

The Effect of Fuel Temperature on Particulate Matter Formation in Gasoline Direct-Injection Engines

2010-01-1469

Published
05/05/2010

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ABSTRACT

This work experimentally investigated the effect of fuel temperature on nano-scale particulate matter (PM) from a Direct-Injection Spark-Ignition (DISI) engine. The first part of the investigation focused on the effect of fuel temperature on combustion characteristics and the second part focused on the engine-out particulate matter. This study found that the injection of chilled fuel into the combustion chamber led to higher in-cylinder pressure, longer duration of combustion (DOC), lower PM number and lower Geometric Mean Diameter (GMD) of the PM than the injection of fuel at ambient temperature.

INTRODUCTION

DISI engines have improved fuel economy over conventional throttle body (TBI) and multipoint port fuel injected (PFI) engines because of their 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 [1].

However, DISI engines have their drawbacks. 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 the vaporisation of the fuel and mixture preparation to occur, leading to charge heterogeneity with localised fuel-rich regions in the charge cloud [3]. These

locally 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 temperature and local concentration of oxygen and other radicals is low. However, mixing after the combustion process allows many of the particle nuclei to oxidise and form particulates [4]. The growth rates in the 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 formation 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].

The two main types of flame associated with internal combustion engines are premixed and diffusion flames. Premixed flames occur when the fuel and oxidiser are uniformly mixed together before combustion starts. Premixed flames are mostly associated with conventional TBI and PFI 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]. It is difficult to know exactly what type of flame is propagating for any particular ignition event in a DISI engine due to the highly turbulent motion inside the combustion chamber. Regardless of flame

type, however, the fuel undergoes either pure or oxidative pyrolysis [5]. This pyrolysis process can produce soot precursors that can undergo cyclization to create an aromatic ring. Alkyl groups are added to the ring structure, forming polycyclic aromatic hydrocarbon (PAH) structures [5, 8]. Under certain flame conditions, the elements forming large aromatic structures will form particle nuclei via dimerisation. Such condensed-phase carbon particles contain large amounts of hydrogen. These newly formed particles dehydrogenate in the high-temperature combustion chamber while physically and chemically absorbing gaseous hydrocarbon (HC) species. This process results in a large increase in soot mass. The absorbed species undergo chemical reformation which results in the carbonaceous soot structure [5].

PM number and size depend heavily on the various engine parameters such as injection and ignition timing, coolant temperature, speed and load [9, 10]. For DISI engines, with constant ignition timing, PM number increases as the injection timing is retarded, i.e. as the fuel is injected later in the compression stroke. Early fuel injection in DISI engines leads to a homogeneous charge mixture resembling that of TBI engines. This is due to the longer time available for mixture preparation and fuel vaporisation. Late fuel injection leads to a stratified charge mixture with localised fuel-rich regions in the combustion chamber. This is due to the reduced time for fuel evaporation and mixture preparation [9].

With constant injection timing, advancing the spark timing can lead to an increase in the number of particles formed and can also lead to an increase in GMD of the particles [9]. Maricq et al [9] suggests that as the spark is advanced, more nuclei are formed, possibly due to faster nucleation rates at the higher peak temperatures [9, 10]. As the spark is advanced, the fuel injected into the combustion chamber has less time to vaporise and mix completely. Thus the charge will be more like a stratified charge than a homogeneous charge.

The engine speed and load exerted on it contribute to the total amount of PM emitted in the exhaust gases. Increasing the load on the engine requires the injection of a larger volume of fuel into the combustion chamber. This reduces intake temperature and, therefore reduces 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. As a result of increasing engine speed and load, the residual fuel aerosol increases leading to higher PM emissions [9]. 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]. If the location of peak pressure (LPP) is close to top dead centre (TDC), the GMD of the particles tends to be small, and if the LPP is away from TDC, the GMD of the particles tends to increase [6].

The effect of coolant temperature on PM emissions is normally attributed to the effect the coolant temperature has on the combustion chamber surface temperature and on the temperature of the injected fuel. When the engine is operated under cold start conditions, the contribution to mixture preparation from heat transfer from the combustion chamber surfaces is low, thus less fuel vaporises by the time of ignition in comparison to warm operating conditions. Therefore low combustion chamber surface temperature and low cylinder head temperature will result in poor mixture preparation, thus there will be more localised fuel-rich regions in the charge cloud. This will result in an increase in PM number emissions [11].

The area of fuel temperature and vaporisation rate has been studied by various researchers. However, these researchers have dealt mainly with elevated fuel temperatures. Regardless of this fact, their findings are quite relevant to this experiment and can provide insight into what could be expected from the low fuel temperature tests.

Kobayashi et al. [12] discovered that under high ambient temperatures, the Sauter Mean Diameter (SMD) of the fuel particles in the spray decreased in relation to normal ambient temperatures. This is mainly due to the increased rate of fuel vaporisation at higher temperatures. Under high ambient temperatures, the spray-tip penetration distances are longer than those under normal conditions and the velocity profiles of the fuel particles are larger than those for normal ambient temperatures [12]. Moon et al [13] studied the effect of injector temperature, i.e. fuel temperature, on spray and combustion characteristics in DISI engines. It was discovered that as the fuel temperature was increased, the spray penetration and width decreased, i.e. the spray collapsed for swirl injectors.

Romunde et al [14] found that the reduction in penetration distance was due to the increased evaporation rate of the fuel at elevated temperatures. Smaller fuel droplets were also found to occur under operation at higher fuel temperatures which correlates to the work carried out by Kobayashi et al [12]. The fact that the rate of fuel atomisation increases with increasing fuel temperature could be a result of the reduced surface tension and viscosity at elevated temperatures. This characteristic could also be due to the rapid film break-up as a consequence of the expansion of the locally formed bubbles and cavitations of the fuel in the injector nozzle [12].

With new emissions regulations on PM for gasoline engines on the horizon (Euro V, Sept '09 and Euro VI, Jan '14),

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 increasingly stringent regulations. The effect of low fuel temperature on PM number emissions from gasoline engines is not well known. If it has a significant influence on engine-out PM number, fuel temperature will become another variable that needs to be set for PM emission measurement in order to ensure repeatability of the measurements. Therefore the main aim of this work is to answer one question; does fuel temperature have any effect on engine-out nano-particle emissions from DISI engine?

This study has two parts; the first part of this paper investigates the effect of low fuel temperature on various combustion characteristics of DISI engines and the second part investigates the effect of low fuel temperature on PM formation in DISI engines.

EXPERIMENTAL APPARATUS

ENGINE

The DISI engine used for this research was a 4-cylinder, four-stroke, water-cooled, turbocharged and intercooled, Euro IV engine. A list of the complete test engine specifications is provided in [Table 1](#).

(See [Table 1](#) after last section of paper)

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.

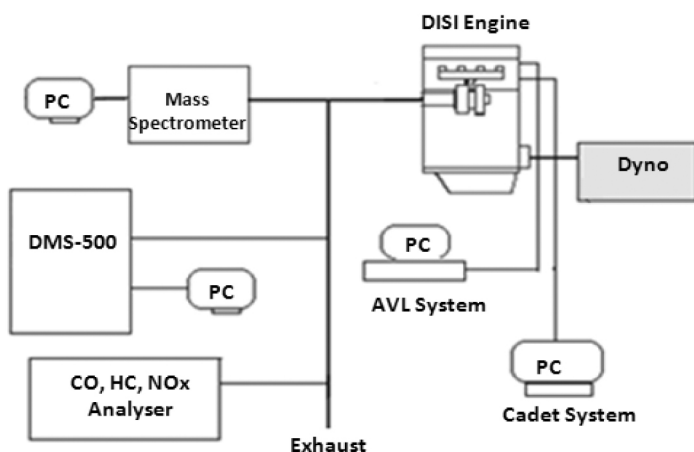


Figure 1. Test Cell Layout

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.

The DISI engine utilises wall guided, stratified charge, direct-injection (WGDI) at a maximum pressure of 120bar. WGDI engines introduce the fuel into the combustion chamber via a side mounted swirl injector. The mixture is then guided toward the spark plug by reverse tumble turbulent motion and a bowl shaped pocket in the piston crown. At this 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, it is inevitable that some of the fuel spray will impact upon the piston crown and cylinder walls. Any form of fuel impingement on the walls of the combustion chamber may cause lubricating oil to mix with the bulk gas. This may result in increased PM and HC emissions.

Most wall wetting occurs when the fuel injection is advanced, i.e. when the piston is near top dead centre on the intake stroke. The degree of fuel evaporation from these surfaces decreases with injection retard. With the optimised flow motion in the combustion chamber of modern DISI engines, the amount of wall wetting may be reduced in relation to the first generation DISI engines.

FUEL CHILLER UNIT

The low fuel temperature tests were conducted in conjunction with a Cornelius Maxi 310 Chiller Unit. This unit is capable of cooling the fuel down to temperatures of around 0-3 degrees C and, if an anti-freeze is utilised as the cooling medium, fuel temperatures as low as -3 degrees C could be obtained. The rig was set up in such a way that ambient fuel temperature and low fuel temperature tests could be completed in the same test session. This was achieved via a T-piece valve situated at the inlet to the chiller unit, [Figure 2](#). This allowed the user to either send the fuel through the coils in the chiller unit and on to the engine or send it straight to the engine.

The unit was placed between the two stages of the fuel pressure pump system of the test engine, i.e. the fuel pressure entering the rig was 5bar and then the chilled fuel was pressurised up to a maximum of 120bar depending on the speed and load of the engine.