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RESEARCH MEMORANDUM

APPLICATION OF STREAM-FILAMENT TECHNIQUES TO DESIGN OF DIFFUSER BETWEEN COMPRESSOR AND COMBUSTOR IN A GAS-TURBINE ENGINE

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RESEARCH MEMORANDUM

APPLICATION OF STREAM-FILAMENT TECHNIQUES TO DESIGN OF DIFFUSER BETWEEN COMPRESSOR AND COMBUSTOR IN A GAS-TURBINE ENGINE

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SUMMARY

A rapid design method based on stream-filament techniques was developed to obtain the boundaries of an annular combustor-inlet diffuser from a given stagnation streamline, given boundaries of the combustor liner, and given inlet and terminal velocities.

INTRODUCTION

The design of a compressor in a gas-turbine engine is affected by the design of the diffuser between the compressor and the combustor. To minimize the number of compressor stages and, therefore, the length and weight of the compressor, the velocity at the diffuser inlet (compressor outlet) should be as high as possible (e.g., ref. 1). The diffuser design problem is then to uniformly decelerate the air to the desired terminal velocity.

If the velocity along the walls of the diffuser is at any point greater than the inlet velocity or less than the terminal velocity, unnecessary adverse velocity gradients are formed. A design technique that permits control of these surface velocities is therefore required.

This report adapts an impeller design method based on stream-filament techniques to the design of annular combustor-inlet diffusers. By application of this method, the unnecessary reverses in velocity gradient along the diffuser wall can easily be avoided.

METHOD OF SOLUTION

In the theoretical analysis of flow in an annular combustor-inlet diffuser of given boundaries, difficulties arise from the presence of the

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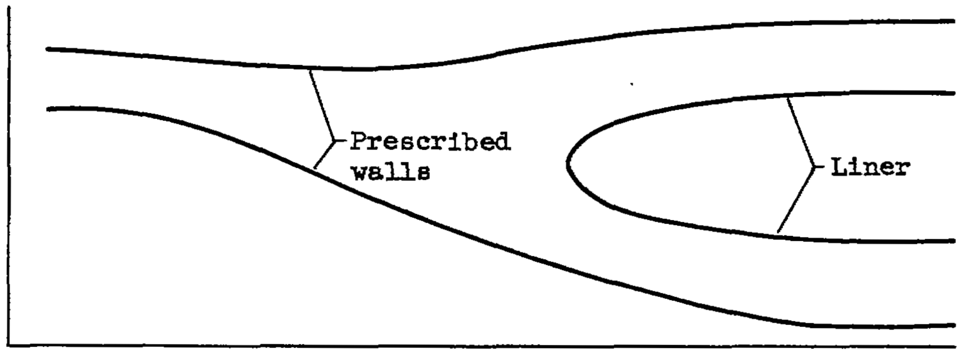
annular combustor liner which divides the flow into two annular channels (sketch (a)).



(a)

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Exact determination of the division of flow by the liner and the stagnation streamline would be lengthy and difficult.

The design of an annular diffuser (in which both walls are to be determined) is much simpler than the analysis because the division of flow by the liner and the stagnation streamline can be prescribed at the outset. The problem is easily attacked by the techniques of stream-filament theory developed in reference 2 for the design of impellers. By this method, the walls of the diffuser are obtained from a prescribed stagnation streamline, liner, and velocity distribution along the streamline and walls of the liner.

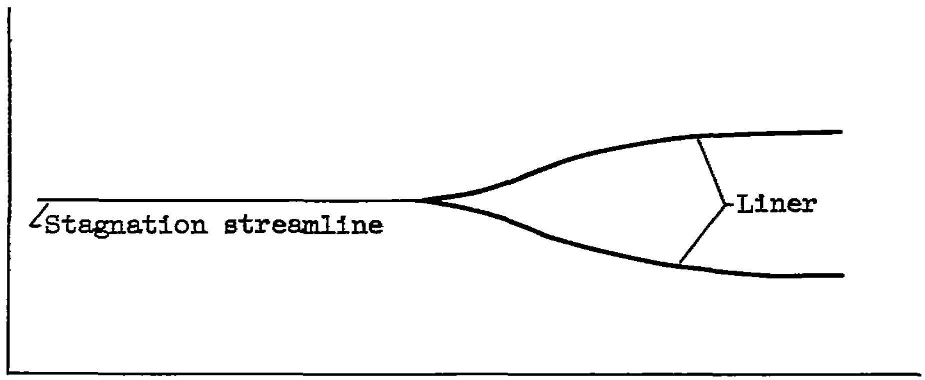
Assumptions

The flow is assumed to be isentropic, steady, compressible, and axially symmetric. Constant total energy is assumed from wall to wall across the channel. The velocity is assumed to have no tangential component.

Outline of Procedure

The procedure for solving the problem by the method of stream-filament theory is outlined in this section.

(1) A profile of the liner and stagnation streamline is drawn in the axial-radial plane. The nose of the liner is streamlined to form two continuous streamlines with the stagnation streamline (see sketch (b)).



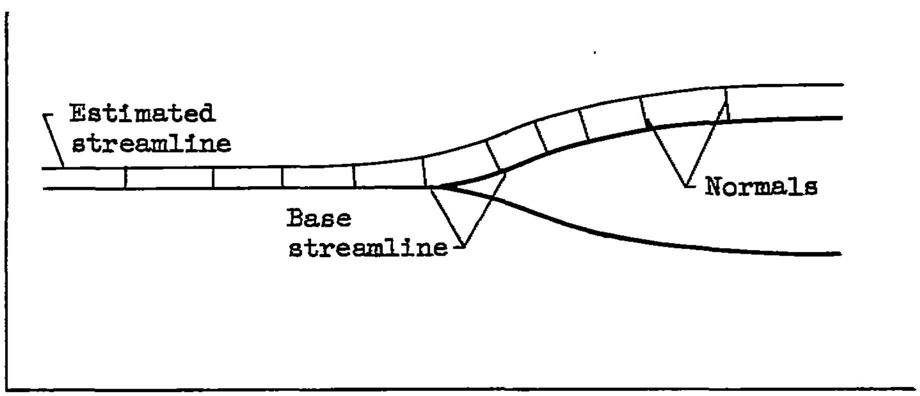
(b)

The stagnation streamline need not be straight; the shape depends on the relative positions of the compressor outlet and the combustor liner. For example, in designing a diffuser similar to that shown in sketch (a), the stagnation streamline is not straight.

(2) A velocity distribution is prescribed along the streamlines. The velocity distribution should result in the necessary diffusion but should not lead to a velocity distribution on the diffuser walls that is known to result in boundary-layer separation.

The outer and inner channels must be designed separately. The only common factor is the stagnation streamline and its velocity distribution. The velocity distributions on the two walls of the liner need not be the same. Only the design of the outer channel will be discussed, since the design of the inner channel proceeds similarly.

(3) An estimated streamline is drawn forming an annular streamtube with the stagnation streamline and the liner as the base streamline (sketch (c)).



(c)

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The distance between streamlines depends on the number of streamtubes desired and the expected size of the channel. For a discussion of streamline spacing, see reference 2. For the first trial a one-streamtube solution would help in prescribing the desired velocity distribution on the stagnation streamline and liner walls. It might give a very good approximation to the final diffuser shape. However, no rule can be given for the usefulness of a one-streamtube design because the difference between a one-streamtube design and a design with many streamtubes will vary with the configuration of the liner and its position relative to the compressor outlet.

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(4) Several stations are chosen between the inlet and the outlet along the base streamline. Since each station eventually yields a point on the next streamline, enough stations must be chosen to establish the streamline. (As the design progresses, new stations may be added if necessary.) At each station, curves are drawn normal to both streamlines as follows: (a) a line is drawn normal to the base streamline extending approximately to the middle of the streamtube, (b) from this point a line is drawn normal to the estimated streamline, (c) the two normal lines are replaced by a smooth orthogonal curve, hereinafter referred to as a normal.

(5) The velocity q is computed at the intersection of each normal with the estimated streamline by means of the velocity equation (refs. 2 and 3)

$$q = q_0 e^{\bar{a}\Delta n} \tag{1}$$

where q_0 is the velocity at the intersection of the normal and the base streamline, $\bar{a}$ is the average of the values of the curvature a of the two streamlines at the normal, and Δn is the distance along the normal between streamlines. The normal distance Δn is positive in the direction of increasing radius.

The curvature a at any point is obtained from the relation

$$a = 1/r_c \tag{2}$$

where r_c is the radius of curvature. The radius of curvature may be determined from the equation

$$r_c = \frac{\left[1 + (r')^2\right]^{3/2}}{r''} \tag{3}$$

where

$$r' = \frac{dr}{dz} \quad \text{and} \quad r'' = \frac{d^2r}{dz^2}$$

r radial distance from axis of annulus

z axial distance from diffuser inlet

The radius of curvature can also be obtained by means of an instrument such as a radometer (ref. 4). By whatever means r_c is determined, care must be taken in assigning the proper sign. In the first quadrant of the axial-radial plane, r_c is positive for streamlines that are concave upward. In doubtful cases the sign can be determined from an examination of d^2r/dz^2.

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(6) The weight flow w through the streamtube is computed at each normal by means of the continuity equation (refs. 2 and 3)

$$w = 2\pi \, \overline{r\rho g q} \, |\Delta n| \tag{4}$$

where

ρ fluid mass density

g acceleration due to gravity

$\overline{r\rho g q}$ average of the values of the quantity $r\rho g q$ at intersection of the normal and the two streamlines

The density ρ is obtained from

$$\rho = \rho_{t,i} \left[1 - \frac{\gamma-1}{2} \left(\frac{q}{c_i}\right)^2\right]^{\frac{1}{\gamma-1}} \tag{5}$$

where

$\rho_{t,i}$ stagnation mass density at inlet

γ ratio of specific heats

c_i stagnation velocity of sound at inlet

(7) If continuity is not satisfied at any station, the streamline spacing is adjusted and the process repeated until equal weight flows are established at all stations. A new estimate of the spacing Δn at a station may be obtained by multiplying the original estimate by the ratio of the desired weight flow to that computed by equation (4). The desired weight flow through a streamtube may be prescribed (e.g., so that streamtubes have equal weight flow), or it may be taken as the value obtained by equation (4) at any station. The latter method saves some computing time.

(8) When continuity is established, the streamline obtained becomes the base streamline for the next streamtube.

(9) The next estimated streamline is drawn forming a second streamtube.

(10) The existing normals are extended normal to the new streamline as in step (4) (see sketch (d)).

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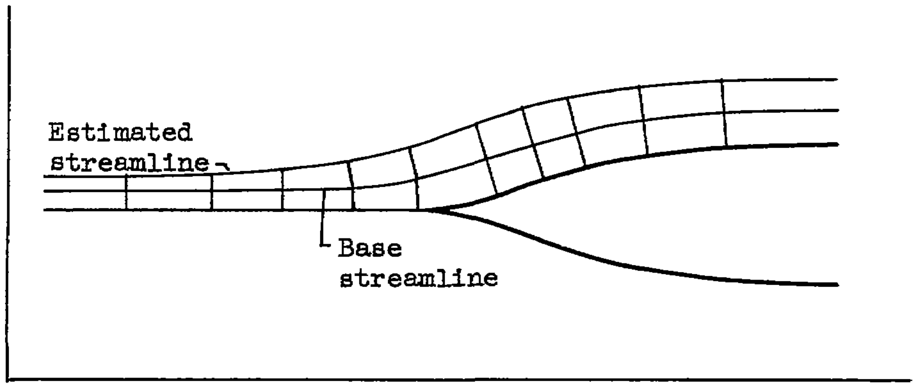


(d)

(11) Steps (5), (6), and (7) are repeated using the velocities on the new base streamline for the computations.

(12) Streamtubes are constructed in this manner until the sum of the weight flows through the several streamtubes equals the total weight flow prescribed for the outer channel. The final streamline is the outer wall of the diffuser.

(13) If the velocity distribution along any portion of the outer wall is unsatisfactory, new velocities may be prescribed along the initial streamline at those stations affected. The design process is then repeated until a satisfactory velocity distribution is obtained along the wall.

(14) The lower wall is obtained in a similar manner. Note, however, that Δn is negative when proceeding radially inward.

Accuracy

The chief source of inaccuracy in this method is determination of the streamline curvature. A better estimate of the curvature can be obtained by plotting the curvatures measured at the several stations along a streamline against axial distance, drawing a curve that best fits the points thus plotted, and reading the curvature at each station from this curve.

It is to be noted that this method does not give an accurate solution of the flow at the nose of the liner where the nose is of blunt shape.

NUMERICAL EXAMPLE AND DISCUSSION

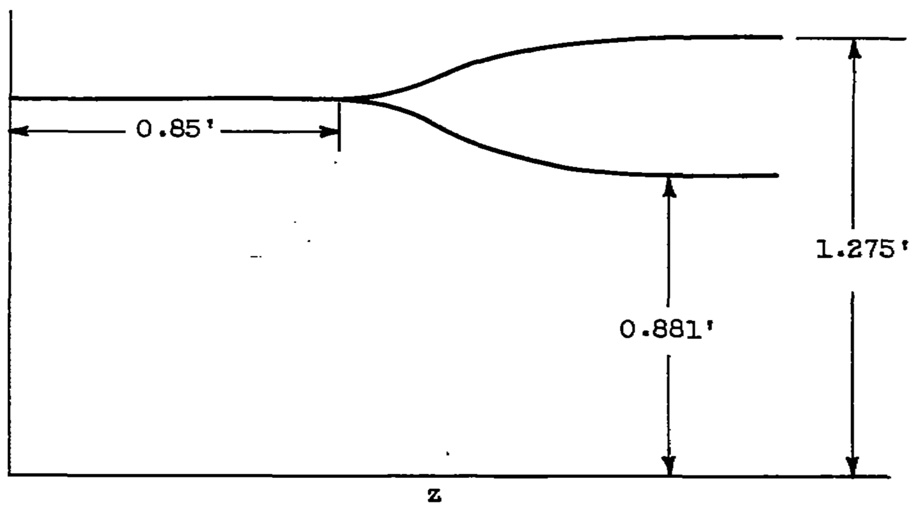
The method described in the preceding section was applied to the design of a diffuser with the following conditions prescribed:

3687 (1) NACA standard sea-level (stagnation) conditions of temperature and density at the inlet

(2) A uniform velocity of 438 feet per second at the inlet and a uniform velocity of 173 feet per second at the outlet (these velocities were obtained from an approximate analysis of the flow in an existing diffuser)

(3) A total weight flow of 35 pounds per second through the inlet, divided by the liner in the following manner: 20 pounds per second through the outer channel and 15 pounds per second through the inner channel

(4) The shape of the liner and the axial length from inlet to liner (sketch (e)).



(e)

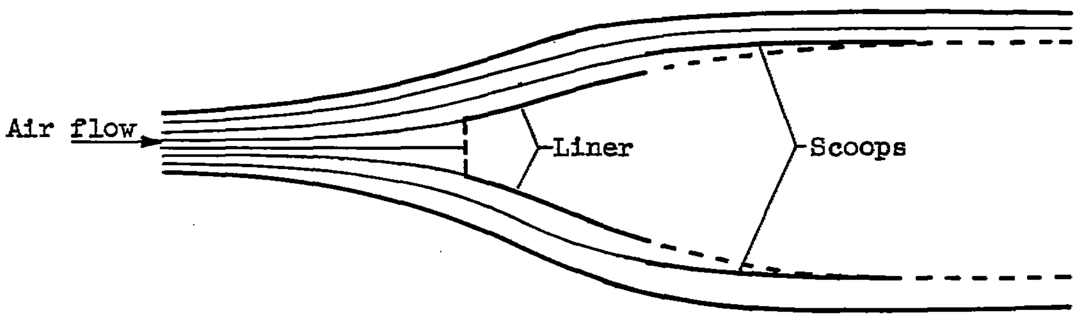
Seven streamtubes, each carrying a weight flow of 5 pounds per second, were used in the solution. Each streamtube required approximately 8 hours computing time. For the initial design a velocity distribution obtained from a rough approximate analysis of an existing diffuser was prescribed along the stagnation streamline and the liner walls (fig. 1).

The design presented in figure 2(a) resulted from this initial velocity distribution and the other prescribed conditions. The velocity distribution on the inner and outer walls of this design is shown in figure 3. Note that the velocity goes below the terminal velocity and the velocity gradient is unnecessarily steep. To eliminate the undesirable velocity gradient on the walls, the prescribed velocity distribution on the stagnation streamline and liner walls was adjusted until, in its final form (final design in fig. 1), it resulted in the design shown in figure 2(b). (The walls of the initial design are also shown for comparison.) The velocity gradient on the walls of the final design (fig. 3) is very nearly constant during diffusion. (Diffusion was completed before the flow began to turn around the nose because in an actual diffuser primary air would be bled off here.) The final design is not necessarily a diffuser in which the boundary layer does not separate; nor is it even a realistic diffuser; it is an illustration of what can be done with this method. 3687

Although in the development of the method and in the numerical example the flow was assumed to be nonviscous, boundary-layer separation might be predicted and therefore avoided by using the method of reference 5 in conjunction with the design method. Reference 5 presents a method for predicting the separation point from the pressure distribution on the boundary and is based on the more fundamental work of references 6 and 7.

The diffuser-inlet velocity was assumed to be constant in the radial direction in the example design. However, the method can be used for the case of a radial velocity gradient provided the gradient is known and provided the total head is constant across the channel.

There was also assumed to be no change in mass flow in the diffuser. In an actual combustor primary and secondary air are bled from the flow into the liner. This removal of air can readily be taken into account in the design method. The streamline spacing is so chosen that the streamtubes carry mass flow in the increments that are to be bled off. The streamtube supplying the primary air can be made to pass through the nose of the liner. Other streamtubes pass around the nose and into the liner at the appropriate stations, forming scoops which direct the flow through the openings in the liner. The resulting configuration would be similar to that shown in sketch (f).



(f)

SUMMARY OF RESULTS

A rapid design method based on stream-filament techniques was developed and used to obtain the boundaries of an annular combustor-inlet diffuser from a given stagnation streamline, given boundaries of the combustor liner, and given inlet and terminal velocities. An initial velocity distribution was prescribed along the streamline and liner, but this led to reverses in velocity gradient on the diffuser walls. The initial velocity distribution was therefore adjusted and the design process repeated until the reverses were eliminated.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 7, 1955

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APPENDIX - SYMBOLS

The following symbols are used in this report:

a curvature of streamline, $1/r_c$, ft^{-1}

c stagnation speed of sound, ft/sec

g acceleration due to gravity, ft/sec^2

Δn distance between adjacent streamlines along normal, ft 3687

Q velocity ratio, q/q_i

q velocity, ft/sec

q_0 velocity along base streamline, ft/sec

r radial distance from axis of annulus to point being considered, ft

r_c radius of curvature of streamline, ft

w weight flow through streamtube, lb/sec

z axial distance from diffuser inlet, ft

γ ratio of specific heats

ρ mass density, $\text{lb-sec}^2/\text{ft}^4$

ρ_t stagnation mass density, $\text{lb-sec}^2/\text{ft}^4$

Subscript:

i inlet conditions

Superscript:

$-$ average of values at adjacent streamlines

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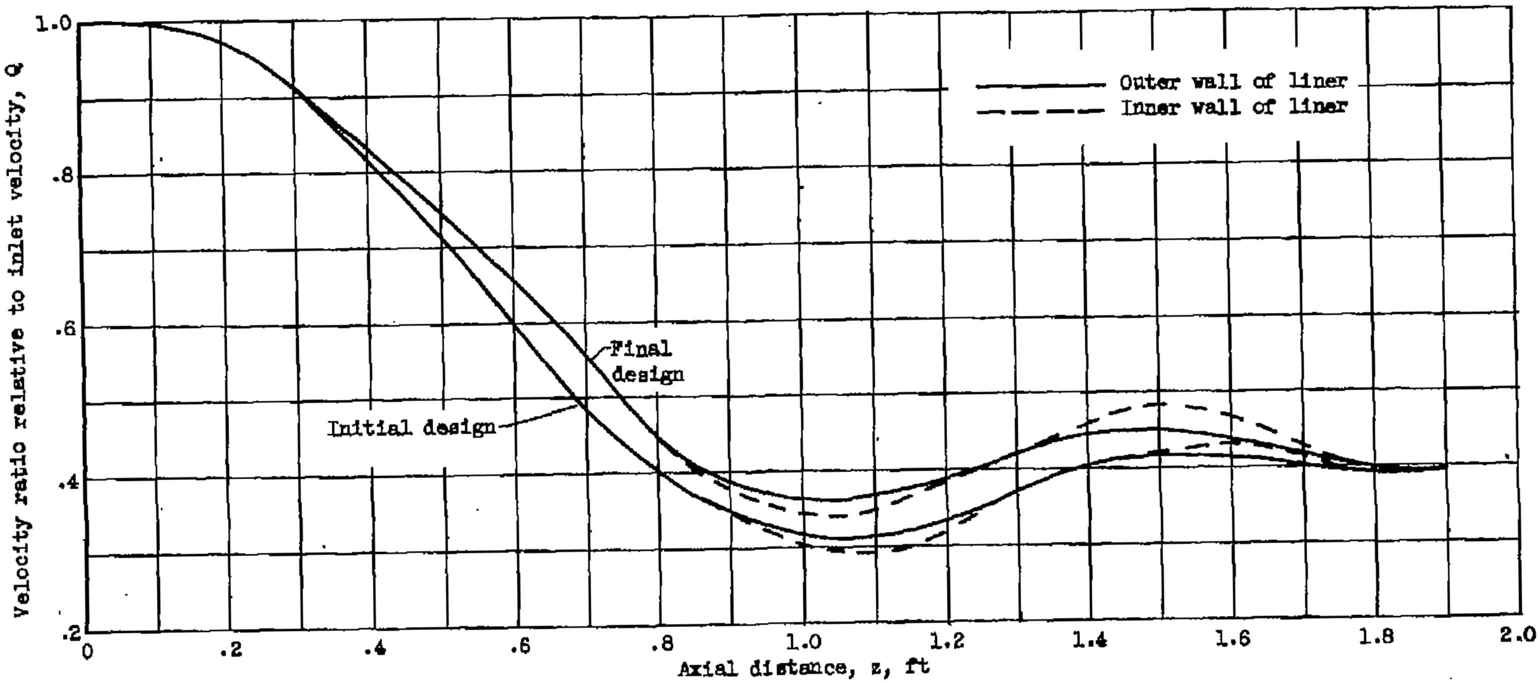
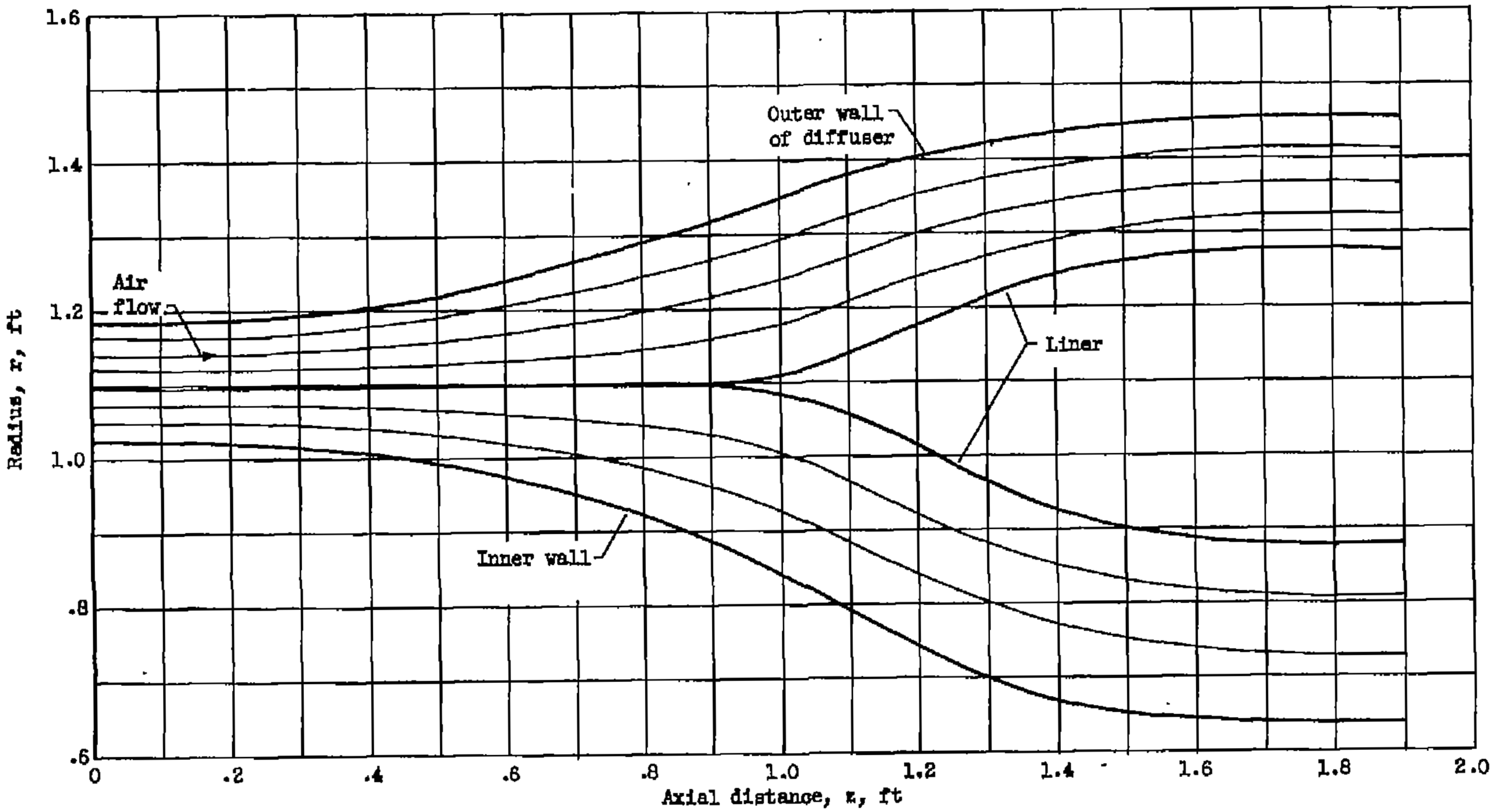
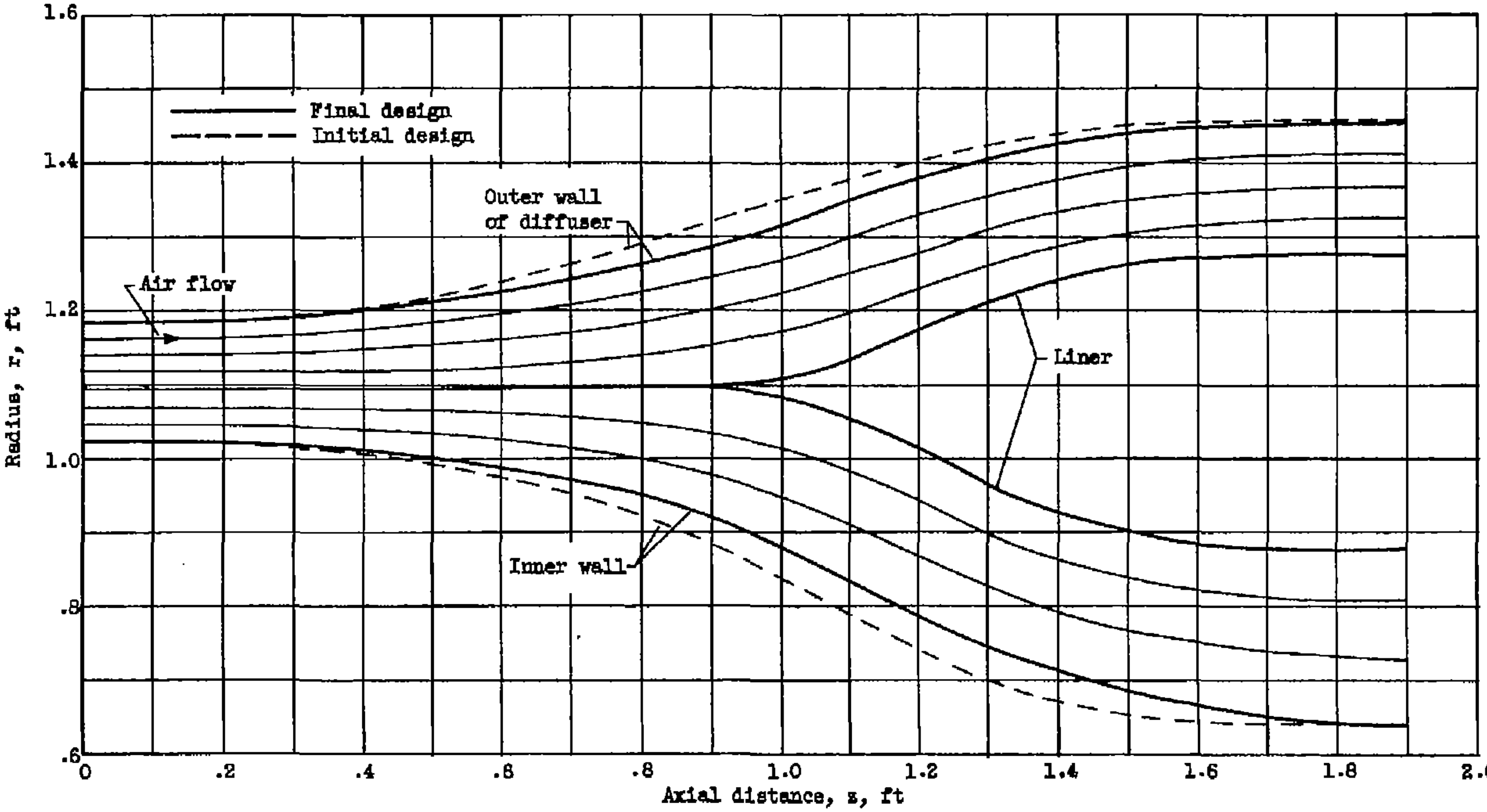


Figure 1. - Prescribed velocity distributions along stagnation streamlines and walls of liner of initial and final designs.



(a) Initial design.

Figure 2. - Flow, showing streamlines, through annular diffuser in axial-radial plane.



(b) Final design.

Figure 2. - Concluded. Flow, showing streamlines, through annular diffuser in axial-radial plane.

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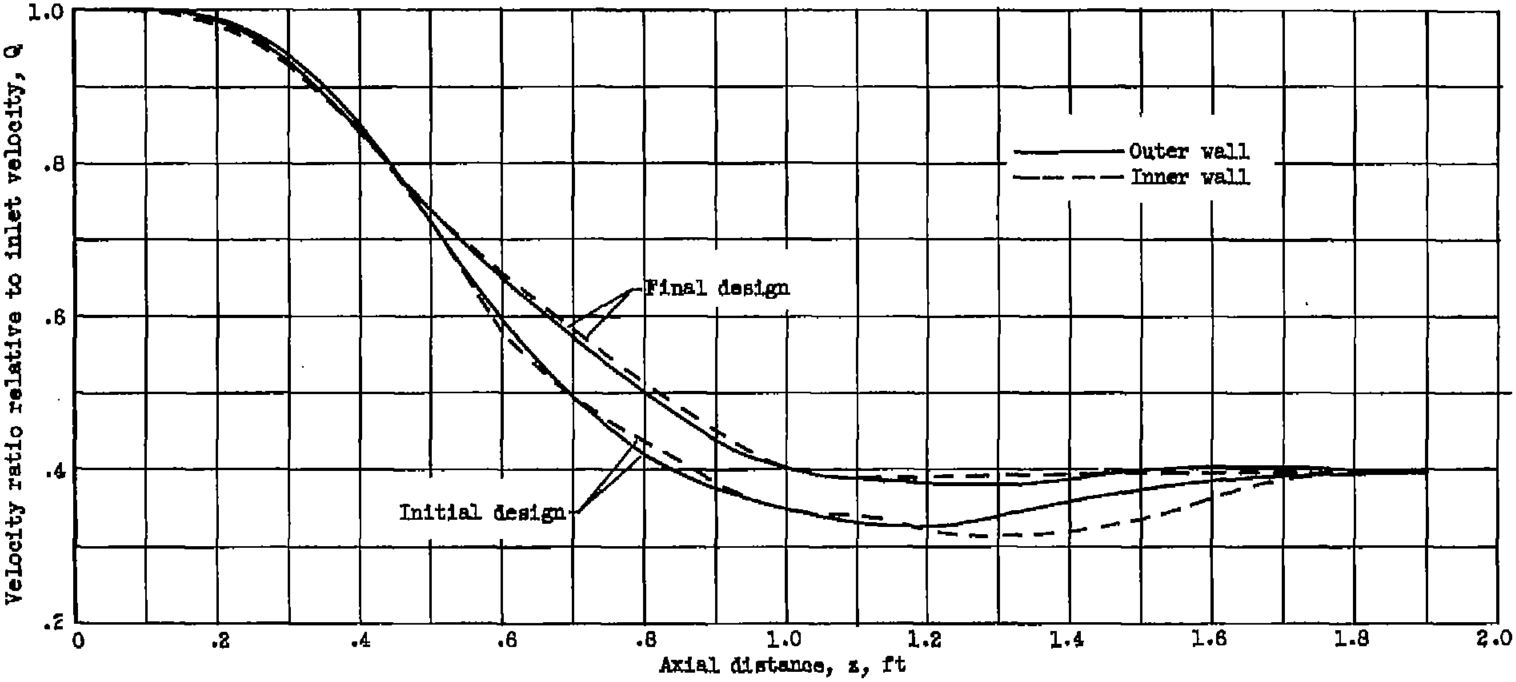

Figure 3. - Velocity distributions along walls of diffusers shown in figure 1.

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