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PRESENT AND FUTURE PROBLEMS OF AIRPLANE PROPULSION

By J. Ackeret

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PRESENT AND FUTURE PROBLEMS
OF AIRPLANE PROPULSION*

By J. Ackeret

In a lecture delivered at Winterthur in February 1938, reference was made to several problems and results, a brief presentation of which may be of some interest.

A. THERMODYNAMICS OF SURFACE FRICTION

It is a fact to be noted that the work expended in towing a surface is not entirely given by the theoretical minimum required to overcome the friction.

Consideration is given to a parallel flow past a plate about which a boundary layer is built up in the usual manner (fig. 1). The latter has a velocity distribution (relative to the plate at rest) which may be represented nondimensionally in the form

$$u = U f\left(\frac{y}{\delta}\right) \text{ (distance)}$$

where δ is the boundary-layer thickness.

From the momentum theorem there follows for the drag (incompressibility being assumed for simplicity)

$$W = \rho \int_0^{\delta} (U - u) u \, dy$$

for one side of the plate.

*"Probleme des Flugzeugantriebes in Gegenwart und Zukunft."
Schweizer Bauzeitung, vol. 112, no. 1, July 2, 1938.

The towing work which, for example, may be supplied by a propeller is

$$L = W U = \rho U \int_0^{\delta} (U - u) u \, dy$$

The retarded air is warmed up somewhat by friction. However, the heat does not represent the equivalent of the work of towing, the latter being larger. If consideration is given to the processes from the point of view of the air at rest, it is seen that behind the plate there is a wake of heated air. From the wake there is produced in each second at the distance Y a layer of length

$$U - (U - u) = u$$

the kinetic energy of which is

$$K = \frac{\rho}{2} \int_0^{\delta} (U - u)^2 u \, dy$$

This amount is to be deducted from the towing work in order to obtain the heat generated. For the latter we find (expressed in mechanical units)

$$\begin{aligned} Q = L - K &= \frac{\rho}{2} \int_0^{\delta} u \, dy [2U (U - u) - (U - u)^2] \\ &= \frac{\rho}{2} \int_0^{\delta} (U^2 - u^2) u \, dy \end{aligned}$$

This is exactly the amount that is obtained if, for each of the streamlines of the friction layer, the sum of the heat content and kinetic energy is set equal to a constant.

We may now imagine an ideal propulsion apparatus for which the mechanical wake may be avoided. In principle

each part of the boundary layer must be brought up to the full velocity U . Thermodynamically this means the avoidance of all macroscopic motion in the wake, only that portion of the work being unavoidable which is actually irreversible. The minimum of the propulsive work therefore may be considered as the heat output

$$Q = \frac{\rho}{2} \int_0^{\delta} (U^2 - u^2) u \, dy$$

which may be directly verified as the necessary work expenditure for the production of the complete velocity U at constant pressure starting from any velocity u .

The ratio $\alpha = \frac{Q}{L} = 1 - \frac{K}{L}$ is thus a measure of the

gain that such a control of the boundary layer would make possible. For the exponential law

$$\frac{u}{U} = \left(\frac{y}{\delta} \right)^{\frac{1}{n}}$$

(fig. 2) there is easily obtained

$$\alpha = \frac{n+2}{n+3}$$

(fig. 3).

B. APPLICATION OF THICK WING SECTIONS

It is well known that thick profiles offer more resistance than thin ones. At the present time, the thickness chord ratios are usually about 12 to 16 percent while higher ones are practically excluded. Figure 4 shows the normal increase in drag with thickness. What is this due to? The drag may be decomposed into a component due to the tangential surface forces and one depending on the normal pressures. It is quite certain that for very

blunt bodies this second component of the drag contributes the most. In the case of medium thickness (for example, 25 to 30 percent) the answer is less certain. The results of measurements show that the pressure drag predominates. At the trailing edge there is a theoretical rise in pressure up to full dynamic pressure; actually only a fractional part of this pressure rise occurs and hence a drag. The low pressure is due to the fact that the boundary layer thickens very rapidly toward the trailing edge and the flow thereby is less deflected. If it were possible to make the boundary layer before entry into the pressure-rise zone very thin, there would be a closer approach to the theoretical curve. By increase of the boundary-layer thickness through artificial roughness, a further impairment is actually observed (fig. 5); by suction of the boundary layer, an improvement (fig. 6).

With suitable design of the suction slots the required low pressure is quite small.* The slot shapes previously used were less favorable in this respect. Another solution would be the addition of kinetic energy to the boundary layer directly by means of blowers. It is possible to use for this purpose old types of blowers (Mortier) which, with present-day improvements, may be made to give entirely useful efficiencies. The boundary-layer air enters and leaves the wheel radially and imparts to it a primary velocity which is desirable. The dimensions required are surprisingly small (fig. 7).

C. SPECIAL APPLICATIONS OF CONTROLLABLE PROPELLERS

a) For Accelerating Gliding Flight

In coming down from altitude the pilot cuts off the gas and brings the engines to idling. The flight path receives an inclination φ downwards, the drag W being balanced by the component of the weight G along the flight path, $G \sin \varphi = W$, neglecting the effect of the propeller. If in this condition full throttle is applied and no change is made in the propeller pitch, the engine would be dangerously loaded. If, however, it is possible

* A more detailed report on the boundary suction experiments by Alfr. Gerber will soon appear in the Reports of the Institute for Aerodynamics.

greatly to increase the pitch, the engine, running at full throttle torque, may be kept down to normal rotational speed. Then the velocity receives very large increments. The propeller efficiency is still quite good at the high pitches, and the cooling effectiveness at the high speeds is more than sufficient so that the cooling flaps may be practically closed. The diagram of forces is shown on figure 8. To the propulsive component $G \sin \phi$ there is now added the force S by which the increased drag due to the high velocity can be overcome. Figure 9 shows an example of the relations to be expected. The possible steady flight speeds have been plotted for different flight path inclinations. At greater flight altitude the values reach 800 kilometers per hour. It may be added that the effect of the compressibility should make itself felt so that these values may become smaller. Actually, a further steady flight is not possible because of the shortness of the path. Furthermore, the denser air layers in which the velocity again decreases, are soon reached (fig. 10).

b) For Decreasing the Length of Landing Run

If the propeller is rotated toward small pitches, a sharp braking action results. The curves of figure 11 show, in nondimensional form, the variation in thrust for various flight speeds at fixed pitch. Starting from high speed, a maximum of 50° rotation is necessary which can be practically performed immediately upon touching the ground. It is possible, for example, to shorten the landing run by less than one half, the retardation taking place without a higher stressing of the wheel brakes as in the case of a very sharply braked automobile (fig. 12). For the practical application of this very useful possibility for our terrain, there are still a number of questions to be answered, such as controllability on the ground, etc. Electrical operation of the pitch control seems hardly possible since a very high-power output is required for a short period, and hydraulic methods are to be preferred. The Escher Wyss company has recently put out a very elegant hydraulic hub design which makes possible large changes in pitch (fig. 13).

D. GAS TURBINES FOR AIRCRAFT

Today, the gas turbine is finding application for the utilization of the exhaust gases of airplane engines

and for supercharger drive. The question arises whether direct gas-turbine drive without any reciprocating engine is feasible. It is clear that the gas turbine will find application as a stationary unit without consideration of structural weight, etc. The application to the airplane offers a number of special difficulties. On the other hand, even for the airplane, a part of the gas turbine process is now finding application. In general, the gas turbine problem is considered as a question of strength of material, but it can be shown that it is just as much an aerodynamic problem. If the entropy diagram of a simple constant-pressure gas-turbine process is considered, then very good compressor and turbine efficiencies are obtained with the present assumptions of extreme but not impossible temperatures (fig. 14). In particular, the method of regeneration, i.e., exchange of heat between the exhaust gases leaving the turbine and the combustion air leaving the compressor, has a very favorable effect. In figure 14, for equal temperature range and a somewhat lower compression ratio, regeneration without loss has been assumed. Naturally, the losses to be accounted for are greater, the lighter and more compact the regenerator is designed. It is of interest to note that the turbine losses are partially compensated for by the smaller heat expenditure. As may be readily computed, the efficiency of the gas-turbine process with complete regeneration is

$$\eta = 1 - \frac{1}{\eta_t \eta_K} \frac{T_{\min}}{T_{\max}} \delta$$

where η_t , η_K are the adiabatic efficiencies of the turbine and compressor and δ is the temperature ratio of the adiabatic compression. With zero loss regeneration, a value of δ near one is favorable, but this means a low compression ratio. For the limiting case $\eta_t = \eta_K = 1$ there is then obtained exactly the Carnot efficiency.

Because of the problem of weight, it is questionable whether regenerators, which must be provided with large surfaces, can be considered for airplanes. For future stationary installations, however, there is no question that regeneration will be the method used for raising the efficiency without excessive temperatures. On figure 14, left, the efficiency has been computed as 32.6 percent

($T_{\min}$ is very favorable at high altitude). In practice, about 30 percent would be obtainable. Is it possible to design compressors with 85-percent and turbines with 90-percent efficiency (referred to adiabatically)? Any considerable progress must occur at the expense of the structural weight; for, in spite of the relatively small heat drops, very many stages must be employed in order to obtain a system of blades without large curvatures. A consideration of the losses in a cascade system of airfoils shows that the blade losses alone make quite good efficiencies necessary. Considering the velocity and force diagrams (fig. 15), the stage efficiencies may, with good approximation, be given by

$$\eta = \frac{1}{\varphi} \frac{1}{\cot(\alpha_{\infty} - \rho_1) + \cot(\beta_{\infty} - \rho_2)}$$

where

$$\tan \rho_1 = \frac{c_{w1}}{c_{a1}}; \quad \tan \rho_2 = \frac{c_{w2}}{c_{a2}}$$

and

$$\varphi = \frac{c_m}{u}$$

If $\rho_1 = \rho_2 = \rho$, the loss may be approximated by

$$\delta = 1 - \eta \sim \rho \left\{ 2\varphi + \frac{1}{\varphi} \left(1 - \frac{\psi}{2} + \frac{\psi^2}{8} \right) \right\}$$

where

$$\psi = \frac{2c_u}{u}$$

$$\delta \text{ is a minimum for } \varphi_{\text{opt}} = \sqrt{\frac{1 - \frac{\psi}{2} + \frac{\psi^2}{8}}{2}}$$

$$\text{and } \delta_{\min} = 4\rho\varphi_{\text{opt}}$$

If $\tan \rho$ is 2 percent.- in favorable cases (small blade curvatures), 1 percent.- then wheel efficiencies of above 90 percent are obtained. Careful detail construction of gaps, bearings, etc., should make possible, also in the case of smaller units, efficiencies not below 90 percent. It must be remembered that the actual impeller efficiencies for Kaplan turbines reach 96 to 98 percent and furthermore, that the friction relations at the blades, also for small Reynolds numbers, need not be less favorable than for very large Reynolds numbers. From a consideration of figure 16, the following may be concluded: In the case of thin, lightly loaded sections, which behave very much like flat plates, a minimum for the drag is obtained in the region where the laminar layer extends to the profile trailing edge. Since there is a pressure drop, it is entirely possible, for small blade curvature, to extend the laminar flow condition to the higher Reynolds numbers. Extremely favorable values would then be obtained. At the present time, tests are being conducted which indicate this behavior for smooth plates in accelerated flow. It must be added that the frictional drag depends very much on the degree of turbulence of the flow. This turbulence for high impeller speeds may be unusually low. Certainly, a large amount of work is still to be done before a practical airplane gas turbine is created. It would be reasonable not to make the weight requirements too stringent at first. It is then possible to obtain good designs both from the viewpoints of strength and aerodynamics. It is to be expected that the factory processes with regard to precision of design, surface-smoothness control of material, etc., should not be below the usual standard in engine construction. It is to be remembered, however, that the present-day steam and gas turbines are still quite far from having attained this accuracy.

Figure 17 shows that the present Kaplan turbine attains an incomparably higher degree of fineness than a normal steam turbine. All clearances are relatively smaller, all surfaces smoother, irregularities in the flow are much fewer. The development of aircraft will, before long, make necessary very powerful power plants which will be required to deliver full output also at the higher altitudes. Here, the turbine may bring about a revolutionary change and through its noiseless, smooth operation (which among other advantages makes possible the application of welded hollow propellers) will also increase the comfort of the passengers.

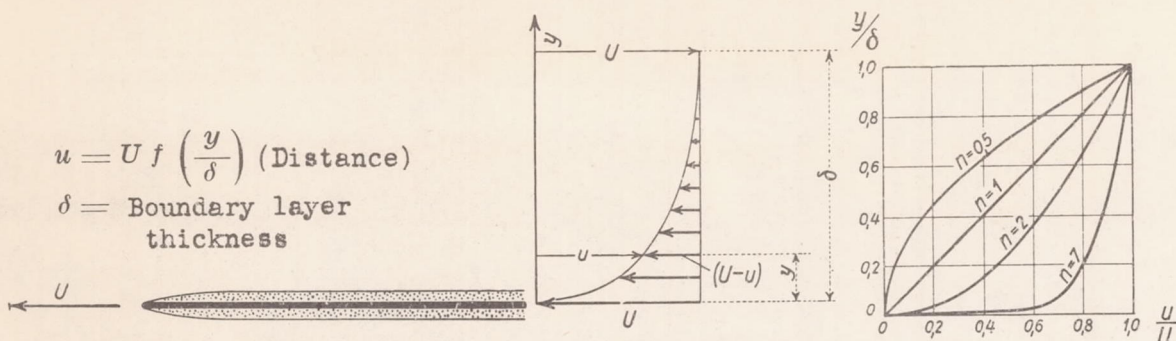


Figure 1.- Boundary layer of a plate moving with velocity U . On right, magnified velocity profile.

Figure 2.- Velocity distribution law for various exponents.

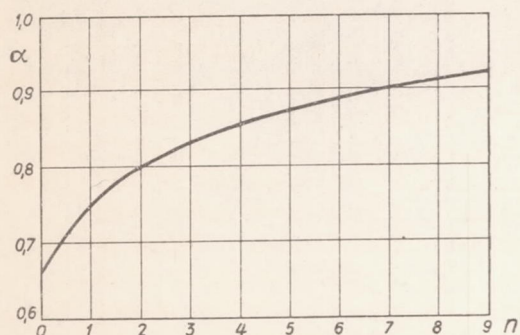


Figure 3.- Theoretical minimum work of propulsion for various exponents of the velocity distribution.

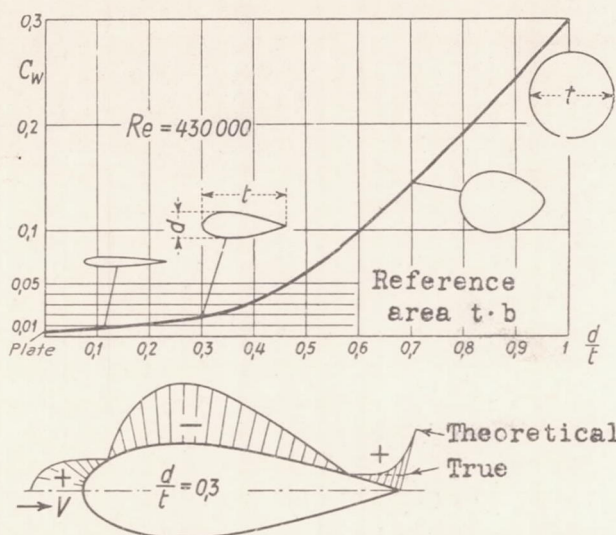


Figure 4.- Increase in profile drag with profile thickness. Below, pressure distribution over a thick symmetric profile.

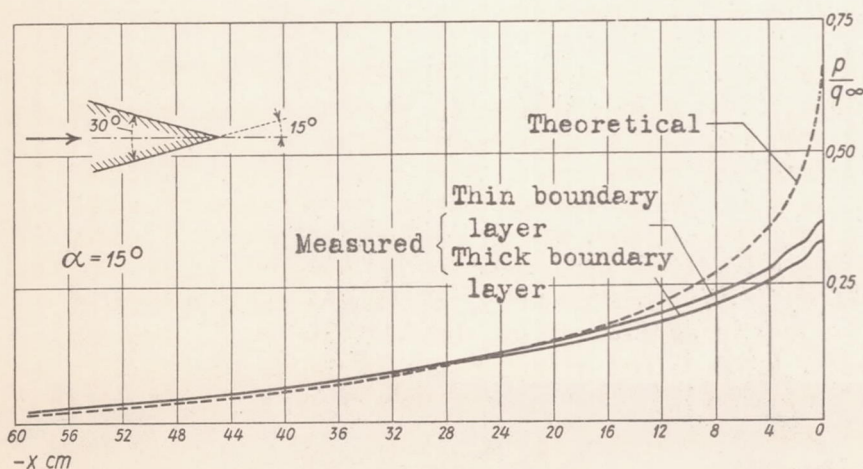


Figure 5.- Pressure distribution in the neighborhood of the trailing edge of a thick section for thin and thick boundary layers. (measurements by A. Gerber)

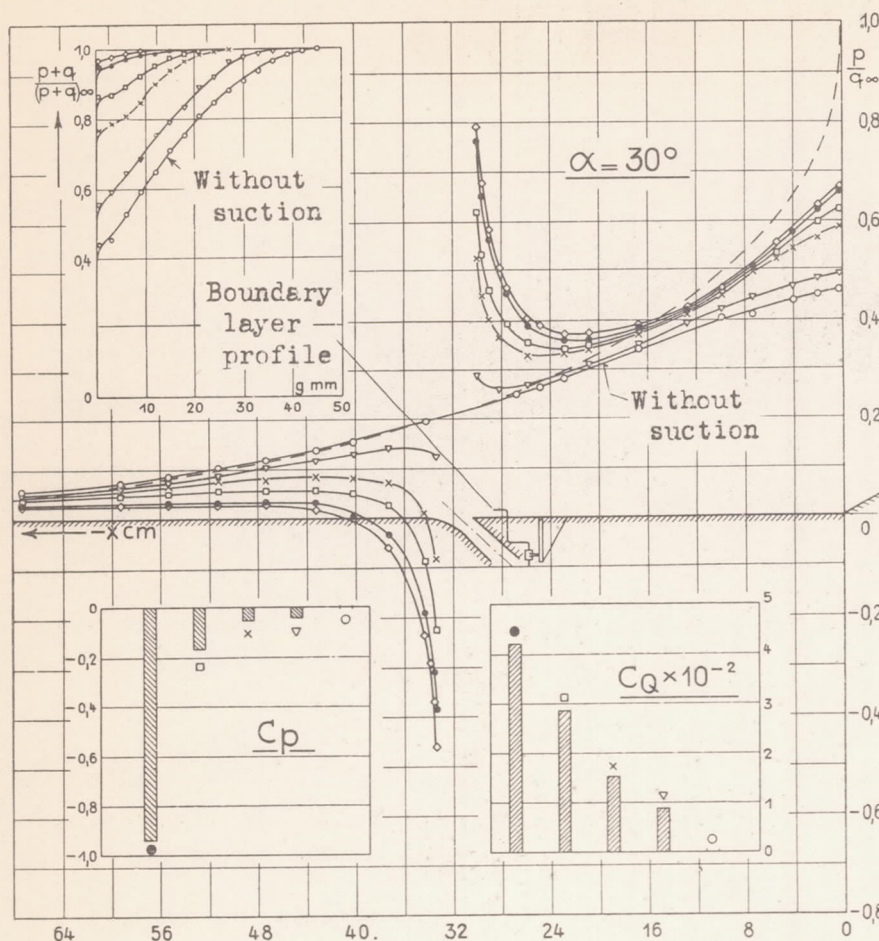


Figure 6.-
Pressure distribution with boundary layer suction for various degrees of suction. Top left, energy distribution in the boundary layer region behind the suction slot. c_p is the necessary pressure difference for the suction as compared with the pressure without suction in the region of the suction slot, referred to the total energy of the air. c_q is a measure for the suction quantity.

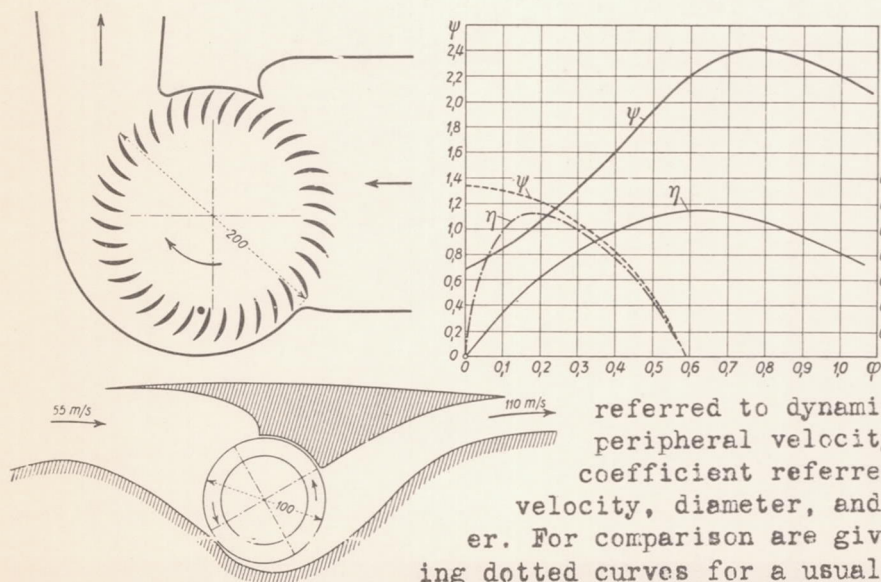


Figure 7.-
Upper left, Mortier blower with radial passage. Right, characteristics of Mortier blower with account taken of diffuser losses. ψ pressure coefficient

referred to dynamic pressure of peripheral velocity. ψ discharge coefficient referred to peripheral velocity, diameter, and width of impeller. For comparison are given the corresponding dotted curves for a usual centrifugal blower. Below, Mortier blower for accelerating the airfoil boundary layers, drawn for a thick profile of about 6 m chord.

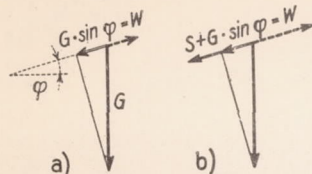


Figure 8.- Forces on airplane in usual gliding flight a and in accelerated gliding flight b.

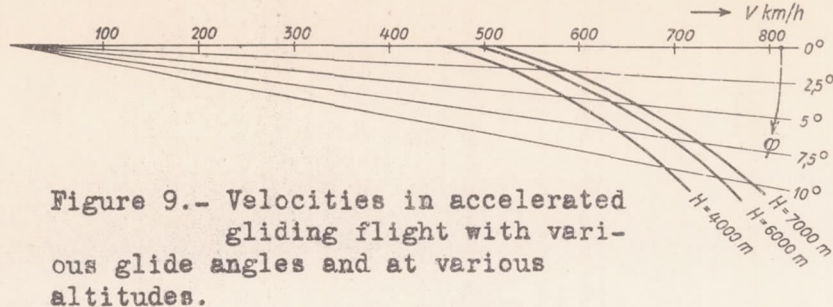


Figure 9.- Velocities in accelerated gliding flight with various glide angles and at various altitudes.

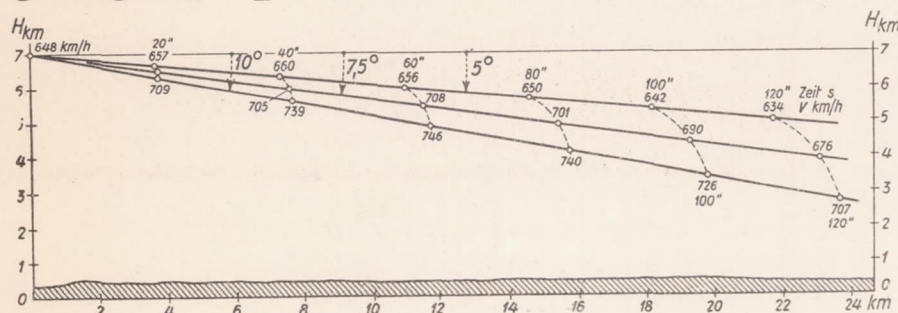


Figure 10.- Example of accelerated gliding flight.

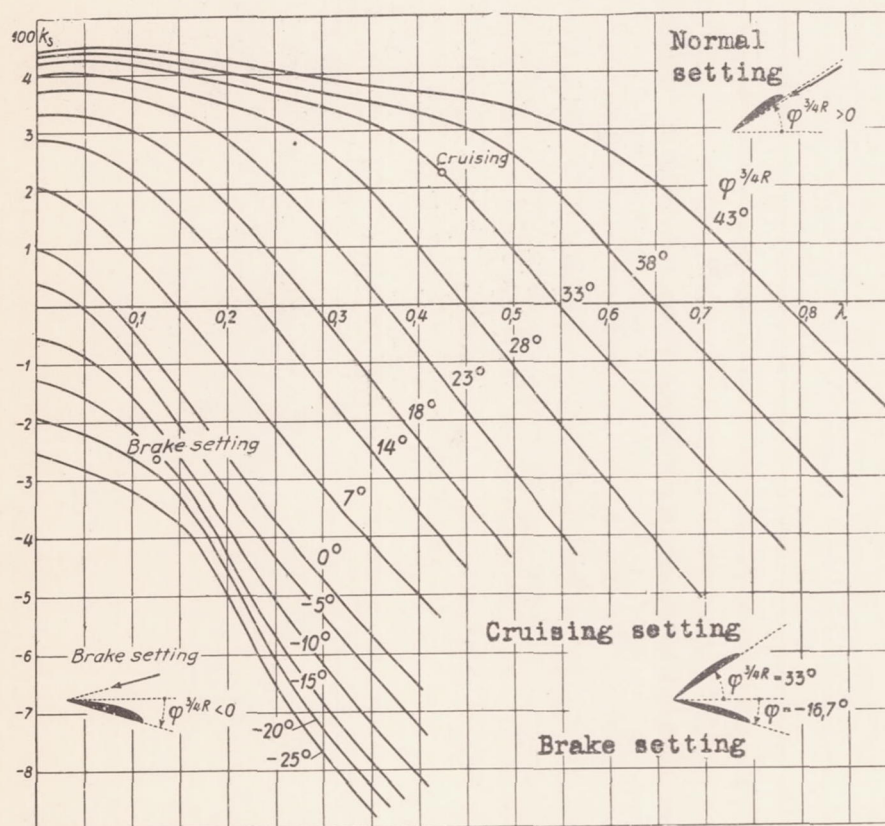


Figure 11.- Thrust curves of a controllable propeller for various blade settings λ = flight velocity/peripheral velocity. k_s = thrust coefficient referred to propeller disk area and dynamic pressure of peripheral velocity.

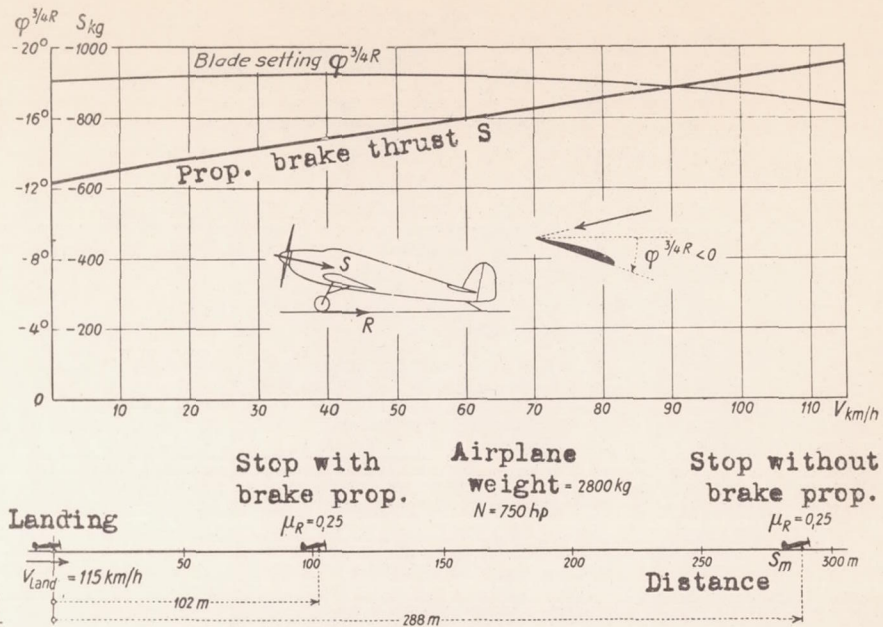


Figure 12.- Brake thrust of a controllable propeller. Below, take-off run with wheel brakes alone and with additional propeller braking effect.

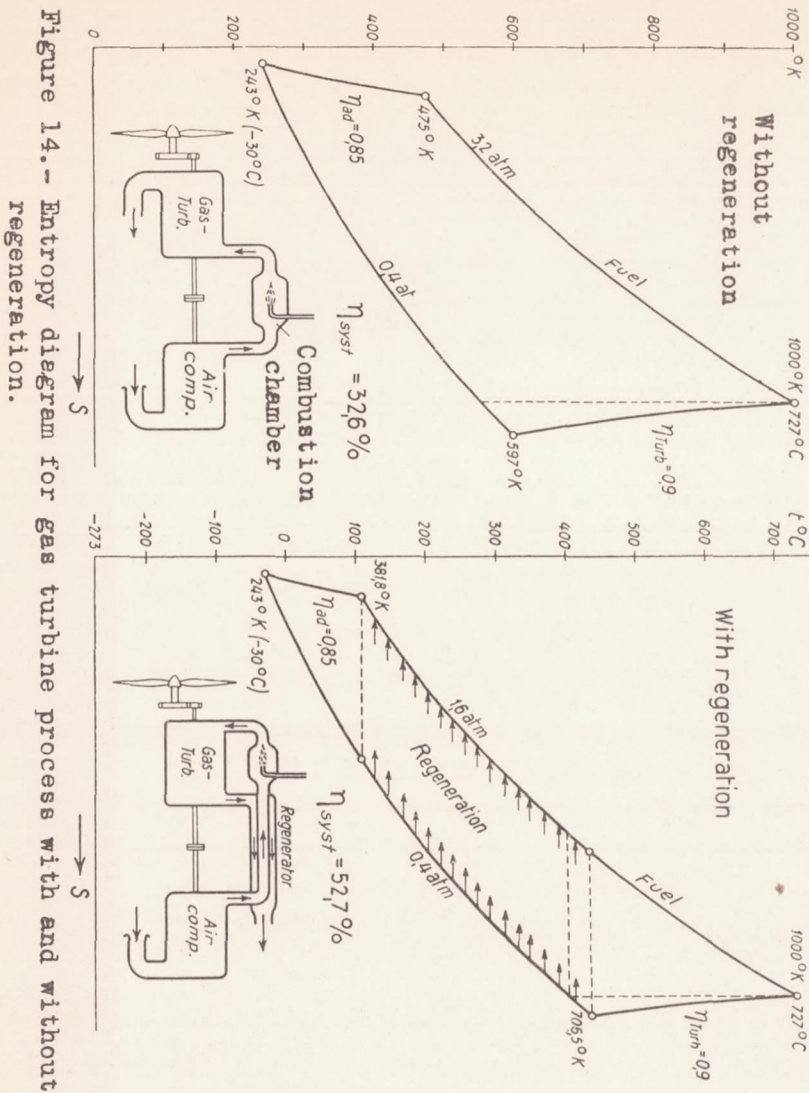
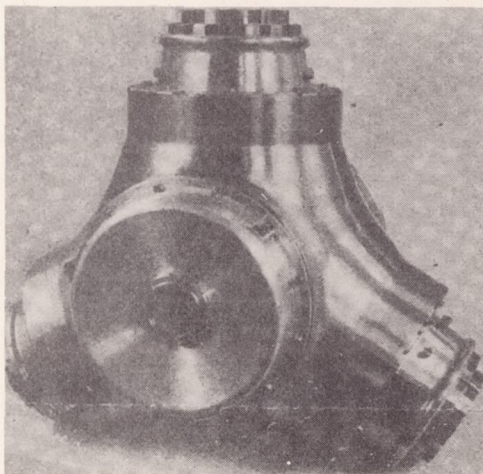


Figure 14.- Entropy diagram for gas turbine process with and without regeneration.

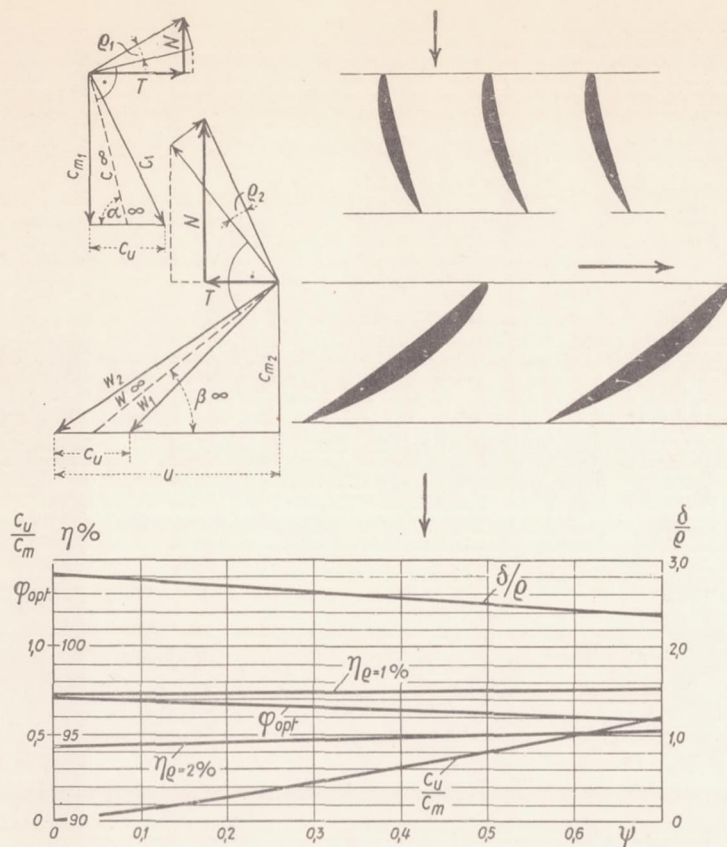


Figure 15.- Efficiencies and losses of air-

foil type buckets $\varphi = \frac{cm}{u}$; $\psi = \frac{2cu}{u}$

Figure 17.- Comparison of fineness of design of Kaplan turbines(above) and steam turbines(below). Even for very good designs(right) there are sections at which the steam flow must be very unfavorable

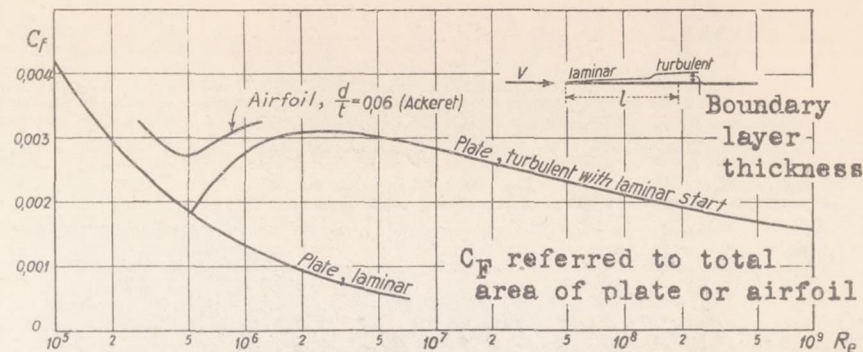
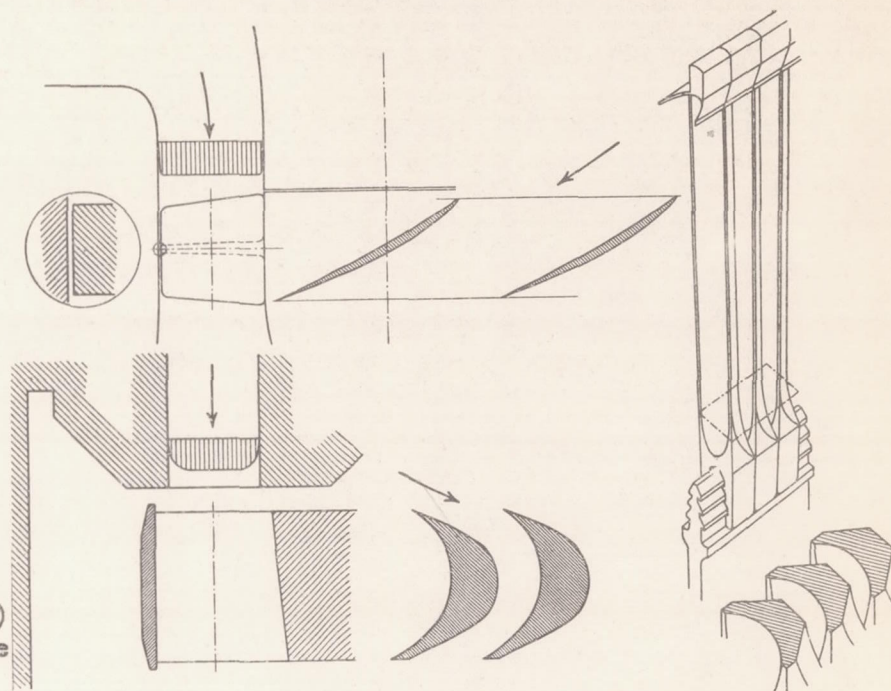


Figure 16.- Drag coefficients of flat plate as a function of the Reynolds number.