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DESIGN AND PERFORMANCE EVALUATION OF SLOTTED WALLS FOR TWO-DIMENSIONAL WIND TUNNELS

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SUMMARY

The purpose of this paper is to present a procedure for designing slotted walls for two-dimensional wind tunnels. The design objective can be the minimization of blockage or streamline curvature or the reduction of both. The slotted-wall boundary condition is derived both for flow from the tunnel into the plenum and vice versa, and the procedure for evaluating wall interference is described. A correlation of experimental data for the slotted-wall boundary condition is given. Results are given for several designs and evaluations of slotted wind-tunnel walls.

INTRODUCTION

The traditional procedure for estimating subsonic wind-tunnel interference effects caused by slotted walls is based on a boundary condition which relates the pressure and streamline curvature near the wall and perhaps the flow angle in the slot. The procedure consists of the determination of the constant of proportionality in the boundary condition for a given wall and the determination of the interference associated with this constant of proportionality. In general, one of two theoretical methods has been used previously to determine the constant of proportionality. The most widely used of these methods was first developed by Davis and Moore (ref. 1), and the second was developed by Chen and Mears (ref. 2). An error in the method of Chen and Mears has recently been corrected by Barnwell (ref. 3). The procedures for determining wall interference effects in two-dimensional tunnels due to thickness and lift effects were developed by Baldwin, Turner, and Knechtel (ref. 4) and Wright (ref. 5), respectively. It should be noted that a comprehensive study of these and other wall interference effects has been given by Pindzola and Lo (ref. 6).

It is generally known that the results of the traditional procedure for estimating wall interference effects do not agree with experimental observations. In this paper it is shown that better agreement with experiment can be obtained if values for the boundary-condition coefficient are obtained from a correlation of experimental values rather than from the previously used theories.

SYMBOLS

A	cross-sectional area of model
A_{RAKE}	average cross-sectional area of wake rake
a	slot spacing
C	speed of sound

$C_{D,o}$	zero-lift drag coefficient
C_L	lift coefficient
C_p	pressure coefficient
c	airfoil chord
h	semiheight of tunnel
K	slotted-wall performance coefficient
k	slotted-wall boundary-condition coefficient
M_∞	free-stream Mach number
p	static pressure
p_∞	free-stream static pressure
U_∞	free-stream speed
u,v	velocity components in free-stream direction and cross-flow plane
u_r	rapidly-varying part of u velocity component due to flow through slot
$\overline{u},\overline{v}$	u and v velocity components on plenum side of interface
x	distance in free-stream direction
x_{RAKE}	distance in x direction between rake and model
y	distance perpendicular to tunnel wall
β	$\sqrt{1 - M_\infty^2}$
γ	ratio of specific heats
Δ	slot-width parameter in Chen and Mears' theory
ΔM	change in Mach number due to blockage
ΔU	blockage due to wall

$\overline{\Delta U}$	blockage at model due to wall
$\overline{\Delta U}_{RAKE}$	blockage at model due to wake rake
$\delta U'$	blockage gradient due to wake
$\overline{\delta U'}$	blockage gradient at model due to wake
$\Delta\alpha$	downwash due to wall
$\overline{\Delta\alpha}$	downwash at model due to wall
$\overline{\Delta\alpha'}$	downwash gradient at model due to wall
δ	slot width
θ	flow angle relative to free-stream direction
τ	wall thickness parameter in Chen and Mears' theory
Φ	nondimensional perturbation velocity potential; see equation (A-4)
ϕ_r	rapidly-varying perturbation potential governing flow through slot

Subscripts:

CLOSED	for closed tunnel wall
INTERFACE	at interface
MAX	maximum value
OPEN	for open tunnel wall
PLENUM	in plenum
SLOT	at slot
w	ambient conditions near tunnel wall

ANALYSIS

In this section the slotted-wall boundary condition is discussed, the procedure for evaluating the wall interference for a given value of the boundary-condition coefficient is described, and a correlation of experimental data for this coefficient is given.

Slotted-Wall Boundary Condition

The usual slotted-wall boundary condition is obtained from the ideal slot condition, which states that the pressure of the fluid at the slot is equal to the plenum pressure. The ideal slot condition is applicable if the flow is from the tunnel into the plenum, but it is not applicable if the flow is from the plenum into the tunnel because the total pressure of the fluid in the slot is then equal to the plenum pressure. Consequently, the static pressure of the fluid in the slot must be something less than the plenum pressure. The proper boundary condition for flow from the plenum into the tunnel is obtained by equating the pressure and the normal component of velocity of the fluids from the free stream and the plenum at the interface.

A schematic of a two-dimensional tunnel is shown in figure 1. The coordinates in the free-stream and vertical directions are x and y, respectively; the free-stream velocity is U_∞, the flow deflection angle is θ, and the tunnel height is 2h. A cross section of the tunnel wall is shown in figure 1. The slot spacing is a, and the slot width is δ.

It is shown in the appendix that the usual slotted-wall boundary condition, which applies for flow from the tunnel into the plenum, can be written as

$$C_{p,SLOT} = C_{p,w} - \theta_{SLOT}^2 - 2\frac{Ka}{h}\frac{\partial\theta_w}{\partial x/h} = C_{p,PLENUM} \tag{1}$$

where $C_{p,SLOT}$ and $C_{p,PLENUM}$ are the pressure coefficients at the slot and in the plenum, θ_{SLOT} is the flow deflection angle at the slot, $C_{p,w}$ and θ_w are the pressure coefficient and flow deflection angle in the tunnel near the wall, and K is a dimensionless coefficient which depends only on the wall geometry. The x coordinate has been made nondimensional with the tunnel semiheight h, the only length scale in the $x - y$ plane which characterizes the tunnel itself. (There is no length scale in the x direction since the tunnel is assumed to be infinite in length.) The difference between the pressure coefficient at the slot $C_{p,SLOT}$ and the pressure coefficient in the tunnel near the wall $C_{p,w}$ is due to the rapid flow variation near the wall depicted in figure 1(b).

Equation (1) can sometimes be simplified. From conservation of mass in the cross-flow plane, it can be shown that the flow angle at the slot θ_{SLOT} is related to the flow angle in the tunnel near the wall θ_w by the equation

$$\theta_{SLOT} = \frac{a}{\delta}\theta_w \tag{2}$$

It is usually assumed that the effect of θ_{SLOT} in equation (1) can be ignored. It can be seen from equation (2) that this is equivalent to making the assumption

$$\left|\theta_w\right| << \frac{\delta}{a} \tag{3}$$

It is also customary to assume that the plenum pressure is the free-stream pressure so that

$$C_{p,PLENUM} = 0 \tag{4}$$

With these assumptions, equation (1) can be written as

$$C_{p,w} = 2 \frac{Ka}{h} \frac{\partial \theta_w}{\partial x/h} \tag{5}$$

Equation (5) is the usual form of the slotted-wall boundary condition. It is shown in the appendix that equation (5) is the proper form of the boundary condition for flow from the plenum into the tunnel even if the flow angle at the slot θ_{SLOT} is large. Consequently, equation (5) is the form which will be used in this paper.

Estimation of Interference Effects

The influence of the tunnel-wall characteristics on the flow in the tunnel is determined by the coefficient

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$$k = \frac{a}{h} K \tag{6}$$

in equations (1) and (5) and perhaps by θ_{SLOT}, the flow deflection angle at the slot. If θ_{SLOT} has no effect, the influence of the wall on the flow in the tunnel is determined completely by the coefficient k, and the effects of the wall characteristics such as the wall openness ratio δ/a are important only in the way they affect the coefficient K.

Model blockage and downwash.- The wall interference effect due to model thickness is called blockage. This effect is a change in the magnitude of the flow velocity in the tunnel. If the tunnel is closed the blockage at the model is

$$\overline{\Delta U}_{CLOSED} = \frac{\pi}{24} \frac{A}{\beta^3 h^2} U_\infty \tag{7}$$

where the bar indicates that the quantity is evaluated at the model, A is the cross-sectional area of the model and β is related to the free-stream Mach number by the equation

$$\beta = \sqrt{1 - M_\infty^{\ 2}} \tag{8}$$

The wall interference effect due to lift, called downwash, is a change in the effective angle of attack. If the tunnel is open, the downwash at the model is

$$\overline{\Delta\alpha}_{OPEN} = -\frac{1}{8} \frac{C_L c}{h} \tag{9}$$

and the gradient of the downwash or streamline curvature at the model is

$$\overline{\Delta\alpha'}_{OPEN} = - \frac{\pi}{48} \frac{C_L c}{\beta h^2} \tag{10}$$

where C_L and c are the lift coefficient and the model chord, respectively.

A comprehensive summary of wall interference effects in two-dimensional and three-dimensional open, closed, slotted and porous tunnels is given by Pindzola and Lo (ref. 6). The results of that reference for the distributions of blockage ΔU and downwash $\Delta\alpha$ along the axis of a two-dimensional slotted tunnel are shown in figure 2. The tunnel is assumed to be infinite in length. It can be seen that the blockage is symmetric about the model location and that the blockage at the model vanishes for the value $k = 1.18$. The symmetry of blockage about the model is important because it means that the blockage at points near the model will be small if the blockage at the model is small. It should be noted that blockage is not symmetric about the model in perforated tunnels. It should also be noted that the distributions shown in figure 2 may differ somewhat if the slotted walls are finite in length and that blockage will not be symmetric if the model is not placed in the center of the finite slotted walls.

As previously mentioned, the blockage ΔU is a change in the fluid speed due to wall interference. This change in fluid speed can be related to the change in Mach number ΔM by the equation

$$\Delta M = M_\infty \left\{ 1 + \frac{\gamma - 1}{2} M_\infty{}^2 \right\} \frac{\Delta U}{U_\infty} \tag{11}$$

where M_∞ is the free-stream Mach number and γ is the ratio of specific heats.

The downwash distributions shown in figure 2 are not symmetric about the model. However, it should be noted that the downwash distribution is nearly constant in the vicinity of the model for values of k near the value for zero blockage. Consequently, a slotted tunnel designed for low blockage will also have low streamline curvature. It should be noted that, although near-zero values of blockage and streamline curvature can be achieved with a properly-designed slotted-wall tunnel, it is not possible to achieve zero downwash at the model except in a closed tunnel. From the point of view of downwash reduction, it is beneficial to have as large a value of the coefficient k as possible since the downwash decreases monotonically with k.

The variations of blockage, downwash, and streamline curvature at the model with the coefficient k are depicted in figure 3. It is seen that blockage and streamline curvature at the model vanish for $k = 1.18$ and $k = 1.58$, respectively.

It should be noted that the results shown in figure 3 are independent of Mach number. Consequently, these results will tend to be valid when there are regions of supercritical flow at the model although the results are calculated from subsonic theory.

There is a lower limit to the openness ratio δ/a below which the results shown in figures 2 and 3 are suspect, particularly for high-lift flows. The validity of the results of these figures depends on the validity of equation (5), which, in turn, may depend on the validity of inequality (3). The magnitude of the flow deflection at the wall can be characterized by the values of the maximum flow deflection angle at the wall due to lift

$$\theta_{w,max} = \frac{C_L c}{8\pi h} \tag{12}$$

and the wall-induced downwash at the wall immediately over the model

$$\overline{\Delta\alpha_w} = -\frac{C_L c}{8(1+k)h} \tag{13}$$

If the ratio of the model chord c and the tunnel semiheight h is of the order of 1/3 or 1/4 and if C_L and k have values of order one, the magnitudes of $\theta_{w,MAX}$ and $\overline{\Delta\alpha_w}$ are of the order of several percent. It can be seen from equation (2) that, unless the openness ratio δ/a is considerably larger than these values, the velocity through the slot $U_\infty \theta_{SLOT}$ becomes of the same order of magnitude as U_∞. Consequently, the usefulness of the slotted wall becomes questionable. For example, if the free-stream is transonic, the flow at the slot might well become sonic. In addition, equation (5) may no longer be a valid approximation to equation (1). Consequently, results shown in figures 2 and 3 are not valid under these circumstances.

Wake blockage.- Pindzola and Lo (ref. 6) show that the wake blockage at the model is zero. However, they also show that the gradient of the wake blockage at the model does not vanish in general. The gradient of the wake blockage at the model for a closed wall is

$$\overline{\delta U'}_{CLOSED} = \frac{\pi}{48} \frac{C_{D,o} c}{\beta^3 h^2} U_\infty \tag{14}$$

where $C_{D,o}$ is the zero-lift drag coefficient. Pindzola and Lo show that the ratio of the gradient of the wake blockage $\delta U'$ to $\delta U'_{CLOSED}$ is the same as the ratio for model blockage $\Delta U/\overline{\Delta U}_{CLOSED}$ given in figure 2a. As a result, the wake blockage gradient $\delta U'$ vanishes at the same value of k at which the model blockage ΔU vanishes.

Wake-rake blockage.- The blockage at the model due to a wake rake located a distance x_{RAKE} downstream of the model along the tunnel centerline is

$$\Delta U_{RAKE} = -\frac{1}{2\pi}\frac{A_{RAKE}}{\beta x_{RAKE}^{2}}U_{\infty} \tag{15}$$

where A_{RAKE} is the cross-sectional area of the rake. It should be noted that the wake rake blockage is negative. In other words, the effect of the presence of a wake rake behind an airfoil is to slow down the flow. This effect is present whether the airfoil is in a tunnel or an infinitely wide air stream.

It is possible for the wake-rake blockage and the blockage due to wall interference to cancel if the wall interference blockage is positive. From figure 2 it can be seen that the wall interference blockage is positive if the wall is closed and negative if it is open. Consequently, if the wake-rake blockage and the wall interference blockage are to cancel, the wall must be more closed than for zero wall-interference blockage.

Coefficient for Slotted-Wall Boundary Condition

The performance of the slotted wall is governed by the parameter K, which depends on the wall geometry. There are two basic analytical derivations of this parameter. In one derivation, first published by Davis and Moore (ref. 1), it is assumed that the wall has no thickness and that the slots act as sources (or sinks). The expression obtained by Davis and Moore is

$$K = -\frac{1}{\pi}\,\ell n\left[\sin\left(\frac{\pi}{2}\frac{\delta}{a}\right)\right] \tag{16}$$

In the second basic derivation, which was obtained by Chen and Mears (ref. 2) and corrected by Barnwell (ref. 3), it is assumed that the wall slats can be represented by doublet rods. The expression obtained from the Chen and Mears theory is

$$K = \frac{1}{2}\left(1 - \frac{\Delta}{a}\right)\frac{\cos\left(\frac{\pi\Delta}{a}\right) + \cosh\left(\frac{\pi\tau}{a}\right)}{\sin\left(\frac{\Delta\pi}{a}\right)} \tag{17}$$

It is shown in reference 3 that the parameter Δ/a is related to the wall openness ratio δ/a and the slat centerline thickness parameter τ/a by the equation

$$\sin\left[\frac{\pi}{2}\left(\frac{\Delta}{a}+\frac{\delta}{a}\right)\right] = \sin\left[\frac{\pi}{2}\left(\frac{\Delta}{a}-\frac{\delta}{a}\right)\right]\exp\left\{\frac{\pi\sin\left(\frac{\pi\Delta}{a}\right)(1-\delta/a)}{\cos\left(\frac{\pi\Delta}{a}\right)+\cosh\left(\frac{\pi\tau}{a}\right)}\right\} \tag{18}$$

For small values of δ/a, equation (17) can be approximated as

$$K = \sqrt{\frac{1 + \cosh\left(\frac{\pi\tau}{a}\right)}{8\delta/a}} - \frac{1 + \cosh\left(\frac{\pi\tau}{a}\right)}{2\pi} \tag{19}$$

A comparison of equations (16) and (19) shows that the functional dependence of the two solutions on the openness ratio δ/a is quite different. Values for the parameter K obtained from equations (16) and (17) are compared in figure 4. It can be seen that the two theories are not in agreement.

Only three experimental measurements of the parameter K have been made. Chen and Mears (ref. 2) and Baronti, Ferri, and Weeks (ref. 7) measured the pressure and flow angularity near the wall and determined the parameter K from equation (5). Berndt and Sörensen (ref. 8) measured the pressure at the center of a wall slat, the plenum pressure, and the normal velocity in the slot and determined K from equation (1). In each case, measurements were made for only one wall openness ratio.

A fourth experimental value of the wall openness ratio can be inferred from the work of Osborne (ref. 9) in which surface pressure measurements were made on two models of the same airfoil with chords which differed by a factor of 2. The wall openness ratio and slot spacing were varied by taping various combinations of slots closed. An optimum slot spacing and wall openness ratio were found for which blockage effects did not occur. A value of K is obtained with equation (6) and the assumption that k has the zero-blockage value of 1.18.

The three measured values of K and the inferred value are shown in figure 4. These experimental values are substantially larger than the theoretical values. It can be seen that empirical curves which are twice the corrected Chen and Mears theory and four times the Davis and Moore theory interpret the data fairly well.

The same type of model arrangement was used to obtain the data presented in references 2, 7, 8, and 9. A symmetric airfoil model at zero angle of attack was used in each case. As a result, the disturbances in all of these experiments were due only to two-dimensional thickness effects.

Experimental values for the coefficient K obtained with disturbances due principally to three-dimensional lift effects can be inferred from the results of Binion (ref. 10). Some of these data are also presented in reference 11, and the experiment is described there. The lift on a wing-tail model was measured in a slotted tunnel with solid side walls for different numbers of slots and different values of the openness ratio. These lift data were compared with results obtained in a large tunnel to determine the lift interference factors. The apparent values of K were obtained from figure 5(c) of reference 11 (the three-dimensional equivalent of figure 3(b)) and equation (6). These values are shown in figure 4.

It can be seen that there is some scatter in the lift data. This scatter is probably due to the fact that small errors in the measured lift can cause disproportionately large errors in the apparent value of k and, hence, K when the tunnel openness ratio is small. As a result, the data obtained with thickness-effect disturbances are probably more reliable than those obtained with lift-effect disturbances.

On the basis of the above considerations, it is concluded that a reasonable correlation of the data presented in figure 4 is given by the band between the curves in that figure labeled "4 X Davis and Moore" and "2 X Corrected Chen and Mears." This is the correlation for the dependence of the slotted-wall boundary-condition coefficient K on the openness ratio δ/a which is used in this paper.

RESULTS

Analysis of Two Slotted Tunnels

Langley 8-foot transonic tunnel.- This is a continuous-flow pressure tunnel. The tunnel semiheight and slot spacing are 4 feet and 21 inches, respectively, and the average openness ratio in the vicinity of the model is 0.063. From figure 4, it is concluded that the parameter K has a value of about 3. Consequently, the approximate value of the wall boundary-condition coefficient is found to be $k \approx 1.3$.

Original Langley 6- by 28-inch transonic tunnel.- This tunnel is a blowdown pressure tunnel. The tunnel semiheight and slot spacing are 14 inches and 1.5 inches, respectively, and the wall openness ratio is 0.125. From figure 4, it is seen that K has a value of about 2. The approximate value of the wall boundary-condition coefficient is $k \approx 0.20$. It can be seen from figure 3 that this tunnel is very close to an open jet. This tunnel is probably even closer to an open jet than the figure indicates because the slotted wall transitions to an open jet just downstream of the model.

Design of Minimum-Blockage Tunnels

Langley 6- by 28-inch transonic tunnel.- The tunnel semiheight is 14 inches. If the tunnel is to be blockage free, the coefficient k must have a value of 1.18. Values of the parameter K for a given slot spacing a are determined from equation (6), and approximate values for the openness ratio δ/a are determined from figure 4. These quantities are shown in table I for slot spacings of 1.5, 3, and 6 inches.

a(in)	K	δ/a
1.5	11.0	very small
3.0	5.5	0.02
6.0	2.8	0.06

Table I.- Parameters for zero-blockage version of Langley 6- by 28-inch tunnel.

Because of the scarcity of data for the parameter K these values must be considered to be approximate. However, for engineering purposes they are considered to be reasonable.

It can be seen from table I that only the slot spacings of 3 inches and 6 inches can be considered to be reasonable. It can be shown that the flow velocity through the slots becomes excessively large for high-lift flows and the 3-inch spacing. If the tunnel semiheight h and model chord c are 14 inches and 6 inches, respectively; and if the values of C_L and k are of order one, the magnitudes of $\theta_{w,MAX}$ and $\overline{\Delta\alpha}_w$ obtained from equations (12) and (13) are of the order of 0.02, the openness ratio for the 3-inch spacing. From equation (2), it is seen that θ_{SLOT} is of order one so that the flow velocity through the slots,

$U_\infty \theta_{SLOT}$, becomes large. Consequently, the slot flow may become sonic if the flow in the tunnel is transonic. In addition, equation (5) is no longer a valid approximation to equation (1) so that the design charts in figure 3, which were obtained with equation (5), are no longer valid. Another reason for selecting the 6-inch spacing is that the openness ratio for this spacing lies within the experimental data band whereas the ratio for the 3-inch spacing lies outside the band. It is concluded that the slotted wall with the 6-inch slot spacing is the only one which can yield relatively blockage-free flows for a wide range of lift coefficient.

It is probably preferable for the value of k to be a little larger than the theoretical zero-blockage value of 1.18. It can be seen from figure 2 that this choice will enlarge the region of low-blockage flow around the model. It will also provide some positive blockage to cancel the negative wake-rake blockage and will reduce the streamline curvature. Consequently, the openness ratio δ/a was chosen to be 0.05 rather than 0.06.

Langley 0.3 meter transonic cryogenic tunnel.- The tunnel semiheight is 12 inches, and the tunnel width is 8 inches. The coefficient k is assumed to have the blockage-free value of 1.18. Values for the parameter K are determined from equation (6), and approximate values for the openness ratio δ/a are determined from figure 4. These quantities are shown in table II for slot-spacings of 4 and 8 inches.

a(in)	K	δ/a
4	3.5	0.04
8	1.8	0.15

Table II.- Parameters for zero-blockage version of Langley 8- by 24-inch tunnel.

As stated before, these values must be considered approximate because of the scarcity of data for the parameter K.

If the model chord is 6 inches, and the values of C_L and k are of order one, the magnitudes of $\theta_{w,MAX}$ and $\overline{\Delta\alpha}_w$ obtained from equations (12) and (13) are of the order of 0.02 or 0.03. It can be seen from these values and equation (2) that the value of the flow angle in the slot θ_{SLOT} is approaching one for a slot openness ratio of 0.04. Certainly the openness ratio should be no smaller than 0.04 for this tunnel. In order to keep the cross flow at the slot relatively small and still maintain small blockage and streamline curvature effects, the slot openness ratio was chosen to be 0.05.

CONCLUDING REMARKS

A procedure for designing slotted walls for two-dimensional transonic wind tunnels has been presented. The design objective can be the minimization of blockage or streamline curvature or the reduction of both. It is shown that the slotted-wall boundary condition differs somewhat depending upon whether the flow is from the tunnel into the plenum or vice versa. The procedure for evaluating tunnel interference for a given value of the slotted-wall boundary-condition coefficient is reviewed, and a correlation of experimental data for this coefficient is given. It is shown that in order to cancel drag-rake blockage a tunnel must be made more closed. Results are given for several designs and evaluations of slotted wind-tunnel walls.

APPENDIX

DERIVATION OF SLOTTED-WALL BOUNDARY CONDITION

The ideal slot condition, from which the usual form of the slotted-wall boundary condition is derived, states that the pressure in the slot is equal to the plenum pressure. This condition is written as

$$p_\infty \left\{ 1 - \frac{\gamma - 1}{2} M_\infty^2 \left(\frac{2u}{U_\infty} + \frac{u^2 + v^2}{U_\infty^2} \right)_{SLOT} \right\}^{\frac{\gamma}{\gamma - 1}} = p_{PLENUM} \qquad \text{(A-1)}$$

where p_∞ and p_{PLENUM} are the free-stream and plenum pressures, and u and v are the perturbation velocity components in the free-stream direction and the cross-flow plane, respectively. If the perturbations are small, equation (A-1) can be written as

$$\frac{2u_{SLOT}}{U_\infty} + \frac{v_{SLOT}^2}{U_\infty^2} = - C_{p,PLENUM} \qquad \text{(A-2)}$$

Near the wall, the u component of velocity can be written as

$$u = u_w + u_r \qquad \text{(A-3)}$$

where u_w is the ambient value in the tunnel near the wall, and u_r is the rapidly-varying value associated with the slot. This rapidly-varying component can be obtained from the perturbation potential

$$\phi_r = v_w(x)\ a\Phi(x,y,z) \qquad \text{(A-4)}$$

where v_w is the apparent free-stream velocity normal to the wall, a is the characteristic length scale of the rapidly-varying flow, and $\Phi(x,y,z)$ is a perturbation potential which is at best a weak function of x. It follows that equation (A-2) can be written as

$$\frac{2u_w}{U_\infty} + \frac{2aK}{U_\infty}\frac{\partial v_w}{\partial x} + \frac{v_{SLOT}^2}{U_\infty^2} = -\ C_{p,PLENUM} \qquad \text{(A-5)}$$

where K is the value of Φ at the slot. With the definitions

$$C_{p,w} = -\ \frac{2u_w}{U_\infty} \qquad \text{(A-6)}$$

$$\theta_w = \frac{v_w}{U_\infty} \qquad \text{(A-7)}$$

$$\theta_{SLOT} = \frac{v_{SLOT}}{U_\infty} = \frac{a}{\delta}\ \theta_w \qquad \text{(A-8)}$$

equation (A-5) can be written as

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$$C_{p,w} - \theta^2_{SLOT} - \frac{2Ka}{h}\frac{\partial \theta_w}{\partial x/h} = C_{p,PLENUM} \tag{A-9}$$

Equation (A-9), which is the usual form of the slotted-wall boundary condition, pertains for flow from the tunnel into the plenum.

The slotted-wall boundary condition for flow from the plenum into the tunnel is obtained from the conditions that the pressure and normal velocity of the fluids from the free-stream and the plenum are equal at the interface. The second condition can be replaced by the more general condition that the cross-flow velocity component is continuous everywhere. These conditions are expressed as

$$p_\infty \left\{1 - \frac{\gamma - 1}{2} M_\infty{}^2 \left(\frac{2u}{U_\infty} + \frac{u^2 + v^2}{U_\infty{}^2}\right)_{INTERFACE}\right\}^{\frac{\gamma}{\gamma - 1}}$$

$$= p_{PLENUM} \left\{1 - \frac{\gamma - 1}{2} \frac{(\bar{u}^2 + \bar{v}^2)_{INTERFACE}}{C^2_{PLENUM}}\right\}^{\frac{\gamma}{\gamma - 1}} \tag{A-10}$$

$$v_{INTERFACE} = \bar{v}_{INTERFACE} \tag{A-11}$$

where $\bar{u}$ and $\bar{v}$ are the velocity components of the fluid from the plenum in the free-stream direction and cross-flow plane, respectively, and C_{PLENUM} is the speed of sound in the plenum. It should be noted that the components v and $\bar{v}$ may become much larger than the components u and $\bar{u}$ near the slot. For small perturbations, equation (A-10) can be approximated as

$$\frac{2u_{INTERFACE}}{U_\infty} = - C_{p,PLENUM} \tag{A-12}$$

This equation is similar to equation (A-2), but it does not have the cross-flow term. With equations (A-3), (A-4), (A-6), and (A-7), equation (A-12) can be written as

$$C_{p,w} - \frac{2Ka}{n} \frac{\partial \theta_w}{\partial x/h} = C_{p,PLENUM} \tag{A-13}$$

where K is the value of the potential Φ at the interface.

The derivation of equation (A-12) is similar to a derivation of Berndt (ref. 12) for flow from the plenum into the tunnel. However, the boundary condition presented in reference 12 erroneously includes the cross-flow term.

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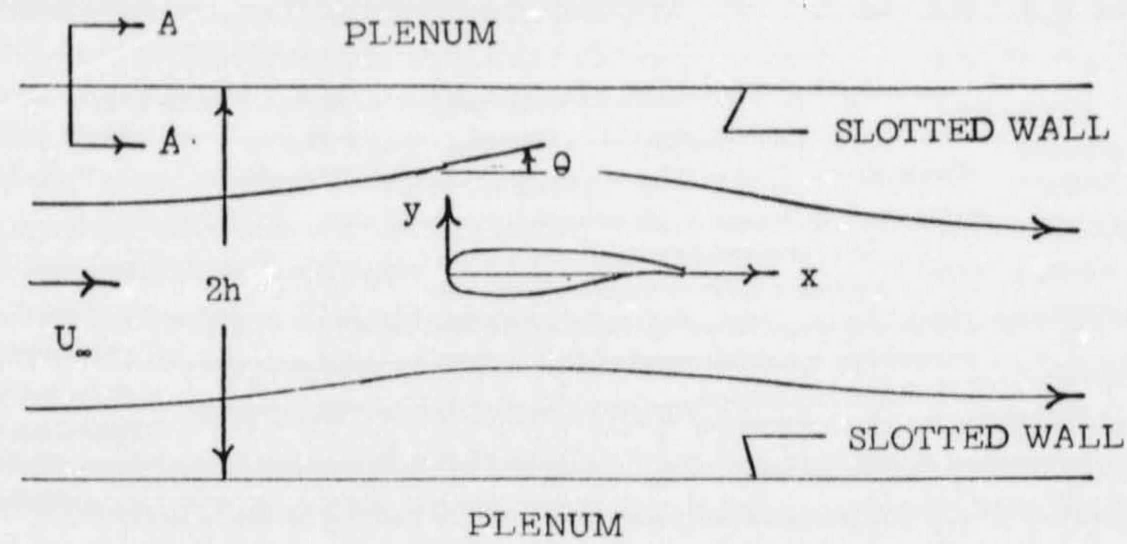
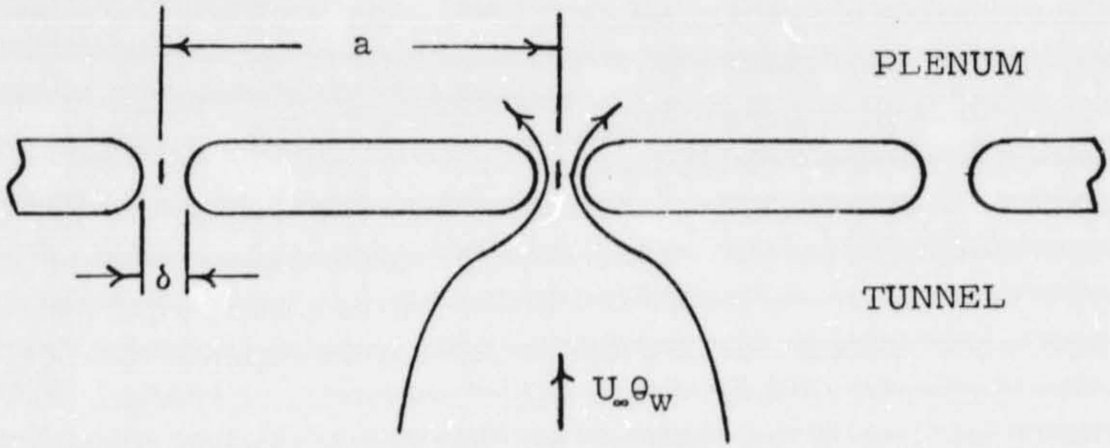
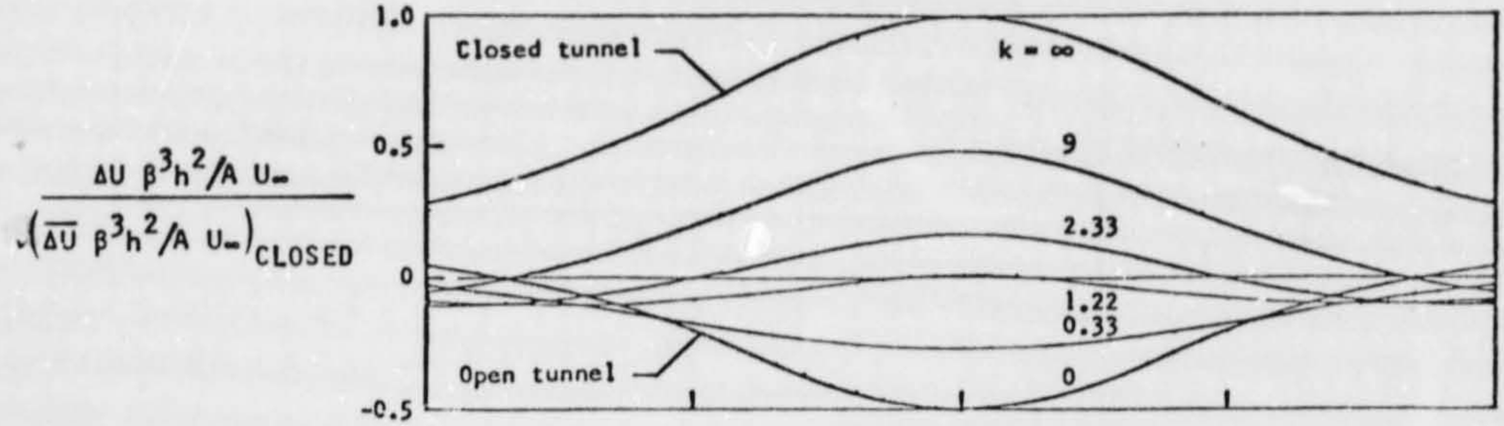


(a) Cross-section of two-dimensional tunnel.

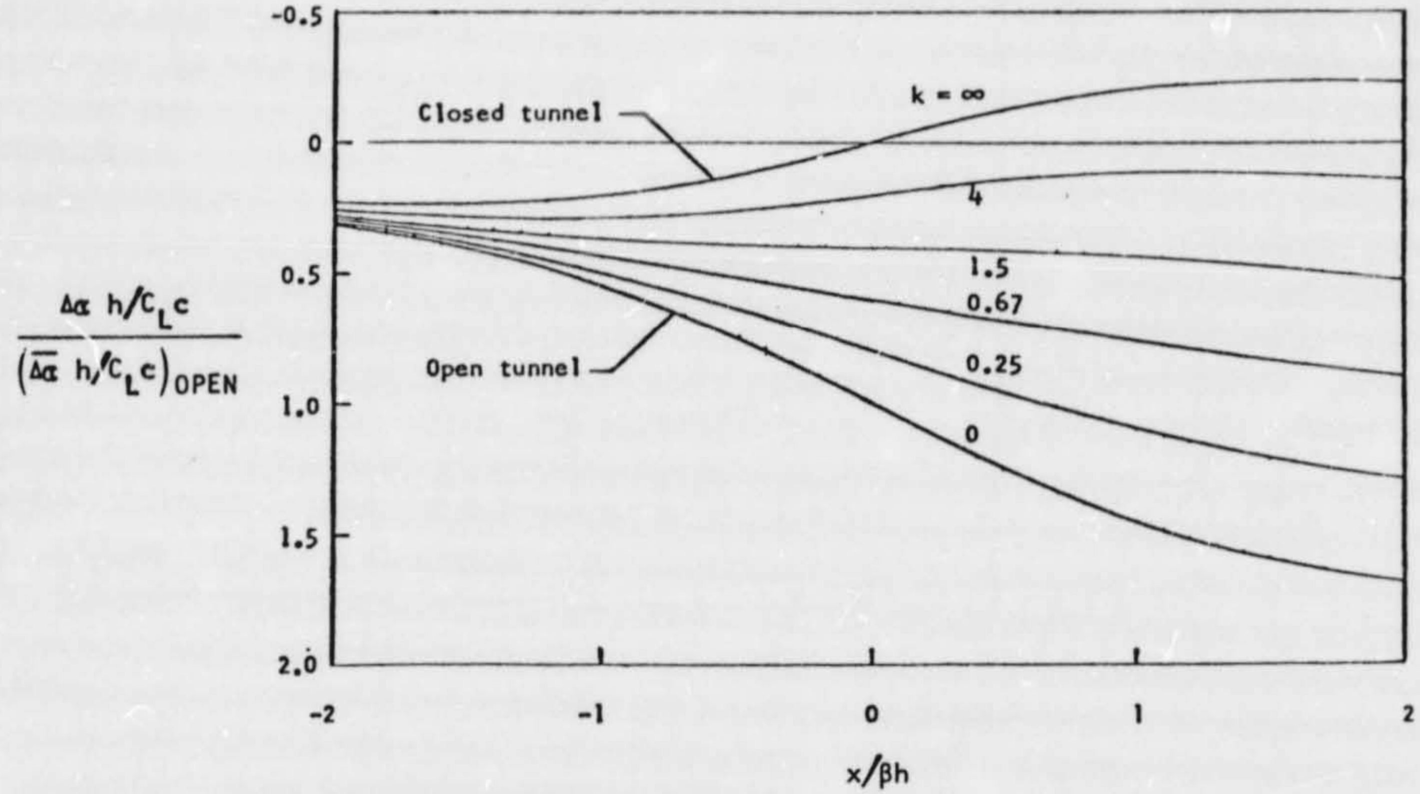


(b) Section A-A: cross-section of tunnel wall.

Figure 1. - Schematic of two-dimensional tunnel.



(a) Distribution of blockage along tunnel axis.



(b) Distribution of downwash along tunnel axis.

Figure 2. - Distribution of wall-induced blockage and downwash along the axis of a slotted tunnel.

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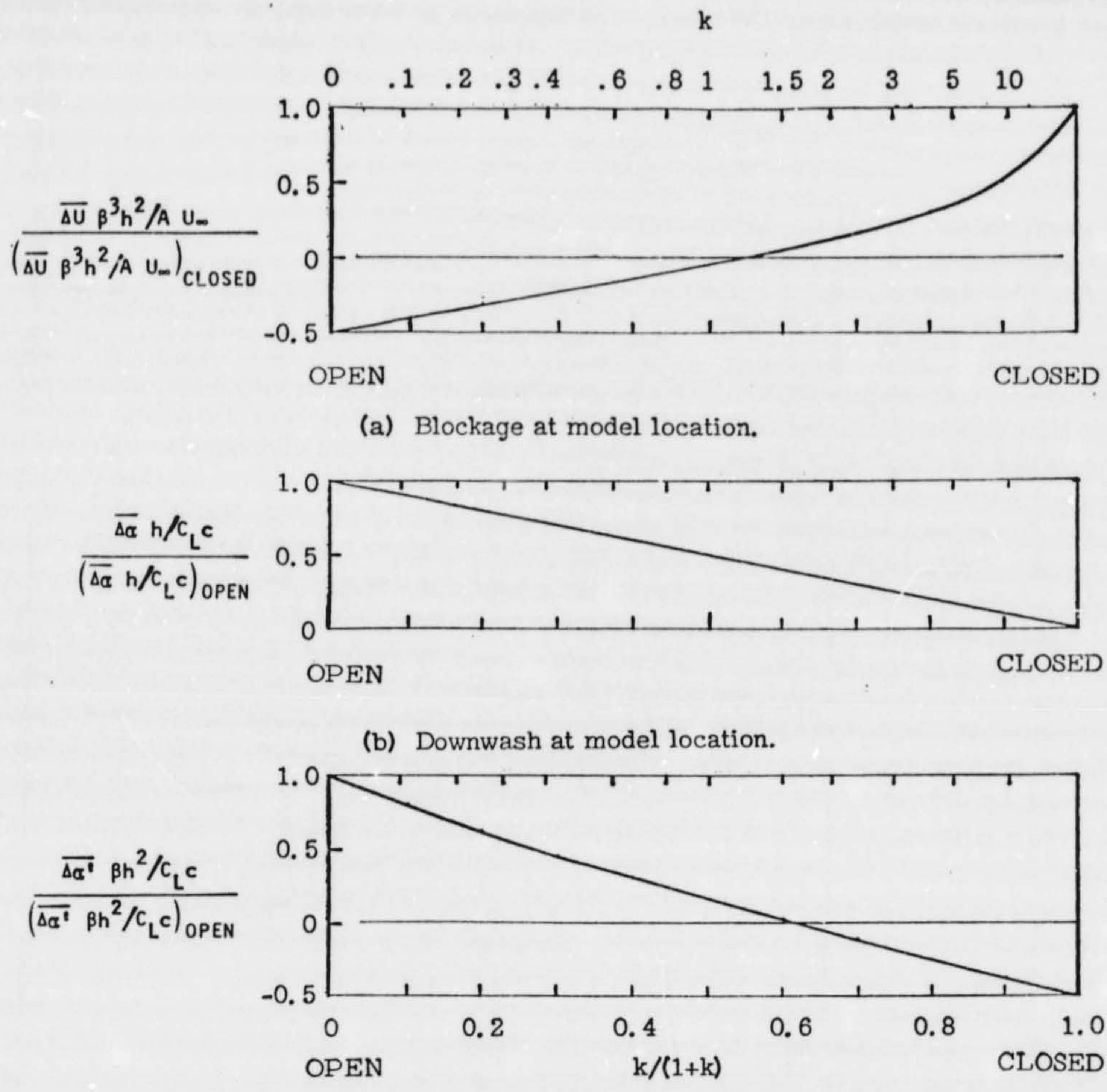

(c) Streamline curvature at model location.

Figure 3. - Wall-induced interference effects at model location in slotted tunnel.

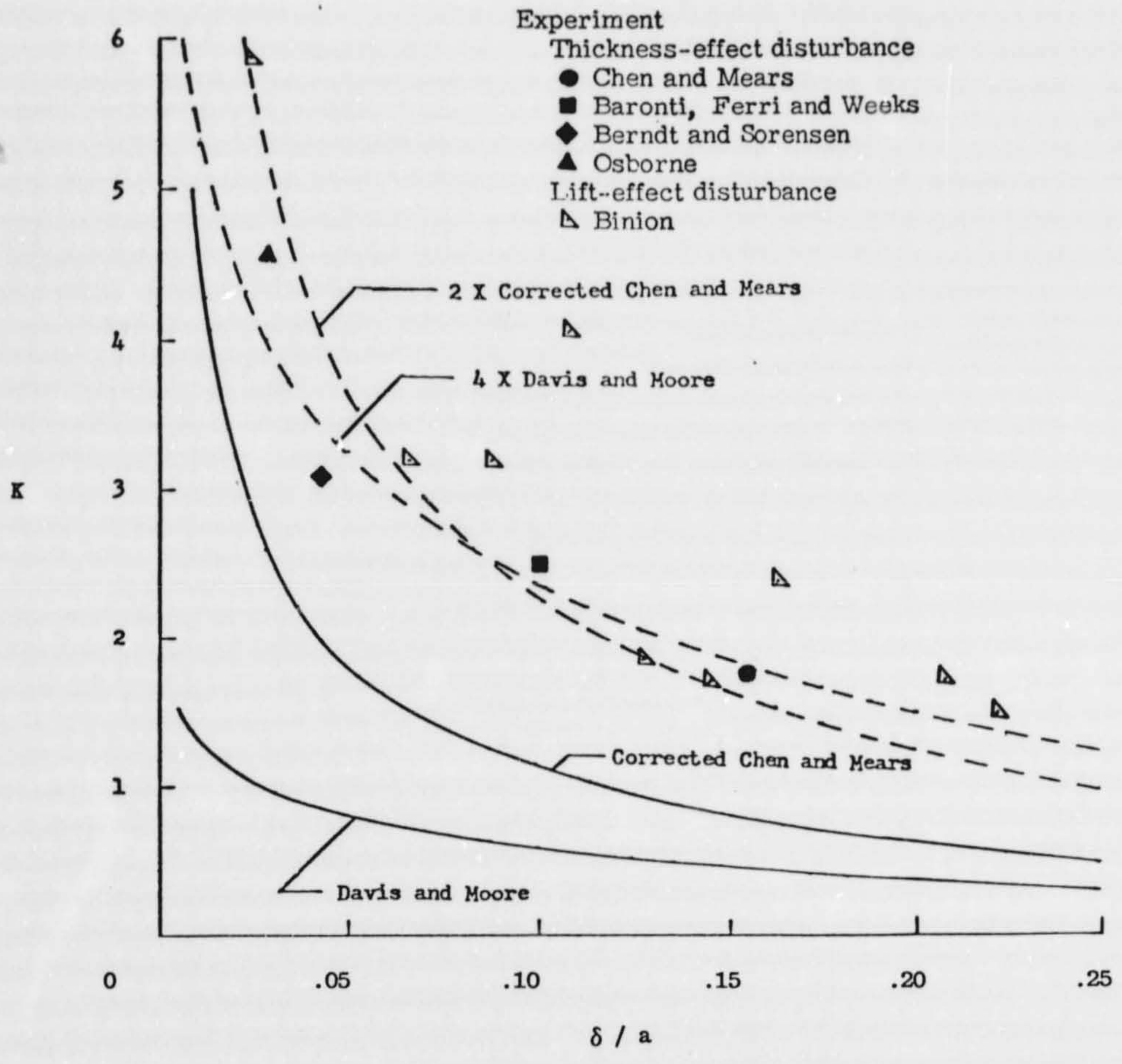

Figure 4. - Parameter K for slotted-wall boundary condition.

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15. Supplementary Notes

16. Abstract

The purpose of this paper is to present a procedure for designing slotted walls for two-dimensional wind tunnels. The design objective can be the minimization of blockage or streamline curvature or the reduction of both. The slotted-wall boundary condition is derived both for flow from the tunnel into the plenum and vice versa, and the procedure for evaluating wall interference is described. A correlation of experimental data for the slotted-wall boundary condition is given. Results are given for several designs and evaluations of slotted wind-tunnel walls.

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