1998

Wind Tunnel Tests of a Shrouded Aircraft Inlet

D. M. Murphy

Aeronomy Laboratory, NOAA/ERL, Boulder, CO

M. E. Schein

Aeronomy Laboratory, NOAA/ERL, Boulder, CO

Follow this and additional works at: <http://digitalcommons.unl.edu/nasapub>

Murphy, D. M. and Schein, M. E., "Wind Tunnel Tests of a Shrouded Aircraft Inlet" (1998). *NASA Publications*. 183.
<http://digitalcommons.unl.edu/nasapub/183>

This Article is brought to you for free and open access by the National Aeronautics and Space Administration at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in NASA Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Wind Tunnel Tests of a Shrouded Aircraft Inlet

D. M. Murphy and M. E. Schein¹*

AERONOMY LABORATORY, NOAA/ERL, BOULDER, CO 80303

ABSTRACT. We describe tests of a shrouded aerosol inlet for a high-altitude jet aircraft. Both the lip of the inlet and the shroud are NACA (National Committee for Aeronautics, now known as NASA, or National Aeronautics and Space Administration) airfoils. Wind tunnel tests show a smooth growth of the boundary layer in the inlet, with an undisturbed core more than 1 m back from the entrance. The shroud makes the inlet performance insensitive to angle of attack. Aerosol transmission tests showed accurate sampling, although the Stokes numbers accessible in the wind tunnel were less than 0.2. AEROSOL SCIENCE AND TECHNOLOGY 28:33–39 (1998)
© 1998 American Association for Aerosol Research

INTRODUCTION

The problem of bringing aerosols from outside a jet aircraft into aerosol instruments without changing the number or composition of aerosols is a difficult problem. The Airborne Aerosol Inlet Workshop held in 1991 found that many existing aircraft aerosol inlets were inadequate (Baumgardner et al., 1991). In particular, 50–90% losses of aerosols have been observed in aircraft inlets (Huebert et al., 1990). As the Mach number becomes larger, isokinetic sampling is important not only to maintain representative aerosol numbers but also to avoid ram heating. Such heating is over 20 K if the flow is brought to stagnation from a Mach number of 0.7, enough to affect volatile species on the aerosols.

We are building an aircraft version of a new instrument to analyze the chemical composition of single particles (Murphy and

Thomson, 1995). This instrument is intended to be flown in the nose of a WB-57F aircraft, which can reach altitudes above 18 km. Our approach to an inlet is to bring in a large excess flow through a 5.2 cm ID circular duct at isokinetic conditions, then sample into our instrument from the core of that flow. The inlet extends about 40 cm ahead of the tip of the nose in order to sample aerosols before they are warmed by the stagnation region ahead of the nose. The Reynolds number of such a duct at Mach 0.7 ranges from $5.5 \cdot 10^5$ at 8 km to $1.1 \cdot 10^5$ at 19 km.

At high Reynolds and Mach numbers, sharp-edged inlets, traditionally employed to avoid particle bounce, are susceptible to both flow separation and shock formation at the entrance. Instead of a sharp-edged inlet, we use an airfoil at the entrance to suppress flow separation and shock formation. A shroud reduces the sensitivity of this inlet to angle of attack. The inlet is shown in Figure 1. The entrance is a NACA Series 1 airfoil with a modified inner radius of 2.8 mm. This larger inner radius inhibits flow separation. An ellipse might further suppress flow sep-

*The Author to whom correspondence should be addressed.

¹ Also with the Cooperative Institute for Research in Environmental Sciences, University of Colorado.

FIGURE 1. Drawing of the shrouded inlet wind tunnel model described in this paper.

FIGURE 2. (a) Examples of velocity profiles through the boundary layer. Arrows show the boundary layer thicknesses used in the next panel (b) Boundary layer thickness as a function of distance from the entrance. Dashed curve derived from figure in Barbin and Jones (1963).

aration (Soderman et al., 1991). The shroud is a toroidal NACA 0009 symmetrical cross section airfoil.

WIND TUNNEL TESTS

Tests were conducted at the U.S. Air Force Academy wind tunnel in Colorado Springs. This tunnel has a 91 by 91 cm test section and a maximum speed of Mach 0.6. It is run at the ambient pressure of 81 kPa. A full-scale inlet model was used for testing. The lower air speeds and higher air density compared to flight conditions combine to give realistic Reynolds numbers. The length of the duct could be adjusted, as could the position of the shroud relative to the entrance. Three different diameter shrouds were also tested, one of which was made of plexiglass to allow flow visualization at the entrance.

A pitot tube on a computer-controlled motorized probe was used to measure the air velocity at various points in the inlet. The probe mechanism was also encased in an aerodynamic enclosure to avoid upsetting the flow in the test section. Three types of tests were conducted: measuring the boundary layer in the inlet by measuring air velocities, using tufts to visualize the flow, and

comparing the aerosol size distribution in the inlet to the preexisting size distribution in the wind tunnel.

BOUNDARY LAYER GROWTH

Boundary layer thicknesses were derived from velocity profiles measured with the pitot probe at 50 points across the diameter of the tube. The probe was positioned relative to the entrance by inserting different sections of various lengths between the entrance and the probe assembly. Results are shown in Figure 2. The boundary layer is thicker farther downstream from the entrance, and the core flow accelerates because of mass continuity as the boundary layer becomes thicker. The inlet is not quite isokinetic, but small difference from isokinetic conditions is satisfactory for our purposes. If desired, the overall flow velocity could be fine-tuned by changing the shape of the flow exit. More important for our purposes, air can be sampled from the core flow as much as 1 m downstream from the entrance without encountering the boundary layer.

Growth of a boundary layer in fully turbulent flow is only weakly dependent on the Reynolds number. For example, it depends on $Re^{1/7}$ for a boundary layer growing on a

flat plate (Blevins, 1992). As shown in the figure, our results at larger Reynolds numbers and those of Barbin and Jones (1963) are all similar, consistent with a weak dependence on the Reynolds number. The exception is our data at $Re = 3.8 \cdot 10^5$. There, the boundary layer thickness is far less than expected. At these Reynolds numbers, laminar boundary layers are much thinner than turbulent boundary layers, so one explanation is that the boundary layer was not fully turbulent at this Reynolds number. In flow over a flat plate, the boundary layer does not always become fully turbulent until $Re \approx 10^6$ (Blevins, 1992). In contrast to our experiments, Barbin and Jones (1963) tripped the boundary layer with a sand surface near the entrance to their inlet, so their inlet was fully turbulent.

Besides velocity profiles, Barbin and Jones also measured the turbulent intensity in the flow at a Reynolds number of $3.9 \cdot 10^5$ and found that the turbulence extends slightly farther from the wall than the boundary layer defined by the velocity. Longitudinal turbulence developed faster than tangential turbulence. Since our sampling position is at a position where the boundary layer is still far from the center of the duct, there is probably little turbulence there. A model by Yakhout and Orszag (1993) supports the Barbin and Jones data.

EFFECT OF SHROUD

The main purpose of the shroud is to avoid flow separation and maintain a consistent velocity profile at non-zero angles of attack. Without the shroud, the inlet performed well up to about a 3° angle of attack. Beyond that, the velocity profile degraded rapidly without the shroud. Figure 3 shows that the shroud clearly improves the performance of the inlet at a 7° angle of attack. The velocity profile with the shroud remained consistent until at least a 10° angle of attack.

The flow into the inlet was visualized by stringing a fine wire with tufts on it across the shroud just ahead of the inlet. The tufts verified the effectiveness of the shroud: they pointed straight into the inlet even when the

angle of attack was non-zero. This continued until the shroud stalled at an angle of attack of about 16° , at which point the tufts vibrated violently in the unsteady flow.

The performance of several shroud positions and sizes was also examined. The shroud was moved up to 7.5 cm behind the nominal position shown in Figure 1, to a point where the tip of the shroud was almost flush with the tip of the inlet. Only a weak dependence in the effectiveness of the shroud was noted for this range of positions. Since the wind forces on the inlet could be reduced substantially if the shroud were smaller, we supplied the Air Force Academy with two smaller shrouds that were tested as a student project by C1C J. Gibson and C1C K. Rouser. At zero angle of attack, changing the shroud diameter from 15 cm to 13 or 10 cm had only a small effect on the flow.

AEROSOL TRANSMISSION

Transmission of aerosols through the inlet was estimated using particle counters to monitor ambient aerosols in the wind tunnel. Due to sampling issues, an initial problem was to determine a reference size distribution of the aerosols in the wind tunnel. We measured the aerosol size distribution in the center of the wind tunnel at low air speeds and saw no change with speed. We also compared the distribution in the boundary layer of the tunnel with that at the center at low air speeds and found no significant differences. We believe that these measurements show that a reference size distribution could be obtained either from the wind tunnel at low speed or from the low-speed boundary layer of the tunnel while it operated at high speed. The latter was used for the comparison here. Additional support for the reference distribution is that the wind tunnel uses outside air and particle size distributions in the wind tunnel were similar to those outside the building.

Two particle counters were used to measure the size distribution. One was a PMS LasAir 1001 counter with a size range of 0.1 to $2 \mu\text{m}$ diameter. The other was a Climet 208A white light counter with a size range of

FIGURE 3. Flow profiles in the inlet. Without the shroud, the flow becomes asymmetric and the total flow is reduced at a 7° angle of attack, probably due to an eddy inside the inlet. With the shroud, the inlet is insensitive to angle of attack. The small bumps in flow velocity near the right wall are due to a hole in the wall where the pitot probe enters the inlet.

0.35 to 9 μm and a custom all-digital pulse height analyzer board.

Figure 4 compares size distributions measured with an isokinetic probe on the center-line of the inlet 71 cm from the entrance with the reference size distribution. The size distributions are quite similar except for the largest bins of each counter, which have so few parti-

cles that the differences are not statistically significant. Since the size distributions were obtained sequentially, there is another possible error due to the stability with time of the ambient aerosols. This latter error could cause the small systematic differences between the distributions seen for the smaller size bins.

The wind tunnel operates at lower velocity

FIGURE 4. Comparison of particle size distributions measured 71 cm from the entrance with a reference distribution. The error bars show the statistical error on one size distribution for a few selected particle diameters. The differences in the largest bins of each counter are not statistically significant.

and higher pressure than flight conditions. Although these conditions counterbalance to provide appropriate Reynolds numbers, the Stokes numbers for particles in the wind tunnel are smaller than expected at 19 km for the same sized aerosols by about a factor of four. Since the Stokes number varies as the square of the particle diameter, the results in Figure 4 are appropriate in flight for aerosols up to a factor of two smaller. That is, the data in Figure 4 showing fairly accurate sampling up to at least $3\ \mu\text{m}$ diameter aerosols in the wind tunnel can be used to predict accurate sampling up to at least $1.5\ \mu\text{m}$ at flight levels. The duct diameter was used for calculating these Stokes numbers. A question that remains is whether the shroud diameter might be more appropriate for calculating the Stokes numbers of particles entering the inlet.

DISCUSSION

Sharp-edged inlets have traditionally been used in aerosol work to avoid particle bounce and because isokinetic flow does not guarantee representative sampling for a blunt inlet (Rader and Marple, 1988). However, airfoil shapes at the inlet tips are essential to avoid flow separation and possible

shock formation at aircraft speeds (Baumgardner et al., 1991). In general, a more rounded shape is required for higher Mach numbers and for larger angles of attack. These shapes are well defined from historical wind tunnel work (Baals et al., 1948), although much of the literature focuses on avoiding flow separation on the outside of an inlet rather than on the inside. For lower-speed aircraft, sharper inlets may be used. Baals et al. (1948) provides good guidance. For instruments that need slower flow, Ram et al. (1995) designed a shrouded inlet that was deliberately not isokinetic.

Our data confirm that an inlet can be built that brings air into the nose of an aircraft with a relatively undisturbed core. Much of our inlet may even be laminar at the higher aircraft altitudes (lower Reynolds numbers). The calculated entrance length for fully developed flow in the turbulent regime is $L_{\text{ent}} = D(14.2 \log_{10} \text{Re} - 46)$ (Blevins, 1992). This entrance length indicates that inlet lengths of well over 1 m are feasible for high-altitude aircraft while maintaining an undisturbed core. These results showing little aerosol loss are only for sampling on the centerline, so they are not directly comparable to the results of Huebert et al. (1990),

which measured substantial losses in the bulk flow.

The shroud has little effect for on-axis flow but is very important for sampling at non-zero angle of attack. A shroud will be more important to aircraft other than the WB-57F, which does not fly with angles of attack as large as 7° . Operation at high angles of attack can also be used to deliberately exclude rain droplets from the sampling probe simply by deliberately tilting the inlet so there is no direct line of sight from the outside to the sampling point (F. Eisele, personal communication, 1995).

It is of interest to note that the Air Force Academy wind tunnel, at an altitude of about 1.8 km above sea level and a maximum speed of over 100 m s^{-1} , can reach conditions of interest to many turboprop atmospheric sampling experiments with no scaling required.

We gratefully acknowledge the assistance of the Air Force Academy, including Major Harvell, Mr. George West, and Lt. Col. Mouch in conducting these tests. This work was funded in part by a grant from the NASA subsonic assessment program.

References

- Baals, D. B., Smith, N. F., and Wright, J. B. Wright (1948). The Development and Application of High-Critical-Speed Nose Inlets, NACA Report no. 920.
- Baumgardner, Huebert, D., B., and Wilson, C. (1991). Extracts from the Meeting Review: Airborne Aerosol Inlet Workshop, NCAR Report TN-362+1A, Boulder, Colorado.
- Barbin, A. R., and Jones, J. B. (1963). Turbulent Flow in the Inlet Region of a Smooth Pipe, *J. Basic Eng.* March 1963:29–34.
- Blevins, R. D. (1992). *Applied Fluid Dynamics Handbook*, Krieger Publishing, Malabar, Florida.
- Huebert, B. J., Lee, G., and Warren, W. L. (1990). Airborne Aerosol Inlet Passing Efficiency Measurement, *J. Geophys. Res.* 95:16,369–16,381.
- Murphy, D. M., and Thomson, D. S. (1995). Laser Ionization Mass Spectroscopy of Single Aerosol Particles, *Aer. Sci. Tech.* 22:237–239.
- Porter, J. N., Clarke, A. D., Ferry, and G. Ferry, and Pueschel, R. F. (1992). Aircraft Studies of Size-Dependent Sampling through Inlets, *J. Geophys. Res.*, 97, 3815–3824.
- Rader, D. J., and Marple, V. A. (1988). A Study of the Effects of Anisokinetic Sampling, *Aer. Sci. Tech.* 9:283–299.
- Ram, M., Cain, S. A., and Taulbee, D. B. (1995). Design of a Shrouded Probe for Airborne Aerosol Sampling in a High Velocity Airstream, *J. Aerosol Sci.* 26:945–962.
- Soderman, P. T., Hazen, N. L., and Brune, W. H. (1991). On the Aerodynamic Design of Gas and Aerosol Samplers for Aircraft, NASA Technical Memorandum 103854 Ames Research Center, Moffett Field, California.
- Yakhout, A., and Orszag, S. A. (1993). Numerical Simulation of Turbulent Flow in the Inlet Region of a Smooth Pipe, *J. Sci. Computing* 8: 111–121.

Received December 27, 1996; accepted July 31, 1997.