AIRCRAFT PARTICLE INLETS

State-of-the-Art and Future Needs

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This supplement gives some additional information on the International Workshop on Airborne Particle Inlets, which was held within the framework of the European Fleet for Airborne Research (EUFAR) project in Leipzig, Germany, on 12 and 13 April 2002. It includes a list of participants (Table S1), the agenda of the workshop (the appendix), and a summary of the presentations.

After a welcome and introductions to the workshop, the EUFAR project, and the workshop objectives, an overview of airborne inlet–related problems and a summary of previous studies on this subject were given. Subsequently, 14 invited speakers gave oral presentations in four thematic sessions on (i) inlet designs, (ii) experimental inlet characterization, (iii) inlet characterization using models, and (iv) applications. The sessions were followed by a roundtable discussion of all workshop participants. The introduction and thematic sessions are reported next.

Difficulties associated with sampling of particles from aircraft platforms were summarized by J. Wilson. This review discussed the impact on aerosol sampling of airflow around the aircraft, misalignment of sample probes with the external flow, turbulence in sample probes, losses in transport of particles from the inlet to the instruments, and thermodynamic alteration of particles (Wilson and Seebaugh 2001). In addition, inlet designs were reviewed. A list of inlets described in the literature (Wilson and Seebaugh 2001) was presented and discussed. It is given in Table S2, together with associated references.

INLET DESIGNS. Six talks described state-of-the-art inlet designs. M. Fiebig introduced the aerosol inlet used on the Falcon aircraft by the Deutsches Zentrum für Luft und Raumfahrt (DLR) that uses a forward- and a backward-facing configuration. This particle inlet is used for near-isokinetic sampling of super- and submicrometer aerosol particles with the forward-facing component, whereas only submicrometer interstitial aerosol particles are collected with the nonisokinetic backward-facing part of the inlet system, which samples directly from nondecelerated airflow. The diameter at which 50% of the particle is passed by the backward-facing inlet, that is, D_{50}, were calculated to be 0.19 *m*m at the ground and 0.06 μm at 10-km altitude. A D_{50} of about 2.3 μm at the ground and of about 1.5 μm at 10-km altitude is derived for the forward-facing inlet component (Fiebig 2001).

S. Osborne reviewed the inlets on the Met Office C-130 aircraft (out of operation since 2001) and their transition to the new British community research BAe-146 aircraft, which is intended to be operational

TABLE S1. List of participants, in alphabetical order, with regard to country.

Participant	Institute, Location	Country
P. Nacass	Météo-France/CNRM, Centre d'Aviation Meteorologique, Brétigny-sur-Orge	France
J.-L. Brenguier E. Mathieu	CNRM/GMEI/D Météo-France, Centre National de Recherches Météorologiques, Toulouse	
A. Schwarzenböck	Université Blaise Pascal, Laboratoire de Météorologie Physique, Aubière	
J. Heintzenberg M. Hermann S. Mertes M. Reichelt F. Stratmann M. Wendisch	Leibniz-Institut für Troposphärenforschung, Leipzig	Germany
J. Curtius L. Schütz H. Vössing	Johannes Gutenberg-Universität, Institut für Physik der Atmosphäre, Mainz	
M. Krämer A. Afchine	Forschungszentrum Jülich, Institut für Chemie und Dynamik der Geosphäre I: Stratosphäre, Jülich	
M. Fiebig	Deutsches Zentrum für Luft und Raumfahrt, Institut für Physik der Atmosphäre, Wessling	
V. Dreiling	Abteilung Flugbetrieb, Deutsches Zentrum für Luft und Raumfahrt, Wessling	
R. Maser	*enviscope* GmbH, Frankfurt am Main	
T. Böttger N. Hock J. Schneider	Abteilung Wolkenphysik und -chemie, Max-Planck-Institut für Chemie, Mainz	
Z. Levin	Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv	Israel
D. Baumgardner	Universidad Nacional Autónoma de México Centro de Ciencias de la Atmósfera, Mexico City	Mexico
P. Formenti	Centre of Geophysics, Tel Aviv University, Évora	Portugal
K. J. Noone*	Department of Meteorology, Stockholm University, Stockholm	Sweden
H. Coe	Physics Department, University of Manchester Institute of Science and Technology, Manchester	United Kingdom
S. Osborne	Met Office, Farnborough	
J. C. Wilson	Department of Engineering, University of Denver, Denver, Colorado	United States

*Could not participate in person, but submitted a presentation.

TABLE S2. List of different inlet types (not complete) after Wilson and Seebaugh (2001).

	Classification	Characteristics	True air speed (m s^{-1}), altitude (km)	Reference
1	Sharp-edged diffuser	A passive instrumented near-isokinetic inlet.	200, 20	Wilson et al. (1992), Jonsson et al. (1995)
2	Blunt-edged diffuser	A near-isokinetic inlet with a velocity reduced by factor of 16.	60, 3.5	Pena et al. (1977)
3	Blunt-edged diffuser	Intended to be isokinetic.	235, 12	Hermann et al. (2001)
4	Shrouded diffuser	Tolerates variations in angle of attack. Anisokinetic.	15	McFarland et al. (1989)
5	Shrouded diffuser	Tolerates variations in angle of attack. Anisokinetic.	100, 6.1	Ram et al. (1995), Cain and Ram (1998), Cain et al. (1998)
6	CVI	Separates large particles and droplets from the atmosphere and deposits them in a gas of known composition for analysis.	100	Noone et al. (1988), Laucks and Twohy (1998)
7	Shrouded CVI	Shroud straigtens flow upstream of the CVI. Shroud does not slow flow.	250	Twohy (1998)
8	Shrouded capillary	Shroud straightens flow and provides high-speed sample to the capillary.	200, 20	Murphy and Schein (1998)
9	Nonseparating double duct	Anisokinetic inlet. Turbulence is prevented from disturbing the slowed sample flow.	200, 20	Soderman et al. (1991)
10	Boundary layer suction diffuser	Low turbulence in the diffuser. Elliptical leading edge and isokinetic operation.	100, 6	Lafleur et al. (2000)
11	Inertial aerosol separator	Large particles are unable to follow curved streamlines upstream of a sampling inlet.	200, 20	Fahey et al. (1989)
12	Gas/particle separating inlet	Variable geometry permits the inlet to operate either as a counterflow virtual impactor or an inertial aerosol separator.	200, 20	Dhaniyala et al. (2003)
13	Transsonic and supersonic inlets	Solid-wall diffusers.		Martone et al. (1980), Ivie et al. (1990)

by spring 2003. Some of the instruments on the C-130 [condensation particle counter (CPC), particle soot absorption photometer (PSAP), nephelometer, aerosol volatility] sampled from an inlet that is normally used by Rosemount temperature sensors. This inlet could sample submicrometer aerosol particles satisfactorily. The cloud condensation nuclei (CCN) counter on this aircraft used a Gas and Aerosol Sampling Project (GASP) probe, which is the only inlet that is not going to be transferred to the BAe-146. An inlet based on the principal of operation of a counterflow virtual impactor (CVI) was used to collect cloud droplets and to analyze the aerosol particle residuals. For filter sampling (principally for analyzing the chemistry of bulk aerosol samples) two near-isokinetic inlets were used (Talbot et al. 1990). Particle Measuring Systems (PMS) canister instruments were mounted in pods under the C-130 wings. These include a Passive Cavity Aerosol Spectrometer Probe (PCASP) and a fast Forward Scattering Spectrometer Probe (fast FSSP) that have their own inlets. Under the wings a small ice detector (SID) is mounted that, although designed for measuring the size and shape of ice crystals down to 1 μm in diameter, can also be used to characterize supermicrometer aerosol particles (Hirst et al. 2001). Wind tunnel results show large variations in particle sampling efficiency of the PCASP for supermicrometer particles as attack and side-slip angles were changed. Airflow alignment is also crucial for the CVI inlet. During the transition to the BAe-146, computational fluid dynamics (CFD) modeling studies are being used to ascertain the most suitable mounting positions for installation.

R. Maser presented a droplet-separating aerosol inlet consisting mainly of an isokinetic tip, with variable D_{50} ($\approx$ 6, 5, 4 μm), and an impaction plate inside, which prevents most of the droplets from entering the system (Maser et al. 1994). The theoretical values of D_{50} have been verified experimentally. The inlet was installed on several types of aircraft. Line lengths and flow distortions by an aircraft fuselage can be decreased by using an under-wing pod. This type of pod significantly reduces the distance from the inlet tip to the aerosol-sensing instrument. It can be used as a standardized validation tool traveling from aircraft to aircraft or from hard point to hard point on a single aircraft to localize and quantify local distortions in particle-mixing ratios. A mobile pod tested under the wing of a Learjet was 288 cm long, 39 cm in diameter and had a maximum payload of 150 kg. In two successful applications of this type of pod, transport losses were minimized. In the future, by use of a tow rope, the pod will be kept far below the aircraft and, thus, disturbances due to the aircraft body will be further minimized.

Z. Levin developed an airborne dust sampling system for supermicrometer-sized particles, specially designed for the purpose of analyzing individual particles. In this system the particles are brought into the airplane and subsequently collected onto sampling substrates (electron microscope grids or precoated plates) in single and multistage impactors. However, many of the particles with diameters larger than 2 μm were lost to the walls of the sampling system. Therefore, Levin has built a dedicated big-particle sampler (BPS) for collecting supermicrometer particles in the free air outside the airplane. A rotating wheel of grids behind the inlet tube collects several samples per flight. The instrument is placed on the roof of the aircraft fuselage.

J. Wilson introduced the low-turbulence inlet (LTI) concept (Wilson and Seebaugh 2001). The major focus of the LTI development was the active control of the turbulence within the inlet diffuser that is the main cause for serious supermicrometer particle losses at the inlet walls (Sheridan and Norton 1998; Huebert et al. 1990). Turbulence is controlled by boundary layer suction, which prevents the development of a turbulent boundary layer and propagation of turbulence into the flow. The turbulence continuously decreases with increasing suction fraction, nearly disappearing for a suction fraction of larger than 44%. The LTI was installed on the National Center for Atmospheric Research (NCAR) Hercules C-130 and evaluated during an extensive airborne field intercomparison (Huebert et al. 2002, manuscript submitted to *J. Atmos. Oceanic Technol.*). The LTI is intended to function under a normal range of angles of attack that can change with speed and fuel load. Sharp-edged inlets initiate particle separation if alignment is not perfect; therefore, the LTI leading edge has a parabolic shape and encompasses 13% more area than the throat of the inlet. The laminar flow assured by the suction flow allows CFD calculations of particle trajectories and inertial enhancement to be performed. The LTI significantly increases passing efficiency for super-micrometer aerosol particles. A continuous monitoring of the inlet performance (e.g., inlet and exit air velocities and temperatures) is crucial.

A. Schwarzenböck reported on French plans to establish an airborne CVI on their aircraft. In general, a CVI separates cloud elements (droplets, crystals) from the interstitial particles and gases in clouds (Ogren et al. 1985). The counterflow can be used to adjust the D_{50} of the CVI within certain limits (Schwarzenböck and Heintzenberg 2000). In order to avoid misalignment of the inlet with the free airstream a coaxial shroud is placed upstream of the CVI tip (Twohy 1998).

EXPERIMENTAL INLET CHARACTERIZATION. M. Hermann described the experimental determination of the passing efficiency of a particle inlet for submicrometer aerosol measurements aboard a commercial aircraft (Hermann et al. 2001). The experiment assumes that flow field and particle transport under atmospheric conditions and in the laboratory calibration experiment are similar if characteristic properties of the flow and the particles are similar, and that particles with the same characteristic particle property in the laboratory and in the atmosphere experience the same particle losses. The inlet-passing efficiency, as a function of particle diameter, was first determined in a scaled wind tunnel experiment. Thereafter, the derived passing efficiency was scaled to the atmospheric conditions under which the measurements were to be performed. The resulting passing efficiency functions revealed diffusive losses of small particles (smaller than 20-nm diameter) of up to 30% and inertia-related losses of particles larger than about a 400-nm diameter between 10% and 100%.

D. Baumgardner reported some of the difficulties associated with validating inlet performance. He described an experiment designed to measure the passing efficiency of the University of Denver LTI. A PMS FSSP-300 optical particle counter (OPC) was suspended from the wing of the NCAR C-130 and operated normally. A second FSSP-300 was plumbed into the sample line from the LTI inside the cabin. The cabin-mounted FSSP used a special insert to prevent leaks and was ventilated with a pump to provide airflow through the probe. Comparison from flight tests of particle size distributions from the two probes showed enhancement of large particles by the LTI for diameters larger than 1 μm. The integrated number concentration and volume of supermicrometer particles was always greater in the cabin but there was an unexplained sensitivity to altitude. There were large discrepancies, however, of concentrations below 1-μm particle diameter. Possible distortions in airflow at the probe locations may alter the size distribution measurements and cause discrepancies additional to those caused by the different probe characteristics. The advantage of using the same model of OPC to evaluate aerosol inlets is that differences should only be a result of inlet effects. However, in practice great care must be taken when modifying an OPC designed for exterior use for measurements in a pressurized cabin. Discrepancies between measurements of the two FSSP-300s suggest problems that are related to individual probe characteristics and flow distortion. These discrepancies have not been resolved. This clearly illustrates the difficulties associated with trying to use even well-understood instruments in ways that have not been validated in prior experiments.

K. Noone submitted a presentation on CVI passing efficiency characterization using experimental and modeling tools. The first CVI laboratory calibration yielded a rather broad passing efficiency curve (Noone et al. 1988). A more sophisticated calibration approach yielded a sharper cut (Anderson et al. 1993). Even sharper passing efficiency curves were indicated by more recent modeling results (Lin and Heintzenberg 1995). With regard to the total droplet collection efficiencies, preliminary two-dimensional compressible flow model results suggest a rather low efficiency (Laucks and Twohy 1998). However, a comparison between ground-based CVI and FSSP measurements, assuming that after evaporation each droplet only releases one residual particle, showed very good agreement (Hallberg et al. 1994). So it does not appear to be the case that the droplet losses inside the CVI probe predicted by the compressible flow model were occurring in the field experiment. Airborne measurements show that on the whole the agreement between residual particle number concentrations and estimated droplet number concentrations above the cut size of the CVI are within 25%, and in some of the cases it is even much better (10% or less, Glantz et al. 2003). Furthermore, it is shown that droplet shattering can qualitatively be identified and that it occurs often when there are elevated concentrations of drizzle droplets in the clouds. As a consequence, CVI measurements obtained in precipitating clouds must be interpreted cautiously. The results of this study also indicate that the assumption that a droplet only releases a single residual particle upon evaporation seems to be valid (at least in warm, nonprecipitating clouds).

INLET CHARACTERIZATION USING MODELS.

P. Nacass gave an overview of the inlet systems deployed on five French research aircraft presently in use or intended for future research operation. CFD modeling (Fluent Inc., Lebanon, New Hampshire, www.fluent.com) was applied to describe the flow field around these aircraft and several microphysical sensors (different PMS probe inlets, particle volume monitor, special developments) mounted on the fuselage of the aircraft. The importance of the shape of the inlet lips was studied using the CFD calculations. The need to extend these calculations to particle trajectories and derivation of passing efficiencies was emphasized.

M. Krämer investigated the passing efficiency of four anisokinetic inlets installed on three aircraft. For this purpose the results of an approximate formula by Belyaev and Levin (1974) and a CFD code (CFX, ANSYS Inc., Canonsburg, Pennsylvania, www.ansys.com/cfx) were compared. For the standard inlet geometries and Stokes numbers larger than 0.1 generally good agreement was found, although the approximate method systematically underestimated the aspiration efficiency for small particles ($d_p < 0.3\ \mu$m). The inlet geometry was varied and a strong influence of these variations on passing efficiency was revealed. Approximate methods can generally be used to yield valuable results in planning the design of an inlet; however, these simple methods require extensive validation with more detailed CFD codes or, even better, measurements under realistic conditions.

F. Stratmann presented a recently developed new tool for FLUENT. It includes the Eulerian simulation of particle formation, transport, transformation, and deposition processes. Furthermore, it describes the thermodynamic changes of the particle size distribution coupled with heat/mass transfer and fluid flow processes. It also accounts for particle dynamical effects, such as nucleation, condensation/evaporation, coagulation, diffusion, and external forces (e.g., sedimentation, thermophoresis). This approach offers great advantages and presents the possibility that the transport of particles and their thermodynamic modifications in and around airborne aerosol inlet systems can be modeled much more explicitly.

APPLICATIONS. J. Schneider introduced three instruments that require well-characterized particle inlets: an aerosol mass spectrometer (Jayne et al. 2000), a single particle laser mass spectrometer, and a special CPC for stratospheric particle measurements. The single particle instrument, which is designed to measure supermicrometer particles, especially requires an inlet that efficiently transmits large particles. Possible inlet designs suited for these three instruments were discussed.

P. Formenti reported on aerosol measurements using particle inlets installed on the Met Office Hercules C-130. Aerosol particle size distributions were measured with a wing-mounted PCASP, the particle volume scattering and absorption coefficients were measured with a nephelometer and a PSAP placed behind a Rosemount inlet. Additionally, particles were collected on filters and their ionic chemical composition was determined. Discrepancies between the measured and calculated particle volume scattering coefficients were discussed in terms of the different passing efficiencies of the three inlets used.

APPENDIX: WORKSHOP AGENDA

All presentations can be downloaded (available online at www.eufar.net; under “Consult Expert/Workshop;” workshop names are listed).

Session 1: Introduction
Chairs: M. Wendisch, H. Coe

- J. Heintzenberg (ifT[a], Leipzig, Germany): Welcome.
- M. Wendisch (ifT[a], Leipzig, Germany) and H. Coe (UMIST[b], Manchester, United Kingdom): Introduction to the workshop.
- J.-L. Brenguier and E. Mathieu (Météo-France, Toulouse, France): Introduction to EUFAR.
- H. Coe (UMIST[b], Manchester, United Kingdom) and M. Wendisch (IfT[a], Leipzig, Germany): Objectives of the workshop.
- J. C. Wilson (University of Denver, Denver, Colorado): A review of inlets for use on aircraft.

Session 2: Inlet designs
Chairs: P. Formenti, D. Baumgardner

- M. Fiebig (DLR, Wessling, Germany): The DLR Falcon aerosol inlet: Design and characteristics.
- S. Osborne (Met Office, Farnborough, United Kingdom): A review of aerosol inlets during the transition from the C-130 to the BAe-146.
- R. Maser (enviscope GmbH, Frankfurt, am. Main, Germany): Design of whole air inlet system and variations for use in under-wing instrument pods.
- Z. Levin (Tel Aviv University, Tel Aviv, Israel): A new airborne big particle sampler (BPS) for measuring dust and other large particles.
- J. C. Wilson (University of Denver, Denver, Colorado): A low-turbulence inlet for measuring supermicrometer particles from aircraft platforms.
- A. Schwarzenböck (CNRS[c], Clermont, France): Plans for an airborne counterflow virtual impactor (CVI) in France.

Session 3: Experimental inlet characterization
Chairs: M. Krämer, J. C. Wilson

- M. Hermann and F. Stratmann (IfT[a], Leipzig, Germany): Calibration of an aircraft-borne aerosol inlet using a similarity approach.
- D. Baumgardner (University of Mexico City, Mexico City, Mexico): Lessons learned from inlet validation tests.
- K. J. Noone (Stockholm University, Stockholm, Sweden): Airborne counterflow virtual impactors: Comparison with Forward Scattering Spectrometer Probes (FSSPs; not presented at workshop, but available online at www.esf.org/eufar/).

Session 4: Inlet characterization using models
Chairs: S. Osborne, M. Hermann

- P. Nacass (Météo-France, Centre d’Aviation Météorologique, Brétigny-sur-Orge, France): Model calculations of an airborne isokinetic inlet: Shroud, pumping, pathlines.
- M. Krämer (Research Center Jülich, Jülich, Germany): Efficiency of particle inlets at low U/U_0 ratios—Verification of Belyaev and Levin’s formula using a computational fluid dynamics (CFD) model.

- F. Stratmann and M. Hermann (IfT[a], Leipzig, Germany): A fine particle model for fluent: Background and application.

Session 5: Applications
Chairs: A. Schwarzenböck, P. Nacass

- J. Schneider (Max-Plank-Institute, Mainz, Mainz, Germany): Aircraft-based mass spectrometric analysis of aerosol particles.
- P. Formenti (University of Évora, Évora, Portugal): Calculating particle scattering from the Passive Cavity Aerosol Spectrometer Probe (PCASP) number size distribution: An example.

Roundtable discussion
Chairs: H. Coe, M. Wendisch

- Discussion and conclusions.

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[c] Centre National de la Rechere Scientifique.

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