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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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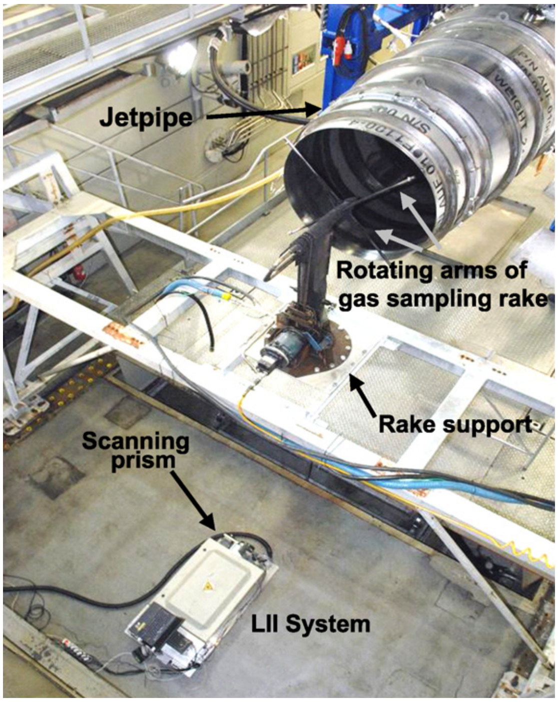
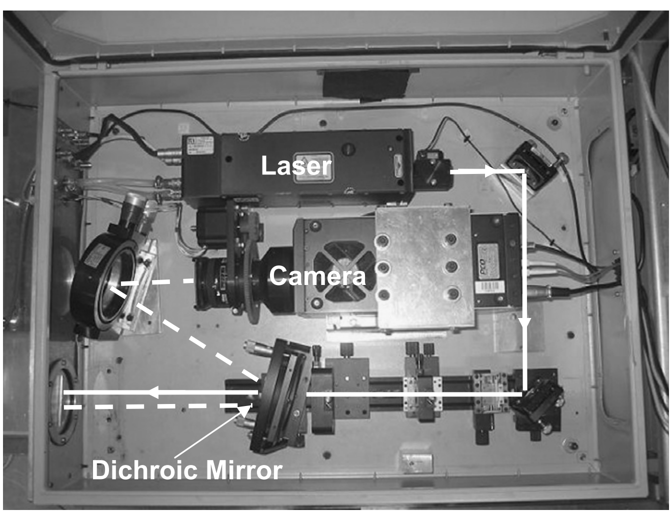


(a)



(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.

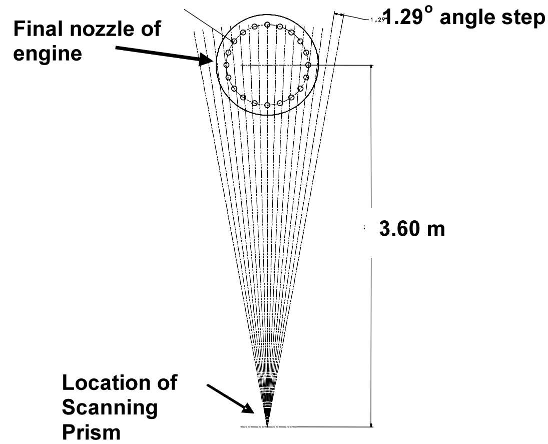


Fig. 2. Sketch of laser beam tracks through plume during a profile scan.

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

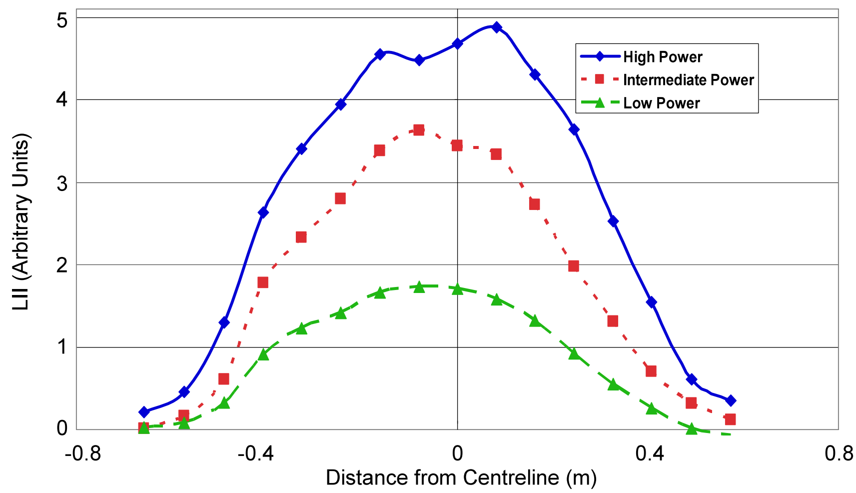


Fig. 3. Examples of three unprocessed soot profiles from different engine running conditions.

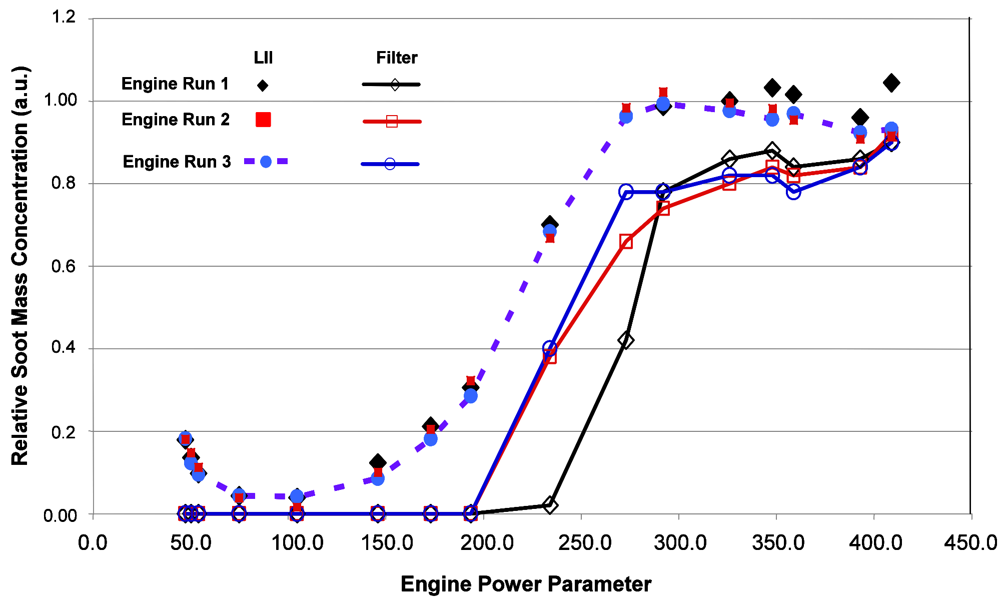


Fig. 4. Comparison of soot mass concentration derived from the LII signal measured along the vertical diameter through the plume with values derived from certification style filter paper reflectance measurements conditions on the same engine runs.

reduced by the bypass ratio of ~ 4. The refractive index ratio between plume and ambient air is estimated to be > 0.9998. Hence, beam steering due to refractive index change is much less important.

For an initial comparison with conventional filter paper measurements, the value of the LII measured along the path of the beam through the vertical diameter of the plume was converted to mass concentration, based on the calibration in a kerosene burner at Lille University [2,6], assuming a soot particle density of $1.85\ \mathrm{g\,cm^{-3}}$. The filter paper SAE Smoke Number values were converted to mass concentration using the correlations of Hurley [7]. Fig. 4 shows a comparison of these converted values.

Clearly, the trends in soot particle mass with increasing engine power are very similar at intermediate and high power. At low power the sensitivity of the filter paper method is not adequate, but LII shows a clear minimum soot concentration. The data in Fig. 4 were obtained during three successive engine runs for emissions certification style testing. An LII profile was recorded at each engine condition step. The consistency of the LII measurement is apparent from Fig. 4, where lines joining the points for LII in Runs 1 and 2 have been omitted for clarity. Average deviations from the mean of the three runs are 5.5%, 6.6% and 5.8% for Runs 1, 2 and 3 respectively. If the two lowest soot concentration points are excluded, the deviations are 3.1%, 3.8% and 3.4% respectively. Otherwise, no trends in deviation over the range of measurements are apparent.

Unfortunately, the quantity being measured by the two techniques, although a measure of the soot emitted by the engine in each case, is not the same; any “comparison” is dependent on a number of factors which will be discussed below. Samples from each probe of the rotating sampling rake are mixed in a single transfer line, so that the filter paper sees an averaged concentration of sampled gas, weighted by the mass-flow through each individual probe. There will be losses due to particles sticking to the probes and the transfer line. The LII measurement for each point on a profile is a line-of-sight integration of LII emitted at all points along the laser beam.

4. Analysis of line-of-sight integrated LII

In a profile generated by scanning the laser beam as shown in Fig. 2, each orientation of the beam will see a different pathlength through a cylindrical exhaust plume. As a first stage in relating line-of-sight LII to total soot in a plume, a simple geometric correction for pathlength can be made using the scheme shown in Fig. 5.

The main uncertainty in this pathlength correction is the assignment of a value of **r**. If, as in engine certification, emissions measurements are made less than half a diameter downstream of the final nozzle, it is a reasonable assumption that **r** is the radius of the final nozzle (0.5 m in this case). However, for these measurements, the LII system was 1.55 m behind the engine (to accommodate the support for the gas sampling rake) and the exhaust gas was mixing with surrounding air around the edges of the plume, as shown by the broader profile at high power in Fig. 3. A value of **r** was assigned based on the point in a profile where no significant LII signal was detected. Because this engine had an internal mixer 0.97 m upstream of the final nozzle, core and bypass streams were fairly well mixed by the time the exhaust emerged from the engine. However, the mixer performance depends on the relative velocities of the core and bypass gas streams, and hence engine power. Thus, at low power assignment of **r** as the radius of the final nozzle for a measurement close to the nozzle may not be valid.

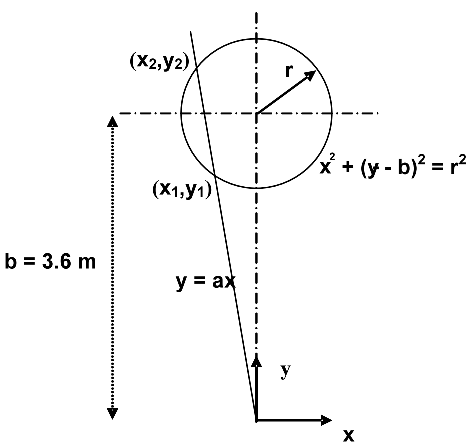


Fig. 5. Geometric correction for pathlength through the cylindrical plume. Points of intersection of the beam with the edge of the plume calculated as follows: $x_i = [ab \pm \{(1+a^2)r^2 - b^2\}^{1/2}]/(1+a^2)$; pathlength $= [(x_1 - x_2)^2(1+a^2)]^{1/2}$.

Because LII is an incoherent emission process, the contributions to line-of-sight integrated LII decrease as the square of the distance from the detector. At the soot concentrations found in engine exhaust plumes, absorption of the LII by soot in the path, as is common in sooting flames, is not significant. In calculating an LII profile the distance of the LII source from the detector has to be taken into account.

For a mixed flow engine the concentration profile of molecular species in the exhaust is, at least at most power conditions, a truncated (or 'flat-topped') Gaussian [8]. In other words, when the exhaust emerges from the final nozzle, it is well mixed. Gaussian edges to the plume develop as shear layer mixing takes place downstream, but there is no significant mixing in the core of the plume, at least for several diameters downstream. It is assumed that the soot profile is also 'flat-topped' Gaussian (FTG).

Fig. 6 shows the calculated relative contributions to a line integrated LII signal from different distances along the beam as it intersects a FTG plume with a top diameter 0.7 m and Gaussian $1/e^2$ radius of 0.2 m for three scanning prism angles from the vertical diameter (0°) until the beam intersects the Gaussian edge of the plume (6.45°). Where the beam passes through the flat top, the contribution decreases quadratically with distance.

Figs. 7(a) and 7(b) are calculated LII profiles for FTG, including correction for pathlength and distance from the detector, showing the effect of varying the Gaussian radius (a) and the width of the flat top (b). The minimum Gaussian radius shown in Fig. 7(a) is 0.03 m. For lower values the calculation failed due to precision errors. However, it illustrates that even a plume with no Gaussian edge (i.e. a 'top-hat' plume) will give rise to a LII profile with a curved top when pathlength effects are taken into account. The degree of curvature will depend on the distance from the LII equip-

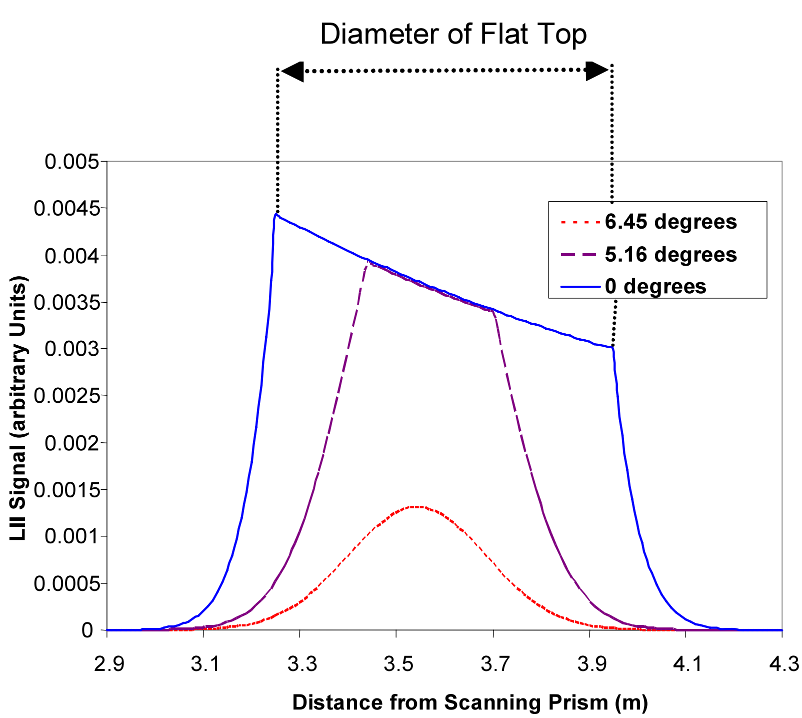


Fig. 6. Relative contributions to the integrated LII signal with increasing distance from the scanning prism for a three prism angles from 0° (vertical diameter) to 6.45° (in the Gaussian edge of the plume) calculated for FTG with a top diameter 0.7 m and a Gaussian $1/e^2$ radius 0.2 m.

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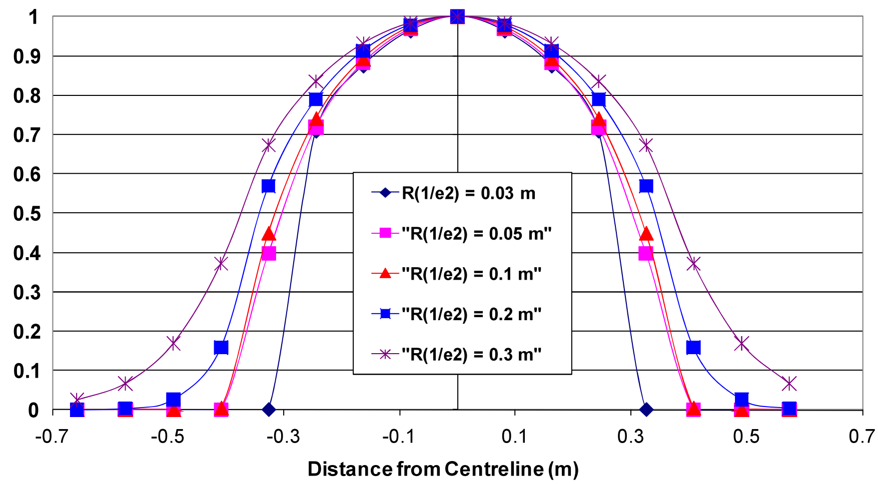

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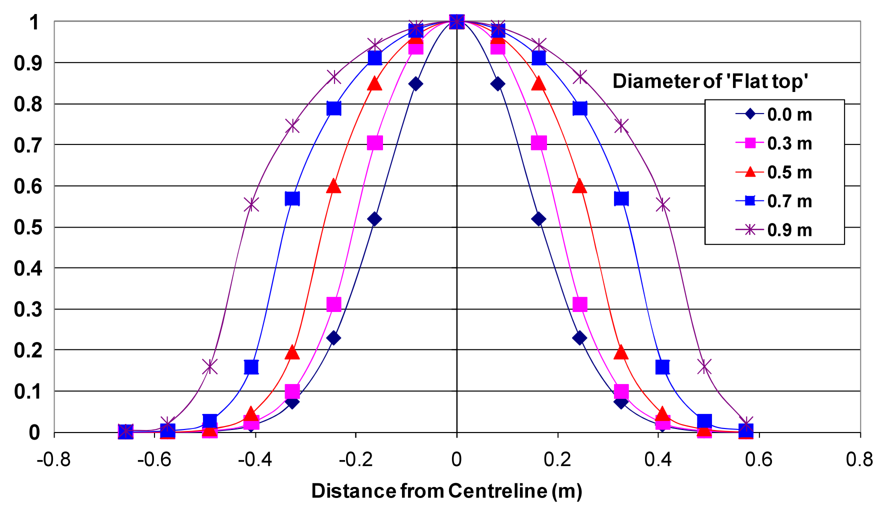

(b)

Fig. 7. (a) Calculated profiles for 'flat-top' Gaussian plume with 0.7 m diameter 'flat top' for various Gaussian $1/e^2$ radii. (b) Calculated profiles for 'flat-top' Gaussian plume for various flat-top diameters with $1/e^2$ radius = 0.2 m.

ment to the engine centerline. Both figures have been calculated for a distance of 3.6 m.

Fig. 8 shows comparisons of the profiles recorded for the three highest power engine conditions (corrected for pathlength) with a calculated profile for a FTG, with flat-top diameter = 0.73 m and Gaussian $1/e^2$ radius = 0.2 m, normalized by area. This combination produced the shape which gave the best fit, by eye, to observed profiles. Run 1 was the first engine run and it deviates further from the calculated profile than Runs 2 and 3, which are remarkably consistent. Trends in all three plots are similar with the calculated curve being lower than the observed between −0.5 m and −0.3 m and higher between 0.2 m and 0.4 m from engine centerline. The observed data do not appear to be randomly distributed around the calculated profile, suggesting that the effect is real. Overall, the observed profile shape is close to the calculated profile. Hence, it appears the FTG is a reasonable approximation.

At the beginning of the emissions testing the engine was run at three high power conditions and then shutdown to correct an instrumentation problem. Run 1 was then restarted from the beginning. On the three initial conditions, a slightly different profile (shown in Fig. 9), best fitted with a Gaussian radius of 0.25 m, was observed. Between this initial running and Runs 1, 2 and 3 no significant differences in measured engine parameters were apparent. However, the ambient temperature was lower at the beginning of the run, as shown in Table 1. The engine would also be cold at the beginning of the initial run.

The absolute values of LII signal along the vertical diameter (data used to derive Fig. 4) are very consistent for the three emissions curves, except that the values at high power conditions on Run 1 show more scatter than those on the other runs. These points were the first to be recorded after the engine restart. This, together with the observation of a more ragged profile, suggests that the engine emissions may not have completely stabilized at the time these measurements were made.

At lower power unprocessed profiles have more of a triangular appearance (Fig. 10). After pathlength and distance corrections have been applied, comparison with a calculated FTG profile gives reasonable matches for the two conditions corresponding to engine power parameter values 146 and 173 in Fig. 4 in Runs 1 and 2 (Fig. 10) when values of 0.5 m and 0.3 m for the flat-top diameter and Gaussian $1/e^2$ radius are input to the calculation. Asymmetry is more pronounced than in the high power cases. For Runs 1 and 2 the points at the extremities of the experimental profiles appear high as a result of the use of the value of **r** derived from high power curves in the pathlength correction calculation. It is difficult to determine a better value of **r** from the noisier profiles at low power. For the 'minimum soot condition' there is obviously a scatter of points around the profile. Run 3 data are shown in Fig. 10 for completeness, but the background level of the camera,

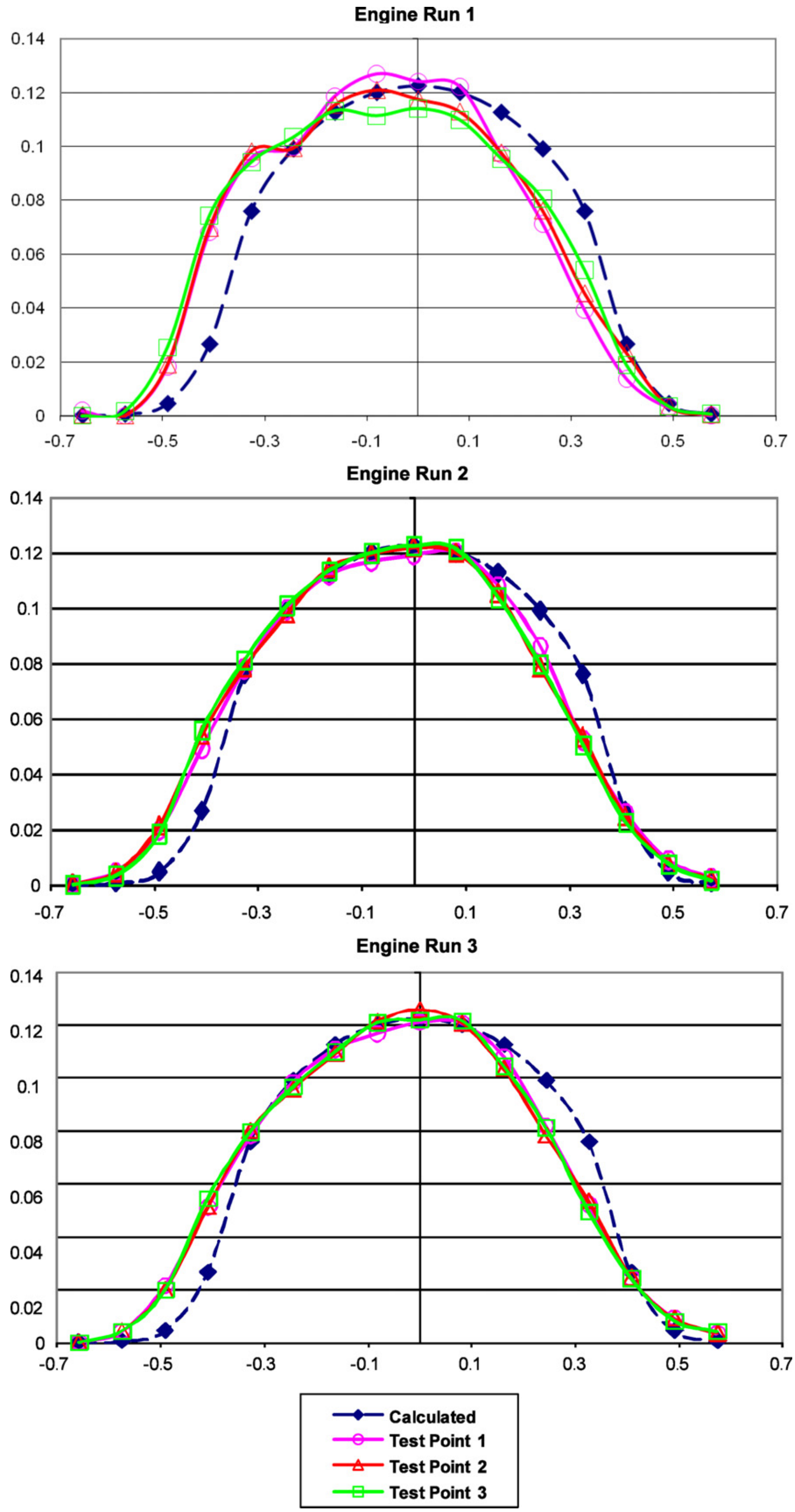

Fig. 8. Comparison of calculated and measured profiles for the three highest power conditions on engine Runs 1, 2 and 3.

which was recorded at the start of the test and is subtracted during processing, had changed sufficiently between Runs 2 and 3, so that meaningful profiles could not be obtained from the low power data of Run 3.

5. Comparison with calibration burner measurements

The LII soot mass values presented in Fig. 4 were derived from the raw LII data by comparison with a calibration of LII using ex-

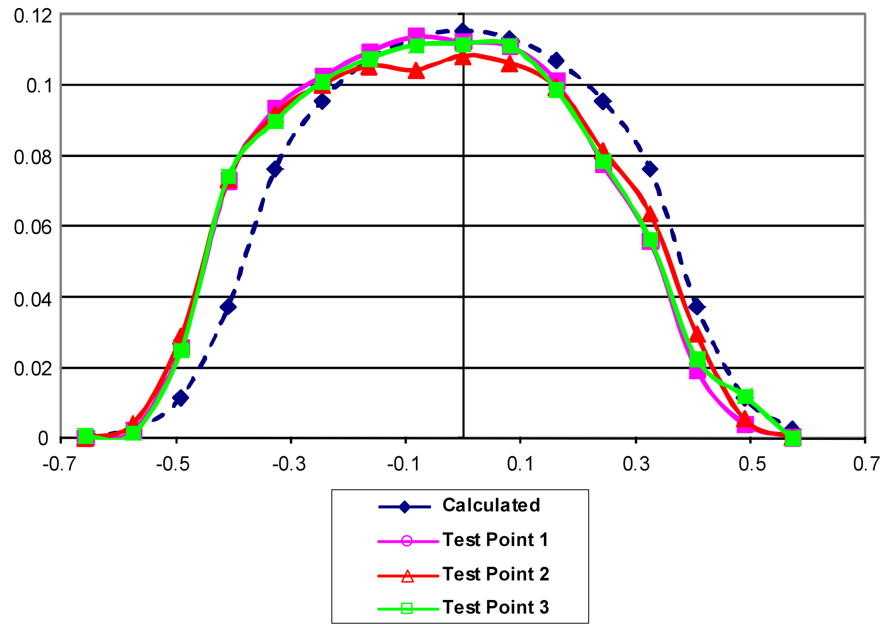

Fig. 9. Comparison of calculated and measured profiles for three high power conditions on the initial, aborted, engine run.

Table 1
Ambient temperature (°C) at test points 1–3 on each engine run.

	Initial run	Run 1	Run 2	Run 3
Test point 1	18.3	21.8	23.5	24.7
Test point 2	18.9	21.7		24.7
Test point 3	19.9	21.9	23.7	24.8

tinction measurement in the exhaust of an atmospheric pressure kerosene burner according to a procedure fully described in [6]. The burner measurement was made in an enclosed exhaust duct where the soot concentration was shown to be homogeneous by viewing LII with a separate camera at 90° to the laser beam direction. The conversion of raw LII signal counts to soot volume fraction involves a correction for the difference in pathlength between the burner exhaust duct (10 cm) and the engine exhaust plume [6]. However, an exhaust plume is not perfectly homogeneous, approximating to FTG in this case, but often a more complex profile for an 'unmixed' exhaust where the soot particles are emitted in an annular gas stream.

For an FTG it is possible to define an 'equivalent plume diameter' for use in pathlength correction. Cumulative growth of LII signal along a beam through the diameter of the calculated profile of Fig. 8 is shown in Fig. 11. On the Gaussian edges it follows the 'error function' curve of an integrated Gaussian, while in the central flat top the curve is quadratic. A homogeneous ('top-hat') profile, which could be directly ratioed to the calibration burner pathlength of 10 cm, would give rise to a pure quadratic curve. The equivalent diameter is the distance between the intercepts of the extrapolated quadratic part of the FTG curve with the zero and maximum levels of LII signal. Applying the equivalent plume diameter would increase the values of the LII derived soot mass concentrations shown in Fig. 4 by a factor of 1.35. However, this value is extremely dependent on the initial choice of plume radius (**r**).

6. Summary and conclusions

LII measurements have been compared to conventional emissions certification testing of smoke from a current technology, mixed flow, mid-size turbofan aero-engine. LII data collected in the backward direction along a collimated laser beam passing through the diameter of exhaust plume, when converted to soot mass concentration, show good agreement with trends in conventionally measured soot emission with engine power. Although a large number of assumptions are involved in converting LII intensities and filter paper reflectivity measurements to mass concentration, which can be compared, at high engine power the LII measurements are within 25% on the high side of the filter paper measurements. The accepted uncertainty in filter paper measurements of SAE Smoke Number is ±3. Smoke Number for a modern engine is normally < 10. Thus, the LII, as measured in this test, is well within the limits accepted for filter paper measurements. LII measurements show deviations $< 7\%$ between the three emissions runs. It is expected that the LII measurements will give higher soot volume fractions than the filter paper measurements since in-situ LII is not subject to losses in probes and transfer lines.

LII is more sensitive than the filter paper method and has been shown to be capable of measuring, in-situ, the levels of soot anticipated from the most modern combustors burning low-aromatic fuel.

The conversion of LII signal counts to soot volume fraction, and hence mass concentration is based on a single calibration exercise [6] in which LII was compared to extinction measurements in a homogeneous flow in the exhaust duct of an atmospheric pressure burner. An engine exhaust plume is not homogeneous and does not have the 'top-hat' profile of the burner exhaust. Profile measurements, made by angle scanning the LII laser beam, show that a flat-top Gaussian (FTG) profile is a reasonable approximation for the plume of this particular engine, at least at high power conditions. It is possible to define an effective plume diameter for comparison of the burner and a FTG plume, but this depends on the initial choice of a plume diameter. Use of the effective diameter will further increase the LII measurements relative to the filter paper. The scanned profiles show there is asymmetry of the plume in the horizontal direction. There is no reason why there should not also be asymmetry in the vertical direction, which would affect the effective diameter differently.

With the present state of knowledge, for LII generated with a collimated laser beam and collected in the backward direction, a measurement taken across a plume diameter as close as possible to the final nozzle is the least ambiguous measurement. For some engines, for example large civil engines with unmixed ex-

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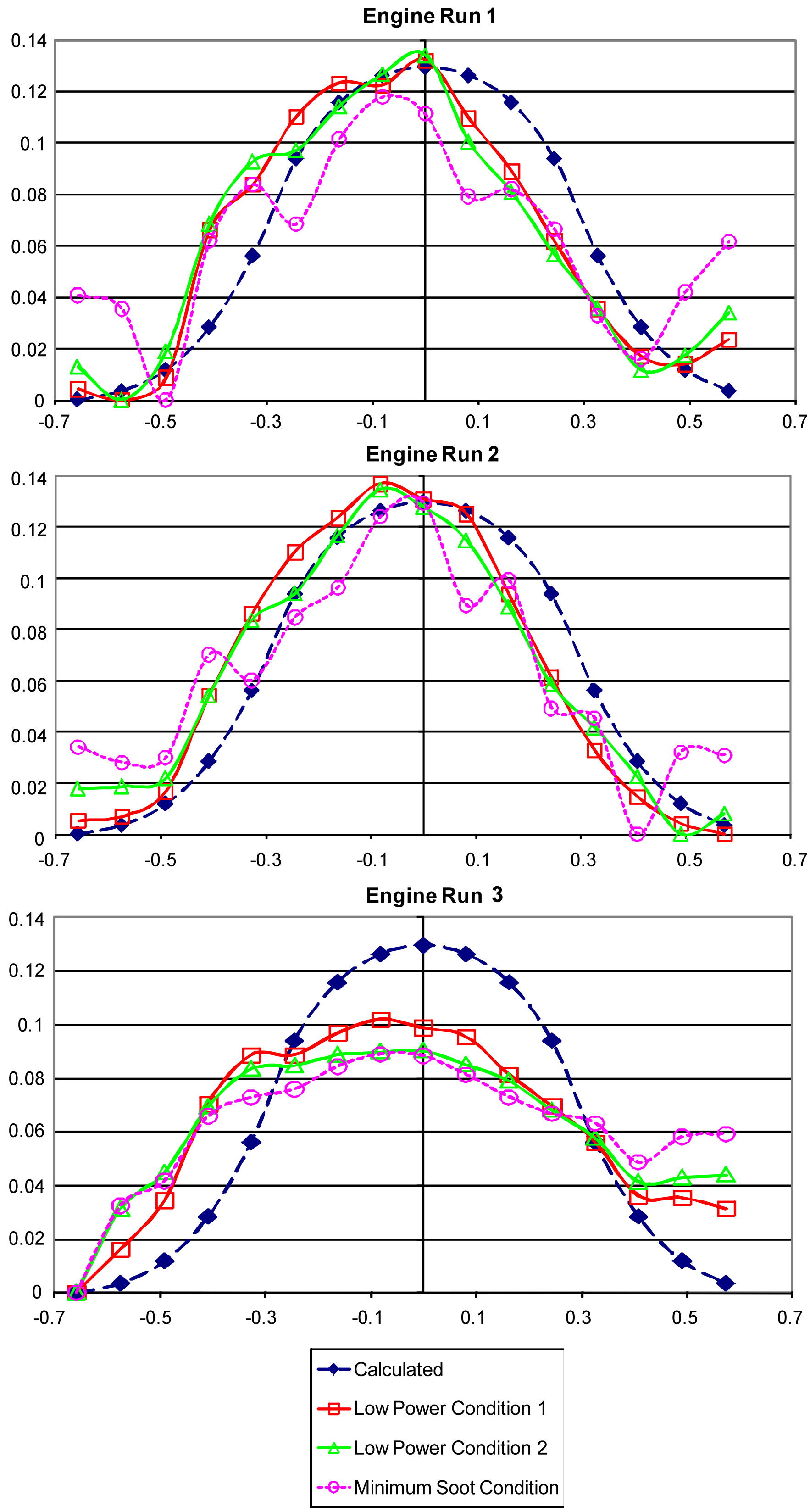

Fig. 10. Comparison of calculated and measured profiles for low power conditions: engine power parameter 173, engine power parameter 146, and minimum soot condition.

haust, this measurement is not possible. It may be possible to use an LII system with light collection in a different directions to the laser to produce a two-dimensional map of particle concentration in the plume, but the logistics of installing such a system in engine test beds and the time taken to record data may be problematic.

There is also the potential to use exhaust LII as an engine diagnostic which does not involve fitting any sensor to the engine. This

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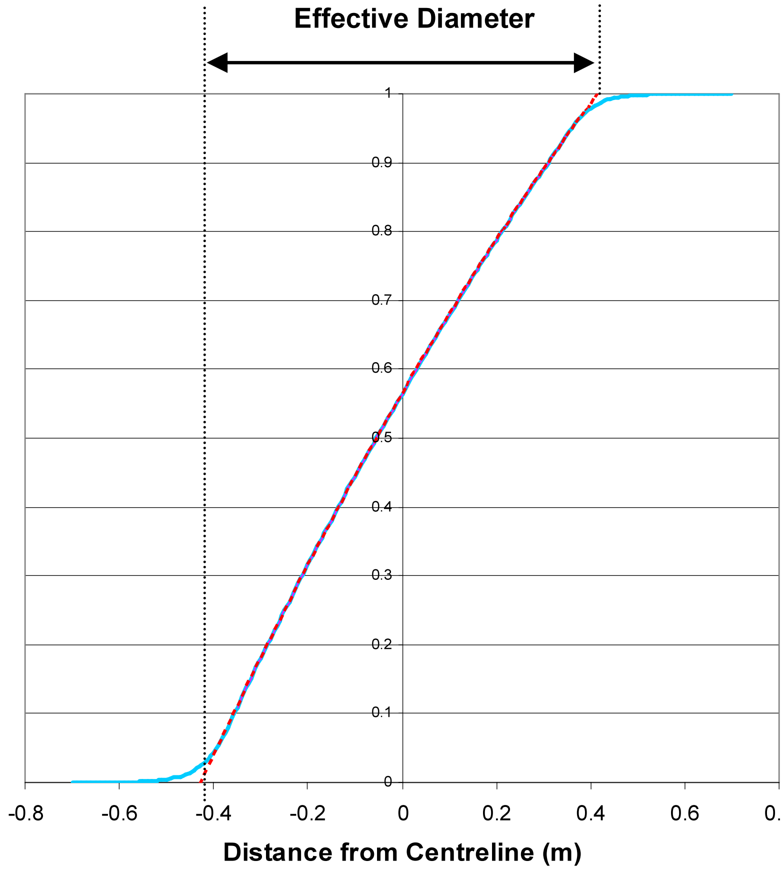

Fig. 11. Cumulative growth of LII signal along beam through diameter of flat-top Gaussian plume (solid line). Dotted line is projection of quadratic to zero and maximum value to give effective diameter.

is illustrated in this paper by the sensitivity of the profile to ambient or engine temperature, and variation of the profile with engine condition which may be indicative of internal mixer performance.

In-situ LII has been shown to be more, sensitive, faster, cheaper than filter paper measurement. A system has survived test bed conditions for several months and then been transported to another test bed to make the measurements described in this paper. The system has now been automated and does not require the presence of a specialist operator.

In this and previous work [2], the potential to use LII to monitor soot emission from an engine throughout an engine development cycle has been demonstrated. In-situ LII should be seriously considered as an engine certification method, especially since emissions tests on engines producing much lower levels of soot than current engines are likely to become more common.

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