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Numerical study of effect of injection and ignition timings on combustion and unregulated emissions of DISI methanol engine during cold start

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ABSTRACT

Numerical simulations were performed for the effect of injection and ignition timings on combustion and the generation of formaldehyde and unburned methanol emissions in the cylinder of a stratified charge direct injection spark ignition (DISI) methanol engine during cold start using AVL-fire, coupling the methanol chemical and kinetic reaction mechanisms. A non-uniform spray-line distribution nozzle was used to form stratified charge methanol-air mixtures during cold start. The simulation shows that injection and ignition timings have a significant effect on the concentration distribution of the methanol-air mixture, and hence the affect combustion and generation of formaldehyde and unburned methanol emissions. Optimized injection and ignition timings form an ideal stratified charge distribution. Formaldehyde and unburned methanol emissions decrease with retarding of the injection timing, but increase with retarding of the ignition timing. Formaldehyde and unburned methanol emissions at injection timing 41°crank angle before top dead center (CABTDC) were 48% and 82% higher than for 57°CABTDC, and those at ignition timing 8°CABTDC were 125% and 900% higher than for 20°CABTDC, respectively. Optimal injection and ignition timings provide the best compromise between the maximum cylinder pressure, maximum heat release rate, maximum cylinder temperature, and formaldehyde and unburned methanol emissions. Injection timing 45°CABTDC and ignition timing 14°CABTDC obtained the best compromise on cold start performance.

1. Introduction

Methanol can be produced from a wide variety of renewable sources and alternative fossil fuel based feed stocks, such as biomass, coal, nature gas, etc. [1–5], and can be used in low-cost internal combustion engines with only minor adjustments to ensure material compatibility [6]. Therefore, methanol is considered to be one of the most favorable fuels for engines of the future [7]. In addition, nitric oxides (NO_X) emission can also be significantly decreased due to its higher latent heat of vaporization, which decreases the cylinder temperature [8]. Methanol (CH_3OH) can be used in lean combustion mode, and a direct injection system is desirable as it generates a stratified-charge mixture which is effective for lean combustion [9]. However, methanol engines have problems with producing more formaldehyde (HCHO) and unburned methanol emissions as well as issues with cold start [10–13].

Much research has focused on the combustion and regulated emissions of spark ignition (SI) methanol or ethanol engines. Hedfi et al. [14] modeled a bioethanol combustion engine under different operating conditions. They found that a delay of the ignition timing increased the gas mixture temperature and cylinder pressure, with carbon monoxide (CO) lower near the stoichiometry, and lower rich mixture values, producing less NO_X emission. Huang et al. [15] studied the combustion behavior of a compression ignition engine with diesel/methanol blends under various fuel delivery advance angles. They found that the ignition delay, rapid burn duration, and total combustion duration all increased, and the center of the heat release curve was close to the top-dead-center

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(TDC), with advancing the fuel delivery advance angle. Terry et al. [16] investigated the influence of stratified-charge fuel preparation on the misfire rate of a DISI engine at idle, and Liao et al. [17] reported the effect of methanol-gasoline blends on combustion characteristics at relatively low temperatures. Hydrocarbon (HC) emission during the rich mixture combustion increased with additional methanol in the methanol-gasoline mixture at relatively low temperatures, because of the increased evaporation heat absorbed by the blended fuel compared to gasoline. Li et al. [18] investigated the effect of injection and ignition timings on performance and emissions from a high-compression stratified-charge direct injection spark ignition (DISI) methanol engine. They found that both injection and ignition timings had a significant effect on performance, combustion, and exhaust emissions, and injection and ignition timings could provide an improvement of brake-specific fuel consumption of more than 10% compared to non-optimized timing in the overall load range for engine speed of 1600 rpm. Zhen et al. [19] developed a new combustion to overcome the methanol engine knocking by incorporating exhaust gas recirculation. Zhang et al. [20] studied the combustion and emissions characteristics of an SI engine fueled with hydrogen-methanol blends under lean and various load conditions. They found that brake thermal efficiency was improved after hydrogen addition. The addition of hydrogen also contributed to lower HC and CO emissions. Li et al. [12,21] investigated the effects of ambient temperature on unregulated emissions of SI methanol and liquefied petroleum gas (LPG)-methanol engines during cold start. They found that with the ambient temperatures below 16 °C, the methanol engine could not be started reliably without assistant measures, and that formaldehyde emissions increased significantly while unburned methanol decreased with rising ambient temperature.

A great deal of effort has been devoted to study unregulated emissions in SI engines fueled with methanol and gasoline, ethanol and gasoline, methanol and liquefied petroleum gas (LPG), etc. blends. Agarwal et al. [22] measured unregulated emissions from a gasoline alcohol blend (gasohol) fueled SI engine using an online high resolution Fourier transform infrared emission analyzer under steady-state engine operating conditions. Ethanol based gasohols emitted higher acetaldehyde and there were higher alcohol emissions from higher alcohol proportion gasohols. Wang et al. [23] evaluated the effects of engine misfire on regulated and unregulated emissions from a methanol fueled engine. Unburned methanol emission increased by least 1.6 and 5.7 times for misfire rates of 6% and 9%, respectively. Li et al. [21,24,25] investigated the effects of ambient temperature on unregulated emissions of SI methanol and LPG blend and methanol engines during cold start. They found that formaldehyde emissions increased significantly whereas unburned methanol decreased with rising ambient temperature. Clairotte et al. [26] investigated the effects of low temperature on cold start gaseous emissions from light duty vehicles fueled by ethanol and gasoline blend. They found that unregulated emissions at −7 °C were higher than at 22 °C, regardless of the ethanol content in the fuel blend.

Previous research has concentrated on combustion and regulated emissions of gasoline, methanol, gasoline-methanol blends, etc. in SI engines [27–33], with little work addressing numerical simulation of combustion and unregulated emissions during cold start. Therefore, it is important and necessary to have a better understanding of the effects of injection and ignition timings on formaldehyde and unburned methanol emissions and formation processes. This study will help to clarify the generating mechanisms of cold start unregulated emissions for stratified charge DISI methanol engines.

2. Modeling methodology

2.1. Numerical model

Numerical models to describe combustion and spray were provided in AVL-fire [34], and the k-zeta-f, Dukowicz, and Huh-Gosman models were chosen for turbulence, evaporation, and breakup, respectively. The spherical selection module replaced the spark plug in the computational domain. A general gas phase reaction module was defined from the material composition and a reaction mechanism model and incorporated the influence of the combustion process. The 3-D CFD and chemical reaction calculations were coupled, incorporating AVL-fire and detailed chemical kinetic mechanisms of methanol oxidation consisting of 21 species and 91 reactions [35–37]. The adopted methanol mechanism was validated by many experimental results [38].

2.2. Parameter settings and model validation

The initial temperature was determined by combining the experimental results and the calculated results from the one dimensional (1D) engine simulation model. The 1D engine simulation model is established by the GT-Power, and the established 1D engine simulation model can be founded in Ref. [39]. The boundary conditions were as follows: all the temperatures of the piston, cylinder liner, and cylinder head were assumed to be −7 °C; intake air temperature was set to 10 °C (by intake air preheating); the global excess air ratio 1.5 was adopted, as this is known to provide lower formaldehyde and unburned methanol emissions during cold start for a high compression ratio stratified charge DISI methanol engine.

The methanol engine was modified from a single cylinder, four stroke, naturally aspirated direct injection diesel engine. A non-uniform spray-line distribution nozzle was used to form stratified charge methanol-air mixtures in the engine cylinder. The cylinder head was modified to use a spark plug. A high energy multi-spark-ignition system which can produce a series of successive spark was used to ignite the methanol mixture. A long electrode spark plug which was mounted near the edge of ω combustion chamber was used to protrude into the combustion chamber and match the injector spray lines. The spark plug location, injector spray distribution and air swirl direction are shown in Fig. 1, and the engine specifications in Table 1. Description of the experimental engine setup is provided in Ref. [18]. An electric power dynamometer was directly coupled to the engine output shaft to measure the engine torque. In-cylinder pressure was measured using a SYC04A quartz crystal pressure sensor which was mounted on the cylinder head, matched with a WDF-3 charge amplifier. A CB366 combustion analyzer was used to analyze the in-cylinder pressure. The test fuel

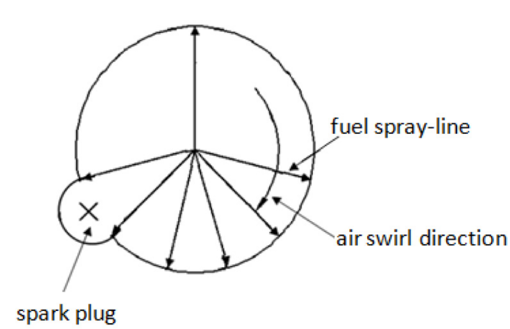

Fig. 1. Spark plug location, injector spray distribution and air swirl direction.