BOUNDARY LAYER
AND
FLOW CONTROL

ITS PRINCIPLES AND APPLICATION

Edited by

G. V. LACHMANN

Volume 1

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PREFACE

PROFESSOR TOLLMIEN* related how PRANDTL's interest in hydrodynamics was awakened when as a young engineer, with the M.A.N. firm in Augsburg, he had arranged a diffusor in a large airduct but failed to achieve the expected pressure recovery. The firm was not too concerned with the loss of pressure but the question as to why and how the flow separated from the diffusor walls occupied Prandtl's inquiring mind, until three years later, after he had become a professor at the University of Göttingen, his theoretical concept of the boundary layer and initial experiments on the nature of flow separation provided him with the answer.

Having gained insight into the "why" and "how" of the phenomenon of separation, and in view of the circumstances which had provided a catalyst to the conception of boundary layer theory, the idea of application occurred to him almost at the same time. This was characteristic of his breadth of mind which never lost contact with the world of engineering and its problems throughout his career as a scientist.

Thus he proceeded to demonstrate how separation could be prevented by removing fluid from the boundary layer. This was the first experimental demonstration of boundary layer control, an application made respectable, so to speak, at this very early date by the originator of the theory himself. However, it took about half a century, until the aeroplane and its powerplant had sufficiently matured, to make practical application of the concept of boundary layer control feasible.

Apart from this brief and very premature excursion into the field of potential application, boundary layer research initiated by PRANDTL and his scholars in Göttingen, and later by VON KÁRMÁN and his disciples in Aachen, remained for years confined to a small and select circle of mathematicians and physicists. It retained the stamp of "pure" or fundamental research even after the circle had widened at an ever increasing rate, embracing research workers in many countries.

The tremendous expansion of this field of fluid dynamics is indicated by the fact that from 1904 to 1914 fewer than ten papers on boundary layer were published whilst in 1954 the average number of papers had risen to 120 in one year.†

* 50 Jahre Grenzschichtforschung.

† H. L. Dryden. Fifty Years of Boundary Layer Theory and Experiment. *Sciences*, 121, pp. 375–380, 1955.

Only 25 or 30 years ago the use of the term "boundary layer" marked an aeronautical engineer almost as highbrow. Aircraft designers of this period were accepting lift and drag of aerofoils as predestined characteristics with which no man could or should tamper, and devices like slots and flaps were almost grudgingly adopted and often derisively termed "slattery and flappery".

Their benefits, however, were irrepressible and so they came to stay, and a successful marriage between functional necessity and rational technology took place. Chiefly stimulated by the resuscitation of PRANDTL's early fundamental concept through BETZ and ACKERET in Göttingen in the late 'twenties and subsequent German research in boundary layer control pursued with great vigour during the war, this new field of applied aerodynamics has rapidly expanded since the end of the Second World War.

Both boundary layer control and related techniques of circulation and flow control have a fascinating appeal to theoretically minded engineers as well as to theorists who do not look down upon applied science as an inferior field of endeavour. Successful application of boundary layer control demands that accurate physical concept, exact theoretical analysis and comprehensive experimental effort are matched by highly refined technical skill. The challenge to the combined effort of aerodynamicists, mathematicians, designers and technologists is particularly exacting when dealing with the whims of the fickle laminar boundary layer.

There are so many facets to this relatively new art that it would be beyond a single author's capacity to present a comprehensive up-to-date picture encompassing fundamental aspects, theoretical and experimental methods developed as tools for rational design, and dealing also with engineering aspects of practical applications, either already achieved or foreseen.

Thus arose the concept of this book, with many authors contributing from the particular branches in which they pioneered or gained eminence as theorists, experimental aerodynamicists or aeronautical engineers. Only thus was it possible to cover an expanding field by authors still actively engaged in it.

It is, of course, impossible to give a book written by a multitude of authors of different nationalities the same homogeneity of style, treatment of subject and general balance of text as can be achieved by a single author. The reader's indulgence is requested in this respect and also for occasional unavoidable overlappings. Uniformity of notation had to be restricted to the most important symbols only.

The editor's task in such an enterprise may be likened, if the analogy be permitted, to that of a shepherd who selects and guides a variegated flock of contributions into a pen of predetermined size and layout. Impending declassifications and other reasons caused delays of unforeseen magnitude to a number of very important contributions. Some of the latecomers had unexpectedly grown in bulk but were found to carry so much good and solid meat that it seemed a pity to subject them to enforced slimming; this led to expansion of the originally allocated space and changes in the planned layout of the book.

In preference to a rigid framework of chapters, possible in a book planned and written by a single author, the contributions to parts II and III have been more loosely grouped in a pattern which in rising order starts with fundamental theoretical principles, followed by theoretical and experimental methods, and leads up to practical applications and to special engineering problems.

Consecutive treatment of theoretical, technical and practical aspects may be considered unconventional, but in this new form of applied aerodynamics these aspects are closely interwoven and have to be simultaneously mastered.

This book, with its exhaustive compilation of references to earlier work, has been written by dedicated men for the use of dedicated men of the present and those of the future who will continue their efforts and benefit from their work and experience.

It is an international effort and, being printed in a single language with which the vast majority of aerodynamicists and aeronautical engineers in the world have become familiar, it is also a truly supra-national document of constructive endeavour in a field of applied science and modern scientifically orientated engineering.

In conclusion I wish to express my thanks to the members of the BLC fraternity in various parts of the world who followed my call and to the publishers and their staff for making this first comprehensive book on boundary layer and flow control possible.

G. V. LACHMANN

April, 1961

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HISTORY OF BOUNDARY LAYER CONTROL IN GERMANY

By A. Betz

1. FIRST BASIC EXPERIMENTS

Professor Prandtl's epoch-making lecture on the importance of the boundary layer for motion of a fluid of very low friction was given in 1904. This lecture put the entire theory of fluid motion on a new basis(1). At least one could understand the cause of the large energy losses which were found in practice and which up to then had been so mysterious. As an important check on his theory, Prandtl had at that time already made use of the artificial control of the boundary layer and was thereby able to show the great influence such a control exerted on the flow pattern. Figures 1 and 2 show two photographs taken by Prandtl at that time. Figure 1 was taken in 1904 and shows a cylinder, from one side of which the boundary layer is removed by suction. The flow on this side follows the contour of the cylinder over a greater distance. This renders the flow unsymmetrical and results in a force at right angles to the direction of flow. Figure 2 shows two cylinders with axes at right angles to the direction of flow and rotating in opposite directions. This causes the relative velocity between the stream and the cylinders to vanish and the formation of a boundary layer is thus avoided. The wake behind the cylinders is quite small, from which it follows that the arrangement cannot have any marked resistance. For this reason the device was called at that time "Ship of zero resistance".

Although these early experiments of Prandtl showed clearly that the control of the boundary layer could be put to practical use, no further work in this direction was undertaken at that time. Prandtl's ideas and experiments were rather taken up from the point of view of flow theory with the object of understanding the cause of body resistance and, if possible, to calculate it.

2. START OF PRACTICAL UTILIZATION

A strong new impetus towards practical utilization of boundary layer control was given by the publication by Handley Page in 1921 of his slotted wing results, with lift coefficients higher than any known up to then. A very similar arrangement had been proposed earlier by Lachmann in Germany;

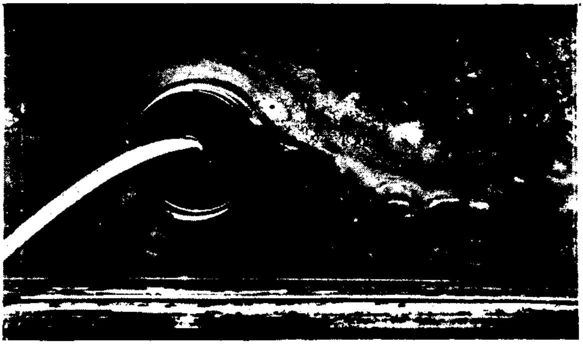

Fig. 1. Flow around a cylinder with boundary layer suction applied on one side (Prandtl, 1904).

Fig. 2. Flow around two counter-rotating cylinders. "Ship of zero resistance" (Prandtl, 1910).

the first model designed by the inventor on the basis of his patent specification of 1918 was tested in Göttingen in 1921 and gave 60 per cent increase of $C_{L\max}$ compared with the basic (unslotted) aerofoils; but the idea did not reach practical application at that time.

The present author was able to explain the effect of the slots as a form of boundary layer control, the air flowing through the slot accelerating the boundary layer[2]. This interpretation led Prof. BAUMANN of Stuttgart to replace the air passing through the slot invented by LACHMANN and HANDLEY PAGE by a jet of air ejected from the interior of the wing by a special blower[3]. The effect produced was roughly the same as that of the Lachmann–Handley Page slot; there was, however, a greater choice of efflux speed and by changing the excess pressure inside the wing, the effect of the air ejection could be increased or decreased. With the Lachmann–Handley Page slot, on the other hand, the existing excess pressure on the pressure side of the aerofoil had to be used.

The experiments showed that the expected improvements were obtained throughout. Whilst PRANDTL had already used two methods of boundary layer control—suction and movements of the surface in the direction of flow—BAUMANN added a third, the ejection or blowing out of air into the boundary layer.

At that time, the possibility of increasing the lift was receiving more and more attention, as with increasing flying speed, take-off and landing became more difficult. After it had been shown that the slots proposed by LACHMANN and HANDLEY PAGE helped to overcome these difficulties effectively, J. ACKERET and the present author tried to increase the performance of aerofoils by the general application of boundary layer control. The first experiments made in 1923 were at once very promising[4]. However, before a real practical application could be achieved, long and rather tedious development work had to be undertaken. O. SCHRENK played an important role in this further development.

In addition to the removal of the boundary layer by suction, ACKERET also renewed the experiments with rotating cylinders and demonstrated in particular that the lateral force exerted on a rotating cylinder placed in a stream can reach a considerable magnitude (so-called Magnus effect), when the ends of the cylinder were provided with rotating discs. This device was suggested by PRANDTL and obviated flow disturbances originating at the cylinder ends. These experiments showed that by far the most effective way of influencing the boundary layer consisted in moving the surface in the direction of the flow. When the circumferential speed of the cylinder reached three to four times the value of flow velocity, ACKERET obtained lift coefficients C_L of the order of 9[5]. In this case the front and rear stagnation points on the pressure side of the cylinder came closer together[6] (the corresponding flow pictures are given in Ref. 7). The theoretical limit of C_L

when the two stagnation points coincide, amounts to $C_L = 4\pi \approx 12{\cdot}6$. If the number of revolutions per second of the cylinder is still further increased, C_L will increase beyond this limit, although at a much reduced rate (Fig. 3).

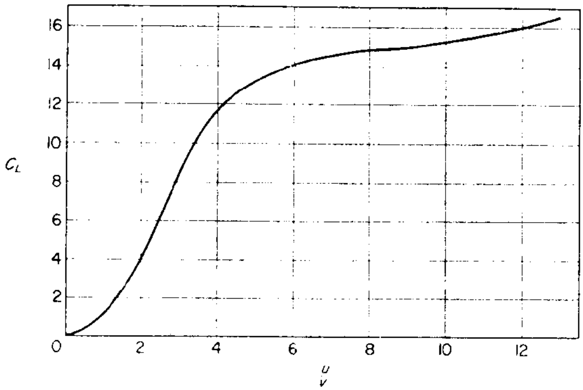

FIG. 3. Lift coefficients of a rotating cylinder of 720 mm length and 160 mm diameter fitted with end disks of 180 mm diameter, as a function of the ratio of circumferential speed u of the cylinder to free stream velocity v (BUSEMANN, 1932).

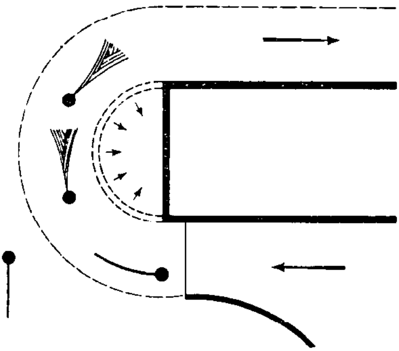

FIG. 4. Deflexion of a free jet through 180°. The silk tufts attached to a probe indicate direction of flow (ACKERET, 1926, Flow picture in Bibliography No. 13).

This was shown by BUSEMANN in 1932[8]. In this case the cylinder is surrounded by a rotating annular boundary layer which increases the effective diameter of the cylinder[6]. Unfortunately, the application of this most effective method of boundary layer control has been limited to a few special cases on account of the inherent technical difficulties. Best known of these applications were the Rotor Ships built by FLETTNER. In view of the economic conditions which existed at that time these ships however did not prove a commercial proposition[9–11].

The increase in maximum lift by control of the boundary layer is due to the prevention of the separation of the boundary layer, and it is this prevention which is also responsible for many other effects. First among these is the general problem of reducing resistance caused by the wake behind the body, a resistance which generally is large. Simultaneously with this we studied at the time the probability of large flow deflexions and the improvement of the flow in diffusors[12]. In all these cases extraordinarily large effects could be recorded (Figs. 4 and 5). If, however, the power required to

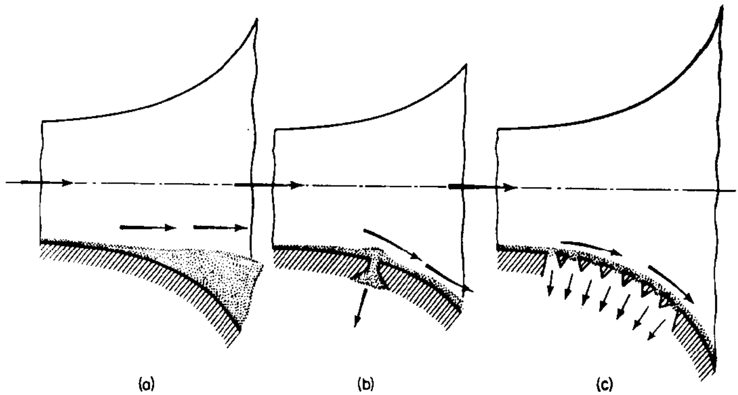

FIG. 5. Flow in a diffuser of large angle of divergence.
(*a*) without suction (*b*) suction through a slot (*c*) continuous suction.
Boundary layer and wake shown dotted. (ACKERET, 1926—Flow picture in Ref. 13 of Bibliography.)

operate the suction was taken into account, there was, in general, no marked economic gain and the same results could be obtained by making the body sufficiently slender. In these cases, the application of suction is only justified if limitations of space rule out the use of such favourable shapes, e.g. if a diffusor has to be very short.

3. PRODUCTION OF HIGH LIFT

At that time, as already mentioned, the main interest was concentrated on obtaining high lift coefficients. The question was examined, for which arrangements the removal of the boundary layer by suction was likely to give the most promising results. Application to relatively thick wings seemed to be especially promising, on the basis of the following considerations. In the case of a thin wing, lift at high angles of incidence is concentrated over narrow regions at the nose in the form of peaks of intensified suction and very steep pressure gradients are involved; if separation of the boundary layer is to be avoided, the removal of the boundary layer by suction is rather difficult. A wing with heavily cambered suction side has lift more evenly distributed over the chord, and the suction peaks are much less pronounced. Such a profile is more suited for producing high lift; on the other hand, at small lift coefficients, i.e. at high flying speed, it has a relatively high resistance on account of its thickness.

If, however, means are already installed to remove the boundary layer by suction with the object of increasing lift at take-off and landing it was obvious that the device should also be used when flying at high speed. By this means the drag of a thick wing can be reduced very markedly. A further important advantage of a thick wing is the fact that it will be lighter for a required degree of stiffness in bending and torsion than a thin wing.

All these considerations led the AVA to develop a thick wing[13]. Its aerodynamic characteristics are given in Fig. 6 for the most favourable suction

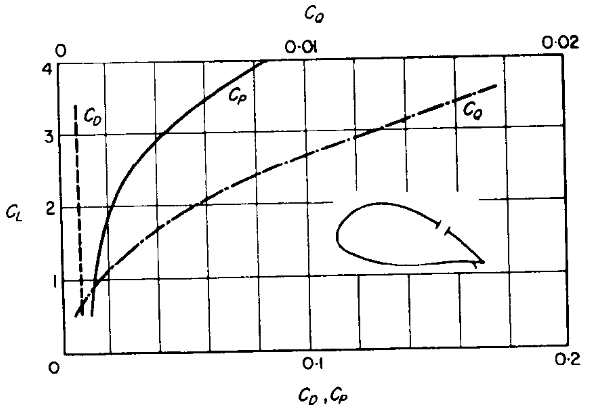

FIG. 6. Drag coefficient C_D, power coefficient C_P (power absorbed in overcoming drag + pump work) and suction coefficient C_Q as a function of C_L for a thick suction profile (SCHRENK, 1931).

quantities in each case. The diagram is similar to the usual Polar diagram, except that, in addition to the drag coefficient C_D, a power coefficient C_P has been plotted. This latter comprises the drag coefficient C_D and an additional pump drag which takes into account the power required by the pumps. In addition, the quantity Q of air removed by suction per unit length of wing is represented in the diagram by the coefficient $C_Q = Q/UC$, where U = flying speed and C = chord of wing section.

The required suction powers, expressed by the difference between C_P and C_D, proved to be within tolerable limits and the results obtained with this thick section were very encouraging[14–16]. Lift coefficients $C_{L\max}$ ranging approximately from 4 to 5 could be obtained, whilst still keeping power requirements within reasonable limits.

In the meantime speeds of aircraft kept on increasing. This, on the one hand, made the provision of effective means for reducing take-off and landing speeds more urgent; the approach to high subsonic Mach numbers, on the other hand, rendered the thick wing section, which had been initially adopted for the application of suction, increasingly inefficient. For flying speeds approaching the speed of sound one needs thin wing sections. It goes without saying that at that time, as even at present, there existed many applications involving moderate flying speeds for which the thick wing would have been eminently suitable. The urgent problem was, however, how to master the ever increasing flying speed and efforts had to be concentrated on this task. In consequence, although very promising results had been obtained with the thick wing, this line of development was discontinued. All energy was concentrated on the most urgent problems concerned with obtaining the highest possible speeds by using wings with thin sections.

For this reason, an alternative method of influencing the maximum lift by sucking the boundary layer or by blow out was investigated, taking as starting point an aerofoil with a flap. If the flap is undeflected, the profile is normal and suitable for high speed flight. If the flap is deflected, a heavily cambered profile with a higher maximum lift results. The effect of the flap is, however, limited since the flow will separate from the upper surface of the flap if the latter is deflected too far. Here matters can be improved by influencing the boundary layer. If the boundary layer is removed by suction near the flap knee (a region which normally is especially unfavourable) the flap can be deflected further without causing separation of the flow and lift can thus be increased very markedly. This line of development was investigated very thoroughly[15–23] and finally tried on two experimental aircraft[17,24] (Figs. 7, 8, 9). The results were quite encouraging. A lift coefficient $C_L = 4{\cdot}2$ was obtained compared with $C_L = 2{\cdot}3$ without suction applied to the flaps. The handling characteristics of the experimental aircraft were very satisfactory.

In connexion with this development many subsidiary problems had to be considered, as for example the most favourable arrangement and shape of single slots[14–17] and of perforated surfaces for distributed suction. The effect of blow-out was also investigated in detail, mainly by SCHWIER[25–29]. Compared with suction, this method showed fundamental differences. For low velocities of ejection the effect was very small, since under these conditions the boundary layer is not appreciably accelerated and may even be retarded. For this reason, narrow slots proved more efficient that wide ones for the same value of C_Q. On the other hand, narrow slots required higher

FIG. 7. First experimental aircraft with boundary layer suction built by the Aerodynamic Research Institute of Göttingen (O. SCHRENK *et al.*, 1940).

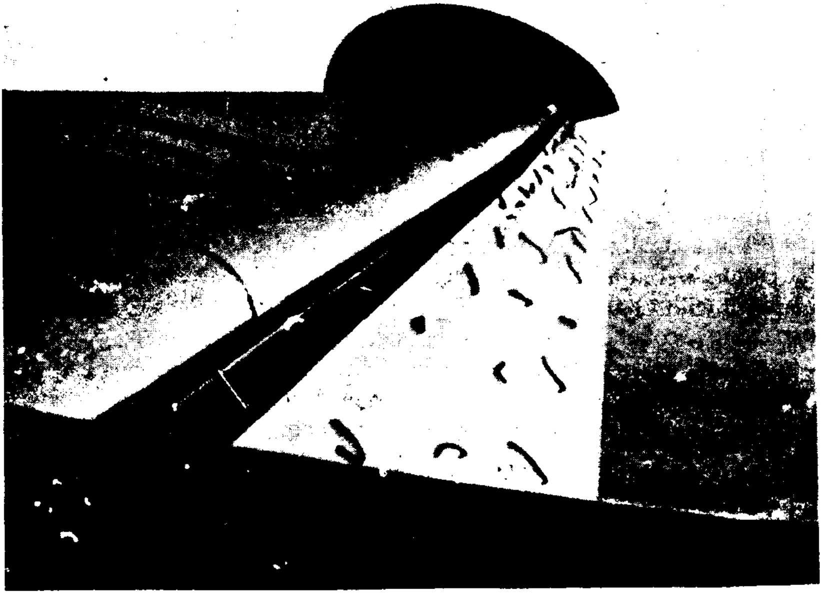

FIG. 8. Separated flow on the flap without suction.

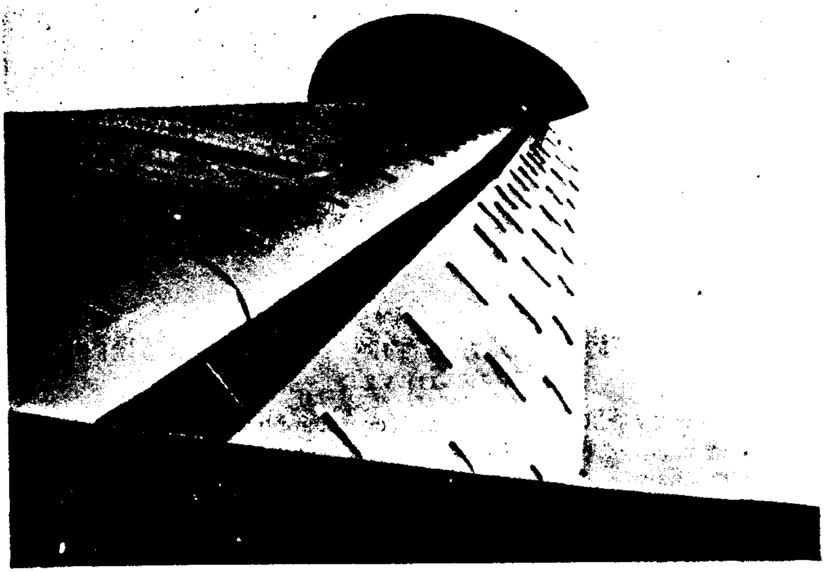

FIG. 9. Attached flow on the flap with suction.

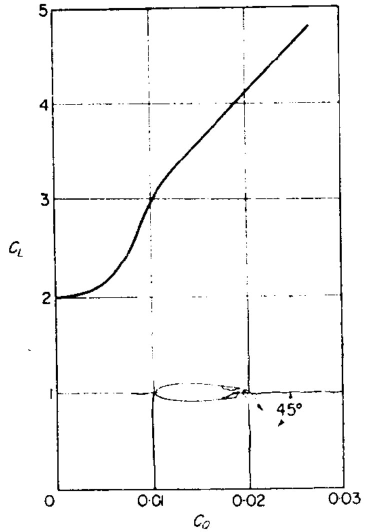

FIG. 10. Increase in lift due to flap deflexion and blow-out at flap knee for wing section N.A.C.A. 23015, angle of incidence $\alpha = 15°$ and flap deflexion $\eta = 45°$ (SCHWIER, 1943).

excess pressure in the interior of the wing, and thus more power was absorbed by the blowers. By intensifying the blowing it was possible to obtain lift increases which even exceeded those obtained by suction. Figure 10 shows an example of a typical behaviour with blow-out.

Subsequently, attempts were made to deflect the flow by a jet of air issuing on the pressure side of the wing at right angles to the flow. The aim was to produce a similar increase in lift as that induced by a split-flap[30]. Here, however, we were influencing potential flow and not the boundary layer. This method was not investigated further since the energy required was found to be too great.

4. METHOD OF REDUCING THE STRUCTURAL EFFORT INVOLVED

At that time the main obstacle to the general application of boundary layer control for increasing lift was seen in the relatively large structural alterations involved by the installation of suction or ejection devices. In parallel with the investigations aiming at the most favourable method for increasing the lift, experiments were undertaken to reduce this large installation effort. In addition, investigations were carried out with the aim of using boundary layer control for other purposes apart from increasing maximum lift. A case in point was the improvement of aircraft controls.

An installation of distinct structural promise proposed by the Arado

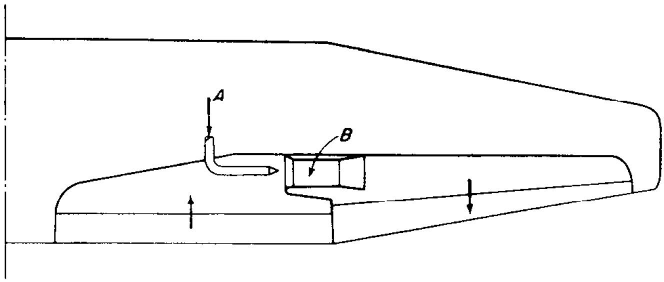

Fig. 11. Combination of suction over the inner portion and air ejection over the outer portion of a wing. Jet pump operated with Walter fuel (H_2O_2).
A = steam supply pipe B = jet pump.
(Arado, 1941).

Company was tried out[31]. It is illustrated in Fig. 11. In this method the boundary layer was sucked off at the flap slot in the region of the wing root. Ejection of the air over the outer part of the wing kept the flow attached on the ailerons. In this way air ducts became shorter and, in addition, only half the quantity of air had to be passed through the ducts, compared with the