Because S_p is inversely proportional to ν_0, viscosity plays the role of a wave-attenuation agent. Moreover, the chamber geometry appears to have an effect on the penetration number. In fact, decreasing the motor's effective radius causes the penetration depth to grow proportionately larger, which is to be expected because the effect of blowing becomes more appreciable when the cross-sectional area is reduced.

Conclusions

The classical concepts of boundary-layer theory regarding inner, near-wall, and outer, external regions are almost reversed for unsteady flows over transpiring surfaces. Near the wall, instead of observing the traditionally thin viscous layer, a thick rotational layer is established near the solid boundary when sidewall injection is introduced, and this can be ascribed to the strong vortical transport in the radial direction. The acoustic boundary layer, in the context described here, is a region of highly concentrated vorticity. The corresponding penetration depth is, therefore, a measure of the vortical reach into the core. The thin layer where viscous friction is important is removed from the wall to the edge of the rotational region. The penetration depth appears to be a direct function of a similarity parameter that is 1) proportional to the cube of the injection speed, 2) inversely proportional to the square of the frequency, and 3) inversely proportional to the viscosity and chamber effective radius. This dependence is in agreement with empirical observations and numerical simulations. Finally, the pressure-to-velocity phase shift is found to vary from a few degrees or less at the wall to 90 deg along the core after undergoing a phase overshoot that is reminiscent of the Richardson effect. At the wall the phase shift is controlled by the quotient of the convection and diffusion speeds of the vortical waves.

References

[1]Majdalani, J., and Van Moorhem, W. K., "Improved Time-Dependent Flowfield Solution for Solid Rocket Motors," *AIAA Journal*, Vol. 36, No. 2, 1998, pp. 241–248.

[2]Flandro, G. A., "On Flow Turning," AIAA Paper 95-2530, July 1995.

[3]Majdalani, J., and Van Moorhem, W. K., "A Multiple-Scales Solution to the Acoustic Boundary Layer in Solid Rocket Motors," *Journal of Propulsion and Power*, Vol. 13, No. 2, 1997, pp. 186–193.

[4]Richardson, E. G., "The Amplitude of Sound Waves in Resonators," *Proceedings of the Physical Society, London*, Vol. 40, No. 27, 1928, pp. 206–220.

[5]Beddini, R. A., "Reacting Turbulent Boundary-Layer Approach to Solid Propellant Erosive Burning," *AIAA Journal*, Vol. 16, No. 9, 1978, pp. 898–905.

[6]Beddini, R. A., "Injection-Induced Flows in Porous-Walled Ducts," *AIAA Journal*, Vol. 24, No. 11, 1986, pp. 1766–1773.

[7]Beddini, R. A., and Roberts, T. A., "Turbularization of an Acoustic Boundary Layer on a Transpiring Surface," *AIAA Journal*, Vol. 26, No. 8, 1988, pp. 917–923.

[8]Beddini, R. A., and Roberts, T. A., "Response of Propellant Combustion to a Turbulent Acoustic Boundary Layer," *Journal of Propulsion and Power*, Vol. 8, No. 2, 1992, pp. 290–296.

[9]Cherng, D. L., Yang, V., and Kuo, K. K., "Numerical Study of Turbulent Reacting Flows in Solid-Propellant Ducted Rocket Combustors," *Journal of Propulsion and Power*, Vol. 5, No. 6, 1989, pp. 678–685.

[10]Jarymowycz, T. A., Yang, V., and Kuo, K. K., "Numerical Study of Solid-Fuel Combustion Under Supersonic Crossflows," *Journal of Propulsion and Power*, Vol. 8, No. 2, 1992, pp. 346–353.

[11]Tseng, I. S., and Yang, V., "Combustion of a Double-Base Homogeneous Propellant in a Rocket Motor," *Combustion and Flame*, Vol. 96, No. 4, 1994, pp. 325–342.

[12]Roh, T. S., Tseng, I. S., and Yang, V., "Effects of Acoustic Oscillations on Flame Dynamics of Homogeneous Propellants in Rocket Motors," *Journal of Propulsion and Power*, Vol. 11, No. 4, 1995, pp. 640–650.

[13]Apte, S., and Yang, V., "Effects of Acoustic Oscillations on Turbulent Flowfield in a Porous Chamber with Surface Transpiration," AIAA Paper 98-3219, July 1998.

[14]Vuillot, F., and Avalon, G., "Acoustic Boundary Layer in Large Solid Propellant Rocket Motors Using Navier–Stokes Equations," *Journal of Propulsion and Power*, Vol. 7, No. 2, 1991, pp. 231–239.

[15]Culick, F. E. C., "Rotational Axisymmetric Mean Flow and Damping of Acoustic Waves in a Solid Propellant Rocket," *AIAA Journal*, Vol. 4, No. 8, 1966, pp. 1462–1464.

[16]Sexl, T., "Über den von E. G. Richardson Entdeckten 'Annulareffekt,'" *Zeitschrift für Physik*, Vol. 61, No. 6, 1930, pp. 349–362.

[17]Richardson, E. G., and Tyler, E., "The Transverse Velocity Gradient near the Mouths of Pipes in Which an Alternating or Continuous Flow of Air is Established," *Proceedings of the Royal Society of London, Series A*, Vol. 42, No. 1, 1929, pp. 1–15.

[18]Rott, N., *Theory of Time-Dependent Laminar Flows, High Speed Aerodynamics and Jet Propulsion—Theory of Laminar Flows*, Vol. 4, edited by F. K. Moore, Princeton Univ. Press, Princeton, NJ, 1964, pp. 395–438.

[19]Flandro, G. A., "Effects of Vorticity Transport on Axial Acoustic Waves in a Solid Propellant Rocket Chamber," *Combustion Instabilities Driven by Thermo-Chemical Acoustic Sources*, edited by A. S. Hersh, I. Catton, and R. F. Keltie, Noise Control and Acoustics Vol. 4, American Society of Mechanical Engineers, New York, 1989, pp. 53–61.

[20]Flandro, G. A., "Effects of Vorticity on Rocket Combustion Stability," *Journal of Propulsion and Power*, Vol. 11, No. 4, 1995, pp. 607–625.

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Correlation for Formation of Inlet Vortex

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Introduction

IT is well known that under certain conditions, a tornado-like vortex is formed between an air inlet or a water intake and a nearby solid wall or water surface (see, e.g., Ref. 1). The properties of the flow with vortex are so radically different from the case without it that one cannot ignore the possibilities and the consequences of the vortex in any application. In the case of a jet engine inlet of an aircraft, the consequences range from reduced engine performance to damage of engine components due to ingestion of foreign objects by the action of the vortex motion.[2–4]

On the basis of the results of his pioneering experiments, Kline[2] gave three conditions for the formation of the inlet vortex: 1) the existence of vorticity in the ambient flow, 2) a stagnation point on the wall, and 3) an updraft from the stagnation point to the inlet. Using a twin-inlet model, in which one inlet acts like an image of the other instead of a solid wall, Kline[5] showed that the boundary layer on the wall is not critical as the source of the vorticity. Also, Shin et al.[6] pointed out that, when the incident flow is at yaw, circulation is generated around the inlet itself, and the ambient vorticity is not needed. Hence, the most critical condition for inlet vortex formation is the requirement of the stagnation point on the wall. Based on this argument, it has been widely believed that the examination of the formation of the stagnation streamline would give a good idea of the possibility of forming a vortex.[7,8]

The present Note takes up the question of the conditions of the formation of the inlet vortex and tries to give more quantitative answers than before by examining the existing data and newly obtained data on large inlet diameters mounted close to a wall or ground such as recent high-bypass engines. The present results indicate that a simple method based on the potential flow stagnation point gives the correct trend for formation of a vortex but predicts a vortex at higher suction velocity than observed in experiments.

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Data on Inlet Vortex and Their Correlation

Figure 1 shows the general inlet flowfield near a wall that we consider in detail. It may be thought of as a simplification of a typical flow around the inlet of a wing-mounted engine moving along a runway at a speed of V_o. V_i is the velocity averaged over the inlet throat, the minimum-area section; D_i is the internal diameter at the throat; and H is the height of the inlet axis from the wall or ground. A_o and A_i are the cross-sectional areas of the streamtube entering the inlet far upstream and at the inlet throat, respectively, which are used to represent the inlet mass flow. A number of investigations of inlet vortex for the present configuration have been carried out by many workers, and many sets of data are now available. Figure 2 summarizes the data[3,6,8–10] in terms of two parameters: the relative position of the inlet with respect to the wall and the relative strength of the inlet as the area ratio of the streamtube captured by the inlet. Figure 2 also contains our new data and computational results that are explained later. We have found that these two parameters collapse the data better than the way done previously by Shin et al.,[6] particularly in the experiments involving small H/D_i and high Mach numbers. Experiments conducted in ambient flow at various directions relative to the inlet axis are also included. The flags on the symbols indicate the ambient flow direction relative to the downstream direction of the inlet axis. The 3 o'clock position corresponds to zero yaw. For clarity of the presentation, only the data points near the vortex/no-vortex boundary are plotted. It is seen that the vortex/no-vortex boundary implied by all of the data points can be well correlated by the dashed curve whose equation is

$$A_o/A_i = 24(H/D_i) - 17 \qquad (1)$$

This is remarkable because the data shown here range from water tunnel data to wind tunnel and test field data. The methods of detection of a vortex also are quite different from one case to another. In most cases, however, appearance of a vortex was reported to be rather abrupt and clearly defined.

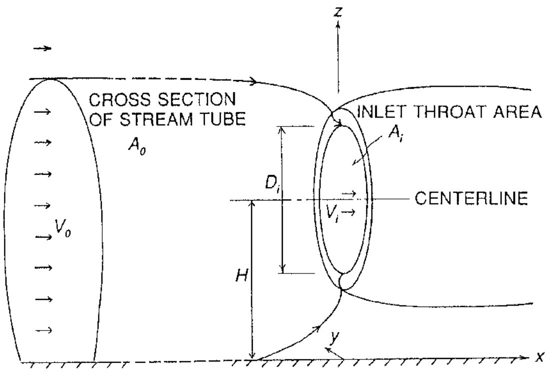


Fig. 1 Definition of flow around an inlet near a wall.

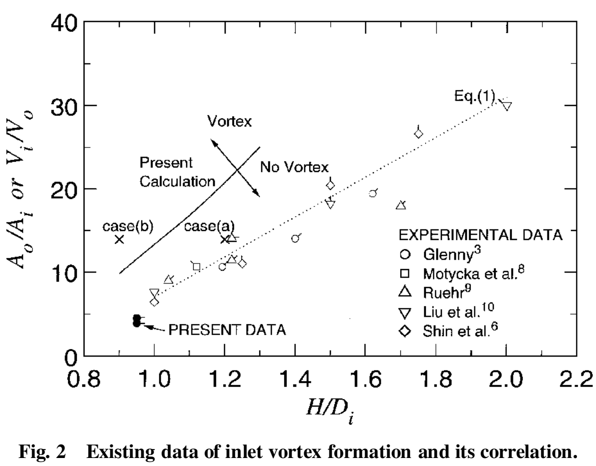


Fig. 2 Existing data of inlet vortex formation and its correlation.

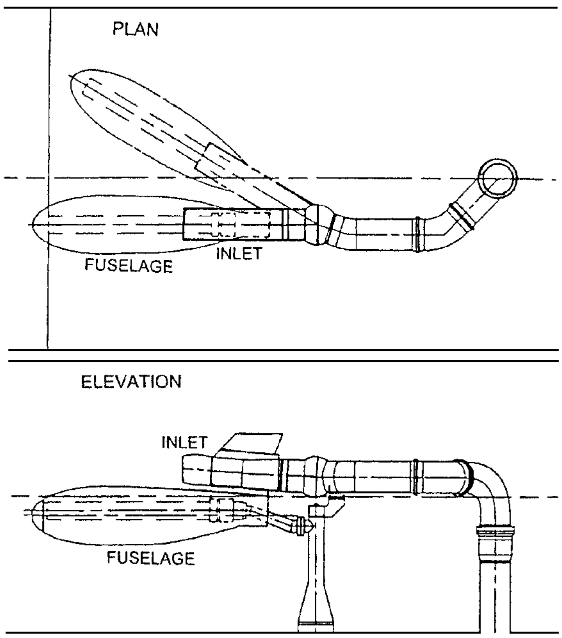
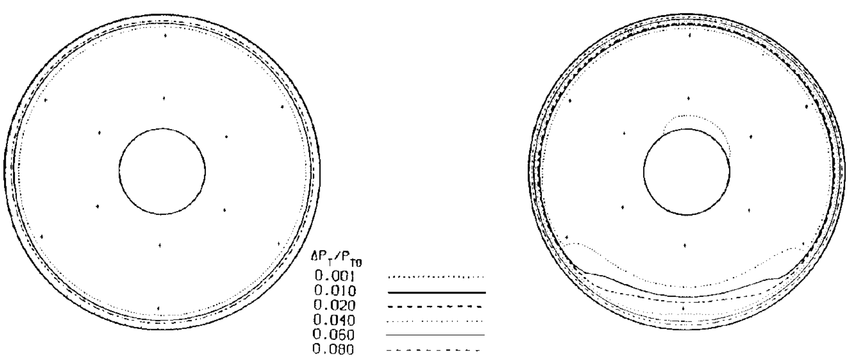


Fig. 3 Test of inlet on aft fuselage.

The existing data do not cover the cases for small H/D_i, or inlets of large diameters such as recent high-bypass ratio engines, and so we examine our test results of an inlet with large diameter, as large as $D_i = 0.95H$. The inlet is mounted on a simulated fuselage, as shown in the setup in Fig. 3. The entire model can be yawed, and a pipe is connected to the aft end of the inlet to withdraw the flow by a pump. It was operated at a high mass flow rate such that the duct was nearly choked. The tunnel freestream Mach numbers were 0.1, 0.15, and 0.20. The total pressure was measured inside the inlet using radial arrays of pitot tubes positioned at six circumferencial angles at the presumed engine fan face. The rake included some Kulite transducers so that the fluctuating pressure could also be measured at selected positions. The vortex lies in the bottom center of the inlet cross section if it is formed, so that these large fluctuations in the output of these probes and depression of the total pressure in that region indicate occurrence of a vortex. Figures 4a and 4b show the contours of constant total pressure measured by the pitot rake. Both cases are the results of the freestream Mach number of $M_o = 0.1$, and Fig. 4a is a case where $A_o/A_i = 3.45$ and $M_i = 0.357$, in which no vortex was formed and the constant pressure curves are very smooth curves parallel and very close to the inlet inner wall. Figure 4b is a case where $A_o/A_i = 4.82$ and is a case with clear vortex presence. An appreciable total pressure defect is seen near the bottom, and the contours curve off the wall. The borderline between the cases with and without vortex are also indicated in Fig. 2.

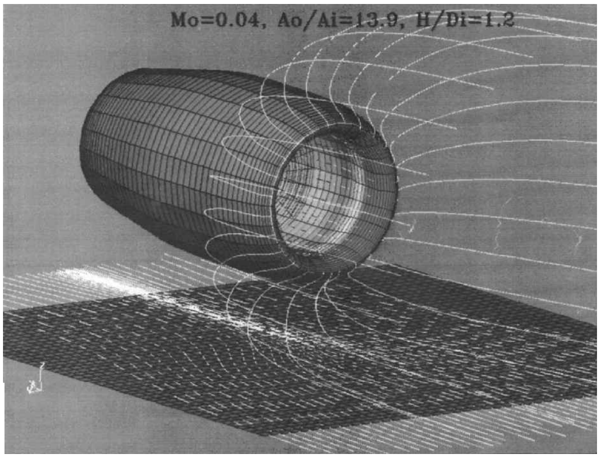
Analysis and Discussion

To explain the described experimental relation using Kline's criterion,[2] simple potential flow calculations were performed for various values of A_o/A_i and H/D_i with a typical axisymmetric inlet. The calculation used a Douglas Neumann program modified for inlet flow calculations.[11] The inflow at 6 inlet diameters upstream and the outflow at a plane inside the inlet close to the aft end of the nacelle were specified. Two examples of the calculation are shown in Figs. 5a and 5b. Figure 5a shows the results of the case $A_o/A_i = 14$ and $H/D_i = 1.2$, and Fig. 5b shows the results for the same inlet flow rate A_o/A_i, but the inlet is placed closer to the wall at $H/D_i = 0.9$. It is seen that in the case of Fig. 5a, there is no stagnation point on the ground, and streamlines traced near the ground are all swept downstream. Figure 5b, however, shows that a stagnation point forms just below the inlet face, and the near-ground streamlines are sucked into the inlet. According to the stagnation streamline criterion, this means formation of a vortex. Repeated calculations of similar kind for various values of A_o/A_i and H/D_i

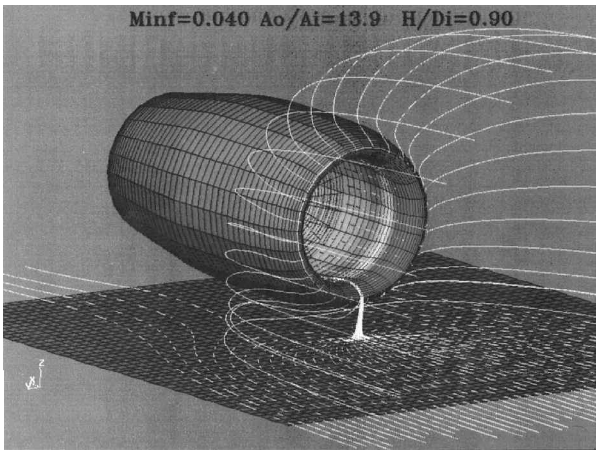


a) $A_o/A_i = 3.45$**, no vortex** **b)** $A_o/A_i = 4.82$**, vortex**

Fig. 4 Examples of total-pressure contour results.



a) $A_o/A_i = 14$**,** $H/D_i = 1.2$**, no vortex**



b) $A_o/A_i = 14$**,** $H/D_i = 0.9$**, vortex**

Fig. 5 Examples of potential flow calculations.

have been conducted, and the boundary between vortex and no-vortex formation is shown in Fig. 2 as a solid line. It is seen that the potential flow calculation predicts a trend similar to the experimental correlation, but the curve lies higher, which indicates a higher mass flow rate for vortex formation for a given H/D_i.

In their comparison, Motycka et al.[8] noted that the potential flow model freestream speed needed to blow away the vortex was much lower than their own experimental observation and the data of Glenny.[3] They attributed this discrepancy tentatively to the difference in the Rossby number (inverse of normalized ambient vorticity level). Careful examination of Glenny's data indicates that there is no consistent trend with Rossby number. It is quite possible that a sufficiently strong vortex stretching can occur even without a stagnation streamline. A computation may be made that includes such effects as the upstream flow nonuniformity using the complete Navier–Stokes equations or its Reynolds-averaged ones with an appropriate turbulence model to examine conditions when a vortex core forms. Though the authors[12] are attempting such computation, for a reasonably large Reynolds number appropriate for aerodynamic applications, the vortex core becomes too small to be resolved by a realistic grid.

Conclusions

The present study indicates that a good correlation can be obtained for the occurrence of an inlet vortex in terms of relative flow rate and the position of the inlet irrespective of ambient wind direction. It also revealed that the potential flow stagnation point criteria previously used for estimating the presence of a vortex give the correct trend but predict vortex at higher inlet velocities. An analysis indicates that sufficiently strong streamline contraction can occur to stretch existing vortex without a stagnation point, but it will have to be analyzed with complete Navier–Stokes equations. At present a numerical method that can resolve a fine vortex filament at a practically large Reynolds number requires too many grid points for a moderate-size computer.

References

[1]Lugt, H. J., *Wirbelstromung in Natur und Technik*, Verlag, Berlin, 1979.

[2]Kline, H., "Small Scale Tests on Jet Engine Pebble Aspiration Test," Douglas Aircraft Co., Rept. SM-14885, Long Beach, CA, Aug. 1953.

[3]Glenny, D. E., "Ingestion of Debris into Intakes by Vortex Action," Aeronautics Research Council, CP-1114, 1970.

[4]Motycka, D. L., "Ground Vortex-limit to Engine Reverser Operation," *Journal of Engineering for Gas Turbines and Power*, Vol. 98, April 1976, pp. 258–266.

[5]Kline, H., "An Aerodynamic Screen for Jet Engines," Douglas Aircraft Co., Rept. SM-22625, Long Beach, CA, March 1957.

[6]Shin, H. W., Greitzer, E. M., Cheng, W. K., Tan, C. S., and Shippe, C. L., "Circulation Measurements and Vortical Structure in an Inlet-Vortex Flow Field," *Journal of Fluid Mechanics*, Vol. 162, 1986, pp. 463–487.

[7]Colehour, J. L., and Farquhar, B. W., "Inlet Vortex," *Journal of Aircraft*, Vol. 8, No. 1, 1970, pp. 39–43.

[8]Motycka, D. L., Walters, W. A., and Muller, G. L., "An Analytical and Experimental Study of Inlet Ground Vortex," AIAA Paper 73-1313, 1973.

[9]Ruehr, W. C., "Inlet Vortex Ingestion Characteristics—GE 1/16 Scale Model Test Results Scaled to CF6 Engine Size," General Electric, Technical Information Series Rept. R75AEG384, 1975.

[10]Liu, W., Greitzer, E. M., and Tan, C. S., "Surface Static Pressure in an Inlet Vortex Flow Field," *Journal of Engineering for Gas Turbines and Power*, Vol. 107, April 1985, pp. 387–393.

[11]Hess, J. L., Friedman, D. M., and Clark, R. W., "Calculation of Compressible Flow About Three-Dimensional Inlet with Auxiliary Inlets, Slats and Vanes by Means of Panel Method," McDonnell Douglas Corp., Rept. MDC J3789, 1985.

[12]Nakayama, A., and Jiao, T., "Numerical Calculation of a Vortex Flow in an Intake Bay," *Proceedings of the 53rd Annual Conference of the Japan Society of Civil Engineers*, Vol. 2, Japan Society of Civil Engineers, Tokyo, 1998, pp. 626, 627.

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