

An Experimental Investigation of Effects of Wall Porosity and Suction on the Flow Quality in a Transonic Wind Tunnel

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A transonic wind tunnel was modified to improve its flow quality when operating at transonic speeds through perforated walls and side suction. The usefulness of such a perforated wall, already known, is reduction of the blockage effect as well as the shock elimination. Two types of perforated walls were used in this investigation. The first wall had a porosity of about 22% and the holes were drilled perpendicular to the surface. However, the second wall had a variable porosity, 0 to 6%, and the holes were drilled at an angle of 60 degrees with respect to the normal vector of the plate. The flow in the test section of the wind tunnel was surveyed extensively at various Mach numbers ranging from 0.6 up to 1.2. The effect of porosity was studied by comparing the results related to the present perforated with the previous closed wall data for various conditions. The amount of suction could be adjusted through the side walls. Flow quality along the nozzle and test section was studied by a long tube installed in the center of the wind tunnel test section.

NOMENCLATURE

M	Mach Number.
MSD	Mach number Standard Deviation.
Re	Reynolds Number.
x/L	Distance from entrance of test section over test section length.

INTRODUCTION

One of the most critical flow regimes during flight is when the vehicle operates at transonic speed. There are two types of problems involved in this regime. First, lack of governing rules and theories for analysis. This problem increases the need for performing laborious wind tunnel and flight tests. Another problem is the interaction between the model and the wind tunnel

walls. When a model is inserted in a nearsonic flow with solid walls, the flow will be choked in the test section. In addition, the normal shock that exists in the transonic flow may reflect from the wind tunnel walls and interact with the model surface, a phenomenon that is not desirable.

In order to solve this problem, adaptive walls, porous walls, perforated walls or combinations of them are used to eliminate the boundary layer, shocks and choking of the flow. Perforated walls are also used for high angle of attack in the subsonic wind tunnels; where the governing equations are non-linear.

The test section walls of the tunnel are changed to take advantages of the favorable characteristics of the perforated walls.

PERFORATED WALLS IN TRANSONIC WIND TUNNEL TESTING

There are two main problems in the transonic wind tunnel testing. The first one is choking of the flow and the second one is the shock reflection.

When a model is inserted in the test section of the wind tunnel with solid walls, as a result of the model blockage, it's highly probable that the flow will

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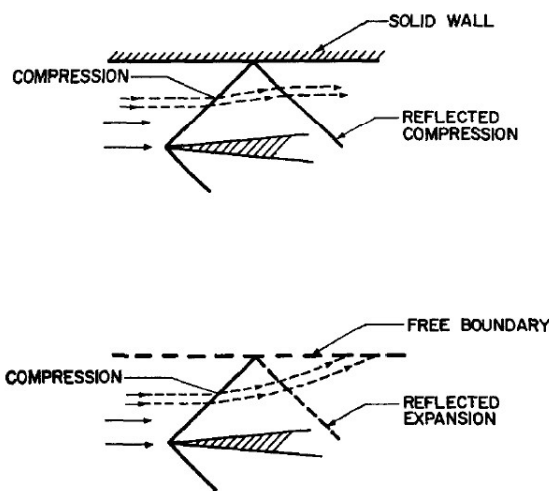


Figure 1. Wave reflection in supersonic flow on solid and on free jet boundaries [1].

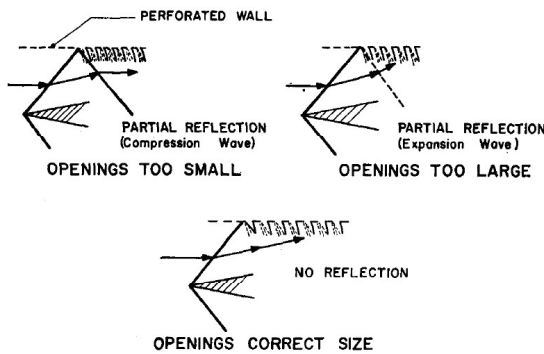


Figure 2. Effect of the amount of perforation on the wave reflection [1].

be choked and under this condition the flow pattern is different from the one that occurs during the free flight one; thus, the accuracy will be reduced. The solution for this problem is through adaptive or partially open walls *i.e.*, porous, slotted or perforated walls.

Another problem is due to the shock waves. In the supersonic wind tunnels, models produce compression and expansion waves that are reflected from the test section boundaries. If the models are not small enough, the reflected waves will interact with the model at some places and will cause discrepancies in the flow field; hence, it will affect the corresponding aerodynamic forces and moments. If the wind tunnel walls are solid, not perforated, the incident shock wave will be reflected with the same sign, that is, as a compression wave. Expansion waves are reflected as expansion waves. It is known as a general principle in supersonic flow that waves are reflected with the same sign and with the same absolute flow turning angle (also approximately the same intensity) from a plane solid wall because the flow direction must be maintained parallel to the

solid wall (Figure 1). On the other hand, along an open boundary, perforated wall, the condition of a constant static pressure along the boundary must be met. Therefore, a compression wave meeting an open boundary will be reflected as an expansion wave of equal intensity with the same absolute pressure change. In the case of an expansion wave impinging upon an open boundary, the reverse relationships hold (Figure 1). In supersonic tests, models must be located in lozenge Mach, but as the free stream Mach number decreases, this zone will be shortened. So for Mach numbers below 1.4, there is no space for the model and the shock must be removed by any means.

Since solid boundaries and open jet boundaries produce wave reflections that have opposite characteristics, there is a possibility of eliminating wave reflections by means of a suitable mixing of open and solid boundaries. Such mixed boundary condition is usually produced through perforated walls.

Several examples of two-dimensional shock-wave reflections without consideration of the wall boundary layer are presented in Figure 2. The inclined flow behind an oblique shock wave meets the perforated wall and produces a pressure drop when it flows through the wall. If this pressure drop is equal to the pressure rise through the main oblique shock wave, the static pressures in the flow and in the plenum chamber are in equilibrium, and the condition of "no reflection" is obtained. However, when the open-area ratio of the perforated wall is smaller than that of the "no reflection" one, a partial reflection in the form of a compression wave occurs since the cross flow through the wall must be reduced to produce pressure equilibrium. On the other hand, if the open-area ratio is greater than the "no reflection" one, a partial reflection in the form of an expansion wave occurs, and the pressure equilibrium is established by increasing the cross flow through the wall [1].

Note that all of the aforementioned statement is valid for the inviscid flow, where there is no boundary layer on the walls. With the presence of the boundary layer, the shock that impinges on the boundary layer will form a lambda one and will not be canceled. In this situation, the wall boundary layer must be sucked out of the test section to prevent the wave reflection from the wall.

FURTHER DEVELOPMENT OF THE PERFORATED WALL WIND TUNNELS

In the course of detailed investigations of the perforated wind tunnels, walls with slanted holes were studied in the mid-1950's. It was recognized that normal perforated walls with perpendicular holes do not provide the proper boundary conditions for three-dimensional wave patterns and for two dimensional or three-dimensional

expansion waves. This is the result of the fact that stagnation air from the plenum chamber can be easily sucked into the test section. Consequently, the slanted holes were arranged in such a manner that they offered a larger resistance to the inflow into the test section than to the outflow out of the test section. Thus, in this manner slanted holes provide a much improved matching for the wave cancellation of both types, compression and expansion (Figure 3).

Examples of transonic wind tunnels with perforated walls of the slanted-hole type are the modern AEDC 16 ft transonic and supersonic wind tunnels and the 8×6 ft supersonic wind tunnel of the NASA/ Lewis Laboratory.

Various experiments have shown that the perforated walls are effective only when the individual holes in the perforation area are comparable in size to or larger than the thickness of the boundary layer along the tunnel walls. Therefore, in order to produce the desired ratios between the hole size and the boundary layer thickness without drilling undesirable large holes in the wall, the boundary layer is frequently thinned by sucking the air out of the test section through the plenum chamber. Suction has been found to be a suitable choice to make the perforated wall effective for the wave cancellation. It is also extremely beneficial from the viewpoint of the overall power consumption of the wind tunnel. As a consequence, wind tunnels benefit greatly when a large portion of the total drive power is used for the plenum chamber suction drive system. For example, the 16 ft transonic wind tunnel of the AEDC provides 216,000 hp for the main drive system and approximately 180,000 hp for the plenum evacuation system. It was shown that, in the transonic speed range, an addition of power to the plenum chamber suction system is frequently two or three times as effective as addition of the same power to the main drive engines.

According to the theory and the previous experiments, when the holes are normal to the surface of

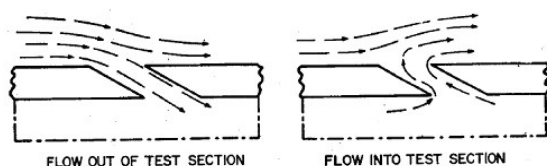


Figure 3. Streamline pattern for inflow and outflow through a wall with inclined holes [1].

the wall, suitable porosity is about %22. Diameters of the holes must also be in the range between 1/80 and 1/100 of the wind tunnel height [1]. From these clues, the porosity of the designed wall for the present wind tunnel has been considered to be %22 and the hole diameters were designed to be about 7 mm. In addition, the plate thickness must be less than the hole diameter; thus, a thickness of 6 mm is considered.

As mentioned in the previous section, wall porosity is a must for transonic tests, but using this type of walls has a drawback too. Boundary layer growth on a porous wall is much faster than on a solid one. This phenomenon will reduce the effective test section area and will accelerate the flow in the test section. It will further affect the flow uniformity in the test section too. At the same time, in this condition, choking of the diffuser is more probable and the test section Mach number will be limited to the subsonic regime. In addition, if the operating regime is supersonic, impingement of the shock and the boundary layer will create a lambda shock on the wall. To deal with this problem, boundary layer suction is needed. Moreover, suction is needed for reaching Mach numbers of larger than unity. Theoretically, suction can make a virtual divergent nozzle through modifying the streamline patterns.

EXPERIMENTAL FACILITIES AND INSTRUMENTATION

Numerous pieces of equipment were used in this investigation. Since all items of equipment except the wind tunnel and jet engines were designed and manufactured for these tests, they will be discussed in the following sections.

a) Wind tunnel

All tests were performed in a wind tunnel with a test section of (60cm (W) * 60cm (H) * 150cm (L)). The tunnel is of open circuit suction type. The main circuit power is supplied by two engines that eject their exhaust gases downstream of the test section through ejector systems. Side suction is supplied by a smaller engine (Figure 4). Side walls are solid and there are three types of upper and lower walls: closed, normal perforated and inclined perforated walls. Two plenum chambers are installed above the upper and lower walls of the tunnel.



Figure 4. ST2 Wind Tunnel Circuit.

b) Designed and manufactured perforated walls

To investigate the effects of porosity, hole inclination and side suction on the Mach number distribution along the center line of the test section as well as the maximum achievable Mach number, three types of side walls were designed, manufactured, and tested. The first wall was a closed solid one which is suitable for subsonic tests. The other two walls are perforated and are discussed in the following sections.

1) Normal perforated walls

Perforated walls that are commonly used in transonic wind tunnels, must satisfy some criteria to be more effective [1,3-6]. Some of the criteria include proportionality between thickness of the walls, hole diameter, hole inclination angle and porosity. In the case of normal holes, the optimum porosity is about 22% [1]. Hole diameter must be in the range of 1/100 to 1/80 of the test section height. In order to have an efficient side suction, the slab thickness to hole diameter ratio shouldn't be more than one.

Therefore, based on the above criterion, the designed and manufactured perforated walls that are installed on the top and bottom of the test section have 22% porosity with the holes diameters of 7 mm. Thickness of the walls are 6 mm. The hole arrangements are shown in Figure 5.

2) Inclined perforated walls

According to the nature of flow, perforated walls can not provide the proper boundary conditions for three-dimensional wave patterns and for two dimensional or three-dimensional expansion waves [1]. This is from the fact that stagnated air from the plenum chamber can easily be sucked into the test section. The problem can be removed by drilling slanted holes instead of the normal holes

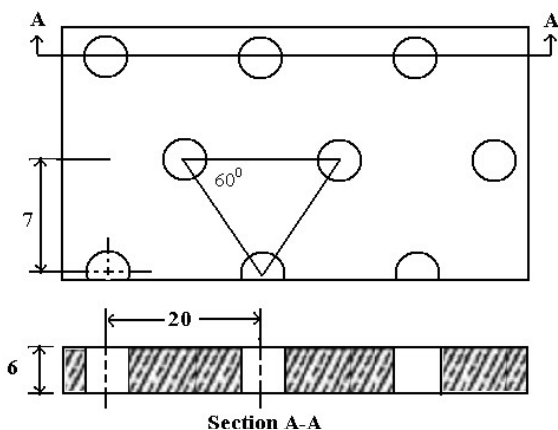
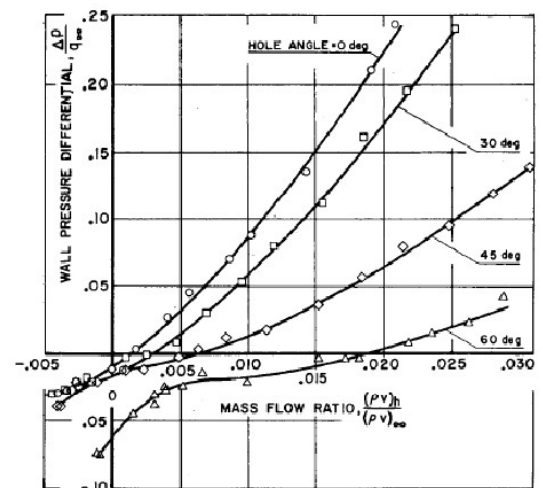
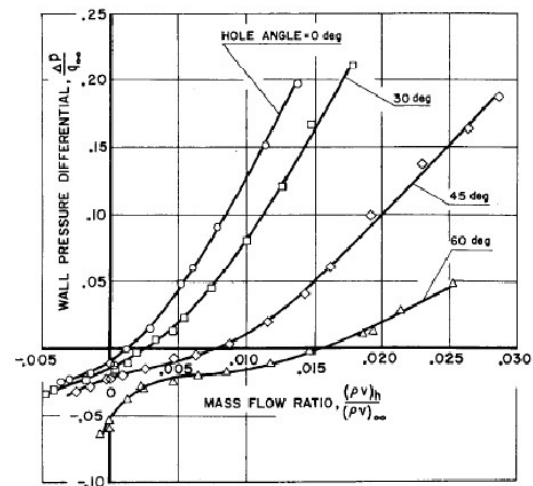


Figure 5. Holes arrangements for the normal perforated walls (all dimensions are in mm).



a. $M = 0.90$.



b. $M = 1.10$.

Figure 6. Influence of hole inclination on the cross-flow characteristics [1].

on the porous walls. Under this condition, the best porosity ratio is about 6 percent.

According to Figure 6, increasing of hole inclination angle from zero to 60 degrees decreases the required side suction power, both in Mach numbers higher and lower than one. In addition, as a result of manufacturing process, inclination angles of higher than 60 degrees are not conventional in transonic wind tunnels. In addition, according to Figure 7, the optimum side porosity in transonic regimes is a function of free stream Mach number. Thus, the designed walls have variable porosity.

The designed and manufactured perforated wall, which is shown in Figure 8, has a variable porosity of 0 to 6 percent. The wall is composed of two sheets of 2 and 4 millimeters thickness. The 2mm one is able to slide on the other sheet to open and close the holes that would change the porosity of the walls.

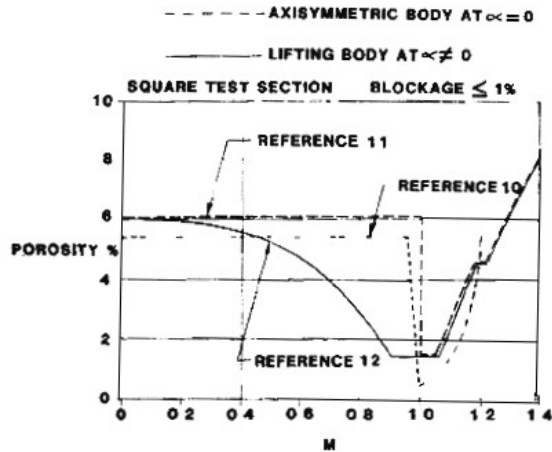


Figure 7. Optimum porosity for inclined perforated wall as a function of free stream Mach number.

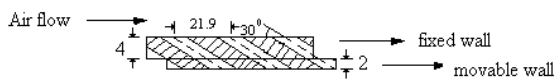


Figure 8. Hole arrangements for the inclined perforated walls (all dimensions in mm).

Each wall is divided into 9 different parts in order to change the porosity of every section independently. The hole diameter is equal to 7 mm.

c) Side suction system

Side suction was provided by a jet engine. The required air is entered into the intake of the engine from the plenum chambers through a duct. Suction mass flow rate was controlled by two valves. There exists an ejector system between these valves and the jet engine that would accelerate the side flow to supply the necessary pressure ratio for the suction.

d) Long tube

In order to inspect the pressure and Mach number distribution along the center line of the test section, a long pitot tube which is shown in Figure 9 was designed, manufactured and installed in the wind tunnel. Long tubes usually start in the settling chamber and extend through the test section [2]. However, in this wind tunnel, because of the long distance between the settling chamber and the test section, the long tube was shortened; hence, it only covers the test section area. Each static probe on the long tube rotates 90 degrees with respect to the previous probe in order to minimize the interactions. The main probe is 1550 mm long and is equipped with 24 static pressure ports (Figure 9). In addition, the distance between each two probe is equal to 60 mm. Outer diameter of the probe holes are equal to 0.5 mm. The tube diameter is about 25.4mm and the overall length of the tube is equal

to 2033.4mm. This instrument was installed at the center line of the test section by means of a fixed strut located at the end and its nose was fixed by 4 thin wires that were connected to the wind tunnel walls.

e) A/D board

The data were acquired and reduced by an A/D board which had 64 channels.

RESULTS AND DISCUSSION

One of the most important steps in the establishment and calibration of a wind tunnel is inspection of the macroscopic situation of the flow in the test section, including flow uniformity and angularity. This work is more critical in the transonic wind tunnel. Asymmetrical suction will yield both non-uniformity and flow angularity in the test section; hence, the flow quality will be undesirable.

In order to survey the state of the flow along the test section, the illustrated long tube, Figure 9, was installed in the wind tunnel. Note that, as stated previously, the tube covered only the test section length. In this series of tests, the pressure and Mach number distribution along the center line of the test section with the presence of the suction from the upper and the lower walls were measured. The results are presented in the following sections.

MACH NUMBER DISTRIBUTION WITH CLOSED WALLS

A long tube was installed at the center line of the wind tunnel test section. The wind tunnel was then

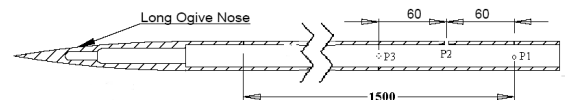


Figure 9. Plan of the designed long tube.

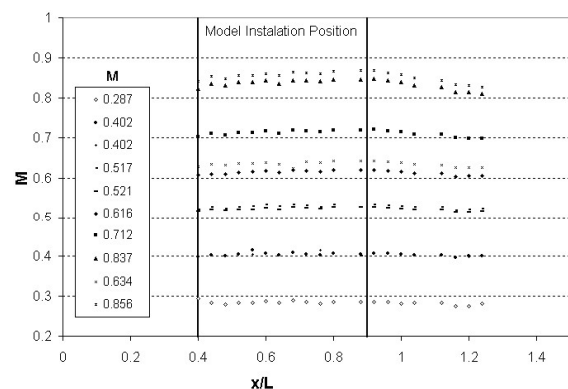


Figure 10. Mach number distribution along the centerline of the test section, closed walls.

operated in the subsonic and transonic regimes with closed walls, but as discussed in the previous section, in the transonic regimes, porosity and suction is needed to reach transonic speeds. Mach number distribution for various cases, when the walls were closed, are illustrated in Figure 10.

As seen in Figure 10, for the closed walls case, the flow uniformity along the centerline of the test section is acceptable. In addition, this figure shows that even when the tunnel operates at its maximum power, maximum achievable Mach number in the test section is about M 0.86. One of the most probable problems that prohibits reaching higher Mach number was existence of the long tube in the test section. The long tube would create large blockage in the test section; thus, higher Mach number couldn't be achieved. In order to further clarify this matter, wind tunnel was operated with empty test section, and the static pressure signature along the test section walls was measured. From this measurement, local Mach number was calculated. The results were the same as the previous ones, long tube data. Hence, maximum achievable Mach number for the case, when the walls were solid (no perforation), is about 0.86, as seen in Figure 10.

MACH NUMBER DISTRIBUTION ALONG THE CENTER LINE OF THE TEST SECTION WITH NORMAL PERFORATED WALLS

In order to inspect the effect of porosity and suction, the normal perforated walls were installed on the top and bottom of the test section. As discussed earlier, perforated walls are suitable for shock cancellation, but side suction is needed for the boundary layer suction in order to prevent boundary layer growth along the perforated walls. The results for this case are presented in Figure 11.

It can be inferred from Figure 10 and Figure 11 that by applying the porosity and suction, the test section operating Mach number has increased from 0.85 to 1.05. Note that the standard deviation in these tests is not higher than 2% which lies in the acceptable range for wind tunnels of this type. Further, from Figure 11 it's quite obvious that for all tested Mach numbers, the flow uniformity in the test section is acceptable.

Figure 12 compares Mach number standard deviation for the three cases of closed, normal perforated and normal perforated with diffuser. As illustrated in Figure 12, Mach number standard deviation for both closed and perforated walls are in the same order. In addition, by opening the diffuser or second throat, standard deviation has been increased because of the turbulence spreading of jet engines upstream to the test section.

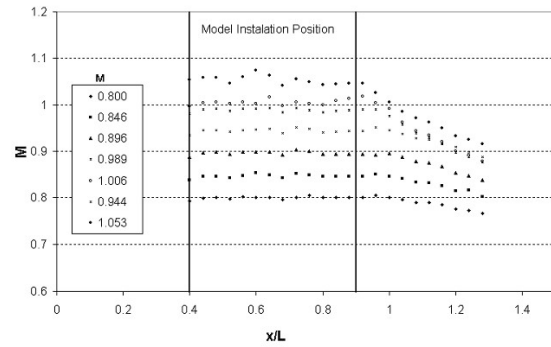


Figure 11. Mach number distribution along the centerline of the test, normal perforated walls.

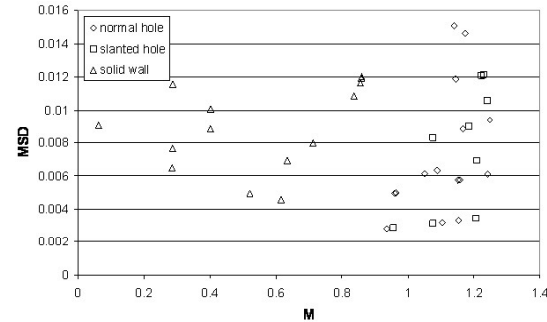


Figure 12. Mach number standard deviation Vs. Mach number for various walls.

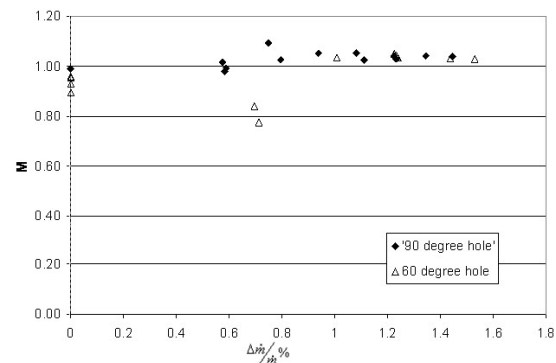


Figure 13. Effect of side suction on the Mach number.

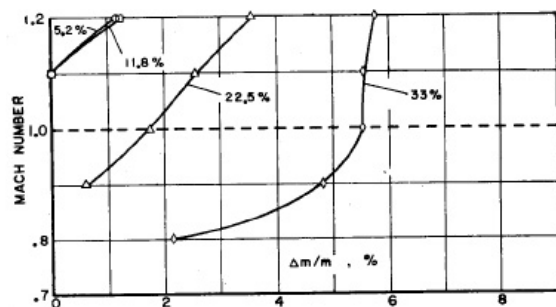


Figure 14. Effects of side suction mass flow rate and porosity on the Mach number [1].

In this series of tests, the side suction was adjusted such that the boundary layer wouldn't grow; hence,

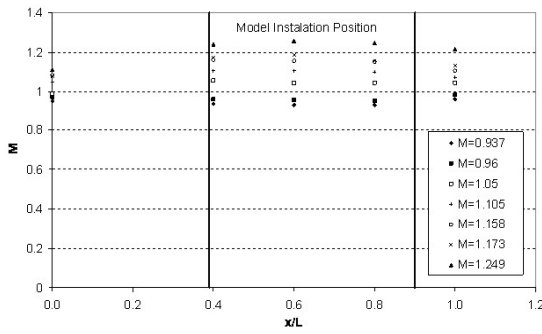


Figure 15. Mach number distribution along the test section walls for empty test section, normal hole walls.

higher Mach numbers couldn't be achieved. Effect of side suction on the Mach number for the normal hole perforated walls is shown in Figure 13.

It can be inferred from Figure 13 that when there is no suction on the side walls, test section Mach number can be increased from 0.85 to 0.91 by replacing the solid walls with the perforated ones. Under this situation, the flow can be sucked to the plenum chamber through the perforated walls and again injected to the circuit at the end of the test section. In addition, by applying the side suction, Mach number is increased up to 1.05 when the tunnel operates at the maximum power of the side suction and the main engines. Side suction mass flow rate is about 1.5% of the main circuit mass flow rate. It has been shown [1] that for a transonic wind tunnel with normal holes having a porosity of 22.5 percent, a test section divergent walls of 30, and side suction mass flow rate of about 2%, maximum Mach number of 1.04 is achievable. This is in accordance with our measured data shown in Figure 13. Figure 14 shows variations of the Mach number with $\Delta m/m$ for different porosities. It can be concluded that with more side suction, higher Mach number can be achieved. Note that with $\Delta m/m = 33\%$ and a side suction of about 5.8%, maximum Mach number of about 1.2 can be easily obtained.

One of the most probable obstacles in achieving higher Mach numbers in the test section of the wind tunnel is due to the blockage. As a result, more side suction might be needed to overcome this phenomenon. To further investigate this matter, Mach number distribution along the test section walls were surveyed while the tunnel was empty. The results are illustrated in Figure 15.

According to Figure 15, when the test section is empty, maximum achievable Mach number is about 1.25 which is much higher than the case where the long tube was installed in the test section. These results prove that the blockage of the model prevents reaching Mach number higher than 1.05. Moreover, by comparing Figure 15 with Figure 10 and Figure 11, it is clearly seen that the Mach number distribution for the

empty tunnel, Figure 15, is much more uniform than the case where the long tube was installed in the test section, Figure 10 and Figure 11.

MACH NUMBER DISTRIBUTION ALONG THE CENTER OF THE TEST SECTION WITH INCLINED PERFORATED WALLS

A comparison between the acquired data for the case of Mach number distribution along the center and side walls of the test section showed that in the case of perforated walls side suction the achievable Mach number of the transonic wind tunnel can be increased. This method can eliminate the blockage effect of the installed model in the test section. At the same time, it can produce an imaginary divergent nozzle that can increase the Mach number to near one and above.

After investigation of the effect of porosity and suction by means of normal perforated walls, effects of inclined perforated walls were studied by installing the walls shown in Figure 8 inside the test section. All of the performed tests on the normal perforated walls and the solid walls were repeated for this case, too. The results of the tests are shown in Figure 16.

From Figure 16, it can be concluded that the maximum attainable Mach number has been increased from 1.05 to 1.15, but the results above Mach 1.05 are not acceptable. Mach standard deviation above this

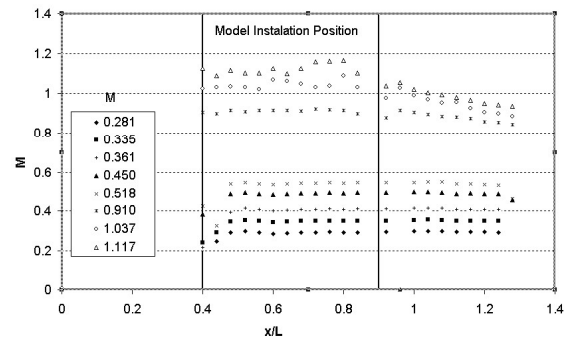


Figure 16. Mach number distribution along the centerline of test section, inclined perforated walls.

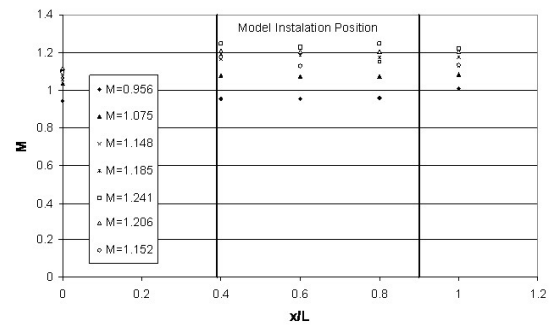


Figure 17. Mach distribution along test section walls in empty test section, inclined hole wall.

Mach number has been increased which is the result of the shock-model interaction.

In this series of tests, the side suction mass flow rate is about 1.5 percent of the main circuit one. As a result of the low side suction, shock reflection can't be eliminated on the side walls and it affected the pressure distribution along the long tube.

To investigate the effect of the blockage of the installed long tube at the center of the test section, Mach distribution along the side walls of the test section was measured while there was no model in the test section. The Mach number distribution along the side walls of the test section are shown in Figure 17.

As seen in Figure 17, when there was no model in the test section, maximum Mach number of 1.25 was obtained. From this result, it can be concluded that the applied side suction is not enough for the model blockage and boundary layer elimination and, at the same time, it produces an imaginary divergent nozzle to increase the Mach number above 1.05.

Mach standard deviation (MSD) versus Mach number is illustrated in Figure 12. According to this figure, MSD is less than one percent for Mach numbers less than one which is acceptable for this wind tunnel. For Mach numbers more than 1.05, the MSD increases rapidly by increasing the free stream velocity. As mentioned above, this is due to the fact that the side suction power is not enough and can't produce the required imaginary divergent nozzle.

CONCLUSION

In this series of tests, effects of porosity and suction on transonic Mach numbers and flow distribution in the test section were studied. For surveying the flow uniformity in the center of the test section, a long tube was designed and manufactured. From this series of data, the following conclusion can be made:

- With solid walls, it is impossible to reach transonic Mach numbers in the present tunnel with the available power system.

- By using porosity without applying suction, the maximum achievable Mach number is increased, but still it's impossible to reach Mach number of unity in the tunnel.
- Suction is definitely needed to reach transonic Mach numbers in the present tunnel.
- Standard deviation of the Mach number distribution after applying the suction is in the order of 2% which is acceptable for transonic regime.
- Side suction system must be converted to gain higher Mach numbers.
- Inclined porous walls can increase the achievable Mach number and reduce the side suction power, but for reaching high transonic Mach numbers, when a model is installed in test section, the side suction should be increased.

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