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Laboratory and modeling studies on the effects of water and soot emissions and ambient conditions on the formation of contrail ice particles in the jet regime

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Abstract

Contrails and contrail-induced cirrus clouds are identified as the most uncertain components in determining aviation impacts on global climate change. Parameters affecting contrail ice particle formation immediately after engine exit plane (<5 s in plume age) may be critical to ice particle properties used in large scale models predicting contrail radiative forcing. Despite this, detailed understanding of these parametric effects is still limited. In this paper, we present results from recent laboratory and modeling studies conducted to investigate the effects of water and soot emissions and ambient conditions on the near-field formation of contrail ice particles. The Particle Aerosol Laboratory (PAL) at the NASA Glenn Research Center and the Aerodyne microphysical parcel model for contrail ice particle formation were employed. Our studies show that exhaust water concentrations have a significant impact on contrail ice particle formation. When soot was introduced, ice particle formation was observed only when exhaust water concentration was above a critical level. When no soot or sulfuric acid was introduced, homogeneous ice particle formation was unfavorable. Soot particles were found to compete for water vapor condensation, and higher soot concentrations emitted into the chamber resulted in smaller ice particles being formed. Chamber conditions corresponding to higher altitude standard day conditions were found to favor ice particle formation as expected. The microphysical model captures experimental trends well, but discrepancies between the model and the experiments exist as the model predicts narrower ice particle size distributions and ice particle sizes nearly a factor of two larger than measured. These discrepancies are likely due to the lack of treatment of turbulent mixing in the model and particle loss and scatter during the experimental sampling process. Future measurement activities are planned to investigate other important parameters, such as soot surface properties and sulfuric acid concentrations, using the PAL and microphysical model.

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1 Introduction

As air traffic and the aviation industry continue to grow, the impact of aviation emissions on climate has also gained increased attention (Brasseur and Gupta, 2010). Condensation trails (contrails) behind aircraft engines are the products of water vapor and soot emissions at cruise. Currently, large uncertainty exists in determining potential impact of contrails and contrail-induced cirrus clouds on global climate change. Consequently, contrails and contrail-induced cirrus clouds have been identified as the most uncertain components of the aviation impacts on climate change with a low level of scientific understanding (Penner et al., 1999; Lee et al., 2009).

The onset of contrail ice particle formation is believed to be within one wingspan behind the engines. Several processes are involved in the formation of contrail ice particles, including hydrophobic soot surface activation, water vapor condensation on soot surfaces, freezing of the liquid water soot coatings, and further water vapor condensation onto frozen ice surfaces (Kärcher et al., 1996, 1998; Kärcher, 1998). The possibility of contrail formation is traditionally described by the Schmidt-Appleman Criterion (Appleman, 1953; Schmidt, 1941; Schumann, 2005), which states that a contrail will form if the exhaust plume reaches or surpasses saturation with respect to liquid water. The Schmidt-Appleman Criterion has been confirmed by observations to be reliable in predicting contrail formation (Kärcher et al., 1996; Jensen et al., 1998; Penner et al., 1999; Heymsfield et al., 2010), suggesting that the controlling factor for contrail formation is thermodynamics. However, recent modeling studies suggest that some parameters, such as fuel sulfur content and soot number density and size, may also affect formation mechanisms of contrail ice particles (Kärcher and Yu, 2009; Wong and Miake-Lye, 2010). These parameters are not considered in the Schmidt-Appleman Criterion, but they may be critical to properties of contrail ice particles used in large scale models to predict contrail radiative forcing, especially for scenarios reflecting future fleet emissions burning alternative fuels. A detailed understanding of these parametric effects on contrail ice particle formation in the jet regime (i.e., with a plume age <5

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s) is still limited. Since in-situ measurements of ice particles in aircraft plumes in the jet regime are challenging due to instrument limitations, well-controlled laboratory experiments in concert with modeling studies provide a cost-effective way to understand initial formation mechanisms of contrail ice particles.

This paper discusses results from our coupled laboratory and modeling investigation of the effects of water and soot emissions and ambient conditions on the near-field formation of contrail ice particles. The Particle Aerosol Laboratory (PAL) at the NASA Glenn Research Center (Tacina and Heath, 2010) was employed to simulate a broad range of conditions that bracket those found in the exhaust from aircraft engines at cruise altitudes. The Aerodyne microphysical parcel model for contrail ice particle formation (Wong and Miake-Lye, 2010) was used to guide experimental design and analyze experimental results. Experimental setup and procedures, modeling methodologies, and the results obtained from our studies are presented.

2 Experimental setup and procedures

2.1 NASA's Particle Aerosol Laboratory (PAL)

The PAL at the NASA Glenn Research Center (Fig. 1) contains a chamber facility designed to study aviation emissions at simulated altitudes up to 40 000 ft. During operation, the simulated exhaust is injected upwards into the chamber through a heated transition pipe measuring 2.43 cm in diameter by 1.6 m in length. The transition pipe terminates at a 1.0 cm diameter nozzle centered in the bottom and inside the chamber. Upstream of the nozzle exit, an in-line orifice drops the pressure of the exhaust products to near the chamber background pressure. Controlled amounts of soot particles, humidified air, sulfuric acid, and other trace species may be artificially introduced into the heated transition pipe to mimic aircraft exhaust. The heated pipe can also be connected to a laboratory-scale combustor burning liquid fuels to provide actual combustion exhaust to the chamber.

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The cylindrical test section of the chamber measures 1.83 m in height and has an inner diameter of 0.597 m. A cold nitrogen gas source supplies the working background fluid for the chamber. Relative humidity of the gas supply may be set up to 100 % for operation below 35 000 ft standard day conditions. Under chamber temperatures lower than 35 000 ft standard day temperature, reduced maximum relative humidity levels can be achieved due to facility limitations. A 1.52 m tall by 0.102 m wide instrumentation plate is located on one side of the chamber and contains a series of 1/4-in ports through which exhaust and ice particle samples may be extracted. Three double-paned windows, also 1.52 m tall by 0.102 m wide, are spaced 90° apart around the remaining circumference to provide optical access. The background nitrogen and combustion products exit the chamber through an exhaust duct located on top; the exhaust, in turn, is connected to a high-flow vacuum source to maintain the chamber at pressures simulating upper tropospheric conditions. More details on chamber operation, including background temperature and pressure profiles, can be found in the paper by Tacina and Heath (2010).

2.2 Sample introduction and instrumentation

To simulate aircraft exhaust gas at cruise, water vapor and soot particles were artificially introduced into the PAL chamber via a heated transition pipe upstream of the exhaust nozzle. The water vapor was introduced by a nafion-tube humidifier (Perma Pure, Toms River, NJ). Air flow entering the humidifier is split between 250 nafion tubes. On the outside of the tubes, heated water (70 °C) is circulated. The nafion acts as a selective membrane allowing water to pass into the air stream. The water content of the humidified air can be controlled by varying the air flow rate through the humidifier. A Jing Industries mini-Combustion Aerosol Standard 5200 (miniCAST) burner was used to generate combustion soot particles. The miniCAST burns a mixture of propane and air at variable fuel to air ratios to produce a well-characterized steady-size output of soot particles. During this experiment, the propane-to-air ratio was set at values to give 30–60 nm diameter soot particles, typical of aircraft exhaust (Timko et al., 2010).

To prevent any microphysics from taking place in the transition pipe, the whole transition pipe was heated to 400 °C. The particle size distributions of the introduced soot were measured by an engine exhaust particle sizer (EEPS, Wang et al., 2006), and the soot particle mass emitted was measured by a multi-angle absorption photometer. (MAAP, Petzold et al., 2005) before injecting into the chamber.

To measure ice particle size and number density in the simulated exhaust in the chamber, three horizontal sampling lines with a length of about 0.3 m were installed inside the chamber. The entrances of the sampling lines were located at 0.61, 1.02 and 1.47 m downstream of the exhaust nozzle and aligned with the chamber centerline. A small optical particle counter (OPC) was connected to each sampling line through a port on the instrumentation plate. The OPCs were operated with eight channels that measure ice particle size distributions larger than 300 nm. However, due to low signals (likely due to low chamber pressures) the data was combined into two channels (0.3–1 µm and greater than 1 mm). In addition to OPCs, a spectrometer system was also employed to measure the wavelength-dependent optical scattering and extinction of ice particles at 0.61 m downstream of the nozzle. The spectrometer is composed of a broad-band, xenon light source and three collecting optics precisely positioned to view the exhaust plume/light source intersection at angles of 14, 166, and 180 degrees. The collecting optics are fiber coupled to CCD-type monochromator/detectors to provide forward (166 degree) and backward (14 degree) scattering and extinction (180 degree) measurements over the 400 to 900 nm range.

For the sets of experiments presented in this paper, initial water concentration introduced into the chamber was varied between 0 and 5 % in molar fraction. The number density of the polydisperse soot particles introduced by the miniCAST burner ranged between 10^3 and 10^7 particles per cm^3 , and two different soot size distributions (peaking at 30 and 60 nm in diameter, respectively) prescribed in the exhaust were examined. The ranges of water and soot emissions studied in this work were selected to cover typical aircraft emissions at cruise (about 2.5 % molar fraction of water vapor emissions and about 10^7 cm^{-3} of soot particles with a mean diameter of 40 nm). The chamber

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background pressure and temperature were set between 25 000 ft and 40 000 ft standard day conditions. Relative humidity of the chamber co-flow stream was set at 0 %. This is because we do not believe it plays a critical role in the onset of contrail ice particle formation and 0 % relative humidity in the chamber co-flow stream avoids the possible introduction of undesired ice nuclei that may be contained in the chamber humidification air.

3 Modeling methodologies

In this work, our microphysical parcel model of ice particle formation in the jet regime at cruise (Wong and Miake-Lye, 2010) was employed to assist experimental data analysis. Our model tracks time evolution of a gaseous or a particle species in a jet engine exhaust plume in terms of contributions of chemistry, plume dilution and mixing, and microphysical processes as (Kärcher, 1998):

$$\frac{dX_i}{dt} = \left. \frac{dX_i}{dt} \right|_{\text{chemistry}} + \left. \frac{dX_i}{dt} \right|_{\text{mixing}} + \left. \frac{dX_i}{dt} \right|_{\text{microphysics}} \quad (1)$$

The contribution of chemistry comes from the chemical molar production rates of gaseous species. In this work, formation of H_2SO_4 from SO_3 and water (Brown et al., 1996) is the only significant chemical reaction under the conditions of interest.

The contribution of plume dilution and mixing is described as:

$$\left. \frac{dX_i}{dt} \right|_{\text{mixing}} = (X_i - X_{\text{amb},i}) \cdot \frac{df(t)}{dt} \cdot \frac{1}{f(t)} \quad (2)$$

where $f(t)$ is the exhaust mass fraction which explains how the exhaust is diluted by the co-flowing air as a function of residence time. In our model, a semi-empirical correlation describing the mixing of an axisymmetric jet in a co-flowing ambient fluid (Nickels and Perry, 1996) was used to evaluate plume centerline properties. The calculated exhaust plume centerline temperature, velocity, and dilution ratio as a function of downstream

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distance were found to be consistent with experimental data collected in the chamber (Tacina and Heath, 2010).

The contribution of microphysical processes is further divided into contributions of (1) homogeneous nucleation of new liquid particles, (2) coagulation among liquid particles, (3) activation of hydrophobic soot surfaces, (4) condensational growth of water vapor on soot particles, and (5) heterogeneous freezing of liquid coated soot particles:

$$\left. \frac{dX_i}{dt} \right|_{\text{microphysics}} = \left. \frac{dX_i}{dt} \right|_{\text{nucleation}} + \left. \frac{dX_i}{dt} \right|_{\text{coagulation}} + \left. \frac{dX_i}{dt} \right|_{\text{activation}} + \left. \frac{dX_i}{dt} \right|_{\text{condensation}} + \left. \frac{dX_i}{dt} \right|_{\text{freezing}} \quad (3)$$

In our model, homogeneous nucleation of new liquid particles is described by the kinetic quasi-unary nucleation theory developed by Yu (2005, 2006, 2007). Coagulation of different liquid particles is described using Brownian coagulation kernels (Fuchs, 1989). Activation of hydrophobic soot surface and condensational growth of water vapor on soot are treated the same way as Kärcher (1998) and our previous studies (Wong et al., 2008, 2011; Wong and Miake-Lye, 2010). Finally, heterogeneous freezing rate of liquid water coatings is described by the expression reported by Fornea et al. (2009).

4 Results and discussions

4.1 Effect of exhaust water vapor content

Our first set of experiments investigated the effect of exhaust water vapor content on the formation of contrail ice particles. In this set of experiments, the soot particles introduced by the miniCAST burner was kept constant at $2 \times 10^5 \text{ cm}^{-3}$ with 30 nm in diameter. The chamber temperature and pressure were also kept constant at 35 000 ft

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standard day conditions. Water vapor content in the exhaust was varied between 0–5 % in molar fraction. To measure stable ice particle concentrations, each level of water vapor content was held constant for approximately 1 minute before switching to the next level, as illustrated in Fig. 2a. Our experimental results show that exhaust water vapor concentration has a dominant effect on ice particle formation. As shown in Fig. 2b, particle optical extinction measured at 0.61 m downstream of the nozzle increased with increasing exhaust water vapor content. OPC measurements, however, did not observe ice particles formed until a certain level of exhaust water content was reached (this level was about 3 % in molar fraction in Fig. 2b). Above this threshold level, increased ice particle concentration was measured by the OPC with increasing exhaust water vapor concentration, consistent with the extinction data.

To further understand what can be learned from our measurement data, we performed detailed microphysical parcel simulations using the model described in Sect. 3. To simplify our simulations, only the dilution profiles describing average mixing behavior in the exhaust centerline were used. As a result, turbulent mixing in the chamber was not considered in calculating dilution history that was used in our microphysical simulations. Note that we did not introduce compounds that can activate hydrophobic soot surfaces in the experiments (such as sulfuric acid) but observed ice particle formation in the chamber. Filter samples of the soot were collected and analyzed with a Sunset Laboratory Organic-to-Elemental Carbon (OC/EC) Analyzer (Birch and Cary, 1996). An OC/EC ratio of 2–5 was found. However, because a volatile organic denuder was not used before the filter, this ratio can only be treated as an upper limit for the amount of organic carbon. Previous studies have found OC/EC ratios of 1 when the larger version of the miniCAST was used to make 30 nm soot from propane. This analysis suggests that the soot surfaces were coated with organic carbon atoms, some of which may be oxygenated, hydrophilic carbon atoms. Consequently, we assumed in the model that 20 % of the soot surface area is pre-activated. We did not observe significant sensitivity to this quantity in our model calculations as long as larger than 5 % of the soot surface area is assumed to be activated. Future laboratory studies are

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planned to quantify and control the hydrophilic fraction of the soot surface.

Figure 3a shows a comparison between the predicted and measured ice particle concentration at 0.61 m downstream of the exhaust nozzle. To be consistent with the known OPC instrument limitation, the model assumed that any particles smaller than 300 nm were not detected. As the figure depicts, the model predicts a sharp onset of ice particle formation at an exhaust water level of about 0.5 % in molar fraction. This can be explained by the Schmidt-Appleman Criterion, which states that ice particles are only formed if the exhaust plume reaches or surpasses saturation (i.e., $\geq 100\%$) with respect to liquid water at some point of the dilution history. Since the smooth dilution trajectory used in our model suggests that this would occur at exhaust water levels of more than about 0.5 % in molar fraction (also plotted in Fig. 3a) under this chamber condition, our microphysical parcel model predicts a sudden onset of ice particle formation at the same exhaust water level. The onset of ice particle formation measured by the OPC, however, is less steep and at a higher exhaust water level. This is likely due to the fact that the model only considered a smooth dilution history in the chamber centerline and did not consider any turbulent mixing effects that could alter the history of water vapor concentration, which would cause larger variation in ice particle size distributions, especially close to threshold conditions of the Schmidt-Appleman Criterion.

Figure 3b compares the predicted and measured fraction of the ice particles that are larger than 1 μm (termed as super-micron fraction) as a function of exhaust water level at 0.61 m downstream of the exhaust nozzle. Similar to what is shown in Fig. 3a, a sharp onset of super-micron fraction at a lower exhaust water vapor concentration is predicted by the model compared to the experiments. The model also predicts greater ice particle super-micron fraction, which reaches 100 % at exhaust water levels of more than 0.6 % in molar fraction compared to at most about 30 % measured experimentally. Again, this discrepancy is likely due to the fact that the model does not consider turbulent mixing in the chamber such that all the particles experienced the same water vapor dilution history. As a result, narrower particle size distributions are predicted. In reality, turbulent mixing introduces more deviation in the dilution history of water vapor, and

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therefore, some liquid water coated soot under threshold conditions might not freeze to form ice particles in the measurements.

Although our model does not capture the wider particle size distributions measured experimentally, our model was able to capture the experimental trends well. As demonstrated in Fig. 3c, the predicted mean ice particle size increased with exhaust water vapor content, consistent with the particle extinction measurements. Note that total extinction is proportional to particle cross-sectional area for particles larger than $1\text{ }\mu\text{m}$, and model predicted particle diameter squared was able to capture this trend very well, as also depicted in Fig. 3c. The predicted mean particle size is about a factor of two larger than the OPC measured particle size. This is likely due to particle loss or scatter during the sampling process, which is not considered in the microphysical model.

A similar set of experiments varying exhaust water vapor contents were also performed without introducing any soot particles. In that set of experiments, we did not observe any evidence of ice particle formation even at exhaust water vapor level of 5 % in molar fraction. This suggests that homogeneous ice particle formation is unfavorable under the conditions studied in this work. Note that this statement may change if sulfuric acid is present in the exhaust, as suggested by recent modeling study by Kärcher and Yu (2009).

4.2 Effect of soot emissions

The second key parameter investigated in our laboratory and modeling studies is the effect of soot particles emitted into the chamber. Several sets of experiments were performed with constant chamber conditions and exhaust water level but with variable soot particle concentrations introduced ranging from 10^2 – 10^7 cm^{-3} . Figure 4 illustrates one of these sets of experiments, where exhaust water level was set at 2 % in molar fraction and the chamber was set at 40,000 ft standard day conditions. Note that the soot particles introduced in this experiment set were kept as close to the same size as possible, and soot particle concentration was increased from about 10^3 to 10^7 cm^{-3} and back to 10^3 cm^{-3} to study experimental reproducibility. A video camera trained

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on the intersection of the spectrometer light source and exhaust plume was employed for visual confirmation of particle formation. As shown in the figure, maximum ice number concentration measured by the OPC at 0.61 m downstream of the nozzle was observed at a soot concentration of about 10^6 cm^{-3} . When soot particle concentration was introduced above this level, the measured ice particle counts decreased. However, particles were still visible in the video snap shots when OPC measured this reduced ice concentration. This is likely due to the size limitation of OPCs that any liquid or ice particles smaller than 300 nm in diameter cannot be detected. The decrease in ice particle super-micron fraction with increasing number of soot particles injected into the chamber (color coded in the ice concentration curve in Fig. 4) further supports this statement. Our measurement results suggest that smaller ice particles were formed when higher concentration of soot particles was introduced, implying that competition for water vapor condensation among soot particles exists. This is also consistent with findings from our previous modeling study (Wong and Miake-Lye, 2010).

We again performed model simulations to assist experimental data analysis and interpretation. Figure 5a shows a comparison between the predicted and measured ice particle counts. The measured particle optical extinction is also plotted for comparison. As shown in the figure, model predicted ice particle concentrations at initial soot concentrations lower than about $1 \times 10^5 \text{ cm}^{-3}$ agree very well with experimental data when exhaust water level is at 2–3 % in molar fraction. However, at soot concentrations higher than $1 \times 10^5 \text{ cm}^{-3}$, the model over-predicts ice particle concentrations by as large as about two orders of magnitude. This is because the model over-predicts ice particle size (about a factor of two, as mentioned in the previous section), and consequently number of ice particles that are larger than the OPC cutoff at 300 nm is over-predicted. This over-prediction from the model is not present by comparing the modeling results with the optical extinction data. The size discrepancy between the model and experiments can be due to the particle loss and scatter during the sampling process, which is not accounted for in the model and was not a factor in the extinction measurements. At 0–1 % molar ratio of exhaust water level, the model consistently predicted less ice

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particle formed than 2–3 %, the same trend observed experimentally. Compared to the experimental data, the model again over-predicts ice particle concentrations for all soot concentrations studied. Since smaller ice particles are formed at this exhaust water level, more ice particles were not measured by the OPC due to its cutoff and the discrepancy between the model and the OPC measurements was larger compared to higher exhaust water levels.

Figure 5b compares model predicted and measured ice particle super-micron fraction at 0.61 m downstream of the nozzle. The figure clearly shows that the model was able to capture the fall-off of the super-micron fraction very accurately at an exhaust water level of 2–3 % in molar fraction. Since no significant amount of ice particles was measured at an exhaust water level of 0–1 % in molar fraction (Fig. 5a), a large uncertainty in the experimental super-micron fraction exists, as shown by the red-filled circles in Fig. 5b. The predicted ice particle super-micron fraction from the model, however, is about a factor of two larger than what was measured experimentally. Again, this is likely due to the effect of turbulent mixing, which may cause heterogeneity and reduced experimental super-micron fraction.

4.3 Effect of chamber conditions

Figure 6 shows a comparison between the experimental and modeling results on ice particle concentration at 0.61 m downstream of the nozzle under three different chamber conditions. As depicted in the figure, our model predicts that the onset of ice particle formation takes place at lower exhaust water levels under higher altitude standard day conditions. The model also predicts a sharp onset of ice particle formation with respect to exhaust water level for each chamber condition. This is because for each chamber condition, there is a critical exhaust water level that corresponds to surpassing liquid water supersaturation in the exhaust plume. Based on the dilution trajectories estimated by the semi-empirical correlation described in Sect. 3 (Nickels and Perry, 1996), this level was about 0.5–0.6 % molar fraction under 40 000 ft and 35 000 ft standard day conditions and about 1 % molar fraction under 30 000 ft standard day conditions. As a

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result, our model predicts the onset of ice particle formation at similar exhaust water level (0.5–0.6 % molar fraction) under 40 000 ft and 35 000 ft standard day conditions, but the onset under 30 000 ft standard day conditions requires a higher exhaust water level at about 1 % in molar fraction. This finding is again consistent with the Schmidt-Appleman Criterion. Figure 6 also shows ice particle counts measured by the OPC at 0.61 m downstream of the nozzle under different chamber conditions. Unlike the modeling results, higher concentration of ice particles were measured under higher altitude standard conditions (i.e., lower chamber temperature and pressure). Again, this discrepancy is likely due to the effect of turbulent mixing and particle loss and scatter during the sampling process.

5 Conclusions

In this paper, we present results from our recent laboratory and modeling investigation of the effects of water and soot emissions and ambient conditions on the near-field formation of contrail ice particles. The Particle Aerosol Laboratory (PAL) at the NASA Glenn Research Center and the Aerodyne microphysical parcel model for contrail ice particle formation were employed. Our studies show that exhaust water level has a significant effect on contrail ice particle formation, and an onset exhaust water level of ice particle formation exists when soot is present. When no soot or sulfuric acid was introduced, homogeneous ice particle formation was found to be unfavorable. Soot particles were found to compete for water vapor condensation, and higher soot concentration emitted into the chamber results in smaller ice particles formed. Chamber conditions corresponding to higher altitude standard day conditions were found to favor ice particle formation as expected. The microphysical model captures experimental trends well, but discrepancies between the model and the experiments exist as the model predicts narrower ice particle size distributions and ice particle sizes nearly a factor of two larger than measured. These discrepancies are likely due to the lack of treatment of turbulent mixing in the model and particle loss and scatter during the experimental

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sampling process. Parametric understanding obtained in this work is aimed at better estimates of ice particle properties used in large scale models predicting contrail radiative forcing and impact of contrail on global climate change. Future measurement activities are planned to investigate other important parameters, such as soot surface properties and sulfuric acid concentrations using PAL and the microphysical model.

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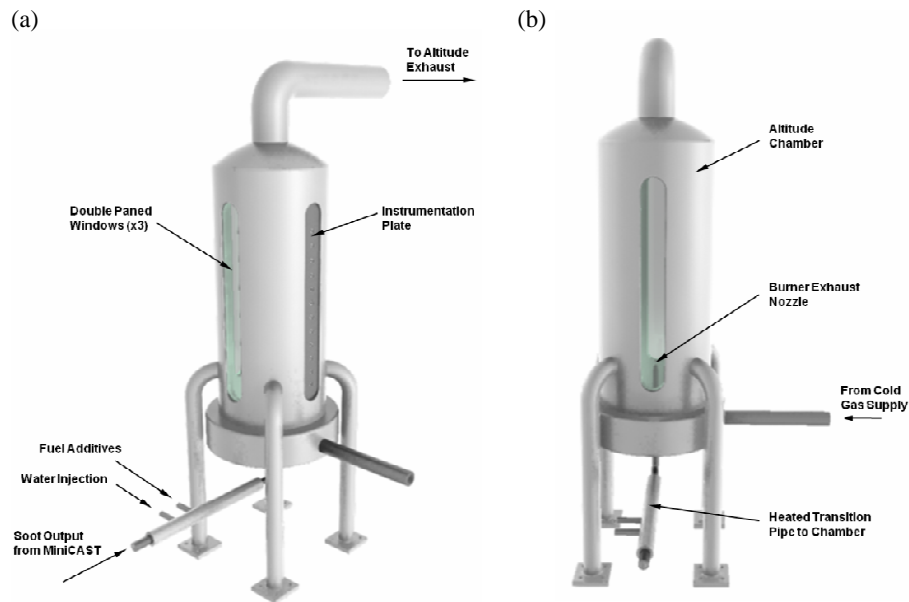


Fig. 1. Particle Aerosol Laboratory (PAL) altitude simulation chamber **(a)** isometric view and **(b)** front view.

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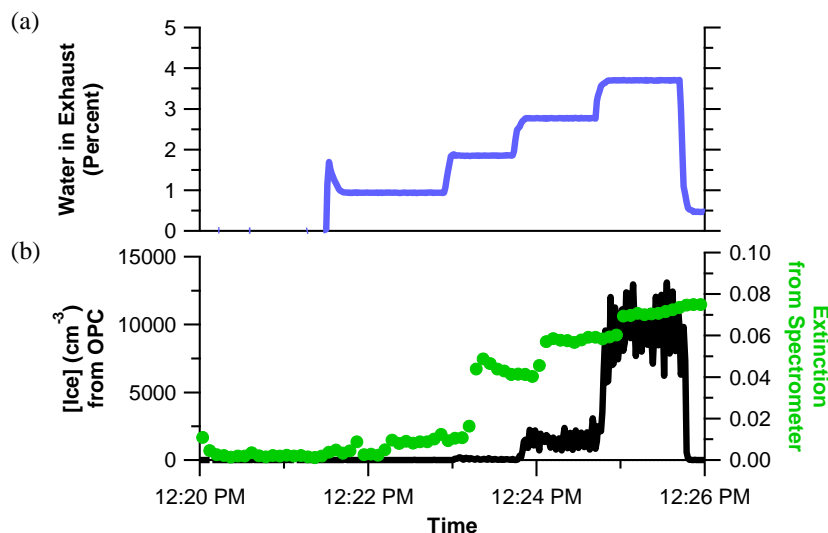


Fig. 2. Effect of water vapor level in the exhaust on ice particle formation: **(a)** the water vapor level was varied between 0–4 % molar fraction in the exhaust, and each water level was held constant for approximately 1 min in order for the ice concentrations to stabilize; **(b)** real-time measurement of OPC counts (black) and particle optical extinction (green) at 0.61 m downstream of the exhaust nozzle.

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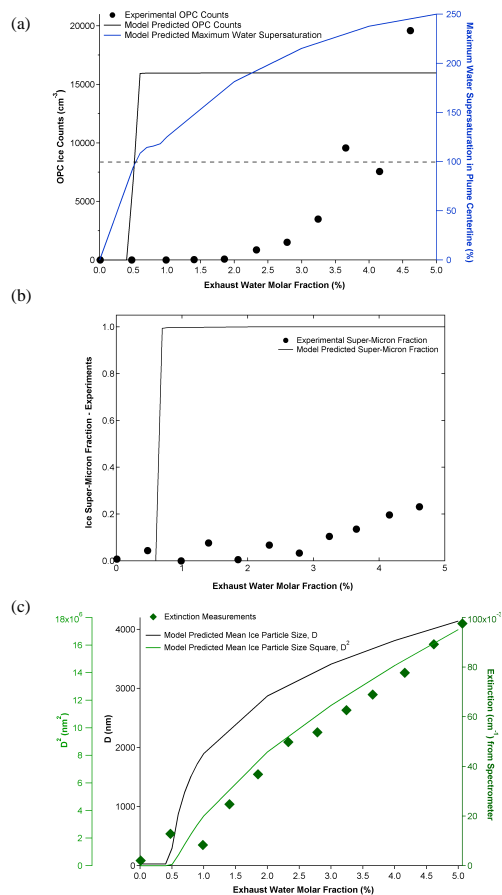


Fig. 3. Comparison of experimental and modeling results on **(a)** OPC counts; **(b)** ice super-micron fraction; **(c)** predicted ice particle size and measured particle optical extinction as a function of exhaust water molar fraction at 0.61 m downstream of the exhaust nozzle.

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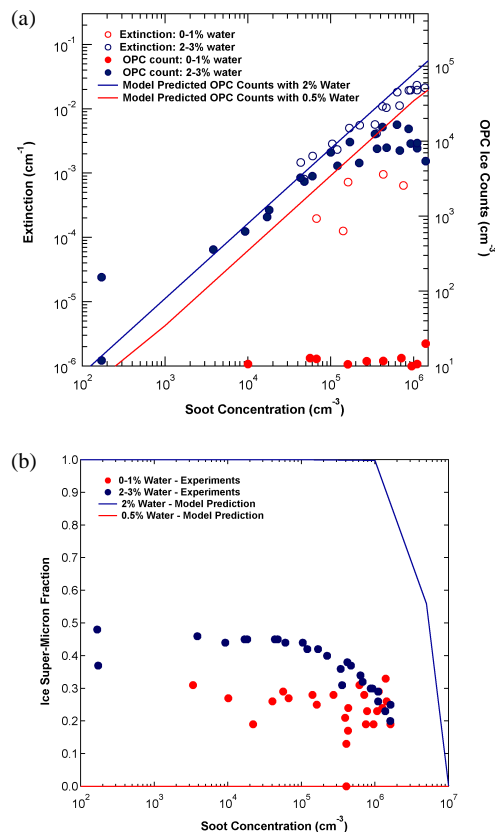


Fig. 5. Comparison of **(a)** model predicted ice particle concentration and measured ice particle concentration and particle optical extinction values and **(b)** model predicted and measured super-micron fraction of ice particle at 0.61 m downstream of the nozzle (note that the experimental values of ice particle super-micron fraction for 0–1 % exhaust water vapor mole fraction have large uncertainties due to low OPC counts).

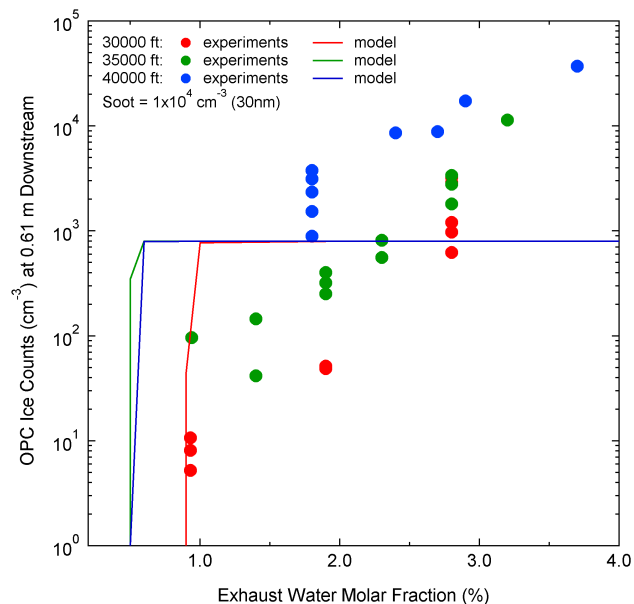


Fig. 6. Comparison of experimental and modeling results on OPC counts at 0.61 m downstream of the nozzle for different chamber conditions.

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