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# PROPULSION BY REACTION

By Maurice Roy

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# PROPULSION BY REACTION.*

By Maurice Roy.

Any system of propulsion in a fluid develops a reaction effect. Propulsive reaction is set up by mechanical propelling devices working in a surrounding fluid or by a certain amount of material expelled from the propelled object toward the rear. The first class comprises the ordinary propeller and the second the ordinary rocket. Both are therefore, in this sense, reaction propellers. Yet, according to the general acceptation, this designation is confined to jet devices (or those with fluid veins blown into the surrounding medium). The best known examples of the latter type are the pyrotechnic rocket and Barker's mill.

I now propose to speak about this particular type. Let me remind you that this question was already, at an earlier date, the subject of an address delivered before this society. It was followed by an interesting discussion, one essential point of which I shall recall shortly.

The rocket, although a very old invention, never ceased to charm the imagination of investigators. Its use was not only contemplated for flights beyond the limits of the atmosphere,

*"La Propulsion par réaction." From La Technique Aéronautique, Jan. 15, 1930, pp. 9-20. A paper read before the Société Francaise de Navigation Aérienne, on January 29, 1930.

for which it is the only possible means of propulsion, but also for flying in air, as confirmed by recent tests. According to the inventors, the rocket propelling device is designed as an ordinary explosive rocket or as a machine running on liquid fuel and producing a jet of burned gases. In this case atmospheric air is absorbed for the combustion of the gases. In addition to the strictly required amount of air there may be added a more or less important excess.

If, instead of directly applying the reaction exerted on a rocket to the object it is proposed to propel, the rocket is mounted at the end of a revolving arm so as to make the reaction peripheral, an actual gas turnstile is formed which constitutes a motor capable of driving any type of mechanical propelling device. This idea, advocated by many authors of gas turbine designs, is found again in the so-called reaction propellers designed by several inventors in which the propeller is driven by the suitably directed exhaust of rockets mounted at the tips of the propeller blades.

Although, at first sight, they seem to differ materially from each other, all these propelling systems are not only closely related to each other but also to the ordinary engine-propeller system. They all work on the principle of the combustion of an explosive or of a combustible mixture producing a gaseous jet which flows from a fixed or movable aperture and is capable of developing a useful propelling effect, or exerting an optional mechanical stress on a shaft, transformed by a propeller into useful propulsion work. These different systems are comparable among themselves, provided suitable conditions of comparison are adopted.

I shall now confine myself to considerations on the efficiency of propulsion. In the first place this efficiency must be accurately defined and mathematically expressed. The general system considered is shown diagrammatically in Figure 1. Atmospheric air penetrates into the device through a fixed axial intake A pointed forward. Fuel is carried in the device. The physical and chemical properties of the air and fuel undergo certain changes during their passage through the device. These consist chiefly in compression, combustion, and expansion. This thermodynamical evolution takes place partly in a heat engine M and partly in a revolving system of turbine T. The turbine T is connected with the engine M and either receives power from the engine or supplies the latter with it (in which case the engine M becomes a receiver). The turbine T exhausts into the air through apertures pointed rearward and perpendicular to their absolute trajectory which is helicoidal. The turbine drives a propeller H with which it can be identified as in the case of the figure.

This general scheme includes, as individual cases, all the systems considered above and also the ordinary engine-propeller system. The latter is obtained on the assumption that the turbine T is reduced to a simple transmission between the engine M and the propeller. Then this part of the machine is locked automatically on the engine casing and, with its fixed exhaust, restores its normal silhouette to the aviation engine.

For the purpose of developing a rocket propelling device, the turbine T must be assumed to be motionless and the propeller H inexistent. The engine M accomplishes no work on the outside and the fixed exhausts are of course located below the engine and at the rear of the group, according to the normal rocket arrangement. A rocket working merely on explosives without using atmospheric air can be developed by closing the air intake A.

By cutting out the engine M, a propeller working strictly on the reaction principle is developed. Compression then takes place in the hollow propeller blades and combustion in a burner located at the blade tips and feeding the rocket exhaust pipes, the direct reaction of which drives the propeller. Besides, the above scheme permits of devising an infinite number of moto-propelling systems forming a continuous series between the extreme and specific cases just considered.

What is the total efficiency of any one of these propelling systems? The useful propulsion effect and the power spent in producing it are defined by an always arbitrary but as logical as possible convention. If the propelled system is towed under ideal conditions and with a simplified shape which permits of suppressing the moto-propulsion system, its aerodynamic resistance is $R$ and the power required for its propulsion at the speed $V$ is $R\,V$.

During the operation of the moto-propulsion system the tractive power which it develops at the speed $V$ balances the actual resistance of the propelled system. This resistance is affected by the presence and by the action of the moto-propelling system. Let $R'$ be the actual tractive stress and

$$R = R' (1 + \epsilon).$$

The coefficient $\epsilon$, usually positive and small, represents, at the considered speed, the total influence of the moto-propelling system on the resistance. $R'\,V$ is the supplied propelling power, but we shall adopt, for the measurement of the useful power, the term $R\,V$ which is independent of the moto-propelling system used. This system develops a useful power $R'\,V$ for a fuel consumption of meter kilogram per second, the calorific capacity of which is $L$.* Its efficiency proper is $R'V/mL$.

This ratio can be resolved into two others, so as to show the function of the thermodynamic transformation undergone by the air and fuel. This transformation is usually characterized by a so-called thermic efficiency. The latter is defined as the ratio of the actual work to the calorific capacity, the actual work being that of an ordinary stationary engine obtained

*I assumed that coherent units are used and that the heat and work factors in particular are expressed by the same unit. In the present case the kilogram is taken as the unit of mass.

by the same transformation for the same heat exchange with the outside and for the same passive resistances.

We assume, by definition, that the efficiency proper of the moto-propelling system is a product of the thermic efficiency $\eta_{th}$ by a term which we shall call the efficiency of the propelling device $\eta_p$. Then we have

$$\frac{R'V}{m\ L} = \eta_{th} \times \eta_p \ ;$$

whence, by definition

$$\eta_p = \frac{R'V}{m\ \eta_{th}\ L}.$$

Reverting to the total efficiency, the latter is found to be the ratio of the useful effect, measured conventionally by $RV = R'V\ (1 - \epsilon)$, to the power which it absorbs. Following the general practice, this power is measured by the calorific capacity (mL) of the weight of the burned fuel. Although I shall maintain this customary convention, I will expound subsequently the apparently paradoxical character of one of its consequences. We can thus put

$$\eta_g = \frac{RV}{mL} = (1 - \epsilon)\ \frac{R'V}{mL} = (1 - \epsilon) \times \eta_{th} \times \eta_p.$$

This formula which results from the adopted definitions has the theoretical advantage of bringing into evidence the followung three terms of quite different nature:

The influence $\epsilon$ of the moto-propelling system on the resistance which must be overcome;

The quality $\eta_{th}$ of the thermodynamic evolution of the active agents (air and fuel) passing through the machine;

The efficiency $\eta_p$ of the propelling device.

We shall now consider the means of calculating the total efficiency of a system corresponding to the scheme of Figure 1. The tractive stress $R'$ is calculated by application of the theorem of the momentum projected on the direction of translation $V$ to the system and elements which it contains (air and fuel) during a period of operation assumed to be periodical. In this connection attention is called to the resistance of fixed fairings, the thrust or traction of propeller blades, the drag of rocket shells, and lastly, the impulse of the pressures against the intake and exit apertures of the machine, as well as the momentums lost above and gained below. An easy, though delicate discussion, shows that the aerodynamic drag of rocket shells (hollow and open bodies) can be neglected in general, while the inherent drag of the fairings proper, which to a certain extent cover and streamline the propeller hub, can be included in the propeller thrust. On the other hand, the theorem of the kinetic moments about the propeller axis applied to the preceding system provides a second relation which includes the power absorbed by the resisting aerodynamic propeller moment. This power is related with the useful propelling power of the propeller by its efficiency $\eta_h$, defined in the usual way and which is now a very well-known propeller characteristic.

Besides, the equations, which are thus developed, bring in the mechanical power supplied by the engine M to the turbine T, identified in principle with the propeller H. It is convenient to consider this power as a specific fraction h of the actual thermodynamic evolution work of the burned active elements. It is expressed as follows: $h\ m\ \eta_{th}\ L$. In order to determine the relative exhaust velocity, which is an essential unknown quantity, a third relation must be derived from the principle of the conservation of energy applied under the same conditions as the preceding theorems.

Without going into the details of the calculation which does not offer any difficulty and in which I had only to make a few quite secondary assumptions, the following formulas are thus obtained

$$\eta_g = (1 - \epsilon)\ \eta_{th}\ \eta_p$$

$$\eta_p = h\ \eta_h + (1 - h)\ \eta_f \cdots\cdots$$

$$(1-h)\ \eta_f = \frac{1}{q}\left\{(1+\eta_h \tan^2 \beta_e)\left(\sqrt{\alpha[1+2\ (1-h)q \cos^2 \beta_e]}-\alpha\right)+ (q-1)\right\}$$

In these formulas $\eta_{th}$, h and $\eta_h$ have the same significance as above. The parameter $\alpha$ represents the ratio $\frac{a+1}{a}$ in which a denotes the weight of air absorbed by the machine during a period corresponding to the consumption of one kilogram of fuel. $\beta_e$ is the angle formed by the resultant speed of the rocket with its translational speed. With a rocket mounted at the blade tip, $\tan \beta_e$ represents the functional parameter $U_e/U$ of the propeller. Lastly, the expression for the parameter q is

$q = \frac{\eta_{th} L}{a V^2}$. It plays a very important part, as will be seen.

The above equation is greatly simplified when $a$ is large enough in comparison with unity. This actually occurs for all liquid-fuel machines, provided there is a slight excess of air. $\alpha$ is then assimilated to unity, and

$$(1 - h) \eta_f = \left\{ (1 + \eta_h \tan^2 \beta_e) \left( \sqrt{1 + 2 (1 - h) q \cos^2 \beta_e}^{-1} \right) \right\}$$

This equation is of direct use to the comparison of different systems characterized by the same value of $q$ and using a propeller of the same efficiency. These systems differ from one another only by the proportion $h$ of the thermodynamic work effected in the engine and transmitted to the propeller, or by the argument $U/V$ of propeller operation. The case $h = 1$ corresponds to the normal engine-propeller system. The case $h = 0$ corresponds to the reaction rocket proper which contains its own motor.

Figures 2 and 3 are examples of the variation of $h \eta_h$, $(1 - h) \eta_f$, and $\eta_p$ for $h$ changing from 0 to 1, for different $U/V$ values and for the value $q = 50$, taken as a reference. This value corresponds to the following data:

$$a = 20$$

$$L = 11{,}000 \text{ cal/kg}$$

$$\eta_{th} = 0.30$$

$$V = 117 \text{ m/s} = 420 \text{ km/h}$$

which characterizes a very good aviation engine and a very fast airplane. An examination of the curves which represent $\eta_p$ is particularly instructive. It shows directly that for constant $q$ and $\eta_h$ values, like those of the considered case, it is particularly advisable to depart as much as possible from the case $h = 0$ and to approach as closely as possible to the case $h = 1$.

Other examples, of which I could give a great number, show that the above conclusion always holds good for all values of the parameter $q$ of any practical interest. This is a condemnation of the pure reaction propeller as against the ordinary engine-propeller system under the conditions which we have assumed, i.e., for a constant value of the ratio $\frac{q_{th} L}{a V^2} = q$ and equal thermic efficiency.

In order to escape the consequences of this unfavorable conclusion, very small $q$ values or better values of thermic efficiency $\eta_{th}$ should be used for reaction propellers ($\eta_g$ increases with $\eta_{th}$ although $q$, when it increases, causes $\eta_p$ to decrease). These are manifestly conditions for which the reaction propeller is unfit. As a matter of fact, it can only produce compressions greatly inferior to those of a standard aviation engine and, on the other hand, it cannot be run on very poor combustible mixtures, owing to the thinness of the compression pipes inside the blades.

Incidentally, attention is called to the fact that, with a partial-reaction propeller, the total efficiency may possibly be slightly improved over that of the ordinary engine-propeller system. This result would be most certainly achieved if, by causing the burned engine gases to escape through nozzles at the propeller-blade tips (i.e., by using the propeller as an exhauster of burned gases), the thermic efficiency of the whole system could be improved without reducing the propeller efficiency too much. This possibility is not merely imaginary and may lead, at least as far as theorists are concerned, to an interesting investigation.

We shall now consider the case of the direct-reaction propelling device or rocket proper, which appeals to many investigators. Before turning to the case of the liquid fuel rocket, we shall consider the explosive rocket. For the latter, the general formulas given above are simplified by putting $h = 0$ and $a = 0$. They become

$$\eta_f = V \sqrt{\frac{2}{\eta_{th} L}} = \frac{2 V}{w}$$

$$\eta_g = (1 - \epsilon) \eta_{th} \eta_f = (1 - \epsilon) V \sqrt{\frac{2 \eta_{th}}{L}}$$

These formulas directly result from the following considerations. The utilized part $\eta_{th}$ of the fuel energy is transformed into relative kinetic energy $m \frac{w^2}{2}$. The value of the jet reaction is $m w$ and the power which it supplies or useful power, neglecting the propeller interference $(\epsilon \doteq 0)$, is

$$mw V = \frac{2V}{w} m \frac{w^2}{2} = \frac{2V}{w} m \eta_{th} L$$

The total efficiency is therefore

$$\eta_g = \frac{2V}{w} \eta_{th} = \eta_{th} \times \eta_f .$$

This proves that

$$\eta_f = \frac{2V}{w} \ldots$$

and, since $w^2 = 2\, \eta_{th}\, L$,

$$\eta_f = V \sqrt{\frac{2}{\eta_{th}\cdot L}} .$$

$$\eta_g = V \sqrt{\frac{2\, \eta_{th}}{L}}$$

The efficiencies given by these formulas grow indefinitely with V. However, the fundamental efficiency principle prevents this value from ever exceeding unity.

The resulting paradox is merely apparent and can be easily removed. As pointed out at the beginning, it is due to the fact which sometimes receives insufficient attention, that the power absorbed by propulsion is expressed by the term $m\,L$, which represents only part of the actual power. As a matter of fact, the absolute energy theoretically available per unit of mass (1 kilogram taken as the unit of mass) of fuel is not $L$, but $L + \frac{V^2}{2}$ (calorific capacity + absolute kinetic energy). Considering this fact in its relation to the denominator of the total efficiency, the latter becomes (still on the simplifying assumption that $\epsilon = 0$):

$$\eta_g = \frac{m \cdot w\, V}{m\, L + m\, \frac{V^2}{2}}$$

with $$m\,w = 2\,m\,\eta_{th}\,L$$

whence, by eliminating $w$,

$$g = \frac{V\sqrt{2\,\eta_{th}\,L}}{L + \frac{V^2}{2}}.$$

In this form $\eta_g$ no longer grows indefinitely with $V$. Assuming $\eta_{th}$ constant, $\eta_g$ passes, for $V = \sqrt{2\,\eta_{th}\,L}$, through a maximum value equal to $\sqrt{\eta_{th}}$, which is always smaller than unity. What are the values of the total efficiency $\eta_g$ that we can estimate? They are easy to calculate from the above formulas after computing the values of $\eta_{th}$ and $L$.

The thermic efficiency of the explosive rocket depends on the combustion pressure and on the perfection of the expansion nozzles. According to calculation, even under the most favorable assumptions regarding the behavior of the walls of the combustion chamber and of the nozzles, this efficiency does not probably exceed 45 to 50%. The $L$ values are much smaller for explosives than for any known liquid fuel, since one kilogram of explosive compound contains, in addition to the fuel (atoms of C, H, ...), oxidizing agent $O^2$. We have, for example,

$L$ = 10,000 to 11,000 cal/kg for kerosene,
= 650 cal/kg for black powders,
= 1,200 cal/kg for colloidal and B powders.

The total efficiency of a B powder rocket is tabulated below for different cases:

| | $\eta_{th} = 0.40$ | $\eta_{th} = 0.60$ |
|---|---|---|
| V = 40 m/s (144 km/h) | $\eta_g = 0.016$ | $\eta_g = 0.019$ |
| 120 m/s (432 km/h) | = 0.048 | = 0.058 |
| 200 m/s (720 km/h) | = 0.080 | = 0.098 |

In practice, up to speeds of 700 km/h (435 mi./hr.) the total efficiency does not even reach 8%, while engines and propellers now in use have a total efficiency of from 15 to 22%.

The translational speed above which any specific rocket would surpass the normal engine-propeller group can be easily calculated. This speed is of the order of 1200 to 1600 km/h (746 to 994 mi./hr.), according to whether the contemplated rocket is driven by ordinary black powder or by B powder.

Aside from the smallness of its total propelling capacity, the explosive rocket is greatly handicapped by its heavy weight, due to the smallness of the above-mentioned capacity and of the calorific capacity. These fundamental objections deprive the explosive rocket of its value as a means of airplane propulsion, except at speeds of no less than 1000 to 1500 km/h (620 to 932 mi./hr.). Incidentally, technicians will find rocket investigations involve very interesting problems related to those of interior ballistics. During the last war these problems received important contributions by several French scientists, including the famous president of this society.

Since as the explosive rocket is of no immediate interest to air navigation, there only remains to be considered the liquid-fuel rocket. The latter can be designed as an internal combustion engine with highly truncated expansion. In that case the stresses developed by the gases in the engine accurately balance the preliminary compression work of the carbureted mixture or of the combustion air. The high-pressure exhaust is transformed by suitable nozzles into a regular jet, the direct reaction of which produces the propelling power. The general equations given above are still applicable. After putting $h = 0$, and $\tan \beta = 0$, $\alpha$ can be set equal to unity, as soon as the excess of air in the explosive mixture reaches a certain value. The very simple formulas

$$\eta_g = (1 - \epsilon) \cdot \eta_{th} \, \eta_f$$

$$\eta_f = \frac{1}{q} [\sqrt{1 + 2 q} - 1]$$

are thus obtained.

The efficiency $\eta_f$ of the propelling device increases continually and tends toward unity, when $q$ decreases and tends toward zero. It only depends on the parameter $q = \frac{\eta_{th} L}{a V^2}$. Thus, referring back to the expression for $\eta_g$ in which the thermic efficiency $\eta_{th}$ occurs twice, it appears that the best way to increase $\eta_g$ is to increase $\eta_{th}$, increase $a$, and increase $V$.

As ever, the practical interest of the direct-reaction propulsion device increases with the speed of propulsion. The important point is the increase of $a$, that is, of the weight of air on which the propelling device exerts its action per kilogram of burned fuel. This point, which is directly related to the problem of improving the rocket by blower effects, has been considered in the discussion previously referred to.

A simple consideration shows the advantage of increasing the output of the propelling device. In this output the mass of fuel is neglected with respect to that of air. This corresponds to our assumption $\alpha = 1$ which is perfectly admissible when the dilution reaches a certain small degree.

Let the state and speed of the fluids be uniform at the entrance and exit of the propelling device, respectively. The stress of propulsion (neglecting the coefficient of influence $\epsilon$) equals the increase of the relative momentum $m\,a$ of the fluid mass, namely, $m\,a\,(w - V)$, during the passage through the propelling device. The useful power is $m\,a\,(w - V)\,V$. The absorbed power is $m\,L$. The variation in the relative kinetic energy $m\,a\,\frac{w^2 - V^2}{2}$ of the fluid delivered by the propelling device is caused by the utilized part $(m\,\eta_{th}\,L)$ of the expended power:

$$m\,a\,\frac{w^2 - V^2}{2} = m\,\eta_{th}\,L \tag{1}$$

The total efficiency is thus immediately given ($\epsilon$ being neglected) by the ratio

$$\eta_g = \frac{ma\,(w - V)\,V}{m\,L} = \frac{(w - V)\,V}{w^2 - V^2}\,2\,\eta_{th} = \eta_{th} \times \frac{2V}{V + w}$$

In order to increase $\eta_g$, w must be reduced when $\eta_{th}$ is assumed constant. Hence, according to equation (1) a must be increased. In other words, it is more advantageous to produce a great output at low speed than a small output at high speed. At the limit for a infinite, we have $w = 0$ and $\eta_f = 1$; $\eta_g = \eta_{th}$; which marks the upper limit of the total efficiency.

Besides, the preceding conclusion remains correct only when the increased output does not affect $\eta_{th}$. The theory of nozzles is still incomplete and uncertain. Lack of time prevents me from giving you now the reasons which seem to make it useless to attempt an increase of the output by means of more or less adequately arranged nozzles, without, at least to a certain extent, impairing the thermic efficiency of the evolution of the whole of the active bodies (i.e., fuel, combustion air and dilution air passing through nozzles). This does not necessarily deprive the nozzles of all their value. Only, the reduction of $\eta_{th}$ which they occasion must be smaller than the benefit derived from the increase of the output which they enable. This is another problem which requires systematic investigation.

The above formulas clearly remind us of the classical formulas and their derivatives which roughly express the propeller efficiency. As a matter of fact, these formulas are found to be identical. Under these conditions, considering the propeller as a propelling device acting only on a limited layer and neglecting the rotational energy of the layer, the propeller efficiency, as a function of the speed of recoil $v$, is

$$\eta_h = \frac{2\,V}{2\,V + v} = \frac{2\,V}{V + (V + v)}$$

and the total efficiency of the engine-propeller group is

$$\eta_g = \eta_{th} \times \frac{2\,V}{V + (V + v)}$$

The efficiencies of a nozzle-rocket and an engine-propeller unit are of course equal when they have the same thermic efficiency and when $V + v = w$, namely, when the relative air delivery through the two compared machines is equal.

The nozzle-rocket corresponding to the engine-propeller group is diagrammatically represented in Figure 4. In this case in which it is difficult to anticipate a nozzle system with the same thermic efficiency as a good engine, it is found, moreover, that the nozzle propelling device no longer possesses the advantages of simplicity and small space requirements which are usually attributed to it.

For purposes not yet contemplated, such as the driving of torpedoes or special airplanes at very high speeds (of the order of 1000 km/h = 620 mi./hr.), it is nevertheless possible that reaction propulsion may be of sufficient interest to warrant its experimental investigation. In such a case the value of this propulsion is partly attributable to the fact that the propeller is probably handicapped at such speeds (near that of sound in air) by a considerable reduction of its efficiency.

Thus, at the end of this summary of a somewhat arid question, the conclusion to which I am brought will cause no surprise. It consists merely in an acknowledgment of the fact that the combination of a heat engine with a propeller forms the most advantageous moto-propelling system for airplanes. This is actually the solution adopted since the early days of aviation and it is responsible for the first airplane flight. The reaction power plant cannot impair its supremacy except within the range of very high speeds not yet reached nor utilizable under present conditions.

This is an encouragement to technicians working for the improvement of heat engines and propellers to persevere in their efforts, which have already been rewarded by such important progress and which are not endangered by competition

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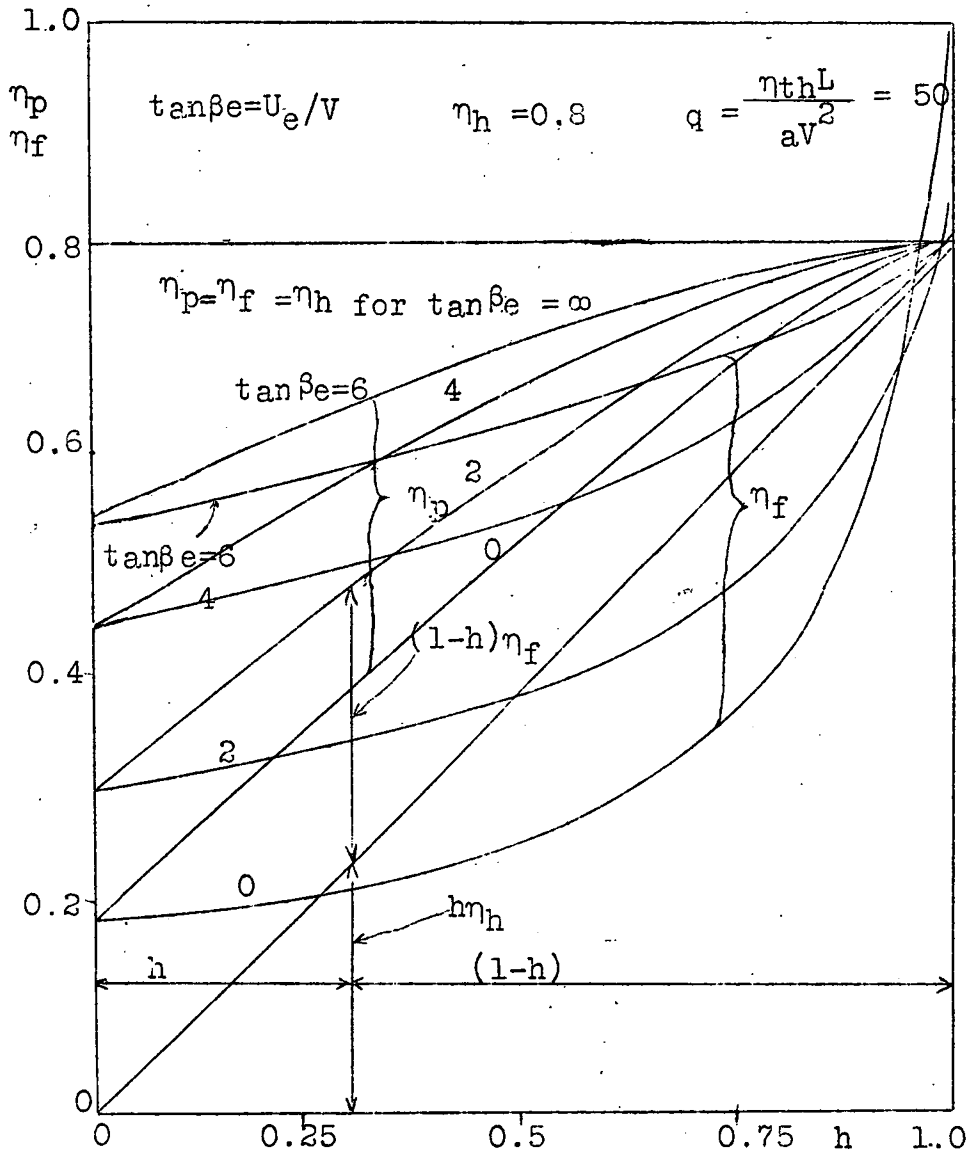
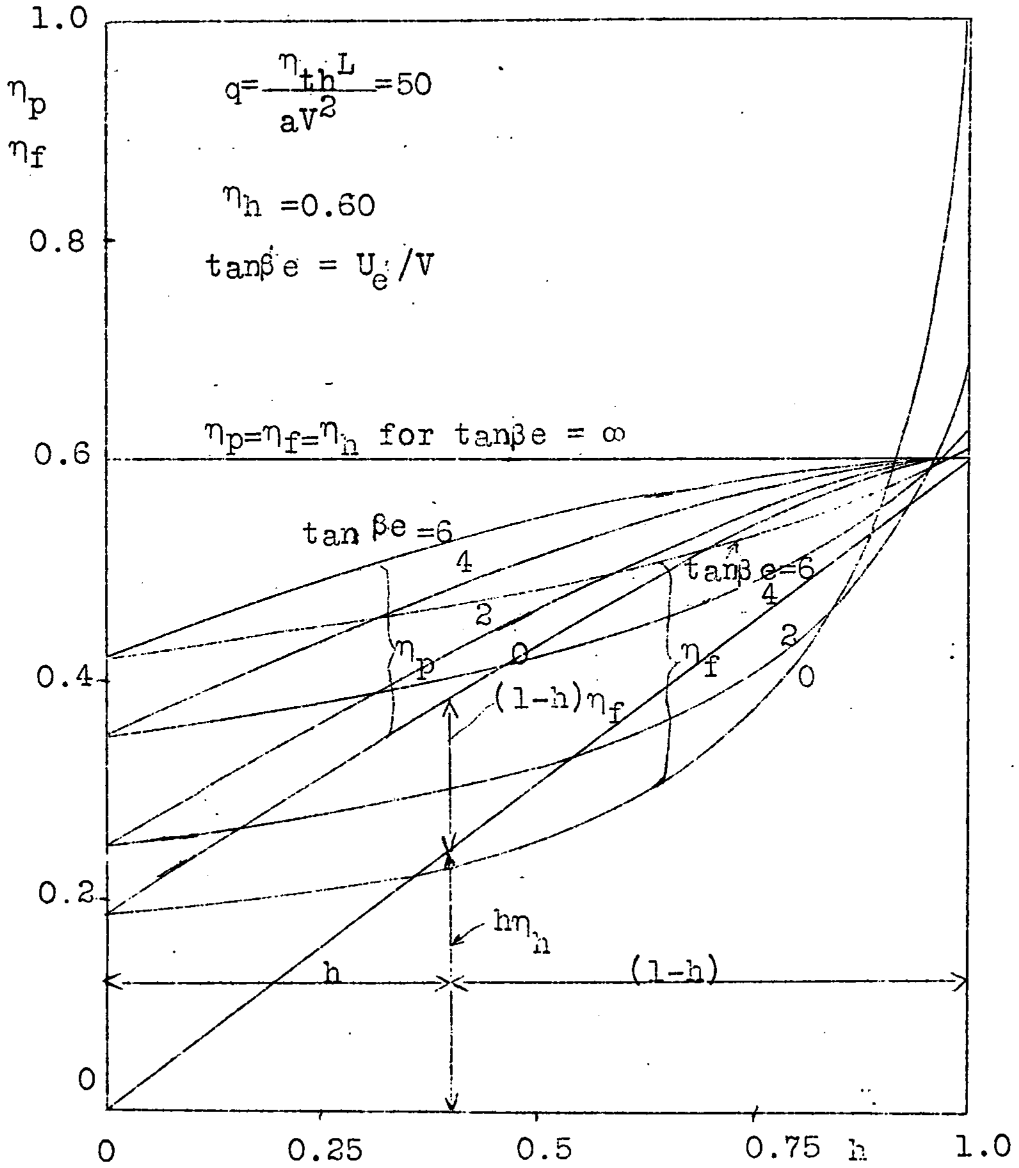


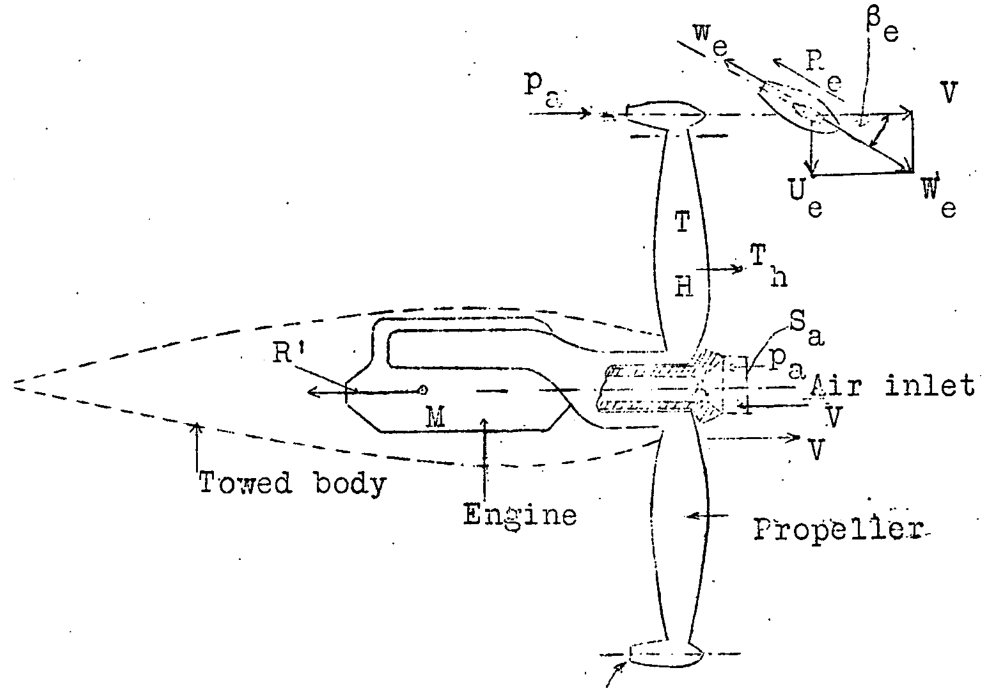
1.0
$\eta_p$
$\eta_f$
$\tan\beta e = U_e/V$
$\eta_h = 0.8$
$q = \frac{\eta_{th} L}{aV^2} = 50$
0.8
$\eta_p = \eta_f = \eta_h$ for $\tan\beta_e = \infty$
$\tan\beta e = 6$
4
0.6
2
$\eta_p$
$\eta_f$
$\tan\beta e = 6$
0
4
0.4
$(1-h)\eta_f$
2
0
0.2
$h\eta_h$
h
(1-h)
0
0
0.25
0.5
0.75
h
1.0


Fig.2



1.0
$\eta_p$
$\eta_f$
$q=\frac{\eta_{th}L}{aV^2}=50$
$\eta_h=0.60$
0.8
$\tan\beta e = U_e/V$
$\eta_p=\eta_f=\eta_h$ for $\tan\beta e = \infty$
0.6
$\tan\beta e=6$
4
2
0
$\eta_p$
$\tan\beta e=6$
4
2
0
$\eta_f$
0.4
$(1-h)\eta_f$
0.2
$h\eta_h$
h
(1-h)
0
0
0.25
0.5
0.75
h
1.0


Fig.3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$\beta_e$
$p_a$
$P_e$
V
$U_e$
$W_e$
T
H
$T_h$
$S_a$
R'
$p_a$
Air inlet
M
V
V
Towed body
Engine
Propeller
Exhaust

Fig.1

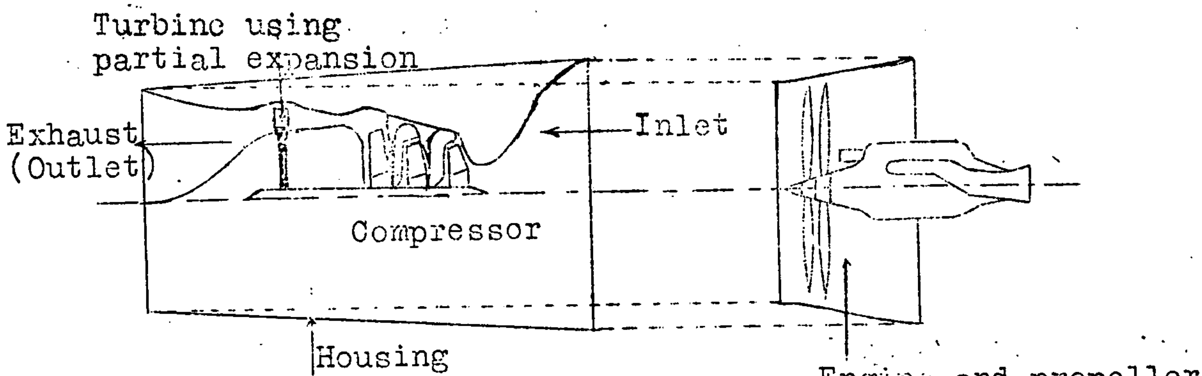
Turbine using
partial expansion
Exhaust
(Outlet)
Inlet
Compressor
Housing
Engine and propeller

Fig.4