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In-situ laser-induced incandescence of soot in an aero-engine exhaust: Comparison with certification style measurements

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ABSTRACT

In-situ (non-intrusive) laser-induced incandescence measurements of soot in the exhaust of a current technology, mid-size turbofan aero-engine running on a sea-level test bed have been performed at the same time as the extractive measurements required for engine emissions certification. Although laser-induced incandescence and the filter paper reflectance measurement specified for engine certification provide different measures of soot concentration which are not directly comparable, trends with engine power are the same. At high engine power, agreement between mass concentration derived from an LII measurement along a diameter through the exhaust plume and that derived from the SAE Smoke Number measured by the filter paper technique was well within the uncertainty of the standard technique. At low power, only the non-intrusive method could measure the levels of soot produced. The interpretation of line-of-sight integrated laser-induced incandescence data from a real engine exhaust is discussed.

1. Introduction

Although aero-engines, especially modern civil engines, are responsible for a very small proportion of global pollution, there is concern that they may have a disproportionate effect on climate. Therefore, there is a constant drive to reduce the already low levels of pollutants emitted. Traditional measurement methods, based on sampling exhaust gas from an engine on a test bed, are well proven, but expensive to implement, requiring specialist hardware capable of withstanding exhaust conditions and extended periods of engine running at high power. As a result, few such measurements are carried out. Smoke measurement, in which a defined volume of sampled gas is passed through a filter paper and then the reflectance of the filter paper measured [1], is the most time consuming and expensive part of the emissions certification process, requiring the engine to be held on condition for approximately 5 minutes for each measurement. Also, when the test as first introduced in the 1960's the soot particle concentration in exhausts was much higher than today. Hence, the sensitivity of the filter paper reflectance was not a problem. However, a current engine will often fail to give any significant change in filter paper reflectivity at low power conditions. Synthetic aero-fuels, with a low aromatic content, have been shown to produce significantly less smoke than conventional oil derived fuel. This, together with increasing concern about health hazards of very small inhaled particles, means there is likely to be a requirement to make more measurements of exhaust soot at very low levels.

Laser-induced incandescence (LII) was first demonstrated as an extremely sensitive method for measurement of soot in aero exhausts in the late 1990's [9], and the use of an LII system to record soot profiles from a number of current generation, large civil engines during engine performance running and transient maneuvers has been described in a previous paper [2]. An LII calibration method relating LII measurements to soot volume fraction by comparison with extinction measurements in the exhaust of an atmospheric pressure kerosene burner has been developed as part of a European Union collaborative research program (AEROTEST) [5,3,6]. However, until now, there has been no back-to-back comparison of LII with filter paper smoke measurements on the same engine test. LII data were recorded during a certification emissions test of a mid-size, mixed flow turbofan aero-engine and a comparison of results is presented.

It should be noted that, although the in-situ LII in this work was performed in parallel with a conventional emissions test, measurements can be obtained during any engine running, with complete profiles being recorded in < 5 minutes as reported in [2]. The cost to an engine development program is negligible, especially since the system has now been automated, so that the presence of a specialist operator is not required. Soot emission data can be available at any stage of an engine development program, when an LII system is installed in the test bed. Comparison of different engines in the same test bed is also possible at no additional cost. The LII system used in this work was positioned in a large engine test bed for several months before this test, and measurements

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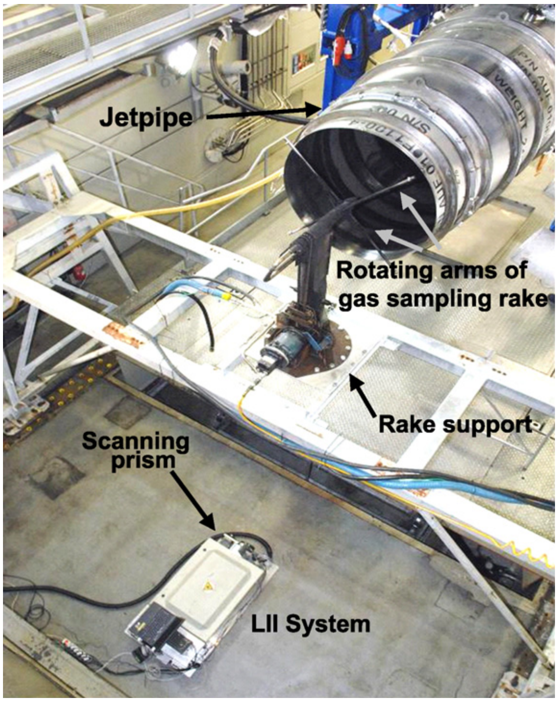
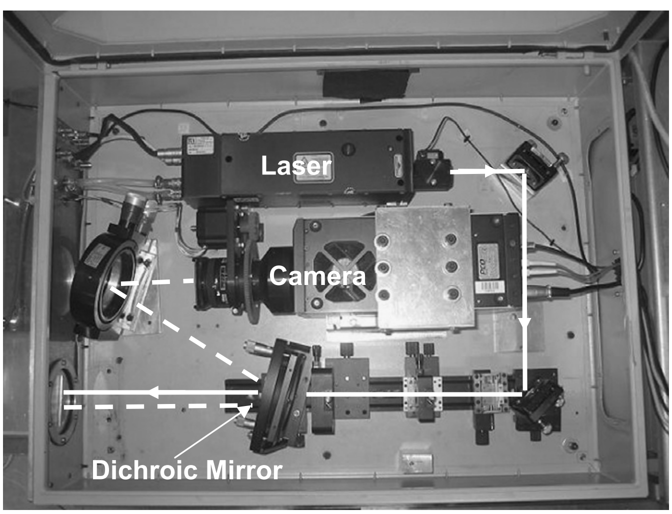


(a)



(b)

Fig. 1. (a) View of the rear of engine with the gas sampling rake and LII system in place. (b) Layout of internal components in the LII system. The continuous white line shows the path of the laser beam while the dashed line shows the path of a ray of incandescent light.

were taken on several development engines. The measurement was completely ‘invisible’, in the sense that no additional engine running or other modification of the predetermined test schedule was required.

2. Description of the test set-up

A picture of the test set up is shown in Fig. 1. The engine test cell is 8 m high and 8 m wide with the engine suspended from rails on the ceiling. In this case the distance from floor to engine centerline was 3.70 m. When the engine is running, typically ~ 5 times the air mass flow through the engine is entrained into the test bed exhaust duct (‘detuner’). Hence the temperature in the test cell, except in the exhaust gas stream, is ambient, or slightly below ambient.

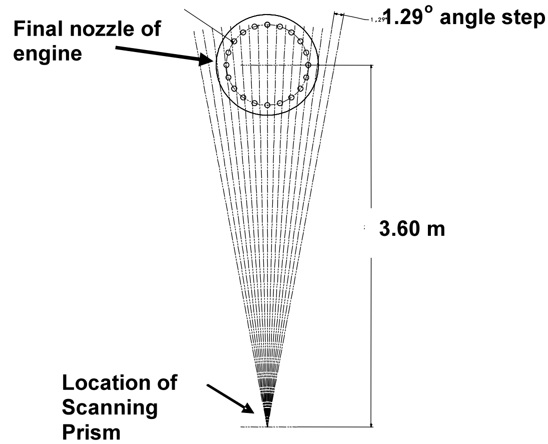


Fig. 2. Sketch of laser beam tracks through plume during a profile scan.

Fig. 1(a) is a view of the rear of the engine from above. The rotating gas sampling rake had to be positioned within half the diameter of the final nozzle to comply with the regulations for emissions certification. The LII system, shown in Figs. 1(a) and 1(b), and fully described in [2], uses the collimated beam from a Quantel/Big Sky CFR400 Nd/YAG laser operating at 1064 nm to induce incandescence along the length of the beam as it passes through the exhaust plume. The incandescent light is collected in the backward direction through the scanning prism and directed by the dichroic mirror, which transmits 1064 nm and reflects broadband visible light, to the gated, intensified CCD camera (PCO Dicam). The system was placed on the test cell floor 1.55 m behind the final nozzle of the engine, to accommodate the support structure for the gas sampling rake, though it would have been desirable to have both systems measuring at the same axial position. The laser beam was scanned by the rotating right-angled prism as shown in Fig. 2 to record soot profiles across the 1.0 m diameter exhaust plume.

In a mixed flow turbofan engine there is a lobed mixer behind the final turbine stage which induces mixing between the hot gas which has passed through the core of the engine and the bypass air which is driven by the fan of the engine only [4]. Mixing continues in the jetpipe, 0.97 m long in this case, so that temperature and species concentrations in the exhaust at the final nozzle are expected to be fairly homogeneous.

3. Test results

For an emissions certification test, the engine was run three times (Runs 1, 2 and 3). In each run power was stepped from an initial high power back to idle in 16 steps. Gas samples were taken and analyzed using the instruments specified in the certification procedure [1] at each step in each engine run. The engine was allowed to stabilize and held on condition while gas sampling and analysis took place.

Examples of three unprocessed LII soot profiles are shown in Fig. 3. Each point is an average of the LII signal for 5 s (50 laser pulses). In contrast to profiles from engines with unmixed exhausts [2], these profiles show a single maximum. The highest soot concentration was observed at highest power. This was expected for the type of combustor in this engine, which is completely different to the type in the larger engines studied in [2].

In a previous paper on LII measurements in unmixed engine exhausts [2], we assigned asymmetry of profiles to the effect of refractive index changes between ambient air and the hot exhaust gas in the plume. However, in this mixed flow exhaust the temperature is lower and concentrations of water vapor and CO_2 are