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Exhaust gas recirculation – Zero dimensional modelling and characterization for transient diesel combustion control

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ABSTRACT

The application of exhaust gas recirculation (EGR) during transient engine operation is a challenging task since small fluctuations in EGR may cause larger than acceptable spikes in NOx/soot emissions or deterioration in the combustion efficiency. Moreover, the intake charge dilution at any EGR ratio is a function of engine load and intake pressure, and typically changes during transient events. Therefore, the management of EGR during transient engine operation or advanced combustion cycles (that are inherently less stable) requires a fundamental understanding of the transient EGR behaviour and its impact on the intake charge development.

In this work, a zero-dimensional EGR model is described to estimate the transient (cycle-by-cycle) progression of EGR and the time (engine cycles) required for its stabilization. The model response is tuned to a multi-cylinder engine by using an overall engine system time-constant and shown to effectively track the transient EGR changes. The impact of EGR on the actual air–fuel ratio of the cylinder charge is quantified by defining an in-cylinder excess-air ratio that accounts for the oxygen in the recycled exhaust gas. Furthermore, a twin lambda sensor (TLS) technique is implemented for tracking the intake dilution and in-cylinder excess-air ratio in real-time. The modelling and analysis results are validated against a wide range of engine operations, including transient and steady-state low temperature combustion tests.

1. Introduction

Exhaust gas recirculation (EGR) is the principal in-cylinder combustion modification technique used in modern diesel engines for reducing NOx emissions [1–3], though it usually results in higher particulate matter (PM) emissions [4–6]. To overcome the NOx-PM trade-off, physical improvements in the air and fuel systems (multi-stage turbocharging, multiple injections per combustion cycle, variable valve timing, etc.) as well as alternate combustion regimes that reduce the combustion temperatures and improve the homogeneity of the fuel–air mixture, are being actively pursued [7–10]. The reduced temperatures inhibit the NOx production while the enhanced mixing reduces the propensity for soot formation by avoiding localized stoichiometric/rich burning, so that ultra-low levels of NOx and PM can be concurrently achieved.

The common strategies for achieving low temperature combustion (LTC) include homogenous charge compression ignition (HCCI) [11–13], single-injection LTC (also called smokeless rich combustion or modulated kinetics combustion) [6,14,15], and reactivity controlled compression ignition (RCCI) [13,16–18] as shown in Fig. 1. The fundamental difference between the conventional diesel high temperature combustion (HTC) and the LTC strategies is the degree of separation between the fuel injection events and the commencement of bulk combustion; that is, the ignition delay duration. Among the various techniques such as injection timing retard, intake charge dilution, higher intake boost, and multiple injections per cycle, intake charge dilution achieved through aggressive application of EGR is a key enabler for realizing a sufficiently long time delay for the fuel and intake charge to attain a high degree of homogeneity before auto-ignition occurs.

While all these alternate modes of combustion target the minimization of NOx and soot production, they are uniquely different in terms of the operability limits and combustion characteristics, with significantly wide-ranging EGR requirements [13,17,19]. The cylinder pressure history and its analysis provide a valuable insight into the characteristics of these different combustion modes as shown in Fig. 2.

HCCI combustion is characterized by earlier than top-dead-centre (pre-TDC) phasing, very high pressure rise rates, short combustion durations, and minimal control over the timing of the combustion event. To offset the high reactivity of the diesel

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Nomenclature

abs	absolute
AFR	air/fuel ratio
ATDC	after top dead centre
BMEP	brake mean effective pressure (bar)
CA50	crank angle of 50% heat release
CDI	charge dilution index
DI	direct injection
$dp/d\theta$	rate of pressure rise (bar)
EGR	exhaust gas recirculation
HCCI	homogenous charge compression ignition
HPL	high pressure loop
HTC	high temperature combustion
IMEP	indicated mean effective pressure (bar)
I_P	pump cell current
k	engine cycle number
LNT	lean NOx trap
LPL	low pressure loop
LTC	low temperature combustion
m	mass (kg)
M	moles
MAF	mass air flow
MW	molecular weight (kg/kmol)
NOx	oxides of nitrogen
p	pressure (Pa, bar, MPa)
PM	particulate matter
ppm	parts per million
R	EGR ratio including the residual fraction
r	mass-based EGR ratio
RCCI	reactivity controlled compression ignition
rpm	revolution per minute
SCR	selective catalytic reduction
T	temperature
TDC	top dead centre
THC	total hydrocarbons
TLS	twin lambda sensor
WBL	wideband lambda

Greek Symbols

θ	crank angle
λ	excess-air ratio
η	efficiency
χ	excess-oxygen ratio

Subscripts

α	number of carbon atoms in fuel
β	number of hydrogen atoms in fuel
γ	number of oxygen atoms in fuel
a	in-cylinder
act	actual
abs	absolute
air	fresh air
cyc	cycle
cyl	cylinder
egr	exhaust gas recirculation
exh	exhaust
f	fuel
i	index for the gas species (O_2, N_2, CO_2, H_2O)
inj	injection
int	intake
max	maximum
o	without EGR
res	residual
vol	volumetric

fuel, large amounts of EGR (30–60%) are usually applied to postpone the initiation of combustion, shift the combustion towards TDC and alleviate to some extent, the high pressure rise rates and the reduced energy efficiency. However, the load range of diesel HCCI combustion is severely limited by the physical constraints of the engine [11–13].

The single-injection LTC, on the other hand, primarily relies on large amounts of EGR (typically 50–70%) to withhold the air–fuel mixture from combustion and to provide ample time for improving the charge mixing process [6]. The highly-diluted cylinder charge (8–12% intake oxygen) makes the combustion sensitive to small changes in EGR – a slight increase in EGR (1–2%) can rapidly deteriorate the combustion stability, often resulting in mis–fire; conversely, a sharp increase in the soot emissions can occur for a small drop in the EGR rate. The single-injection LTC, thus materializes close to the limiting conditions, requiring a tighter control on the operating conditions compared to the conventional diesel HTC. The load level of the single-injection LTC is limited to low loads/ low engine speeds [17] because the ability to separate the fuel injection from the combustion event diminishes rapidly at higher speeds and increased fuelling rates.

The limitations of the HCCI and single-injection LTC modes can be overcome with dual-fuel RCCI combustion in which the reactivity of the cylinder charge is modified by using a highly reactive fuel (typically diesel) to ignite the bulk low reactivity fuel (typically gasoline, ethanol or methanol as the main source of power

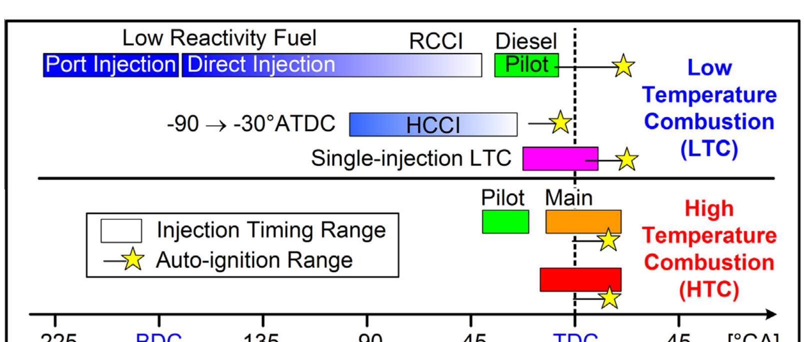

Fig. 1. Advanced combustion modes for diesel engines [16,17].