SOME PROBLEMS ASSOCIATED WITH THE DESIGN OF TRANSONIC WIND TUNNELS

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ABSTRACT

The principles of flow generation in ventilated-wall transonic test-section are briefly reviewed. The application of auxiliary suction is shown to have remarkable advantages in speed control and the reduction of diffuser horse power. Tests in a small scale transonic wind tunnel show how suction and wall divergence can be utilised in an optimum fashion in the subsonic as well as supersonic range of operation.

Introduction

The conventional wind tunnel suffers from two main limitations with regard to aerodynamic testing in the transonic speed range. These limitations are:

(1) Choking which restricts the Mach Number attainable to a subsonic value.

(2) Large Blockage and interference effects due to the presence of the tunnel boundaries.

In recent years a solution to these problems has been found in the ventilated wall type of test section. Although the basic principles of the semi-open type of test section have been known for a considerable period it is only in the last few years that sufficient understanding of the flow phenomenon has enabled actual transonic wind tunnels to go into operation. There are still many fundamental aspects of flow generation in Transonic Wind Tunnels which are yet to be solved. Towards this end considerable research is being carried out in the U.S.A., U.K., and other countries. This paper reports briefly some of the results of a study recently carried out in the Department of Aeronautics, Indian Institute of Science, Bangalore. At the time this study was undertaken much of the information on transonic test sections was classified and may of the results of foreign research not available. Recently some of the information has been released and we find that it confirms generally the results obtained in our study.

Working principles of the ventilated wall transonic test section

Consider the flow pattern past an aerodynamic shape such as an airfoil shown in Fig. 1. The presence of the airfoil gives rise to a perturbation field of velocity and pressure. At low speeds the flow deflections and pressure changes die out rapidly in the lateral directions, but the decay gets less rapid as the flight speeds approach the sonic velocity. Neglecting heat conduction and viscosity, theory shows that the lateral decay of disturbances depends on a factor of the form $(1-M^2)^3/^2$. Thus as $M \longrightarrow 1 \cdot 0$ the decay $\longrightarrow 0$ or in other words the disturbance pattern persists for very large lateral distances. Now if the airfoil with such a flow field is placed in a conventional wind tunnel clearly the presence of the boundaries would modify the flow and it would not correspond to the free flight case. At moderate speeds this interference can be theoretically calculated from potential flow theory. The boundary conditions utilized are :

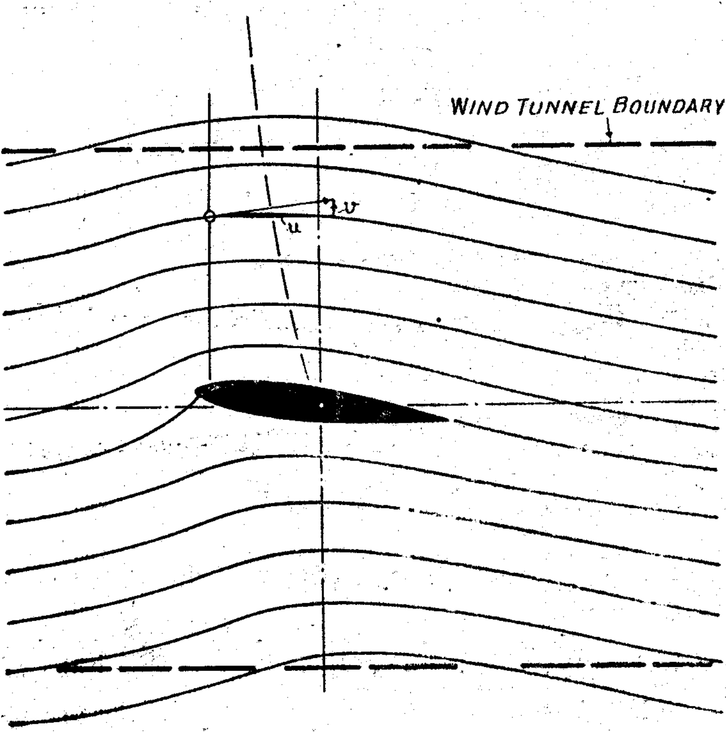


Fig. 1

STREAMLINE PATTERN AROUND A LIFTING AIRFOIL NEAR THE CRITICAL MACH No.

(*a*) $v'=0$ for the solid wall

and (*b*) $u'=0$ (constant pressure) for the open jet.

The corrections turn out to be of opposite sign. These theoretical corrections become progressively questionable as the compressibility effects increase. For subsonic speeds, up to the critical Mach No., one can extend the low speed results by modifying them on the basis of linearized compressible flow theory (e.g. the Prandtl-Glauert, Karman-Tsien and Gothert similarity rules). In the transonic range however shock waves appear and the wall interference corrections become extremely large in magnitude and at the same time the basis of the theoretical predictions quite questionable. An additional complication is the phenomenon of choking. Even in an empty tunnel with parallel solid walls due to boundary layer growth an effective throat is formed at the rear of the test section. Once sonic velocity is attained at this throat no further speed increase is possible and the nozzle is said to be choked at the entry Mach No. which is subsonic (and usually of the order of 0·85). Under such conditions there also exists a strong longitudinal Mach. No. gradient. The remedy for both the choking and the interference problems is essentially contained in providing means for the streamlines of the flow to stretch around the model. The walls are thus made with longitudinal slots or perforations and the test section is vented through these to a surrounding plenum chamber. Fig. 2 shows a sketch of the arrangement. Referring first to the choking aspect of the problem the working of the ventilated wall is as follows:

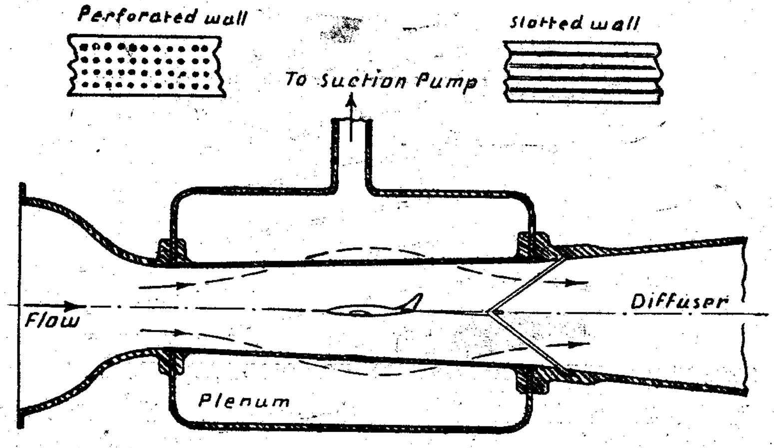


Fig. 2

VENTILATED WALL TEST SECTION WITH AUXILIARY SUCTION

Since the plenum chamber is vented to the flow in the test section the pressure inside it is an average between the nozzle entry and exit pressures—being less than the entry pressure and more than the exit value due to the longitudinal pressure drop in the test section. Thus there will be inflow into the plenum at the entry and outflow at the exit. The immediate result of this process is to

(1) reduce the longitudinal velocity gradient,

(2) permit greater mass flow into the test section and therefore raise the choking limit.

It is however not possible to attain sonic velocity and above with the parallel wall arrangement even with ventilated walls. This is due to the fact that the rear out-flow from the plenum, involving low energy air on mixing with the main stream causes a further pressure loss causing an effective throat to be formed at the rear before the main flow can attain Mach No. 1. To alleviate this there can be two remedies.

(*a*) *Wall divergence*—This allows greater area at the rear, reduces the plenum in and out-flows and effectively raises the choking Mach No. for the nozzle. It is possible to obtain $M = 1 \cdot 0$ by this means even for the solid wall nozzle, but this is not actually usable as the introduction of a model immediately chokes the tunnel. For a ventilated wall nozzle in this condition, there will be no inflow or outflow. Wall divergence is thus beneficial in allowing speed increases. Fig. 3 shows that it causes an improvement even for a solid nozzle allowing higher speeds and better velocity distributions to be attained.

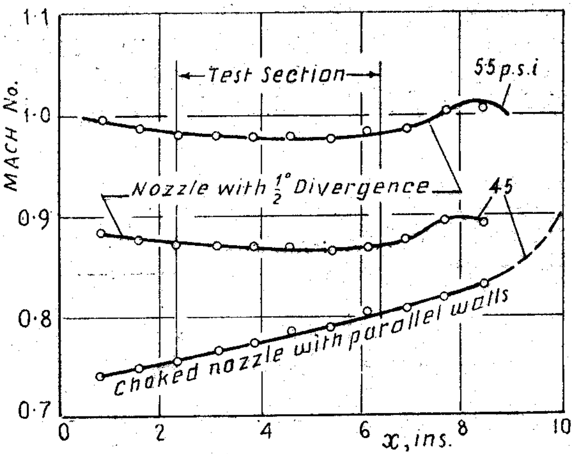


Fig. 3

EFFECT OF DIVERGENCE ON CHOKED SOLID WALL NOZZLE

(b) *Suction*—Even without diverging the walls of a ventilated test section if we apply suction to the plenum chamber and remove some of the mass of air entering from the front portion then the re-entry mass will be reduced thus effectively increasing the rear-area and eliminating the choking limitation. In the simplest arrangement suction can be applied by connecting the rear end of the plenum to a low pressure region in the tunnel circuit, e.g. at the beginning of the main diffuser. In fact many operating wind tunnels employ this scheme. This method has, however, the disadvantage that the re-entry slots have to be very carefully designed to avoid serious extra power consumption. Further the re-entering air having low energy content lowers the diffuser efficiency resulting in power penalties. A more satisfactory and flexible arrangement is to employ auxiliary suction. In this case a separate pump sucks the air from the plenum and this may either be removed from the tunnel circuit or reintroduced into the diffuser after an increase of energy content. This procedure results in a remarkable improvement of the diffuser efficiency and thus considerable power economy. The principal reason for the improvement can be traced to the removal of the boundary layer by suction. It is interesting to note that near sonic velocities a 1 per cent improvement in diffuser efficiency results in approximately 10 per cent reduction in tunnel power. The mass flow removal required to reach various Mach Numbers above choking are shown in Fig. 4 for a small 1″ × 2″ Transonic Wind Tunnel. It is possible to theoretically predict the mass flow requirements by making simple assumptions about the boundary layer growth in the test section. As can be seen the theory reproduces the order of magnitude as well as the form of the experimental data. Removal of 5 per cent of the main tunnel mass flow is sufficient for $M = 1\cdot0$. During the experiments the effects of wall divergence as well as nozzle length were also investigated. As Fig. 4 shows the suction quantities (and therefore suction H.P.) can be reduced to zero for any subsonic Mach No. by an optimum value of wall divergence which of course is precisely that which allows for the convergence effects of boundary layer growth. For the nozzle in the tests this value is approximately 1° for obtaining sonic flow. Increasing nozzle lengths require greater suction, as can be expected, due to increasing boundary layer growth. In an actual case it turns out that both nozzle divergence and suction combine to give an optimum combination to produce the smoothest flow at the lowest power. This point is discussed later.

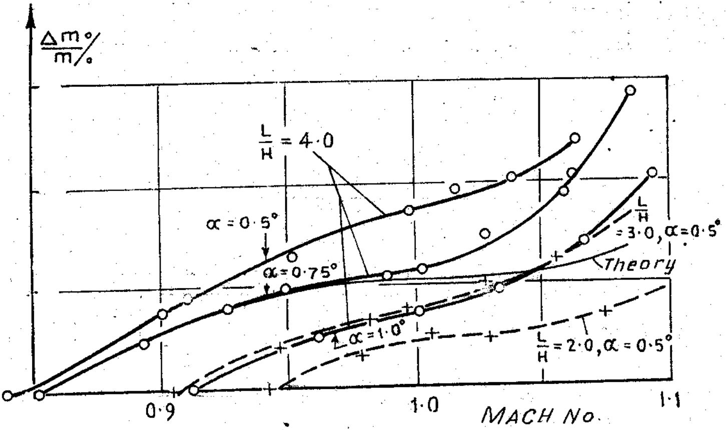


Fig. 4

EFFECT OF NOZZLE DIVERGENCE & LENGTH ON SUCTION MASS FLOW 9% SLOTTED WALLS

Supersonic Operation—By increasing suction or a combination of suction and wall divergence the extra area ratio necessary for expansion to supersonic flow can be provided thus leading to a smooth continuous speed control from subsonic through sonic to supersonic speeds. The extra required mass flow removal above that for M = 1·0 is easily calculated from isentropic flow theory. Fig. 5 shows a set of nozzle Mach Number distributions for a slotted wall nozzle

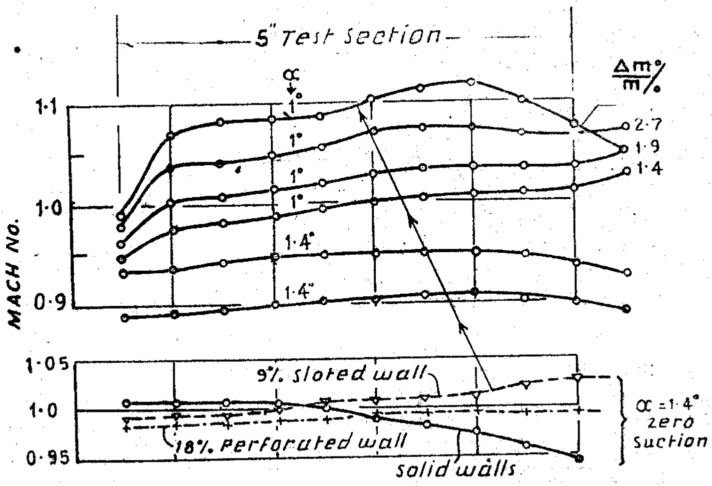


Fig. 5

FLOW NEAR M-1·3 IN SOLID & VENTILATED WALLS operating at subsonic, transonic and supersonic speeds. This figure also shows a comparison of the flow at sonic speed without suction in a diverged nozzle with solid and ventilated walls. Of course at supersonic speeds the tunnel power has also to be adjusted to provide the extra pressure ratio.

Effect of suction on power

It has been observed that suction can lead to considerable improvement of diffuser efficiencies. Fig. 6 shows the results of a series of tests demonstrating this. It is seen that at transonic speeds a 10 per cent investment in suction power can lead to a saving of nearly 40 per cent of the main tunnel power. Another interesting feature which emerges is that this beneficial effect of suction extends well into the subsonic range. In order to study the mechanism by which this improvement is brought about we conducted some detailed tests. Fig. 7 shows

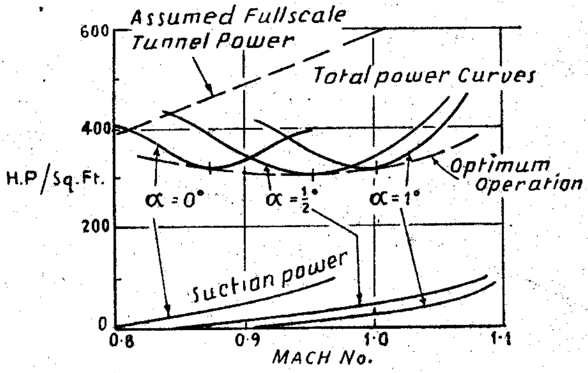


Fig. 6

POWER REQUIREMENTS WITH SUCTION 9% SLOTTED WALLS

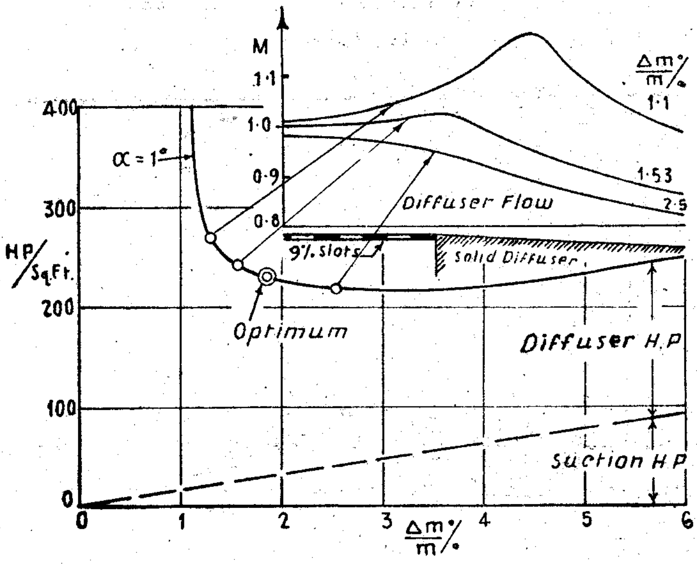


Fig. 7

POWER REQUIRED FOR SONIC FLOW

some typical results and indicates that the improvement is caused by suppression of the tunnel shock. The optimum point is reached when the pressure rise through the rear shock is just compensated for by suction. Beyond this the increased suction power offsets the improvement.

Interference effects

Subsonic Flow—As described earlier the ventilated walls by providing corrections of the opposite type reduce interference and blockage effects. For the two main types of walls employed in transonic wind tunnels, viz. the "slotted" and the "perforated" types the wall boundary conditions have to be defined in terms of the inflow and outflow characteristics. This demands a detailed knowledge of the so called "porosity factor" as well as the boundary layer growth on such walls. Further study is necessary to establish the details necessary for a complete theoretical treatment but from existing information one can obtain fairly satisfactory results. Typical values are 10 per cent open area for slots and 20 per cent for perforations. The boundary conditions employed for the calculations are:

Slotted wall: $u' + C\frac{\partial u'}{\partial y} = 0$

Perforated wall: $u' + K v' = 0$

The constants C and K depend on the wall in-flow out-flow characteristics and are related to the pressure drop and can be determined experimentally.

As an illustration of the working of the ventilated wall Fig. 8. shows decay curves measured in a transonic tunnel with various boundary conditions. As can be seen the ventilated wall results lie between those for solid and open walls.

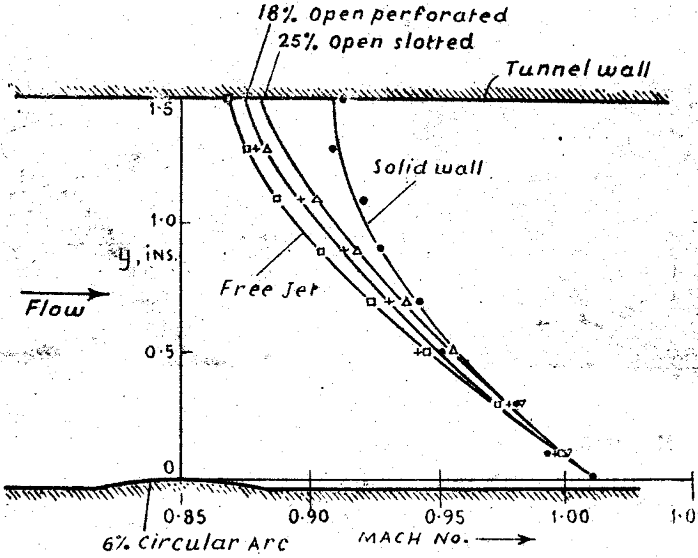
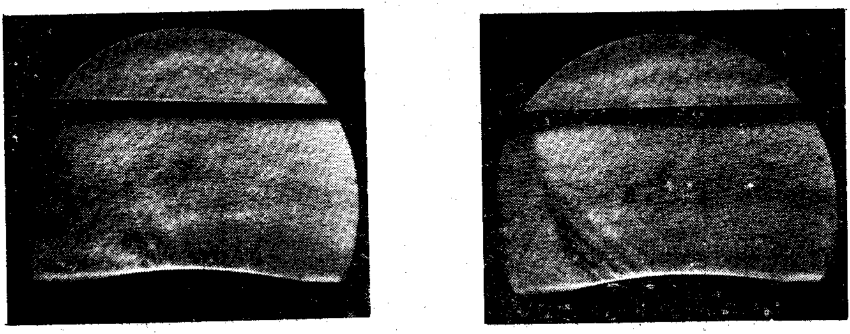


Fig. 8
DECAY OF DISTURBANCE IN WIND TUNNEL WITH WALLS OF VARIOUS TYPES

Interference in Supersonic Flow—This is almost wholly due to shock wave reflection. At low supersonic speeds the bow shock wave is quite steep and hence on reflection from the tunnel walls can cause serious flow distortions on the model. Here the function of the semi-open walls is to reduce the reflections to the point where they are negligible. In principle this can be achieved by control of the porosity of the ventilated walls, but in practice this means that for each supersonic speed and for different model geometry the open/closed areas need adjustment. Recent studies by Gothert in America show that a working solution is possible.

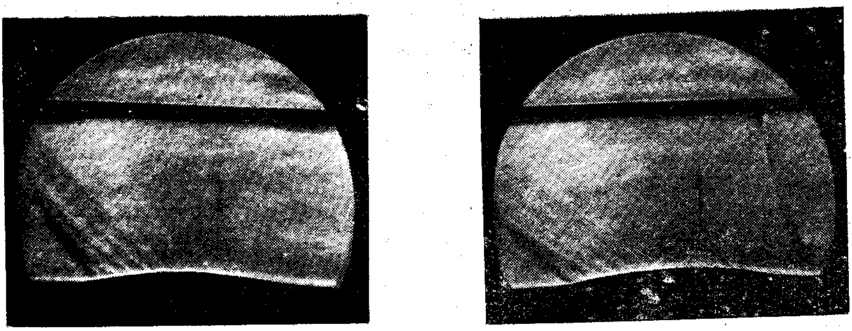
In conclusion Figs. 9 and 10 show some schlieren photographs of the flow pass an airfoil in the transonic region in a ventilated wall test section.



M=0·915

FLOW

M=1·01



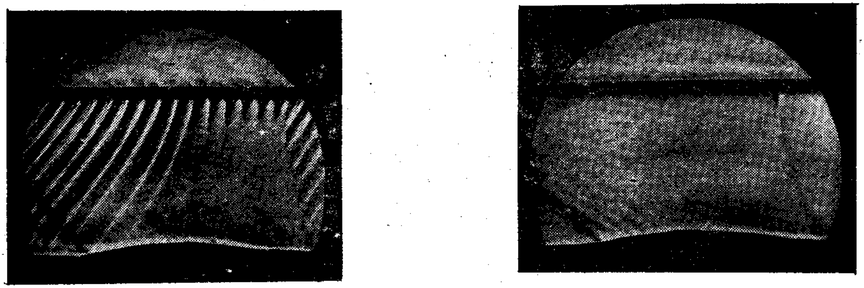
M=1·035

FLOW

M=1·3

Fig. 9

SCHLIERENS OF FLOW PAST AIRFOIL IN TRANSONIC WIND TUNNEL WITH SLOTTED WALLS



PERFORATED WALL FLOW SLOTTED WALL

Fig. 10

FLOW PAST AIRFOIL IN TRANSONIC TUNNEL
M=1·3

Acknowledgment

The Transonic Wind Tunnel tests reported here were conducted by my colleagues Messrs. D. M. Rao and S. M. Ramachandra.

Discussion

Dr. Nilakantan asked whether the speaker had considered the use of a tapering slot as employed in some RAE tunnels. Dr. Dhawan stated that an alternate solution had been studied by him which promised to give better results. The arrangement proposed consisted of a small area of perforations immediately surrounding the leading edge of the rectangular slot. Such an arrangement would reduce the area of disturbance at the leading edge of a rectangular slot.

In reply to a question by Dr. Ghatage about the use of adjustable width slots, Dr. Dhawan stated that altering the width of the rectangular slots was not very suitable for transonic speeds. In reply to a further question as to his preference for slots or perforations, Dr. Dhawan replied that he preferred slots as this enabled considerable simplicity in construction. Perforated walls were preferable only when the tunnel was intended solely for operation at supersonic speeds.