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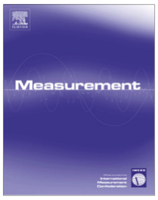

In-situ Laser Induced Incandescence technique for measurement of full stream fast transient soot emissions in real-time

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ABSTRACT

The Laser Induced Incandescence technique (LII) is an emerging optical method for the reliable spatially and temporally resolved measurement of soot concentration and potentially for monitoring primary soot particle size. Due to its origin, this method appears to be suitable for the measurement of fast transient soot emissions from Diesel engines, which form the main fraction of total emissions during standardised test cycles. Current existing commercial LII devices require modifications in the exhaust gas flow, dilution, and measuring with a partial stream in a preconditioned cell. The results from the development of a single window access in-situ LII setup for rapid measurement of soot emission during the combustion process from a Diesel production engine, suitable for direct full stream, measurements in the tail-pipe without the need for dilution or a sampling cell are presented here. Furthermore, the issue of the optical window cleaning, background incandescence due to the laser – tailpipe interaction and possible suppression of disrupted emission by means of time delay constant is addressed. The obtained and corrected in-situ LII results are further compared to commercially available devices for the measurement of soot emissions. Static and dynamic emission tests have been performed in order to demonstrate the viability and applicability of proposed single access optical probe for full stream fast transient soot emission measurement in real-time.

1. Introduction

The Laser Induced Incandescence technique (LII) is an emerging optical method for reliable spatially and temporally resolved measurement of soot concentration and potentially for monitoring primary soot particle size. Due to its origin [1], this method appears to be suitable for the measurement of fast transient emissions from Diesel engines, which form the main fraction of total emissions during standardised test cycles [2]. Current existing commercial LII devices require modifications in the exhaust gas flow, dilution, or measure with a partial stream in a preconditioned sampling cell [3,4].

In this paper, the results from the development of a single access in-situ LII setup for the rapid measurement of soot emission during the combustion process are presented. This setup is suitable for full stream measurements without the need of additional dilution, without the application of a sampling or test cell.

Nowadays many different commercially available devices for soot concentration measurements exist. Most of these devices use techniques based on gravimetric analyses, filter blackening, measurement of continuous opacity, differential mobility spectroscopy [5], photo-acoustic

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Abbreviations

LII	Laser Induced Incandescence
CAN	bus interface message-based protocol for on-board diagnostics
PMT	photomultiplier tube
PM	particulate matter
Euro 5	European emission standard since 2009
ETK ECU	automotive embedded system for real-time measurement
VGT	variable geometry turbocharger
OxiCat	oxidising catalyst
EDC	European Driving Cycles

spectroscopy [6], or more recently a Laser Induced Incandescence (LII) [7]. Usually the measurement devices extract the exhausted gas prior to the measurement and maintain constant measurement conditions. However, extracting the exhaust gas may negatively influence low concentration measurements of soot emission and fast transient particle emission therefore might be lost and not detected [8]. In-situ LII setup is presented for the fast transient particulate matter (PM) emission measurement during combustion processes and it is capable of measuring directly inside the tail-pipe with full stream.

2. Theoretical background

Laser Induced Incandescence occurs when a high power laser radiation is absorbed by soot particles. This causes the particles to heat up, and simultaneously to deliver energy into the surrounding environment by various heat transfer mechanisms, like heat conduction, thermal radiation and vaporisation. When the laser fluence and the energy absorption rate are sufficiently high, the particle temperature will rise up to the levels of vaporisation. At these high temperatures, approximately 4000 K [9], the particles have a significant laser-induced incandescence and emit radiation in an essentially blackbody spectrum. Because of the radiative energy transfer, the particles will cool down, and the incandescence signal will decay with time. This decay time lasts approximately 200–500 ns depending on the size of the primary particles while the excitation time from the laser is corresponding to the laser pulse with duration of about 5–20 ns. From the measured LII signal and by application of energy transfer process models [10], one can obtain the information about the mass fraction and size distribution of the illuminated particles. The excitation of the soot particles by laser is typically performed with pulsed laser systems e.g. Nd:YAG with a pulse duration of 10 ns at fundamental laser wavelength 1064 nm with laser fluence ~0.4 J/cm^2 or with the frequency doubled 532 nm at ~0.2 J/cm^2 [11].

3. Experimental procedure

3.1. Setup of in-situ Laser Induced Incandescence

For the in-situ Laser Induced Incandescence measurements, the high power laser system Nd:YAG laser, lasing at 1064 nm, with 50 Hz repetition frequency has been used. The emerging laser beam was coupled into an optical fibre. This laser system with optical fibre can transfer short ns laser pulses with maximum 200 mJ energy per single pulse. The optical signal from LII has been detected via two fast photomultiplier tubes (PMT) detectors with different spectral sensitivity 400 nm and 800 nm for blackbody radiation. A main advantage of detection at longer wavelengths is in minimising the influence of particle size and temperature variations over the measurement. Using two or more PMT's at two or more different wavelengths during the LII measurement has certain advantages, mainly for the disclosure of laser induced interferences which negatively influence the LII signal, and for two colour methodology for the estimation of the soot temperature and soot concentration from blackbody radiation. Different optical fibres with various core diameters (60–400 μm) and numerical apertures (NA = 0.275–NA = 0.48) have been tested during the development with special attention to capturing the highest optical photon flux. In the presented setup an optical fibre bundle was used, consisting of 100 individual multimode optical fibres for each optical channel. Optical fibre core has been made of pure silica, with numerical aperture NA = 0.48 and diameter of 60 μm. One end of this bundle has been split into two channels with the same number of individual fibres, one for each PMT. The incandescence signal has been sampled with 1 GHz sampling rate and 8 bit resolution via a fast digital oscilloscope. The gain (sensitivity) of the PMT's has been individually controlled and calculated online by a target PC via real-time Linux system. Output signals from PMT's have been digitised and stored in the target PC. An additional PC has been used as the host for controlling the LII device and for monitoring of the target PC. The advantage of a real-time system is in the capability of synchronous acquisition of LII signals, combining control and data acquisition of all relevant devices (temperature, pressure, etc.) via CAN bus interface (message-based protocol for on-board diagnostics) possibly extendable by MatLab Simulink for online evaluation.

A simplified schema of the in-situ LII setup is shown in Fig. 1. Here the cross-section of an exhaust pipe, together with a temperature sensor, and a single access optical probe, are shown. During the measurement an additional sensor for pressure monitoring inside the exhaust pipe has also been used.

3.2. Design and development of the detection part for the in-situ LII

The optical probe design is one of the important parts of the whole in-situ setup. Therefore, it was necessary to