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ADVANCED POROUS TRANSONIC WIND-TUNNEL NOZZLES

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16. Abstract

Porous wall nozzles appear to offer an attractive alternative to conventional variable geometry transonic wind-tunnel nozzles. However, in the past at off-design Mach numbers, the porous nozzle designs resulted in a nonuniform flow within the test section that was unacceptable. In those designs, the single plenum chamber backing the porous walls did not allow proper control of the plenum pressure and effective nozzle length. Now, new advances in the design and control of the porous bleed flow distribution along the nozzle walls promise to solve the problem of nonuniform flow at off-design conditions. This can be accomplished in a two-dimensional nozzle with porous parallel sidewalls backed with a single plenum chamber and employing a sliding compartment wall or backed with multiple plenum chambers within which the pressure can be controlled.

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SUMMARY

Porous wall nozzles appear to offer an attractive alternative to conventional variable geometry transonic wind-tunnel nozzles. However, in the past at off-design Mach numbers, the porous nozzle designs resulted in a nonuniform flow within the test section that was unacceptable. In those designs, the single plenum chamber backing the porous walls did not allow proper control of the plenum pressure and effective nozzle length. Now, new advances in the design and control of the porous bleed flow distribution along the nozzle walls promise to solve the problem of nonuniform flow at off-design conditions. This can be accomplished in a two-dimensional nozzle with porous parallel sidewalls backed with a single plenum chamber and employing a sliding compartment wall or backed with multiple plenum chambers within which the pressure can be controlled.

INTRODUCTION

Conventional transonic wind tunnels usually have square or rectangular shaped nozzles and test sections. These shapes allow two opposing sidewalls to be mechanically flexed to form nozzle contours to expand sonic flow in the throat to the desired supersonic Mach number. Generally, for transonic tunnels, the maximum Mach number is less than 1.4. However, flexing sidewalls may be impractical for some facilities, such as high-pressure (high Reynolds number) transonic wind tunnels or tunnels with circular nozzles and test sections. For high pressure facilities, the nozzle walls are thick and, therefore, may be mechanically impractical to flex and, certainly, expensive to fabricate. For facilities with circular nozzles, flexing walls are mechanically impractical.

To overcome the mechanical problems, porous nozzles with parallel walls appear to offer a promising practical solution. Several porous nozzles which expand the throat flow by bleeding air through the porous nozzle walls downstream of the throat have been operated at small scale in the past. However, at off-design Mach numbers, these designs resulted in a nonuniform flow within the test section that was unacceptable. Now, new advances (ref. 1) in the design and control of the porous bleed flow distribution along the nozzle walls promise to solve this problem of nonuniform flow at off-design conditions. The main objective of this report is to describe the new porous nozzles and show fundamentally how they can be designed and operated.

NOMENCLATURE

A	=	area
a_*	=	sonic velocity
d	=	hole diameter
h	=	height
l	=	hole length
M	=	Mach number
m	=	mass flow
p	=	static pressure
p_{t_∞}	=	free stream total pressure
Q	=	sonic flow coefficient
V	=	velocity
x	=	axial station
ρ	=	static density
ρ_t	=	total density

Subscripts:

bl	=	bleed
℄	=	centerline
cum	=	cumulative
e	=	exit
pl	=	plenum
th	=	throat
w	=	wall
x	=	at x
Δ	=	incremental

Superscripts:

$-$	=	average

DISCUSSION

<u>Conventional Nozzles</u> - The contours for a conventional two-dimensional transonic wind-tunnel nozzle operating at supersonic speeds can be calculated with the aid of available theoretical methods (ref. 2). The contours of such a nozzle are shown in figure 1. In this case, the calculated contours

provide isentropic expansion of sonic flow in the throat to a uniform exit Mach number, M_e, of 1.4 into the test section. With a nozzle inlet throat radius equal to twice the throat height, h_{th}, and for a test flow Mach number of 1.4, the flow must be expanded to an exit height of 1.113 h_{th} at a nozzle length equal to 2.16 h_{th}. These relationships, of course, must change for other supersonic Mach numbers. This requires flexing of the walls into new contours as determined by analysis. As mentioned previously, flexing walls for some wind tunnel applications may be impractical and expensive.

Previous Porous Nozzles - To avoid flexing the walls to vary the exit Mach number, a fixed parallel wall two-dimensional porous nozzle can be designed. The nozzle, shown in figure 2, with only a single plenum chamber to collect the porous bleed flow, represents previous technology (ref. 3). The wall porosity was designed so that for a given ratio of plenum pressure to free stream total pressure, the length and porosity was suitable for only the Mach number for which it was designed. At off-design Mach numbers the plenum was merely back pressured by throttling the plenum exit to provide a lower exit Mach number which led to test section flow nonuniformity. The nonuniformity of the flow is shown in figure 3 where the Mach number distribution along the centerline of the nozzle and the test section is plotted. For the design exit Mach number of 1.28, the Mach number along the nozzle centerline increases linearly and appears nearly uniform along the centerline of the test section. However, at a lower exit Mach number of approximately 1.2, the Mach number distribution in the test section has a nonuniform wave-like form.

Sliding Chamber Porous Nozzle - One possible reason for the nonuniform test section Mach number under off-design conditions is that the effective length of the single chamber porous nozzle is constant. Typically, as shown in figure 4, conventional nozzle length decreases for decreasing supersonic exit Mach number. For a two-dimensional nozzle with an initial throat radius equal to twice the throat height, the length varies from $x/h_{th}/2 = 2.36$ at $M_e \approx 1.4$ to $x/h_{th}/2 = 0$ at $M_e \leq 1.0$.

Changing the effective length of the nozzle can be simply accomplished using a translating plenum chamber divider, as shown in figure 5. At the design exit Mach number the divider is at its most downstream position. For operation at lower exit Mach numbers the divider is translated upstream until at $M_e = 1.0$, the divider is at the throat and no bleed passes through the porous walls.* Shortening the effective length of the nozzle also increases the length of the test section at the lower supersonic Mach numbers where length is needed more than at higher Mach numbers.

Multi-Chamber Porous Nozzle - Another factor believed to contribute to the nonuniform test section Mach number for the single chamber porous nozzle

* In reality some bleed will probably be needed to avoid probable excessive thickening of the boundary layer that could be caused by the disturbing influence of the relatively rough porous surface.

is the lack of proper control of the Mach number distribution through the nozzle. Figure 6 shows the Mach number distributions along the walls of conventional nozzles with design exit Mach numbers ranging from 1.4 to 1.15. Since the length changes with design Mach number, each distribution is unique — something unlikely to be achieved with a single plenum chamber porous nozzle. However, by using a distribution of porous wall bleed, the Mach number distribution and length of a conventional nozzle can be duplicated and should result in the desired uniform supersonic exit flow.

To provide for both a variation in nozzle length and Mach number distribution, a multiple plenum chamber porous nozzle can be designed, as shown in figure 7. In this design the porosity at the design exit Mach number is such that the length and wall Mach number distribution matches that of a conventional nozzle. At the design exit Mach number, the plenum chamber pressures can be equal. At off-design conditions, the length can be reduced by gradually throttling the flow from each chamber starting with the most downstream chamber. Further, the pressure in each active chamber can be throttled to provide a Mach number distribution on the porous walls approximating that of a conventional two-dimensional nozzle or until a desired uniform M_e is achieved.

<u>Design Procedure</u> - The recommended design procedure is based on approximating the length and wall Mach number distribution of a conventional nozzle by properly bleeding along parallel porous walls. For parallel walls the required cumulative bleed mass-flow ratio $(m_{bl}/m_{th})_{cum}$ along the length of the nozzle for M_e up to 1.4 is shown in figure 8.† First, a porous hole pattern is derived for the design M_e using the $(m_{bl}/m_{th})_{cum}$ distribution and known hole sonic flow characteristics shown in figure 9 (ref. 4). Sonic flow coefficients for round holes normal to the surface with a length to diameter ratio of 3 for various wall Mach numbers, M_x, are plotted as a function of plenum pressure ratio p_{pl}/p_{t_∞}. The required hole area distribution on the porous walls at design M_e is then calculated using coefficients for a constant p_{pl}/p_{t_∞}. At off-design M_e the plenum pressure required to maintain the cumulative bleed requirements is then calculated using figures 8 and 9.

The results of the above procedure for a typical porous nozzle design are shown in table I. Shown are the hole area and the off-design plenum pressure schedules for each chamber of a six-chamber nozzle with a design $M_e = 1.4$ such as shown in figure 7. The porous pattern necessarily is designed in a stepwise manner for each compartment (see appendix). At the design M_e the plenum pressures, as mentioned before, are constant at $p_{bl}/p_{t_\infty} = 0.2$. As the M_e is reduced the aft chambers are successively closed and the plenum pressures are increased in the remaining open chambers until $M_e = 1.0$, all chambers are closed. The greater the number of chambers

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† Details of the mathematical procedure are shown in the appendix.

the more accurate the design procedure can be. However, there appears to be a practical limit to the number of chambers if for no other reason than the exit piping would be too complex, heavy, and expensive, at least for a large wind tunnel.

Porous Cylindrical Nozzles - The previous discussion concerned only two-dimensional nozzles. Circular conventional nozzles can be designed, of course, but to vary the geometry of cylindrical walls seems less practical than using a porous cylindrical nozzle as shown in figure 10. In the scheme shown, rotating porous rings control the length and porosity of the nozzle. The design procedure for determining the proper design porous distribution should be similar to that of the two-dimensional porous nozzle, only using an axisymmetric conventional nozzle as the basis for the porous design procedure.

CONCLUDING REMARKS

To maintain a uniform off-design nozzle exit Mach number in a porous transonic nozzle, the effective length needs to be varied and the Mach number distribution along the walls of the nozzle must be controlled. This can be accomplished in a two-dimensional nozzle with parallel sidewalls backed with a single plenum chamber with a sliding compartment wall or backed with multiple plenum chambers within which the pressure can be controlled. Tests are needed now to verify the design concepts and procedures.

APPENDIX

Wind tunnel tests (ref. 3) have established that properly bleeding flow through parallel porous walls can expand sonic flow to supersonic flow similar to a conventionally shaped supersonic nozzle. It is assumed in this paper that the required cumulative bleed from the throat of the porous wall nozzle to the exit is distributed so that the increase in local wall Mach number, and, therefore, the flow expansion, approximates that of a conventionally shaped nozzle. The total amount of bleed flow required up to the exit, then, will be

$$\frac{m_{bl}}{m_{th}} = \frac{A_e - A_{th}}{A_{th}}$$

if the porous walls are parallel and the nozzle flow is isentropic and uniform. With this premise the porous hole distribution and size can be calculated, first, by determining the distribution of m_{bl}/m_{th} required to approximate the Mach number distribution along the walls of a conventional nozzle at the design exit Mach number (highest M_e). This can be done, for example, for a six-plenum chamber porous nozzle (fig. 10) by plotting the increase in nozzle Mach number and area between the throat and the exit of a conventional nozzle as shown in figures 6 and 11, respectively. At the design M_e, each incremental nozzle area increase, $\Delta(A_x - A_{th})/A_{th}$, for each of the six equally spaced plenum chambers is used together with the corresponding average wall Mach number, $\bar{M}_{\Delta x}$, over each increment to define the terms (ref. 5) in the following equation:

$$\left(\frac{m_{bl}}{m_{th}}\right)_{\Delta x} = \frac{(\rho/\rho_t)_{\bar{M}_x}}{(\rho/\rho_t)_{M_{th}}} \cdot \frac{(V/a_*)_{\bar{M}_x}}{(V/a_*)_{M_{th}}} \cdot \frac{\Delta(A_x - A_{th})}{A_{th}} \tag{1}$$

Assuming sonic flow in the bleed holes and nozzle throat

$$\left(\frac{A_{bl}}{A_{th}}\right)_{\Delta x} Q_{\Delta x} = \left(\frac{m_{bl}}{m_{th}}\right)_{\Delta x} \tag{2}$$

or

$$A_{bl_{\Delta x}} = \left(\frac{m_{bl}}{m_{th}}\right)_{\Delta x} \frac{A_{th}}{Q_{\Delta x}} \tag{3}$$

where the sonic flow coefficient for each plenum chamber, $Q_{\Delta x}$, is determined from figure 9 for a constant p_{bl}/p_{t_∞} for each $\bar{M}_{\Delta x}$ (fig. 6).

Next, for lower off-design M_e operation, the plenum chamber pressure required to maintain the proper distribution of $(m_{bl}/m_{th})_{\Delta x}$ is calculated. As for the design M_e, $(m_{bl}/m_{th})_{\Delta x}$ is calculated for each plenum chamber involved in the shorter nozzle lengths. Since $(A_{bl}/A_{th})_{\Delta x}$ is known, $Q_{\Delta x}$ can be calculated from equation 2. Then, using $Q_{\Delta x}$, figure 9 can be entered to determine p_{bl}/p_{t_∞} for the corresponding $\bar{M}_{\Delta x}$. Sample calculations should check with the tabulations shown in table I.

REFERENCES

1. Sorensen, Norman E.: Wind Tunnel Flow Generation Section. U.S. Patent 3,853,003, Dec. 1974.

2. Sims, J. L.: Calculation of Transonic Nozzle Flow. NASA TM X-53081, 1964.

3. Stokes, George M.: A Method for the Design of Porous-Wall Wind Tunnels. NACA RM L55J139, 1956.

4. Sybert, J.; and Hickcox, T. E.: Design of a Bleed System for a Mach 3.5 Inlet. NASA CR-2187, 1973.

5. Ames Research Staff: Equations, Tables, and Charts for Compressible Flow. NACA Rep. 1135, 1953.

TABLE I. - TYPICAL POROUS NOZZLE SCHEDULE

DESIGN $M_e = 1.4$

Plenum No.	$\frac{x}{(h_{th}/2)}$	$\frac{A_{b1}}{A_{th}}$	P_{p1}/P_{t_∞}				
			$M_e = 1.4$	1.3	1.2	1.15	1.0
1	0 - 0.4	0.1056	0.20	0.30	0.40	0.45	Closed
2	0.4 - 0.8	0.1616	0.20	0.34	0.43	0.47	Closed
3	0.8 - 1.2	0.1453	0.20	0.34	0.45	0.47	Closed
4	1.2 - 1.6	0.1184	0.20	0.36	Closed	Closed	Closed
5	1.6 - 2.0	0.0675	0.20	0.39	Closed	Closed	Closed
6	2.0 - 2.4	0.0130	0.20	Closed	Closed	Closed	Closed

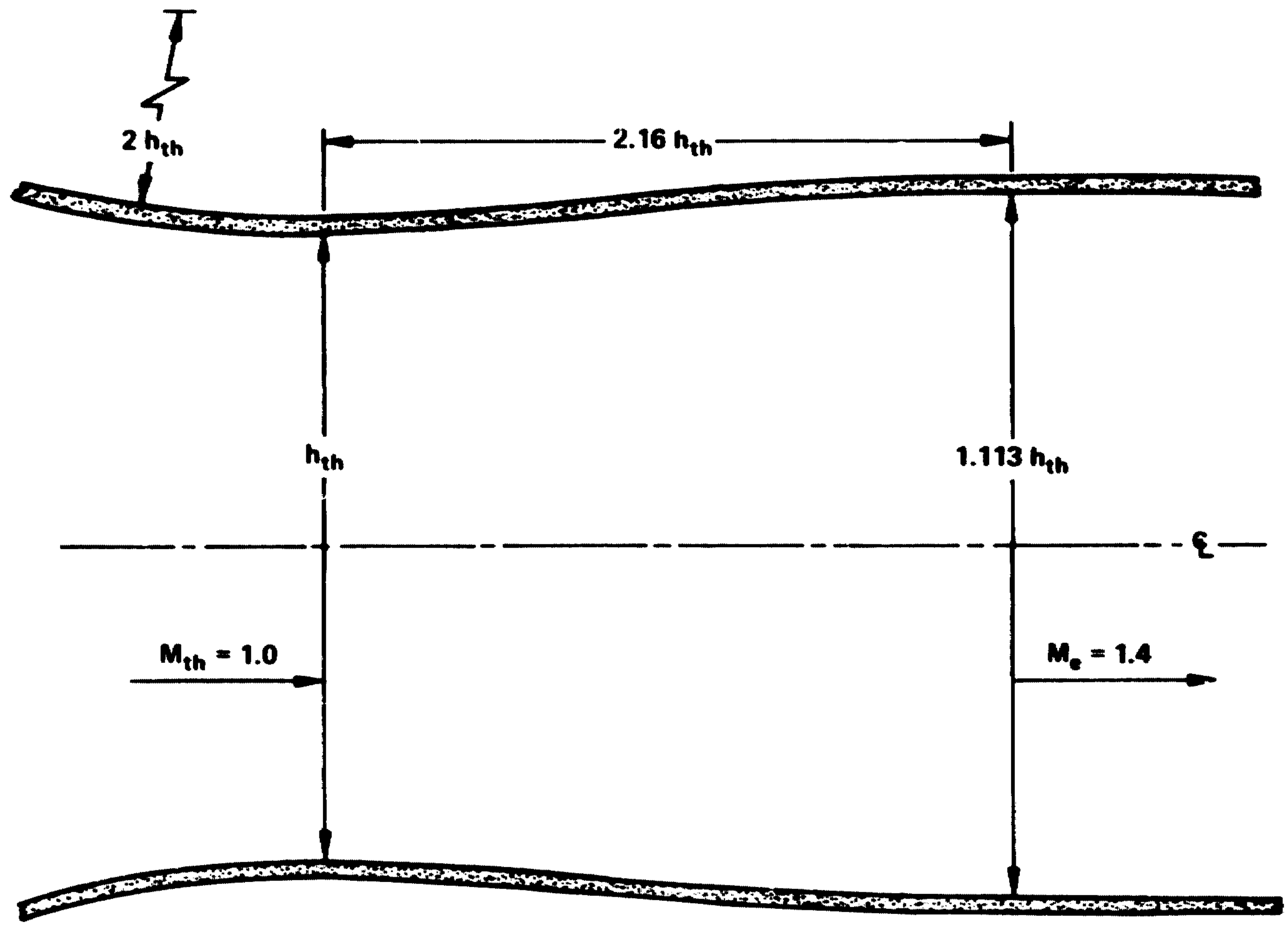

Figure 1.- Conventional 2-D nozzle.

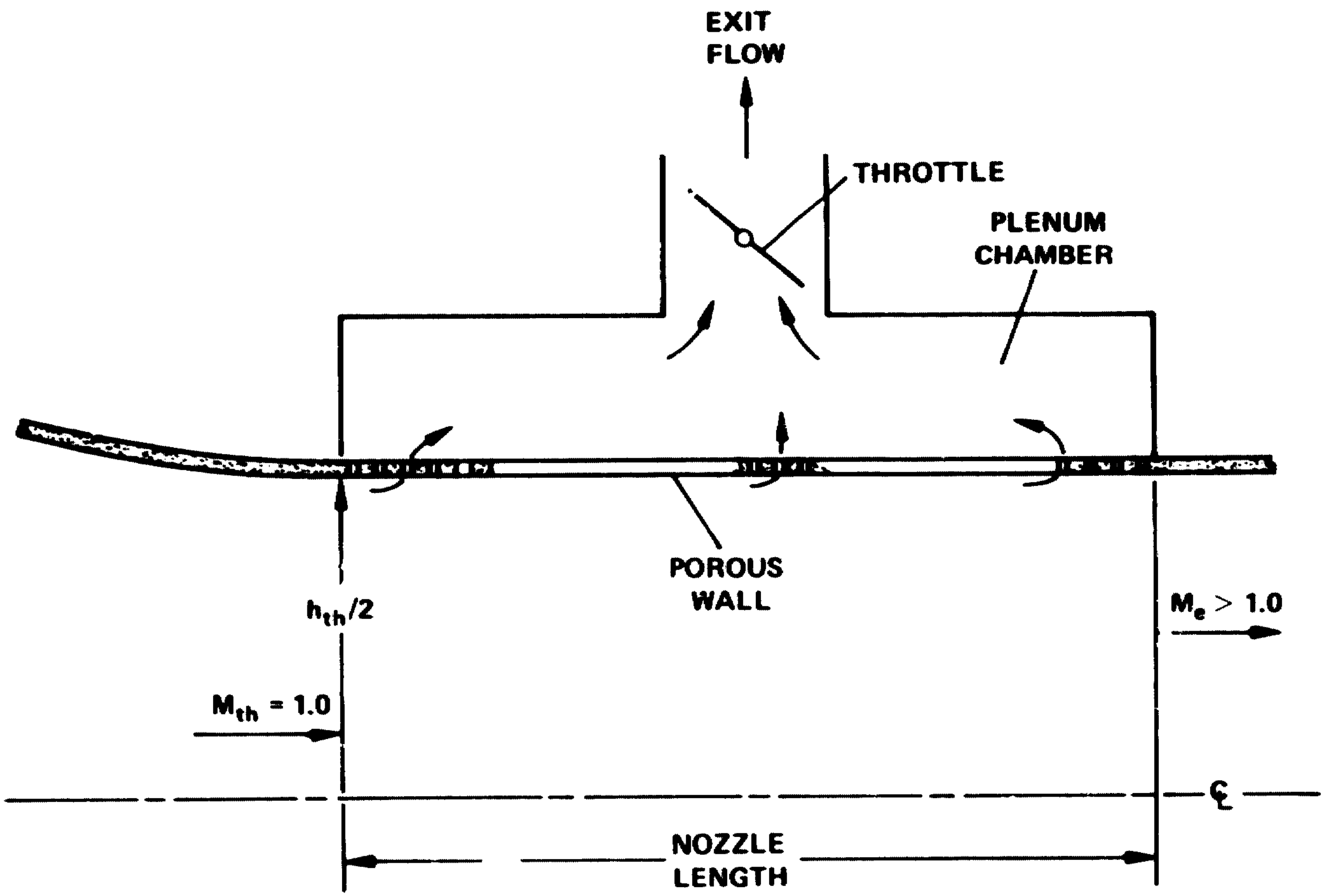

Figure 2.- Porous 2-D nozzle.

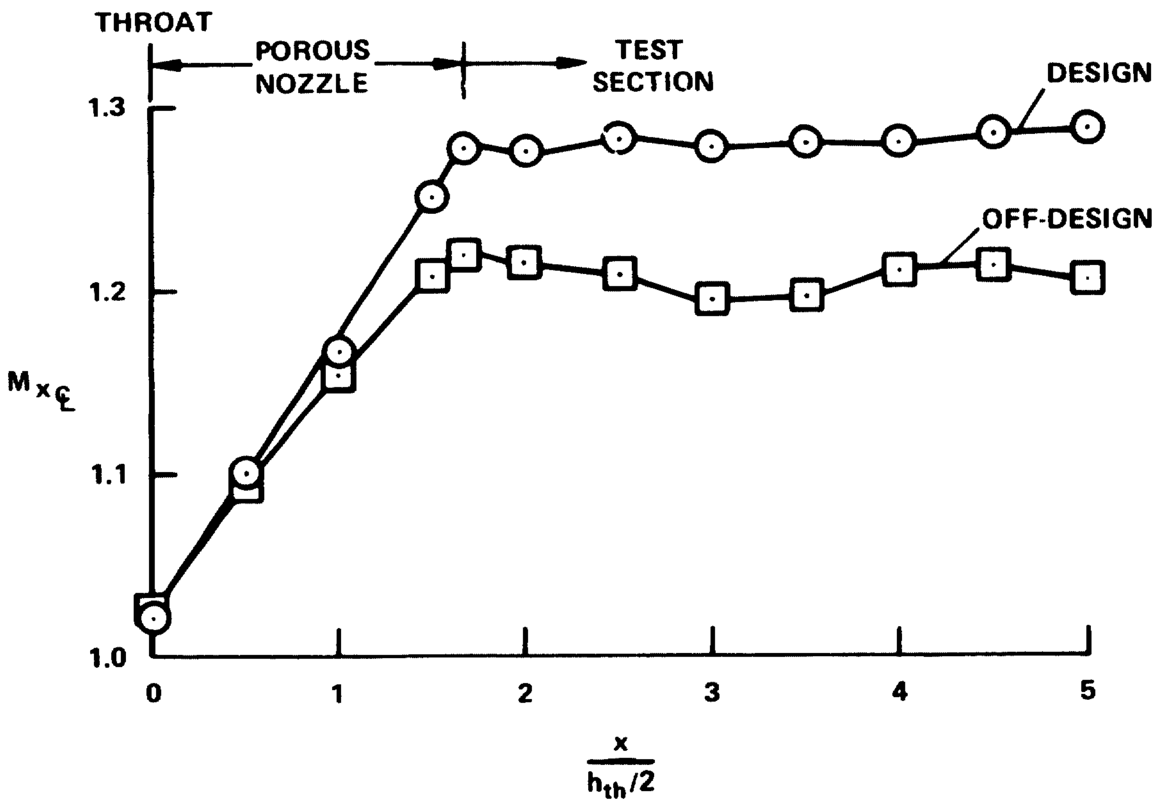

Figure 3.- Flow nonuniformity.

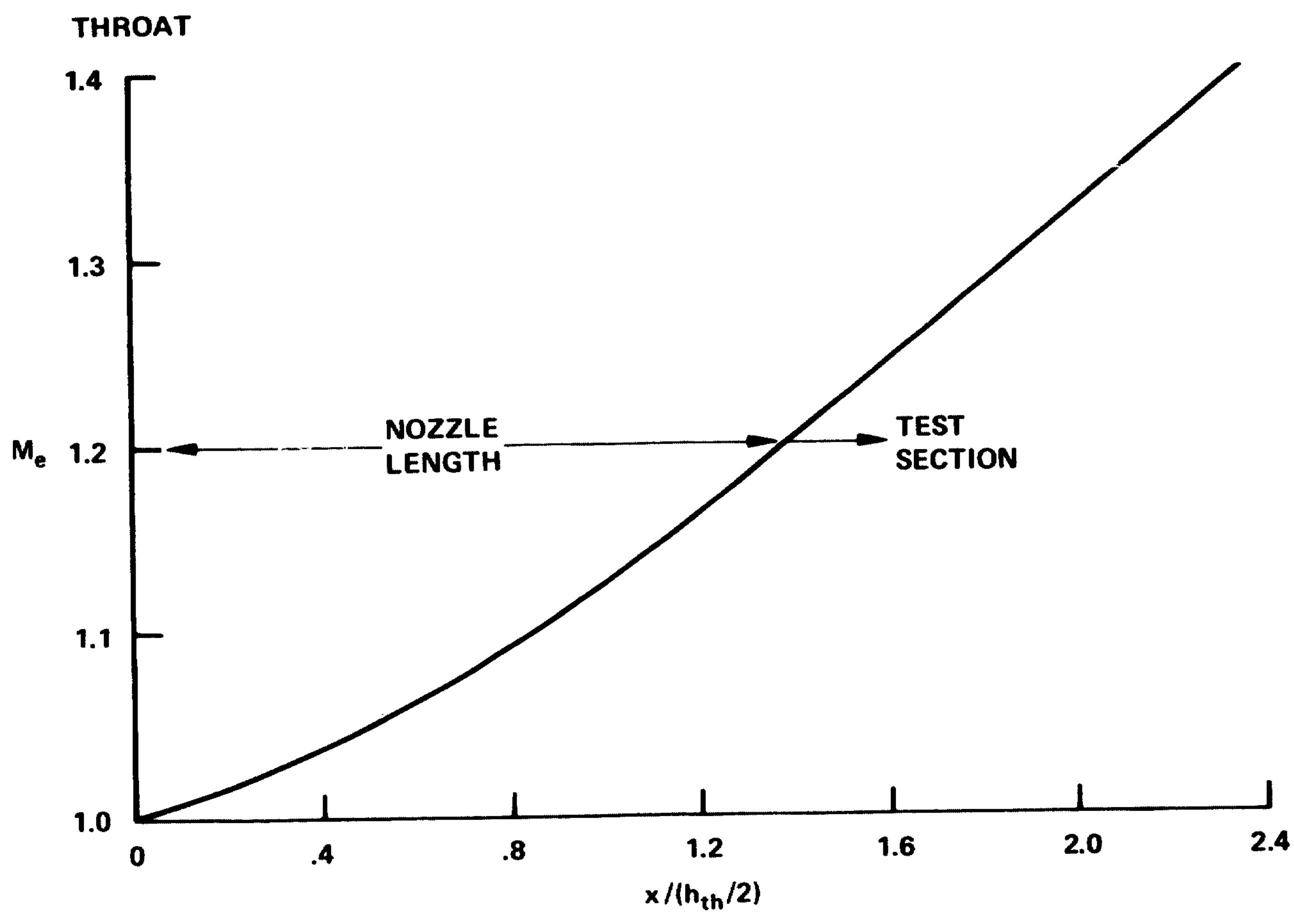

Figure 4.- Conventional 2-D nozzle length.

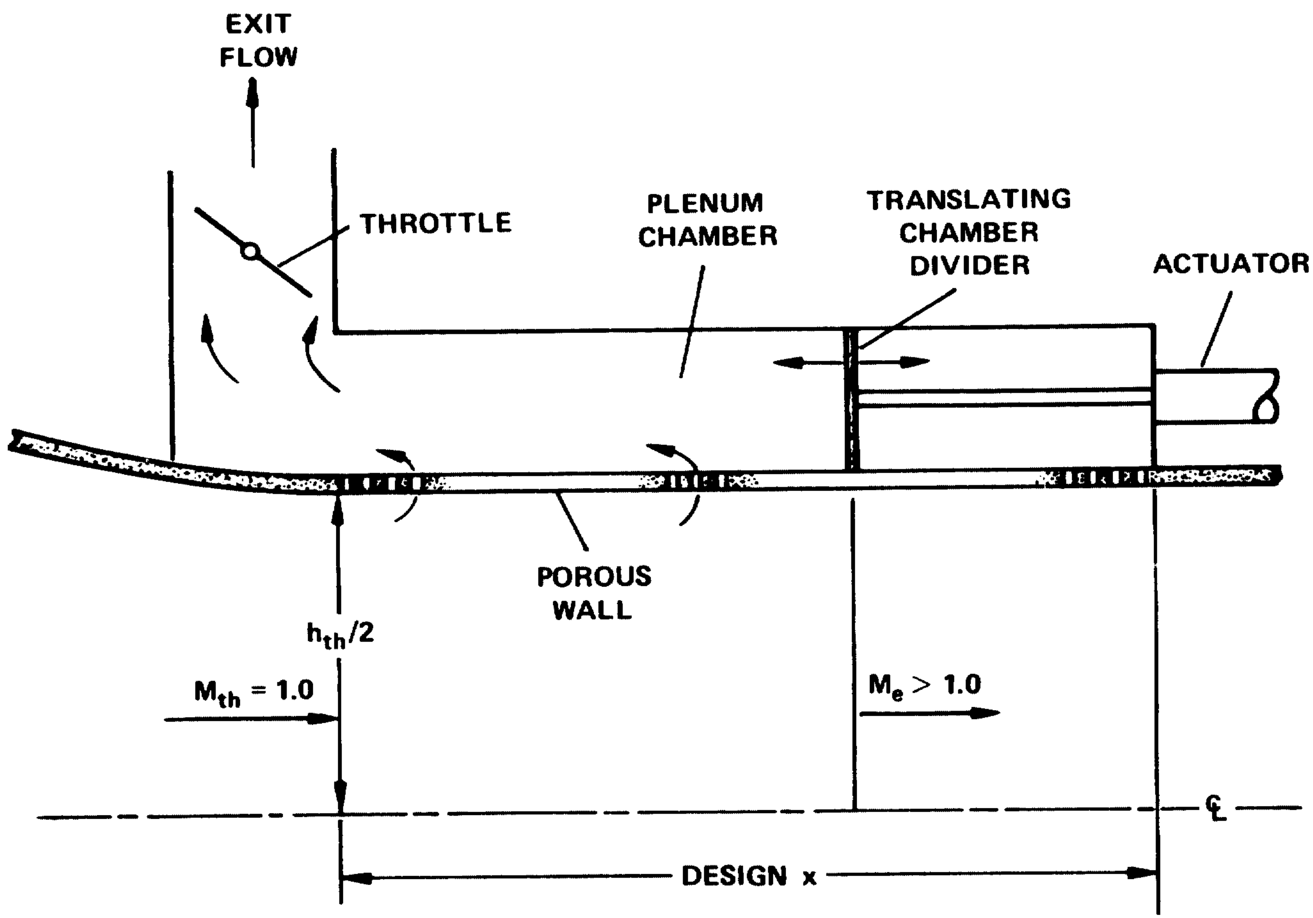

Figure 5.- Sliding chamber porous 2-D nozzle.

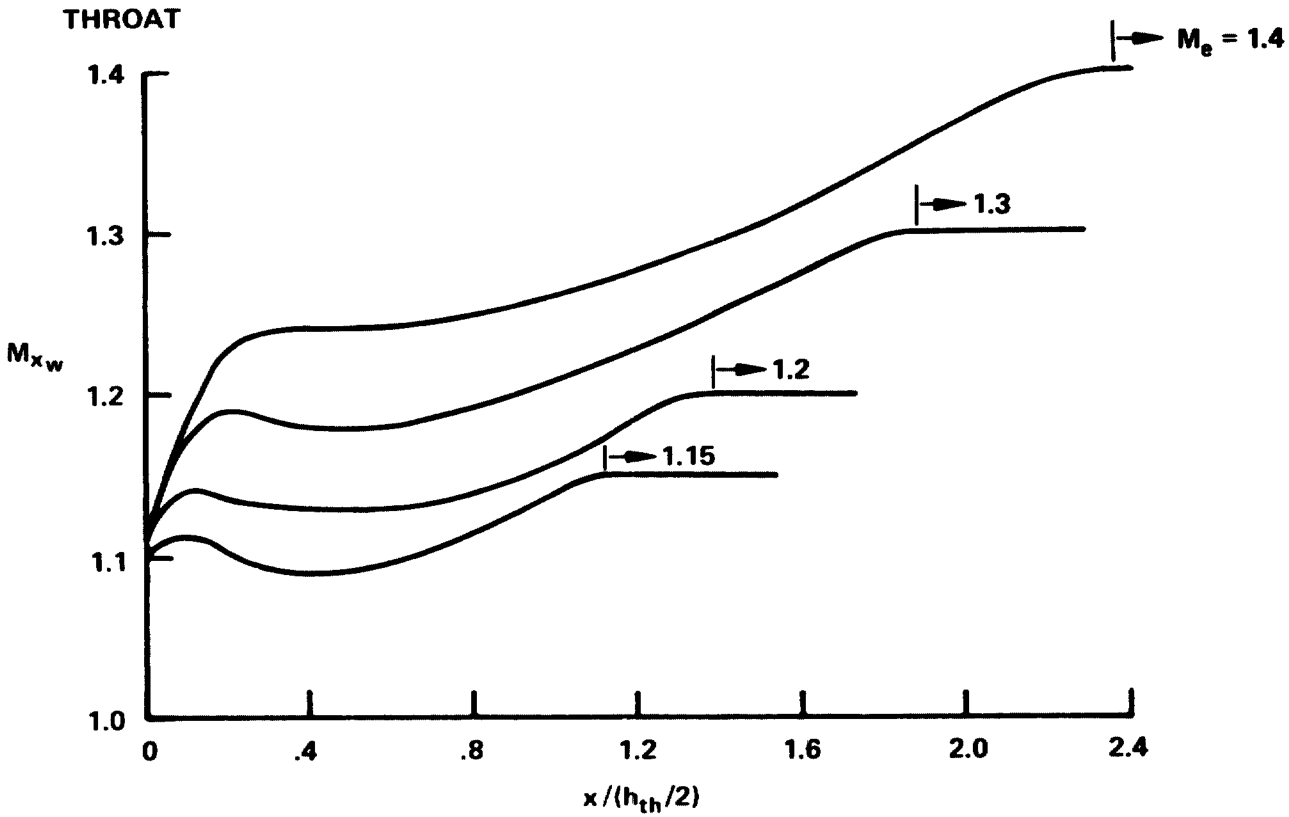

Figure 6.- Mach number distributions, 2-D conventional nozzles.

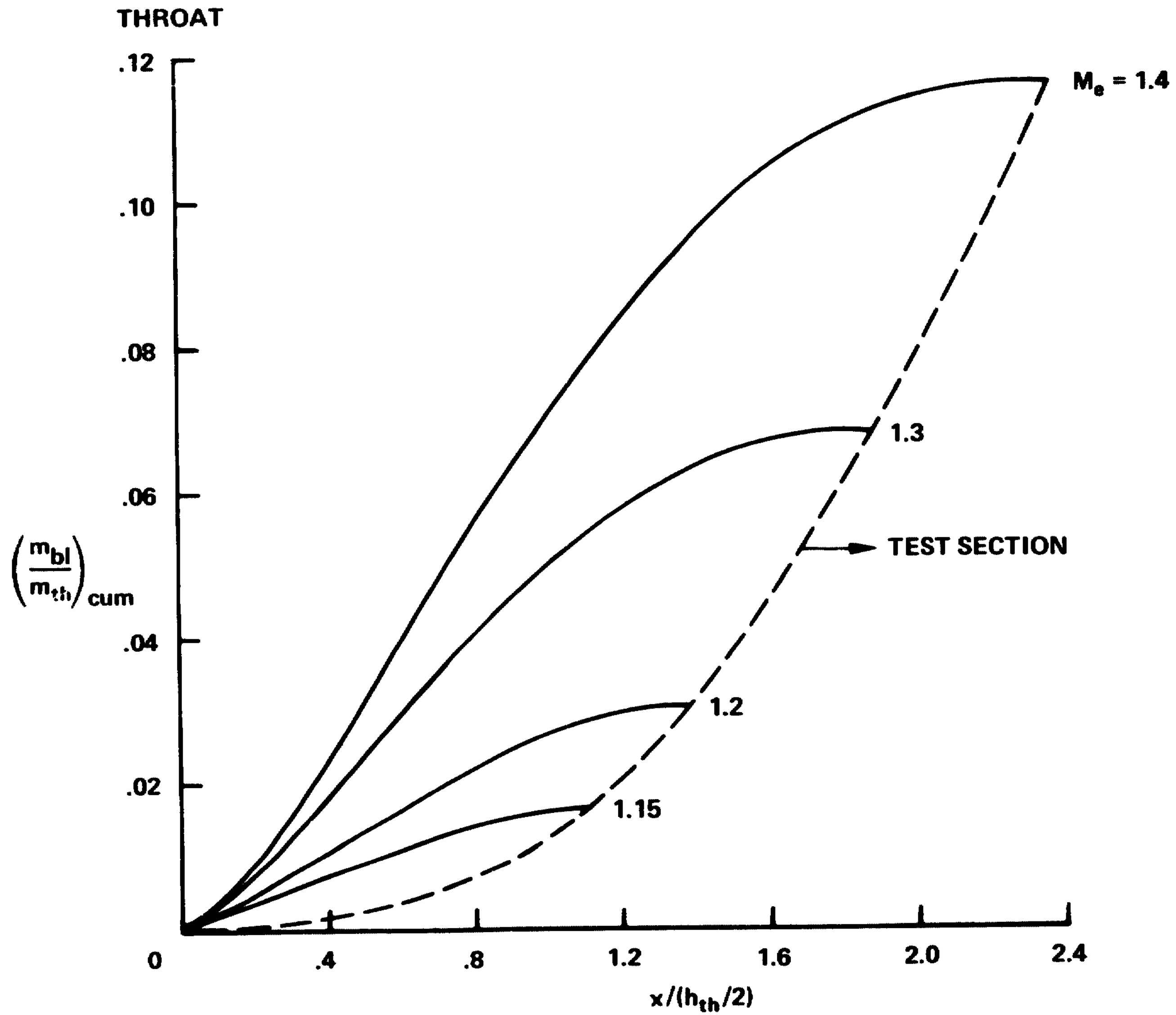

Figure 8.- Cumulative bleed.

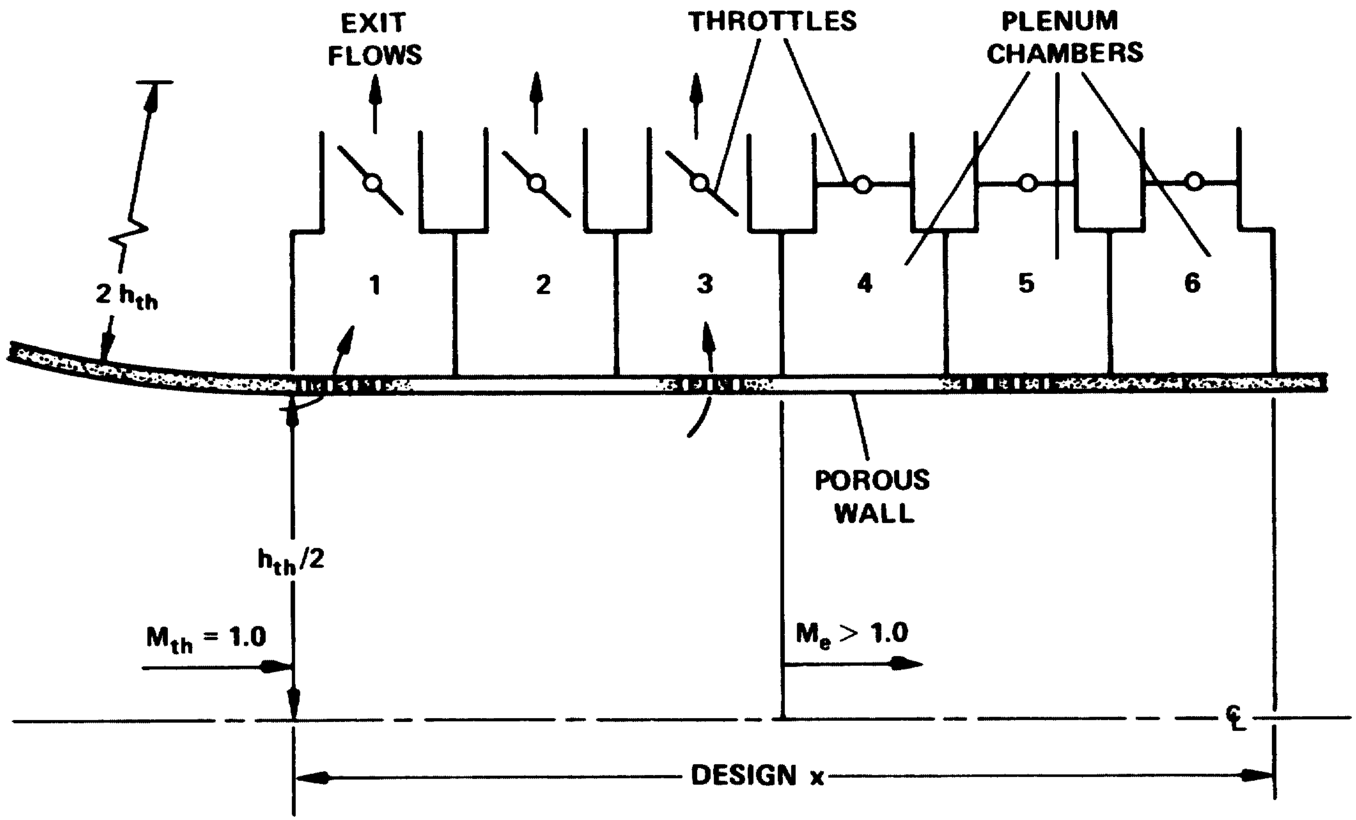

Figure 7.- Multi-chamber porous 2-D nozzle.

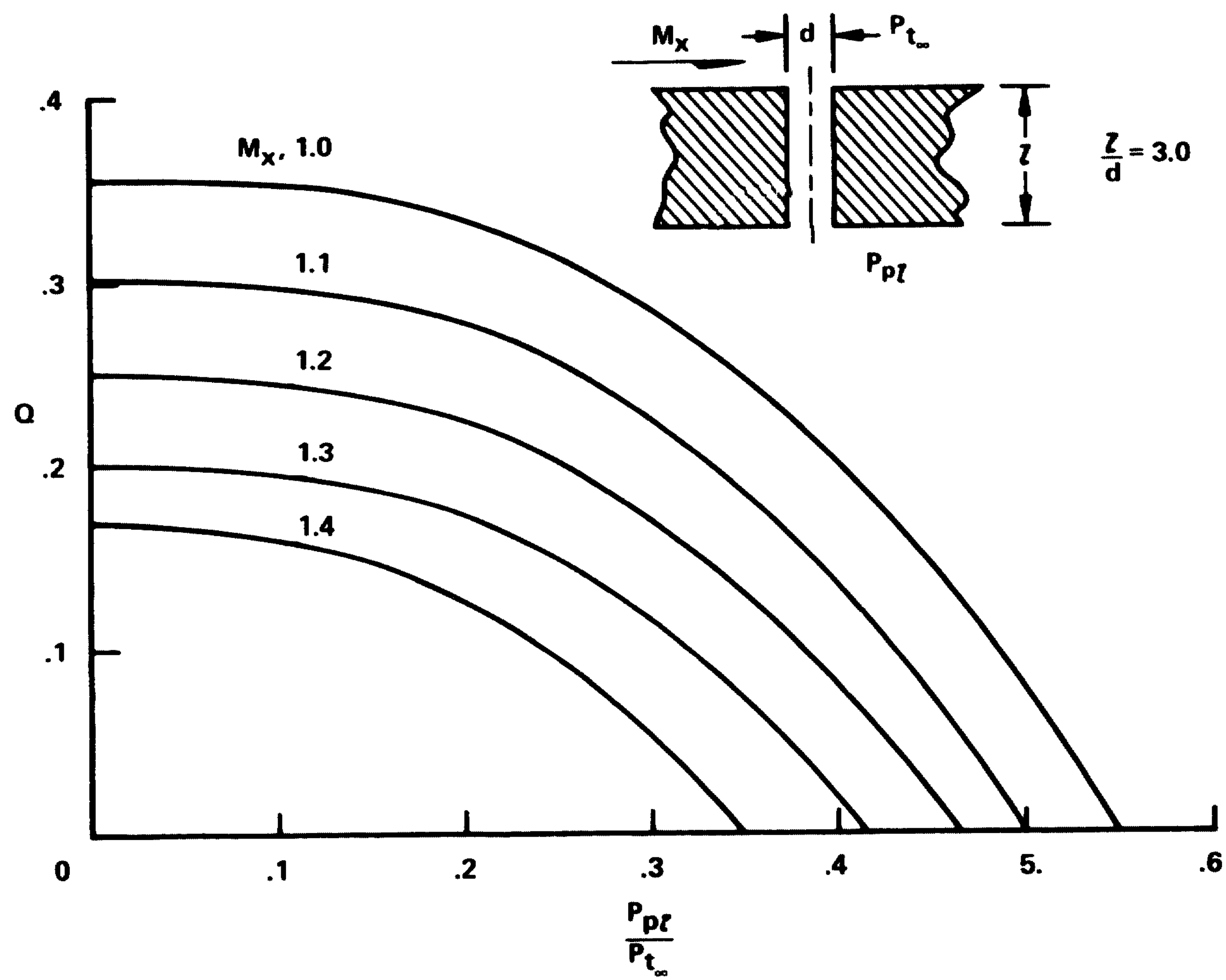

Figure 9.- Bleed hole characteristics.

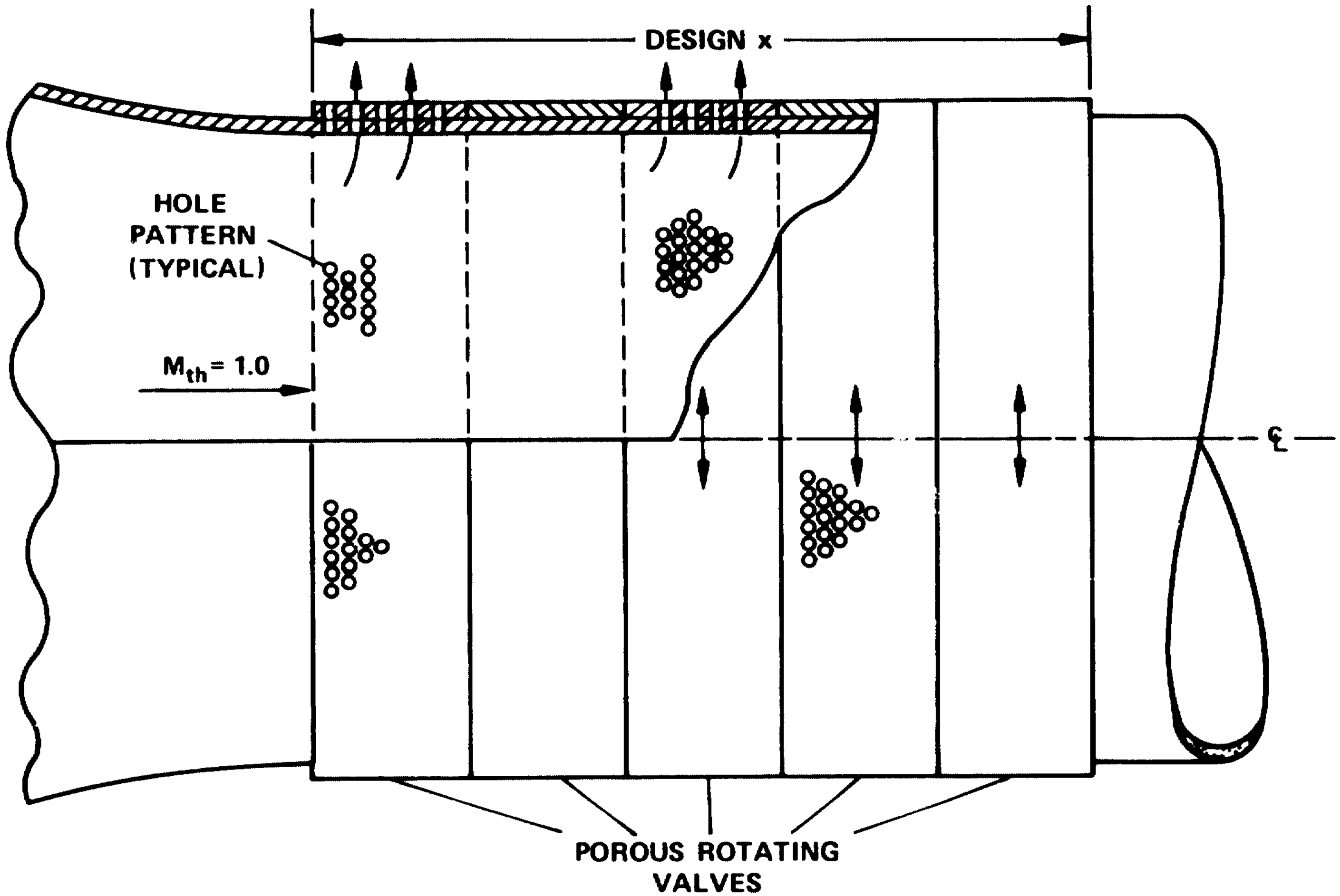

Figure 10.- Porous cylindrical nozzle.

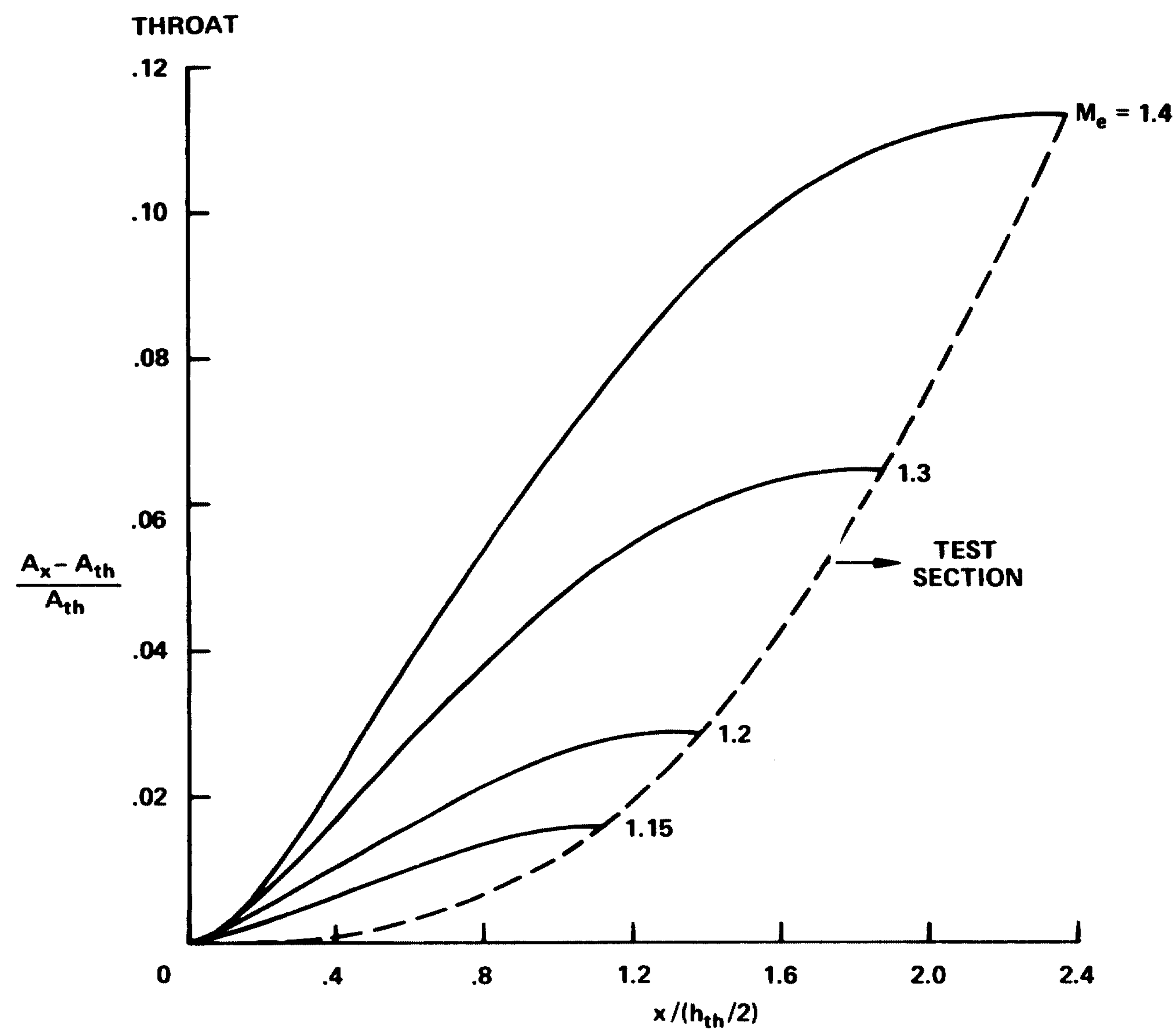

Figure 11.- Area distributions, 2-D conventional nozzles.