NOTES AND CORRESPONDENCE

Comments on "A Reexamination of the Formation of Exhaust Condensation Trails by Jet Aircraft"

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Hanson and Hanson (1995) (henceforth HH) discuss the thermodynamic conditions for condensation trail (contrail) formation from aircraft exhaust. They reexamine the classical criterion as described in Appleman (1953), account for engine differences as proposed by Peters (1993), propose a new condition to compute the critical temperature below which contrails are to be expected, and claim that this fits previous observations better than the classical theory.

It is generally assumed that contrails form when isobaric mixing between the hot and humid exhaust gases and cold ambient air leads to a mixture reaching saturation with respect to water so that cloud droplets form, which then might freeze to form ice particles (Appleman 1953). This fact was already understood in the 1940s, as documented in several German and British wartime reports (e.g., Schmidt 1941) well before it was documented in the open literature. A review of the historic development of the theory and its experimental verification is given in Schumann (1996).

For 100% relative humidity (RH), HH follow the classical approach, where the critical temperature T_c, below which contrails form, satisfies

$$\frac{de_s(T_c)}{dT} = G, \tag{1}$$

that is, where the saturation pressure for liquid saturation e_s as a function of temperature T takes the same gradient as the mixing line between the engine exit and environmental states with gradient

$$G = \frac{p\mathrm{CF}}{\epsilon}. \tag{2}$$

Here, $\epsilon = 0.622$ is the ratio of the molar masses of water vapor and air, p is the ambient pressure, and CF is the so-called contrail factor. Peters (1993) found that CF is engine dependent. Busen and Schumann (1995) showed that CF actually depends on the emission index (EI) of water vapor mass per mass of burnt fuel, specific combustion heat Q, specific heat of air c_p, and propulsion efficiency $\eta = FV(\dot{m}_F Q)^{-1}$, which depends on engine thrust F, aircraft speed V, fuel flow rate $\dot{m}_F$, and specific combustion heat Q:

$$\mathrm{CF} = \frac{\mathrm{EI}c_p}{Q(1-\eta)}. \tag{3}$$

In agreement with Peters (1993), the value of CF for the same fuel is larger for high-bypass engines than for low-bypass and nonbypass engines because the propulsion efficiency is largest for high-bypass engines, but its value depends not only on the type of engine but also on the aircraft speed.

For relative humidities RH < 100%, HH propose a new relationship in which T_c follows from $de_s(T_c)/dT = (100/\mathrm{RH})G$. They note that T_c approaches minus infinity when RH goes to zero. In contrast, the classical theory requires that the ambient conditions be on the mixing line, which tangents the saturation curve. It predicts finite critical temperatures even for perfectly dry air.

Hanson and Hanson (1995) give no physical reason for this new relationship except the statement that the critical temperature should "provide a saturation condition that contains the same mass of water vapor per unit volume as is present under the reduced relative humidity present at the higher temperature" for contrail formation at 100% relative humidity.

The purpose of this comment is to point out that the proposal of HH does not lead to the correct critical temperature for contrail formation under subsaturated ambient conditions. This follows first from the fact that HH give no convincing explanation of why the classical thermodynamic theory should be wrong. The theory assumes that the ambient state must be located on the mixing line. Hanson and Hanson (1995) state that

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''this is not a valid assumption'' because of the nonlinearity of the saturation vapor pressure with temperature. However, the classical theory did not require such linearity. I agree that the Appleman criterion may be wrong, but for reasons that have to do with the finite time required to form visible particles and the possibility that some particles may perhaps form in the exhaust plume even before reaching liquid saturation (Kärcher et al. 1996). However, such aspects are not considered by HH.

Second, the new condition deviates from observed contrail conditions more strongly than the classical one. This can be seen from observations reported in Busen and Schumann (1995). They observed a contrail behind a jet aircraft at $p = 302.3 \pm 0.7$ hPa, RH = 34% (at most 44%), $Q = 43$ MJ kg^{-1}, EI = 1.21, and $\eta = 0.14 \pm 0.005$ at ambient temperature of $T = -49.7° \pm 0.5°$C. For these conditions, the classical criterion (including the η-dependent value CF = 0.0329 g kg^{-1} K^{-1}) predicts $T_c = -50.4$°C. The difference between the observed ambient temperature and the computed critical temperature amounts to 0.7°C. This difference is within the uncertainties of the data and the approximate nature of the thermodynamic conditions, which neglects the details of particle formation processes and the requirements for contrail visibility. Further examples of such good agreement between observed and computed values for the critical temperature are given in Schumann et al. (1996). In contrast, the theory of HH implies $T_c = -52.9$°C, which is more than 3°C below the observed value. This difference is definitely larger than the error bounds of the measured data.

Finally, the theory of HH computes extremely low critical temperatures for very dry ambient conditions as prevailing in the stratosphere, where (short) contrails are often observed in spite of the commonly low relative humidity (typically less than 10%). In contrast, HH suggest that the humidity must be above 25% in order to explain 95% of previously observed contrails.

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