ANALYSIS OF EXHAUST GAS RECIRCULATION(EGR) SYSTEM.

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ABSTRACT

exhaust gas recirculation (EGR) is a common way to control in-cylinder NO x and carbon production and is used on most modern high-speed direct injection (HSDI) diesel engines. However EGR has different effects on combustion and emissions production that are

difficult to distinguish (increase of intake temperature, delay of rate of heat release (ROHR), decrease of peak heat release, decrease in O2

concentration (and thus of global air/fuel ratio (AFR)) and flame temperature, increase of lift-off length, etc.), and thus the influence of

EGR on NO x and particulate matter (PM) emissions is not perfectly understood, especially under high EGR rates. An experimental

study has been conducted on a 2.0 l HSDI automotive diesel engine under low-load and part load conditions in order to distinguish and

quantify some effects of EGR on combustion and NO x /PM emissions. The increase of inlet temperature with EGR has contrary effects

on combustion and emissions, thus sometimes giving opposite tendencies as traditionally observed, as, for example, the reduction of NO x

emissions with increased inlet temperature. For a purely diffusion combustion the ROHR is unchanged when the AFR is maintained

when changing in-cylinder ambient gas properties (temperature or EGR rate). At low-load conditions, use of high EGR rates at constant

boost pressure is a way to drastically reduce NO x and PM emissions but with an increase of brake-specific fuel consumption (BSFC) and

other emissions (CO and hydrocarbon), whereas EGR at constant AFR may drastically reduce NO x emissions without important

penalty on BSFC and soot emissions but is limited by the turbocharging system.

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1. INTRODUCTION

Future regulations like EURO 5 and presumably 6 will force diesel engine manufacturers to drastically reduce NO_x and particulate matter (PM) emissions.

External exhaust gas recirculation (EGR) is a well-known in-cylinder method to reduce NO_x emissions, particularly on modern direct injection (DI) automotive diesel engine, and offers the possibility to decrease temperature during combustion [1,2]. The decrease in NO_x emissions with the increase of EGR rate is the result of various effects:

The thermal effect: Increase of inlet heat capacity due to higher specific heat capacity of recirculated CO_2 and H_2O

compared with O_2 and N_2 (at constant boost pressure) resulting in lower gas temperatures during combustion, and particularly in a lower flame temperature.

In order to better understand the effects of a reduction in in-cylinder gas concentration oxygen flame development and combustion when EGR is used to reduce NO_x emissions, Siebers and co-workers have studied typical DI diesel sprays with a single-hole common-rail injector mounted on a constant volume quiescent combustion vessel. They showed that the location of flame lift-off on diesel fuel jet plays an important role in combustion and emissions processes, by allowing fuel and air to mix upstream of the lift-off length (i.e. prior to any combustion). Just downstream of the lift-off length, the partially-premixed air–fuel mixture is undergoing a premixed combustion that generates a significant local heat release and a fuel-rich product gas that becomes the ‘‘fuel’’ for the diffusion flame at the jet periphery. The soot formation was shown to be directly dependent on the equivalent fuel–air ratio at the lift-off length; no soot would be produced when it is lower than approximately . Another important result is the following: the lift-off length is inversely proportional to the ambient gas oxygen concentration. Thus, when reducing ambient gas oxygen concentration, the total amount of gases entrained in the spray upstream of the lift-off length increases that compensates for the reduction in oxygen concentration, so that the total amount of oxygen entrained in the premixed mixture does not change. These observations made the authors to propose a new LTC concept, the so-called ‘‘non-sooting, low-flame-temperature mixing-controlled combustion’’ that consists in promoting the air–fuel mixing before the lift-off length (thanks to very small injector holes) and dramatically reducing the combustion temperature with the use of high EGR rates.

2. Experimental apparatus and procedure

The easier way to study the effects of single parameter variation while maintaining all others constant is to

perform the test on a single cylinder engine with separate systems for the control of EGR rate, inlet temperature, air and fuel flows. By the way, this hides some limits of an actual engine: for instance, the boost pressure depends on energy available at the exhaust when using a turbocharger. The ultimate objective of our study being to propose in-cylinder strategies to control NO x and PM emissions for future emissions standards, we have chosen to carry out the tests on a standard engine with limited modifications. The EGR valve permits to control the EGR flow. The angle of the VGT modifies the EGR flow and the fresh air flow at the same time: when the EGR valve is closed, the turbine accelerates when the VGT closes, thus increasing the boost pressure P 2 00 and the fresh air flow. When the EGR valve is opened (partially or totally), the pressure P 3 in exhaust manifold increases when closing the VGT, thus increasing the EGR flow, but generally the boost pressure is almost constant (i.e. decrease of fresh air flow). Thus, it is particularly difficult to maintain the AFR constant when increasing the EGR rate.

Intake air temperature T 2 0 was controlled separately, allowing control over the temperature T 2 00 of inlet gases after mixing with EGR independently of EGR rate.

3 Influence of EGR at constant inlet temperature

The influence of EGR on combustion and NO x and soot emissions is studied for operating points no. 1 and 2 both at constant boost pressure P 2 00 and constant AFR:. For operating point no. 1, both mixing-controlled and premixed combustion are studied. Inlet temperature T 2 00 is held constant. For operating point no. 2, when increasing EGR rate, it is not possible to maintain inlet temperature T 2 00 constant. Thus, there are two values of inlet temperature: 33 1C for moderated EGR rates, and 53 1C for higher EGR rates.

3.1 Premixed combustion

Constant boost pressure. For a premixed com-
bustion with constant boost pressure P 2 00 ID increases when increasing EGR rate. The combustion occurs later in the cycle duringexpansion, at a lower.in-cylinder temperature, thus reducing combustion speed

and ROHR peak. Influence of EGR on NO x and soot emissionsThe influence of EGR on NO x and soot emissions is

given in The corresponding NO x /soot trade-offs are given Firstly, for a given EGR rate, NO x emissions are higher and soot emissions lowerwithout pilot injection for operating point no.1 as for the influence of inlet tempeture.

3.2 Diffusion combustion

For operating point no. 1 with pilot injection, the increase of EGR rate results in a large decrease of NO x emissions and increase of soot emissions, whether at constant boost pressure P 2 00 or constant AFR.

For operating point no. 2 with constant boost pressure P 2 00 , soot emissions first increase with EGR rate from 0% to 30%, and then decrease for high EGR rates over about 30%, thus entering a low-NO_x /low-soot combustion mode, as observed by other researchers . This low-NO_x –low soot condition is very near to the ‘‘smokeless rich Diesel combustion’’ from Akihama et al. [13]. It must be underlined that this decrease in both soot and NO_x emissions is accompanied with an increase of 8.5% of BSFC and a large increase of CO and hydrocarbon

emissions.

NO_x reduction and soot increase with EGR are lower at constant AFR for operating point no. 1. Nevertheless, the soot penalty of EGR increase cannot be totally suppressed

by maintaining the AFR, as said by other authors [10]. For operating point no. 2, contrary effects are shown: for a given EGR rate, soot emissions are higher at constant AFR, resulting in a bad NO_x /soot trade-off .

Furthermore, when trying to maintain a constant AFR, it was not possible to have EGR rates greater than 17% for both operating points no. 1 and 2, because the VGT was not able to increase boost pressure to a higher value.

Indeed, with a classical high-pressure (HP) EGR loop, an

increase of EGR rate leads irremediably to a decrease of gas flow through the turbine and thus to a decrease of boost pressure. As a consequence, trying to drastically reduce NO_x emissions without an important penalty on soot emissions by maintaining a suitable AFR is not achievable with the actual EGR configuration. Some modifications on the air loop could be made to obtain simultaneously high boost pressure and high EGR rates: a better matching of the turbocharging system at low- and part load conditions (with, for instance, a two-stage turbocharging), or a different EGR loop (decreased pressure loss in the HP EGR loop, or low-pressure (LP) EGR loop). With an HP EGR loop, the recirculated gases is taken after the turbine; thus the gas flow through the

turbine, and consequently the boost pressure, are maintained when increasing EGR rate. It is thus easier to maintain a suitable AFR with an LP EGR loop.

4.conclusion

1. For some operating conditions, EGR at constant AFR is a way to drastically reduce NO x emissions without

important penalty on BSFC and soot emissions. Nevertheless, under some operating conditions, contrary

effects were observed. Further experimental investigations (modified EGR loop and turbocharging system)

will be undertaken to study combustion under high EGR rates at low load conditions with a constant AFR

to try to achieve very low-NO x –low-PM emissions without sacrificing fuel consumption.

2. For a purely diffusion combustion, when changing in-cylinder ambient gas properties (temperature or EGR

rate), the ROHR is unchanged when the AFR is .maintained.

3. At low-load conditions, very low-NO x and -PM emissions can be obtained with high EGR rates at constant

boost pressure, because the combustion is delayed due to the high dilution. This is accompanied with an

increase of BSFC (that can be higher that 10%) and CO and hydrocarbon emissions.

4. The increase of inlet temperature at constant EGR rate has contrary effects on combustion and emissions, thus sometimes giving opposite tendencies as traditionally observed, as, for example, the reduction of NO x

emissions with increased inlet temperature. As a consequence, the increase of inlet temperature generated by EGR can be either positive or negative depending on operating conditions, indicating that some care must be

taken during engine design and calibration.

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