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The effect of diluent composition on homogeneous charge compression ignition auto-ignition and combustion duration

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Abstract

In this work, the effect of diluent composition is studied on the ignition timing and combustion duration of homogeneous charge compression ignition (HCCI) combustion. Full-cycle 3-D computational fluid dynamics (CFD) simulations were performed using two different dilution schemes, one which employs air dilution and the other which employs external exhaust gas recirculation (eEGR) dilution. Both cases used a fixed breathing strategy, and had the same fueling rate and engine speed typical of automotive applications. A premixed fuel–air mixture was used in the intake charge to avoid the fuel stratification effects associated with direct injection, while the valve events were selected to minimize the internal residual and its associated thermal and compositional stratification. With ignition timing held constant near top dead center (TDC) for both methods, there is a 10% increase in the combustion duration going from air to eEGR dilution. While the thermal stratification prior to ignition is similar for both methods, the eEGR-dilute case has an overall higher temperature throughout the charge. A reactivity stratification analysis, based on the distribution of ignition delays within the charge prior to ignition, showed nearly identical initial reactivity for the two methods, with the higher temperatures of the eEGR case compensating for this method's lower oxygen content. A quasi-dimensional multi-zone model was subsequently used to decouple the chemical kinetic and thermodynamic effects of eEGR on the combustion process. This analysis showed that the primary factor contributing to the longer combustion duration for the eEGR-dilute case is the lower ratio of specific heats (γ) in the unburned charge post-ignition which is thought to lower the rate of compression-induced heating of the unburned charge by the ignited and burning regions, leading to slower sequential auto-ignition.

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1. Introduction

Homogeneous charge compression ignition (HCCI) is a novel combustion mode that

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combines many desirable features of the spark-ignited and diesel combustion modes [1,2]. One major challenge associated with HCCI is the near volumetric combustion event which results in high rates of energy release relative to modes utilizing premixed or diffusion flames. Dilution of the charge by introducing excess air (compared to stoichiometric) or by introducing exhaust gases into the cylinder, serves to reduce rates of energy release as well as peak combustion temperatures.

One common method for charge dilution in HCCI is through the use of external exhaust gas recirculation (eEGR), where the products of combustion from the previous cycle are intentionally recirculated typically by extracting them from the exhaust runner, passing them through a cooler to control their temperature, and then finally mixing them with the intake air at the intake runner. The differing thermodynamic and chemical properties of EGR and air affect combustion characteristics such as phasing, rate and emissions. Early HCCI studies which investigated the effect of diluent composition, [3–5] showed that with all other parameters being held the same, increasing the fraction of eEGR within the charge retarded ignition timing while increasing combustion duration. The later phasings were due in part to the lower end-of-compression temperatures associated with the increased mixture heat capacity, which reduced the mixture specific heat ratio (C_p/C_v, γ), resulting from the larger fraction of tri-atomic H_2O and CO_2 molecules within the EGR dilute mixture.

In their 2009 work, Dec et al. [6] showed that addition of eEGR resulted in a small reduction in the peak heat release rate (HRR) when combustion phasing (represented by the crank angle of 50% burn, CA50) was matched. Olsson et al. [4] reached similar conclusions, finding that the effect of replacing air with eEGR was small in terms of HRR when combustion phasing was matched.

Despite the above work, the mechanism behind the increased combustion duration at a given combustion phasing with eEGR remains unclear. While some homogeneous reactor studies have been performed to better understand the chemical and thermal factors associated with the use of EGR [7], these studies are only applicable to the ignition event. Rapid compression and shock tube studies similarly concentrate on the ignition event while the combustion itself is much faster than typically observed in engines. This difference is thought to be due to the thermal and compositional stratification in engines. It is therefore of interest to use more detailed models to better understand the fundamental impact of dilution method on combustion characteristics such as combustion duration for a given ignition timing.

In the current work, full-cycle reacting CFD simulations were performed with gasoline kinetics to investigate the impact of air as well as eEGR dilution on HCCI combustion. The reason why full-cycle simulations are needed is to identify potential stratification effects arising from trapped residuals which cannot be captured by closed-cycle simulations such as those used in previous EGR studies [8]. Fueling and ignition timing were maintained constant to remove the impact of these variables from the combustion process. Reaction space analysis, based on the distribution of ignition delays within the charge prior to ignition, was performed on the CFD results to determine the effects of dilution method on the pre-ignition reactivity stratification. Finally, a quasi-dimensional (Quasi-D) multi-zone model was used to decouple the chemical and thermodynamic effects of air vs. eEGR dilution on combustion duration. Detailed description and evaluation of both the CFD model as well as the Quasi-D multi-zone model used in the current work are given in [9].

2. CFD predictions for the dilution method study

To compare air vs. eEGR dilution, full-cycle reacting CFD simulations (starting from 80° CA aTDC of the previous cycle and simulating the exhaust and intake strokes) were performed at 2000 revolutions per minute (RPM), with the engine mesh shown in Fig. 1. This mesh is based on a fully flexible valve actuation (FFVA) engine on which several HCCI and spark assisted compression ignition (SACI) experiments have been performed [10,11]. The engine specifications are given in Table 1. The standard k-ε turbulence model is used with law of the wall. Constant and uniform temperatures were prescribed for the head (450 K), liner (450 K) and piston (480 K). There is no crevice treatment in this study. Multiple cycles were not run to reach convergence. Positive valve overlap (PVO) with negligible overlap was used in this study to minimize the possible stratification effects caused by the retention of internal residuals from the previous cycle [12]. The internal residuals trapped within the clearance volume contribute to approximately

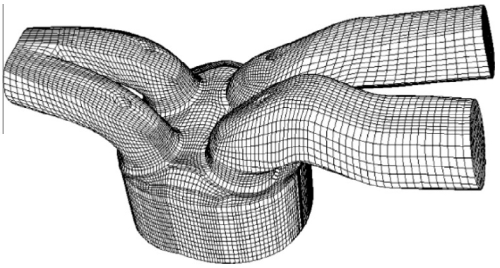

Fig. 1. Computational mesh of the engine used in the simulations.

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