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Exhaust gas recirculation for advanced diesel combustion cycles

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HIGHLIGHTS

- Analysis of the incremental (cycle-by-cycle) build-up of EGR.
- Proposed one-step equations for transient/steady-state gas concentration estimation.
- Defined an in-cylinder excess-air ratio to account for the recycled oxygen with EGR.
- Demonstrated the use of intake oxygen as a reliable measure of EGR effectiveness.
- Demonstrated the impact of engine load and intake pressure on EGR effectiveness.

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ABSTRACT

Modern diesel engines tend to utilize significantly large quantities of exhaust gas recirculation (EGR) and high intake pressures across the engine load range to meet NOx targets. At such high EGR rates, the combustion process and exhaust emissions tend to exhibit a marked sensitivity to small changes in the EGR quantity, resulting in unintended deviations from the desired engine performance characteristics (energy efficiency, emissions, stability). An accurate estimation of EGR and its effect on the intake dilution are, therefore, necessary to enable its application during transient engine operation or unstable combustion regimes. In this research, a detailed analysis that includes estimation of the transient (cycle-by-cycle) build-up of EGR and the time (engine cycles) required to reach the steady-state EGR operation has been carried out. One-step global equations to calculate the transient and steady-state gas concentrations in the intake and exhaust are proposed. The effects of engine load and intake pressure on EGR have been examined and explained in terms of intake charge dilution and in-cylinder excess-air ratio. The EGR analysis is validated against a wide range of empirical data that include low temperature combustion cycles, intake pressure and load sweeps. This research intends to not only formulate a clear understanding of EGR application for advanced diesel combustion but also to set forth guidelines for transient analysis of EGR.

1. Introduction

The recycling of some of the exhaust back into the engine intake system, commonly known as exhaust gas recirculation (EGR) has become almost essential for achieving significant NOx reductions to meet the current and future diesel emission regulations [1–5]. EGR is also an important enabler for alternate combustion strategies such as low temperature combustion (LTC), homogeneous charge compression ignition (HCCI) and premixed charge compression ignition (PCCI) that result in simultaneous low emissions of NOx and soot, using EGR levels commonly up to 50–70% at low engine loads [6–12]. EGR alters the diesel combustion process because of three broadly defined effects [3,5,8,13,14]. The recycled inert gases, predominantly carbon dioxide (CO_2) and water vapor (H_2O), increase the specific heat capacity of the intake charge (thermal effect), thereby lowering the temperatures during the compression and combustion processes. The replacement of intake oxygen with the inert gases dilutes the intake charge (dilution effect), results in a reduced excess-air ratio (λ), increases the ignition delay and slows down the fuel burning rate due to the deceleration of the mixing between oxygen (O_2) and fuel [3,15]. Furthermore, the dilution effect contributes to the reduction of the oxygen partial pressure and thus affects the kinetics of the elementary NO formation reactions. The recycled gases also introduce free radicals such as O, H and OH in the cylinder charge, formed by the dissociation of CO_2 and H_2O (chemical effect) that are believed to affect the combustion process and NOx formation. In particular, a reduction in the flame temperature is caused by the endothermic dissociation of H_2O [3,13,15].

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Nomenclature

abs	absolute
AFR	air/fuel ratio
ATDC	after top dead center
BMEP	brake mean effective pressure (bar)
CA50	crank angle of 50% heat release
$dp/d\theta$	rate of pressure rise (bar)
EGR	exhaust gas recirculation
HCCI	homogenous charge compression ignition
IMEP	indicated mean effective pressure (bar)
IVC	intake valve closing
LTC	low temperature combustion
m	mass (kg)
MAF	mass air flow
n	engine cycle number; number of moles
NOx	oxides of nitrogen
p	pressure (Pa, bar, MPa)
PCCI	premixed charge compression ignition
ppm	parts per million
R	EGR ratio including the residual fraction
r	mass-based EGR ratio
rpm	revolution per minute
t	time duration (ms)
THC	total hydrocarbons

Greek Symbols

θ	crank angle
λ	excess-air ratio
τ	time constant (ms)

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
amb	ambient
exh	exhaust
f	fuel
int	intake
max	maximum
o	without EGR
res	residual

There has been extensive research, both theoretical and empirical, for establishing the fundamental impacts of EGR on the diesel combustion and emissions [3,8,9,15–21]. Abd-Alla [4] reviewed the effects of EGR on diesel combustion including the combustion burn rate, specific fuel consumption, in-cylinder heat transfer and NOx emissions. Zheng et al. [2] outlined the requirements and limitations for the physical implementation of EGR on diesel engines using high-pressure loop and low-pressure loop systems. They also proposed treatment of the EGR stream (cooling, oxidation, fuel reforming) to deal with the combustion instabilities as a result of EGR application and also highlighted the need for real-time EGR feedback for enabling transient EGR operation. Zhao et al. [8] developed an engine simulation model with detailed chemical kinetics to analyze the effects of the recycled gases on HCCI combustion. Aithal [13] reported the development of a 0-D modeling tool to quantify the impact of EGR on diesel combustion parameters under steady-state conditions. It is pertinent to mention here that these models are limited to studying the impacts of EGR under steady-state engine operation.

The lean nature of diesel combustion, together with advancements in turbo-charging, peak cylinder pressure limit and the fuel injection pressure systems have allowed for aggressive use of EGR, especially to enable LTC cycles. The current trend is to employ significantly large amounts of EGR in conjunction with high intake boost pressures across the engine load range to reduce the NOx emissions while minimizing the soot penalty [22,23]. The use of higher intake pressure changes the fuel-strength of the cylinder charge and in turn has a significant effect on the quality and effectiveness of EGR. Additionally, the heavy use of EGR generally makes the combustion sensitive to small fluctuations in the EGR flow rate that may result in the engine-out emissions or the efficiency to deviate from the desired values [24].

At present, the application of alternate combustion modes on production diesel engines is hindered because these combustion modes have a limited load range with significantly wide-ranging EGR requirements [25–27]. To utilize these modes, some sort of a mode-switching mechanism needs to be devised that is able to adapt the air, EGR and the fuel systems within a few engine cycles to the new mode [28–30]. A major impediment to such an implementation is the lack of a robust feedback on the amount of recycled gases that would be necessary for managing EGR during the transition. The disparity between the response time of the air-path system (turbocharger inertia, air-path volume) and the combustion system (fuel injection) further complicates this task. Because of the lack of any real-time EGR feedback, the current trend in production vehicles is to shut off EGR during transients (tip-in or tip-out) and to use static look-up tables (calibrated during the development stage), with a few model-based corrections for commanding the EGR valve opening during steady-state operation. Nonetheless, there is a clear need to track the EGR quantity and the resulting intake charge dilution during transient load and intake pressure changes so as to enable the use of EGR under the advanced clean combustion regimes [31].

The difficulties in the implementation of these advanced combustion modes have resulted in exhaust aftertreatment devices such as selective catalytic reduction (SCR) to be widely used to meet the legislative NOx requirements. It should be noted that even with the SCR-urea approach, the raw engine-out NOx has to be reduced to 100–200 ppm for efficient operation of these devices and to meet the NOx targets set by the applicable emission standards. This is primarily achieved by using moderate to large amounts of EGR, usually with very little associated efficiency penalty.

Based on the reviewed literature and the authors' own work [7,24,26–28,31], the following aspects need to be analyzed and addressed to enable the transient estimation of EGR:

- Re-examining the application of EGR as a global one-step process – the first step is the complete combustion of any fuel in a cylinder charge comprised of fresh air and is expressed as

$$\begin{aligned} C_\alpha H_\beta O_\gamma + \lambda_o\left(\alpha+\frac{\beta}{4}-\frac{\gamma}{2}\right)(O_2+3.76N_2) \\ \rightarrow \alpha CO_2 + \frac{\beta}{2}H_2O + \lambda_o\left(\alpha+\frac{\beta}{4}-\frac{\gamma}{2}\right)3.76N_2 \\ +(\lambda_o-1)\left(\alpha+\frac{\beta}{4}-\frac{\gamma}{2}\right)O_2 \end{aligned} \quad (1)$$