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A study of the relationship between NO_x and the ion current in a direct-injection diesel engine

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ABSTRACT

This paper presents a modelling study of the ion current formed in a direct-injection diesel engine via chemical kinetics in order to investigate the strong correlation observed experimentally between tailpipe NO_x and the ion current. An established n-heptane mechanism augmented with ionic and NO_x sub-mechanisms is used to model the formation of ions and NO_x in three combustion systems, including a phenomenological diesel engine model whose validation is also presented here. Sensitivity analyses are conducted on electron and NO_x formation to determine species and reactions common to both. The O radical and, by extension, the mixture temperature are found to be important to both NO_x and electron concentrations via mechanisms identified here.

1. Introduction

Ion currents and ion sensors in engines have been studied extensively for two decades. In the cylinders of SI engines, ion sensors have been proven able to predict quantities such as air-fuel ratio [1–5], peak pressure position [6,7], and in-cylinder pressure [8] using appropriate post-processing techniques. The ion current signal has also been used as an input to the engine control unit to control spark advance timing [4] and to detect and control knock and misfire [9–15].

Ion sensors have also been used in diesel engines, leading to accurate estimations of crank angle at start of combustion [16–19], detection of combustion resonance [20], closed-loop control of injection [21], estimations of soot formation [22] and prediction of engine-out torque [23].

A significant limitation of these studies is the absence of any detail concerning the mechanisms of ion formation and transport. Without studying such phenomena, it is difficult to understand why the ion current may be used for these purposes and what other predictions it may yet prove able to make.

In contrast, the field of chemical kinetics has achieved much in understanding ion formation in recent years. The basic mechanisms responsible for the production of charged species in simple hydrocarbon flames have been discovered and the major charge carriers identified. It is thus surprising that these findings have largely not been incorporated into engine models and used to suggest explanations for the various correlations seen between the ion current and several engine operating parameters of interest.

Some studies [24–27] have used chemical kinetics techniques to study ion formation in engines but have shown no link to other parameters of interest. For example, Liu et al. [28] presented modelled formation rates of important charged species and NO_x in an HCCI engine but, significantly, no important species or mechanisms linking these variables were identified.

This study aims to apply knowledge derived from chemical kinetics research to the phenomenon of ion formation in engines. Presented in this paper is an analysis of the link between the ion current and NO_x formation in diesel combustion using three modelling approaches – combustion in a perfectly stirred reactor, in a pre-mixed laminar flame and in a spray in a diesel engine. The first two models are established codes from CHEMKIN; the diesel engine model is developed specifically for this study. Chemical kinetics techniques are used to determine the species and reactions most strongly affecting both ion and NO_x formation in order to identify the reasons for the correlation observed in experiments.

2. Experiment

Experimental measurements were conducted on a Hino W04D 4 litre 4 cylinder direct-injection diesel engine coupled to a Heenan–Froude eddy current dynamometer. Engine specifications are presented in Table 1. Engine speed and load are measured by a Froude–Hofmann V4 dynamometer controller. The engine is

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Table 1
Engine specifications [30].

Model	Hino W04D
Displacement	4.009 L
Number of cylinders	4
Bore × stroke	118 mm × 104 mm
Compression ratio	17.9
Peak power	65 kW at 2550 RPM
Peak torque	245 Nm at 1600 RPM
Nozzle holes	5 × 0.29 mm
Piston crown	Bowl in piston

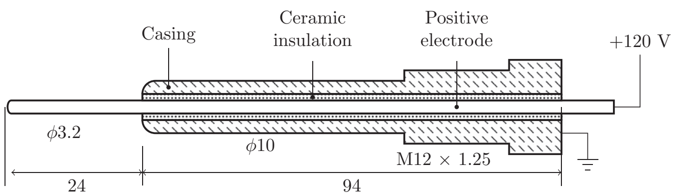

Fig. 1. Schematic of ion sensor.

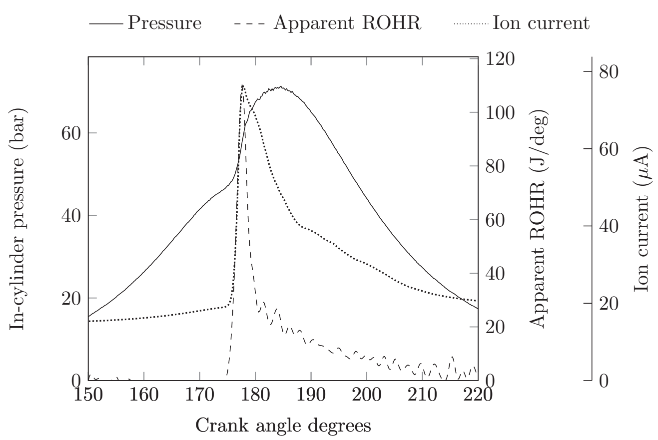

Fig. 2. Experimental in-cylinder pressure, rate of heat release (ROHR) and ion current at 1600 RPM, 140 Nm.

instrumented with two AVL GU12P pressure transducers in cylinders 1 and 4 and an AVL needle lift indicator in cylinder 1. NO_x emissions are measured by a CODA 5-gas exhaust gas analyser to an accuracy of ± 1.32% with a resolution of 1 ppm. Further details on the experimental setup can be found in previous studies on this engine [29,30]. The in-cylinder pressure is presented as the average of 80 consecutive cycles at each engine operating point. The sampling frequency is 0.2 crank angle degrees (CAD).

The ion sensor is inserted into the glow plug port in cylinder 3. Figure 1 shows a schematic of the sensor. The tip of the sensor protrudes approximately 15 mm into the piston bowl. To match the data from the AVL pressure transducers, ion current curves are presented here as an average of 80 consecutive cycles at each engine operating point, at a sampling frequency of 0.2 CAD.

In-cylinder pressure, NO_x emissions and the ion current were measured at several values of engine-out torque at 1600 RPM. Figure 2 shows typical curves for the in-cylinder pressure, rate of heat release and ion current at 1600 RPM, 140 Nm.

There is considerable cycle-to-cycle variation in the ion current signal due to the turbulent nature of flow within the cylinder. When the ion current was ensemble-averaged over 20 or more consecutive engine cycles, good repeatability was able to be achieved. In addition, important parameters of the ion current curve such as the minimum, the maximum and the integral show very good repeatability, with covariance of 0.6% or less. Experimental ion current curves presented in this paper are ensemble-averages of 80 consecutive engine cycles. Values for the maximum, minimum and integral are those for the 80 cycle ensemble averaged ion current curve.

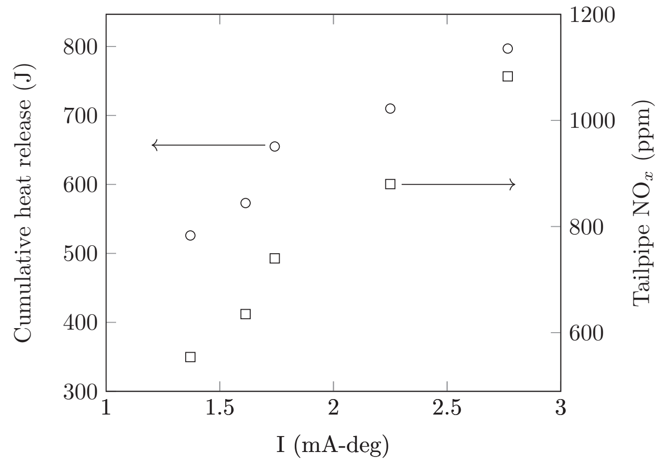

Fig. 3. Variation in experimental cumulative heat release, tailpipe NO_x concentration and I for changing engine load at 1600 RPM.

The ion current can be seen to have a non-zero cycle-minimum value. This has been observed in previous studies [17,19,31] and attributed to the deposition of electrically conductive soot on the surface of the sensor. This phenomenon persisted when the engine was switched off and the cylinder flushed. When the ion sensor was removed, a black deposit was observed on the ceramic insulation between the casing and the centre electrode. When cleaned of this deposit, the sensor output decreased to zero. The non-zero cycle minimum value is then not related to ions produced during combustion but is caused by soot deposition. The electrical resistance of this deposit decreases slightly with temperature; therefore a small portion of the ion current signal lying above the cycle-minimum value at TDC is caused by soot deposition.

The area under the ion current curve lying above its cycle-minimum value, I, is highly correlated with both cumulative heat release and tailpipe NO_x ($r^2 = 0.96$ and 0.99 respectively), as seen in Fig. 3. Although not shown here, there is also a strong correlation with peak rate of heat release ($r^2 = 0.96$).

Whilst these correlations can evidently be used to provide fairly accurate predictions of NO_x and heat release, there is currently a lack of understanding of the reasons why the ion current can be used in this manner.

3. Diesel engine model

A phenomenological diesel engine model is developed and validated here for use in the investigation of the relationship between the ion current and NO_x . This style of modelling is chosen over CFD modelling for reasons of computational cost and speed of processing.

To model the spray and its deceleration after injection, Hiroyasu's relations [32] are used with the modifications made by Jung and Assanis [33] to account for discharge coefficients of modern injector nozzles. Air entrainment is calculated via conservation of momentum. The geometry of the piston bowl (Fig. 4) greatly increases the likelihood of spray-spray interaction once the sprays have entered the bowl, which decreases air entrainment. Therefore, an entrainment factor of 1.9 is used before impingement on the bowl surface and 1.0 after. The Woschni model [34] is used to calculate heat loss to the cylinder walls.