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Characterization of Exhaust Gas Recirculation for Diesel Low Temperature Combustion

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Abstract: Exhaust Gas Recirculation (EGR) is common on most modern diesel engines resulting in significant reduction of NOx emissions. Heavy EGR application is an enabling technique for the advanced combustion modes operating in the low temperature combustion (LTC) regime, wherein simultaneous NOx and soot emission reduction can be attained. The primary effect of EGR is the dilution of the intake charge following the displacement of fresh air by the combustion products. However, the correlation between EGR and its effectiveness is non-linear due to the lean burn nature of boosted diesel engines. This correlation is further complicated when oxygenated fuels are used for combustion in the LTC mode. In this work, the intake oxygen concentration $[O_2]_{int}$ is selected as a representative of EGR and its effectiveness in emission abatement is shown using an array of experimental results. An EGR characterization model is developed to quantify the dynamic interaction between $[O_2]_{int}$ and engine operating variables, namely the intake boost, exhaust gas recirculation (EGR) amount, the fueling quantity and the fuel type. The model is validated on the research engine platform in steady state and transient tests. Finally, the control of EGR effectiveness is experimentally demonstrated to achieve ultra-low NOx emissions at different engine operating points.

Keywords: Diesel engines, NOx emissions, Exhaust gas recirculation control, Low temperature combustion.

1. INTRODUCTION

Exhaust Gas Recirculation (EGR) is implemented in modern engines by routing a portion of the exhaust gases into the intake manifold. The dilution of the intake charge by the combustion products has proven extremely effective in the abatement of nitrogen oxide (NO_x) emissions from the diesel engine. The main causes of NO_x emission reduction by EGR are well explained by Mitchell et al. (1993), Ropke et al. (1995), Ladommatos et al. (2000), Zheng et al. (2004) and Maiboom et al. (2008). They are summarized here for completeness. Dilution of the fresh intake charge is the primary effect of EGR where the oxygen in fresh air is displaced by combustion products (CO_2 and H_2O). These combustion products are relatively inert and tend to suppress the combustion rate. Furthermore, CO_2 and H_2O have higher heat capacity which help suppress the in-cylinder temperature following compression and combustion. Portion of the lower temperature rise during combustion can also be attributed to the endothermic dissociation of the CO_2 and H_2O.

The typical external EGR system layout in modern diesel engines is illustrated in Fig. 1. Most production diesel engines implement only the high pressure EGR loop where low to moderate EGR levels (10 to 30%) are common. Higher levels of EGR (up to 60%) have shown to assist in the enabling of Low Temperature Combustion (LTC) wherein simultaneous reduction of NO_x and soot emissions is attained (Kimura et al (2002); Ogawa et al (2006); Asad et al. (2013)). Sufficiently large EGR dilution extends the ignition delay period, resulting in the combustion of an overall lean and diluted premixed fuel-air charge. Recent studies have also suggested that the use of alcohol fuels (such as ethanol) in diesel engines can extend the LTC operating range, while EGR remains necessary for NOx abatement(Reitz et al. (2014); Asad et al. (2015)). Due to the benefits of EGR and the increasing complexity of control implementation, characterization of the EGR amount and its effectiveness is deemed necessary. This however, is a challenge as a result of the left-over oxygen in the exhaust of lean burn boosted diesel engines.

Substantial efforts have been carried out towards modeling of the diesel air-path and EGR. In a classical paper, Guzzella et al. (1998) highlighted the control challenges in modern turbocharged diesel engines and motivated the research and development of model based control of diesel EGR and boost. Kolmanovsky (1998) developed a physical model for the engine air-path and evaluated the performance of MIMO system with EGR and VGT actuator positions as system inputs and the compressor-out flow rate and intake manifold pressure as the system outputs. The objectives of the air-path control, constrained by emissions, were highlighted in this work. Christen (2001) compared the event-based and continuous-time models for EGR and turbocharger dynamics and recommended the use of event based models for coordinated EGR-VGT control. Nakayama (2003) experimentally demonstrated a more effective emission control approach by governing the observed oxygen concentration of the intake charge to a pre-defined value associated with the target NOx emissions at different operating conditions. In a more recent study, Wang (2007) developed

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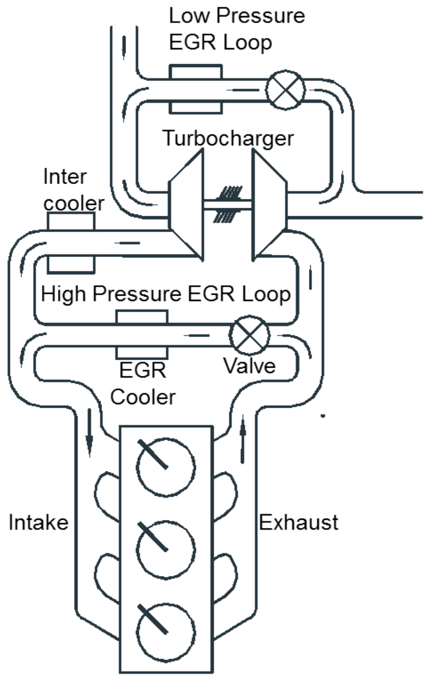

Fig. 1. Typical EGR layout of modern Diesel engines

an air fraction model for the diesel engine intake manifold and implemented the model for sliding mode control of air-fuel ratio in a diesel engine. In Wang (2008) the authors extended the modeling approach to include a dual-loop EGR system and developed a air-fraction observer for the intake and exhaust manifolds. Kocher (2014) developed a linear parameter varying model of the cylinder oxygen fraction for a diesel engine equipped with a variable valve actuation system. They demonstrated the insensitivity of the oxygen estimator to turbocharger flow uncertainty in an advanced diesel combustion mode. Most EGR models including the ones summarized herein implement the manifold dynamics principles for flow estimations across the air-path including the turbo-charger components. The estimation of the mass flow then leads to the computation of air fraction or charge oxygen concentration affected by the EGR application.

In the authors experience, a more fundamental study of EGR and its effectiveness in NOx emission control in diesel engines can lead to a further simplified modeling approach (Asad et al. (2014)). This requires a study of EGR interaction with other engine operating parameters such as the load level, intake boost, the fueling strategy, and the fuel type. In this work, the authors have developed an EGR effectiveness model that is initially applied to steady state conditions and then extended for application to transients. The use of available sensor measurements is made to avoid modeling of the gas flow phenomena. The remainder of the paper is organized as follows; the EGR effectiveness model with the derivations of the relevant expressions is explained in the next section. The result discussion is divided into four sub-sections. The first two sub-sections highlight the EGR relationship with engine load and intake boost. The third sub-section demonstrates the experimental implementation of EGR effectiveness control for NOx emission reduction. Finally, some comments on future work in EGR control are presented followed by the conclusions.

2. NOMENCLATURE

EGR,	Exhaust gas recirculation
LTC,	Low temperature combustion
$[O_2]_{int}$,	Oxygen concentration at the intake manifold
$[O_2]_{exh}$,	Oxygen concentration at the exhaust manifold
$[O_2]_{fr}$,	Fresh air oxygen concentration
VGT,	Variable-geometry turbocharger
$MIMO$,	Multiple-input and multiple-output
R,	Molar EGR ratio
EGR_{mass},	Mass flow rate based EGR definition
$m_{\dot{E}GR}$,	EGR flow rate
$\dot{m}_{in}$,	In-cylinder mass flow rate
$\dot{m}_{fr}$,	Fresh air mass flow rate
$[CO_2]_{int}$,	Intake CO_2 concentration
$[CO_2]_{exh}$,	Exhaust CO_2 concentration
EGR_{CO_2},	CO_2 based EGR definition
r,	Total moles of exhaust gas recirculated
n_i,	Number of moles of i of the intake charge
e_i,	Number of moles of i of the combustion products
M_y,	Molecular masses of the intake charge
M_f,	Molecular masses of fuel
y,	Intake molar gas quantity
x,	Exhaust molar gas quantity
z,	Reminder of the intake charge
n_f,	Fuel molar quantity
η_V,	Cylinder volumetric efficiency
$\bar{R}$,	Universal gas constant
T_{im},	Intake manifold temperature
p_{im},	Intake manifold pressure
V_s,	Swept volume
λ,	Air-excess ratio
λ_{cyl},	In-cylinder air-excess ratio
n_{em},	Gas molar quantity at the exhaust manifold
p_{em},	Pressure at the exhaust manifold
V_{em},	Volume of the exhaust manifold
T_{em},	Temperature at the exhaust manifold

3. EGR CHARACTERIZATION

3.1 Definitions

In theory and in most engine air-path models (Zheng et al. (2004)) EGR is quantified as the mass flow rate across the EGR valve relative to the total mass flow rate into the combustion chamber.

$$EGR_{mass} = \frac{\dot{m}_{EGR}}{\dot{m}_{in}} \tag{1}$$

where, $\dot{m}_{EGR}$ is the EGR flow rate and $\dot{m}_{in} = \dot{m}_{EGR} + \dot{m}_{fr}$ is the in-cylinder mass flow rate. While the fresh air mass flow rate ($\dot{m}_{fr}$) is typically measured using a mass air flow (MAF) sensor, the EGR flow rate is estimated using the orifice flow model (Guzzella et al (2004)).

In experimental studies, the method for quantifying EGR relies on the measurement of exhaust and intake CO_2 concentration, typically using gas analyzers. This definition of EGR is based on the notion that the fresh intake air contains negligible amount of CO_2, while the exhaust carries a significant quantity of this combustion product. All the CO_2 in the intake is assumed to be contributed by EGR. Therefore, the CO_2 based EGR definition is as follows,