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RESEARCH MEMORANDUM

AN INVESTIGATION OF THE ADAPTATION OF A TRANSONIC SLOTTED TUNNEL TO SUPERSONIC OPERATION BY ENCLOSING THE SLOTS WITH FAIRINGS

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AN INVESTIGATION OF THE ADAPTATION OF A TRANSONIC SLOTTED TUNNEL TO SUPERSONIC OPERATION BY ENCLOSING THE SLOTS WITH FAIRINGS

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SUMMARY

An experimental investigation of the adaptation of a transonic slotted tunnel to supersonic operation by enclosing the slots with fairings has shown that this adaptation can be made with a reasonable degree of success and that only a few corrective steps need be taken to produce an acceptable supersonic test section.

This adaptation allows the extension of the peak Mach number of the tunnel to be made at a reasonable cost in both time and effort, provided simplicity and ease of installation are taken into consideration during the design of the cover fairings.

This nozzle has been found to be somewhat sensitive to boundary-layer phenomena and to humidity effects.

INTRODUCTION

The use of slotted nozzles and test sections (see ref. 1) as a means of producing high-speed flow has generally restricted large transonic tunnels to a top Mach number of about 1.1 to 1.2 because of the lack of available power to drive the tunnels at a higher Mach number. An examination of the origin of the losses in those tunnels shows that if a more efficient test section were used, quite an appreciable increase in Mach number could be attained. In order to achieve this end various means were considered for the installation of more efficient nozzles and test sections which could be made at a minimum of both cost and effort.

One of the methods considered for increasing the Mach number of the Langley 8-foot transonic pressure tunnel was that of enclosing the slots with fairings (see fig. 1) located outside the tunnel proper into which the flow would be allowed to expand. This method would allow an extension of the supersonic Mach number range by making a simple conversion from a variable Mach number transonic nozzle to a fixed Mach number supersonic nozzle. This idea had previously been tried in a smaller facility but no special effort had been made to obtain a uniform Mach number distribution. A consideration of the possibility of calculating the exact wetted surface required for the slot fairing that would produce a theoretical supersonic nozzle indicated that such a computation was almost impossible because of the complicated surfaces involved and the fact that a true three-dimensional characteristic system was necessarily required. In view of the difficult nature of this calculation it was decided to try a simplified approach. This approach consisted of designing the slot cover fairings so that the distribution of the total cross-sectional area of the tunnel plus the cross-sectional area of the slot fairing would be the same as that of a two-dimensional supersonic tunnel of the desired Mach number. This nozzle could be installed and tested and then a new nozzle could be designed with corrections as indicated by the preliminary nozzle. It was hoped that this scheme would result in a nozzle design which would produce a satisfactory flow.

A nozzle designed according to this plan was installed and tested in the Langley 8-foot transonic pressure tunnel. The results of the tests on the nozzle indicated that the plan was feasible; however, the quality of the flow was such that corrections to the nozzle were considered necessary. A corrected nozzle was then designed, installed, and tested. Although the tests of the corrected nozzle showed that the flow was not perfect, it was sufficiently uniform so that it could be used for model testing.

As this plan is of relatively low cost both in money and labor it is felt that it may be of interest for increasing the top Mach number of other tunnels.

DESIGN PROCEDURE

The design of a nozzle using the basic principles as given in the Introduction requires that several precautions be taken because of the existence of regions with velocities either higher or lower than would appear in a conventional nozzle. If these regions contain excessively high or excessively low velocities, then the possibility of having the effects of these areas cancel each other at reasonable distances from the walls of the tunnels is diminished and, as a result, undesirable irregularities will occur in the center-line velocity distribution. It is then necessary to design the slot wells so that such regions are kept to a minimum. In order to keep such regions to a minimum it is suggested that the slot wells be designed so that the flow enters with a minimum of restriction or turning. This requires that the slot opening be as wide as possible, that the slot edges be well rounded, and that the angles around which the flow must turn be kept as small as is reasonable.

These precautions are also very helpful in reducing the boundary-layer problems which can occur in a nozzle of this type. That is, if the design is such that the boundary layer has a strong tendency to thicken in the slot covers, then the full Mach number cannot be attained and possibly even more trouble will occur in making any correction to the nozzle so as to improve its flow characteristics.

The basic design of the nozzle must also deal with the problem of the disposal of the flow after it leaves the downstream end of the slot wells. It is expedient for the overall efficiency of the nozzle to return this flow to the tunnel through a closed channel connected directly to the diffuser. This channel should be faired to return the flow in a gradual manner. A possible design procedure would be to reduce the total cross-sectional area distribution no more than would occur in a conventional supersonic diffuser, or preferably to allow the total area distributions to remain constant or even to expand slowly, thus assuring a gradual return of the air to the diffuser.

This method of returning the air to the diffuser was applied in the Langley 8-foot transonic pressure tunnel by using the boundary-layer-control flaps. These flaps are located just downstream of the slots for the purpose of directing the flow out of the slots back into the tunnel. This arrangement provides closed channels which empty directly into the diffuser. Thus, the slot wells were designed so that the flow through them dumped directly into the return channel created by the control flaps.

Design of Nozzle

The basic supersonic nozzle was designed for a Mach number of 1.4 in a conventional manner by use of the method of characteristics given in reference 2. The method of designing a basic nozzle, as given in reference 3, could also be used and would save much of the labor involved in calculating the characteristic network.

Corrections for the boundary layer were also applied to the basic nozzle. These corrections were made by using the momentum boundary-layer-thickness equations as developed in reference 4 to calculate the momentum thickness. These results were converted to displacement thickness by equations relating the momentum and displacement thicknesses given in reference 5. The calculated displacement thickness was assumed to exist around the entire periphery of the tunnel including the box covers outside the slots. This method is not accurate, but insufficient data were available to make a better correction, and as will be shown later, the assumption seemed to suffice for this purpose.

As will be shown under the discussion of results the first test was not considered satisfactory, so that a correction to the original nozzle was necessary. This correction was made by plotting the measured Mach number distribution against the theoretical distribution and calculating the difference between the two to determine a correction Mach number increment. This increment was then subtracted from the theoretical Mach number distribution and this distribution was used to calculate a new characteristic network, from which a corrected nozzle was designed. The tunnel area as given by this design was compared with the area of the original basic tunnel and an increment of area determined from the difference in area between the two designs. This increment was added to the original boundary-layer-corrected nozzle to determine the area distribution of the second approximation. The magnitude of the correction is seen by comparing the ordinates of the two nozzles as given in figure 2. The comparison of these nozzles will be made under the section concerned with discussion of results.

Construction and Installation of Nozzle

For convenience the first set of slot covers was fabricated out of wood. The second set, which included the corrections, were made out of a plastic-coated wood. The various boxes for each slot were fabricated into convenient sized sections for handling and were installed in their respective locations in the tunnel. The cross-sectional shapes at various sections along the tunnel axis are shown in figure 2. As the method used in the design gave no means for determining the proper shape of the cross-section configuration, the actual shape was determined by the space available in the neighborhood of each slot. In the Langley 8-foot transonic pressure tunnel, I-beams back up the panels for structural strength. It was the spacing of these beams that controlled the width of the cross-section configuration. The only criterion that can be used in the design of the cross section of the boxes is to fair the flow space so as to restrict the flow as little as possible.

Two other factors should also be considered in the design of the boxes. One is the ease with which the boxes can be installed or removed from the tunnel, and the other is the accuracy with which the boxes can be repeatedly installed in the tunnel. The first is necessary to insure a minimum of tunnel shutdown time and a reasonable cost of changing the nozzle. The second consideration is necessary to insure that the boxes have the same contours after each installation and that the calibration will remain unchanged. Also, an accurate installation will reduce the fairing required to smooth the joints of the boxes, thus preventing changes in the nozzle contours due to the removal of material at the various joints.

It was observed that in this nozzle, as in conventional supersonic nozzles, great care must be exercised to insure that all surfaces of both the nozzle and the test section are smooth and continuous.

Conditions of Tests on Nozzle

The Langley 8-foot transonic pressure tunnel, in which the slot covers were installed, is a closed return-type tunnel, with internal radiators for cooling. It is possible to vary the total pressure from 1/4 atmosphere to 2 atmospheres, with power available for top-speed operation at 1 atmosphere total pressure. The tunnel also has a drying system which is capable of drying the air to a dewpoint temperature of -20° F. Thus, a fair range of operating conditions was available for the test of this nozzle.

Pressure surveys were taken along the center line of the tunnel by use of a 3-inch-diameter pressure-survey tube with orifices located every 1/2 inch. Other pressure data were taken along a panel between two slots in the top wall of the tunnel (see fig. 1). The pressures indicated by both the tube and the wall orifices were read on a set of 10-foot manometer boards using tetrabromoethane as the manometer liquid.

The tunnel was operated at 130° F stagnation temperature. The tunnel air was dried to -20° F stagnation dewpoint temperature. Most of the runs were made at dewpoint temperatures held as near to this temperature as possible. One set of runs was made, however, to check the effects of changing dewpoint temperature on the Mach number distribution of the test section. Other runs were made on the nozzle at various pressures to show the effects of varying the Reynolds number of the tunnel.

ANALYSIS OF DATA

Presentation of Data

The final Mach number distribution with the tunnel operating at 130° F, 1 atmosphere total pressure, and -20° F dewpoint temperature is presented in figure 3. A comparison is made of this distribution and the theoretical distribution of the basic nozzle in figure 4. The distribution of the first trial and the second, which was the result of making a correction to the first one, is shown in figure 5. The effects of varying the total pressure or otherwise the Reynolds number, are presented in figure 6. The effects of varying humidity are shown in figure 7 and figure 8.

Mach Number Distribution of Nozzle

The flow that was obtained with the final version of the nozzle is shown in figure 3. It may be seen that this flow is still not perfect inasmuch as there is some positive gradient between the 90-inch and the 140-inch stations and a negative gradient from the 140-inch station to the end of the test section. The positive Mach number gradient is about 0.0008 per inch and the negative one is about -0.0012 per inch. The positive gradient is not very serious and can be corrected for in the test data. In fact, for the typical model to be tested in this tunnel (about 1 square foot wing area) the additional drag is about 0.0006 to 0.0010. The model can also be balanced across the "hump" to reduce this interference to a minimum.

The flow contains a rapid variation of Mach number of about ±0.005. This variation is believed to be the result of unevenness in the walls such as waves, window joints, or scratches. Roughnesses in the joints where the boxes connected, or rather were faired to the slot edges, could also contribute. An example of the small amount of roughness that will cause a disturbance in the flow is seen in the compression which occurs at the 118-inch station. This irregularity can be traced back to a joint in the sections of the tunnel which has been faired as smooth as is practical. This joint, even though smooth to a few thousandths of an inch, still produces a compression several times greater than the variation existent in the flow. This compression as well as the overall variation emphasizes the necessity for the smoothest possible machining and finishing of the surfaces of the test section and the nozzle.

Comparison of Mach Number Distributions Obtained With Basic Theoretical and Experimental Nozzles

Graphs of the center line and the wall Mach number distributions for both the experimental and the theoretical nozzles are shown in figure 4 for comparison. Examination of figures 4(a) and 4(b) shows that the shape of the Mach number distribution at the wall is similar to the shape of the corresponding distribution at the center. The design Mach number is attained in the experimental distribution farther upstream than would be indicated by the theoretical design. In fact, at the wall the full tunnel Mach number is attained about 40 inches upstream of the point indicated in the theoretical design, whereas the advance is only about 4 inches at the center line of the tunnel. It is not surprising that the shape of the wall Mach number distribution differs appreciably from the corresponding theoretical distribution, as this distribution is taken in a region in which the flow characteristics differ widely from those of the conventional supersonic tunnel. This difference tends to emphasize the three-dimensional nature of the nozzle. The fact that the experimental wall distribution is roughly equivalent to the experimental center-line distribution is more or less coincidental.

Comparison of Original and Corrected Nozzles

Figure 5 presents the center-line Mach number distribution of both the original nozzle and the corrected nozzle, dimensions of which are given in figure 2. Examination of figure 5 shows that several changes occurred. For example, the Mach number gradient between the 110- and 140-inch station was reduced from 0.0017 per inch in the original nozzle to 0.0008 per inch in the corrected nozzle. A peak Mach number of 1.445 has been reduced to a peak Mach number of 1.436. The Mach number in the region between the 140- and 160-inch station has been built up sufficiently so that the test section extends to the 162-inch station rather than only to the 145-inch station as in the first nozzle.

The local disturbances are about the same in both nozzles, but fewer large disturbances, such as are produced by roughness or surface discontinuities, exist in the second nozzle.

Effects of Varying Reynolds Number

Mach number center-line distributions at various total pressures are presented in figure 6 to show the effects of varying the Reynolds number of this nozzle. It is noted that lowering the total pressure from 1 atmosphere to 1/2 atmosphere causes only a slight drop in Mach number and this is mostly over the rear portion of the nozzle. Lowering the total pressure from 1/2 to 1/4 atmosphere does appreciably reduce the entire center-line Mach number distribution over the test section region. It is also noted that downstream from the 140-inch station the lowering is more severe than in the fore part of the test section, indicating that possibly the boundary layer in the slots has not been swept out as completely as in the case with the higher pressure air. This decrease of Mach number with decrease in Reynolds number is generally to be expected because of the more rapid buildup of the boundary layer.

Effects of Varying Humidity

In order to insure the absence of condensation in a wind tunnel it is necessary to dry the air sufficiently so that the relative humidity in the test section will not exceed 100 percent. At a Mach number of 1.4 and with a tunnel total temperature of 130° F it is necessary to dry the air to a dewpoint temperature of -20° F in the stagnation regions of the tunnel to insure that the air in the test section will be no more than saturated (see reference 6). Although the dewpoint temperature of -20° F can be attained with the drying equipment of the Langley 8-foot transonic pressure tunnel, it is very time-consuming to dry the tunnel to that value. In view of the fact that for many tests it may not be necessary to dry to this value, runs were taken on the nozzle at various dewpoint temperatures from -20° F to 44° F to find the effects of humidity on the Mach number distribution so that the operator may determine the degree of drying necessary.

The results of these tests are presented in figure 7 which shows the average Mach number between the 120-inch and 160-inch station plotted against dewpoint temperature. The average Mach number of the test section is little affected by condensation until the dewpoint temperature is about 10° F, or about 30° above the point at which condensation starts for this tunnel condition. The fact that the average Mach number was but slightly affected below a dewpoint temperature of 10° F is believed to be due to the small amount of moisture in the air rather than to the absence of condensation in the flow. Even at 25° F dewpoint temperature the Mach number has not fallen severely. Dewpoint temperatures higher than this do, however, cause an appreciable drop in Mach number.

The actual effects of varying the humidity are shown in figure 8. This figure shows that the effects of condensation accumulate as the flow progresses downstream. This is noticed in that the Mach number falls off faster for the high dewpoint cases than it does for the low dewpoint cases. As the falling off is gradual it indicates that the condensation occurs over the entire length of the tunnel rather than in a sudden compression shock, or if a shock occurs, it has occurred upstream of the test section.

Estimation of Capabilities of Nozzle

Since the pressure ratio required to operate this Mach number 1.4 nozzle was less than the maximum pressure ratio available in the tunnel, it is believed that a nozzle for a somewhat higher Mach number could be designed and operated in this tunnel. It is also believed that the pressure ratio requirement of this type nozzle is not appreciably different from that of a conventional supersonic nozzle so that the design Mach number for a tunnel using this nozzle could approach the design Mach number of a conventional supersonic nozzle. Also, the experience with this nozzle indicates that higher Mach number nozzles of this type are feasible provided the space and power are available. It would seem reasonable to expect that a practical limit exists to the top Mach number attainable with this type nozzle. The data obtained in this investigation are insufficient, however, to estimate this limit.

CONCLUDING REMARKS

The use of the scheme of converting a slotted tunnel to a supersonic tunnel of a higher Mach number by covering the slots with fairings such that the cross-sectional area is the same as that of a conventional supersonic tunnel has been shown by tests in the Langley 8-foot transonic pressure tunnel to be a reasonably feasible idea. The fairings can be corrected in one or two attempts to produce a fairly good flow.

This scheme of conversion not only furnishes a low supersonic Mach number which is an extension of the top Mach number available in the tunnel, but also allows the conversion at a minimum of cost and effort. The slot cover fairings can be designed so that they may be added to the tunnel or removed in a practical time interval.

This nozzle is found to be sensitive to phenomena that will cause thickening of the boundary layer in the slot cover fairing. Too low a Reynolds number and possibly too moist air can cause a small but still appreciable drop in the Mach number of this nozzle. Design of the slot fairing cover must also be such that the flow can easily enter or leave the fairing. This precaution is also necessary to help reduce the variation from the basic supersonic nozzle design and to improve the workability of the nozzle.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 28, 1955.

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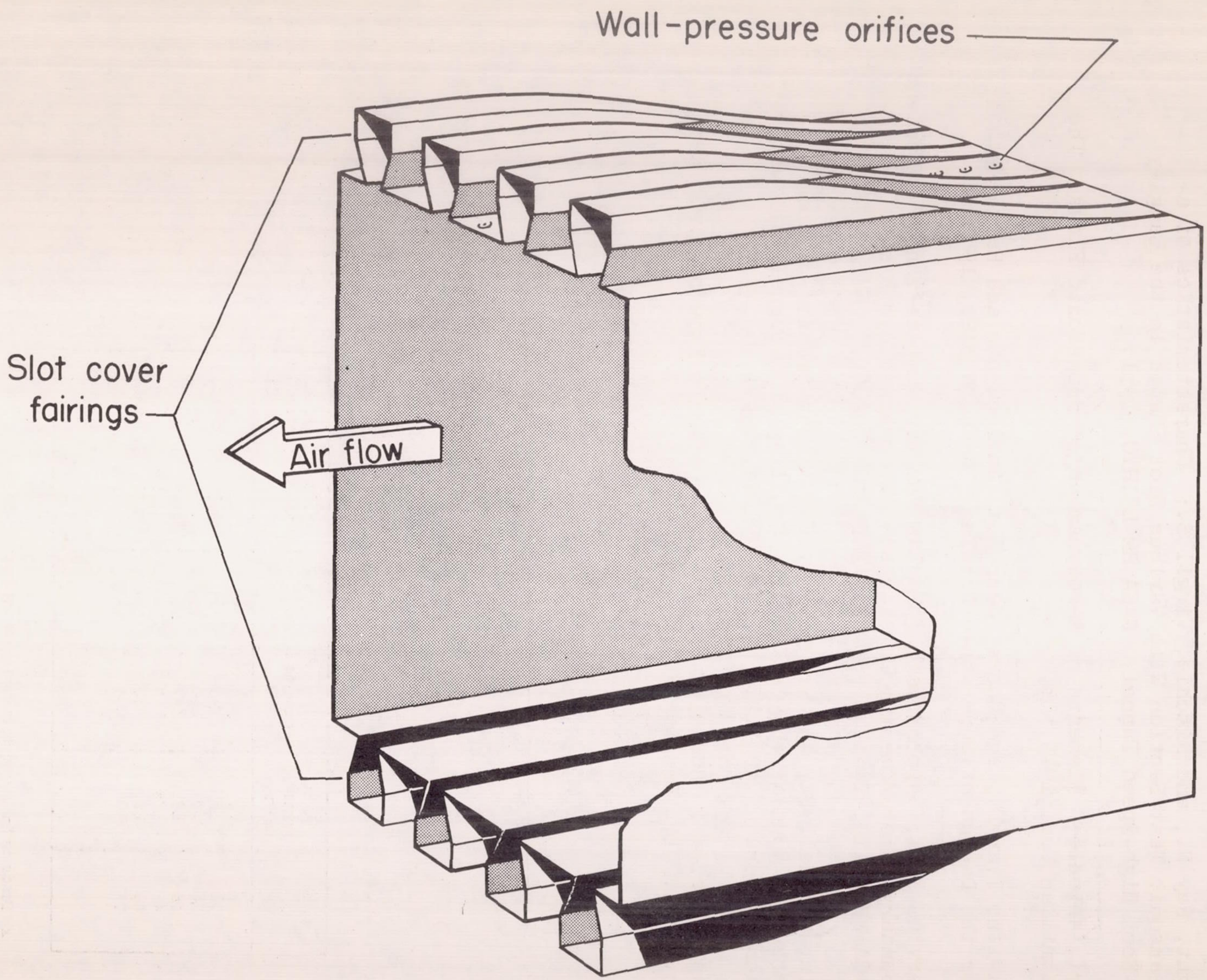

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Figure 1.- Schematic drawing of a transonic tunnel with the slots enclosed for supersonic operation.

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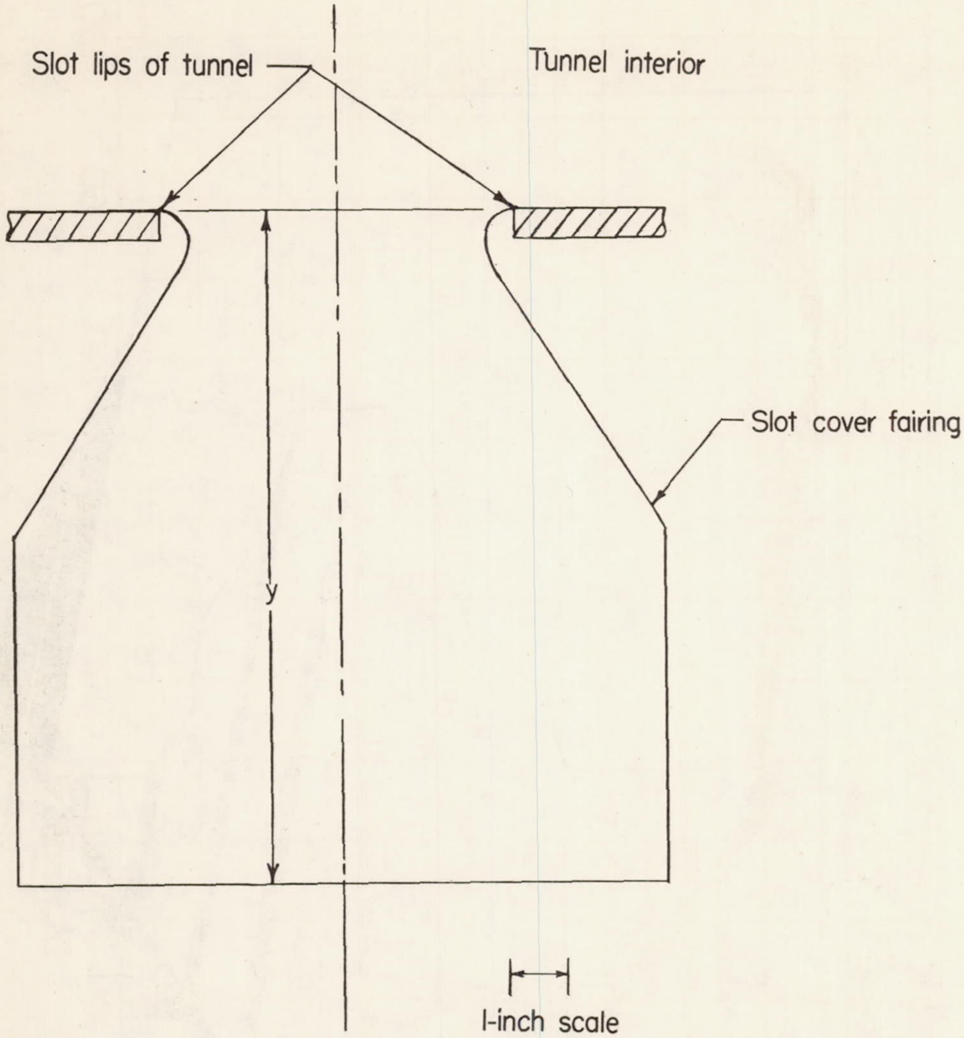

x, in.	y, in. original nozzle	y, in. corrected nozzle	x, in.	y, in. original nozzle	y, in. corrected nozzle
0	0	0	84	9.37	9.14
12	.51	.51	96	10.31	10.02
24	1.90	1.90	108	11.00	10.64
36	3.61	3.61	120	11.27	11.01
48	5.25	5.25	132	11.35	11.14
60	6.73	6.73	144	11.40	11.32
72	8.09	8.04			

x Distance from throat, measured along center line

y Defined on sketch

Figure 2.- Cross-sectional shape of the slot cover fairing.

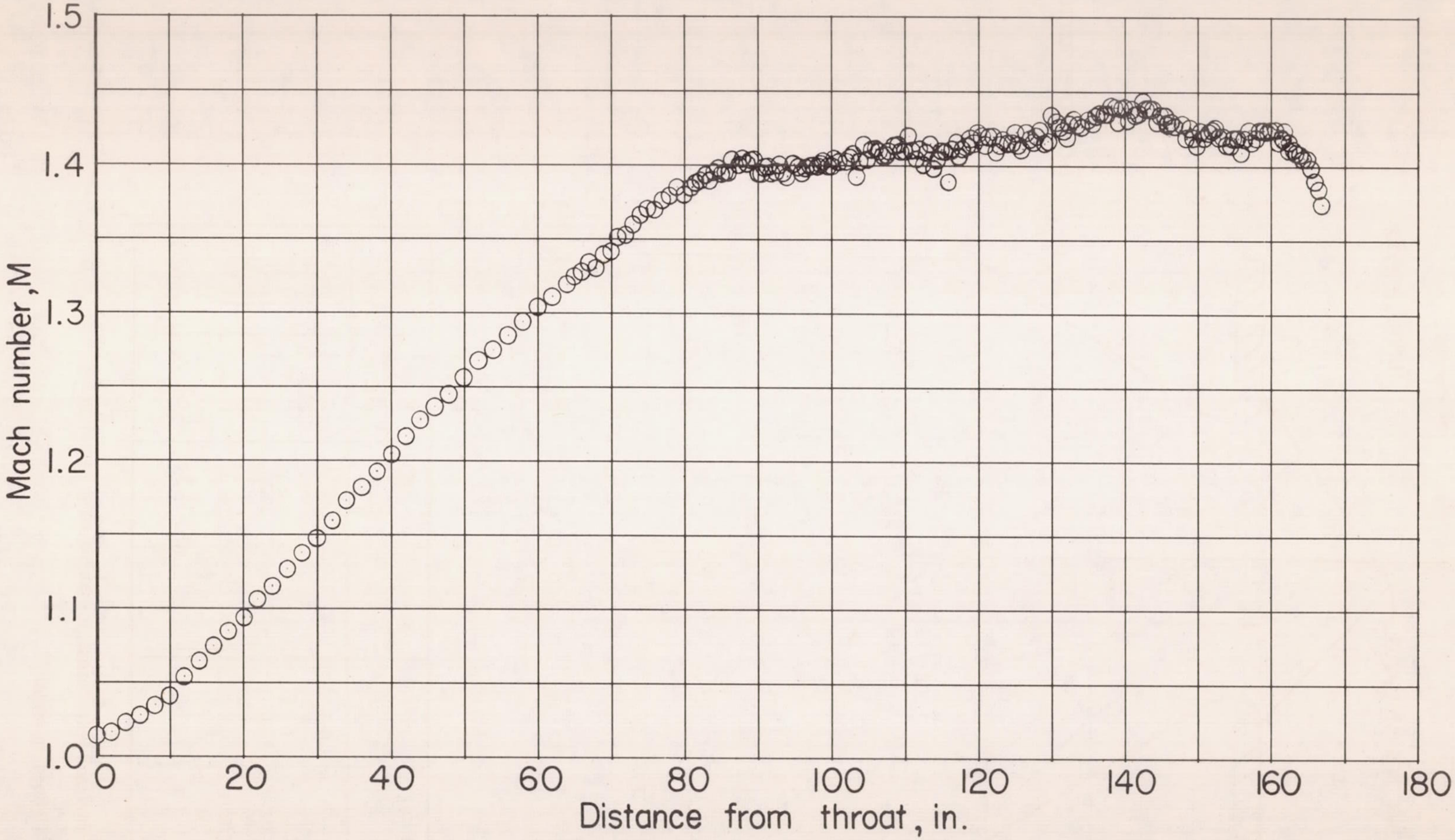

Figure 3.- Center-line Mach number distribution of the final nozzle.

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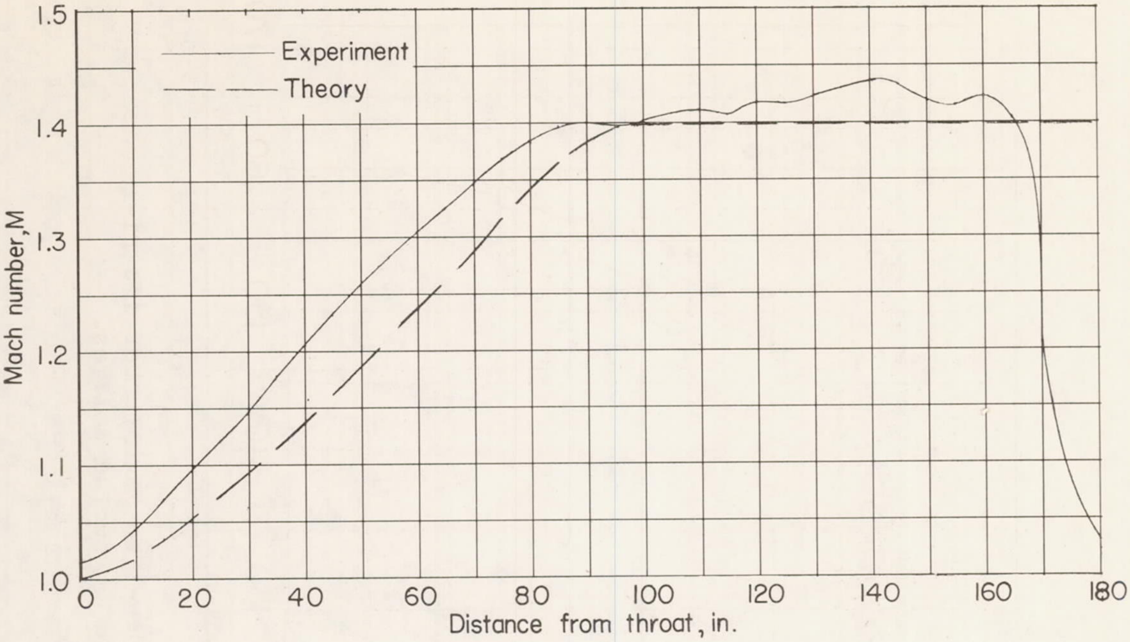
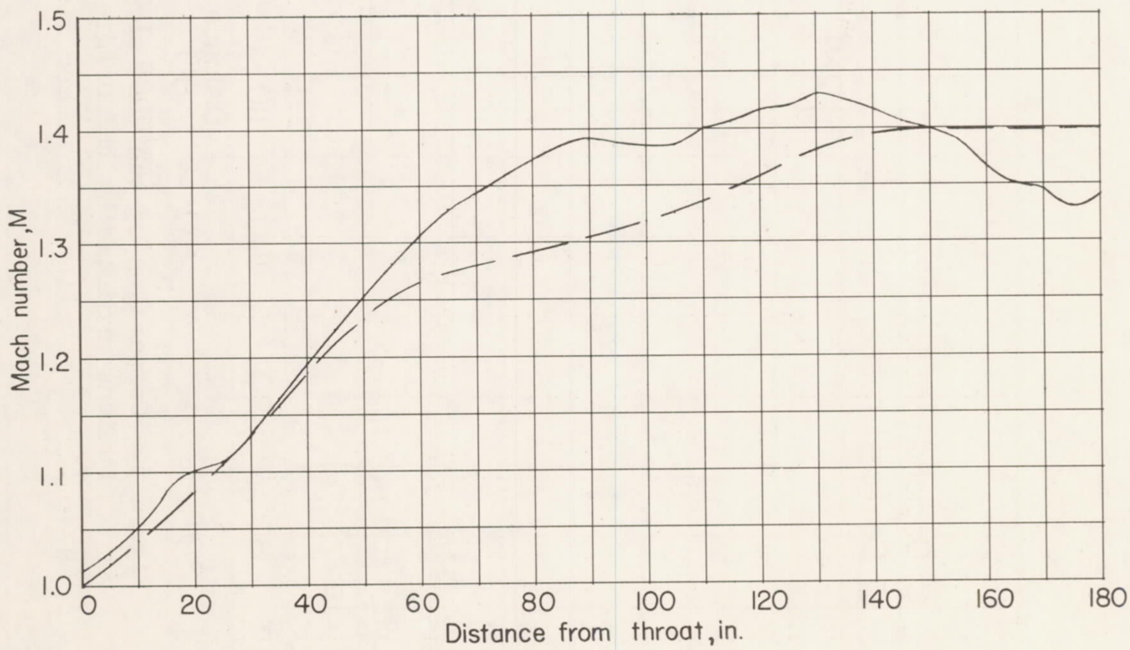


(a) Center-line Mach number distribution.



(b) Wall Mach number distribution.

Figure 4.- Comparison of experimental and theoretical Mach number distributions of the center and at the walls of tunnel.

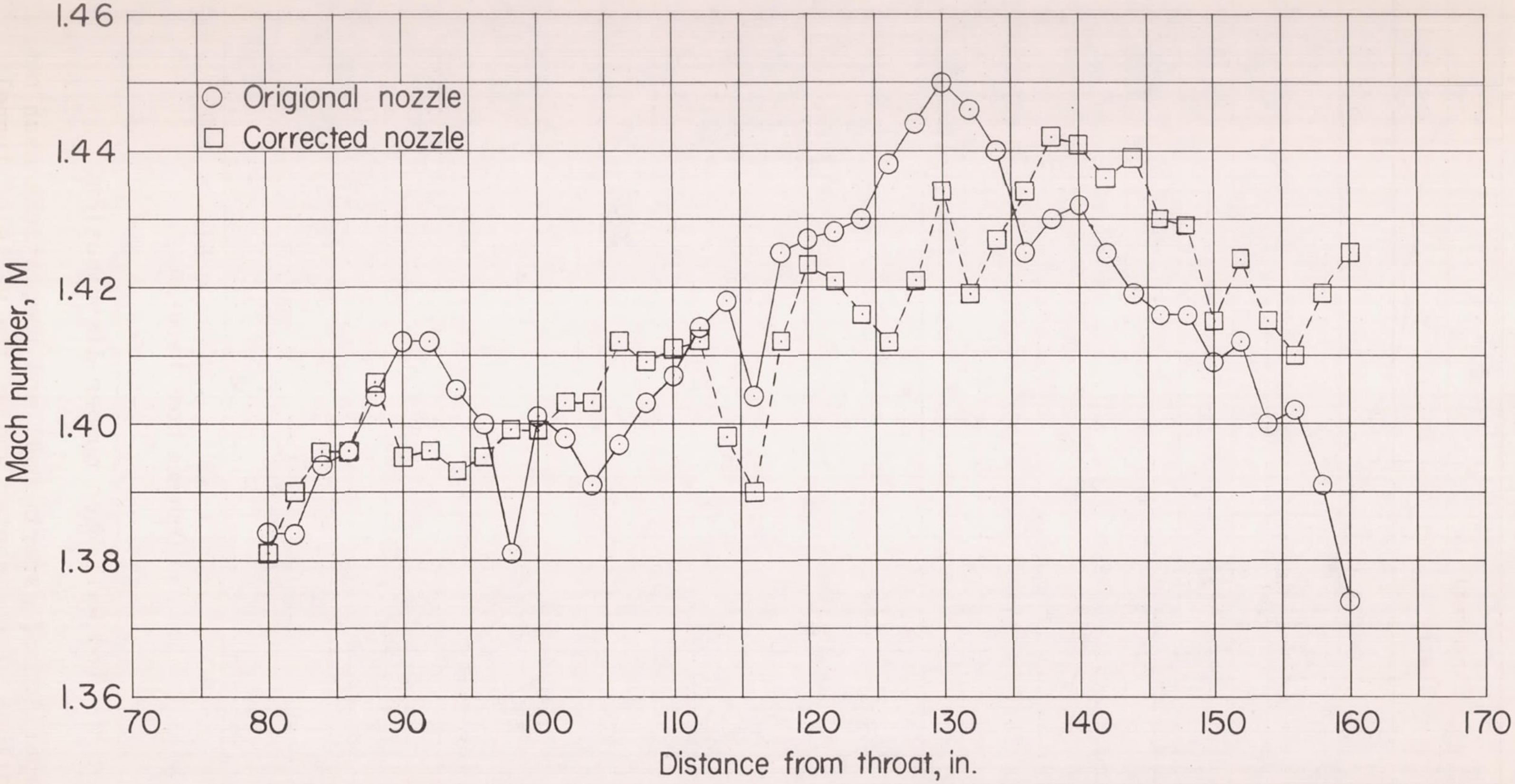


Figure 5.- Comparison of the test section center-line Mach number distributions produced by the original and the corrected nozzles.

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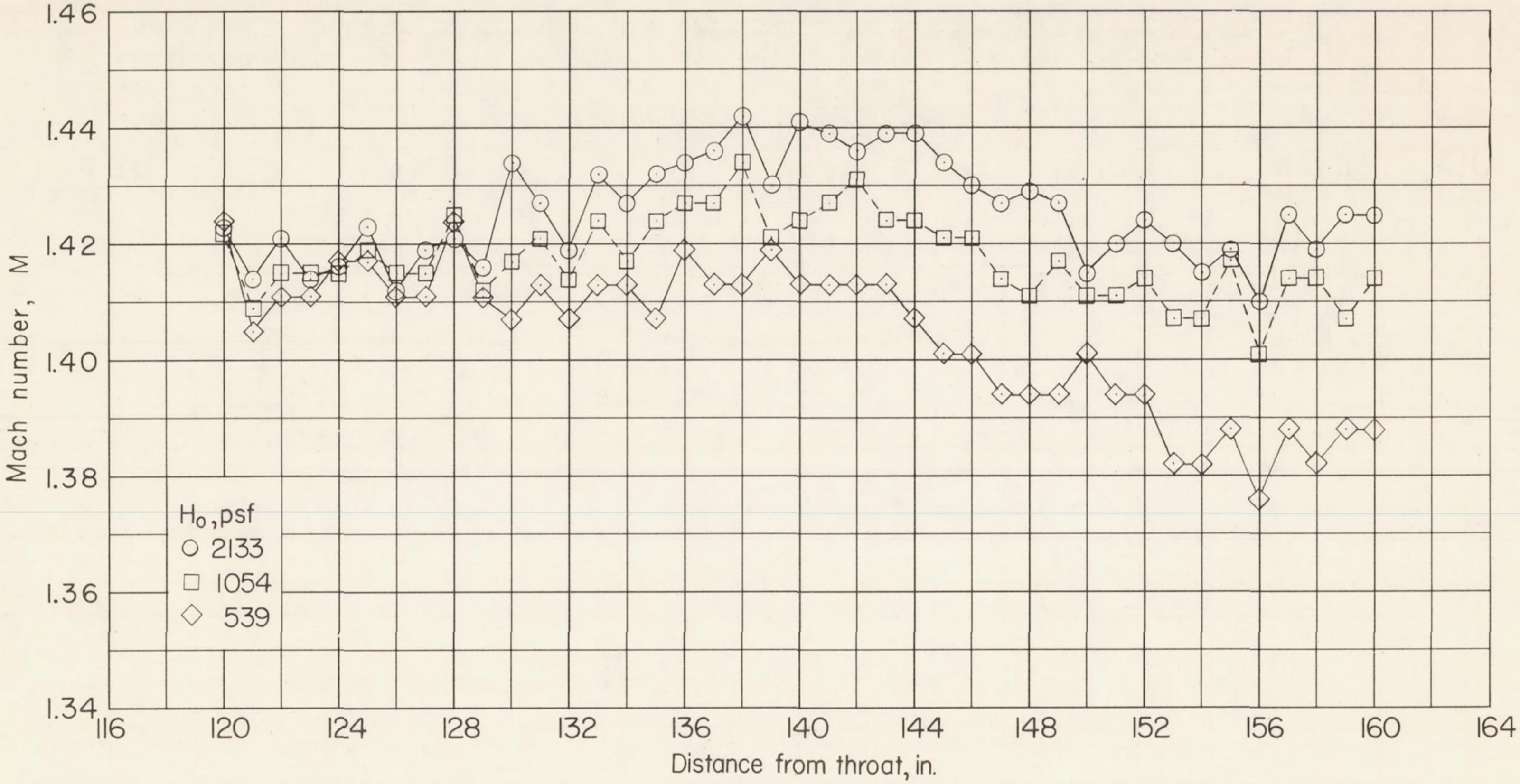

Figure 6.- The effect of varying the total pressure of the Reynolds number on the center-line Mach number distribution of the test section.

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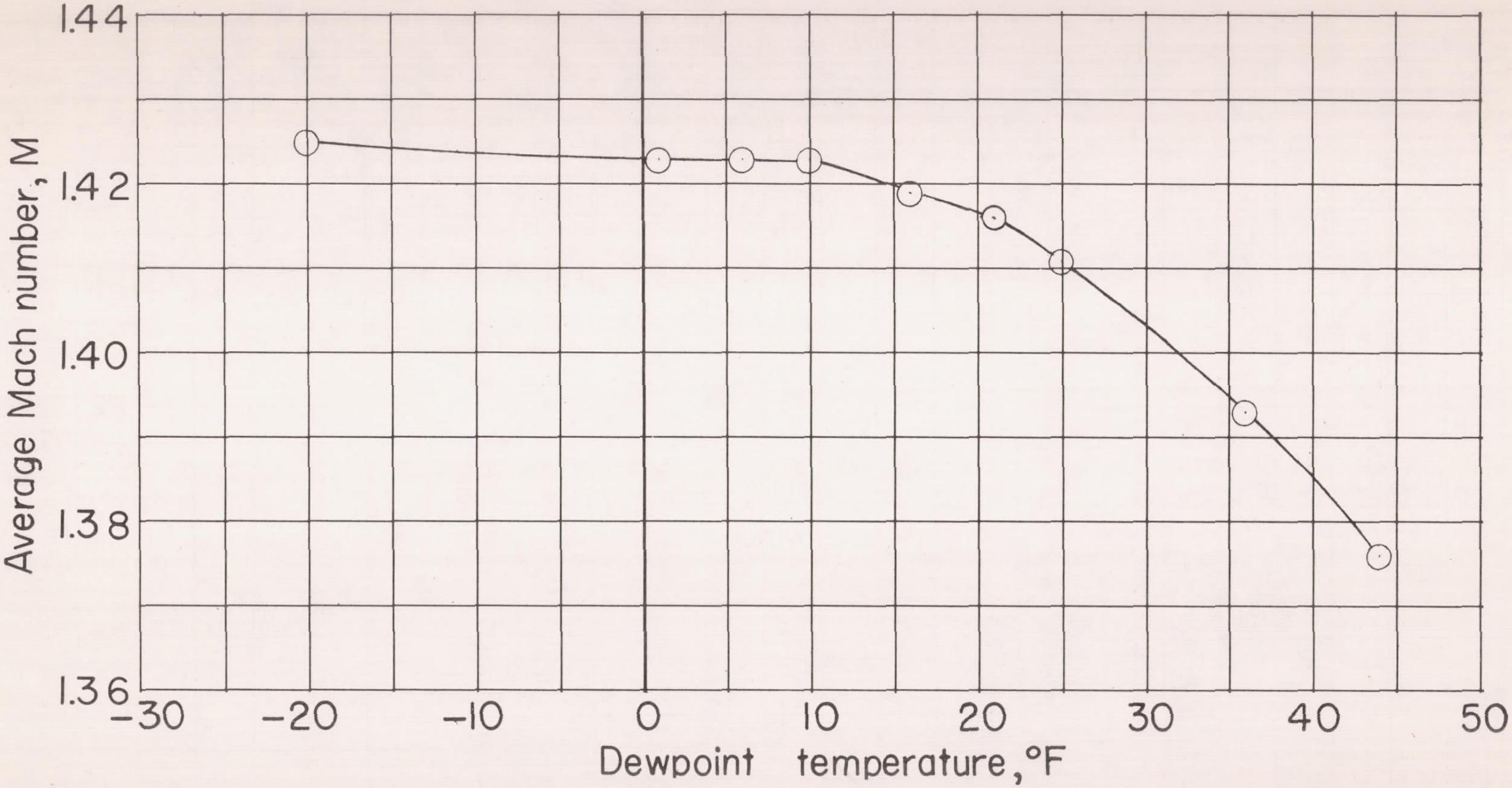

Figure 7.- The effect of varying the dewpoint temperature on the average Mach number between the 120-inch and the 160-inch station.

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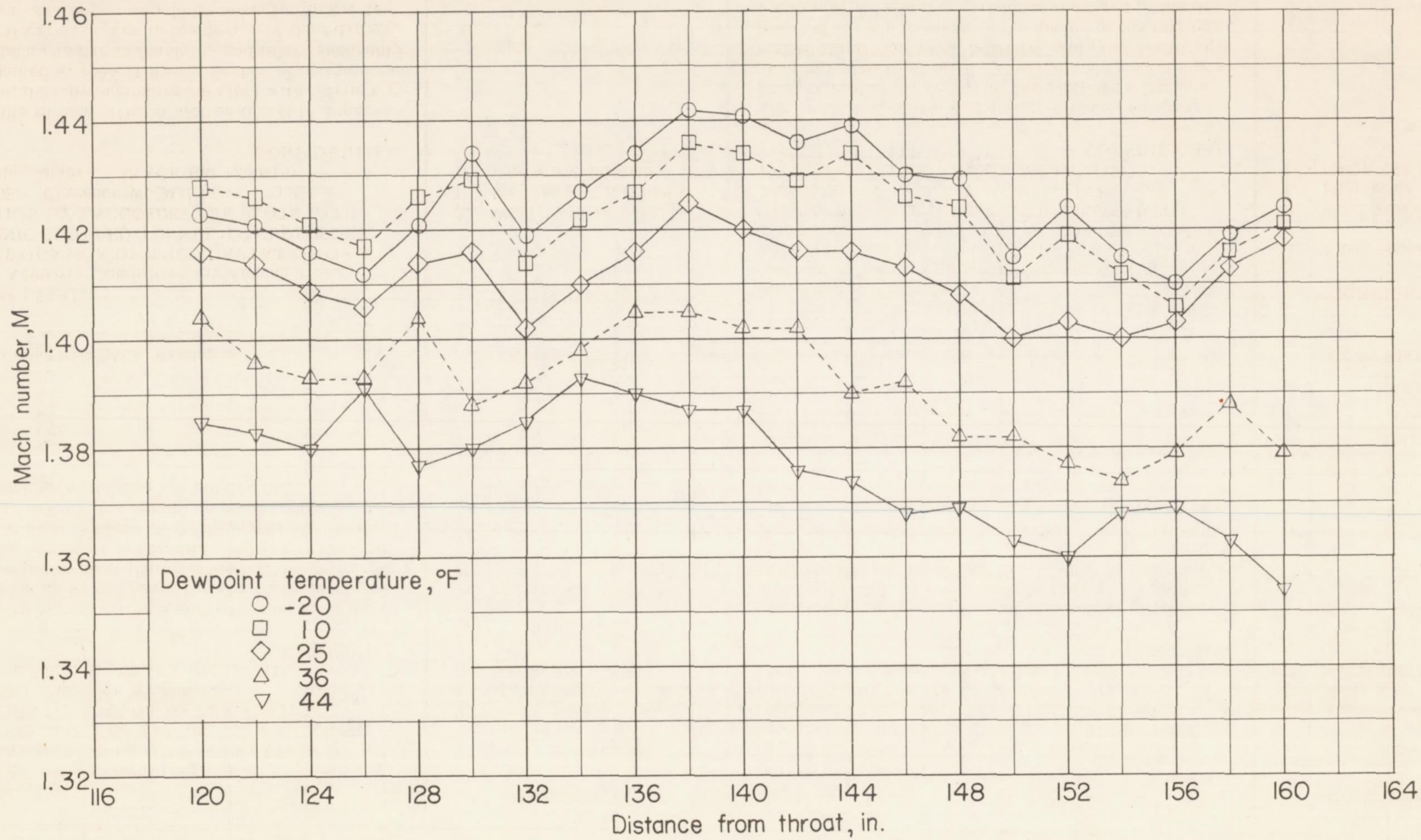

Figure 8.- The effect of varying the humidity on the test section center-line Mach number distribution.

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