Fuel Processing Technology 92 (2011) 1756–1763

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

A study on the reduction of exhaust emissions through HCCI combustion by using a narrow spray angle and advanced injection timing in a DME engine

Hyung Jun Kim [a], Kwan Soo Lee [b], Chang Sik Lee [b,*]

[a] Department of Mechanical Engineering, Hanyang University, and currently in National Institute of Environmental Research, Gyeongseo-dong, Seo-gu, Inchon, 404–704, Republic of Korea
[b] Department of Mechanical Engineering, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul, 133–791, Republic of Korea

ARTICLE INFO

Article history:
Received 13 May 2010
Received in revised form 21 March 2011
Accepted 14 April 2011
Available online 17 May 2011

Keywords:
HCCI combustion
Injection timing
Narrow spray angle
DME fueled engine
Combustion characteristics
Emission characteristics

ABSTRACT

This paper describes the combustion and emission characteristics as well as engine performance according to the narrow spray angle and advanced injection timing for homogeneous charge compression ignition (HCCI) combustion in dimethyl ether (DME) fueled diesel engine. The bowl shape of the piston head was modified to apply the narrow spray angle and advanced injection timing. The spray, combustion and emission characteristics in a DME HCCI engine were calculated by using numerical method of the KIVA-3 V code coupled with the detailed chemical kinetic model of DME oxidation. Model validation was conducted by a comparison of experimental results for the accurate prediction. The injection timing ranging from BTDC 80° to BTDC 10° and two fuel masses were selected to evaluate the combustion, emission and engine performance. The calculated results were in good accordance with the experimental results of the combustion and emissions of the engine. Nitrogen oxide (NOx) emissions at injection timing before BTDC 30° remarkably decreased, while hydrocarbon (HC) and carbon monoxide (CO) emissions at an injection timing of BTDC 70° showed high levels. Also, the IMEP and ISFC have decreasing and increasing patterns respectively as the injection timing was advanced.

1. Introduction

Studies of future automobile technologies have focused on the reduction of engine exhaust emissions. Due to the finite petroleum resources and deepening atmospheric contamination, many countries around the world have restricted exhaust emissions from all vehicles. For this reason, the development of next generation technologies for vehicles is progressing steadily and is the subject of many studies of the reduction of harmful emissions and improvement of fuel consumption, without scarifying engine performance. Among the various developed technologies to reduce harmful emissions, the homogeneous charge compression ignition (HCCI) engine is widely known for the diesel-like efficiency and smooth running at a limited operating range. This method has made combustion with wide spatial distributions in the cylinder possible by using a premixed air-fuel mixture. In addition, the low combustion temperature leads to low exhaust emissions, including nitrogen oxides (NO_x) and particulate matter (PM). However, many problems still must be solved in order to realize the high thermal efficiency and low exhaust emissions. Disadvantages of HCCI combustion include limited operating range, difficult ignition timing control, and increased hydrocarbon (HC) and carbon monoxide (CO) emissions during combustion at low temperature. In order to overcome the weaknesses of HCCI combustion, various injection strategies (e.g. multiple injections, injection angles, and advanced injection timings), variable nozzle concepts, and modified piston head shapes were applied to extend the operating area in HCCI combustion by many researchers [1–4].

Vressener et al. [5] investigated the effect of two combustion chamber geometries with a square volume and disk bowls on combustion characteristics in an HCCI engine using high-speed chemiluminescence imaging. They reported that the rate of heat release and combustion duration of a square bowl piston were increased and decreased, compared to those of a disk bowl piston, respectively. In addition, combustion started from the same corner of the bowl and propagated into the squish volume. Lee and Reitz [6] studied the influence of injection angle on the soot and CO emissions in a premixed charge compression ignition (PCCI) combustion engine. These authors revealed that NO_x emission was more affected by the equivalence ratio than the injection timing and spray targeting at the piston bowl edge near the squish region, which showed excellent soot and NO_x trade-off, as well as better CO emissions. A numerical study on the HSDI engine performance and emission characteristics, according to the piston bowl shapes and operating parameters, was conducted by Zhu et al. [7]. From their investigations, it was revealed that the piston bowl with a large toroidal radius has better combustion characteristics and lower soot emissions than that with a small radius. Also, various investigations [8–12] of the narrow spray

* Corresponding author. Tel.: +82 2 2220 0427; fax: +82 2 2281 5286.
E-mail address: cslee@hanyang.ac.kr (C.S. Lee).

0378-3820/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.fuproc.2011.04.024

angle and advanced injection events in diverse engine types and operating conditions have been conducted due to the limitation of fuel wall impingement and promotion of air-fuel mixture. In order to optimize the narrow spray angle, researchers modified the design of the piston bowl, which yielded a very advanced injection timing for adequate air–fuel mixing. Their results reported that NO_x emissions showed near zero amounts, but large HC and CO emissions were still exhausted at a low engine speed and load [13,14]. In addition to the various technologies in the diesel engine, alternative fuels, such as dimethyl ether (DME) and biodiesel, have recently been studied for application to the HCCI combustion engine, as alternative fuels are expected to reduce harmful emissions by inclusion of oxygen in the fuel [15–17].

The aim of this paper was to analyze the combustion and emission characteristics according to the narrow spray angle and early injection timing for HCCI combustion, in a DME-fueled diesel engine, because there were many uncertainties regarding DME combustion in a HCCI mode. In order to realize this purpose, a modified piston bowl shape was used for application of narrow spray angle and advanced injection timing, and model validation, using the experimental results was performed. Furthermore, the combustion (combustion pressure, temperature, and spatial distribution), emissions (NO_x, soot, CO, and HC), and performance (IMEP and ISFC) characteristics according to the start of injection, and fuel mass was investigated by using a KIVA-3 V code, coupled with a detailed chemical kinetic model of DME oxidation.

2. Test engine and model formulation

2.1. Test DME engine and apparatus

Various numerical models were used for analysis of the combustion and emissions in a three-dimensional grid. Therefore, model validation is essential to the prediction of accurate combustion and emissions characteristics. In this study, a four-valve single-cylinder DME-fueled compression ignition (CI) engine with a common-rail injection system was used to compare the calculated results. This test engine has a compression ratio of 15, and a re-entrant type is applied to the piston bowl shape. The depth of the bowl shape in this study is deeper than that of conventional pistons, and the detailed specifications of the piston bowl size are illustrated in Fig. 1(a). In addition, the piston bore and stroke are 75.0 mm and 84.5 mm, respectively. In the common-rail injection system, the return line of the diesel injector was adjusted to prevent DME fuel leakage due to its low viscosity. The spay angle and the number of injection holes were 60° and six, respectively, with a 0.126 mm hole size. In addition, the test fuel used for this experiment is made by mixing the neat DME and small amount of lubricity additive. Detailed engine specifications, including valve open and close timing for the intake and exhaust processes, were listed in Table 1. The combustion pressure and heat release rate were calculated from the obtained data by using a pressure sensor and charge amplifier. In addition, exhaust emissions, such as NO_x, soot, and CO, were acquired from emission analyzers.

2.2. Model formulation for DME fuel spray and combustion

To analyze the combustion and emission characteristics with a narrow spray angle and advanced injection timing, KIVA-3 V release 2 code [18], including various sub-models, was used in combination with a Chemkin II chemistry solver [19] for the calculation of DME oxidation reactions. Information regarding the liquefied DME fuel properties were appended to the fuel library in the code in due consideration of investigations [20–24] about the DME fuel properties according to temperature. Also, the computational cell size at the squish region during piston movement varies with the crank angle. The cell size, 128 degrees BTDC at the start of calculation, is larger than that of TDC. In addition, the case of advanced injection timing is greatly influenced by the size of the computational grid in the squish region. Therefore, the spray improvement model based on a gas jet theory [25] was applied for reducing grid-dependency by the effect of relative velocity in this study. This model showed improved grid-independency results by various investigations [26,27]. Further, the Kelvin–Helmholtz (KH) and Rayleigh–Taylor (RT) hybrid breakup model [28] was used to analyze the atomization characteristics. Breakup model constants regarding the time and size were modified for the gas jet spray model on the basis of previous research [26]. The spray-wall interaction model [29] and the modified Renormalization Group (RNG) k-ε model [30] were applied to the process of wall impingement and analysis of turbulence flow in the cylinder, respectively. The self-ignition and combustion process of DME fuel

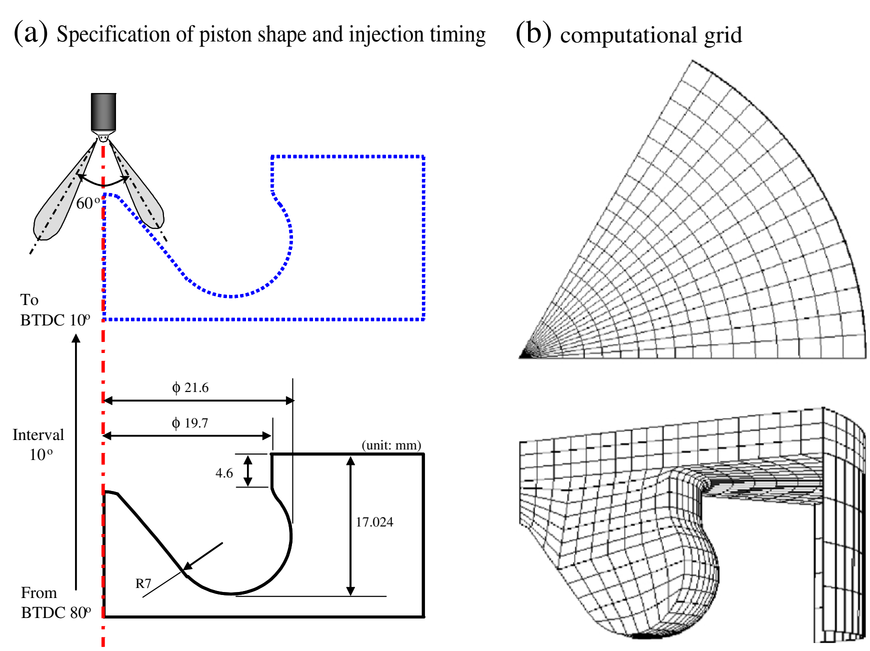

Fig. 1. Specification of piston shape, injection angle and timing, and computational grid at the BTDC 20 degrees.