Method for Producing a Uniform, Low Reynolds Number Jet

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Nomenclature

R = nozzle radius
Re = Reynolds number based on nozzle diameter
u = local velocity
u_{max} = maximum velocity at a given axial station
x,y = axial and radial coordinates, respectively

Introduction

WITH the increased interest in monitoring the Earth's upper atmosphere, it has become necessary to develop testing facilities on the ground in which instrument calibrations in a simulated high-altitude flight environment can be performed. Perhaps the most difficult environment to simulate is that encountered by an instrument package falling slowly through the atmosphere while suspended beneath a parachute. For altitudes greater than 100,000 ft, the combination of low atmospheric density and low fall velocity can produce a very low flow Reynolds number. For Reynolds numbers less than about 1000, based on nozzle diameter, conventional wind-tunnel nozzles develop extremely thick boundary layers. Therefore, simulation of the flight environment with a conventional nozzle is very expensive since a large nozzle is required to produce a sizable stream of uniform properties.[1]

In one attempt to produce a simple inexpensive nozzle, a 2-in. diam plate with 37 holes was investigated,[1] anticipating that the small jets emanating from the plate would combine to form a uniform stream. This experiment was unsuccessful because a uniform flow was not established until the flow had progressed many nozzle diameters downstream. However, an extension of this concept to a much larger number of very small jets, viz, a porous plate, did provide a method for producing a uniform, low Reynolds number jet almost immediately downstream of the nozzle.[2] This Note describes the method and presents some typical jet velocity profiles for nozzle Reynolds numbers from 50 to 1000.

Apparatus

Figure 1 shows a schematic diagram of the apparatus used to generate the low Reynolds number jet. The porous plate was bolted to the end of a $7\frac{5}{8}$ in. diam pipe which penetrated the wall of a large vacuum chamber. The plate was made of $\frac{1}{8}$-in. thick sintered stainless steel which is sold commercially as a filter material. The plate was made of five screens of varying mesh size, sintered to form a rigid plate. The innermost screen had a mesh size of about 5 μin. The outer screens were of larger mesh to provide the necessary rigidity. The sintered plate can be cut, drilled, etc., using standard machining practices.

Velocity profiles were measured downstream of the nozzle using a $\frac{3}{8}$-in. diam open-end impact tube essentially identical to one calibrated by Sherman.[3] Viscous corrections based on Sherman's data were applied to the measured velocity profiles.

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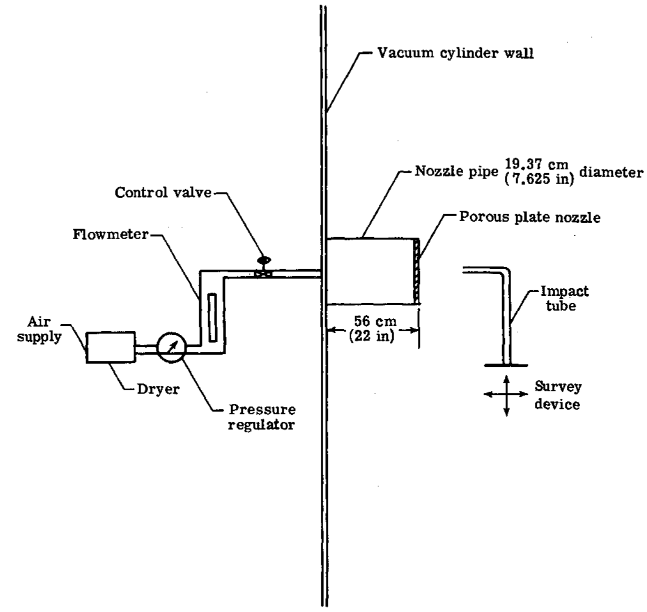

Fig. 1 Schematic diagram of test apparatus.

Static pressure was measured outside the jet near the nozzle exit. For the velocity calculations, the static pressure was assumed constant throughout the jet mixing region. The nominal velocity for the lowest Reynolds number was 100 ft/sec with a corresponding Mach number of 0.089, and for the Reynolds numbers of 200 and 1000, the nominal velocity was 200 ft/sec with a Mach number of 0.178. These Mach numbers were low enough to insure that the flow was essentially incompressible.

Results

Figures 2 and 3 present measured velocity profiles and jet spreading data for Reynolds numbers between 50 and 1000 based on the diameter of the nozzle. For comparison, theoretical calculations based on the analysis of Fox, Sinha, and Weinberger[4] are also shown. Because measured velocity profiles were symmetric, only half-jet profiles are shown. In Fig. 2a half-jet velocity profiles ($y/R = 0$ corresponds to the nozzle centerline) are shown for three stations along the nozzle axis for $Re = 1000$. The measured velocity profile is not quite uniform across the jet at $x/R = 1.0$ probably because of the sudden expansion of the flow at the entrance of the nozzle pipe just upstream of the porous nozzle. The nonuniformity can be minimized either by increasing the pressure drop across the plate (by using a thicker porous plate) or by installing screens in the nozzle pipe. However, with the present configuration the velocity profile is rapidly smoothed by viscous effects as the flow moves downstream. At $x/R = 7.0$ the velocity is uniform within $\pm 1\%$ over most of the nozzle exit area.

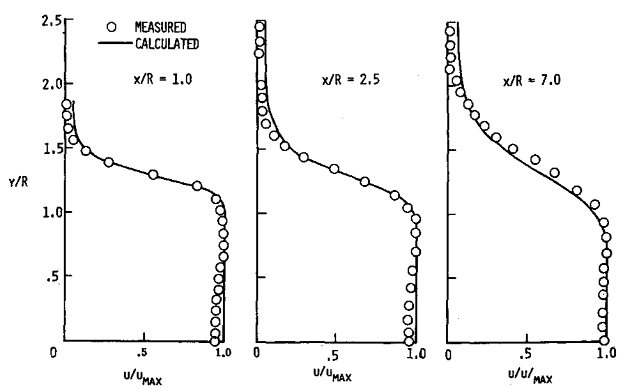

Fig. 2a Jet velocity profiles for $Re = 1000$.

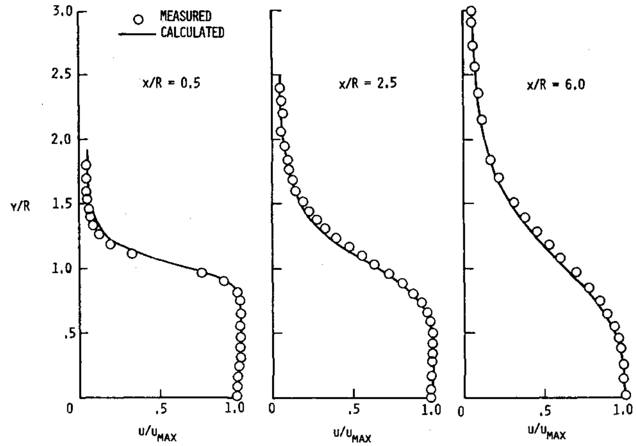

Fig. 2b Jet velocity profiles for $Re = 200$.

Figure 2b shows jet velocity profiles for $Re = 200$. A large region of uniform flow exists at $x/R = 0.5$ and $x/R = 2.5$, and the potential core extends downstream to about $x/R = 6.0$. It should be noted that a conventional nozzle would be completely filled by the boundary layer at Reynolds numbers less than about 200.

Jet velocity profiles for $Re = 50$ are shown in Fig. 2c for $x/R = 1.0$, 2.5, and 5.0. The data indicate that there is no significant region of uniform flow as far downstream as $x/R = 1.0$. The calculated results, which are generally in good agreement with the data, indicate that the potential core ends at about $x/R = 1.0$ and that at $x/R = 0.5$ the velocity is uniform out to $y/R = 0.5$. For nozzle Reynolds numbers less than 50, the potential core becomes too short to have a useful region of uniform flow.

The measured and calculated spreading rate of the jet is shown in Fig. 3 in the form of the half-value radius (value of y/R at which $u/u_{\max} = 0.5$) for Reynolds numbers from 50 to 1000. The

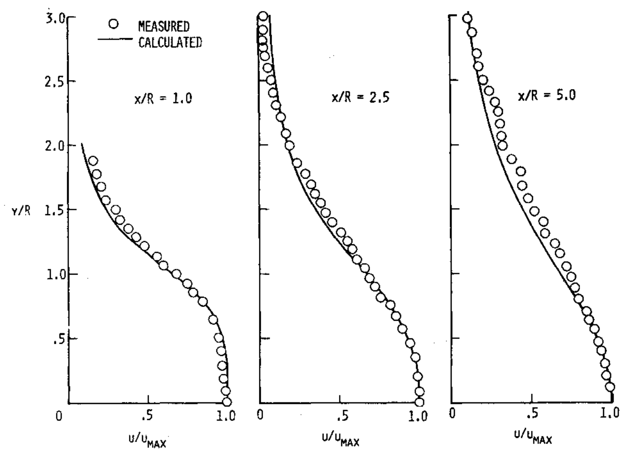

Fig. 2c Jet velocity profiles for $Re = 50$.

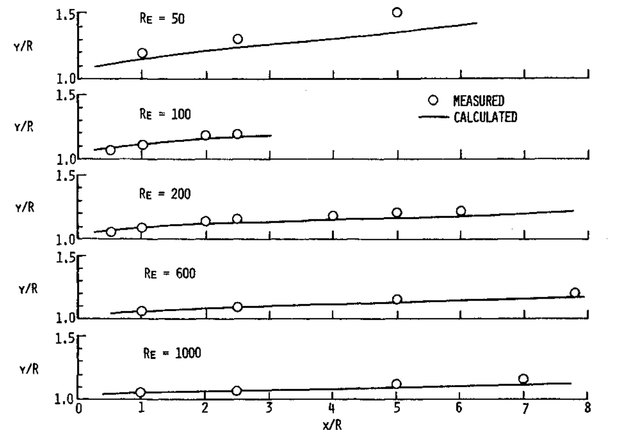

Fig. 3 Variation of the 0.5 velocity radius with x/R and Reynolds number.

computed results based on the boundary-layer equations are seen to be in good agreement with the measured data (as they were for the velocity profiles shown in Fig. 2) and therefore could be used to design a jet to give a desired uniform flow field for any Reynolds number.

Conclusions

The porous plate nozzle provides a simple, inexpensive method for producing a reasonably uniform, incompressible jet for nozzle Reynolds numbers between 50 and 1000. For Reynolds numbers greater than 1000, a conventional contoured nozzle is recommended since the flow Mach number can be determined from the stagnation chamber and static pressure measurements without using an impact tube with attendant viscous corrections. For Reynolds numbers below about 50, the potential core is less than one nozzle radius long and therefore is too short for practical use.

Although this concept was developed for simulating the Earth's upper atmosphere, it has potential application in simulating the flight environments of other planetary atmospheres. One possible application is simulating the environment encountered by a parachuted instrument landing on Mars. The concept works well with gases other than air and appears to be limited only by Reynolds number.

References

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