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Contrail Formation and Propulsion Efficiency

Andrew G. Detwiler*
South Dakota School of Mines and Technology, Rapid City, South Dakota 57701-3995
Arthur Jackson†
U.S. Air Force Research Laboratory VSBL, Hanscom Air Force Base, Massachusetts 01731

The contrail factor is the ratio of water vapor to enthalpy added by combustion to the exhaust plume from an aircraft engine. It is the key parameter determining the highest temperature at which contrails will form behind a particular engine on a particular aircraft. Cycle calculations are used to estimate contrail factors for a range of flight environments at a range of power settings, for generic low-bypass and high-bypass turbofan gas-turbine engines. It is found that, contrary to assumptions made in current methods of contrail forecasting, the contrail factor is not constant for a given engine type. The contrail factor varies even for the same engine at different power settings and flight conditions. Results are shown for a range of conditions, including flight levels between 25,000 and 50,000 ft in a standard atmosphere, flight Mach numbers ranging from 0.4 to 0.9, and power settings from idle (low) to military (high). The computed contrail factors range from 0.030 to 0.053 $g \cdot kg^{-1}\,{}^{\circ}C^{-1}$ for the low-bypass engine and from 0.038 to 0.090 $g \cdot kg^{-1}\,{}^{\circ}C^{-1}$ for the high-bypass engine. Changes in contrail factor can be roughly related to changes in the threshold environmental temperature for contrail formation by the relationship that a 10% increase in contrail factor results in a 1°C higher threshold temperature in a typical upper tropospheric environment for threshold temperatures near −50°C. These calculations do not yield precise estimates of contrail factors for specific engines, but demonstrate that contrail factors for a given engine are generally higher at lower power settings at a given Mach number, higher at higher Mach numbers at a given power setting, and higher at higher altitudes in general.

I. Introduction

CONDENSATION trails, or contrails, have been observed since the early days of aviation (for example, see review by Schumann[1]). Combat requirements during the World War II era led to quantitative efforts by all major participants operating air combat units to forecast the conditions in which contrails will form because contrail formation significantly increases the detectability of combat aircraft and, hence, increases their vulnerability to destruction by air defense systems. Detailed discussions of contrail formation forecasting by U.S. Air Force personnel and contractors appeared in the open literature beginning in the 1950s.[2–4] In addition to military interest in the impact of contrails on aircraft detectability, contrails have long been considered as possible agents of weather and climate modification.[5–10] An accurate understanding of conditions in which contrails form is important to climatological estimates of contrail frequency, spatial extent, and climatic impact.[9,11]

Schumann et al.[12] have recently reported limited observations confirming the influence of propulsion efficiency on the threshold temperature below which a given aircraft engine will produce contrails. To put these results in a larger context, we summarize and extend, here, earlier work by Detwiler[13] in which engine cycle computations are used to explore how this threshold temperature varies over a wide range of flight conditions for two different engine types. In this work, we adopt a conceptual thermodynamic framework for analyzing contrail formation that accounts for variations in flight parameters not currently considered explicitly in operational contrail forecasting or in climate studies. Predictions made using this framework are compared to observations of contrail formation obtained during a recent U.S. Air Force Research Laboratory field program.[14]

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*Professor, Institute of Atmospheric Sciences, 501 East Saint Joseph Street.

†Research Meteorologist, VSBL.

II. Contrail Formation and the Contrail Factor

Contrails form in the exhaust plumes behind aircraft powered by engines burning hydrocarbon fuels when they fly in sufficiently cold and humid air. (In very humid air at any temperature they also can form at wing tips and other sharp surfaces around an airframe due to adiabatic expansion and cooling in the airflow accelerating around these locations, but this type of contrail will not be treated here.) Exhaust contrails are an example of a cloud formed by isobaric mixing of warmer air that, although not saturated, contains a relatively high mixing ratio of water vapor generated during combustion with colder air that also is not saturated and contains a relatively low mixing ratio of water vapor. With suitable combinations of such warm and cold airstreams, it is possible for saturation to be reached in some mixtures due to the nonlinear variation with temperature of the saturation mixing ratio over liquid water. This process of cloud formation by isobaric mixing has been understood at least since the beginning of modern meteorology in the 20th century and is described in detail in many modern meteorological physics texts, most recently, for example, by Bohren and Albrecht.[15]

As discussed in detail in many reports[1,2] the highest environmental temperature at which a contrail will form depends on the ratio of water to enthalpy in the exhaust plume. This ratio is called here the contrail factor; following usage by many authors, it can be written as

$$(C_p \Delta r)/\Delta H$$

where C_p is the specific heat of air at the plume temperature, Δr is the increase in plume water vapor mixing ratio due to water vapor generated during combustion, and ΔH is the increase in plume enthalpy due to heat generated during combustion. In this discussion, the contrail factor will have dimensions grams water per kilogram air per degree Celsius. The higher the contrail factor is, the higher the threshold temperature for contrail formation. For a given contrail factor, contrails will form at all environmental temperatures lower than the threshold temperature. Although the initial state of the condensed contrail particles is liquid in the case of distinctly visible contrail formation, at typical contrail formation temperatures these droplets freeze rapidly and continue to grow as ice particles. The contrail particles will continue to grow if the environment is supersaturated with respect to ice, resulting in linear contrails that broaden with time due to turbulent dispersion. If the environment is subsaturated with respect to ice, the contrail will be short because the ice particles will evaporate as the plume mixes with the dry environment.

The basic problem in forecasting or diagnosing contrail formation is to have accurate knowledge of the contrail factor and the environmental temperature, pressure, and water vapor mixing ratio. We focus our further discussion on accurate determination of the contrail factor.

III. Determination of Contrail Factor

Appleman[2] estimated the contrail factor by taking laboratory measurements of the ratio of water to heat produced during aircraft fuel combustion without considering any of the details of engine operation, using combustion data for an unspecified aircraft fuel type used during World War II. He estimated that for every kilogram of fuel burnt, 1.4 kg of water and 41.9 MJ of heat were produced. He divided the enthalpy change due to combustion in the air passing through the engine by the specific heat at constant pressure, C_p, for air at typical ambient upper tropospheric temperatures ($1005\ \mathrm{J \cdot K^{-1}\ kg^{-1}}$) to estimate the temperature change due to combustion. The ratio of the water production rate to the rate of change of temperature due to heating yields a contrail factor of $0.034\ g \cdot \mathrm{kg^{-1}{}^{\circ}C^{-1}}$. The implicit assumptions in this approach are that all of the water and energy generated during combustion is contained in the gases leaving the exhaust nozzle and that C_p is independent of temperature.

Pilié and Jiusto,[4] in the same manner, computed a contrail factor for JP-4, the most common military jet fuel in use in the 1950s (similar in properties to the JP-5 and JP-8 fuels currently in use by the U.S. military aviation interests now, and very close in relevant properties to Jet-A, the most common civilian jet fuel both then and now). They found for JP-4 a smaller mass of water created per unit mass of fuel combusted and a higher heat of combustion compared to the fuel properties Appleman[2] used in his calculation, yielding a lower contrail factor of $0.030\ g \cdot \mathrm{kg^{-1}{}^{\circ}C^{-1}}$. Actual fuel properties for all fuel types vary from batch to batch. Busen and Schumann,[16] for instance, estimate somewhat variable and lower contrail factors, as low as $0.028\ g \cdot \mathrm{kg^{-1}{}^{\circ}C^{-1}}$, based on actual measurements of the hydrogen content and heat of combustion of Jet-A fuel used in their flight experiments.

A different approach to estimating the contrail factor is to use measurements or numerical simulations of aircraft gas-turbine engine operating parameters to determine the water generated during fuel combustion and the difference in total enthalpy between the inlet air, that is, air in the surrounding environment, and the gases leaving the engine exhaust nozzle. Peters[17] obtained manufacturers' engine cycle data for several engine types, from which he calculated contrail factors in this manner. These engine types included turbojet and low- and high-bypass gas-turbine engines. Peters's computed cycle parameters included fuel flow and exhaust gas temperature for a wide range of power settings, flight Mach numbers, and flight levels. He does not report explicitly, but for the bypass engines it appears that he used parameters characteristic of the engine core exhaust. Other critical details not described in his report include the ratio assumed for water created per unit of fuel consumed and whether the exhaust temperatures used were static or total (stagnation) temperatures. He found the following contrail factors for three generic types of engines: nonbypass (turbojet), 0.036 (g/kg)/°C; low-bypass, 0.040 (g/kg)/°C; and high-bypass, 0.049 (g/kg)/°C.

Contrail factors also have been computed empirically based on measured flight parameters, using measured fuel flow m_f, engine airflow m_e, ambient static temperature T_a, and exhaust exit plane total (stagnation) temperature T_{e0}. One form of a contrail factor estimate is

$$\text{contrail factor} = \frac{EI_w m_f}{(m_e)(T_{e0} - T_a)} \tag{1}$$

where EI_w represents the ratio of mass of water emitted per unit mass of fuel combusted. If fuel is chemically represented as $(CH_2)_n$ then EI_w is 1.3. (Note that an EI_w of 1.3 is lower than the value of 1.4 used by Appleman,[2] but higher than actual measurements of fuel composition reported in the literature,[12,16,18] which yield EI_w as low as 1.22.) The fuel flow m_f multiplied by EI_w yields the water added to the exhaust by combustion. Fuel flow can be neglected with respect to the engine airflow m_e, in the denominator of Eq. (1) for all practical calculations because engine airflow is usually not known to be better than ~2%, and typical maximum fuel/air ratios are less than 3–4%. The engine exit total temperature T_{e0} is a measure of the total energy, or thermal plus directed kinetic energy of motion, present in the engine exhaust. The difference $(T_{e0} - T_a)$ is proportional to the enthalpy added by combustion, but fails to account for the variation with temperature of the specific heat of air and exhaust gases. This variation is significant in the case of contrail formation behind gas-turbine engines because there is a large difference in temperature between the environment and the exhaust gases at the nozzle exit plane. The quantity $(C_{Pe}T_{e0} - C_{Pa}T_a)$ is exactly the enthalpy difference between exhaust and environment, where C_{Pe} is the specific heat at the exhaust temperature and C_{Pa} is the specific heat at the environmental temperature. Therefore, a more precise relationship for computing a contrail factor is

$$\text{contrail factor} = \frac{C_{Pa}[EI_w m_f]}{(m_e)(C_{Pe}T_{e0} - C_{Pa}T_a)} \tag{2}$$

An important assumption in the computation of contrail factor from fuel properties, following Appleman,[2] is the assumption that all of the enthalpy added to the engine airstream during combustion is present in the exhaust leaving the engine. Schumann, quoting earlier work presented in technical reports by Schmidt describing work done in Germany during World War II (see Ref. 1), points out that some of the energy generated during combustion must be used to propel the aircraft. (A similar approach was reported to have been followed in the United States by F. Osterle in work published in 1956, although the authors have been unable locate a copy of his report.) This energy is not present in the near-field engine exhaust plume, but dispersed in the wake of the aircraft outside of the engine exhaust plume. This separated energy eventually mixes back together with the energy in the engine exhaust plumes, but not for many aircraft widths aft. Contrail formation typically occurs well before these separate regions mix back together. Recent observations using two aircraft, one with older, low-bypass engines and the other with newer, high-bypass engines[12] show that engine/aircraft systems operating at higher overall propulsion efficiency indeed have higher contrail factors and higher threshold temperatures for contrail formation. These observations confirm that energy extracted for propulsion and dissipated in the wake of the airframe is indeed not present in the near-field exhaust plume where contrails initiate.

In this paper, we evaluate the efficiency with which the kinetic energy in the exhaust generated by the engine is converted into the work of propelling the aircraft, assuming steady-state nonaccelerating motion, using

$$\eta_P = 2u_0/(u_e + u_0) \tag{3}$$

where η_P is propulsion efficiency, u_0 is the forward aircraft speed, and u_e is the higher rearward exhaust gas speed at the exit plane of the exhaust nozzle, relative to the engine. As u_e approaches u_0, propulsion efficiency approaches unity, and thrust, equal to exhaust mass flow multiplied by the quantity $(u_e - u_0)$, approaches zero.[19] Modern transport aircraft are propelled by high-bypass ratio gas turbines that create high thrust by using large fans to create a large fan-stream mass flow while at the same time minimizing $(u_e - u_0)$ so that propulsion efficiency is maximized. Propulsion efficiency for these high-bypass ratio engines at typical cruise conditions typically exceeds 30%, whereas for low-bypass ratio engines used on supersonic fighter aircraft, propulsion efficiency can be less than 20%.

When a computation of propulsion efficiency was used to estimate the fraction of combustion-generated energy in the aircraft wake outside of the exhaust plumes, and contrail factors were computed using the Appleman[2] approach but subtracting this propulsive energy from the exhaust, researchers report reasonable agreement between calculated and observed contrail onset temperatures.[1,12,16,20] These workers find higher contrail threshold temperatures for high-bypass compared to low-bypass engines, due to higher propulsion efficiency for high-bypass engines.

IV. Engine Cycle Computations Used to Estimate Contrail Factor

In the present work, engine cycle parameters are computed for two engine types and a variety of flight conditions, following the general plan used in Ref. 17, but using the cycle information in such a manner that propulsion efficiency is accounted for in computing the contrail factor. Contrail factors are computed using Eq. (2). (It is presumed that in the work of Peters[17] Eq. (1) was used, although insufficient detail is presented to verify this.) Water produced during combustion EI_w is estimated as 1.28 kg/kg of fuel, a compromise between the theoretical value of 1.3 and the lower value of 1.22 kg/kg reported in several recent studies.[12,16] For sensitivity studies of the sort reported here, the exact value does not strongly affect the desired result, which is an exploration of the range of variability of contrail factor with varying flight conditions.

One difference between the present work and the previous work just described is that, in the previous work, the mixing process was incorrectly represented as linear mixing between two different initial states in vapor mixing ratio vs temperature space. Isobaric mixing is more correctly represented as linear mixing in vapor mixing ratio vs enthalpy space. A computation of contrail factor at some particular temperature, in units of grams per kilogram per deg Celsius, equivalent in definition to the contrail factor of Appleman[2] can be made by multiplying the slope of the mixing line in mixing ratio, enthalpy space, which has dimensions of gram per joule, by the temperature specific value of C_p ($\mathrm{J \cdot kg^{-1}\ K^{-1}}$). When this contrail factor estimate is based on the ratio of water to heat produced during combustion and when the value of C_p employed is appropriate for upper tropospheric temperatures, then the contrail factor found is appropriate for estimating the threshold temperature for contrail formation by the usual methods.[2,4,21]

The hotter the exhaust, the more the contrail factor will be overestimated if variation of C_p with temperature is ignored. For exhaust stagnation temperatures around 700°C, the contrail factor overestimate will be ~6%, resulting in an estimate of contrail onset temperature ~0.6°C too high for typical upper tropospheric conditions.

V. Further Refinements in Estimating Contrail Factor

A. Engines with Separate Exhaust Streams

In turbofan gas-turbine engines, one stream passes through the core of the engine, including the compressor, combustor, and turbine sections, and exits with relatively high velocity. The second stream passes through the fan section only, undergoes compressional heating, and typically exits with lower velocity. The ratio of the fan mass flow to the core mass flow is called the bypass ratio. On most modern transport aircraft, the turbofans have a bypass ratio significantly greater than 1. Bypass ratios may reach values greater than 7 in the newest high-bypass ratio transport turbofans. In fighter and other high speed military engines, bypass ratios are often of the order of one or less.

For some turbofan engines the two streams mix back together before leaving an exhaust nozzle; in other designs the fan stream exits separately, ahead of the core exhaust nozzle. In turbofan engines with separate, initially unmixed, exhaust streams, all of the water generated during combustion is in the core stream, but the enthalpy generated is distributed to both the core (by combustion) and bypass (due to work done by the fan section) streams. According to Eq. (2), the contrail factor in the core stream will be much higher than the contrail factor of completely mixed core and fan streams. In the results presented hereafter, the contrail factor for turbofan cycles with separate exhausts is computed two ways, once based on the core properties, and again assuming completely mixed core and fan streams. Contrail factors for the core flow in turbofan cycles with separate exhausts represent a maximum possible contrail factor. Contrail formation typically does not occur until some mixing between core and fan streams has occurred. The appropriate contrail factor should be somewhere between the core contrail factor and a contrail factor representing completely mixed bypass and core streams.

B. Appropriate Frame of Reference for Contrail Factor Calculations

A novel reference frame for contrail factor calculations is adopted here to simplify the interpretation of the results in terms of propulsion efficiency and, in the case of turbofan engines, separate exhaust streams. Most work on contrail formation[2,16,17] looks at formation in a reference frame moving with the engine. This is convenient in some respects because exhaust gas total temperature (EGT) and total pressure measurements (in the case of real engines), and EGT, pressure, and exit velocity computations (in the case of cycle calculations) are all made in this reference frame. However, contrail formation occurs in mixtures that are almost completely environmental air. If one assumes that turbulent mixing of heat, water vapor, and momentum proceed at the same rate, then this newly formed contrail region should be moving almost with the environmental winds. Almost all of the directed kinetic energy in the exhaust plume will be reduced to random thermal energy by the time contrail formation occurs. Thus, a natural frame of reference for computing contrail factors is the one of the environment through which the aircraft is moving.

In a reference frame moving with the environmental winds, one can imagine a parcel of air lying in the path of an advancing jet engine. The parcel is overtaken by the engine, drawn into it, compressed, heated, has enthalpy added by combustion, expands through the turbine and has energy extracted from it to do the work of driving the compressor and fan, is expanded and exhausted at a high speed through the nozzle, and is left behind mixing with the surrounding environment as the engine moves away. Some parcels pass through the fan section only, being accelerated but having no energy directly added by combustion. Energy that is used to propel the aircraft will not be present in the engine exhaust plume, but will be dissipated in the wake of the airframe, with a large fraction represented by the wingtip vortices.

For the parcels passing through the engine core, the water vapor mixing ratio on the exhaust side is estimated as

$$1.28 m_f / (m_f + m_e) \tag{4}$$

The total enthalpy of this exhaust air is

$$H_{eS} + \tfrac{1}{2}(u_e - u_0)^2 \tag{5}$$

where H_{eS} is the static enthalpy of the exhaust at the exit plane in the reference frame of the moving engine $C_{pe}T_{eS}$. The second term in Eq. (5) is the kinetic contribution to total enthalpy, in the reference frame of the air through which the engine is moving, where u_e is the rearward speed of the exhaust relative to the aircraft and u_0 is the forward speed of the aircraft relative to the environment. The quantity $(u_e - u_0)$ represents the rearward exhaust speed at the exit plane relative to the environment. It is assumed that the exhaust gases are brought to rest relative to the air around it as they mix with it, so that this total enthalpy, initially the sum of both static and kinetic parts, is converted completely to static enthalpy at the point where contrail formation begins.

In the reference frame of the air, there needs to be no additional correction for propulsion efficiency, as has been employed by others.[12,16,20] In this earlier work, in the reference frame moving with the engine, kinetic energy can be computed by using the exhaust speed relative to the engine, and static temperature, to give EGT. This total temperature determines the total enthalpy of the exhaust at the exit plane, in the reference frame of the engine, as if it were not doing any work. A separate calculation of propulsion efficiency is required to account for energy not in the exhaust plume of the moving engine. Note that in Eq. (5), as the aircraft speed more nearly approaches the exhaust speed (as it does for high-bypass ratio turbofan applications and also for low-bypass engines at supersonic flight conditions), the enthalpy of the exhaust as seen in the reference frame of the environment through which the engine is moving, also decreases. In the unattainable limiting steady-state where the exhaust is moving aft at the same speed the aircraft is moving forward, the propulsion efficiency becomes unity, the thrust disappears, the enthalpy added to the air passing through the engine is minimized, and the contrail factor is maximized.

All of the results presented here apply to steady-state conditions. As will be shown, contrail factors estimated using the approach

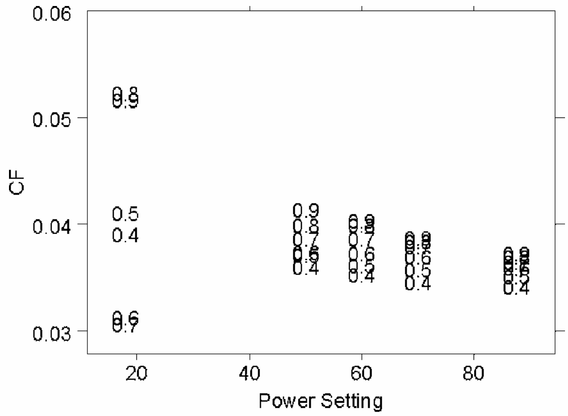


Fig. 1 Contrail factors for a generic low-bypass engine in a reference frame at rest relative to the air, for five power settings ranging from idle to full power: engine is operating at 30,000 ft MSL in a standard atmosphere; results are labeled with flight Mach numbers ranging from 0.4 to 0.9, at each power setting; thrust increases with power setting, but not linearly; high Mach number, low power setting conditions are probably not attainable in most installations.

adopted here, when applied to calculated engine cycle parameters, are in reasonable agreement with contrail factors inferred from observations of contrail formation behind aircraft in steady flight. Effects of transient conditions, such as decelerations/accelerations, are not accounted for in these calculations.

VI. Contrail Factors for Low- and High-Bypass Turbofan Engines

Results of engine cycle computations were obtained from the U.S. Air Force Aeronautical Systems Center for generic low-bypass (1:1 bypass ratio) and high-bypass (5:1 bypass ratio) gas-turbine engines. These cycle calculations are based on detailed specifications of engine performance and parameterizations of thermodynamic processes. Results were calculated for a range of power settings, altitudes, and flight Mach numbers in a standard atmosphere. Many of these conditions may be rarely attained in actual military or commercial operations. The intention here is to explore a very wide range of flight conditions to illustrate potential variations in almost any conceivable flight condition. Cycle parameters used to estimate contrail factors include temperatures, pressures, and speeds at the exhaust nozzle exit planes (and fan section exit plane, in the case of separated fan and core streams in the high-bypass engine), compressor bleed flow (flow extracted from the compressor section to drive auxiliary aircraft systems, such as air conditioners), fuel flow, flight Mach number, altitude, and environmental temperature. The fuel is assumed to have the properties of JP-4. The enthalpy change in the air flowing through the engine is taken to be the total exhaust enthalpy in a reference frame relative to the air through which the engine moves, minus the static enthalpy in the environment. Based on the results of these cycle calculations, contrail factor estimates are made for these low-bypass and high-bypass engines for a range of flight conditions. No explicit correction for propulsion efficiency is made. However, this correction is implicit in the transformation to environment-relative coordinates.

Results for the low-bypass engine are computed assuming complete mixing of the core and fan air flows before the exit plane. The situation is more complex for the high-bypass engine cycles. Contrail factors for the generic high-bypass engine are computed for two extreme situations. The first assumes that core air is mixing in an undiluted form with ambient air. The second assumes that core and fan air are completely mixed before contrail initiation and that this mixture has a mass-weighted average speed. In actuality, some, but not complete, mixing between core and fan air probably occurs in most cases before contrail initiation, and the actual contrail factor probably would lie between these two extremes for most installations.

Examples of results computed for a low-bypass engine over a range of power settings from idle to full military power at 30,000 ft altitude in a standard atmosphere are shown in Fig. 1. The power setting scale is proportional, but not exactly linearly proportional, to engine thrust.

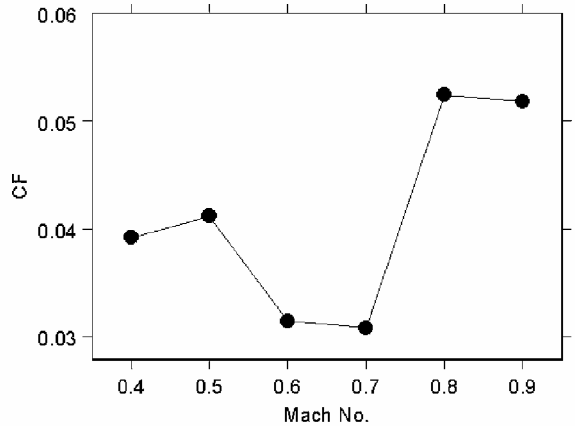


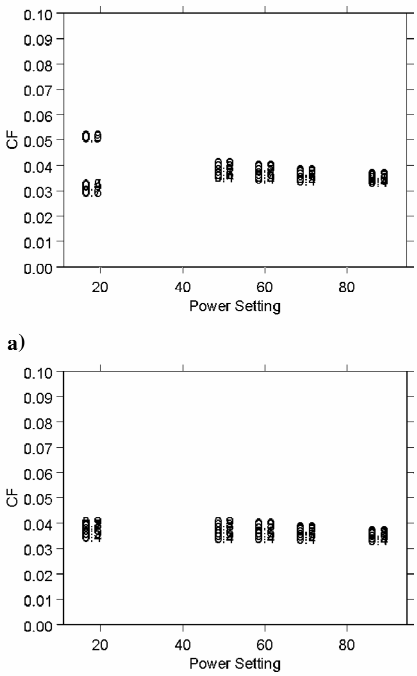
Fig. 2 Extracting results from Fig. 1, contrail factor is shown as a function of Mach number for the idle power setting only; lower Mach number conditions are probably the only attainable ones in most installations for this power setting.

Figure 1 shows that there is little variation in contrail factor for power settings above 50, but a big increase in contrail factor as settings decrease from 50 (cruise) to 18 (idle). Except for the lowest power setting, contrail factors increase with increasing flight Mach number at constant power setting because the exhaust is moving more slowly relative to the air at higher airspeeds. As Mach number increases, the rearward exhaust speed becomes closer to the forward aircraft speed, propulsion efficiency is higher, and more of the energy generated by combustion is used to propel the aircraft forward. The total range of variation of the contrail factor is about ±25% over the range of conditions examined.

In Fig. 2, data extracted from Fig. 1 are shown only for power setting 18. Contrail factor increases dramatically between Mach numbers 0.7 and 0.8. In fact, in most installations, it may be impossible to attain such high flight Mach numbers at such low power settings, but if power is reduced from higher to lower settings starting at higher Mach numbers, the contrail factor during the transition may roughly approximate the values indicated in Fig. 1 for low power setting and high Mach number.

Calculations were performed for flight Mach numbers from 0.4 to 0.9 and flight levels from 25,000 to 50,000 ft mean sea level (MSL) in a standard atmosphere. Figure 3 shows information similar to that given in Fig. 1, for a low-bypass engine operating at altitudes of 25,000 and 45,000 ft. The range of variation of contrail factor over the range of Mach numbers and power settings examined diminishes somewhat with increasing altitude. Overall mass flow through the engine diminishes with increasing altitude as inlet air density decreases. Also, at higher altitudes, there is less variability in engine conditions over the same range of power settings. However, other major trends are as shown in Fig. 1. The contrail factors at higher power settings are in the range estimated by Schrader[21] based on flight-test observations of low-bypass turbofan-equipped aircraft making contrails. These contrail factors deduced from observations implicitly include the effects of propulsion efficiency.

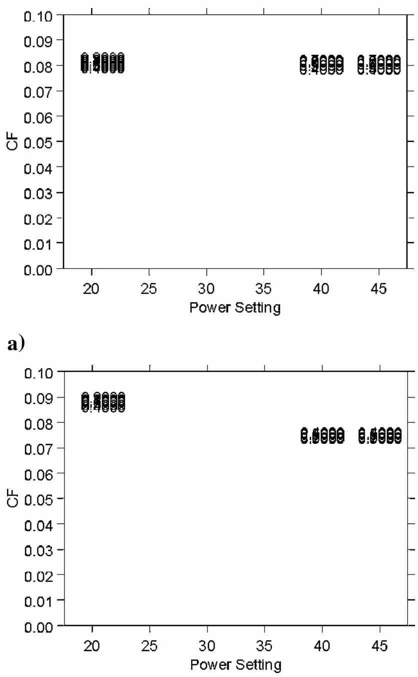
The situation for high-bypass engines is shown in Figs. 4 and 5. Figure 4 shows results for contrail factors with the assumption of unmixed core air mixing with environmental air. Note that the scale for power setting is different than in Figs. 1–3. The range from idle to full power is still represented, but over a smaller range of numerical setting values. Contrail factors for the core stream of this high-bypass engine are generally a factor of two higher than for the low-bypass engine assuming the same conditions. This is because all of the water generated during combustion is in the core air, but a significant fraction of the energy is extracted to accelerate the bypass air. Contrail factor decreases with increasing power setting because at higher power settings proportionally less energy is extracted to propel the bypass airstream.



a)

b)

Fig. 3 Contrail factors for a low-bypass engine in a reference frame at rest relative to the air, as a function of power setting and flight Mach number at a) 25,000 ft and b) 45,000 ft MSL in a standard atmosphere, following the format of Fig. 1.

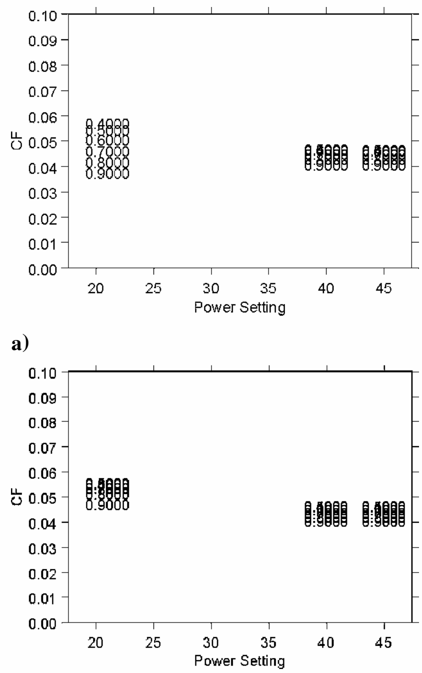


a)

b)

Fig. 4 Contrail factors for the core stream of a high-bypass engine in a reference frame at rest relative to the air as a function of power setting and flight Mach number; results are presented for a) 25,000 ft and b) 45,000 ft MSL, following the format of Fig. 1.

By mixing the fan and core streams for the high-bypass engine, and computing a contrail factor for the mixed exhaust, we have a situation where all enthalpy except that converted into propulsive movement of the aircraft should be accounted for in the computation of the contrail factor. This mixing assumption is used in calculating the results shown in Fig. 5. Figure 5 shows that contrail factors for the mixed streams are lower than the contrail factors for core streams only shown in Fig. 4. There is a stronger trend of decreasing contrail



a)

b)

Fig. 5 Contrail factors for mixed core and fan streams of a high-bypass engine, in a frame of reference at rest relative to the air, as a function of power setting and flight Mach number. Results are presented for a) 25,000 ft and b) 45,000 ft MSL, following the format of Fig. 1.

factor with increasing power setting in Fig. 5 compared to Fig. 4 because in Fig. 5 the exhaust speed in the environmental frame of reference increases more dramatically with power setting.

The contrail factors shown in Fig. 5 are only slightly higher than those given by Schrader,[21] deduced from flight tests of high-bypass engines. This near agreement suggests that the plumes from the high-bypass, separated core, and fan-stream engines used in the flight tests from which the Schrader contrail factors were derived probably had well-mixed fan and core streams before condensation began. It is possible that the assumption that 1.28 kg of water is generated during the combustion of 1 kg of fuel, used in this work, is not representative of the properties of fuel used in these tests. A value of 1.22, as suggested in recent fuel analyses,[16] would lower the contrail factors in Fig. 5 to a range even closer to that suggested by Schrader for the high-bypass engines he observed.

VII. Summary of Contrail Factor Calculations

It is seen that, contrary to assumptions made in early methods of contrail forecasting, the contrail factor is not constant for all flight conditions. Contrary to assumptions made in current forecasting methods, the contrail factor is not even constant for a given engine type. It varies even for the same engine at different power settings and flight conditions, mainly due to variations in propulsion efficiency. Cycle calculations were performed for a range of conditions for generic low-bypass and high-bypass engines, in a manner that implicitly accounts for propulsion efficiency. This range included flight at altitudes between 25,000 and 50,000 ft in a standard atmosphere, Mach numbers ranging from 0.4 to 0.9, and power settings from idle to military. Although all results were examined, only results for a range of Mach numbers and power settings at two altitudes are shown here. Although aircraft typically operate as much as possible near cruise conditions, they must climb, descend, and, in the case of military aircraft, perform dashes and combat maneuvers. The entire range of flight conditions considered here is not uniformly populated by air traffic on a normal day, but many of these conditions are attainable. The computed contrail factors range from 0.030 to 0.053 $g \cdot kg^{-1\circ}C^{-1}$ for a generic low-bypass engine, and from 0.038 to 0.090 $g \cdot kg^{-1\circ}C^{-1}$ for a generic high-bypass engine, over this range of conditions. Contrail factors are generally higher at lower power settings at a given Mach number, and are higher at higher

Mach numbers at a given power setting. Contrail factors tend to be higher at higher altitudes in general. Overall, contrail factors are generally higher for high-bypass engines than for low-bypass engines.

VIII. Diagnosis of Contrail Factors from Contrail Observations

During the fall of 1995, the U.S. Air Force Phillips Laboratory (now U.S. Air Force Research Laboratory) at Hanscom Air Force Base, Massachusetts, undertook an intensive aircraft observation campaign.[14] Meteorological radiosondes were launched from five sites in the Boston metropolitan area at intervals as frequent as 3 h. Observers at these five sites observed aircraft and whether or not they were making contrails. Confirmation of the altitude and aircraft type for each sighting by the observers was obtained in real time via phone link with the nearby Federal Aviation Administration (FAA) en-route traffic control center.

There were 563 observations of aircraft in-flight made in a two-week period. A summary of these data is shown in Fig. 6. It can be seen that, generally, there is a mixture of contrail and no contrail observations at a given temperature and pressure, with contrail observations generally prevailing at lower temperatures at a given pressure. This variation between contrailing and noncontrailing behavior at similar temperatures at a given pressure level is due to dependence of the critical temperature for contrail formation on ambient humidity, engine bypass ratios, and flight settings.

From this set, a subset of ~100 observations was extracted in which visual descriptions of the contrail observed were recorded. This subset was examined for short-lived contrails. Contrails that are short lived (last less than a few seconds) may be short lived because the air in which they form is very dry or because the conditions in which they are forming are at the very threshold for contrail formation. A group of 59 observations of short-lived contrails was selected for further analysis.

Environmental conditions in which short-lived contrails were observed were interpolated from the dense network of soundings to the location of the contrail observation. Assuming the observed environmental temperature represents the threshold temperature for contrail formation at the environmental pressure, a lower limit to the contrail factor can be derived using procedures described by Schumann[1] and Schumann et al.[12] If the ambient air was dry enough, the plume could mix out to a subsaturated state quickly and yield a short-lived contrail even though the temperature was well below the threshold temperature, and, in this case, the actual contrail factor could be higher than the estimated one.

From the aircraft type, as obtained from the FAA, an estimate was made of the bypass ratio of the engines on the observed aircraft based on tabulated aircraft characteristics.[22] Different aircraft of the same type may be outfitted with different engines with different bypass ratios. In cases where more than one bypass ratio was characteristic of the various engines in common use on aircraft of a given type, a mean bypass ratio was assigned to all aircraft of that type.

The contrail factor estimates based on the observed contrails are summarized in Fig. 7. Although the sample is relatively small, and

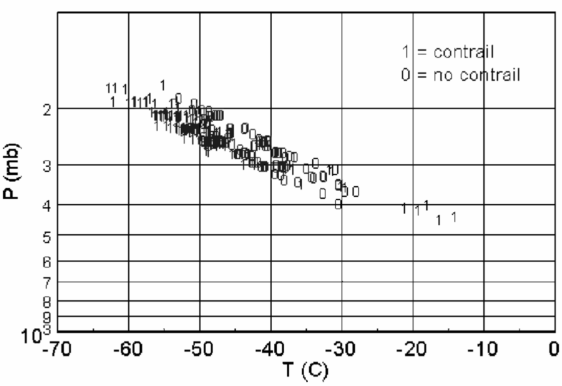


Fig. 6 Observations of aircraft contrailing (1) or not contrailing (0), as a function of ambient temperature and pressure.

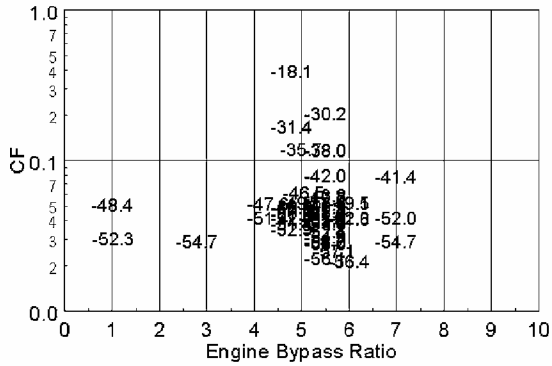


Fig. 7 Inferred contrail factors based on 59 observations of short-lived contrails. The temperatures (degrees Celcius) at which the contrails were observed are plotted as a function of the deduced contrail factor and the estimated bypass ratio of the engines on the aircraft.

by frequency heavily weighted toward higher bypass ratios, in general, it can be seen that most inferred contrail observations are within the range suggested by our computations implicitly accounting for propulsion efficiency. Most observations yield an estimated contrail factor between 0.030 and 0.10 $g \cdot kg^{-1\circ}C^{-1}$. Some inferred contrail factors are less than 0.030 $g \cdot kg^{-1\circ}C^{-1}$, the theoretical minimum contrail factor estimated assuming a propulsion efficiency of zero. However, the estimating procedure used yields only a lower bound on the contrail factor, and so the actual factor in these cases could have been greater than the inferred one. Without more precise information on engine type and power settings, these observations can provide only a limited comparison to relationships suggested by our cycle calculations.

Five contrails in Fig. 6 were observed at temperatures analyzed to be higher than -40°C. These observations yield inferred contrail factors much greater than 0.10 $g \cdot kg^{-1\circ}C^{-1}$. All five were produced by aircraft with engines with higher bypass ratios than are characteristic of the generic high-bypass engine used in our computational study presented before. It is possible that these inferred contrail factors are relatively high due to these higher bypass ratios, or were produced by aircraft in nonsteady-state flight or at a very low power setting during a slow descent, where the exhaust gas velocity was even closer to the forward airspeed than for the low power setting engine cycle data used in this study. A low power setting and low exhaust speed leads to very high propulsion efficiency, very low total enthalpy in the exhaust in the reference frame of the air, and, thus, to very high contrail factors. It also is possible that the altitude of the contrailing aircraft was reported incorrectly, or that a lower aircraft was identified in place of a higher contrailing aircraft at nearly the same geographic position.

There are many uncertainties in inferring bypass ratios for the aircraft observed in this study, and there are additional uncertainties in the temperature, pressure, and most importantly humidity, in the contrail environment. Humidities reported by radiosonde instrument packages at low temperatures are characteristically low.[23] An underestimate of environmental humidity would yield an overestimate of contrail factor. Given these uncertainties, the bulk of the inferred contrail factors presented in Fig. 7 support the validity of the method developed earlier for computing the contrail factor using total exhaust enthalpy in the reference frame of the air, implicitly accounting for propulsion efficiency. This comparison is suggestive, but not conclusive. Clearly, a more controlled experiment would be desirable, in which a wide range of engine characteristics and power settings are known precisely and environmental conditions are measured more precisely (preferably exactly at the aircraft position).[12]

These results also suggest that the threshold temperature for contrail formation can be used as a diagnostic for overall propulsion efficiency. Changes in overall propulsion efficiency, due to degradation of engine performance, or perhaps additional drag due to change in configuration of the airframe or addition of military stores under wing, can be diagnosed by observing changes in contrail onset temperature. These observations could be used for lifecycle monitoring of aircraft system performance and mission planning purposes.

IX. Summary

A physically consistent procedure for computing contrail factors based on engine cycle calculations has been presented. It follows general procedures used in past studies, but care is taken in choosing the proper reference frame for estimation of exhaust gas total enthalpy. If the total enthalpy of the exhaust is computed in the frame of reference of the air through which the engine is being carried by the aircraft, then propulsion efficiency is implicitly accounted for in the estimate of contrail factor. Contrail factors computed in this way are equal to or greater than the contrail factor of $0.030\ g \cdot \mathrm{kg}^{-1}{}^{\circ}\mathrm{C}^{-1}$ computed assuming all water and enthalpy generated during combustion exit the exhaust nozzle. Contrail factors are typically greater than this because some of the energy generated by combustion is used to propel the aircraft and some is lost in parasitic flows. When exhaust gases have high exit speeds relative to the airspeed of the aircraft, when fan and core streams are well mixed, and when there is little energy extracted in the form of parasitic flows, the contrail factor should approach $0.030\ g \cdot \mathrm{kg}^{-1}\mathrm{K}^{-1}$. For high-bypass engines, which move more air more slowly than low-bypass engines for a given net thrust, contrail factors generally are higher.

Calculations in the environmental reference frame yield contrail factors ranging from 0.030 to $0.053\ g \cdot \mathrm{kg}^{-1}{}^{\circ}\mathrm{C}^{-1}$ for the generic low-bypass engine and 0.038 to $0.090\ g \cdot \mathrm{kg}^{-1}{}^{\circ}\mathrm{C}^{-1}$ for the generic high-bypass engine cycle calculations performed in this study, over the range of environmental conditions assumed. Contrail factors are generally higher at lower-power settings at a given Mach number, higher at higher Mach numbers at a given power setting, and generally higher at higher altitudes.

The relationship between contrail factor and contrail onset temperature varies with temperature and pressure. Changes in contrail factor can be roughly related to changes in contrail threshold temperature using the result that a 10% increase in contrail factor results in a 1°C higher contrail onset temperature in a typical upper tropospheric environment for onset temperatures near −50°C. Thus, threshold temperatures estimated using a constant contrail factor for all aircraft may be in error by many degrees Celsius due to variation of contrail factor with engine type and flight settings. For nominal cruise conditions, at which most aircraft are operating most of the time, propulsion efficiency is typically near the design maximum for a given airframe and engine combination, and a constant contrail factor can be used to represent the contrailing characteristics of a particular engine and airframe combination. Thus, the variation of contrail factor with engine and flight settings is of more importance to military strategists than to climate researchers. Even brief episodes of contrailing may be unacceptable to military strategists, although by number of kilometers of contrails, most contrailing is done by aircraft at cruise conditions. However, even for climate researchers, it is important to correctly compute the contrail factor for cruise conditions, and our method is a good way to do this.

Contrail factors are diagnosed from a detailed set of observations of contrails forming at threshold conditions for formation. These contrail factors are compared to those computed from cycle calculations. Reasonable agreement is found between the range of contrail factors inferred from observations and those estimated from generic cycle calculations. A few observations of contrails forming at relatively high temperatures are likely to be the result of engine cycles or flight conditions inconsistent with the assumptions used in this study, or errors in reported aircraft altitude.

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