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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION AT SUPERSONIC SPEEDS OF TWIN-SCOOP DUCT INLETS OF EQUAL AREA. IV - SOME EFFECTS OF INTERNAL DUCT SHAPE UPON AN INLET ENCLOSING 37.2 PERCENT OF THE FOREBODY CIRCUMFERENCE

By Wallace F. Davis, Sherman S. Edwards, and George B. Brajnikoff

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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EXPERIMENTAL INVESTIGATION AT SUPERSONIC SPEEDS OF TWIN-SCOOP DUCT INLETS OF EQUAL AREA. IV – SOME EFFECTS OF INTERNAL DUCT SHAPE UPON AN INLET ENCLOSING 37.2 PERCENT OF THE FOREBODY CIRCUMFERENCE

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SUMMARY

Tests to determine the recovery of total pressure attainable at Mach numbers between 1.36 and 2.01 were performed with models having twin-scoop inlets situated on the sides of a long forebody. External supersonic compression occurred through an oblique shock wave created by a 12° ramp ahead of an inlet, and boundary-layer removal was obtained through slots in the walls of the duct adjacent to the forebody and extending downstream from the duct entrance. The ducts were designed to produce supersonic compression in a constricted passage behind the inlet and subsonic diffusion in a channel the shape of which was calculated to result in local pressure gradients proportional to the local static pressure. The results of these tests were compared to those of a previous investigation of a model having the same external shape but ducts that expanded from the inlet to a constant diffusion angle at 25 percent of the diffusor length. It was found that the change in internal duct shape caused a large increase in the maximum total-pressure recovery attainable apparently because the conditions for boundary-layer flow in the diffusor were improved. At Mach numbers of 1.7 and less, the pressure recovery was within two percent of that associated with nose inlets.

INTRODUCTION

The results of the investigation described in reference 1 show that the recovery of total pressure attained with a twin-scoop inlet in the presence of a boundary layer at Mach numbers between 1.36 and 2.01 was very nearly equal to that of a normal shock wave occurring at the free-stream Mach number. In order to attain this recovery, three design features were found to be necessary: (1) The scoops had to enclose a relatively small portion of the forebody circumference so that the proportion of boundary layer to unimpeded air flowing into the diffusor was small; (2) the intake Mach number had to be reduced by external compression through an oblique shock wave; and (3) some of the boundary layer that flowed into the scoops had to be forced out of the diffusor through slots in the duct walls immediately behind the inlet. The tests showed that if the intake Mach number were reduced by deflecting the stream with a ramp ahead of the inlet to create an oblique shock wave, ramp angles greater than about 12° caused no additional compression. This limit existed because the boundary layer thickened ahead of the break in the surface when greater ramp angles were used; the boundary layer filled the break and thereby maintained an effective deflection angle of 12°. The slots in the duct walls apparently improved the flow in the subsonic diffusor by reducing the amount of retarded air and delaying separation until the flow was more fully diffused.

Since the ramp and the slots produced a large, though limited, improvement in the pressure recovery attainable with this inlet, it was reasoned that additional methods for creating supersonic compression and improvements in the boundary-layer flow might further increase the recovery. In an attempt to produce supersonic compression besides that through the oblique shock wave from the ramp, a convergent passage was added immediately downstream of the duct entrances of the configuration described in reference 1. This passage was intended to produce nearly isentropic compression of the flow from the intake Mach number to a lower supersonic Mach number at the throat of the duct. The effect of this additional supersonic compression should be a reduction in the pressure losses due to the shock waves through which the flow is decelerated to subsonic speed. In order to improve the flow in the divergent subsonic diffusor beyond the improvement caused by the slots, the shape of the duct downstream of the throat was changed to decrease the adverse pressure gradient in the high-velocity section and so to delay separation of the boundary layer. The present report describes the results of tests of models having these additional considerations in the design of the internal ducts.

SYMBOLS

A area

H total pressure

L length of subsonic diffusor

m rate of mass flow

M Mach number

p static pressure

x distance between the duct throat and a station in the diffusor (considered positive in the downstream direction)

γ ratio of the specific heat of air at constant pressure to the specific heat at constant volume, 1.400

Subscripts

o free stream

1 duct entrance

2 duct throat

3 settling chamber

4 exit throat

x any station in the duct at the distance x from the duct throat

(The subscripts designate the station of the measured quantity. See fig. 1.)

APPARATUS AND TESTS

Two models having different contraction ratios in the inlet passage were tested in the Ames 8- by 8-inch supersonic wind tunnel. The tests were performed through a free-stream Mach number range of 1.36 to 2.01 and at Reynolds numbers, based upon the length of the body ahead of the inlet, between 2.21 and 3.10 million. A description of the wind-tunnel equipment and the test procedure is given in reference 2.

The external shape of the models was the same as that of the model of reference 1. The forebody consisted of a 10-caliber ogival nose followed by a cylindrical section. The twin scoops enclosed 37.2 percent of the forebody circumference, and the height-width ratio of each scoop was 0.75. A 12° ramp was used ahead of each duct entrance.

The model dimensions and the internal duct shapes are shown in figures 1 and 2. The contraction ratios A_2/A_1 were selected for two different inlet Mach numbers. It was originally believed that the flow through a twin-scoop inlet having the proper slot area and dimensions would be similar to that through the perforated inlet of reference 3. If so, there would be no difficulty in causing the normal wave to move into the inlet at the design Mach number, and the scoops could be made to operate with a weak normal shock wave in the throat of the constricted passage. Model A of figure 1 had an inlet-contraction ratio of 0.914, the value for isentropic compression to sonic velocity from a uniform inlet Mach number of 1.36. With the model tested, an average inlet Mach number of 1.36 would occur at a free-stream Mach number of approximately 1.6. If there were no slots in the duct walls and if the flow were unidimensional and inviscid, this contraction ratio would permit a normal shock wave to enter the inlet when the intake Mach number was greater than 1.5 (reference 4) or when the free-stream Mach number was greater than 1.8. Model B had an inlet contraction ratio of 0.748, the value for isentropic compression to sonic velocity from a uniform inlet Mach number of 1.70, a value which occurred at a free-stream Mach number of approximately 2.0. If there were no slots in the duct walls of this model, a normal shock wave could not theoretically enter the inlet at even the maximum test Mach number.

In the subsonic diffusor of the model of reference 1, the rate of change of cross-sectional area with longitudinal position in the diffusor increased slowly from zero at the inlet to a constant value of 0.080 square inch per inch at 25 percent of the diffusor length. The data of reference 5 show that a large adverse pressure gradient exists in the upstream section of such diffusors. Since there was an initial boundary layer on one wall of the scoops being tested, this adverse pressure gradient probably caused the retarded air to separate in the high-velocity section of the diffusor and created excessive pressure losses. To reduce the adverse pressure gradient and the probability of this separation, a diffusor was designed to change the internal pressure distribution. The shape was calculated according to unidimensional theory to produce a pressure gradient proportional to the local static pressure. In other words, as the pressure increased in the diffusor, the pressure gradient increased correspondingly; thus, the smallest gradient would occur immediately downstream of the inlet and, the largest, just ahead of the settling chamber. The resulting diffusor was trumpet shaped; it diverged at a very small angle immediately downstream of the channel throat where the local Mach number was assumed to be 1.0, and at relatively large angles near the settling chamber where the local Mach number was assumed to be 0.2. The equation that relates the area at a given station to the desired pressure variation is derived in the appendix. The distance between the duct entrances and the settling chamber of the two models was about 14 percent less than that of the model of reference 1. This length was reduced because the computed area variation was very small in the high-velocity section of the diffusor if the original length were used. It was believed that the growth of the boundary layer in such a channel would compensate for the slight increase in divergence.

The tests were made with each model set at an angle of attack of 0°. The effects of slots were investigated by testing first without slots and then with the slots that were found to produce the greatest recovery for the inlet form of reference 1. To study the effect of slot area upon total-pressure recovery, the various combinations of slot height and length shown in figure 1 were tested. The slot heights were approximately 28 percent and 14 percent of the scoop height, and the slot lengths were 75 percent and 110 percent of the distance from the scoop entrance to the duct throat. Measurements of the total pressure in the settling chamber of the models were made at three equally spaced circumferential positions. At pressure ratios near the maximum, the differences in the measurements were no greater than 2 percent of the total pressure, a fact which indicates a relatively uniform velocity distribution. However, differences up to 15 percent of the total pressure were observed when the flow into the scoops was unsteady or when the variation of pressure recovery with mass-flow ratio was large. The total-pressure ratios presented in this report are based upon the average of the three pressure measurements.

RESULTS AND DISCUSSION

Several features have been incorporated in the present models to determine if large improvements in total-pressure recovery could be attained. These features were the inlet contractions, slots, and subsonic diffusors designed to reduce the adverse pressure gradient in the high-velocity section. The results, therefore, include the combined effects of these variables. Since the improvement in recovery was found to be relatively large, it is desirable to evaluate the magnitude of the contribution of each variable and to determine the reason for its favorable effect. A subsequent report will discuss tests of models designed to provide this information.

Ducts Without Slots

A comparison of the curves of figure 3 shows that the changes in the internal shape of the ducts without slots produced a large increase in the maximum total-pressure ratios $(H_3/H_0)_{max}$ beyond those attained with the unslotted inlet of reference 1. The increase was 3 percent at a Mach number of 1.36 and 14 percent at a Mach number of 2.01. The degree of constriction had only a small effect on this improvement. Schlieren photographs, such as those of figure 4, of the flow about models A and B indicate that a normal shock wave existed upstream of the duct entrances through the Mach number range of the tests when the total-pressure ratio was at the maximum value. Therefore, the flow into the scoops was subsonic for the conditions of figure 3 and underwent no supersonic compression through the contracting inlet passages. Apparently, the increase in the pressure recovery above that of the model tested in reference 1 was the result of an improvement of the flow in the subsonic diffusor.

The variation of total-pressure ratio H_3/H_0 with mass-flow ratio[1] m_1/m_0 for models A and B is shown in figure 5. Although the maximum total-pressure ratios are nearly the same, the range of flow ratios over which a high recovery can be maintained and also the maximum flow rate are greater with model A. For nearly all of the test conditions represented on these curves, a normal shock wave existed in the stream ahead of the inlets. Only for the greatest values of mass-flow ratio at a test Mach number of 2.01 did this shock wave retreat into the ducts, and then only with model A. The fact that this anticipated event did not occur until a Mach number greater than that calculated was reached is probably caused by the presence of the forebody boundary layer. The relatively large displacement thickness of this boundary layer increased the effective contraction of the inlet passages and thereby delayed the entrance of the normal shock wave beyond the Mach number for which it would be swallowed in unidimensional, inviscid flow.

When the flow through the inlet was subsonic, the stream was accelerated in the constricted passage, and at large mass-flow ratios sonic velocity probably existed in the throat. Downstream of the throat the flow expanded and became supersonic again until a second normal shock wave or a complex pattern of shock waves reduced it to subsonic velocity and it was finally diffused. Since the throat

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[1]Mass-flow ratio is defined as the mass of fluid entering the inlet divided by that which would flow through a tube of the same area in the free stream.

area of model B was less than that of model A and since the throats were choked at high flow ratios, less air flowed through the inlet of model B. As the outlet area of the passages through the models were reduced from the maximum values, the mass-flow ratio could not change because the velocity of the flow in the inlet throats was sonic. However, the total-pressure ratio increased because the shock losses in the subsonic diffusor moved toward the throat and occurred at a lower Mach number. The portion of the curves of figure 5 that indicates that the mass-flow ratio decreased while there was little change in the pressure recovery suggests that the flow through the ducts for this condition was entirely subsonic and there was an increase in the spillage around the lips. This fact is indicated by the schlieren photographs of figure 4 which show that the normal shock wave moved farther ahead of the inlet as the flow ratio was reduced. When the mass-flow ratio was reduced sufficiently, the boundary layer separated and the flow through the ducts became unsteady.

Ducts With Slots

The purpose of cutting slots in the duct walls of the inlet of models A and B was to permit the boundary layer of the flow over the forebody to escape from the ducts and thereby not only to remove low-energy air from the internal stream, but also to permit a sufficient mass of air to escape so that the normal shock wave which forms upstream of a constricted passage at low supersonic Mach numbers could enter the inlet. The expected result would be an increase in the total-pressure recovery attainable with the models. The maximum total-pressure ratios shown in figure 6 for models A and B having inlets with slots are greater than any attained with other similar scoop configurations. There is little difference, however, in the recovery attained by the two models. Of the slot sizes tested, the slots that were found to be best in reference 1 also produced the greatest recovery with models A and B; the effects of changes were small. The maximum total-pressure ratios attained were greater than those across a normal shock wave throughout the Mach number range of the tests and were within 2 percent of those attained with the nose inlets of reference 6 at Mach numbers of 1.7 and less.

Figure 7 shows the variation of total-pressure ratio with mass-flow ratio for models A and B at several Mach numbers. These curves show that, although the maximum recovery with both models is nearly the same, greater mass-flow ratios can be attained with model A and a higher recovery of pressure is maintained at large flow ratios and over a wider range. Operation at the highest possible flow ratio is, of course, desirable because the greatest mass of air per unit of entrance area flows through the system. As indicated on the curves, the maximum recovery at all conditions for either model occurred with a normal shock wave ahead of the inlet. With model A, this shock wave formed ahead of the inlet for all flow ratios at a Mach number of 1.36, and it moved into the inlet only at mass-flow ratios well above those for maximum recovery at the greater Mach numbers. The unexpected result is that, contrary to the pressure variation observed with the convergent-divergent nose inlets of references 3 and 7, the recovery decreased when the shock wave moved toward the throat of the inlet passage. This fact probably means that, although the pressure losses through the shock wave decreased, the total losses increased because of adverse effects of the boundary layer inside the ducts.

Similar flow characteristics were observed with model B having a slotted inlet. The normal shock wave existed upstream of the inlet for all Mach numbers at the mass-flow ratio for maximum pressure recovery, and it retreated into the duct only at high flow ratios at a Mach number of 2.01. Changing the slot area to enable the shock wave to enter the ducts reduced the recovery. The maximum total-pressure ratio of model B occurred at a cusp in the curve of the variation with mass-flow ratio. The following discussion is suggested as an explanation for the occurrence of this cusp. When a normal shock wave existed upstream of the inlet, the flow through the scoop entrances must have been subsonic and accelerated in the constricted passage. With the relatively large contraction ratio of model B, the flow probably was choked at the throat and expanded to supersonic velocity again in the subsequent expanding channel. It was finally reduced to subsonic velocity through a complex pattern of shock waves inside the diffusor. As the back pressure in the settling chamber was increased, these shock waves moved upstream toward the throat and the pressure rise through them was transmitted forward through the boundary layer. This increased pressure forced more boundary-layer air to flow out of the slots, and the amount increased as the shock waves moved toward the throat. With model B, a sudden rise in pressure recovery occurred when these shock losses formed at the throat, possibly because the balance between the pressure losses through the shock waves and the amount of low-energy air forced out of the slots fulfilled the conditions required for flow with the least pressure loss. With model A, the cusp did not occur, perhaps because the contraction and the slots were better proportioned.

With both models, the wide range of conditions for which the mass-flow ratio could be varied with only small changes in pressure ratio indicates that the slots and modified duct shape are not only useful in increasing the pressure recovery but they also improve the stability of operation of an air-induction system. In the operating range of some inlets, a large decrease in pressure recovery can result from a small transient increase in the mass flow to an engine. The thrust force of the engine is thereby reduced with a resulting decrease in aircraft speed and a further decrease in the ram pressure available. Two reasons are suggested why these circumstances do not occur with the inlet having slots and the modified internal duct shape: The slots permit the flow rate through the inlet to adjust itself to changes in pressure and thus damp fluctuations in the mass flow; and, since the internal shock losses for the usual operating condition occur in the portion of the duct where the change in area is small, the magnitude of the losses can change only slightly.

CONCLUSIONS

Tests at Mach numbers between 1.36 and 2.01 of models having twin-scoop inlets situated on the sides of a long forebody indicated that maximum total-pressure ratios greater than those of a normal shock wave could be attained through the Mach number range and that pressure recovery within 2 percent of that associated with nose inlets could be attained at Mach numbers less than about 1.7. These relatively large total-pressure ratios resulted from an internal duct shape that improved the conditions for boundary-layer flow in the diffusor. The variation of total-pressure ratio with mass-flow ratio for the duct system indicated more stability than is usual with other types of inlets.

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APPENDIX

SUBSONIC DIFFUSOR WITH THE LOCAL PRESSURE GRADIENT

PROPORTIONAL TO THE LOCAL STATIC PRESSURE

In the following analysis, it is assumed that the flow through the subsonic diffusor is unidimensional and that the relations for isentropic flow of a perfect gas are applicable.

The ratio of static to total pressure in terms of the local Mach number is indicated by the equation

$$\frac{p}{H} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{-\frac{\gamma}{\gamma-1}} \tag{A1}$$

Differentiating this expression with respect to x/L and collecting terms gives the following equation for the local static-pressure gradient

$$\frac{dp}{d(x/L)} = - H\gamma \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{-2\gamma+1}{\gamma-1}} M \frac{dM}{d(x/L)} \tag{A2}$$

The ratio of the pressure gradient to the local static pressure is then

$$\frac{dp/[d(x/L)]}{p} = - \frac{\gamma H}{p} \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{-2\gamma+1}{\gamma-1}} M \frac{dM}{d(x/L)} \tag{A3}$$

Taking $\frac{dp/[d(x/L)]}{p} = K$, a constant for a diffusor of given length, and substituting for $\frac{H}{p}$ in equation (A3) yields

$$K = - \gamma \left(1 + \frac{\gamma-1}{2} M^2\right)^{-1} M \frac{dM}{d(x/L)} \tag{A4}$$

Assuming that, when $x/L = 0$, $M = 1.0$, integration of equation (A4) gives

$$K\left(\frac{x}{L}\right) = - \frac{\gamma}{\gamma-1} \ln\left[\left(\frac{2}{\gamma-1} + M^2\right)\left(\frac{\gamma-1}{\gamma+1}\right)\right] \tag{A5}$$

Coefficient K is evaluated from equation (A5) by selecting a value for M at $x/L = 1$. This value of M is usually determined by the permissible settling-chamber velocity.

When solved for Mach number, equation (A5) becomes

$$M = \left\{ \frac{2}{\gamma-1} \left[\left(\frac{\gamma+1}{2} \right) e^{\frac{1-\gamma}{\gamma} K \left(\frac{x}{L} \right)} - 1 \right] \right\}^{1/2} \tag{A6}$$

The relation between area and Mach number in an isentropic flow when $M_2 \equiv M_{x/L = 0} = 1.0$ is

$$\frac{A_2}{A} = M \left\{ \frac{(\gamma+1)/2}{1 + [(\gamma-1)/2] M^2} \right\}^{\frac{\gamma+1}{2(\gamma-1)}} \tag{A7}$$

Substituting equation (A6) in equation (A7),

$$\frac{A_2}{A} = \left\{ \frac{2}{\gamma-1} \left[\left(\frac{\gamma+1}{2} \right) e^{\frac{1-\gamma}{\gamma} K \left(\frac{x}{L} \right)} - 1 \right] \right\}^{1/2} e^{\frac{\gamma+1}{2\gamma} K \left(\frac{x}{L} \right)} \tag{A8}$$

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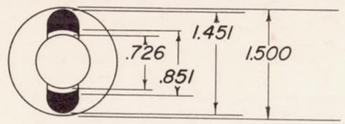
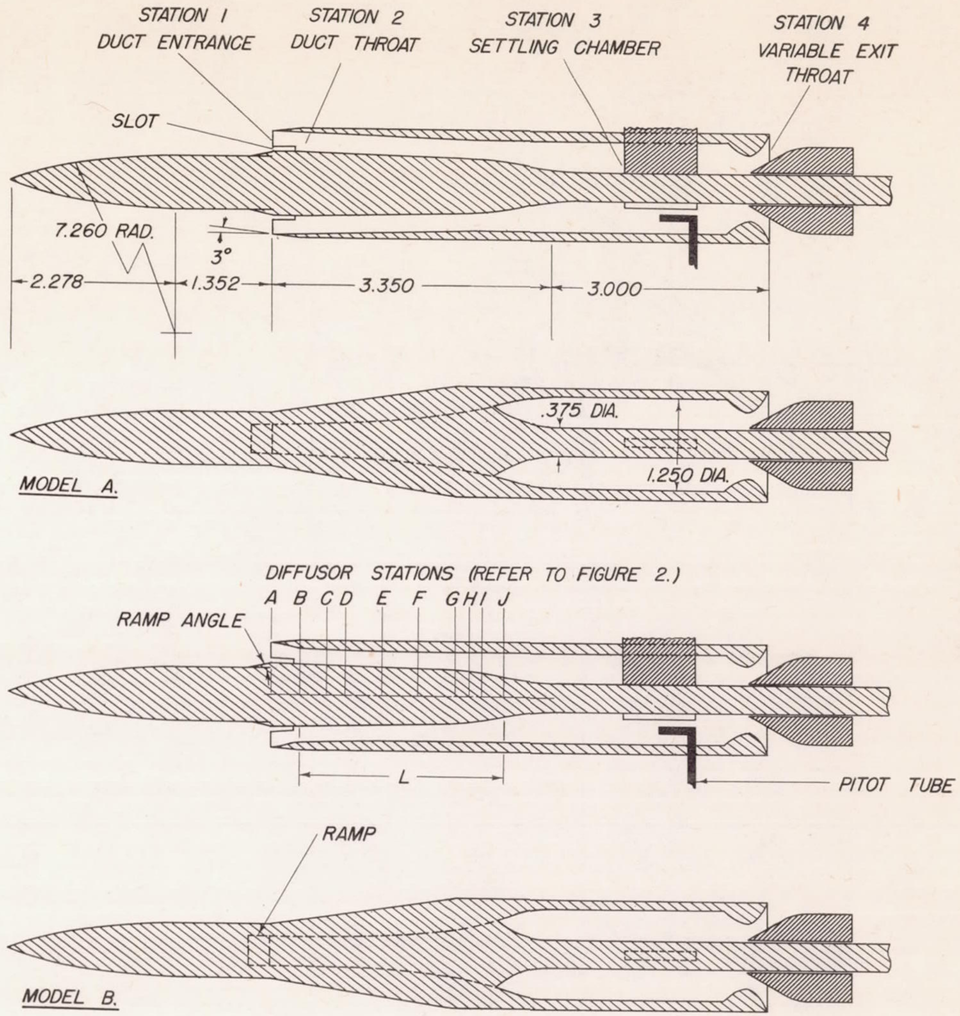


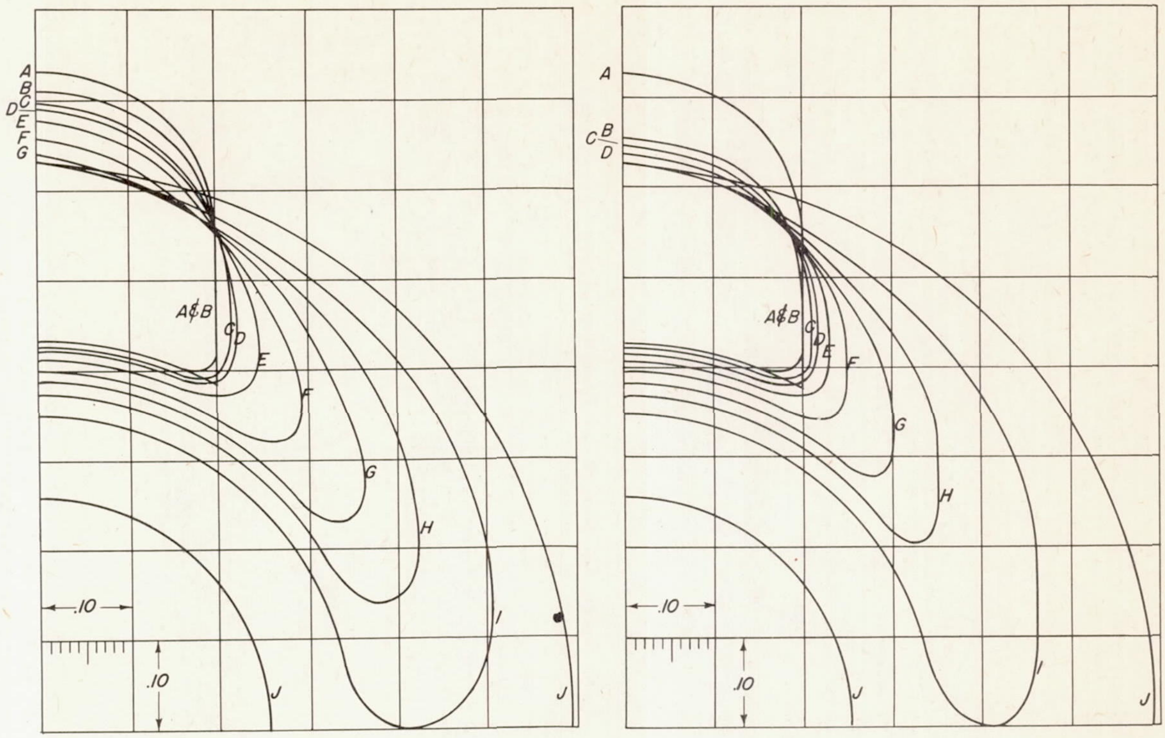


ENTRANCE AREA, $A_1 = 0.2209$
ALL DIMENSIONS IN INCHES

SLOT SIZES TESTED

MODEL A HEIGHT	MODEL A LENGTH	MODEL B HEIGHT	MODEL B LENGTH
.085	.300	.085	.300
.085	.450	.085	.450
		.044	.450

FIGURE 1. — MODEL DIMENSIONS.



All dimensions in inches

STATION	x	A_2/A
A	-0.400	0.914
B	0	1.000
C	0.375	0.994
D	0.625	0.983
E	1.125	0.936
F	1.625	0.839
G	2.125	0.648
H	2.325	0.516
I	2.500	0.334
J	2.800	0.235

Model A

STATION	x	A_2/A
A	-0.400	0.748
B	0	1.000
C	0.375	0.994
D	0.625	0.983
E	1.125	0.936
F	1.625	0.839
G	2.125	0.648
H	2.325	0.516
I	2.500	0.305
J	2.800	0.175

Model B

Figure 2. — Internal shape and areas of the model ducts.

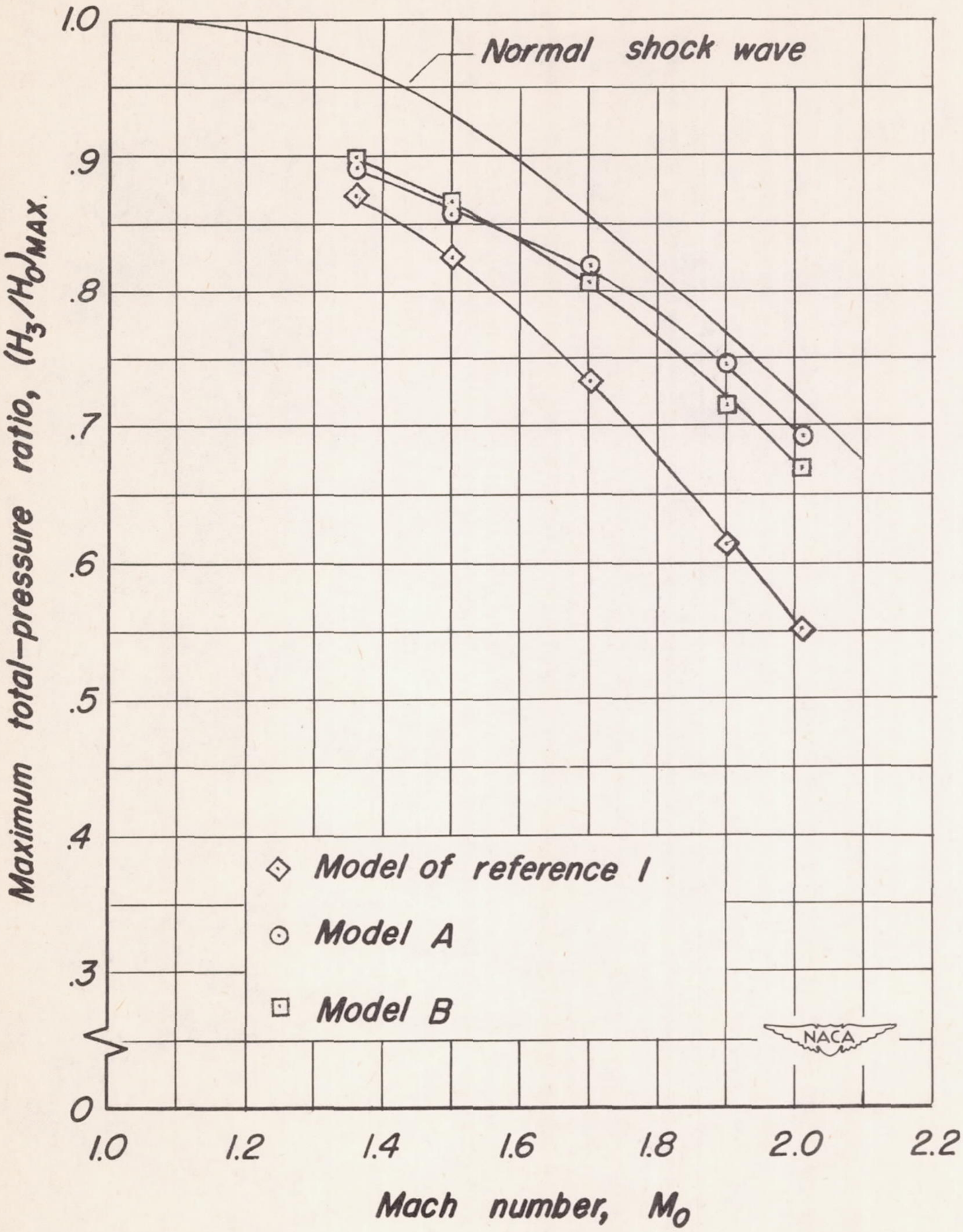
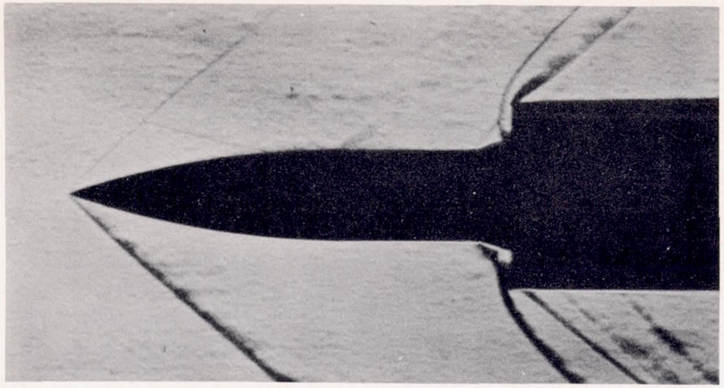
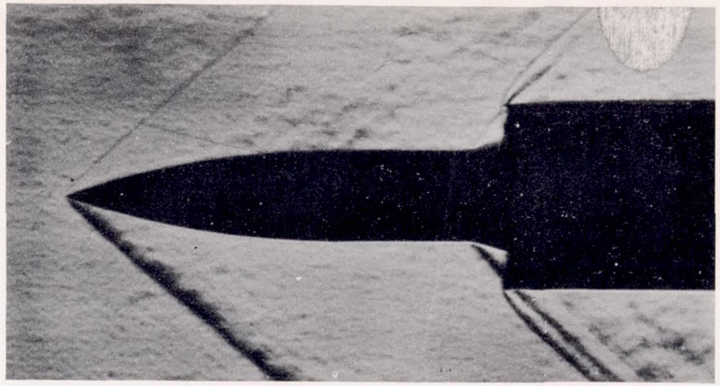


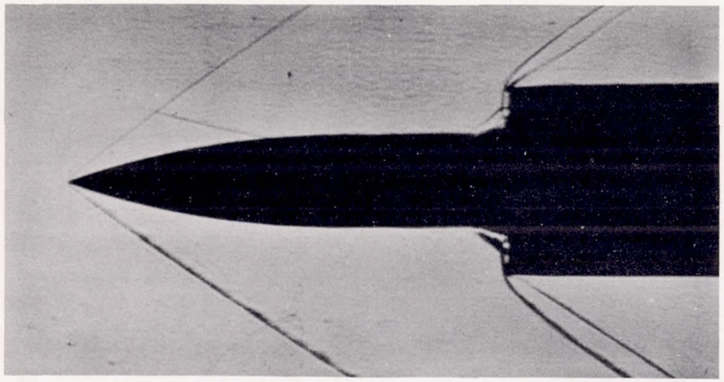
Figure 3.—Variation of maximum total-pressure ratio with Mach number for models without slots.



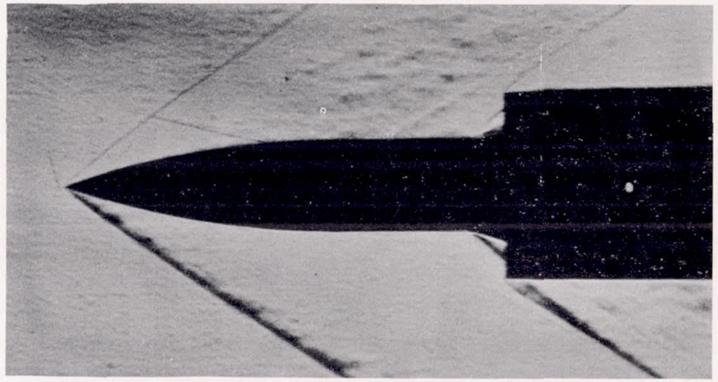
(a) M_0, 1.70; m_1/m_0, 0.801; H_3/H_0, 0.814.



(b) M_0, 1.70; m_1/m_0, 0.987; H_3/H_0, 0.677.



(c) M_0, 2.01; m_1/m_0, 0.872; H_3/H_0, 0.692.



(d) M_0, 2.01; m_1/m_0, 1.007; H_3/H_0, 0.548.

Figure 4.– Schlieren photographs of the flow about model A without slots.

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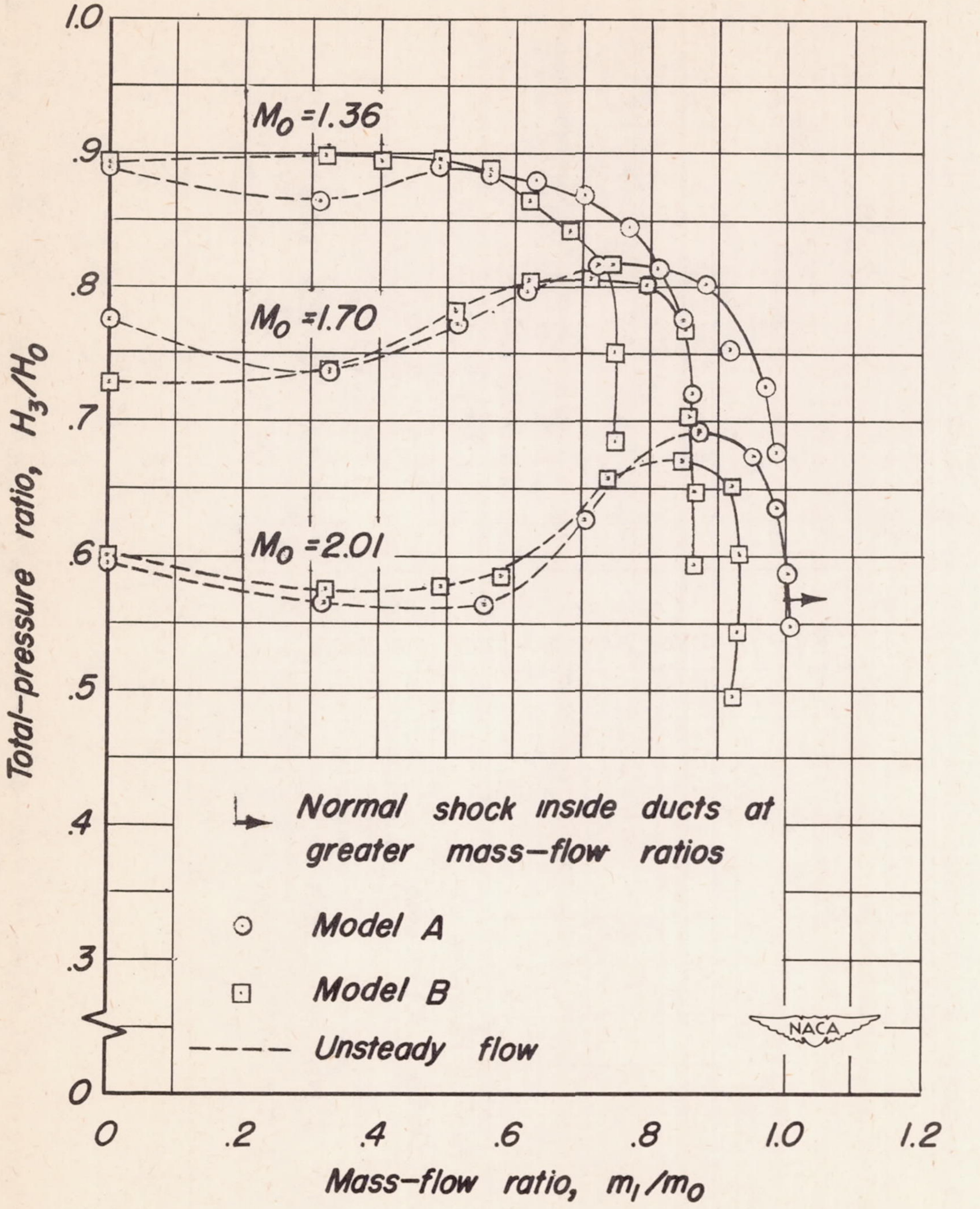

Figure 5.—Variation of total-pressure ratio with mass-flow ratio for models without slots.

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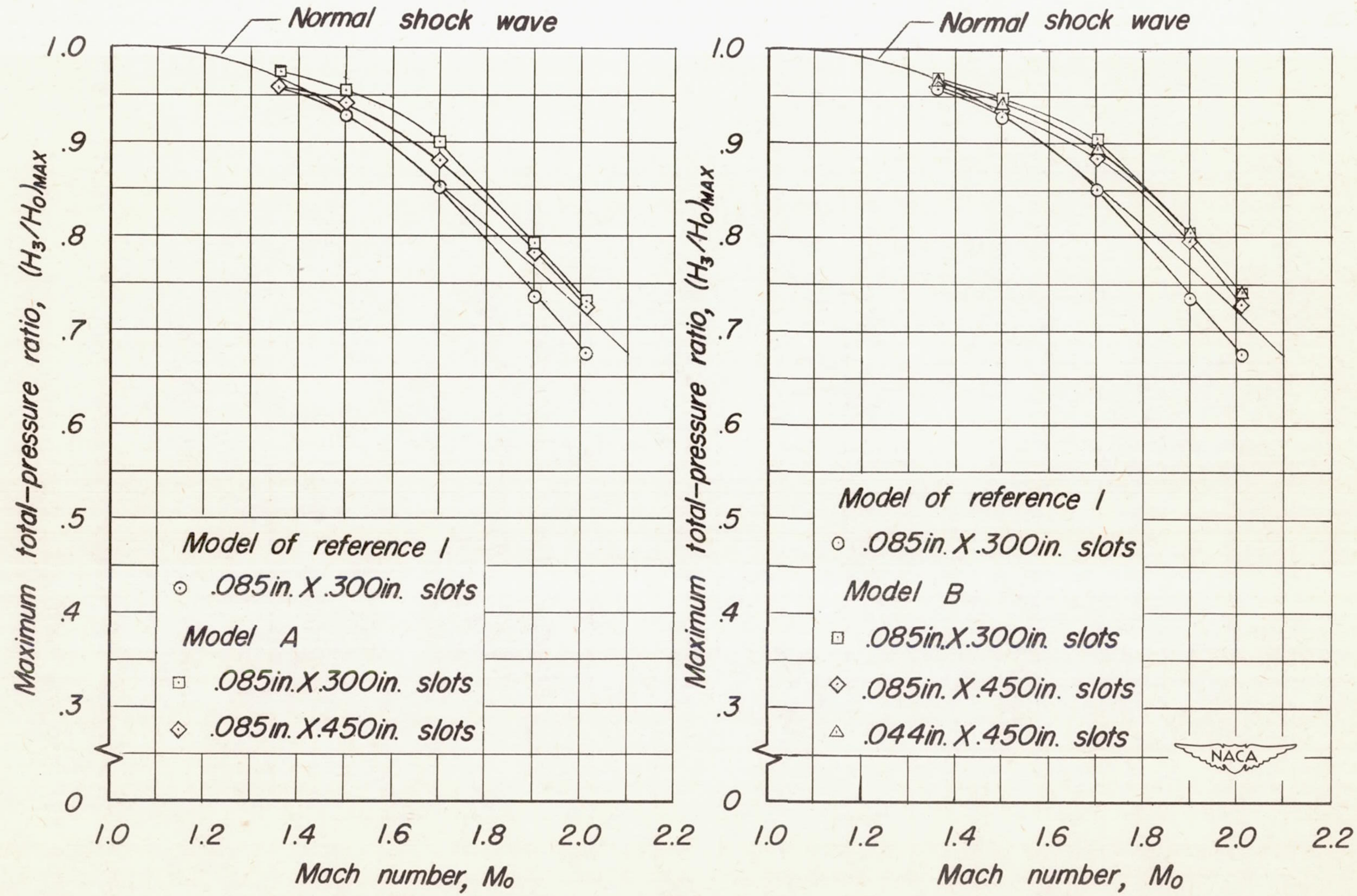

Figure 6.—Variation of maximum total-pressure ratio with Mach number for models with slots.

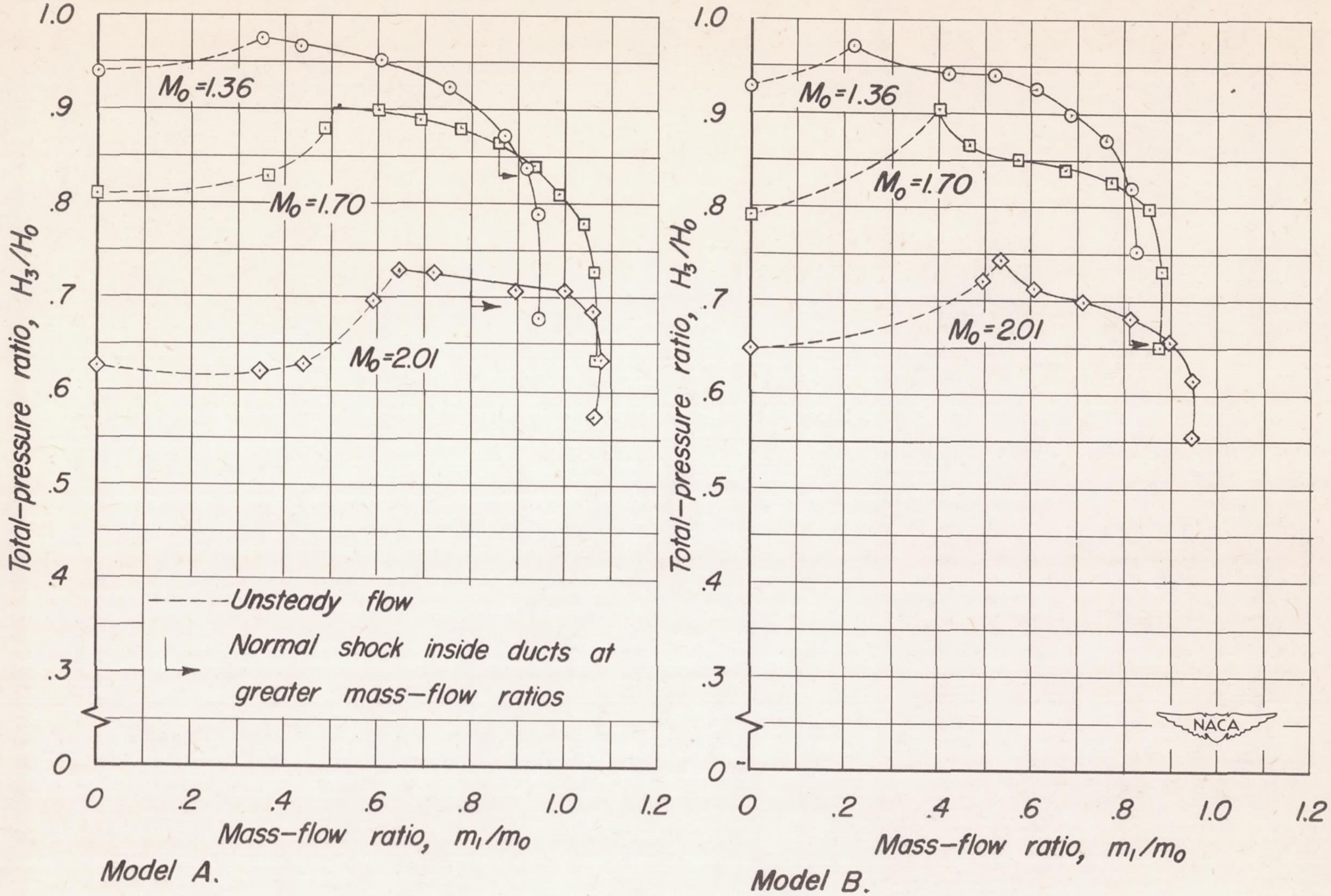

Figure 7.—Variation of total-pressure ratio with mass-flow ratio for models with 0.085-inch by 0.300-inch slots.