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Influence of high and low pressure EGR and VGT control on in-cylinder pressure diagrams and rate of heat release in an automotive turbocharged diesel engine

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HIGHLIGHTS

► Experimental comparison of HP and LP EGR in six part load operating conditions.
► Simultaneous application of HP and LP EGR and VGT opening degree control.
► Variations of EGR fraction, intake pressure and mass flow rate in the tested modes.
► Influence of EGR and VGT control on in-cylinder pressure and heat release curves.
► Pressure diagrams and ROHR effects on engine fuel consumption, NO_x and soot emissions.

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ABSTRACT

An experimental study was developed to compare high and low pressure exhaust gas recirculation systems (HP and LP EGR) fitted on an automotive turbocharged diesel engine, analysing the effects of their control on fuel consumption, pollutant emissions and combustion process. An extensive range of operating modes was considered at different engine part-load conditions, starting from the reference one without EGR, then considering the simple activation of the HP or LP EGR circuit, followed by the simultaneous application of high and low pressure recirculation and the addition of variable geometry turbine (VGT) control. The paper focused on different goals: firstly, to highlight the change of selected operating parameters (intake pressure and mass flow rate, EGR fraction) in the different configurations affecting the development of in-cylinder pressure curves, ignition delay and combustion process. Secondly, to analyse how rate of heat release is affected by the different EGR and VGT control strategies. Finally, to justify the observed trends of fuel consumption, NO_x and soot emissions according to the pressure diagrams and heat release curves, as LP EGR and a different VGT position allowed reductions of 2.1, 50 and 22.8% of these parameters referring to the standard operating mode in the presented experimental point.

1. Introduction

During the last twenty years, diesel engines for light-duty applications have been greatly developed in order to address the evolution of legislation governing exhaust emissions and to become progressively more competitive towards gasoline engines in terms of specific torque and power. Electronically-controlled fuel injection systems, air management based on turbochargers fitted with variable geometry turbine (VGT) and the exhaust gas recirculation (EGR) technique are the milestones of this development, together with their electronic management and control strategies, which led diesel power-trains to conquer a major share on the European market. The optimisation of the intake and exhaust circuit is an important aspect of this approach, since many of its devices (such as compressor and turbine, EGR system, catalyst, particulate trap, etc.) have to be correctly matched and controlled. Particular attention must be paid to the turbocharging unit and the EGR system, fitted with dedicated regulating devices. The problem is complicated by the fact that these components often work with unsteady flows and in transient operating conditions, which are typical of automotive applications, strongly influencing their performance, as analysed for turbocharger compressors in Ref. [1] and turbines in Refs. [2,3].

Further improvements are still required, as the Euro 6 NO_x limit for diesel cars will be 80 mg/km, a reduction of over 50% if compared to the present phase, while conventional combustion

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Nomenclature

Notations

bmep	brake mean effective pressure
bsfc	brake specific fuel consumption
$bsNO_x$	brake specific nitrogen oxides emission
bsS	brake specific soot emission
f	mass flow fraction
n	rotational speed
p	pressure
A	variable nozzle turbine opening degree
AFR	air-fuel ratio
BDC	bottom dead centre
CA	crank angle
DI	direct injection
ECU	electronic control unit
EGR	exhaust gas recirculation
FSN	filter smoke number
HP	high pressure
LNT	lean NO_x trap
LP	low pressure
M	mass flow rate
Q	injected quantity
ROHR	rate of heat release
S	soot, nozzle ring push rod displacement
SCR	selective catalytic reduction
SOI	start of injection
T	temperature [K]
TDC	top dead centre
VGT	variable geometry turbine
VNT	variable nozzle turbine
X	volumetric concentration
τ	time

Subscripts

a	air
d	delay
e	exhaust
est	estimated
f	fuel
i	ignition, intake
main	referred to main injection
pilot	referred to pilot injection
rail	referred to fuel common rail
CO2	carbon dioxide
EGR	exhaust gas recirculation
HP	high pressure
LP	low pressure
MAX	maximum
1	compressor inlet
2	compressor exit
3	turbine inlet
4	turbine exit
5	muffler inlet
6	LP EGR circuit inlet
7	LP EGR valve inlet
8	LP EGR valve exit
9	LP EGR cooler exit
10	LP EGR valve vacuum signal

and injection systems are estimated to cover a significant worldwide market share for at least 10–15 years [4,5].

Among the various solutions for enhanced NO_x control, low pressure exhaust gas recirculation (LP EGR) circuits appear to be an interesting option when compared to traditional high pressure EGR (HP EGR), selective catalyst reduction (SCR) and lean NO_x traps (LNT), as they allow the EGR rate to be increased while controlling intake temperature level with a lower impact on turbocharger operating conditions [6]. Moreover, they require a simpler layout and achieve significant NO_x reductions using a robust technology [7]. The application of LP EGR circuit will introduce further degrees of freedom in engine control development, while its interaction with combustion process and other engine components, in particular HP EGR and turbocharging systems [8], have to be carefully investigated.

While diesel engine layout and management have changed dramatically, the investigating technique based on indicated pressure measurement is still a simple combustion analysis tool, which, also by properly calculating the rate of heat release (ROHR) [9,10], gives basic information on how its main features (ignition delay, premixed and diffusion burning period, duration, etc.) are affected by the activation and control of engine sub-systems or by challenging ambient conditions, such as in cold start at low temperatures [11,12]. On the other hand, real time ROHR evaluation allows closed loop control strategies to be developed for both conventional and advanced combustion concepts [13,14]. Of course, a wide range of advanced investigating methodologies are also available, with experimental, theoretical [15] or integrated approaches [16,17].

In-cylinder pressure diagrams analysis was extensively used within an experimental study on the comparison of high and low pressure EGR systems applied to an automotive turbocharged diesel engine, including the relevant influence of VGT control. This study, performed by the Internal Combustion Engines Group (ICEG) of the University of Genoa, set out to analyse and justify the observed fuel consumption and exhaust emission trends.

As also described in Ref. [18], following the design and set up of an LP EGR system, the effects of different EGR levels were analysed referring to six part-load engine operating conditions, using high and low pressure EGR circuits separately. Both EGR systems were then activated, considering fixed intake air set points to control the high pressure EGR valve duty-cycle. Finally, with the highest overall EGR rate, turbocharger VGT control was applied in order to analyse the interactions between the two recirculating circuits and the turbocharging system.

In this paper, after a brief description of the indicated pressure measuring system and the ROHR calculation procedure, changes in pressure traces, ignition delay, rate of heat release and combustion parameters caused by EGR systems and VGT control will be discussed, starting from the analysis of engine operating parameters (intake pressure and mass flow rate, EGR fraction) mainly affecting in-cylinder pressure diagrams. Finally, these variations will be related to measured levels of engine fuel consumption, NO_x and soot emissions in the various operating modes.

2. Experimental setup

A short description of the main features of the investigation into the application of a low pressure exhaust gas recirculation system to an automotive turbocharged diesel engine is given in this section, referring to the main characteristics of the engine test rig and open control system and summarising the investigation programme. The measuring systems of average engine parameters and in-cylinder pressure diagrams are described, together with the