Meteorol. Zeitschrift, N.F. 6, 304–305 (Dezember 1997)

Contrails — a prototype of cirrus cloud studies since 80 years*

ULRICH SCHUMANN, Oberpfaffenhofen

The clouds often seen to be formed in the wake of aircraft are called condensation trails (BREWER 1946), contrails (APPLEMAN 1953), or Kondensstreifen. Contrails form behind propeller-driven aircraft as well as behind jet aircraft. Contrails often turn over into cirrus clouds covering an essential fraction of the sky. Hence, understanding of contrail formation also helps in understanding formation of natural cirrus clouds. In recent years, the question how far contrails change the climatological or chemical state of the atmosphere triggered intensive research (KÄRCHER et al. 1996, FREUDENTHALER et al. 1996, PONATER et al. 1996, GIERENS 1996).

The first contrail was observed in 1915 (ETTENREICH 1919). Aircaft reached altitudes above 6 km at that time. Observations of a long-lasting contrail were reported for a flight at about 9 km altitude over Munich by L. WEICKMANN (1919), SCHMAUSS (1919), and WEGENER (1920). It is interesting to see how the contrails were explained (wrongly) at that time. It was assumed that aircraft induce particles on which water vapor may sublimate. In the meantime we learned that particles get activated to grow only at humidities considerably above ice saturation (H. WEICKMANN 1945). The early studies ignored the simultaneous release of heat and water vapor. The heat causes a drying of air which needs to be taken into account. Also, it was unclear how a small aircraft may trigger large-scale clouds in the relatively dry upper troposphere. For reviews see KRAMER (1951) and SCHUMANN (1996a).

The explanation of how and when contrails form in the atmosphere is often attributed to APPLEMAN (1953). However, the same theory was given before, and even more elegantly by SCHMIDT (1941). Part of this overlook is explained by the fact that SCHMIDT's work was documented in classified war-time documents. However, APPLEMAN cited British war-time reports and acknowledged talks with H. WEICKMANN and H. J. AUFM KAMPE, who certainly knew of the work by E. SCHMIDT (AUFM KAMPE 1943, WEICKMANN 1945). Hence, he could have known SCHMIDT's work. Even most recent US studies (e.g. HANSON and HANSON 1995, COLEMAN 1996) still cite APPLEMAN as the first who explained contrail formation (SCHUMANN 1996b). Certainly, APPLEMAN's (1953) paper made the contrail concept best available to the public.

Ernst SCHMIDT was born 11 February 1892 in Vögelsen near Lüneburg in Germany. He studied the formation of fog from the exhaust gases of propeller-driven aircraft engines during the second World War when working within the Deutsche Forschungsanstalt für Segelflug, DFS in Braunschweig, one of the forerunners of the present DLR. He later became Professor for Technical Thermodynamics at the Technical University of Munich (SCHMIDT 1963).

SCHMIDT (1941) deduced a thermodynamical theory to show that the conditions for contrail formation depend only on ambient pressure, humidity and the ratio of water and heat released into the exhaust plume. SCHMIDT (1941) used the MOLLIER (1923) concept of isobaric mixing between two states of specific enthalpy and water content per unit mass of dry air. He showed that contrails form when during mixing the plume water content exceeds saturation. SCHMIDT (1941) assumed that contrails form under equilibrium conditions when reaching ice saturation. HÖHNDORF (1941) applied SCHMIDT's theory to saturation with respect to liquid water which explained contrail observations better. He noted that contrails grow fast after onset and this can be explained by freezing of liquid particles. When AUFM KAMPE (1943) reported measurements of temperature in the immediate wake of aircraft, he mentioned SCHMIDT's theory and the condition of liquid saturation as proposed by HÖHNDORF (1941).

SCHMIDT (1941) also explained differences in contrail formation for different aircraft conditions. Only part of the combustion heat is given directly to the exhaust gas depending on the aircraft performance. The other part (fraction η) is released to the ambient air in the form of radiation or kinetic energy of, e.g., turbulence and trailing vortices. This energy gets dissipated by turbulent and viscous mixing and warms the moist plume at later distance from the aircraft so that the early exhaust plume is cooler than to be expected from the total amount of combustion heat. As a consequence, the threshold temperature for contrail formation is higher than when the exhaust gases receive all combustion heat directly. BUSEN and SCHUMANN (1995) identified η with the overall propulsion efficiency of the aircraft which depends on engine and flight parameters. This concept was verified experimentally also in SCHUMANN et al. (1996).

Observations also showed a shortening of contrails in the stratosphere which could not be explained by temperature changes alone. BREWER (1946) developed an air-borne frost-point hygrometer to measure the water vapour content during various high-altitude flights. These observations led to the detection that the stratosphere is much drier than the troposphere (DOBSON et al. 1946).

In order to form droplets when reaching small liquid supersaturation, the exhaust must contain many cloud condensation nuclei. Both soot and sulfur compounds emitted with the exhaust gases are important for ice particle formation (SCHUMANN et al. 1996, KÄRCHER et al. 1996, GIERENS and SCHUMANN 1996, BUSEN et al. 1996, BROWN et al. 1997, PETZOLD et al. 1997). Research on the particle formation processes is ongoing. This research gains from understanding obtained during the last 80 years.

* Editorial note:
Ulrich Schumann had presented a detailed review article on investigations concerning contrails already in Meteorologische Zeitschrift, Neue Folge 5, 1996, to which interested readers are referred to. As a brief information about the primary actors and the relevant literature the extended abstract of the workshop presentation is given here.

References

Appleman, H., 1953: The formation of exhaust condensation trails by jet aircraft. — Bull. Amer. Meteorol. Soc. 34, 14–20.
aufm Kampe, H. J., 1943: Die Physik der Auspuffwolken hinter Flugzeugen. — Luftwissen 10, 171–173. English in NASA-TT-F-14047 (1971).

0941-2948/97/0006-0304 $ 00.90

Brewer, A. W., 1946: Condensation trails. — Weather 1, 34–40.
Brown, R. C., R. C. Miake-Lye, M. R. Anderson, C. E. Kolb, 1997: Aircraft sulfur emissions and the formation of visible contrails. — Geophys. Res. Lett., 24, 385–388.
Busen, R., D. Baumgardner, S. Borrmann, D. Hagen, M. Kuhn, A. Petzold, F. Schröder, U. Schumann, J. Ström, P. Whitefield, 1996: Experiments on contrail formation from fuels with different sulfur content. — Proc. Intern. Coll. "Impact of Aircraft Emissions upon the Atmosphere," Paris, 15–18 Oct. 1996, Vol **1**, 149–154.
Busen, R., U. Schumann, 1995: Visible contrail formation from fuels with different sulfur contents. — Geophys. Res. Lett. **22**, 1357–1360.
Colemann, R. F., 1996: A new formulation for the critical temperature for contrail formation. — J. Appl. Meteor. **35**, 2270–2282.
Dobson, G. M. B., A. W. Brewer, B. M. Cwilong, 1946: Meteorology of the lower stratosphere. — Proc. Roy. Soc. A **186**, 144–175.
Ettenreich, R., 1919: Wolkenbildung über einer Feuersbrunst und an Flugzeugabgasen. — Meteorol. Z. **36**, 355–356.
Freudenthaler, V., F. Homburg, H. Jäger, 1996: Optical parameters of contrails from lidar measurements: Linear depolarization. — Geophys. Res. Lett. **23**, 3715–3718.
Gierens, K., 1996: Numerical simulations of persistent contrails. — J. Atmos. Sci. **53**, 3333–3348.
Gierens, K., U. Schumann, 1996: Colors of contrails from fuels with different sulfur contents. — J. Geophys. Res. **101**, 16731–16736.
Hanson, H. M., D. M. Hanson, 1995: A reexamination of the formation of exhaust condensation trails by jet aircraft. — J. Appl. Meteor. **34**, 2400–2405.
Höhndorf, F., 1941: Beitrag zum Problem der Vermeidung von Auspuffwolken hinter Motorflugzeugen. — Deutsche Luftfahrtforschung, Berlin, FB 1171, pp. 15.
Kärcher, B., Th. Peter, U. B. Biermann, U. Schumann, 1996: The initial composition of jet condensation trails. — J. Atmos. Sci. **53**, 3066–3083.
Kramer, M. P., 1951: Annotated bibliography on condensation trails behind aircraft. — Meteorol. Abstracts and Bibliogr., Part II, Lancaster, p. 765–782.
Mollier, R., 1923: Ein neues Diagramm für Dampfluftgemische. — Z. VDI **67**, 869–872.
Petzold, A., R. Busen, F. P. Schröder, R. Baumann, M. Kuhn, J. Ström, D. Hagen, P. Whitefield, D. Baumgardner, F. Arnold, S. Borrmann, U. Schumann, 1997: Measurements of contrail particles for different fuel sulfur content. — J. Geophys. Res., in press.
Ponater, M., S. Brinkop, R. Sausen, U. Schumann, 1996: Simulating the global atmospheric response to aircraft water vapour emissions and contrails — A first approach using a GCM. — Ann. Geophys. **14**, 941–960.
Schmauss, A., 1919: Bildung einer Cirruswolke durch einen Flieger. Randbemerkungen IV. — Meteorol. Z. **36**, 265.
Schmidt, E., 1941: Die Entstehung von Eisnebel aus den Auspuffgasen von Flugmotoren. — Schriften der Deutschen Akademie der Luftfahrtforschung, Verlag R. Oldenburg, München und Berlin, Heft 44, 1–15, available at Deutsches Museum Munich, DLR Göttingen, and DLR Oberpfaffenhofen. Auszug in: Jahrbuch der Deutschen Akademie der Luftfahrtforschung, 1940/1941, Berlin 126–135.
— 1963: Einführung in die Technische Thermodynamik. 10th ed., Springer, Berlin, pp. 559.
Schumann, U., 1996a: On conditions for contrail formation from aircraft exhausts. — Meteorol. Z., N.F. **5**, 4–23.
Schumann, U., 1996b: Comment on "A Reexamination of the Formation of Exhaust Condensation Trails by Jet Aircraft" by H.H. Hanson and D. M. Hanson. — J. Appl. Meteorol. **35**, 2283–2284.
Schumann, U., J. Ström, R. Busen, R. Baumann, K. Gierens, M. Krautstrunk, F. P. Schröder, J. Stingl, 1996: In situ observations of particles in jet aircaft exhausts and contrails for different sulfur containing fuels. — J. Geophys. Res. **101**, 6853–6869.
Wegener, A., 1920: Frostübersättigung und Cirren. — Meteorol. Z. **37**, 8–12. English abstract in Mon. Wea. Rev. **49** (1921) 349.
Weickmann, L. sen., 1919: Wolkenbildung durch ein Flugzeug. — Naturwissenschaften **7**, 625.
Weickmann, H., 1945: Formen und Bildung atmosphärischer Eiskristalle. — Beitr. Phys. Atmosph. **28**, 12–52.

Prof. Dr. U. SCHUMANN
Institut für Physik der Atmosphäre
DLR Oberpfaffenhofen
D-82230 Weßling

Received 14 August 1997