Jet Engine Soot Emission Measured at Altitude

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THE state of knowledge concerning engine design to minimize air pollution is believed to be such that emission products can be reliably predicted while the engine is still on the drawing board. Verification of such predictions for a given engine in the past has been largely done at ground level and not at the pressure and temperature conditions expected during flight at cruise altitudes. More effort is now being made to measure emission products from engines operating under cruise conditions. Such tests can be conducted in environmental chambers, but the tremendous entrainment of ambient air in the exhaust is difficult if not impossible to reproduce. This is an important consideration, since the emission products may be different if the exhaust is appreciably diluted immediately after leaving the engine and thereby preventing continued self-interaction. The use of an instrumented aircraft to obtain the appropriate data is perhaps a more realistic and less expensive approach. The latter technique was used in the study reported here.

Instrumentation

Several years ago the authors started the development of a photoelectric particle counter for application on a high-performance aircraft. The first tests were conducted at Edwards, Calif., and a more practical second-generation instrument was subsequently built. It can operate for long periods without attention. All necessary calibrations are performed internally and automatically, and zero levels are measured automatically and absolutely. For ground checkout it is operated and interrogated by external equipment. A simple real-time output is available for pilot information but at present is not used.

Prior to aircraft installation, the instrument was tested under environmentally controlled pressure, temperature, and vibration conditions. It was shown that the efficiency of the counter was not a function of these parameters. A similar instrument has been flown on balloons by Rosen[1] for many years. The consistency and accuracy of the results attest to the credibility of the method itself.

The probe (diagramed in Fig. 1) is mounted about 3 ft outboard of the port engine of the NASA RB-57B stationed at the NASA Flight Research Center, Edwards, Calif. The purpose of the probe is to reduce the air speed by about a factor of 30 without changing the size distribution or concentration. After the air enters the probe, it passes through about 7 ft of 1-in.-diam tubing and flushes the intake port of the instrument. This latter fixture is also shown in Fig. 1. Thus the intake of the instrument is continually bathed and surrounded by slow-moving ambient air (at ambient pressure) that has not spent more than one second in the sampling probe.

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Extensive assessment tests have been made to determine any undesirable influence the probe may have on the sampled aerosol. Aircraft velocity and angle of attack at altitudes up to 50,000 ft apparently have little effect on the measured concentrations as long as the aircraft is not performing unusual maneuvers. In addition, the vertical profiles obtained from the aircraft compare favorably with those obtained from balloon flights. More extensive descriptions of the instrument operation, mounting, and testing have been reported by the authors.[2]

Measurements

In the first attempts to sample engine exhaust, the pilot tried to circle back through his own trail. Since the exhaust was subvisible, this maneuver was never successfully accomplished. A second method was employed in which the B-57 was used as a chase aircraft following an F104 equipped with a J79-GE-11B engine. Even in this case the pilot could not see the exhaust trail if it were not for the so-called "heat waves." It should be noted that the measurements reported here are for circumstances in which no visible contrails were observed.

A typical pass through the exhaust trail is shown in Fig. 2 and was made over Edwards, Calif., on May 9, 1972. This sample was taken about 0.37 miles behind the lead aircraft at an altitude of 30,000 ft. The diameter of the trail D_t at the location of the chase plane can be approximately calculated from the following relation:

$$D_t = 2D_e[L/(4 + 12\lambda)D]^{1-\lambda} \quad (1)$$

where L is the distance in back of the engine $\simeq$0.37 miles; D_e is the diameter of the engine exhaust pipe = 21.8 in.; and

$$\lambda = \frac{v_s}{v_p} = \frac{\text{true air speed}}{\text{exhaust gas speed}} \simeq \frac{440 \text{ knots}}{1263 \text{ knots}}$$

This formula is discussed by Forstall and Shapiro,[3] and its validity is well documented from experiment, although it does not take into consideration the effect of the aircraft vortices. However, at short distances behind the aircraft, this effect is small. It should be pointed out that

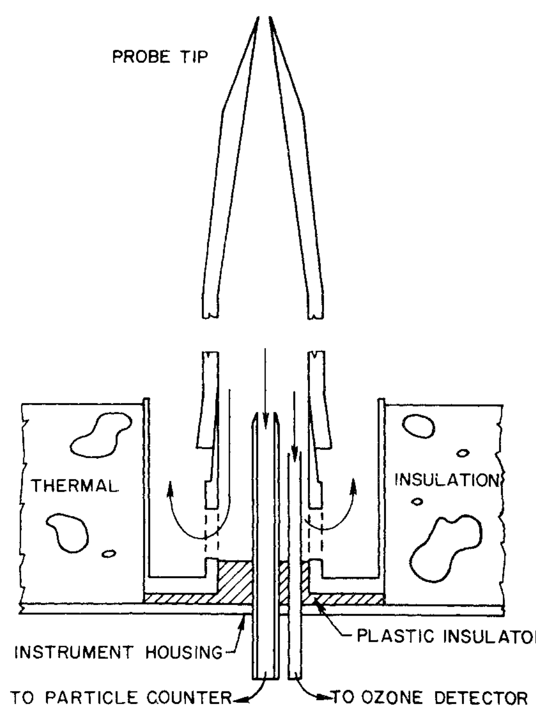

Fig. 1 The probe and intake fixture. Arrows indicate the direction of air flow.

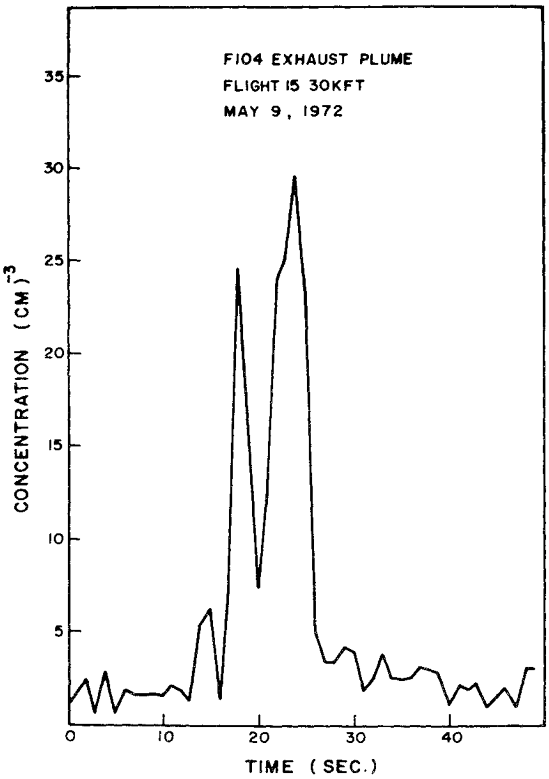

Fig. 2 A typical pass through an exhaust trail of the F104. The concentration refers to carbon particles about 0.30 μm in diameter.

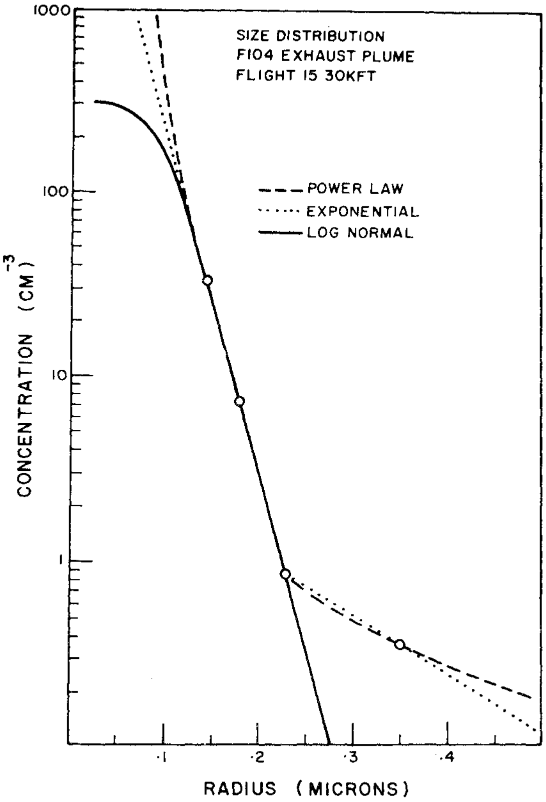

Fig. 3 The size distribution of particles in the exhaust trail. Data points are represented by the open circles.

under the measurement conditions, the exhaust trail itself had become diluted by a factor of about 10^3 by turbulent entrainment of ambient air.

The size distribution of the particles in the exhaust trail is shown in Fig. 3. The ratio of the concentration was determined from the total particle count while the aircraft was in the trail. The sizes were determined from the known response of the instrument to carbon particles, which is assumed to be the major constituent of the particle emission. Although these particles are probably not spheres, as is the calibration aerosol, it has been found from experiment that the exact shape does not affect the calibration as long as the particles are not greatly different from spheres.

In order to obtain the total mass concentration, the complete size distribution must be known. Since only a small range of particle sizes was measured, some extrapolation is necessary. For this purpose, the data were fitted to three types of size distributions: a piecewise continuous exponential, a log normal, and a piecewise continuous power law (Fig. 3). A log normal distribution was considered because Lindauer and Castleman[4] have shown that a high concentration of coagulating nuclei tends toward this type of distribution with a geometric standard deviation σ of about 1.37. The time required for this self-preserving size distribution to become established is on the order of a few milliseconds for the condition at the engine exhaust nozzle. A much longer time is required for the emerging exhaust to become significantly diluted with ambient air.

In the early stages of this dilution the aerosol associated with the entrained air may also participate in the coagulation process. The net effect would probably produce a two-population size distribution: one group resulting from self-coagulation of the original emission nuclei and the other group (of very likely larger diameters) consisting of particles composed of an ambient atmospheric nucleus that has grown by coagulation with the emission products. This may be the reason that the last data point on the observed size distribution curve does not fit the theoretically predicted log normal curve of Lindauer and Castleman. The first three points, however, can be fitted to a log normal curve with $\sigma = 1.37$ with a resulting mean radius of about 0.1 μm. Thus the measured size distribution may depend heavily on the ambient aerosol concentration and consequently other jet engine size distribution measurements made at sea level are very likely not applicable. For this reason, no attempt was made to fit the data to characteristic size distributions obtained at sea level.

The rate of mass emission can be calculated from the formula

$$m = Mv\pi R^2 \tag{2}$$

where M = mass per unit volume of aerosol at the point of observation; v = velocity of exhaust with respect to aircraft at the point of observation; and R = radius of exhaust trail at the point of observation. The results of this computation are shown in Table 1. The rate of mass emission for the power law and the log normal curve were set equal and from this the limits of r were calculated. When compared with Fig. 3 these limits seem to be entirely reasonable, and it was therefore concluded that the two size distributions give results that are not appreciably different. The table also shows the effect of taking the above

Table 1 Mass emission rates from Eq. (2)

m, lb/hr	Functional form of size distribution used to fit data
9.61	Exponential, $0 \leq r < \infty$
2.49	Exponential, $0.131\ \mu m \leq r < \infty$
4.00	Log normal, $0 \leq r < \infty$
4.00	Power law, $0.131\ \mu m \leq r \leq 1\ \mu m$

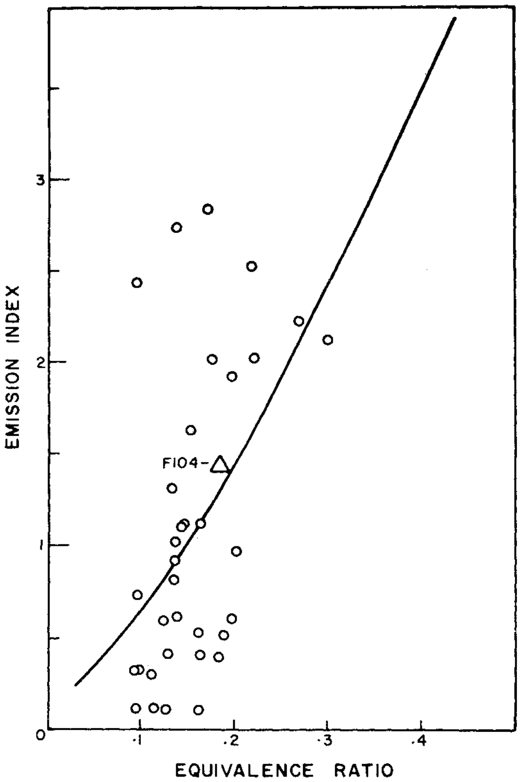

Fig. 4 The emission index obtained from this study (triangle) as compared with the results of a number of other studies conducted at ground level (circles). The smooth curve is a least-squares fit to the data.

lower limit for the piecewise continuous exponential distribution. The mass emission rates were calculated with different but reasonable size distributions to illustrate the sensitivity of the reported values to sizes outside the measurement range.

From Table 1, the emission index (lb aerosol per 1000 lb fuel) was calculated using $m = 4.00$ lb/hr and the fuel consumption rates supplied by the engine manufacturer. Figure 4 is a comparison of the emission index obtained from this study with that obtained from typical jet engines operating at ground level, as reported by Sawyer.[5] Table 1 implies that the uncertainty in the calculated value is probably about a factor of two.

In reporting exhaust emission levels, giving just the emission index provides an incomplete picture. The operating conditions of the engine must also be taken into account. Thus the emission index is more meaningful when it is given as a function of equivalence ratio (the actual fuel-to-air combustion ratio divided by the calculated stoichiometric fuel-to-air ratio) which is roughly proportional to the engine speed. For the cruise conditions reported here, the F104 has a fuel-to-air ratio of about 0.013. The stoichiometric fuel-to-air ratio for JP-4 fuel is about 0.068. The corresponding equivalence ratio is therefore 0.013/0.068, or 0.19.

Conclusions

The results of this study taken at face value indicate that the emission index of typical jet engines calculated from ground level measurements is comparable to the actual in-flight emission index for altitudes up to 30,000 ft. It appears that a properly instrumented aircraft can be used to obtain some worthwhile information concerning emissions at altitude but the size distribution should be more thoroughly investigated, both theoretically and experimentally.

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Slender Delta Wing with Conical Camber

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THE slenderness assumption of Munk[1] and Jones,[2] made over and above that of linearization, has often been used to get closed form analytical solutions for wings, bodies, and their combinations. In this Note, simple expressions are obtained for the aerodynamic characteristics of a slender delta wing, exhibiting an even-order polynomial twist distribution in the spanwise coordinate. In Ref. 3 is derived an integral equation which relates the twist distribution to the pressure distribution. For the slender wing it is

$$\Delta C_p = C_p^- - C_p^+ = \frac{4\,C_0}{\tan\delta\,(1-\eta^2)^{1/2}} + \frac{4\tan\delta}{\pi}\int_0^1 \frac{d\omega}{d\eta_i}\,\eta_i \times \log\frac{(1-\eta^2)^{1/2}+(1-\eta_i^2)^{1/2}}{(1-\eta^2)^{1/2}-(1-\eta_i^2)^{1/2}}\,d\eta_i \qquad (1)$$

and

$$C_0 = \tan^2\delta\left[-\omega(1) + \frac{2}{\pi}\int_0^1 \frac{d\omega}{d\eta}\sin^{-1}\eta\;d\eta\right] \qquad (2)$$

The twist distribution under consideration is of the type

$$\alpha_n(\eta) = -\omega_n(\eta) = -\epsilon_{0n} - \epsilon_n\,\eta^{2n}/2n \qquad (3)$$

Here C_p is the pressure coefficient, η the conical coordinate $y/s(x)$, α the twist distribution, $s(x)$ the local wing semispan, δ the wing semiapex angle, and + and − refer to the top and bottom surfaces of the wing, respectivey. The coordinate system is shown in Fig. 1.

Linearized theory predicts two kinds of solutions. One in which a leading edge singularity appears and the other in which the leading edge experiences zero load. Because

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