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Experimental Test of the Influence of Propulsion Efficiency on Contrail Formation

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According to a previously established thermodynamic theory, contrails are expected to form at a threshold temperature that increases with the overall efficiency of the aircraft propulsion. As a consequence, aircraft with modern engines, with higher overall efficiency, cause contrails over a larger range of cruise altitudes. To validate this theory, an experiment was performed in which contrail formation was observed behind two different four-engine jet aircraft with different engines flying wing by wing. Photographs document the existence of an altitude range in which the aircraft with high engine efficiency causes contrails whereas the other aircraft with lower engine efficiency causes none. For overall efficiencies of 0.23 and 0.31 and an ambient temperature lapse rate of 12 K km^{-1}, the observed altitude difference is 80 m. This value would be larger (200 m) in a standard atmosphere with smaller temperature lapse rate (6.5 K km^{-1}). In a standard atmosphere, an increase of overall efficiency from 0.3 to 0.5, which may be reached for future aircraft, would cause contrails at about 700 m lower altitude.

Introduction

THE special report[1] of the Intergovernmental Panel on Climate Change notes that aircraft equipped with more efficient engines cause more contrails than aircraft with less efficient engines. This statement is based on the so-called Schmidt–Appleman criterion, which is well documented in the literature.[2–6] However, the statement was highly debated during the final acceptance procedure of the report, and not all critics could be convinced that this statement is correct. Therefore, we performed an experiment to test the influence of engine efficiency on contrail formation.

Contrails are visible line clouds that form behind aircraft flying in sufficiently cold air due to water vapor emissions. According to the Schmidt–Appleman criterion,[7,8] contrail formation is due to the increase in relative humidity (RH) that occurs in the engine plume as a result of mixing of the warm and moist exhaust gases with cool ambient air. When the humidity reaches liquid saturation in the young plume behind the aircraft, liquid droplets form, which then soon freeze to form ice particles.[4,8–10] In contrast to the properties of the ice particles being formed, the threshold value of ambient temperature below which contrails form depends only very weakly on the particles emitted or formed with the exhaust gases.[2,4,11] The threshold temperature for contrail formation depends on ambient RH and on the parameter

$$G = \frac{EI_{\mathrm{H2O}}\, p c_p}{\varepsilon Q(1-\eta)}$$

and, hence, on the fuel combustion properties in terms of the emission index EI_{H2O} of water vapor and the combustion heat Q, on ambient pressure p at flight level, on the specific heat capacity of air c_p, the ratio $\varepsilon = 0.622$ of molar masses of water vapor and air, and on the overall efficiency η of propulsion of the aircraft/engine system at cruise.[2,6] The overall efficiency of propulsion is the ratio[12]

$$\eta = FV/(m_f Q)$$

between the work rate FV performed by the thrust F of the engine at true air speed of the aircraft V relative to the amount of chemical energy $m_f Q$ provided by the fuel with specific combustion heat Q at flow rate m_f. The overall propulsion efficiency depends on speed V and on the state of the aircraft operation. The value of Q is known for given fuel, and V and the specific fuel consumption (SFC), SFC $= m_f/F$, are often published by engine manufactorers or can be computed with an engine cycle model,[13,14] so that η can be determined.

Only a fraction $(1-\eta)$ of the combustion heat leaves the engine with the exhaust gases. The remainder appears not as heating of the exhaust, but as turbulence in the aircraft's wake, including the induced wing tip vortices, and dissipates to heat the wake as a whole, partly long after contrail formation. As the value of η increases, exhaust plume temperatures decrease for the same concentration of emitted water vapor, and hence, contrails form at higher ambient temperatures and over a larger range of altitudes in the atmosphere.[7,8] Figure 1 shows the threshold altitude above which contrails form vs η for various RHs in the standard atmosphere (in which the temperature decreases from 15°C at sea level with altitude at a lapse rate of 6.5 K km^{-1} up to the tropopause at 11-km altitude and stays constant at -56.5°C above that level). The altitude difference in contrail formation due to different η values would be larger for a smaller lapse rate.

Early turbojets achieved overall efficiencies of about 0.2, low-bypass-ratio engines made available in the early 1960s offered overall efficiencies of about 0.25, whereas early 1990s high-bypass-ratio turbofans have achieved substantial improvements in both thermal and propulsive efficiencies and offer about 0.35 overall efficiencies. Even higher overall efficiencies, perhaps in the region of 0.50 may be possible after 2010 with ultra-high-bypass-ratio turbofans, such as propfans and advanced ducted propulsion systems.[1,15]

For an increase of η from 0.3 to 0.5, the threshold formation temperature of contrails for kerosene-driven aircraft increases by 4.2–4.9 K (for 0–100% ambient humidity), implying 650–760 m lower altitude in the standard atmosphere (Fig. 1); the altitude difference increases with RH. The present global mean cover of the Earth by contrails is about 0.1%.[16] If η grows from 0.3 to 0.5 in a future fleet of aircraft, contrail cover is expected to grow by about 20% of its value for otherwise fixed conditions.[16–18] Because of this possibly disturbing impact of engine efficiency improvements on contrail formation, an experimental validation is important.

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The validity of the Schmidt–Appleman criterion was supported up to now by contrail observations behind single aircraft. Busen and Schumann[10] observed a contrail forming behind the advanced technology testing aircraft system (ATTAS) of DLR, a two-engine jet aircraft of type VFW 614, consistent with the extended criterion accounting for the η effect, whereas the classical Appleman criterion, which implies $\eta = 0$, would predict that no contrail forms. High-precision measurements of temperature and humidity onboard a research aircraft following the contrail-forming ATTAS aircraft at close distance confirmed that the contrail onset was observed to occur under conditions as predicted by the extended Schmidt–Appleman criterion within an accuracy of about 0.4 K in terms of threshold temperature.[19] Contrail formation was also observed behind an Airbus A310,[20] a DC-8,[4,21] and 12 wide-body aircraft of types B747, DC-10, and A340,[21] in which the ambient conditions were again measured with high-precision instruments. These and further data were compiled into a figure and discussed in Refs. 6 and 11. The analysis showed that all cases in which the aircraft was observed to fly with contrail or without contrail were consistent with the theoretical predictions.

However, these tests considered only single aircraft and do not provide direct evidence that an aircraft with a high engine efficiency would have caused a contrail where an aircraft with low engine efficiency caused none. This paper reports the results of an experiment providing such direct evidence.

Experiment

For a direct test, a formation flight of two different large jet aircraft was arranged, wing by wing, during an ascent and a descent of the aircraft. Contrail formation and ambient conditions were observed simultaneously from a research aircraft. The two contrail forming aircraft were 1) a Boeing B707-307C built in 1968 and equipped with four jet engines of type PW JT3D-3B with bypass ratio of 1.4 and 2) an Airbus A340-300 built in 1998 with four jet engines of type CFM56-5C4 with bypass ratio of 6.8. Observers onboard these aircraft noted altitude, speed, fuel consumption m_f, and turbine speed n_1 from cockpit instruments of the two contrail-forming aircraft vs time. The contrail formation was observed by three observers, video cameras, and a photography camera from the DLR research aircraft Falcon flying less than 1 km behind the two contrail-forming aircraft, at essentially the same altitude. Moreover, ambient pressure p, temperature T, and humidity q were measured vs time with instruments on the Falcon and are recorded with 1-s time resolution. Temperature was measured with platinum resistance thermometers of type Pt500, and the humidity was measured with a cryogenic hygrometer.[22] Fuel samples were taken after landing of the aircraft and analyzed by standard methods by the company Petro Laboratory, Munich.

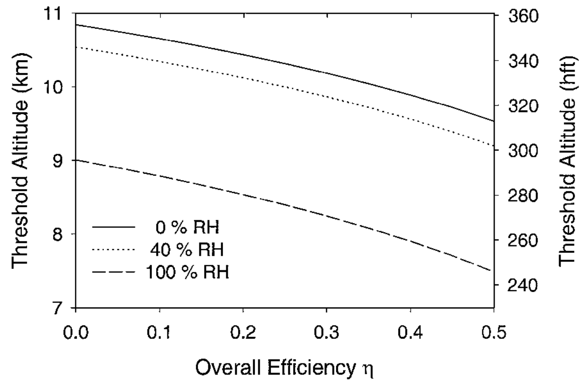

Fig. 1 Threshold altitude in the troposphere above which contrails form vs overall efficiency for various ambient humidities RH relative to liquid saturation in a standard atmosphere and for fuel with EI_{H2O} = 1.223 and Q = 43.2 MJ kg^{-1}.

The two aircraft were selected for this test because the modern A340 engines provide significantly higher engine efficiency than those of the older B707. The maximum cruise speed of the Falcon (about 220 m s^{-1}, Mach 0.74) is considerably smaller than those of the two other aircraft. Therefore, the B707 and A340 flew at reduced power to let the Falcon follow at constant distance. At lower power, the engine efficiencies are smaller than at nominal cruise conditions. For cruise at 9.45-km altitude (288 hPa), at 226.8-K ambient temperature, and at a speed of Mach 0.7, the expected overall efficiencies were computed before the test to be 0.23 and 0.32 for the B707 and A340, respectively, implying a threshold temperature difference of about 1.6 K and an altitude difference of 240 m in a standard atmosphere with RH = 40% (Fig. 1). Because of reduced power, a smaller difference in contrail formation altitudes was expected for descent conditions.

The observations took place over southern Germany at 48.27°N (ascent) and 48.56°N (descent), between 10.5°E and 12°E, from 7:20 to 7:42, 15 September 1999 [all times are universal time, coordinated (UTC)]. The aircraft ascended from 310 to 350 hft while flying eastward, turned, and then descended westward. The aircraft ascended until 7:31 and descended after 7:37 at a rate of 300 ft min^{-1} (100 m min^{-1}). This low rate was used to allow for accurate determination of the altitude of contrail formation and disappearance. The A340 flew under autopilot control whereas the B707 was steered by hand and with open roll-spoiler flaps on the wings to follow close by. As a consequence of the low speed, the autopilot of the A340 caused rather large variations in the engine power settings and fuel flows.

Observations

A contrail was observed to form during ascent first behind the A340 at 7:28:40, at flight level 333 hft. The B707 continued to ascend nearby without a contrail (Fig. 2). About 50 s later, at altitude of about 337 hft, a contrail formed also behind the B707 at

Fig. 2 Airbus A340 with contrails (left) and the Boeing B707 without contrails (right) taken from the Falcon research aircraft at about flight level 333 hft at 7:28 UTC, 15 Sept. 1999 (photographs: U. Schumann and R. Welser, DLR).

7:29:30. The contrails were observed to be forming very suddenly and persisted thereafter. During descent from flight level 350 hft, the contrails disappeared first behind the B707 and disappeared shortly thereafter behind the A340. The contrails occurred again, apparently when entering colder or more humid air, and finally disappeared behind the B707 at flight level 344 hft at 7:40:00 (Fig. 3) and shortly thereafter behind the A340 at flight level 342 hft at 7:40:39. These times were deduced after the flight from the video observations with an uncertainty of less than 5 s. As a curiosity, we note that during descent, for about 20 s, the B707 formed contrails only behind the two engines on the left wing while no contrails were visible for the right wing engines, possibly because of different power settings on the two wings.

As documented in several photographs, an altitude range exists in which the A340 causes contrails while the B707 causes none. Figure 2 shows this fact during ascent and Fig. 3 during descent. The photographs show the contrails best during descent due to the more favorable sun and Falcon positions relative to the two other aircraft. We clearly see the four contrails forming from the four engines of the A340 while the B707 is seen flying without contrails.

The temperature profile measured by the Falcon vs altitude is shown in Fig. 4. During the observation period from 7:28 to 7:41, the ambient humidity varied between 25 and 50% of liquid saturation and was close to 36 ± 10% during contrail formation at ascent and 42 ± 10% at contrail disappearance. The temperatures at times of contrail onset or offset (disappearance) and profiles of the threshold temperature, computed according to the Schmidt–Appleman theory with the method described in Ref. 2, are indicated for various conditions. The measurements with the Falcon in the period when only one aircraft draw a contrail show a negative vertical temperature gradient (lapse rate) of 12 K · km^{-1} during ascent, and a more stable and about 1-K warmer atmosphere with 5-K · km^{-1} lapse rate during descent. The difference between threshold altitudes between the two aircraft was about 80 m during ascent and about 60 m during descent.

The analysis of the two fuel samples taken from the tanks of the B707 and the A340 reveal a combustion heat of 43.2 MJ · kg^{-1} and hydrogen content of 13.7% for both samples, aromatics of 18.3 and 18.6%, and sulfur content of 120 and 380 mg · kg^{-1} for the B707 and A340, respectively. These values are within the expected range of most aviation fuels[23] and imply an emission index of EI_{H2O} of 1.22. According to previous experiments and model results with much larger differences in fuel properties,[11,19] we expect that the different fuel properties have no influence on the threshold conditions for contrail formation.

Table 1 lists the values taken from the cockpit instruments of the two aircraft at the times of the observed contrail onset and offset together with the ambient temperature T, pressure p, and RH measured with the Falcon. Mainly because of temporally variable aircraft/engine states, the aircraft/engine data are observed with typical uncertainties of 20% for the fuel flow rates m_f, 5% for the engine speed n_1, and about 5 m s^{-1} for the true air speed (consistent with the measured speed of the Falcon). The aircraft flew partly slower than planned (minimum Mach number 0.65). The accuracy of the Falcon measurements are about 0.1 hPa for pressure, 0.3 K for temperature,

Table 1 Observed and computed conditions at times of contrail onset or disappearance

	UTC, hr:min:s			
Parameter	7:28:40	7:29:30	7:40:00	7:40:39
Aircraft type	A340	B707	B707	A340
Altitude, m	10184	10260	10485	10423
p, hPa	257.00	254.00	245.32	247.65
T, °C	−49.0	−50.0	−50.9	−50.5
RH, %	42	42	36	36
True air speed, m s^{-1}	190	195	209	203
m_f per engine, kg s^{-1}	0.33	0.47	0.28	0.19
η from observed contrail onset	0.33	0.27	0.25	0.27
n_1 observed, %	80	95	85	73
n_1 computed, %	80	95	80	73
η computed	0.31	0.23	0.24	0.28
T_C from computed η, °C	−49.4	−50.6	−51.0	−50.4

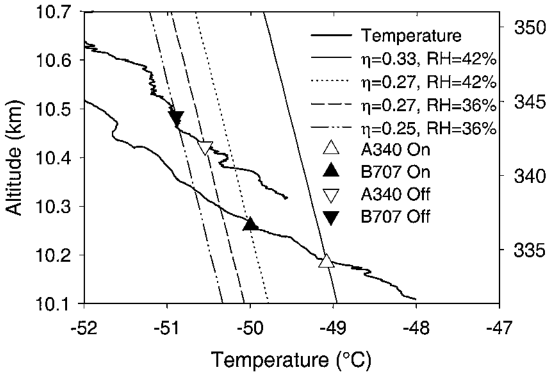

Fig. 4 Observed ambient temperature (thick curve) and threshold temperatures for contrail formation (thin curves) vs altitude, for various values of the overall efficiency η and ambient RH over liquid saturation: triangles pointing up and down are observed contrail formation conditions at ascent and descent, respectively.

Fig. 3 Airbus A340 with contrails (left) and the Boeing B707 without contrails (right) taken from the Falcon research aircraft at about flight level 344 hft at 7:40 UTC, 15 Sept. 1999.

and 10% for relative humidity.[22,24] The accuracy of the humidity is less than usual (4%) in this case, because of some uncertainty in the calibration factors. Small additional errors arise because the Falcon was flying a few hundred meters behind the observed aircraft and possibly at up to 30 m different altitude. Based on takeoff weights and times (B707: 88.2 Mg at 6:25 and A340: 165 Mg at 6:51) the aircraft weights at the time of contrail observations were estimated: 83 and 160 Mg. These values would be required to compute the aerodynamic drag and the thrust required during the flight, although this is complicated by the ascent/descent rates and the flaps being set.

Analysis

As indicated in Fig. 4, the observed contrail onset during ascent is consistent with a computed threshold temperature assuming $\eta = 0.33$ for the A340 and 0.27 for the B707, with RH values as indicated. During descent, the agreement is best for $\eta = 0.27$ for the A340 and 0.25 for the B707. However, during descent, the ambient temperature was incidentally very close to the threshold temperature over a range of altitudes from about 10.45 to 10.55 km. This explains why the contrails did occur intermittently during descent. However, the threshold conditions were clearly defined during ascent. On the other hand, the observed altitude difference between contrail onsets on the B707 and A340 during ascent is smaller than expected because of the rather large ambient temperature lapse rate.

Using the observed values and engine parameters adjusted to published engine data, the engine properties were computed using an engine cycle model.[13] The cycle model was adjusted to match the observed fuel flow. From the results, the rotational speed n_1 of the engine is estimated. Table 1 lists the computed rotational speed and the engine efficiencies η at the times of contrail onset and offset. The computed and observed rotational speeds are in reasonable agreement. In addition, Table 1 lists the threshold temperatures computed from the Schmidt–Appleman criterion for these engine efficiencies and the observed ambient and fuel properties. The differences between the computed threshold temperatures and the observed ones are −0.4, −0.6, −0.1, and 0.1°C for the four observations. Also included is the observed value of η for which the computed threshold temperature equals the observed temperature at contrail onset. The differences between the observed and computed η values are 0.02, 0.04, 0.01, and −0.01, respectively.

Figure 5 shows the computed η as a function of different assumed fuel flow rates m_f for otherwise fixed conditions as observed. The observational uncertainties in the highly variable fuel flow rate of about 20% cause much smaller uncertainty in the computed η values, in particular for large fuel flow rates. Figure 5 also compares the computed and observed η values. The latter are above those computed with the cycle model during ascent and below or close to those during descent, which may be explained by the increased thrust required for ascending and for overcoming the additional drag from the flaps set. The largest difference of 0.04 (0.27 instead of 0.23) between observed and computed η values occurs for the ascending B707, perhaps because of the flaps being set.

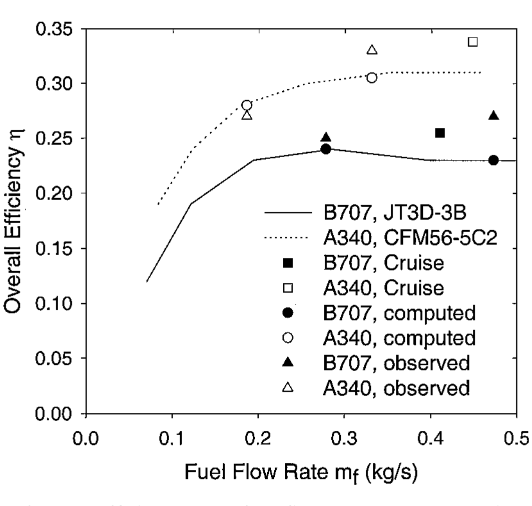

Fig. 5 Overall efficiency η vs fuel flow rate m_f: curves give η values computed by the engine model for the B707 (full curve) and A340 (dashed curve), circles are η value computed by the engine model for the observed conditions during contrail disappearance (smaller fuel flow values) and onset, triangles are η values required to let the observed temperature match the computed threshold temperature for contrail formation, and squares are typical cruise conditions; filled symbols for the B707 and open symbols for the A340.

For cruise conditions, which are computed with the cycle model and an aircraft performance model,[14] for steady flight at the given altitude with Mach 0.8, 75% load factor, and 6000-km range, the model computes values of 0.26, 0.41 $\mathrm{kg \cdot s^{-1}}$, and 21.5 $\mathrm{g \cdot kN^{-1} \cdot s^{-1}}$ for η, m_f, and SFC for the B707, and 0.34, 0.45 $\mathrm{kg \cdot s^{-1}}$, and 16.3 $\mathrm{g \cdot kN^{-1} \cdot s^{-1}}$ for the A340, respectively. These values are consistent with values available from the manufacturers. The η values of the A340 and B707 are smaller during descent than during ascent and smaller than during normal cruise conditions (Fig. 5). The difference between the η values of the two aircraft, A340 and B707, is only 0.04 for descent, a little larger for ascent, and reaches 0.083 for typical cruise conditions at this altitude. Therefore, and because of the smaller temperature lapse rate in the standard atmosphere, the η effect is larger during normal cruise conditions than observed in this test.

If visibility of the contrail is a problem, an aircraft may avoid contrail formation for a short time, at least near threshold conditions, by flying with reduced power. The efficiency η approaches zero for idle engines, with zero thrust but finite fuel flow rate. The fact that contrails can sometimes be avoided by reduced power setting was already known to pilots during World War II.[7,9] For commercial transports, contrails can be avoided only by avoiding flights in cold and humid air masses, for example by flying above the tropopause. However, the net environmental impact of a higher-flying fleet of aircraft is unknown, and this topic is beyond the scope of this paper.

Conclusions

For the first time, contrail formation was observed behind two airliners with different engines under otherwise comparable conditions. As documented by photographs, an altitude range exists in which the aircraft with high engine efficiency causes contrails while the aircraft with lower engine efficiency causes none. Hence, the observations corroborate the validity of the theory according to the revised Schmidt–Appleman criterion: Contrails of more efficient engines form at smaller altitudes than those of less efficient engines.

The contrails were observed to occur at measured ambient conditions that fit the Schmidt–Appleman criterion within reasonable accuracy, in particular during ascent where the ambient temperature profile provided clearly defined threshold conditions. The deviation of the threshold temperature computed for computed engine efficiencies from the observed threshold temperature is less than 0.6°C, which is within the accuracy of the measurements. The engine efficiencies η computed with the cycle model deviates at most by 0.04 from the value of η for which the threshold temperature would match the observed ambient temperature. Such deviations are of a magnitude that has to be expected in view of the given observational and modeling uncertainties and for the experimental conditions that deviate from nominal cruise conditions. Hence, the observed contrail and engine parameters are in reasonable agreement with the analysis.

The observed altitude difference in contrail formation conditions of the two aircraft is about 80 m during ascent. This value is smaller than expected for normal cruise conditions in a standard atmosphere (about 200 m) because of the reduced power settings and because of a rather large temperature lapse rate encountered during ascent in the present experiment.

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