

Characteristics of Nano-Scale Particulates from Gasoline Turbo-Intercooled Direct-Injection Engine

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ABSTRACT

This study aims to identify the factors that control particulate matter (PM) formation and size distribution in direct-injection spark-ignition (DISI) engines. The test engine used for this research was a 1.6 litre, wall-guided DISI, turbocharged, intercooled, in-line 4 cylinder, Euro IV engine. The exhaust sampling point was before the catalytic converter, i.e. engine-out emissions were measured. The first part of this paper investigates the characteristics of PM number and size distribution of DISI and throttle body injected (TBI) engines. The second part investigates the effect of combustion characteristics of DISI engines on the number of 5nm and 10nm (nucleation) and 200nm (accumulation) PM. A statistical analysis of the coefficient of variance (COV) of the maximum rate of pressure rise (RPmax) over 100 cycles was performed against the COV of 5nm, 10nm and 200nm total particle number. The degree of asymmetry of the COV of RPmax around its mean and the relative peakedness or flatness of the distribution were analysed using Skewness and Kurtosis. It was found that the more positive the skewness and more negative the kurtosis of the COV of RPmax, i.e. a distribution with an asymmetric tail extending towards more positive values, higher RPmax, and a relatively flat distribution, lead to the lowest COV of 5nm (nucleation) particulates. For the 200nm (accumulation) particulates, it was found that a relatively flat distribution and

consistent RPmax lead to the lowest COV of particulate number.

INTRODUCTION

DISI engines have improved fuel economy over conventional TBI and port fuel-injection (PFI) engines achieved by a higher thermodynamic efficiency [1]. The higher thermodynamic efficiency is mainly due to the higher volumetric efficiency and compression ratio achieved by charge cooling. Charge cooling is the difference in temperature between the charge mixture before and after the injection of the fuel. As the liquid fuel is injected into the combustion chamber during the intake stroke, it vaporises and absorbs the latent heat from the surroundings, thus, lowering the in-cylinder temperature. This lower charge temperature allows a higher compression ratio to be employed, thus increasing the thermodynamic efficiency.

However, DISI engines are known to emit more PM than TBI and PFI engines [2]. This increase in PM is due to the fact that less time is available for fuel vaporisation and mixture preparation to occur, leading to charge heterogeneity with localised fuel-rich regions in the charge cloud [3]. These localised fuel-rich regions result in a high ratio of carbon to oxygen atoms. The excess carbon atoms combine to form aromatic ring structures that nucleate into particles [4]. The oxidation rate of these locally rich regions is low since the

local concentration of oxygen and other radicals is low and the temperature is low. However, mixing after the combustion process occurs allows many of the particle nuclei to oxidise and form particulate matter [4]. The growth rates in large aromatic structures that lead to soot nucleation are significantly faster than the initial ring formation rates. The rate of incipient, initial stage, soot formation is controlled by the formation of the initial aromatic rings. Therefore the incipient soot particle concentration determines the total amount of soot particles formed [5]. The mean size of PM emissions from DISI engines also tends to be larger than those emitted from TBI and PFI engines [6]. PM size distribution is often bi-modal, with the two main characteristic modes being nucleation mode and accumulation mode. These modes are distinguished by their geometric mean diameter (GMD): nucleation mode generally having a GMD between 5-40nm and accumulation mode between 40-500nm [1].

There are two main types of flame associated with internal combustion engines: premixed and diffusion flames. Premixed flames occur when the fuel and oxidiser are uniformly mixed together before combustion commences. Premixed flames are mostly associated with gasoline spark-ignition engines. Diffusion flames occur when the fuel and oxidiser mix together in the same region where the combustion reaction takes place and must be accompanied by a diffusion process, as occurs in diesel engines [7]. Regardless of flame type, however, the fuel undergoes either pure or oxidative pyrolysis [5]. Pyrolysis is the decomposition or transformation of a compound caused by the addition of heat [5]. Soot precursors are produced via this pyrolysis process and can undergo cyclization to create an aromatic ring. Alkyl groups become attached to the ring structure, forming polycyclic aromatic hydrocarbon (PAH) structures [5, 8]. Coagulation occurs in the post-flame gases causing these PAHs to form soot particles.

Although the physical and chemical mechanisms behind soot formation are exceptionally complex, the common understanding is that soot formation undergoes a four-step sequence: (1) Formation of precursor species, (2) Particle inception, (3) Particle growth and particle agglomeration, and (4) Particle oxidation [8]. The formation of PAHs is thought to be an important intermediate step between the fuel molecule and the primary soot particle [8]. The particle inception stage involves the formation of a small particle of a critical size (3000-10,000 atomic mass units) from both coagulation and growth by chemical means [8]. As the small primary soot particle travels through the flame, it continues to be exposed to the accumulation of species from the pyrolyzing fuel and thus experiences growth and agglomeration [8]. The soot particle will pass through an oxidising region of the flame thus completing the soot formation process [8].

It is known that PM number and size distribution depend heavily on various engine parameters such as injection and ignition timing, operating temperature, speed and load [9, 10]. For DISI engines, with constant ignition timing, PM number and volume increase as the injection timing is retarded, i.e. the fuel is injected later in the compression stroke. As the injection timing is retarded, two things happen with the charge mixture to promote particle formation: (1) Less time is available for fuel vaporisation, and (2) Increased charge stratification results in more localised fuel-rich regions [11]. Previous studies [9] have shown that if the injection timing is maintained constant, advancing the spark timing can lead to an increase in the number of particles formed and can also lead to an increase in the GMD of the particles. Maricq *et al.* [9] suggests that as the spark is advanced, more particle nuclei are formed, possibly due to faster nucleation rates at the higher peak in-cylinder temperatures. Mixture preparation will suffer too as a consequence of spark advance.

Increasing the load requirement on the engine requires the injection of a larger volume of fuel into the combustion chamber. This reduces the charge temperature and will therefore reduce the rate of fuel vaporisation. Increasing the engine speed reduces the time for the fuel droplets to vaporise and mix to form a homogeneous mixture, i.e. higher engine speed results in poor mixture preparation if injection timing is not optimised. When an engine is operated at low load, the rate of combustion is low and thus the total amount of energy released is low. Therefore, at low load the in-cylinder peak pressure will be low and the GMD of the particles will be large due to the longer duration for growth available. At high load and high in-cylinder pressure, the GMD of the particles will be small due to the faster burning rates [6].

In order to supply the enthalpy of vaporisation needed to evaporate the fuel in the intake and compression strokes, heat transfer to the fuel is required [12]. This heat can come from two places: (1) In-cylinder gases and, (2) Combustion chamber surfaces. When the engine is operated under cold start conditions, the contribution to mixture preparation from heat transfer from the combustion chamber surfaces is reduced and thus less fuel vaporises by the time of ignition in comparison to warm operating conditions [12]. Low combustion chamber surface temperature and low cylinder head temperature will result in poor mixture preparation and thus more localised fuel-rich regions in the charge cloud, increasing PM formation [12].

With new emissions regulations on PM for gasoline engines on the horizon (Euro VI, Jan 2014), understanding and controlling the formation of PM in gasoline engines, especially DISI engines due to their increasing popularity, is crucial for automobile manufacturers to meet these regulations. However, detailed mechanism of the formation of particulate matter and the combustion related factors

affecting the size distribution and particle count in DISI engines have not been fully explored to date and limited information is found in the public domain [13, 14, 15]. Therefore, the present work intends to evaluate the particle size distribution as a function of load and also in-cylinder combustion variables that influence the particle size distribution. In addition, the results of direct injected gasoline engine were compared with that of a throttle body injected engine to gain more insight into the effect of load on size distribution.

EXPERIMENTAL APPARATUS

ENGINE

The DISI engine used for this research was a 4-cylinder, 4-stroke, water-cooled, turbocharged and intercooled, Euro IV engine. The TBI engine was a 4-cylinder, 4-stroke, water-cooled, naturally aspirated engine. A list of the complete engine specifications for the DISI and TBI engines are provided in [Tables 1](#) and [2](#) respectively.

Table 1. DISI Test Engine Specifications

Bore (mm)	77.0
Stroke (mm)	85.8
Displacement (cc)	1598
Compression Ratio	10.5:1
Rated Power	132kW @6000rpm
Rated Torque	240Nm @4000rpm

Table 2. TBI Test Engine Specifications

Bore (mm)	75
Stroke (mm)	79
Displacement (cc)	1398
Compression Ratio	9.5:1
Rated Power	69kW @6250rpm
Rated Torque	122Nm @4500rpm

The test bed layout utilised for these experiments can be seen in [Figure 1](#). The AVL Indimeter 621 system with a spark-plug mounted piezoelectric transducer was used for

measuring and analysing cylinder pressure. From this pressure signal, mass fraction burned (MFB), indicated mean effective pressure (IMEP) and duration of combustion (DOC) were estimated. The DOC is calculated from the heat release curve and is the time in milliseconds for 10-90% by mass fraction of the charge cloud to be burned. Below 10% and above 90%, there were large variations in MFB. 10-90% MFB represents a common range for the approximation of DOC.

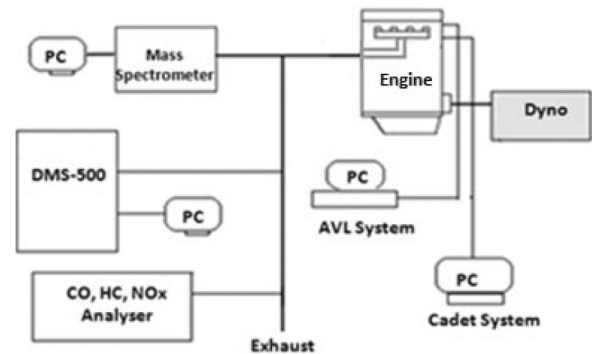


Figure 1. Test Cell Layout

The DISI engine utilises wall guided direct-injection (WGDI) at a maximum pressure of 120bar. WGDI engines introduce the fuel into the combustion chamber via a side mounted fuel injector as shown in [Figure 2](#). The mixture is then guided toward the spark plug by the reverse tumble turbulent motion and the bowl shaped pocket in the piston crown. At this fuel injection pressure the spray velocities are on average an order of magnitude faster than piston velocities and spray penetration distances are of the same order as the stroke [2]. Therefore, some fuel spray may impact upon the piston crown and cylinder walls. Any form of fuel impingement on the walls of the combustion chamber can cause lubricating oil to mix with the bulk gas. This can result in increased PM and hydrocarbon emissions.

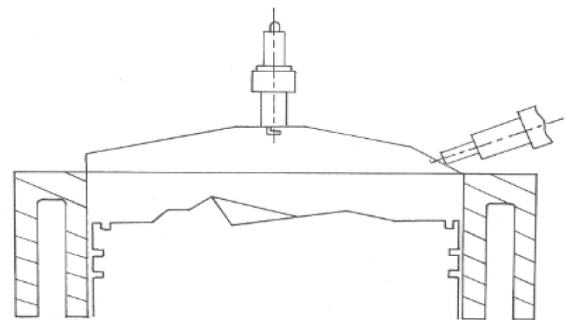


Figure 2. Wall Guided Direct-Injection