Thrust Augmentor Inlet Optimization

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A zonal computational method is developed to optimize inlet shape and primary nozzle location for two-dimensional thrust augmenting ejectors. An inviscid zone comprising the irrotational flow about the device is patched together with a viscous zone containing the turbulent mixing flow. The inviscid region is computed by a higher order panel method, while an integral method is used for the description of the viscous part. A nonlinear, constrained optimization study is undertaken for the design of the inlet region. In this study, boundary layer separation on the walls of the inlet is taken into account through the use of a penalty function. Two nondimensional groups, a thrust based Reynolds number, and the ratio formed by the freestream velocity and a characteristic velocity of the jet, are found to be important parameters in the design of an optimal inlet.

Nomenclature

$[A],[\tilde{A}]$	= coupling coefficient matricies for reduced equations
$\{B\},\{C\}$	= right-hand sides of reduced equations
b	= characteristic width of turbulent region
C_p	= pressure coefficient
H	= shroud inner half-width
k	= eddy viscosity scaling constant
L	= augmentor shroud length
p	= pressure
R_T	= Reynolds number based on jet characteristic velocity and shroud inner width
r,t	= constants in Eq. (10)
T	= 2-D shroud associated thrust
T_0	= 2-D primary thrust
u,v	= x,y velocity components
u_0	= velocity at outer edge of jet velocity profile
u_1	= maximum excess velocity in viscous zone
u_∞	= freestream velocity
u_c	= jet characteristic velocity
$\hat{u}$	= approximate viscous solution
V_N	= velocity component normal to jet boundary
x,y	= coordinates in the viscous solution
x_{end}	= final station at which the viscous and inviscid solutions are matched
X,Y	= coordinates for the shroud description
X_0	= jet nozzle location
X_L	= length of inlet lip
α	= $-\ell n(1/2)$
γ	= ratio of freestream velocity to jet characteristic velocity
Γ	= x-momentum conservation operator
θ	= lip rotation angle
μ	= viscosity coefficient
ν_t	= eddy viscosity
ξ	= dummy variable of integration
ρ	= fluid density
τ	= Reynolds stress in 2-D boundary layer approximation
ϕ	= thrust augmentation ratio
ω	= relaxation parameter

Subscripts

$(\ )_{\mathrm{inv}}$	= quantity computed from the inviscid solution
$(\ )_{\mathrm{vis}}$	= quantity computed from the viscous solution

Superscripts

$(\ )^n$	= iteration level n
$(\dot{\ })$	= denotes differentiation with respect to x

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Introduction

A THRUST augmentor consists of a high momentum primary jet which is exhausted into the confines of an aerodynamic shroud. As the jet evolves, it undergoes turbulent mixing with the surrounding stream and, as a result, induces an entrained flowfield about the device. Augmentation in thrust is realized through the combined effects of the jet being discharged into a region of lowered pressure, and the induced pressure distribution on the surface of the shroud.

In the design of VSTOL aircraft to be fitted with thrust augmentors, a means of evaluating the performance of various ejector configurations is needed to optimize the benefit of such a device. Considerable work has been undertaken in recent years to develop theories which predict thrust augmentor performance. While much progress has been made, at the present time no method exists which is efficient or robust enough to be used in detailed parametric or optimization studies. In this work, a robust model capable of predicting performance in the absence of diffuser stall is developed and applied to the optimization of inlet shape and primary nozzle position.

The earliest attempts at modeling the thrust augmentor were based on control volume approaches[1] which satisfy the equations of motion only in a global sense. Such theories possess the advantages of simplicity and numerical efficiency, but do not resolve the details of the flowfield in the vicinity of the shroud. Due to their inability to provide surface velocity or pressure information, the global formulations are not able to predict the effect of perturbations to the shroud geometry. An alternative is the solution of the full Navier-Stokes equations. Such a detailed simulation would provide all the information needed to evaluate the performance of an arbitrary geometrical configuration. However, computational demand[2] would make this approach exceedingly expensive when applied to optimization studies.

The current effort in thrust augmentor modeling has focused on a viscous-inviscid interaction methodology which retains much of the detailed information provided by a Navier-Stokes solution, while requiring only a modest computational effort. In the viscous-inviscid approach, the flowfield is subdivided into separate regions or "zones" which contain flows of differing character. There is an inviscid zone, postulated to be free of shear, and a viscous zone in which shear and rotational effects are important. Within each zone the simplest justifiable approximations to the equations of motion are made. Each zone is then solved quasi-independently with coupling information appearing through the boundary conditions at their interface.

Bevilaqua et al.[3,4] developed a viscous-inviscid algorithm for the performance prediction of two-dimensional thrust augmentors. Bevilaqua's code makes use of a panel method to compute the flow about the shroud, while the turbulent zone is computed using a finite difference solution to a parabolic set of equations. Tavella and Roberts[5] studied a range of moderate to large mixing channel aspect ratios ($L/2H$) in which the jet has encountered the walls by the time of exit. In their algorithm, the inviscid solution was obtained using conformal mapping, and the viscous turbulent zone was computed using an integral method. This algorithm proved to be extremely economical and several parametric studies were performed. Aside from the attractiveness of its efficiency, the method was limited to shroud geometries which could be described by small perturbations to flat plates.

In the present work, the integral formulation of the Tavella-Roberts model is retained, while the inviscid solution is generated using a higher order panel method.[6] Use of the panel method for the inviscid solution removes the limitations of slightly perturbed shroud geometries. The model is still restricted to augmentors with large mixing channel aspect raio. When applied to optimization, separation within the inlet is accounted for with a boundary layer calculation. Shapes leading to separation are rejected in the optimization process through the use of a penalty function.

Mathematical Model

The flowfied of a generic two-dimensional thrust augmentor is divided into viscous and inviscid zones as illustrated in Fig. 1. The viscous zone originates at the jet nozzle and expands downstream corresponding to the approximate growth rate of the jet. The inviscid zone encloses much of the shroud and extends to infinity in all directions. The common boundary between the viscous and inviscid regions physically represents the region where the shear due to the turbulent mixing has become negligible.

Performance is assessed in terms of the augmentation ratio defined as

$$\phi = (T_0 + T)/T_0 \tag{1}$$

The augmentation ratio is computed in either of two ways: direct integration of the surface pressure or by using the Blasius theorem for a control volume surrounding the device. The two methods agree to within 2%. All results presented here are based on an integration of the surface pressure.

Inviscid Solution

The inviscid portion of the flowfield is used to model the jet entrainment. A uniform flow approaching the device may be considered by including a freestream velocity component. By virtue of symmetry in the shroud geometry, only the upper half plane is considered. The geometry and boundary conditions which define the inviscid problem are shown in Fig. 2. The solid boundary extending in front of the shroud represents the dividing streamline approaching the device. The following linear segment represents the jet boundary with boundary conditions that account for entrainment. The half circle at the downstream end of the jet boundary serves as a control station with a uniform flow transpiration boundary condition imposed. The need for the control station arises from the fact that panel methods become inaccurate in a concave corner region.[6,7] The insertion of a smooth curve such as a half circle avoids this difficulty. The uniform flow condition imposed at the control station is justifiable since experiments have shown that the inviscid flow becomes nearly uniform after approximately one half channel width into the shroud.[10]

The inlet region of the augmentor shroud is modeled as an impermeable surface. The assumption is made that the slipstream surface between the exhausting jet and the inviscid flow at the exit of the device is a continuation of the same streamline defining the body shape. This assumption is physically equivalent to ignoring the shear at the slipstream interface. This is found to be justifiable since computations have shown that modeling of the mixing taking place downstream of the shroud has a negligible effect on global quantities such as the augmentation ratio.

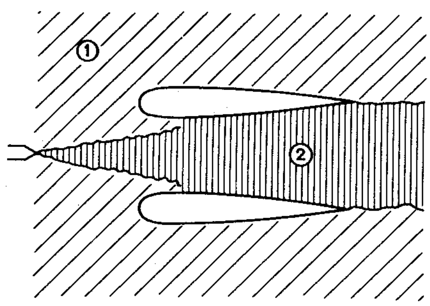
It has been shown that a first order panel method will not accurately represent the flow in an internal region such as an inlet. Thus, a higher-order method, which accounts for curvature of the surface shape and is second order in the singularity distribution, has been adopted.

Viscous Solution

The rotational zone containing the turbulent jet is modeled using an integral method discussed elsewhere.[7,8] In the interest of completeness, the essential features of the method are repeated here.

The boundary layer assumptions are made for steady, incompressible two-dimensional flow in which the molecular and normal turbulent stresses have been neglected. The following equation for the conservation of momentum in the x-direction arises

$$\Gamma(u) = u\frac{\partial u}{\partial x} - \frac{\partial u}{\partial y}\int_0^y \frac{\partial u}{\partial x} d\xi + \frac{1}{\rho}\frac{dp}{dx} - \frac{1}{\rho}\frac{\partial \tau}{\partial y} = 0 \tag{2}$$



① Inviscid zone computed with a higher order panel method. ② Viscous zone computed with an integral method.

Fig. 1 Thrust augmentor and the zonal approach.

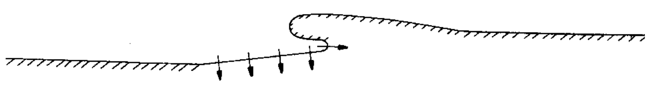


Fig. 2 The inviscid problem.

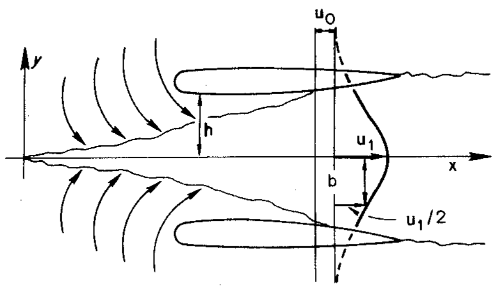


Fig. 3 Viscous solution.

The mass conservation relation used implicitly above is

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{3}$$

A further result of the boundary layer approximation is that the pressure is a constant on any given cross-section.

Equations (2) and (3) are simplified by postulating that the velocity field be expressible from the nozzle to the exit plane in the manner shown in Fig. 3, by a function of the following form

$$u(x,y)=u_0(x)+u_1(x)\exp\left[-\alpha\frac{y^2}{b(x)^2}\right] \tag{4}$$

It should be noted that the boundary layer on the inside of the channel wall is ignored in this representation and, therefore, must be considered in a separate calculation.

The turbulent shear stress is modeled using the simple eddy viscosity concept

$$\frac{\tau}{\rho}=\nu_t\frac{\partial u}{\partial y} \tag{5}$$

with the following scaling hypothesis

$$\nu_t=ku_1b \tag{6}$$

Experimental observations for the growth rate of a free jet are used to assign a value of 0.0283 to the constant k.

Now substituting Eqs. (4-6) into Eqs. (2) and (3), a simplified set of ordinary differential equations in terms of the unknown functions $u_1(x)$, $u_0(x)$, $b(x)$, and $p(x)$ is obtained. A system of independent equations for these quantities is obtained by taking successive moments of the momentum equation as follows

$$\int_0^y y^n\Gamma(\hat{u})\mathrm{d}y=0 \tag{7}$$

These moments together with the continuity relation constitute a closed system of equations of the form

$$[A]\begin{Bmatrix}\dot{u}_0\\ \dot{u}_1\\ \dot{b}\\ \dot{p}\end{Bmatrix}=\{B\} \tag{8}$$

The elements of the matrix A as well as vector B are developed in full in terms of exponentials and error functions in Ref. 8.

Viscous-Inviscid Matching

Communication between the viscous and inviscid zones takes place at their common boundary. The goal of the viscous-inviscid matching is to achieve continuity, in the limit of an iterative process, in both velocity and pressure fields along the jet boundary.

The normal component of velocity for the inviscid solution is required to match the transpiration velocity used to simulate the jet entrainment. Solution of the inviscid problem subject to this boundary condition yields the u and v components of velocity at the zonal interface. A boundary condition for the viscous solution is created by making use of the fact that $\dot{u}_0$ along the jet boundary may be found from the u component of velocity as obtained from the inviscid solution. This allows Eq. (8) to be written with $\dot{u}_0$ appearing as a forcing term:

$$[\tilde{A}]\begin{Bmatrix}\dot{u}_1\\ b\\ \dot{p}\end{Bmatrix}=\{B\}+\dot{u}_0\{C\} \tag{9}$$

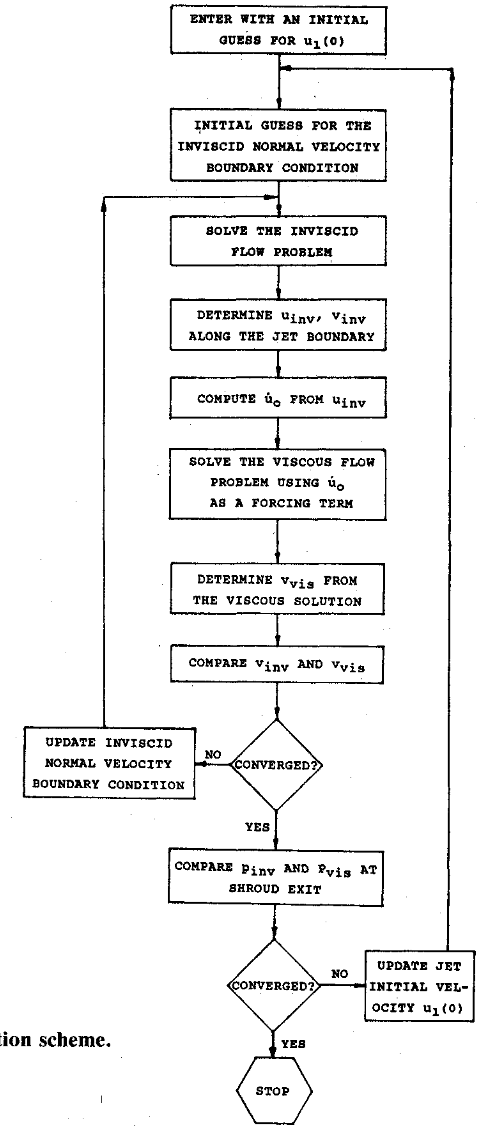


Fig. 4 Iteration scheme.

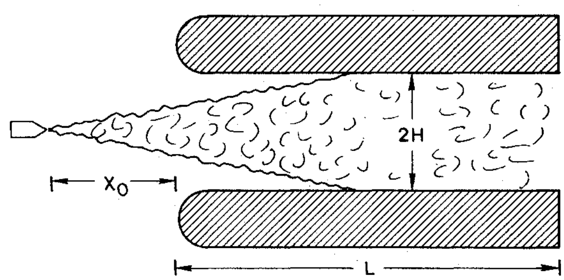


Fig. 5 Test configuration, $L/2H=3.28$, $X_0/2H=1.0$ (taken from Ref. 10).

After solving this set of equations together with a given set of initial conditions, the v component of velocity at the jet boundary is found through use of the continuity equation. This allows for calculation of the v component of velocity along the jet boundary independently by both the inviscid and viscous zones. The aim of the iteration scheme is to find the normal transpiration velocity for the inviscid solution which matches the v component of velocity along the jet boundary as computed from the viscous solution. Matching of the pressure field at the jet boundary is achieved automatically when the velocity field is compatible since the pressure in the inviscid region of the jet profile is required to obey the Bernoulli equation.[8]

To start the iteration process, an initial guess for the boundary condition to the inviscid flow problem is chosen: a reasonable choice is uniform flow. The cycle is terminated when the v components of velocity agree to some specified tolerance.

It has been found that the iteration process is unstable under a relaxation scheme with a constant relaxation factor, whereas, the following scheme with a spatially varying relaxation parameter leads to a fast convergence

$$V_N{}^{n+1} = V_N{}^n + (r+tx)(v_{\text{vis}} - v_{\text{inv}}) \tag{10}$$

$$r = 1.0,\ t = -0.7/(x_{\text{end}}) \tag{11}$$

Once convergence is achieved, the remainder of the viscous flow within the mixing channel is computed from Eq. (8) by marching downstream from the control station to the shroud exit.

Upon exit from the shroud, the requirement is made that the pressure be continuous across the slipstream created between the viscous and inviscid calculations made there. The pressure computed at the primary jet nozzle is used as an initial condition for the marching of the viscous solution. At the exit of the shroud, the pressure predicted there by the viscous solution is compared with the pressure computed by the inviscid solution. Compatibility between these pressure fields is achieved by adjusting the momentum of the primary jet. The following relaxation scheme is used to correct the jet initial conditions in response to an exit pressure inbalance

$$u_1(0)^{n+1} = u_1(0)^n + \omega(p_{\text{inv}} - p_{\text{vis}}) \tag{12}$$

$$\omega = 20 \tag{13}$$

The pressures on either side of the slipstream at the shroud exit can be compared only after the velocity field is matched at the jet boundary. For this reason, it is necessary to nest the iteration scheme for matching the velocity at the zonal interface within the iteration loop for matching the pressure at the exit. Starting with a given value of the centerline velocity as the initial condition for the integral method, the viscous and inviscid zones are matched first, thereby, allowing the viscous and inviscid pressure predictions at the exit to be compared. The outer loop is closed as the initial centerline velocity of the jet is adjusted in response to the computed pressure inbalance. The overall scheme is shown diagrammatically in Fig. 4.

Boundary Layer Calculation

The boundary layer calculation performed here is based on von Kármán's integral formulation of the boundary layer equations. Transition and separation are predicted by monitoring the local shape factors as suggested by Eppler.[9] As theories for a turbulent boundary layer evolving in a turbulent outer field are complicated and not well tested for ejector flows, the boundary layer calculation is terminated at the point at which the jet first interacts with the surface of the shroud. This is not a serious limitation in the present work since the inlet optimization study is conducted for augmentors which do not include a diffuser. The assumption is made that a boundary layer surviving the high rate of pressure recovery within the inlet region wil remain attached through the comparatively mild adverse pressure gradient imposed by a straight-walled mixing channel. Since skin friction along the entire shroud cannot be calculated, viscous drag associated with the boundary layers is neglected.

Comparison with Experiment

The augmentor algorithm has been compared with measurements taken by Bernal and Sarohia[10] on the two-dimensional model shown in Fig. 5. The surface pressure distribution predicted by the augmentor code is compared with experiment in Fig. 6. The agreement is seen to be quite good over most of the shroud with the suction peak location and magnitude being properly predicted. The pressure

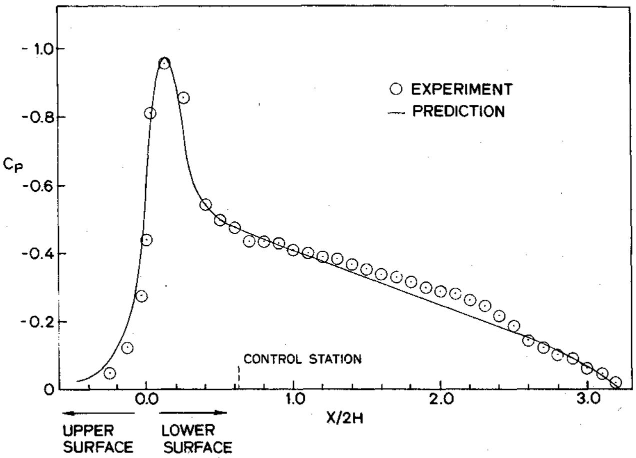


Fig. 6 Comparison of surface pressure distribution.

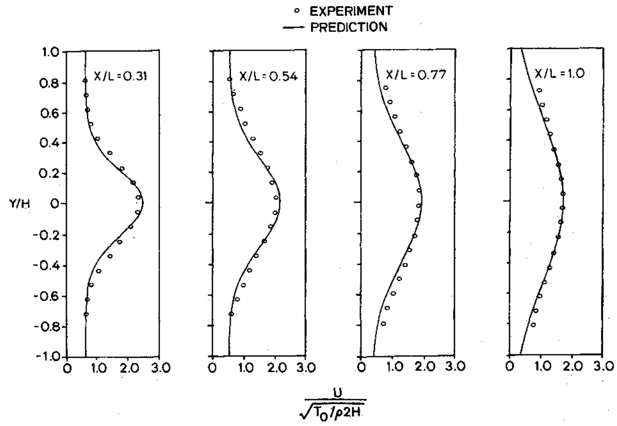


Fig. 7 Comparison of jet velocity profile.

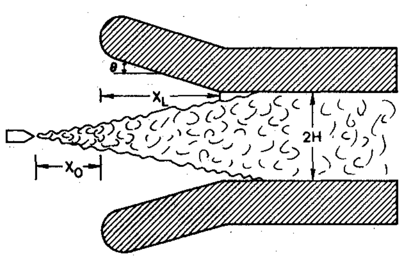


Fig. 8 Optimization parameters. X_0, X_L, and θ are variables; $L/2H$ is fixed at 3.28. u_∞ and T_0 are additional parameters.

deviates most within the mixing channel and is probably a consequence of the crude turbulence model used in this region. Figure 7 shows the evolution of the jet velocity profile within the mixing channel. The overall agreement is good with the computed profiles reproducing the correct shape and velocity magnitude. The code predicts an augmentation ratio of 1.26 while the experiment yielded a value of 1.2. The 5% discrepancy in augmentation ratio falls within the uncertainty of the reported value, and may also reflect the absence of skin friction in the calculation.

The CPU time required for the computation of a single converged flowfield is approximately two minutes on a VAX-11 7/780 system.

Optimization Studies

As an illustration of the capabilities of the model, a simple study for the optimization of the inlet detail for the shroud studied by Bernal and Sarohia is undertaken. Figure 8 shows a perturbed configuration in which the jet nozzle is free to move along the plane of symmetry, and a section of the inlet lip is allowed to rotate. The geometric design variables are the jet nozzle location, the length of the inlet section rotated, and the rotation angle. Additional design parameters are the freestream velocity and the primary thrust, i.e., a given momentum flux from the primary nozzle. The ratio of the overall shroud length to the mixing channel height remains fixed at 3.28. In order to isolate the effects of inlet shape, shrouds with diffusers have not been considered, and the mixing channel walls remain parallel up to the exit station in all cases.

A quasi-Newton optimization routine[11] was coupled with the aumentor code to systematically search through the design parameters. While the optimization code used was designed for unconstrained problems, the constraints imposed by separation and practical limits of the geometric parameters were incorporated through the use of algebraic penalty functions.[12] The penalty functions insure that the optimal solutions be both physically realizable and free of inlet stall.

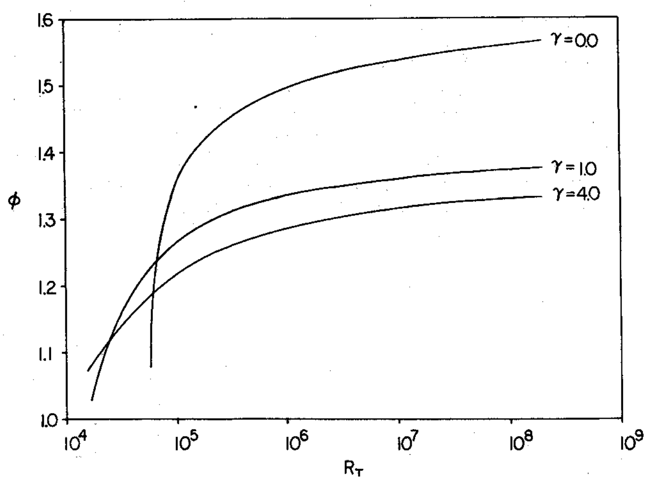


Fig. 9 Performance of an augmentor with an optimized inlet.

The characteristic velocity used in creating dimensionless quantities is one derived from the thrust produced by the primary jet

$$u_c = \sqrt{T_0/\rho 2H} \tag{14}$$

The Reynolds number used here (denoted R_T) is defined as

$$R_T = \frac{2H\sqrt{T_0/\rho 2H}}{\mu/\rho} \tag{15}$$

Optimal configurations, determined over a wide range of R_T and for three values of the velocity ratio:

$$\gamma = u_\infty / u_c \tag{16}$$

Figure 9 shows the variation in the performance of a thrust augmentor with an optimized inlet as a function of both Reynolds number and the freestream speed. The results show that the performance is an increasing function of Reynolds number with strongest dependence in the low Reynolds number range. The rapid increase in performance at low Reynolds numbers is associated with transition from a laminar to a turbulent boundary layer. When a nonzero freestream speed is included, the presence of a strong favorable pressure gradient following the stagnation point helps to energize the boundary layer on the inner side of the inlet, thus, allowing for relatively increased levels of performance in the laminar regime.

Performance decreases substantially with increasing freestream speed. This is to be expected as a result of the reduced shear at the jet boundary and a reduced rate of entrainment.

A few representative optimal shapes corresponding to the performance curve are shown in Fig. 10. The results show that the optimal design shapes are a much stronger function of Reynolds number than they are of the free-stream speed. At low Reynolds number the optimal nozzle position is located up to one channel width ahead of the shroud, while the inlet is slightly expanded. As the Reynolds number is increased, the nozzle moves roughly up to the entrance plane of the shroud. The inlet lips rotate through the horizontal and then toward the jet as the Reynolds number is increased. The length of the

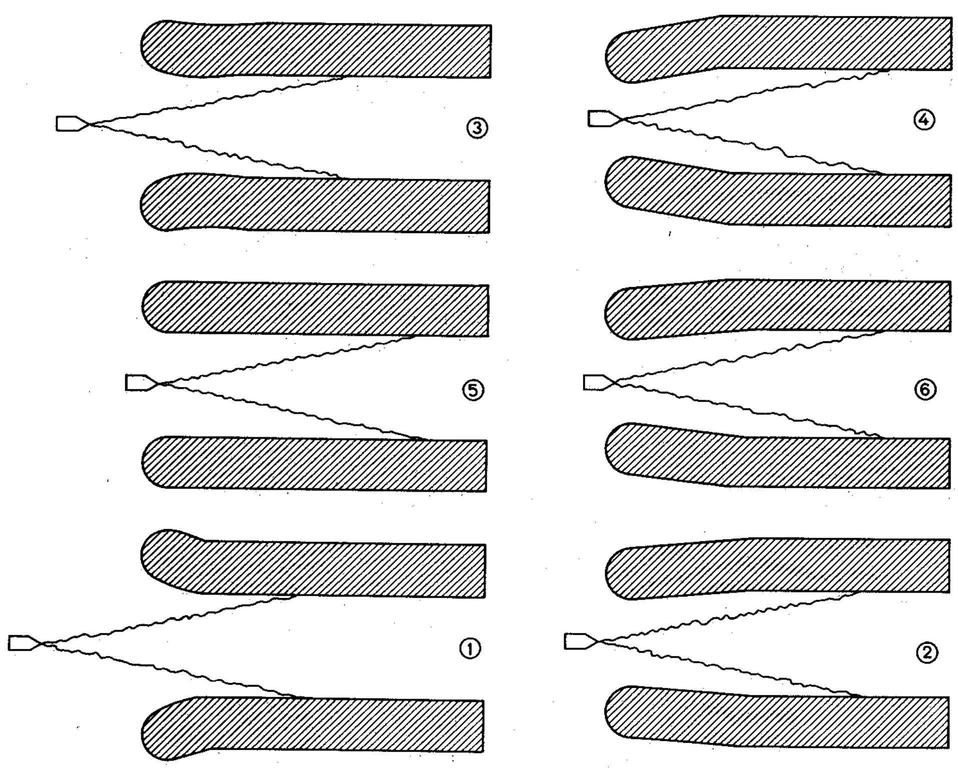


Fig. 10 Optimal configurations:
1) $R_T = 6.8\times10^4$, $\gamma = 0.0$;
2) $R_T = 1.0\times10^7$, $\gamma = 0.0$;
3) $R_T = 2.7\times10^4$, $\gamma = 4.0$;
4) $R_T = 9.2\times10^7$, $\gamma = 4.0$;
5) $R_T = 1.0\times10^5$, $\gamma = 1.0$;
6) $R_T = 6.4\times10^6$, $\gamma = 1.0$.

inlet lip which is rotated is seen to increase with Reynolds number.

Conclusions and Discussion

A constrained optimization analysis of two-dimensional thrust augmentor inlets has been conducted using a viscous-inviscid interaction methodology which combines a higher-order panel method and an integral method. Boundary layer separation within the inlet is shown to be an important design consideration.

An interesting observation is that barring separation and constraining the mixing channel width to be a constant, the optimal configurations each have an inlet which constricts the entering flow. As the inlet is narrowed, the entrained flow is forced to achieve a higher speed as it enters the shroud. This increase in inlet velocity reduces the rate of shear produced at the jet boundary, thereby, reducing the entrainment. However, at the same time, the increased inlet velocity enhances the convective acceleration about the nose, increasing the induced thrust. The increase in fluid speed about the nose plays a more important role than does the decrease in entrainment. Bevilaqua and DeJoode have observed a similar trend for the case of a straight walled inlet where the ratio formed between the inlet area and the jet nozzle area is varied.[3]

An important conclusion of the optimization study is that boundary layer separation is the determining factor in the maximum obtainable performance. It is clear that some means of boundary layer control would not only substantially increase the performance, but also allow a single configuration to operate efficiently over a wider range of Reynolds numbers and free-stream speeds. As a means of boundary layer control, the use of a wall jet may be advantageous since it is likely to also enhance the turbulent mixing within the shroud.

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