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Aircraft testing of the new Blunt-body Aerosol Sampler (BASE)

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Abstract

There is limited understanding of aerosol role in the formation and modification of clouds partly due to inadequate data on such systems. Aircraft-based aerosol measurements in the presence of cloud particles has proven to be challenging because of the problem of cloud-droplet/ice-particle shatter and the generation of secondary artifact particles that contaminate aerosol samples. Recently, design of a new aircraft inlet, called the blunt-body aerosol sampler (BASE), which enables sampling of interstitial aerosol particles, was introduced. Numerical modeling results and laboratory test data suggested that the BASE inlet should sample interstitial particles with minimal shatter particle contamination. Here, the sampling performance of the inlet is established from aircraft-based measurements. Initial aircraft test results obtained during the PLOWS campaign indicated two problems with the original BASE design: separated flows around the BASE at high altitudes; and a significant shatter problem when sampling in drizzle. The test data was used to improve the accuracy of flow and particle trajectory modeling around the inlet, and the results from the improved flow model informed several design modifications of BASE to overcome the problems identified from its initial deployment. The performance of the modified BASE was tested during the ICE-T campaign and the inlet was seen to provide near shatter-free measurements in a wide range of cloud conditions. The initial aircraft test results, design modifications, and the performance characteristics of BASE relative to another interstitial inlet, the sub-micron aerosol inlet (SMAI), are presented.

1 Introduction

Aerosol particles are important from a global climate perspective because of their role in modulating the extent of solar radiation received at Earth's surface. Aerosol particles can interact directly with solar radiation or indirectly, by acting as nuclei for the formation of cloud droplets. The latter contribution, referred to as the aerosol indirect effect, has significant influence on global climate and its accurate representation in global models is important for accurate long term climate change predictions (Forster et al., 2007; Lohmann and Feichter, 2005).

In global circulation models (GCMs), computational considerations require aerosol-cloud interactions to only be incorporated via simple parametric models. With existing parameterizations, the predictions of net radiative forcing associated with aerosol indirect effects can be significantly variable (Forster et al., 2007; Penner et al., 2006). Testing and improvement of the parametric models will require comprehensive aerosol-cloud data from a wide range of cloud systems. Such data can be best acquired using instrumented aircraft. Representative sampling of aerosol from the atmosphere to instruments inside the aircraft cabin is complicated by the presence of cloud droplets or ice particles in the atmosphere. Impaction of cloud droplets/ice-particles on aerosol inlets and aircraft hull can result in their breakup and the subsequent generation of a large number of secondary particles. The generation of these shatter particles results in contamination of aerosol samples, making measurements of background condensation nuclei (CN), or interstitial aerosol, in clouds largely impossible (Rogers, 2008; Korolev, 2005; Weber et al., 1998). The inability to make in-cloud aerosol measurements from aircrafts has stymied efforts to fully understand aerosol-cloud systems.

Recently, design of a new aircraft inlet for aerosol measurements in clouds, called the Blunt-body Aerosol Sampler (BASE), was introduced (Moharreri et al., 2013). In the BASE design, an aerosol inlet was housed on a blunt body, at a location where cloud droplets and secondary particles generated from their shatter were absent. This was achieved by optimizing the shape of the blunt-body such that cloud particles were deflected from its aft region, while ensuring that the boundary layer flow around the body remained largely attached. The cloud particle deflection from the aft of the blunt-body allows for cloud-free sampling from that location, while the constraint of attached boundary layer flow ensures that shatter particles generated from cloud particle impaction on the body can be retained close to its surface. Satisfying the two requirements results in an aerosol sampling region in the aft of the blunt body that is both cloud-particle-free and shatter-free. The operational concept of the sampler is illustrated in Fig. 1.

The initial BASE design was established by Moharreri et al. (2013) with guidance from computational fluid dynamics (CFD) modeling. Wind-tunnel based testing of the inlet provided preliminary validation of the inlet concept, but the challenges of fully reproducing aircraft sampling conditions necessitated field evaluation. For aircraft testing, BASE was flown on the NSF/NCAR C-130 aircraft in two different campaigns – Profiling of Winter Storms (PLOWS) and Ice in Cloud Experiment – Tropics (ICE-T). The aircraft testing procedure, inlet performance results, and inlet design iterations are described here.

2 Flight tests

2.1 First iteration: BASE-I

The first design iteration of BASE, referred to here as BASE-I, was flown on NSF/NCAR C-130 aircraft during the PLOWS (Profiling of Winter Storms; November 2009–March 2010) campaign. The primary objective for the deployment of BASE-I in PLOWS was to test the inlet performance under actual flight conditions and compare the obtained data with wind-tunnel and CFD results of Moharreri et al. (2013). The major dimensions and assembly components of the aircraft-version of BASE-I are shown in Fig. 2. All parts of the inlet were machined from Al-6063 and anodized for corrosion protection. Four 100 watt cartridge heaters (Watlow) and a 1000 ohm miniature embedment RTD (Minco) were embedded in the blunt body housing and connected to a controller circuit to de-ice the sampler when required. The aerosol sample was transported to the cabin through a $1/4''$ flexible conductive tubing (TSI Inc.). To help keep the boundary layer attached, a suction port was located just upstream of the inlet. The suction flow from this port was connected to a passive venturi pump mounted on the side of the aircraft using a $3/4''$ flexible fireproof hose (Parker Inc.).

Three aerosol samplers were flown during the PLOWS campaign, with the purpose of inter-comparing their performance in clouds. The three tested inlets were: BASE-I, NCAR HIAPER Modular Inlet – HIMIL, and NCAR's Sub Micron Aerosol Inlet (SMAI). The HIMIL is a sharp-edge, forward facing diffuser modular inlet design that can be assembled to provide gas or aerosol sampling (UCAR, 2005). NCAR's SMAI was initially developed for gas sampling, but has recently been shown to have promise as an interstitial aerosol sampler (Craig et al., 2013a, b). The three aerosol inlets were installed on the belly of the aircraft hull, towards the aft, and in close proximity to one another.

A variety of microphysical and state parameters were measured on the aircraft and the resulting data were used for performance analysis of BASE-I. Particle concentrations from BASE-I, SMAI, and the HIMIL inlets, were measured using three condensation particle counters (CPCs): TSI 3010, TSI 3760a, and a modified, low pressure TSI 3786, respectively. Size distribution and concentrations of cloud particles in the size range of 2–50 µm were measured by NCAR/RAF using a Cloud Droplet Probe (CDP; Droplet Measurement Technologies). The larger cloud particles (drizzle, if in warm clouds; 25–1600 µm size range) were measured using an imaging technique with a 2 Dimensional Cloud probe (2D-C; Particle Measurement Systems).

2.1.1 CN measurements in liquid clouds

In designing BASE-I, the presence of only liquid droplets was considered and, correspondingly, an appropriate comparison of model predictions with measurements must only consider inlet data obtained in warm clouds. During the PLOWS campaign, however, most cloud penetrations were through ice clouds, though warm liquid clouds were encountered during one flight (PLOWSff03 – 3 November 2009). The BASE-I performance analysis presented here is based on data obtained during this warm cloud passage.

For a selected cloud penetration case, time series plots of cloud and drizzle concentrations and the corresponding particle concentrations measured from the three aerosol inlets flown during PLOWS are shown in Fig. 3. For this case, the average temperature during the analysis time period was −0.4 °C and therefore the cloud particles/droplets are likely to be in liquid phase (Korolev et al., 2003). During this measurement period the concentration of drizzle was negligible. For this drizzle-free, liquid cloud penetration case, CN measurements from a traditional aerosol inlet (HIMIL) are significantly enhanced in the presence of cloud droplets, suggesting contamination of the sample with shatter particles. The CN concentrations obtained from BASE-I and SMAI are, however, seen to be depleted relative to the out-of-cloud samples. This observation is consistent with the expectation that a fraction of the background aerosol will be activated to form clouds and, thus, the interstitial fraction should be lower than the background aerosol concentration. The difference in the measurements of SMAI and BASE-I could be because of the differing cut sizes of the two inlets or because of the locational differences of the inlets, and/or possibly indicative of some shatter artifact in one or both the inlets.

In the presence of drizzle (Fig. 4), however, CN measurements made by BASE-I, and HIMIL, are significantly elevated. The shatter contamination seen in BASE-I data is likely because, for large incoming particles/droplets, a significant fraction of secondary particles generated from impaction may be larger than 2 µm and the CFD simulations of Moharreri et al. (2013) suggested that shatter particles in that size range will entrain the aerosol sample. Thus, it could be concluded that, shatter-free sampling of interstitial aerosol measurements is possible with the BASE-I design, but only in the absence of drizzle/precipitation droplets.

2.1.2 Pressure distribution around the blunt body

To characterize the nature of flow around the blunt-body and compare flow simulation results with experimental data, pressure measurements were made at six different locations on the blunt body housing using an Esterline Pressure Scanner (Model 9116). The pressure ports were placed at: the front stagnation region, the maximum diameter region of the housing, and four locations in the aft region of the blunt body. The four aft pressure ports were at the same streamwise distance along the chord length of the

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

housing, spaced 45° apart azimuthally. These ports were placed to determine if the flow was axisymmetric around the blunt body housing. Pressure distribution measurements from typical flight conditions (Mach 0.4 and 600 mbar to Mach 0.45 and 400 mbar range) during testing of BASE-I are compared against CFD predictions in Fig. 5. The CFD simulation results are obtained following the procedure of Moharreri et al. (2013), using the k-ω SST turbulence model and for boundary conditions consistent with flight data. Good agreement between the CFD predictions and measurement data was observed when the altitudes were below ~21 000 ft (Fig. 5, left column). For altitudes above ~21 000 ft (static pressure lower than ~450 mbar), however, the pressure coefficients obtained from measurements differed considerably from the CFD predictions. At the maximum diameter region of the blunt body housing, the measured pressures were higher than the numerically predicted values, and also, these pressures were also seen to have significant fluctuation (as indicated by the large error bars for this data in Fig. 5, right column). Also, the pressure at the aft ports in the freestream side of the blunt body housing (i.e. away from the aircraft skin) was slightly lower than expected. This suggests that, at high altitudes, the flow around the blunt-body separates.

The deviation between the measured and CFD predicted pressure distributions can be partly attributed to the mismatch between the flight conditions considered initially during the design stage (800 mbar, 100 $\mathrm{m\,s^{-1}}$) and those encountered during PLOWS (significant periods with pressures < 450 mbar and airspeeds $> 140\,\mathrm{m\,s^{-1}}$). At low altitude conditions of 800 mbar and 100 $\mathrm{m\,s^{-1}}$ (the conditions used for BASE-I design), the Reynolds number around the blunt body is $\sim 8 \times 10^5$. For the higher altitude conditions seen in PLOWS, the Reynolds numbers are lower ($\sim 6 \times 10^5$), and for these conditions, accurate predictions require the use of models that can resolve changes in boundary layer flow in the transitional regime, such as the k-ω SST transitional model in FLUENT 6.2.3 (FLUENT user manual, 2006).

New CFD simulations of flow around the blunt-body were conducted with an axisymmetric, k-ω SST transitional model and results are shown in Fig. 5. It is seen that the model results are in excellent agreement with the measured pressures at both high and low altitudes, with the observed flow separation at high altitudes also predicted accurately. Full three-dimensional simulations are, however, required to explain the non-axisymmetric effects in the flow pattern that were evident from the differences in the pressure measurements on the free stream side and the aircraft skin side (Fig. 5, right column).

2.2 BASE-II

From the data obtained during the PLOWS campaign, it was determined that the BASE-I design needed to be modified to address the problems of boundary layer separation at high altitudes and shatter artifact contamination in the sample flow in the presence of drizzle drops. Using the new CFD simulation results obtained with the k-ω SST transitional turbulence model, the BASE-I blunt body shape was streamlined such that separation-free flow fields were possible for all flight conditions encountered during PLOWS. The profile alteration is shown in Fig. 6 and the sampler with the modified profile is referred to here as BASE-II. BASE-II was fabricated and flown during the second half of PLOWS campaign (January 2010–March 2010) and during ICE-T (Ice in Clouds Experiments – Tropical, 2011) campaign. For better characterization of the pressure distribution around the sampler, several additional pressure taps (total of 11) were added to the blunt-body of BASE-II.

To address the shatter contamination issue, it was first necessary to determine the shatter particle sizes that will be present in the sample flow. Following the approach of Moharreri et al. (2013), particles of different sizes were injected on the surface of the blunt body housing with a range of normal velocities and their resulting trajectories were tracked. From analysis of these trajectories, the shatter-particle sampling efficiencies of the interstitial inlet were determined, as shown in Fig. 7 for flight conditions of 400 mb and 0.45 Mach. The modeling results suggest that, almost independent of particle injection velocity, only shatter particles larger than ~ 2 µm aerodynamic diameter are sampled into the inlet. This is consistent with the original design criteria and predictions of BASE-I performance, as established in Moharreri et al. (2013). The sampling efficiency is expected to be maximal for shatter particles of diameter ~ 3 µm. The largest particle sizes that may be present in the sampling volume of the interstitial inlet are, however, strongly dependent on the normal ejection velocities of the particles.

In designing BASE-I, the possibility of large droplet shatter was not considered and hence the likely presence of large numbers of shatter particles larger than 2 µm was ignored. Considering the results shown in Fig. 7, an interstitial inlet that does not sample particles larger than ~ 2 µm will ensure that the contribution of shatter artifact particles to the interstitial sample is negligible. To accomplish this goal, the interstitial inlet design was modified as a cross-flow sampling inlet, shown in Fig. 8. The sampling efficiency of a cross-flow sampling inlet is largely determined by the size of the flow constricting nozzle (Craig et al., 2013b). Using 3-D CFD simulations, the appropriate size of the flow constricting nozzle required for a 2 µm sampling cut-size was determined. For simplicity, these simulations were conducted by ignoring the blunt-body, but considering the flow conditions at the inlet location determined from earlier blunt-body simulations. The calculated sampling efficiency of the final cross-flow sampling inlet is shown in Fig. 9.

The updated BASE-II design with the new cross-flow tube inlet was flown on the NSF/NCAR C-130 during the ICE-T (2011) campaign. In addition to the CN measurements and pressure distributions around the blunt body, the size distributions of the sampled particles were obtained using a Ultra High Sensitivity Aerosol Spectrometer (UHSAS; DMT Inc.) and a High-flow Dual-channel Differential Mobility Analyzer (HD-DMA; Dubey, 2010). Bypass flows were used to increase the sampling flow rate and minimize the transit time of the particles from the inlet to the instrumentation inside the cabin.

2.2.1 Pressure measurements around the blunt body housing

Pressure measurements made during flight testing of BASE-II suggest excellent agreement with CFD predictions for all pressure ports, and the flow was seen to be attached around the blunt body housing for all aircraft speeds and altitudes encountered. Comparison of the measurement data with predictions of CFD simulations using k-ω SST transitional turbulent model is shown in Fig. 10 for 400 mbar and Ma 0.47 condition as an example. These pressure measurements suggest that the modified profile eliminates the problem of flow separation at higher altitudes observed with BASE-I, making BASE-II deployable for the entire range of C-130 flight conditions.

2.2.2 Sampling efficiency

The sampling efficiency of BASE-II with the new cross-flow sampling tube is shown in Fig. 11a. The overall sampling efficiency was calculated using particle trajectory calculations, as a product of two effects: (i) the influence of the blunt body housing on the particle concentration at the inlet location, and (ii) the sampling efficiency for a cross-flow inlet. The cross-flow inlet was modeled separate from the flow around the blunt body and as an internal flow problem with a domain including the tube aligned with external airflow and the cross-flow sample tube. The boundary conditions of the internal flow were extracted from the flow solution results from the external flow around the blunt body housing at the location of the inlet. To validate the overall sampling performance of the BASE inlet, out-of-cloud aerosol size distributions measured from the interstitial sample using a UHSAS (0.055 to 1 µm) and the HDDMA (10 to 300 nm) instruments can be compared with those obtained from two wing mounted instruments: the Passive Cavity Aerosol Spectrometer Probe (PCASP; PMS Inc; 0.1–3.0 µm) and Forward Scattering Spectrometer Probe (FSSP-300; PMS Inc., 0.3–20 µm). For one selected set of sampling conditions, as indicated in Fig. 11b, the two sets of size distributions match reasonably well in the overlapping measurement size range of 0.1 to 1 µm. This provides initial validation of model predictions of inlet sampling efficiency ~ 1 for sub-micron particles.

2.2.3 CN measurements in warm clouds

During ICE-T, there were several warm cloud passages, providing significant data for analysis of BASE-II performance in the presence of liquid droplets. For the current analysis, a cloud event was identified as when the average cloud droplet concentration measured by the Forward Scattering Spectrometer Probe (FSSP-100 by Particle Measurement Systems Inc.) was $> 5\,\text{cm}^{-3}$ for atleast 10 s. Average "ambient air" aerosol concentrations associated with a cloud event were obtained from a 10 second time interval prior to the start of that cloud event, where the average cloud droplet concentrations were $< 5\,\text{cm}^{-3}$.

The ratio of aerosol concentration in a selected cloud system to that in the "ambient" air in its vicinity is referred to as "CN Enhancement". Enhancement values greater than 1 are usually indicative of shatter artifacts in CN measurements (Craig et al., 2013b). To facilitate a direct comparison of the performance of the two BASE designs, the BASE measurements were normalized using measurements from a reference sampler. The normalized enhancements allowed comparison of the performances of BASE-I and BASE-II regardless of differences in the droplet size distribution and flight conditions (aircraft speed, angle of attack, roll, etc.) experienced by the two inlets. The sub-micron aerosol inlet (SMAI; Craig et al., 2013a) was chosen as a reference sampler because it was previously shown to be minimally affected by shatter artifacts during in-cloud sampling (Craig et al., 2013b). For both PLOWS and ICE-T campaigns, the operation and location of SMAI was identical relative to BASE, making it an optimal reference sampler.

The BASE CN enhancements normalized with the corresponding SMAI measurements are shown in Fig. 2. Note that the BASE-I data considered here corresponded to lower altitude flights, where the flow around the blunt-body was largely attached. The BASE-I CN enhancements are significantly higher than the SMAI values when the mean cloud droplet sizes are larger than 12 µm, while the CN enhancements of BASE-II are lower than that of SMAI at all cloud droplet diameters. The BASE-II CN enhancements are seen to slightly decrease with increasing mean cloud droplet size. This comparison suggests that the shatter artifacts with BASE-II design are significantly lower than with BASE-I design and also lower than that seen in SMAI.

The flight test results suggest that the BASE design provides effective interstitial aerosol sampling under a range of ambient conditions. The BASE principle can be extended to design interstitial inlets for other platforms operating under different conditions. While the BASE design represents a significant advance in interstitial aerosol sampling, there is a need for continued development and improvement in the sampler design, as the data suggests that some shatter artifacts may still be present in the BASE sample. It is possible that the observed enhancements during in-cloud measurements made by BASE are not because of shatter artifacts in the inlet, but because of: the choice of the background "ambient" aerosol; or droplet shatter resulting from their impaction on the aircraft fuselage; or shatter artifacts from inlets/objects upstream of BASE. Turbulent dispersion of shatter particles, as they flow around the blunt body housing, could also result in shatter contamination of BASE sample. Turbulence can act to disperse shatter particles from near the blunt-body surface and bring them into flow that is sampled by the interstitial inlet. Further studies that consider the role of the aircraft hull and turbulent particle transport are required to improve characterization of the BASE sampler performance and to propose any further design modifications necessary to improve its performance.

3 Conclusion

The sampling performance of a new blunt-body aerosol sampler (BASE) was established from measurements made on the NSF/NCAR C-130 aircraft. The initial version of the inlet (BASE-I), designed entirely from CFD simulations, was seen to sample shatter-free aerosol in low-altitude, warm clouds in the absence of drizzle. In the presence of large drizzle droplets or when operated at high altitudes, BASE performance was, however, observed to be similar to standard aerosol inlets, with significant shatter contamination of CN measurements. The initial aircraft test results informed changes in the design of the blunt-body and the aerosol inlet on the body. Pressure measurements around the redesigned sampler (BASE-II) revealed that the flow field around the sampler was as predicted by CFD simulations. Comparison of BASE-II performance against that of another interstitial inlet showed that BASE-II samples were minimally contaminated with shatter artifacts over a wide range of atmospheric conditions. The BASE sampler, thus, represents a significant progress in our efforts to probe the characteristics of interstitial aerosol, and the design of this inlet can be extended to other aircraft operating conditions, enabling the study of a large range of cloud systems.

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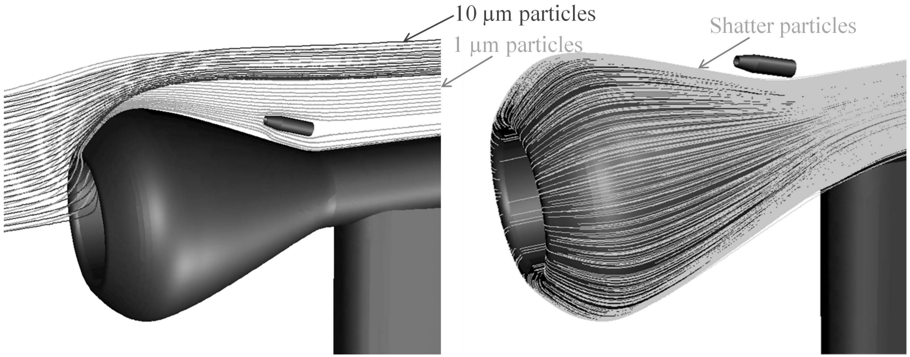

Fig. 1. Design concept of BASE; left: trajectories of free stream particles. Cloud particles (larger particles) are prevented from reaching the inlet tube while interstitial inlets which are smaller can reach the inlet. Right: shatter particles generated at the surface of the blunt body housing. These particles stay close to the surface of the body and do not enter the aerosol sample.

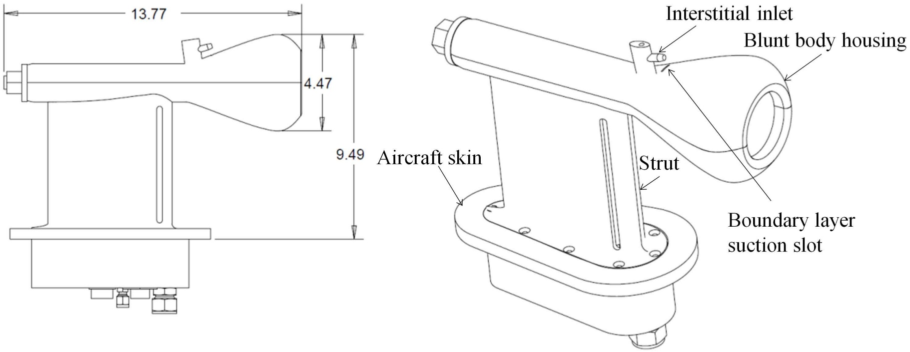

Fig. 2. Blunt-body Aerosol Sampler (BASE), dimensions in inches. The interstitial inlet is a 1/4″ stainless steel tube.

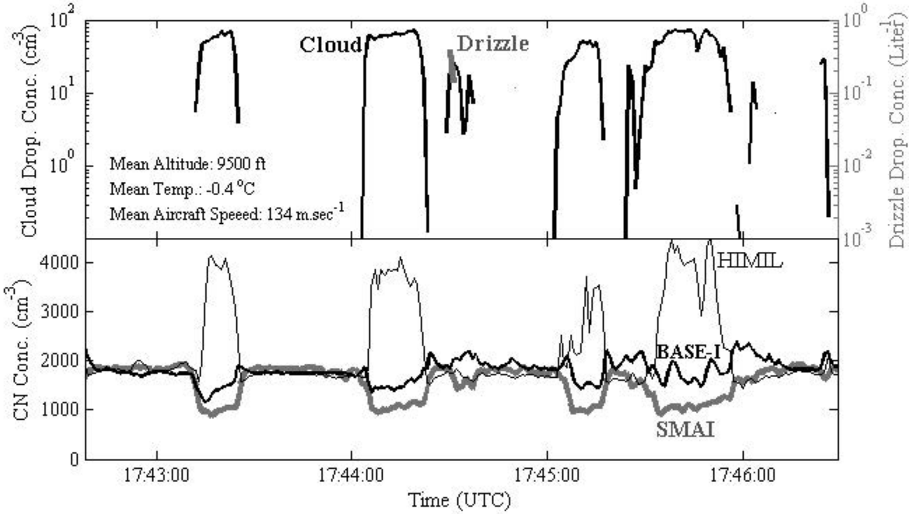

Fig. 3. Performance of three aerosol inlets on the C-130 aircraft during a drizzle-free cloud penetration during PLOWSff03 (3 November 2012) flight.

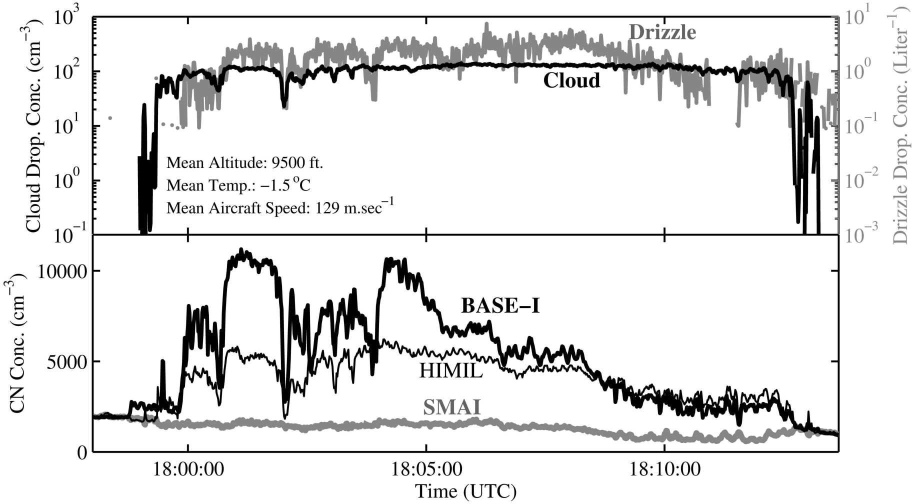

Fig. 4. Performance of three aerosol inlets on the C-130 aircraft during a cloud penetration with presence of drizzle. Data from PLOWSff03 (3 November 2009) flight.

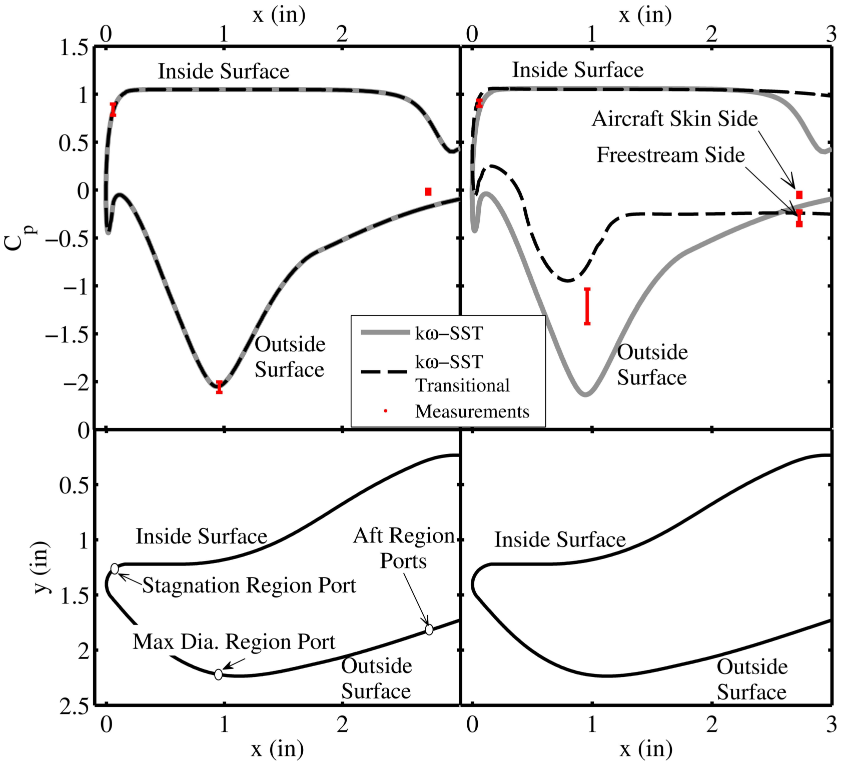

Fig. 5. Comparison of pressure measurements around the blunt body housing and simulation results; experimental data from PLOWSrf01 (13 November 2009) flight. Left column: Low altitude case, experimental data from 18:32–19:05 UTC period, simulation boundary conditions: 600 mbar, Ma 0.4; Right column: High altitude case, experimental data from 17:00–18:00 period, simulation boundary conditions: 400 mbar, Ma 0.45. Values reported are pressure coefficient $\left(C_p = \frac{p-p_\infty}{1/2\rho V^2}\right)$.

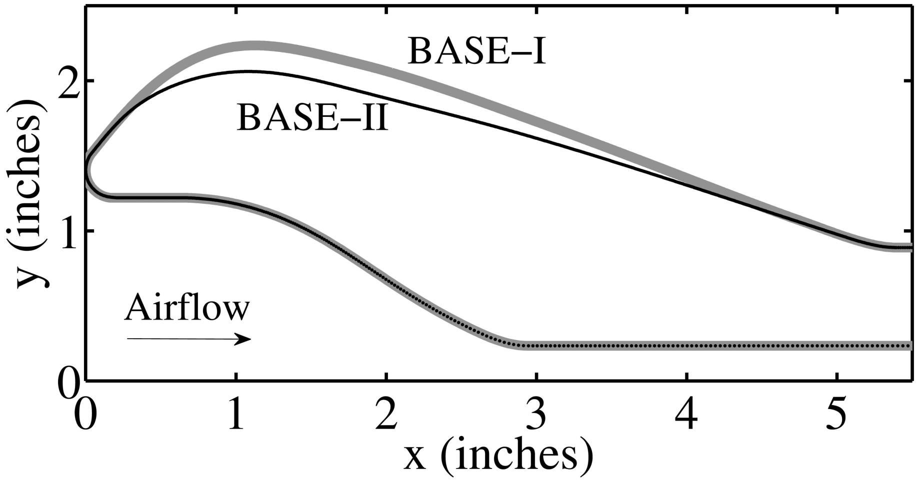

Fig. 6. Profiles of the blunt body housing for BASE-I and BASE-II.

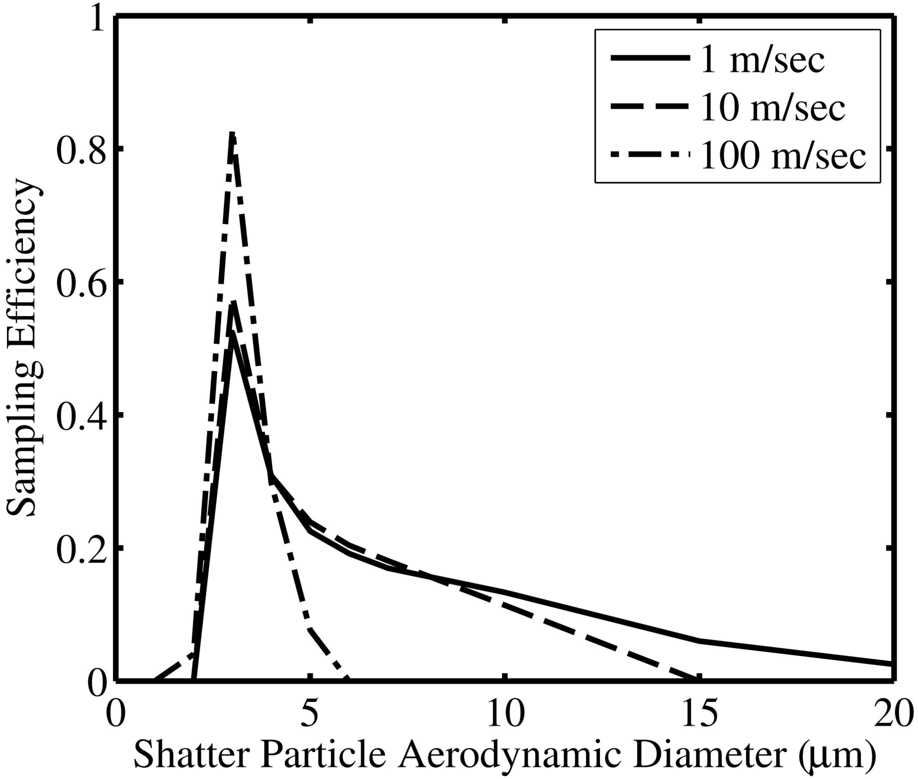

Fig. 7. Sampling efficiency (# sampled/# injected at the surface) of shatter particles of different sizes injected on the surface of the blunt body housing for three values of normal velocity: $1\,\mathrm{m\,s^{-1}}$, $10\,\mathrm{m\,s^{-1}}$, and $100\,\mathrm{m\,s^{-1}}$ (right). Flight conditions are 400 mbar and Ma = 0.45.

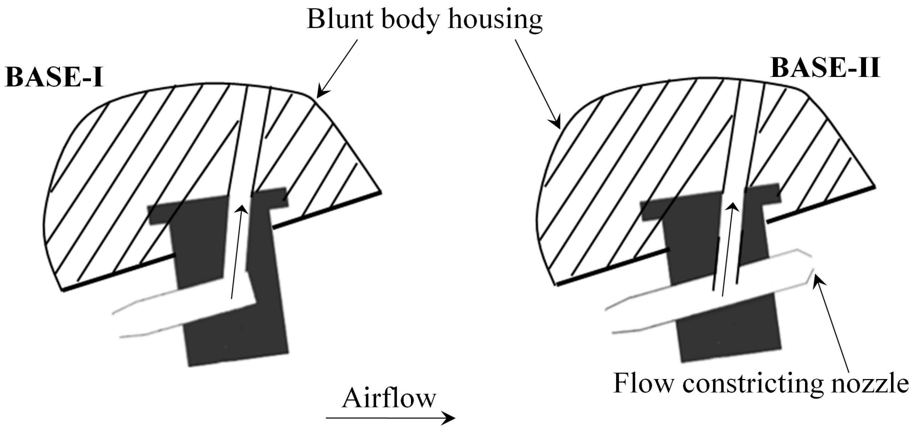

Fig. 8. Schematic diagram of the interstitial inlet in BASE-I (left) vs. BASE-II (right).

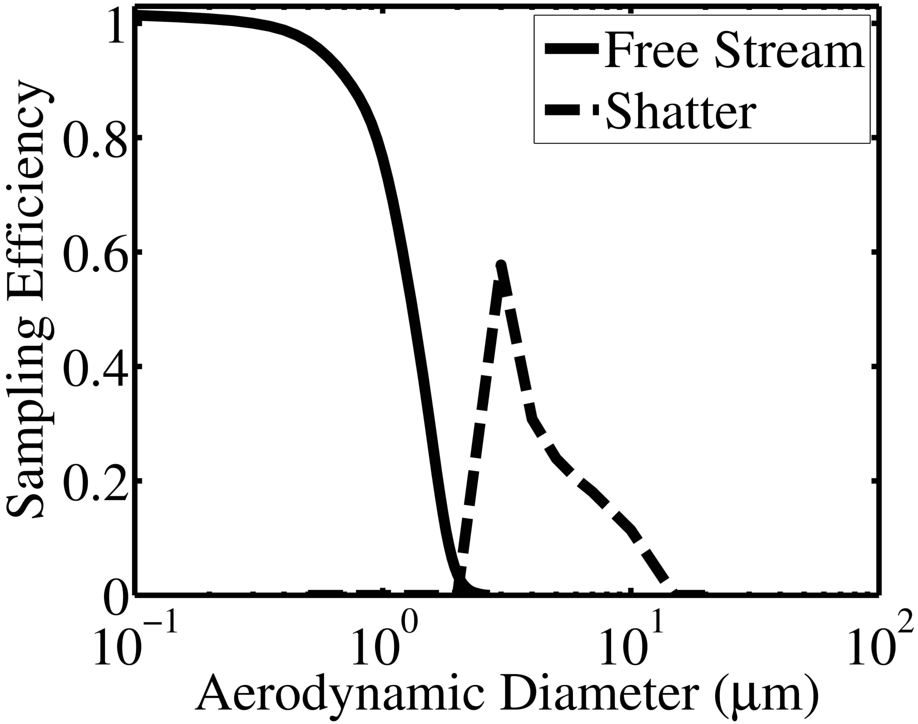

Fig. 9. The cut-size of the cross-flow sampling tube of BASE-II. Also shown is the size-dependent fraction of shatter particles that will be present in the sampling flow region of the cross-flow sampling inlet. Flight conditions are 400 mbar and Ma = 0.45, shatter particles were injected at normal velocity of 10 m s^{-1}.

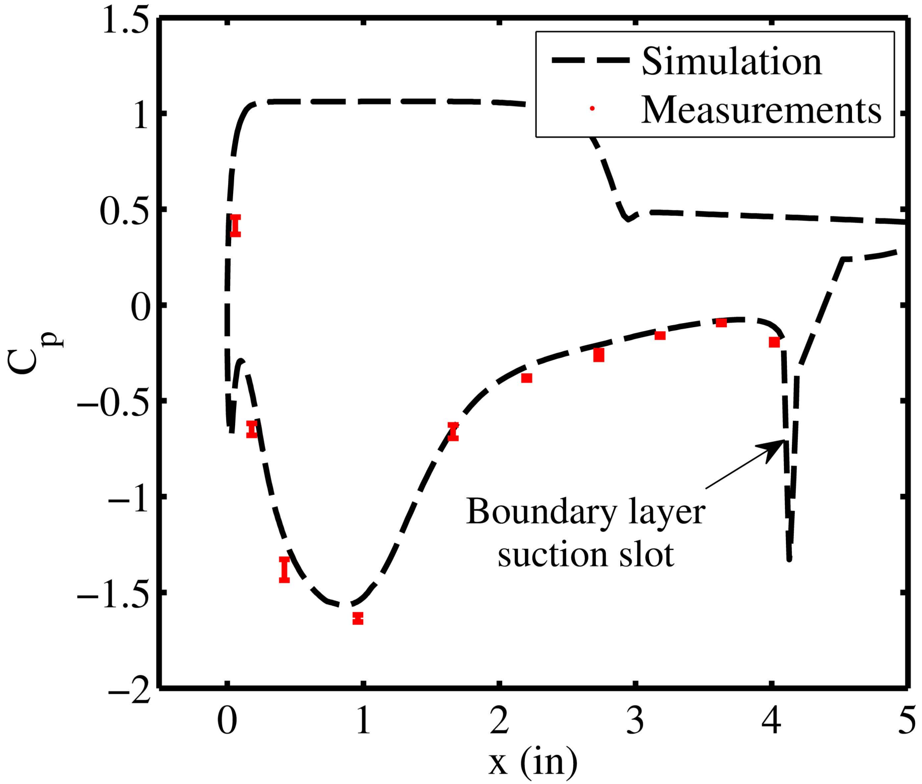

Fig. 10. Pressure distribution around the blunt body housing of BASE-II. Data from ICE-Trf04 (11 July 2011, 16:15–16:20 UTC), simulation boundary conditions: $P = 400$ mbar, Ma = 0.47.

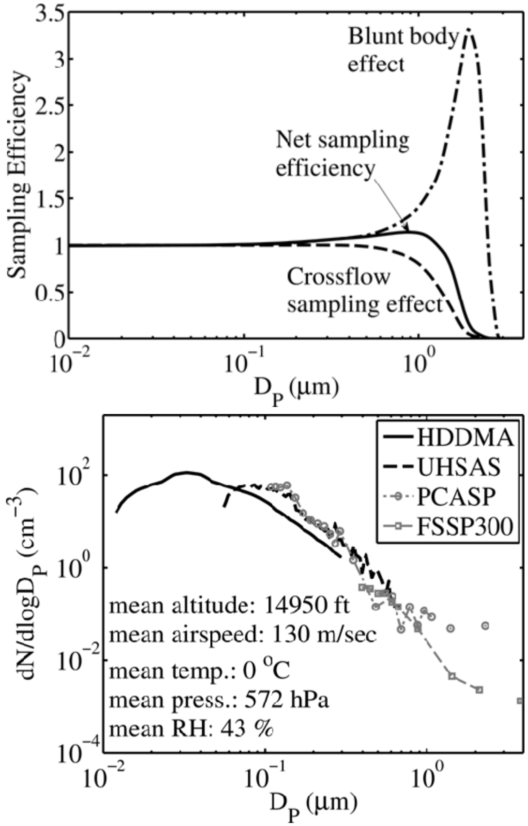

Fig. 11. (a) Predicted sampling efficiency for BASE-II; **(b)** measured aerosol size distribution from BASE-II compared with the freestream measurements in clear air. Measurement data from ICE-Trf04 (11 July 2011, 17:39:00–17:49:30 UTC).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

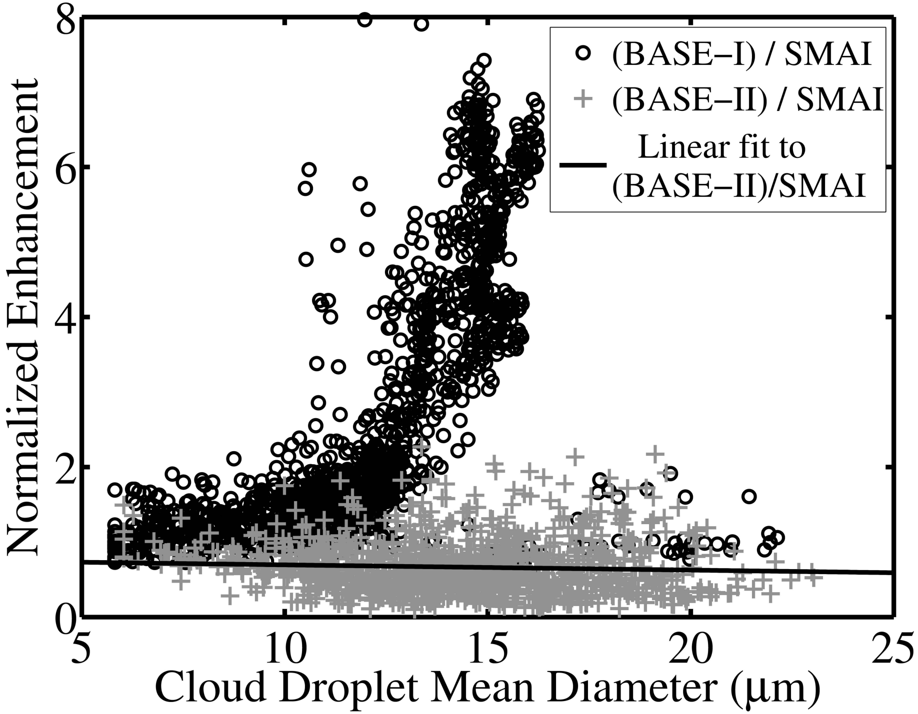

Fig. 12. In cloud CN enhancement of BASE-I and BASE-II, normalized by the enhancement values of SMAI at each data point. Data from all PLOWS and ICE-T campaign flights, atmospheric conditions: temp.: −5 to 1 °C; cloud droplet mean diameter: 5–25 μm; drizzle concentration: < 300 L^{1}; drizzle mean droplet diameter: < 600 μm; aircraft true airspeed: 125–150 m s^{-1}.