Aerodynamic formation of condensation trails

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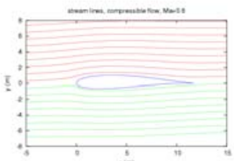
Introduction

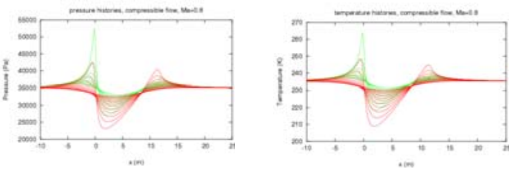
Photographs taken by pilot Jeff Well out of his cockpit show that condensation sometimes starts right above the wings of cruising aircraft. This demonstrates the existence of contrails different from the well studied jet exhaust contrails.
The present study is a first investigation of the conditions that lead to the appearance of aerodynamic contrails. Studies of aerodynamic contrails require interdisciplinary research on compressible gas flow over airfoils, ice and aerosol microphysics, and optics of ice crystals, such as presented on this poster.

Aerodynamics

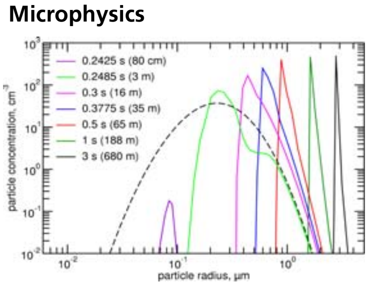


2-dimensional potential flow field (compressible flow) around a Joukowski airfoil, calculated with the method of singularities. Effective angle of attack: 1°. Mach number: 0.8. The dimensions of the aerofoil are typical of a wide-body aircraft close to the fuselage.

Calculation of pressure and temperature along streamlines with generalised Bernoulli equation. $p_\infty = 350$ hPa, $T_\infty = 235$ K.



Microphysics

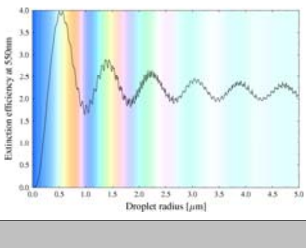


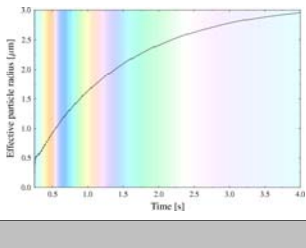
The figure shows results of microphysical calculations using a comprehensive gas-aerosol-ice trajectory model. Water condensation on liquid aerosol droplets, ice nucleation, and depositional growth of the ice crystals have been simulated, driven by one of the T- and p-trajectories close to the wing as shown above. The legend denotes distances behind the leading wing edge and times.

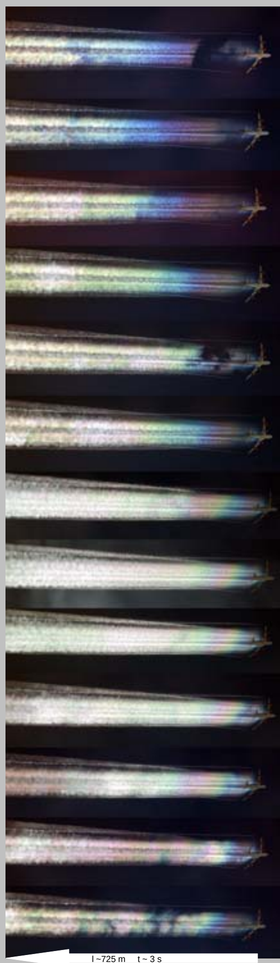
The ice crystal size distributions (solid curves) are generated from homogeneous freezing of liquid aerosol droplets (dashed). The smallest droplets freeze first, followed by freezing of larger droplets, until all available aerosol particles are depleted. Nucleation is finished as the air parcel moves across the wing (after ~16 m). In the subsequent growth phase in highly supersaturated air (RHI=140%), mean crystal sizes increase to ~2.8 µm after ~680 m.

Optics

Mie theory was used to calculate optical properties from the size distributions, assuming spherical ice particles. Spectral radiance was calculated in single-scattering approximation and converted to colour. For a mono-disperse distribution, the colour changes with the effective radius, due to the wavelength-dependence of the scattering efficiency (left image). The right image shows the colours for the actual size distributions which nicely match the photograph.

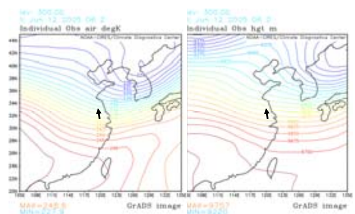






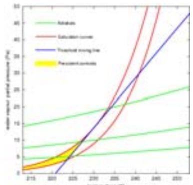
On June 12 2005 from 14:59 to 15:06 Bejing time (~07:00 UTC) pilot and photographer Jeff Well took a series of 45 photos of an exceptionally colourful iridescent contrail produced by an A340-313X aircraft in 9600 m altitude, just 1200 m higher as his position on the same route over eastern China. Both aircraft were heading to North-West (329°) from 32° 14.8’ N, 119° 46.7’ E to 32° 56.8’ N, 119° 10.1’ E.

From NCEP reanalysis data we estimate a temperature of -40 °C, the aircraft altitude is close to the 300 hPa pressure level shown below.

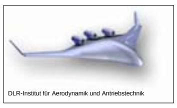


The series of photos on the left shows the development of contrails that cannot be explained by the Schmidt-Appleman criterion. Jet contrails produced from the mixing of exhaust gases with the ambient air would show up as 4 separate lines and start later. The onset of the aerodynamic contrails occurs directly above the wings and is stronger close to the body of the aircraft. Thin vortex lines originate from the wing tips and get mixed into the wake vortices

Conclusions, outlook, open questions



The aerodynamic formation of condensation trails is independent of the Schmidt-Appleman criterion. Aerodynamic contrails can appear and persist whenever the ambient air is ice-supersaturated. The adiabatic cooling in the flow leads to higher supersaturation the warmer and moister is the air. To produce a visible aerodynamic contrail, the numerous ice crystals must grow sufficiently rapid, requiring warm temperatures.



Photographs demonstrate that the effect occurs preferentially on the inner parts of the wings where lift is largest. Hence, aerodynamic contrails may become more relevant for a potential future fleet of blended wing-body aircraft with their large wing depths.

Future work will investigate the properties of the small ice crystals produced in the adiabatic air flow over wings of airliners, the impact of ambient conditions and background aerosol properties on aerodynamic contrail formation and evolution, and how common this process occurs relative to the formation of jet contrails.

Acknowledgement

The photographs shown here are all taken by pilot Jeff Well. We thank him for allowing us to use them and for having kept his eyes open not only for the instruments in his cockpit but also for the beauty of optical phenomena. Many other photographs of aerodynamic contrails can be found on www.airliners.net.