal-combustion engines was not a new one. More or less vague propositions had been made even in the earlier history of these engines to provide some means of supercharging, but it was not until quite recent years that different methods of supercharging were actually carried out, and not until 1914 with any success. It had been generally the two-stroke engine to which supercharging means had actually been applied. Some of the proposals to increase the efficiency and the control of operation of the internal-combustion engine by supercharging had been by means of a reciprocating pump, some by a centrifugal fan, and others by a blower.

Professor Rateau's method was an extremely interesting one, because he employed the waste heat and pressure of the exhaust gases to provide the power for delivering the supercharging air or mixture at a pressure. But this method involved also the provision of a turbine to make use of the energy in the exhaust gases, and it involved under certain circumstances a certain back pressure and a consequent loss of efficiency by not permitting the exhaust gases a free outlet to the air. As he admitted in his Paper, Professor Rateau's system necessitated a considerable addition to the weight of the engine to be supercharged, and this was a serious matter on an aeroplane. He did not appear to have allowed in his estimate of total efficiency for this additional weight, and the writer ventured the opinion from the apparatus made upon the system of his own design, that if Professor Rateau had made experiments upon the lines suggested to him by the Lorraine Dietrich Co. in 1915, he would have found a higher efficiency in the whole apparatus, because in this system there need be no back-pressure upon the working pistons, and a small speed-varying gear for driving the supercharging centrifugal fan off the engine would have involved but a small part of the extra weight found to be necessary in Professor Rateau's system.

A modification of this system was worked out successfully as applied to an internal-combustion engine on a motor vehicle in 1914. The writer had not applied his method or system of

supercharging to aeroplanes, but he believed that experiments were made upon these lines during the War, at Farnborough, at least, so he had been informed. Professor Rateau apparently had had information to a similar effect. But so far as the writer was aware, these experiments were never completed.

In conjunction with the late Mr. Jack Scriven, a woollen manufacturer, who was then President of the Bradford Automobile Club, supercharging apparatus according to the writer's system was applied to motor vehicles in 1914. This system involved the delivery "of the mixture, gas or air, by variable rotary means to the cylinder or cylinders of the engine in volume greater than that supplied by the engine itself, and in accordance with the power or speed required from the engine, this increase of power or speed being effected by accelerating or increasing the rotary delivering means relatively to the engine speed, thereby effecting variation and control of the engine power and speed, and therefore of the vehicle or the like propelled thereby." This was a quotation from the specification of the patent granted in 1914. Mr. Scriven's first experiments were carried out upon a delivery van in which the supercharging centrifugal fan for delivering the mixture at a pressure to the cylinders of the engine was driven by an electric motor, the energy for the motor being provided by the lighting set battery. He found the results after trial so promising that he made a new and more perfect apparatus and fitted it to a Morris Oxford car, which had then just been delivered to him.

The apparatus comprised a centrifugal fan for drawing the mixture from the carburettor coupled directly to an electric motor energized by the lighting set battery, and controlled by means of five buttons on the steering-wheel, by which the speed of the electric motor and therefore of the supercharging fan was varied as required to the speed and power of the internal-combustion engine and therefore of the vehicle.

After some preliminary tests on the roads around Bradford, Mr. Scriven drove the car with two passengers and luggage from Bradford to Aberystwith, and throughout this journey the forward change-speed gear-wheels on the Morris Oxford car were never operated, the control for all forward speeds being effected by varying the speed of the electric motor and fan by means of the contact buttons. So satisfied was Mr. Scriven with this supercharging apparatus that he arranged to manufacture it, but owing to the War he was obliged to postpone its manufacture. Unfortunately, Mr. Scriven died during the War.

It would be observed that in Professor Rateau's apparatus he

varied the speed of the supercharging fan to control and vary the speed and power of the engine. In the writer's opinion it was questionable as to whether Professor Rateau's results could not have been obtained without the introduction of the exhaust turbine which introduced such other serious disadvantages, by means of a small set of change-speed gear driven off the crank-shaft of the engine for varying the speed of the centrifugal supercharging fan. This set of gear-wheels could have been very small and relatively much less heavy than the exhaust turbine apparatus used by Professor Rateau, and yet give an equal range of varying speed, and indeed probably a greater variation of speed. Nevertheless, the writer was convinced from the result of his experiments that by far the best way of effecting supercharging in internal-combustion engines for either aeroplanes or motor vehicles was by means of an electric motor, for no other means offered so complete and perfect a variation and control of the speed of the vehicle upon which the supercharging apparatus was fitted.

It appeared questionable also as to whether it was really necessary to drive the supercharging fan at so high a rate of speed as that mentioned by Professor Rateau, since the speed of the fan in the apparatus used upon the Morris Oxford car already mentioned did not exceed 6,000 revolutions. In a motor vehicle the great increase in the power of the engine when desired was one of the prime advantages, and the relative convenience of the operation was manifest when this was effected by a small lever on the steering-wheel, the response of the engine to which was immediate, as compared with changing the speed-gears and then accelerating.

Professor RATEAU, LL.D., wrote that he had been greatly disappointed by the fact that the state of his health had forced him to remain in Paris, and had prevented his attendance at the discussion of his Paper in London. He wished, in the first instance, to express his sincere thanks to the President, Dr. Hele-Shaw, for the great sympathy he had shown and for the trouble he had taken in giving such an interesting abstract of his Paper as an introduction to the discussion. He wished to thank all those who had taken part in the discussion, whether to clear up certain points or to raise questions; to the latter he replied to the best of his ability, but only briefly, because a very great deal of space would have been required for a complete statement. He wished in particular to express his thanks for the kind remarks made by Professor Bairstow and Mr. Reavell.

Some of the remarks that had been made by various speakers appeared to show that the Author's Paper had been read somewhat

hurriedly. For example, it had been explicitly stated in the Paper, on pages 809 and 810, that he was well aware that several inventors had already proposed the supercompression of air for the supply to internal-combustion engines, and, in his opinion, it was a question either of piston-compressors, or of rotary compressors of the Roots type, or even of centrifugal fans.

Commencing in 1915, he had himself investigated these methods (as well as others of which nothing had so far been said), and in particular the addition of a multicellular fan, such as those that he had been the first to introduce into practice, driven by gearing; but he had abandoned this line of investigation for the reasons briefly given in his Paper, to which he thought it was unnecessary to draw further attention. He had since learnt that trials of this nature had been undertaken in 1915 by the British Aeronautical Service, and later by others, without arriving at any practical result. The difficulties in the way were enormous, and this system could from no point of view (lightness, reliability, independence of the two mechanical units, control of speed, or efficiency of the combination) be in any way compared with the system which he had proposed, a system which consisted in causing the fan to revolve at a very high speed by means of a turbine driven by the exhaust of the motor. When he had conceived the idea, in October 1916, no one, so far as he was aware, had yet tried the system, or had even proposed it, at any rate for aviation motors which *required supercharging to an amount that varied with the altitude*, a supercharging that could be varied at the will of the pilot; this had been effected by the Author by means of the exhaust cut-out which formed an essential feature of the system.

The Author also considered, as an essential feature, the radiator which he had introduced into the fan delivery of the compressed air; this was necessary to cool the compressed air to a normal temperature, so that there should be no loss of power in the motor, and that the exhaust valves should not be subjected to worse conditions than those of ordinary running.

To make the point on which the President had touched at the end of his abstract clearer, the Author desired to point out that the *useful couple* (the torque Q) of a petrol motor of the type used in aviation, the supply of petrol to which is generally in excess of that absolutely necessary chemically for complete combustion, is of the form

$$Q = A (\rho - \gamma) \quad . \quad . \quad (18) \text{ (page 809)}$$

ρ being the density of the incoming air, A and γ two constants,

3 z

or rather, two parameters, which vary, but relatively very little, with the speed of rotation. This is what was found as the result of the analysis he had made of the only series of exhaustive measurements known to him on a motor supplied with air at variable pressures and temperatures, that is to say the trials made of the Liberty motor in the United States laboratory.

This analysis showed that, at constant speeds of rotation, the variation in the couple, for change of density of the admission air, when plotted, gave a straight line analogous to the well-known Willans law for steam-engines. There was accordingly, for each speed, a variation in the couple according to the formula given above. If the constants A and γ corresponding to the different speeds of rotation were determined, it would be found that A varied but little; it reached a maximum at 1720 r.p.m., in the particular case of the Liberty engine; the following were some of the values of A in kilogramme-metres, supposing that ρ did not represent the density of the air supplied, but its specific weight in kg. per cubic metre:—

Revs. per minute . . .	1,300	1,500	1,700	1,900
Coefficient A . . .	175.5	178.6	180.3	177.8

γ varied more, and increased always with the speed.

The following were the values found for γ :—

Revs. per minute . . .	1,300	1,500	1,700	1,900
Coefficient γ . . .	0.206	0.215	0.230	0.264

It would be noticed that these values were in this case considerably higher than that of 0.12, which the Author had used in his Paper; and it followed from this that his conclusions regarding the advantage of supercharging, that is to say, the conclusions that he had set forth in the Appendix, were actually below those that had been obtained in practice.

With regard to the remarks that Professor Bairstow had made, the Author stated that he was in agreement with him generally, except in a few instances. It was true that speed was not the only item to be considered in aviation; but it was doubtless one of the main factors.

He understood the objections that had been raised on the subject of his assertion that the resistance offered by an aeroplane was independent of its speed; he recognized that this resistance was not a simple matter. It depended on the speed of the aeroplane under consideration, on the density of the air, and on the angle of incidence of the wings.

It was first necessary to state the problem that was to be solved. If the speeds were compared *at the same altitude*, near the ground for instance, the conditions were those that would apply to vehicles running on the surface of the earth or on water *and were unable to modify the condition of the resistance encountered*. This resistance increased with the speed and in proportion to the square of the latter, on the one hand, but also, on the other hand, proportionally to a function of the angle of incidence of the wings. The calculation could easily be made when *the characteristics* of the aeroplane were known. But when the possibility of flying at different altitudes was taken into consideration, the speeds obtained might be compared under the condition that the angle of incidence of the wings remained constant. Then, as the weight of the aeroplane was supposed to remain constant, the resistance did not vary, and the speed varied according to the equation $\rho v^2 = \text{a constant}$, that is to say, that it increased with the altitude.

The Author had given a great deal of attention to these problems. He had published memoirs on the subject in the Proceedings of the Académie des Sciences three years previously and in his work : “*Theory of propellers and of aeroplanes in straight flight*” (1920).*

Professor Bairstow had drawn attention to the fact that the use of the turbo-compressor would not be suitable for short journeys such as that from Paris to London. This was evident. It was necessary that the length of the journey should allow for climbing to the higher regions of the atmosphere (at least 4,000 metres) and for coming down. But the question commenced to be of interest for distances greater than 400 km., such as Paris to Lyons, and it became of great advantage for distances of 800 to 1,000 km.

Professor Bairstow had also pointed out that the supercharging which restored the motor to the same running conditions as at ground level, would enable it to run under a load that it could not stand continuously.

Nevertheless, for the last four years a number of military aeroplanes fitted with turbo-compressors had flown for long periods at a height exceeding 5,000 metres, and even up to 10,000 metres, without having shown any trace of special wear ; moreover, it was to be hoped that the engine-builders would soon produce stronger motors capable of running at ground level at full load for long periods, for many hundred hours or perhaps many thousand hours without failure.

* *Théorie des hélices propulsives et des avions en vol rectiligne* (1920).

In reply to Mr. Reavell, the Author wished to explain that actually the construction of such a compressor of very compact form, very light although absorbing about 50 h.p., running at an enormous speed, having gases at $800^{\circ}\text{C}.$ on the one side, and extremely cold air (as low as $-50^{\circ}\text{C}.$) on the other side, was not an easy matter; without the wide experience that he had acquired during the thirty years he had devoted to the construction of steam-turbines and high-speed turbo-compressors, he would doubtless have been unable to succeed except after much trial and error, whereas actually, the trial machine, of which the drawings were made in January 1917, ran perfectly from the first. It was this turbo-compressor that had been run up to as much as 53,000 r.p.m., but it was true that for this trial the turbine was driven by steam. The present turbo-compressors were almost identical with the first one constructed; only very small alterations had been made.

Of course the enormous peripheral speed of 670 metres per second (2,200 feet per second) was not the normal speed for this turbo-compressor. But if it were necessary it would be possible, in the opinion of the Author, to make similar machines in which the maximum stress on the metal would not exceed more than 20 kg. per sq. mm. In the present turbines, the normal stress in the metal of the fan-wheel, at 30,000 r.p.m., nowhere exceeded 12 kg. per sq. mm. It was therefore easy to secure a factor of safety of 5 with a nickel steel having an elastic limit of 60 kg. per sq. mm., which was easily obtainable. The turbine wheel, which was required to withstand temperatures of the order of 700° to $800^{\circ}\text{C}.$, was calculated on a basis which gave still lower stresses.

The Author had been unable to make lengthy bench tests under the temperature conditions which were met with in the upper atmosphere; but it had been found from experience in flight that the turbo-compressors when at work had not suffered from failure, and some of them had run more than a hundred hours. They were stronger than the aero-engine itself.

The Author in his scheme had taken all possible precautions to prevent the high temperature of the turbine from causing deformation of the whole or difficulties with the fan. Fig. 6 of the Paper (page 818) showed clearly the arrangement which had been adopted, an arrangement which was a characteristic feature of the turbo-compressor. The bearing on the turbine side was connected to the fan by three very strong arms which passed round the turbine. The latter was fixed to the arms by three small feet, which allowed expansion to take place freely. The turbine thus

ran perfectly true and heat could only pass in small quantity to the fan through these feet, which were of small section, and through the shaft. The latter ran under difficult conditions. However, by reason of the arrangement adopted, and by carefully calculated dimensioning, it had stood perfectly.

The Author wished to reply to a question that had been put to him by Mr. Reavell, Mr. Chorlton, and Professor Baker. The fan-wheel was machined from the solid from a block of steel; the blades were radial and varied in thickness so that they formed a solid of uniform strength under the action of centrifugal force. From this it had been supposed that the admission of the air to the wheel did not take place correctly; that there must be a great loss due to shock when the blades struck the air. This was not the case; the loss was not so large as might have been thought. Ordinary fans had for a long time past been made with radial blades and they did not give such bad results. Moreover, it should be noted that in Fig. 6 (page 818) the air entered the inlet of the fan through a snail-shaped opening which gave it a velocity component in the direction of rotation. Moreover there were, actually, guide-blades placed before the entrance to the wheel, which gave the air exactly the correct velocity. Fig. 7 had been reduced to too small a scale to enable these to be shown. These guides formed a "distributor" which did make an improvement in the efficiency, but, actually, only to the extent of a small percentage.

The reason why the efficiency of this compressor was not as high as that which could be obtained with compressors at ground level, was because the apparatus was extremely compact and the dimensions had been kept very small. Nevertheless its efficiency was over 55 per cent under its normal running conditions, and this was a good result to have obtained under such unfavourable circumstances. The same was the case with the turbine; an efficiency had been obtained of the order of 50 to 55 per cent; so that the turbo-compressor had an overall efficiency of 25 to 30 per cent according to the running conditions.

In reply to Mr. Chorlton, the Author stated that the high pressure of the gases, at the end of the expansion when the exhaust valve opened, could not be utilized efficiently unless the inlet of the turbine was very near to each exhaust valve. Actually the pipe which connected the exhaust manifold of the engine to the turbine had necessarily a volume much greater than that of one of the cylinders; the pressure of the gas therefore fell rapidly when it had passed through the exhaust-valve. There were nevertheless obviously fluctuations in the admission pressure to the turbine, but they were

not relatively large. This piping had to stand an internal pressure which might exceed half-an-atmosphere. It was necessary that it should be strongly made, but this did not involve any great increase of weight.

The Author was aware that the Germans, who doubtless knew of the work that had been done in France in 1917, had, towards the end of the War, begun to equip aeroplanes with centrifugal compressors run by a petrol motor fitted for this purpose; and the work of design and construction had been entrusted by them to his licensees, the very people to whom he had previously taught the making of centrifugal compressors. The results, however, as given in published figures, had been very poor, which is what might have been expected. This solution of the problem could in no way be compared with that obtained by the use of a turbo-compressor driven by the exhaust gases.

With regard to the first point raised by Professor Baker, it was only necessary to refer to the equations (13) given in the Paper (page 803) to see that the speed v of the aeroplane was determined by its own weight W , the density ρ of the air, and the angle of incidence of the wings (the coefficient γ); for equal angles of incidence the speed should be inversely proportional to the square root of the density.

The curves shown in Fig. 8 (page 821) relating to the aeroplane fitted with the turbo-compressor were broken at the height of 5,400 metres, because, at this height, the running conditions of the whole arrangement of the motor underwent change. Below this, the pressure of the air supplied to the motor was restored to normal atmospheric pressure at ground level; above this height, the maximum permissible speeds for the motor and for the turbine had been attained, and if the propeller had been properly designed, the turbo-compressor could give no more than double, or nearly double, the pressure of the surrounding air; it followed that above this level, the feed pressure would have diminished in proportion as the aeroplane had risen, as was the case on leaving the ground with an aeroplane not fitted with a turbo-compressor.

The diagram shown in Fig. 9 (page 823) was diagrammatic. The line CJ had been drawn as GC produced; it did not follow FJ , for the reason explained above, which was that the pressure of the gases on leaving the cylinders, and between them and the turbine, did not vary much on account of the volume of the manifold and exhaust pipe which formed an intermediate reservoir.

In reply to Mr. W. H. Martin, the Author wished to point out that the balancing of the rotor was a very simple matter. It was

done statically and not dynamically. It was, of course, necessary that it should be done carefully. The whole turbo-compressor required very accurate workmanship. In the case of every one that had been put to work, and many had been made, the running of the turbo-compressor had always been excellent. This was perhaps due to the fact that the speed of rotation was greater than the first critical speed of the shaft, so that the latter by its flexibility gave automatic centring to the rotor.

Dr. Sanford A. Moss, Engineer to the General Electric Co. at Lynn, U.S.A., had admitted that the work of the engineers of that company on the turbo-compressor for aeroplanes had only been commenced after the work done by the Author in France had become known to them. It would have been difficult to come to a different conclusion, because it was known that the General Electric Co. had obtained drawings of the first machine constructed by the Author at the end of 1917, before they commenced their own trials. He was therefore unable to understand why it had been stated in American publications that the work of the General Electric Co. had been done independently and that it had been more successful than that done in France.

Dr. Moss had said that the combination of an internal-combustion engine with a turbine using exhaust gases had been known for long past, as well as that of the supercharging of an internal-combustion engine by means of a centrifugal fan. The Author was well aware of this and had himself drawn attention to it in his Paper. But the combination of the three machines (the aero-engine, the turbine, and the fan) had not been made until the Author had worked it out; it had certainly not been done on aeroplane engines which formed a particularly difficult and special case. The result obtained by the Author was quite original, as he had explained before, and all the features of it were to be found in the American turbo-compressors of the General Electric Co.

In the first instance Mr. Sherbondy, who had worked at the start with the Rateau-Battu-Smoot Co. in New York, had tried some structural modifications. He had abolished the arms which connected the side bearing of the turbine to the body of the fan, and he had built up the parts of the turbine and of the fan on each other by flange joints, as could be seen on page 1039 of the new (1922) German edition of Stodola's "Treaty on Steam Turbines," and in *Flight* for 14th August 1919, which also showed a rotor identical with that in Fig. 5 of the Author's Paper, except that the shaft was shorter and would therefore appear to be rigid. The machine thus designed could not work well on account of the large expansion

of the parts of the turbine which would be raised to a high temperature and by the transmission of heat.

The interesting remarks of Mr. James D. Roots, moreover, confirmed the explanations that had been given above. The system that had been thought out and put into practice by the Author did not add much weight; but, of course, something must be allowed in order to obtain the doubling or more than doubling of the power of the motor at high altitudes. In any case, it would appear impossible to do better, or even as well, with any other system. The comparison between the turbo-compressor run by the exhaust gases, and the compressor run by a geared motor had already been referred to in the Paper.

The Author agreed thoroughly with Sir Henry Fowler in his opinion that the variable pitch propeller would be an important improvement, particularly for very high altitudes. This had been mentioned in the Paper. The construction of such propellers had been begun, but it was necessary that they should not add too greatly to the weight, and particularly that they should prove thoroughly reliable.

Colonel Fell had written that the supercharger was ^{now} ~~not~~ a necessity for aero-engines, and that the Rateau system could only be rationally applied to motors specially built for its use; the heat conditions would be extremely bad for the cylinders, the pistons, the valves, etc. This opinion appeared to him very strange. All the applications that had been made in France, up to the present, had been on quite ordinary motors (Renault or Hispano) without any other modification in the motor than the strengthening of the exhaust flanges, and no more disadvantages had been found with the turbo-compressors than without them, even after many hours of running. And why should it have been otherwise? The turbo-compressor restored the motor to the conditions of running at ground level: the same admission pressure for the air, and the same temperature; why then should the cylinders, or the pistons, or the valves, become heated to a higher temperature? The opinion of Colonel Fell would appear to have been based on an *a priori* decision, and not on actual experiment.

In conclusion, Professor Rateau added, for flight at very high altitudes, such as 10,000 metres and over, where the pressure required to be quadrupled, it would be necessary to make a modification in the fan constructing it with two wheels in series in the same casing, like the multicellular wheels, or to use two separate fans arranged in series. The Author had already thought out an arrangement of this kind which presented no fresh difficulty. But this could

only be applied when an air-tight chamber could be provided for the pilots and the passengers. This was another problem which would also be solved, doubtless, before long. They should have confidence in the genius of man. Had not the inventions that had been brought to light during the last few years given reason for hope ?