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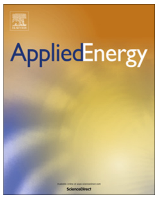

The competing chemical and physical effects of transient fuel enrichment on heavy knock in an optical spark ignition engine

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HIGHLIGHTS

- The optical engine design allowed unusually high knock intensities.
- The full bore optical access provided additional insight into violent auto-ignition.
- Under heavy knock, a small-to-moderate additional mass of fuel would exacerbate knock.
- As the excess fuel was further increased the effects of charge cooling dominated.
- The results highlight the dangers in using excess fuel for heavy knock control.

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ABSTRACT

The work was concerned with improving understanding of the chemical and physical trade-offs when employing transient over-fuelling to control auto-ignition in gasoline spark ignition engines under knock intensities not usually tolerated in optical engines. The single cylinder engine used included full bore overhead optical access capable of withstanding unusually high in-cylinder pressures. Heavy knock was deliberately induced by adopting inlet air heating and a primary reference fuel blend of reduced octane rating. High-speed chemiluminescence imaging and simultaneous in-cylinder pressure data measurement were used to evaluate the combustion events. Under normal operation the engine was operated under port fuel injection with a stoichiometric air-fuel mixture. Multiple centred auto-ignition events were regularly observed, with knock intensities of up to ~30 bar. Additional excess fuel was then introduced directly into the end-gas in short transient bursts. As the mass of excess fuel was progressively increased a trade-off was apparent, with knock intensity first increasing by up to 65% before lower unburned gas temperatures suppressed knock under extremely rich conditions. This trade-off is not usually observed during conventional low intensity knock suppression via over-fuelling and has been associated with the competing effects of reducing auto-ignition delay time and charge cooling/ratio of specific heats. Overall, the results demonstrate the risks in employing excess fuel to suppress knock deep within a heavy knocking combustion regime (potentially including a Super-Knock regime).

1. Introduction

Over the last few decades European automotive manufacturers have met fuel economy targets mainly through increased diesel sales. However, the efficient distillation of crude oil produces similar amounts of gasoline and diesel fuel and European passenger diesel sales have now approached saturated levels [1]. The recent "dieselgate" scandal surrounding diesel engine emissions has also tarnished the reputation of diesel engines for automotive applications. Overall, in the short-to-medium term it is necessary to improve the fuel consumption of the "cleaner" gasoline engine and in the longer term source sustainable alternatives to crude oil. Substitutes such as electric and hydrogen fuel cell vehicles, hybrid vehicles and biofuels are among the alternatives being investigated. However, significant challenges remain with respect to the sustainability of such technologies to meet global demand. For electric vehicles, relatively low energy and power densities and high production cost remain key barriers [2]. For biofuels, advanced fuel production techniques are still required to produce fuels in a near carbon-neutral manner with improved energy security and less reliance on feedstock [3–5].

One method for improving gasoline engine efficiency is engine downsizing, which is currently being widely adopted by

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Acronyms	
aTDC:	after Top Dead Centre
AFR:	Air-to-Fuel Ratio
bTDC:	before Top Dead Centre
BMEP:	Brake Mean Effective Pressure
BSFC:	Brake Specific Fuel Consumption
CA:	Crank Angle
CCV:	Cycle-by-Cycle Variation
COV:	Coefficient of Variation
DI:	Direct Injection
EU:	European Union
ID:	Injection Duration
IDS:	Injection Duration Sweep
IMEP:	Net Indicated Mean Effective Pressure
MFB:	Mass Fraction Burned
NEDC:	New European Drive Cycle
PFI:	Port Fuel Injection
RON:	Research Octane Number
SOI:	Start of Injection
SOIS:	Start of Injection Sweep
SI:	Spark Ignition
TDC:	Top Dead Centre
VVT:	Variable Valve Timing
WOT:	Wide Open Throttle
λ:	Relative air-to-fuel ratio

automotive manufacturers. The basic principle is to reduce the capacity of the engine and hence enforce a larger proportion of operation to higher loads. As a result, under wider open throttle conditions the pumping losses are reduced for a given road-load requirement. In order to maintain adequate vehicle acceleration and top speed, the smaller engine must be pressure-charged and still produce acceptable transient response. Overall, for a large family-sized saloon car, it has been demonstrated that halving total engine capacity from a V6 2.4 L to a three-cylinder 1.2 L unit can reduce fuel consumption by ~25%, with vehicle performance maintained [6].

Such downsizing clearly yields significant part-load fuel consumption benefits, but significant challenges remain including problematic combustion. Downsizing (and "downspeeding" via longer gearing) enforces a considerable proportion of "real world" operation to the low speed/high load regime. Under such conditions the increased energy density of a highly pressure charged mixture leads to an increased tendency for the fuel and air to auto-ignite. The problem of auto-ignition is almost as old as the internal combustion engine itself [7] and still ultimately caps peak thermal efficiency in modern SI engines [8–10], being commonly avoided by selecting a lower compression ratio, retarding the spark timing and/or introducing excess fuel. Such auto-ignition has been established to be the result of exothermic centres, or "hot spots", leading to auto-ignition of the unburned charge ahead of the developing flame [11–13]; so-called end-gas auto-ignition. However, recent aggressively downsized research engines of very high specific output have additionally experienced pre-ignition combustion at low engine speeds and high loads (>15 bar BMEP). Previously pre-ignition was most commonly associated with higher engine speeds, when the components within the combustion chamber are typically at their hottest. Hence such pre-ignition was at first unexpected, arising below the auto-ignition temperature of the charge and occurring in a highly sporadic manner in short violent bursts in an "on-off" pattern, with sometimes tens of thousands of cycles in-between events [14].

This phenomenon, widely referred to as Low Speed Pre-Ignition (LSPI) and "Super-Knock", has been associated with low-to-moderate thermal gradients within the unburned charge leading to developing detonation events. Ultimately, this may produce multiple high frequency and intensity pressure waves within the cylinder that may interact and ultimately destroy the engine. The time to trigger the auto-ignition chemistry of a given mixture under known physical conditions provides a useful relative measure of the expected onset and intensity of such events. This auto-ignition delay period cannot be accurately measured directly in real engines due to the complex nature of the combustion process. The delay period is therefore typically estimated using simplified chemical kinetic schemes [15–18] and/or empirical measurements obtained in idealised rapid compression machines or combustion chambers [19–22].

Researchers at Shell and the University of Leeds [23] have recently postulated that such Super-Knock events originate from a resonance between acoustic waves emitted by an auto-igniting hot spot and a reaction wave that propagates along negative temperature gradients in the fuel-air charge. The theory is based upon the assumption that the temperature gradient extends smoothly over sufficient length across the turbulent flow field. Subsequently, localised detonations may develop which are then able to violently ignite the remaining unburned charge in timescales of less than a millisecond. Ultimately, this can lead to catastrophic mechanical engine failure. Peters and co-workers [24,25] extended this theory developed at Leeds/Shell to at least partially attribute the random nature of the events to the stochastic nature of the in-cylinder turbulence. However, some uncertainty still remains around the triggering of these events. The pre-ignition typically occurs well below the auto-ignition temperature of the bulk charge, considered to be indicative of a deflagration caused by an exothermic centre with the high temperature gradient across it [14,26]. It has also been suggested that the auto-ignition might be caused by a localised volume of charge with particularly low auto-ignition temperature, such as an evaporating droplet of lubricant (or mixtures of fuel and oil due to wall impingement of a directly injected fuel spray). Such droplets, of relatively low octane number (and high cetane number), have been suggested to cause the formation of the deflagration site(s) leading to pre-ignition and Super-Knock. To this end Dahnz et al. [14] produced a simple pre-ignition model to qualify the effects of a low-octane droplet within the main (high-octane) charge. It was found that a region existed where, given sufficient droplet temperature, ignition could be initiated below the bulk auto-ignition temperature of the main charge. When developing their theory Kalghatgi and Bradley [23] used pressure data from real engine Super-Knock cycles to show that gas-phase pre-ignition of an evaporating lubricant droplet could be possible, assuming that the lubricant droplet was substantially more reactive than *n*-heptane. In recent work by SouthWest Research Institute many lubricants were found to meet this condition [27].

With the complex nature of cyclic variations in SI engines influenced by varying turbulence, charge homogeneity, wall temperatures, deposit conditions, fuel and oil properties [13,14,25,27,28] it is quite probable that the stochastic pre-ignition event is caused by a combination of phenomena. However the theory of an increased likelihood of auto-ignition occurring due to suspended oil droplets has widely gained credibility. Amann et al. [27] found that, during a sequence of Super-Knock events in a multi-cylinder engine, the air-fuel ratio was significantly reduced compared to the calibrated air-fuel ratio. When extremely high intensity knocking combustion was artificially induced by intermittently advancing the spark timing, the same trend in air-fuel ratio was not observed. This observation was therefore attributed to the accumulation of lubricant during normal engine running and its subsequent release from the piston top-land crevice during Super-Knock events. In other recent work by some of the current authors [29], oil was deliberately directly injected into the charge of a full bore optical