Hi g h - V o l u m e L o w - T u r b u l e n c e I n l e t
for A e r o s o l S a m p l i n g f r o m A i r c r a f t

1999 A n n u a l R e p o r t
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N a t i o n a l S c i e n c e F o u n d a t i o n
D i v i s i o n o f A t m o s p h e r i c C h e m i s t r y

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P r i n c i p a l I n v e s t i g a t o r
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C o - P r i n c i p a l I n v e s t i g a t o r
J a m e s C . W i l s o n
D e p a r t m e n t o f E n g i n e e r i n g
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T h i s R e p o r t C o v e r s t h e P e r i o d
J a n u a r y 1 , 1 9 9 9 t o D e c e m b e r 3 1 , 1 9 9 9

S u b m i s s i o n D a t e :
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T h i s r e p o r t w a s s u b m i t t e d u s i n g F a s t l a n e .
SUMMARY

The goals of this three-year project are to design, construct, and test an operational high-volume low-turbulence aerosol inlet for use on the NCAR C-130 aircraft that will enable the sampling of supermicron aerosols up to 10-µm aerodynamic diameter. Boundary layer suction in the diffuser section of the inlet will be being used as the turbulence mitigation technique. The inlet will deliver a flow rate of 200-400 lpm to supply a high-volume cascade impactor system.

The major milestones for the second year are:

- To experimentally characterize and optimize (in the laboratory) the high-volume low-turbulence inlet system (designed during the first year) that delivers air at a flow rate of 200-400 lpm to supply a high-volume cascade impactor system.
- To design and construct a high-volume low-turbulence inlet suitable for flight operations (the flight testing will be performed during the third year).

The inlet characterization and optimization procedure was carried out at an inlet stagnation pressure of approximately 835 mbar (5300 feet simulated altitude). The test inlets incorporated porous diffusers with physical area ratios (ratio of exit area to entrance area, which approximately equals the ratio of inlet velocity to exit velocity for a conventional diffuser with solid walls) of 2.3 and 4.0. We tested these inlets at an exit flow of 223 lpm. We achieved completely laminar flow (turbulence intensity below 1%) at a suction rate of 70% of the inlet flow for the area ratio 4.0 inlet. We expect that further optimization will reduce the required suction flow.

We also tested the area ratio 4.0 inlet at a simulated pressure altitude of approximately 520 mbar (17500 feet). At this simulated altitude completely laminar flow was achieved with a suction flow rate of only 42% of the entrance flow. This result showed conclusively that boundary layer suction as a means of laminar flow control increased in effectiveness as the simulated altitude increased. At altitudes below the initial test altitude of 835 mbar we expect that the suction rate required to achieve completely laminar flow will increase above the rate at 835 mbar (we cannot test this condition at the local altitude in Denver).

The area ratio 4.0 inlet nearly meets the requirements for a high-volume cascade impactor system. We still must expand the exit diameter to an area ratio of 9.1 to provide the required velocity reduction from the flight velocity of 100 m/s to the desired exit velocity of approximately 5 m/s. We expect to complete this final step in the characterization and optimization of the high-volume low-turbulence inlet during the remainder of the second year of this project.
GOALS OF PROJECT AND OBJECTIVES FOR SECOND YEAR

The goals of this three-year project are to design, construct, and test an operational high-volume low-turbulence aerosol inlet for use on the NCAR C-130 aircraft that will enable the sampling of supermicron aerosols up to 10-µm aerodynamic diameter. Boundary layer suction in the diffuser section of the inlet will be used as the turbulence mitigation technique. The inlet will deliver a flow rate of 200-400 lpm to supply a high-volume cascade impactor system. This project will also develop techniques to design similar inlets for other more general aerosol sampling applications.

The objectives for the second year are to experimentally characterize and optimize (in the laboratory) the high-volume low-turbulence inlet system designed during the first year and to design and construct an inlet system suitable for flight operations (the flight testing will be performed during the third year). The high-volume low-turbulence inlet is an enlarged version of the inlet successfully demonstrated in the laboratory during a prior NSF project. The inlet is being tested in the laboratory over the flight envelope of the C-130 aircraft using a hot film anemometer (HFA) velocity sensor to determine the flow characteristics (time-mean velocity and turbulence intensity) of the air delivered to the cascade impactor system by the inlet. The physical area ratio of the diffuser (the ratio of exit area to entrance area, which approximately equals the ratio of inlet velocity to exit velocity for a conventional diffuser with solid walls) is 9.1. The desired velocity reduction is a factor of approximately 20 (inlet velocity of 100 m/s and exit velocity of approximately 5 m/s). To meet this requirement, it is necessary to remove a minimum of approximately 55% of the entrance flow through the porous surface of the diffuser.

The major milestones for the second year, as described in our proposal (Seebaugh and Wilson, 1997), are:

- To experimentally characterize and optimize (in the laboratory) the high-volume low-turbulence inlet system (designed during the first year) that delivers air at a flow rate of 200-400 lpm to supply a high-volume cascade impactor system.
- To design and construct a high-volume low-turbulence inlet suitable for flight operations (the flight testing will be performed during the third year).

FACILITIES

The High-Altitude Test Facility at the University of Denver (DU) is the primary experimental facility for the laboratory testing of aerosol inlets. The facility consists of a flow conditioning unit that supplies a measured flow of room air at known temperature and pressure to an altitude simulation chamber, the test inlet which interfaces with the altitude simulation chamber, and a large vacuum tank to which the test inlet attaches (Figure 1). A calibrated exit nozzle controls the rate of air flow delivered by the inlet. Valves control the suction air flow. Calibrated laminar flow elements measure the total air flow through the flow conditioning unit and into the inlet. The suction air flow equals the difference between the measured inlet air flow and the measured exit air flow. Vacuum pumps evacuate the vacuum tank and maintain it at low pressure for testing. The vacuum system and the data acquisition were upgraded to meet the requirements for testing the high-volume low-turbulence inlet during the first year of this project.
In the test results reported in the 1998 Annual Report we observed that occasional disturbances in the air circulation patterns in the laboratory propagated into the inlet, resulting in increased turbulence at high suction rates. We constructed a flow isolation system consisting of a large plastic cylindrical duct mounted on the front of the inlet (when the flow conditioning unit was not in use) with a series of honeycomb panels and screens across the entrance to the duct. This eliminated the air circulation induced fluctuations from the inlet. We installed similar panels and screens within the flow conditioning unit and also added screens between the air inlet control valves and the flow conditioning unit. This also eliminated the air circulation induced fluctuations from the inlet. Some minor residual disturbances propagated through the system into the inlet at certain settings of the air inlet control valves. This increased the turbulence intensity within the inlet by less than 2%, which we consider negligible (see the following section on test results for further discussion).

HIGH-VOLUME LOW-TURBULENCE INLET

The laboratory high-volume low-turbulence inlet is illustrated schematically in Figure 2. The hardware consists of the porous diffuser, a front support which incorporates a bellmouth inlet to accelerate the air to the test velocity, a rear support which incorporates the HFA probe, and an outer shroud which completes the suction flow plenum chamber. Previous low volume porous diffusers were cast from Ultra-High Molecular Weight Polyethylene (UHMWPE). This approach proved to be prohibitively expensive for the new, larger inlet. We investigated a porous ceramic material that could be machined to the desired contours. Unfortunately, the hardened reamers required to cut the internal contours were also prohibitively expensive. We then identified an inexpensive porous polyethylene material that could be purchased in cylindrical bars and machined relatively easily. We constructed a duplicate of the previous low volume UHMWPE inlet using a reamer to cut the internal contour. The flow characteristics of this inlet reproduced those of the inlet successfully demonstrated in the prior NSF project.
When we attempted to increase the exit diameter of the inlet by a factor of two to meet the requirements for the high-volume cascade impactor system for the C-130 aircraft, we discovered that the steel blanks required for the larger reamer were also prohibitively expensive. We abandoned the use of the reamer entirely and machined the internal and external contours of the inlet in four interconnecting sections as shown in Figure 2. This approach proved to be very beneficial in that it permitted us to test and optimize the external contours by starting with the front segment alone. We could then test and optimize the inlet with two segments, etc.

An optimization procedure was required to minimize the suction flow required to eliminate turbulence in the diffuser. Any excess suction flow over the minimum amount required would increase the pumping requirements and the costs of flight programs. The optimization procedure involved adjusting the distribution of suction flow with length along the diffuser. At a specified pressure in the suction flow plenum chamber (Figure 2) the thickness of the porous material controls the suction flow per unit length of the diffuser. The procedure involved three steps: (1) selection of an external contour for the inlet segment (the internal contour was fixed at a total expansion angle of 6 degrees), (2) prediction of the amount of suction flow delivered for a selected suction plenum pressure, and (3) testing the inlet to verify the predicted amount of suction flow and measure the turbulence level at the diffuser exit. The diffusers were initially manufactured with constant external diameter to maintain the concentricity of the inner and outer contours. We generally began the optimization procedure with the constant external diameter diffuser. We then reduced the thickness of the porous material at the front end of the diffuser segment, producing a tapered external contour. This process was repeated until a total external angle of 20 degrees was attained. Larger angles that would produce a flight inlet with a blunt forward external contour were avoided.

A second part of the optimization procedure, which was conducted in parallel with that discussed in the previous paragraph, concentrated on the design of the entrance section for the flight inlet. Experience with flight inlets has shown that a sharp leading edge is a desirable design feature. The available porous materials are not compatible with a sharp leading edge, so a
solid diffuser segment will be designed to replace the bellmouth entrance used for the laboratory inlets. This issue is discussed further below.

**TEST RESULTS**

The optimization procedure was carried out using room air without the flow conditioning unit. This gave an inlet stagnation pressure of approximately 835 mbar (5300 feet simulated altitude). We measured the turbulence intensity with the HFA probe positioned about 1 mm from the diffuser inner surface at the exit plane as a function of suction rate and external taper angle. Figure 3 presents the turbulence intensity results for the first segment of the high-volume low-turbulence inlet. The physical area ratio for this segment was 2.3.

![Figure 3](image)

**Figure 3.** Effect of external taper angle on turbulence intensity in the 2.3-AR Porous Inlet at a delivered air flow rate of 223 lpm.

With zero suction the turbulence intensity was approximately 30% for a single diffuser segment with a cylindrical outer surface. Application of boundary layer suction reduced the turbulence intensity near the surface, with completely laminar flow achieved at suction rates above about 50% of the entrance flow. We decreased the thickness of the porous material at the diffuser entrance by tapering the outer contour. The suction flow required to obtain complete laminar flow decreased with each modification, reaching a minimum of about 40% with a total external divergence angle of about 15 degrees (Figure 3).

The procedure outlined above was repeated with two diffuser segments, which gave a physical area ratio of 4.0. We used a new front segment so that we could begin again with a cylindrical outer surface. Figure 4 shows the results for 835 mbar pressure at a diffuser exit flow rate of approximately 220 lpm. Without any external taper, the turbulence intensity increased with increasing suction rate (open square symbols). At 6 degrees external taper (constant thickness of porous material) the turbulence intensity decreased somewhat at the highest
available suction rate (open circular symbols). Maintaining the 6 degree external taper on segment 2 and increasing the taper on segment 1 produced completely laminar flow at suction rates above about 78% of the entrance flow with a total external angle (for segment 1) of 10 degrees (upright triangular symbols). Increasing the taper on segment 1 to 15 degrees decreased the suction rate for completely laminar flow to about 70% of the entrance flow (inverted triangular symbols). Further modifications decreased the turbulence intensity in the range of suction flows between 60% and 70% but did not decrease the minimum suction rate (70%) required to achieve completely laminar flow (diamond symbols and solid square symbols).

At the present time, segment 1 has an initial total external angle of 20 degrees, which decreases to 15 degrees at 75% of the length of that segment. Segment 2 has a total external angle of 8 degrees. This configuration exhibited completely laminar flow at suction rates above about 70% of the entrance flow for the 835 mbar operating pressure (Figure 4).

Figure 5 presents the turbulence intensity profiles measured across the exit plane of the diffuser described in the preceding paragraph for suction rates of 0%, 50%, 60%, and 70% of the total entrance flow at 835 mbar pressure. The flow delivered by the inlet was approximately 220 lpm. With zero suction the turbulence intensity ranged from 9% to over 50%. The 50% profile in Figure 5 exhibits low turbulence near the inlet centerline but high turbulence near the surface (the diffuser surface was at 12.70 mm radius). Increasing the suction rate to 60% decreased the turbulence intensity to less than 1% across nearly half of the inlet cross section. The flow was completely laminar at a suction rate of 70% of the entrance flow.

Figure 6 presents the time-mean velocity profiles at the same suction rates as in Figure 5. With zero suction the mean velocity was very high at the inlet centerline (18.3 m/s). The inflection points in the profile suggest that the flow had separated near the diffuser entrance. As the suction rate was increased the mean velocity profile flattened considerably. At a suction rate
of 70% the time-mean velocity at the centerline was 8.4 m/s. The area-mean exit velocity was 7.5 m/s, and the ratio of the entrance velocity to the area-mean exit velocity was 16.3.

Figure 5. Turbulence intensity profiles at the exit of the two-segment diffuser.

Figure 6. Time-mean velocity profiles at the exit of the two-segment diffuser.

We also tested the two-segment diffuser at a simulated pressure altitude of approximately 520 mbar (17500 feet). Figure 4 shows the dependence of the turbulence intensity near the
surface on the suction flow rate. At this simulated altitude completely laminar flow was achieved with a suction flow rate of only 42% of the entrance flow. This result shows conclusively that boundary layer suction as a means of laminar flow control increases in effectiveness as the simulated altitude increases. Figure 5 shows the profile of turbulence intensity across the diffuser exit plane for an inlet velocity of 100 m/s (64% suction). The turbulence intensity ranged from 0.6% to approximately 2%, slightly exceeding the 0.5% level typical of this inlet at the lower simulated altitude. This increased turbulence level was caused by residual disturbances propagated through the flow conditioning unit at the settings of the air inlet control valves used for this test. This was not true turbulence and we consider that this inlet exhibited completely laminar flow. Figure 6 shows the corresponding mean velocity profile. At altitudes below the initial test altitude of 835 mbar we expect that that the suction rate required to achieve completely laminar flow will increase above the rate at 835 mbar (we cannot test this condition at the local altitude in Denver).

As discussed above, we conducted a second optimization procedure for the entrance section for the flight inlet. Figure 7 shows the suggested design. The sharp leading edge is a solid section that forms both the internal and external contours of the inlet at the entrance. The solid internal contour merges with the beginning of the porous diffuser, which has a short constant area section to permit removal of the initial boundary layer before the flow enters the diffuser. The external contour continues and forms the outer sheath of the inlet. The design issue is how to provide a void volume between the outer sheath and the porous diffuser to provide a flow path for the suction air near the leading edge while minimizing both the length of the solid internal section and the total external angle of the outer sheath.

![Diagram of inlet design](image)

**Figure 7.** Preliminary design for the entrance of the flight inlet.

We approached this problem using the initial porous diffuser section from the inlet illustrated in Figure 2. During the process of optimizing the overall external contour, we masked off a portion of the porous material using a silicone sealant to simulate the effect of adding a solid plenum sheath. Figure 8 shows the results. With no masking a suction flow rate of 41% of the entrance flow was required to achieve completely laminar flow. A small amount of masking reduced the suction requirement to 36%. Further masking gradually increased the suction...
required to achieve laminar flow. We concluded that we could block off a length of the outside of the porous diffuser about equal to the inlet diameter before significantly increasing the suction flow required to achieve completely laminar flow in the inlet. This result, which is incorporated into the design shown in Figure 7, appears to be sufficient to produce a sound structural design for the flight inlet.

![Figure 8](image_url)

**Figure 8.** Effect of masking the external contour of the 2.3-AR Porous Inlet.

The current two segment inlet nearly meets the requirements for a high-volume cascade impactor system. We still must expand the exit diameter to an area ratio of 9.1 to interface with the cascade impactor system designed by Dr. Barry Huebert. This will be accomplished during the remainder of the second year of the project.

**PLANS FOR REMAINDER OF THE SECOND YEAR**

The final step in the characterization and optimization of the high-volume low-turbulence inlet will be to expand the physical area ratio of inlet from the current 4.0 to the final value of 9.1. There are three options for this step:

1. Continue the expansion at a total internal expansion angle of 6 degrees using solid (non-porous) diffuser segments. This is a straightforward procedure, the results of which can be determined in two days of testing. The components required for these tests are currently being manufactured, with delivery expected by 31 August 1999.

2. Continue the expansion by adding the remaining two porous segments. This will require a continuation of the optimization procedure discussed above to determine the best external contour for the entire four-segment diffuser. This will require several weeks of testing. The porous diffuser segments are currently available. The additional components required for the suction plenum chamber are currently being manufactured, with delivery expected by 31
August 1999. We anticipate that further modifications to the first two segments will be required when segments 3 and 4 are added. If the suction required to maintain completely laminar flow in segments 1 and 2 can be reduced we could achieve the complete expansion to the area ratio of 9.1 with a total suction rate near 70%. Figure 5 suggests that boundary layer transition was probably near the end of segment 1 for a suction rate of 60%. To test this conclusion we will modify the external contour to reduce the thickness of the porous material near the juncture of segments 1 and 2. We expect to perform the modifications to segments 1 and 2 for use with either of the first two options.

3. Continue the expansion at a total internal expansion angle of 1-2 degrees. This will require two days of testing using additional components that have not been designed.

We plan to complete this optimization procedure by approximately 31 October 1999. We will maintain close contact with Dr. Huebert to determine the most satisfactory option to meet the requirements for flight testing during the third year of this project.

The final task of the second year, the design and construction of the high-volume low-turbulence inlet for flight testing, will be accomplished during the remainder of 1999. We will select a material for the porous diffuser portion of the inlet in consultation with Dr. Huebert. We anticipate that the actual construction will extend into the third year with the costs to be paid by the remaining second year funds (see following section on funding).

**PLANS FOR THIRD YEAR**

The objectives for the third year are (1) to measure the performance of the high-volume low-turbulence flight inlet system on the C-130 aircraft and (2) to provide design and operational assistance for users of the inlet system (primarily Dr. Huebert). Our proposal (Seebaugh and Wilson, 1997) outlines the plan for reaching these objectives.

**FUNDING ISSUES**

The funding level for the second year of this grant was $100,237. Approximately 89% of the second year funding will be expended at the anniversary date of January 1, 2000. One item from the second year will extend about one month beyond the anniversary date, the actual manufacture of the flight version of the high-volume, low-turbulence inlet. This item will consume the remaining 11% of the first year funding and will be billed to the grant in early 2000. We request that NSF provide the incremental funding for FY2000 ($72,349) to the University of Denver prior to January 1, 2000 so that continuity in the project can be assured.

**PROBLEMS ENCOUNTERED AND THEIR RESOLUTIONS**

In the 1998 Annual Report we identified a problem with the existing flow conditioning unit, which is needed to simulate high altitude flight conditions in the laboratory. This device induced instabilities into the flow that adversely affected the turbulence measurements. We modified the flow conditioning unit by adding honeycomb panels and screens within the device. This modification reduced the induced instabilities to insignificant levels (less than 2% added turbulence intensity over the entire operating range and less than 0.5% at most operating conditions).
REFERENCES