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An experimental and numerical investigation on the influence of external gas recirculation on the HCCI autoignition process in an engine: Thermal, diluting, and chemical effects

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Abstract

In order to contribute to the solution of controlling the autoignition in a homogeneous charge compression ignition (HCCI) engine, parameters linked to external gas recirculation (EGR) seem to be of particular interest. Experiments performed with EGR present some difficulties in interpreting results using only the diluting and thermal aspect of EGR. Lately, the chemical aspect of EGR is taken more into consideration, because this aspect causes a complex interaction with the dilution and thermal aspects of EGR. This paper studies the influence of EGR on the autoignition process and particularly the chemical aspect of EGR. The diluents present in EGR are simulated by N_2 and CO_2, with dilution factors going from 0 to 46 vol%. For the chemically active species that could be present in EGR, the species CO, NO, and CH_2O are used. The initial concentration in the inlet mixture of CO and NO is varied between 0 and 170 ppm, while that of CH_2O alters between 0 and 1400 ppm. For the investigation of the effect of the chemical species on the autoignition, a fixed dilution factor of 23 vol% and a fixed EGR temperature of 70 °C are maintained. The inlet temperature is held at 70 °C, the equivalence ratios between 0.29 and 0.41, and the compression ratio at 10.2. The fuels used for the autoignition are *n*-heptane and PRF40. It appeared that CO, in the investigated domain, did not influence the ignition delays, while NO had two different effects. At concentrations up until 45 ppm, NO advanced the ignition delays for the PRF40 and at higher concentrations, the ignition delayed. The influence of NO on the autoignition of *n*-heptane seemed to be insignificant, probably due to the higher burn rate of *n*-heptane. CH_2O seemed to delay the ignition. The results suggested that especially the formation of OH radicals or their consumption by the chemical additives determines how the reactivity of the autoignition changed.

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1. Introduction

The combustion mode HCCI has gained much interest as a new technology to reduce the pollution of automotive engines. The difficulty of controlling the autoignition is one of the most important aspects that obstruct the implementation of this mode of combustion. Much experimental and numerical research has been performed analyzing several HCCI combustion mechanisms [1–7]. A certain HCCI engine that turns properly would need a certain fuel, inlet temperature, equivalence ratio, and compression ratio, which are chosen to meet power, emission, and efficiency optima. It is then more likely that a certain optimum would be chosen, which could be found by a detailed study on the effect of such parameters on the autoignition process. However, in order to control efficiently the autoignition process and more particularly the moment of autoignition, another parameter seems to be more interesting for the autoignition analysis. This parameter is called exhaust gas recirculation (EGR). The effect of EGR has been investigated in both diesel and HCCI engines [1,2,5,8–12]. The effect of EGR can be used and changed constantly whenever needed. Therefore it enjoys much attention, with the potential to solve the problem of the autoignition control. Efforts have been made to interpret the results of the influence of EGR on the autoignition process, stating that the effect of EGR on HCCI combustion can be divided into three parts: a dilution effect (inert gasses present in the EGR), a thermal effect (heat exchange, thermal loss to the wall, EGR ratio mixture quality, EGR temperature, heat capacity), and a chemical effect [1,2,8–12]. Especially the chemical effect has gained much interest, leading to investigations about the effect of adding chemically active species to an inlet mixture in an engine [13–16]. The chemical effect influences not only the overall kinetics, but it also can change a specific reaction path, which makes this effect particularly interesting for the investigation of the autoignition process.

This paper aims at investigating the effect of the chemical aspect of EGR on the autoignition process in an HCCI engine. The fuels n-heptane and PRF40 are used for this investigation. PRF40 stands for a primary reference fuel, containing 40 vol% iso-octane and 60 vol% n-heptane. The compression ratio is kept at 10.2, while the equivalence ratios are varied between 0.32 and 0.41. The inlet temperature is kept at 70 °C. The experimental results are backed-up with the same validated surrogate mechanism that has been used in previous work [17]. The 0 D HCCI engine module in the Chemkin code is used for the calculations with this mechanism. The same engine properties and initial parameters are used as in the experiments, which are discussed in Section 2. For the chemical species CO, NO, and CH_2O are chosen. The species CO is issued from incomplete combustion, NO from high temperatures during combustion, while formaldehyde is formed between the cool flame and the final ignition. The objective is to study the effect of some different chemical groups, which can be present in EGR, on the autoignition process.

2. Experimental setup of the EGR installation

A schematic representation of the experimental setup is shown in Fig. 1. The complete experimental setup comprises an HCCI engine itself, the air inlet system, the fuel injection system, a premixture tank for inlet mixture homogeneity, and the EGR installation. The HCCI engine has a compression ratio of 10.2, a bore of 82.55 mm, a stroke of 114.5 mm, and a displacement volume of 612 cm^3. The ratio of the connecting rod to crank radius is 4.44. The exhaust valve opens at 140° after top dead center (ATDC) and closes at 15° ATDC. The intake valve opens at 10° ATDC and closes at 146° BTDC. Three tanks are available in the installation: a stabilization tank, an EGR mixture tank, and a premixture tank. The stabilization tank serves for the stabilization of the impulses of the flow of the intake air, caused by the motion of the engine's piston. In the EGR mixture tank, the different constituents of the EGR, the flow of which is regulated by a flow meter, are mixed to compose the EGR mixture. The idea is to simulate experimentally the three most important effects of EGR (diluting effect, thermal effect, and chemical effect). Either nitrogen or carbon dioxide (the major diluting species in EGR) is chosen for the diluting compounds. The thermal effect can be simulated by heating/cooling the EGR flow or by choosing different diluting compounds with different heat capacities. For the chemical effect, the species CO, NO, or formaldehyde can be chosen, which are one of the most important minor species present in EGR that contribute to toxic pollution. An investigation of the diluting effect is performed in order to choose the optimal amount of dilution for the interpretation of the effect of the chemical species on the autoignition. The influence of the EGR temperature is similar to that of the inlet tem-