



# Visualizations of combustion and fuel/air mixture formation processes in a single cylinder engine fueled with DME



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## HIGHLIGHTS

- Experimental and numerical approaches were used for DME combustion.
- DME fuel properties strongly affected temperature distribution.
- The differences of temperature distribution were showed under various conditions.
- DME combustion and emissions characteristics in comparison with ULSD fuel.

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## ABSTRACT

The purpose of this study is to investigate the effects of various engine conditions on the combustion, flame temperature and emission characteristics of dimethyl ether (DME) fuel compared with ultra-low sulfur diesel (ULSD) fuel through experimental and numerical analyzes. In order to analyze the temperature distribution, the KIVA-3V code and an optical HSDI diesel engine equipped with a visualization system were employed. The numerical validation was conducted with the experimental results from a DME-fueled compression ignition engine. In addition, measurement of the flame temperature from images captured during the combustion processes was performed using AVL-ThermoVision software.

This investigation showed that the combustion pressure and heat release rate attained their peak value at the lowest engine speed condition for DME and ULSD fuels. The characteristics of the flame temperature value and distribution due to the differences in engine speed conditions and fuel properties were clearly revealed. When the engine speed increased, an inhomogeneous and low combustion temperature was observed. Furthermore, the nitrogen oxides (NO<sub>x</sub>) emissions, which are related to the combustion temperature, decreased as the engine speed increased.

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## 1. Introduction

Due to good thermal efficiency and low carbon dioxide emissions, the use of diesel engines has increased since they are one of the most efficient types of internal combustion engine. Compression ignition (CI) engines have been widely employed ranging from high-duty trucks to passenger cars. Particularly, the number of light-duty vehicles with CI engines which offer high power output and low fuel consumption, has increased steeply in recent years. Though the diesel engine has the advantage of reducing fuel consumption, noxious exhaust emissions are increasing, such as NO<sub>x</sub> and particulate matters (PM). These emissions can

induce harmful effects including air pollution and numerous health risks. To decrease the air pollution caused by the diesel fuel, a number of studies have been done to develop diverse combustion strategies. However, these efforts have been limited in their ability to reduce the exhaust emissions of a CI engine. As a result, numerous researchers are performing alternative fuel experiments with CI engines to minimize the level of exhaust emissions [1–4].

DME fuel, one of the alternative fuels, can be applied with conventional diesel engines with little modification of the fuel injection system. Since DME fuel has high vapor pressure, the effect of premixed charge compression ignition combustion can be obtained [4]. In addition, due to the absence of carbon-to-carbon bonds, the soot formation and development were dramatically suppressed [5–8]. However, despite these numerous advantages, DME fuel has a problem with nitrogen oxides emissions. In order to solve the NO<sub>x</sub> problem, a number of studies have been performed using diverse research methods. Yoon et al. [9] investigated

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## Nomenclature

|                   |                                 |
|-------------------|---------------------------------|
| ALE               | arbitrary Eulerian–Lagrangian   |
| ATDC              | after top dead center           |
| BTDC              | before top dead center          |
| BSFC              | brake-specific fuel consumption |
| BSNO <sub>x</sub> | brake-specific nitrogen oxides  |
| BSsoot            | brake-specific soot             |
| CA                | crank angle                     |
| CI                | compression ignition            |
| deg.              | degree (°)                      |
| DI                | direct injection                |
| DME               | dimethyl ether                  |
| ECU               | engine control unit             |
| FVM               | finite volume method            |

|           |                                  |
|-----------|----------------------------------|
| GRI       | Gas Research Institute           |
| HSDI      | high speed direct injection      |
| KH        | Kelvin–Helmholtz                 |
| PAH       | polycyclic aromatic hydrocarbons |
| $P_{inj}$ | injection pressure               |
| PM        | particulate matter               |
| RNG       | renormalization group            |
| RT        | Rayleigh–Taylor                  |
| TDC       | top dead center                  |
| $t_{inj}$ | injection timing                 |
| ULSD      | ultra-low sulfur diesel          |

the effects of a narrow injection angle injector with a multiple-injection strategy in a DME-fueled engine. They revealed that narrow-angle injectors and multiple injections achieved low NO<sub>x</sub> emissions and similar levels of PM emissions, compared with single-injection at advanced first injection timing. Park et al. [10] experimentally and numerically investigated the effects of injection timings and spray behaviors on DME combustion and emissions characteristics. They measured spray behaviors using the DME in-cylinder spray visualization system and calculated the combustion and exhaust emissions results using the KIVA-3V code. Their results showed where the injected DME fuel was distributed for various injection timings and resulted in largely decreased NO<sub>x</sub> emissions for low combustion temperature conditions.

The purpose of the present study is to investigate the effects of DME fuel on combustion, flame temperature and emissions characteristics compared with ULSD fuel under various engine operating conditions. For these purposes, a combustion visualization system, AVL-ThermoVision, is employed, and the KIVA-3V code calculates the DME combustion and temperature distribution using a detailed chemical kinetic model. The visualization system, which is composed of an endoscope and a micro CCD camera synchronized with an engine encoder captures combustion behavior images in high speed conditions. The KIVA-3V code, which is validated with experimental results, predicts the DME combustion phenomena in a cylinder that is not observed in the visualization system. The exhausted emissions, NO<sub>x</sub> and soot, are measured using exhaust gas analyzers.

## 2. Experimental apparatus and procedures

### 2.1. Experimental setup

An AVL 5420 research single-cylinder engine was used for this study. It is composed of a naturally aspirated DI single-cylinder, common-rail injection system, and an electrical engine control system. The engine has a bore of 85 mm, a stroke of 90 mm, a displacement volume of 510.7 cm<sup>3</sup>, and a compression ratio of 17.1. The detailed engine specifications are listed in Table 1. As illustrated in Fig. 1, the single-cylinder DME fueled diesel engine is controlled by a prototype ETAS engine control unit (ETK 7.1, ETAS). The ETAS system, which loads an open loop fuel injection control strategy designed by AVL, allows independent control of the fuel injection parameters. The INCA software can modify the injection parameters such as the injection pressure, timing, and quantity to communicate with the ETAS system. In the fuel supply system, the DME fuel, which was liquefied through pressurization by the

nitrogen gas, was passed through a filter tank in order to remove impurities before entering the high pressure pump. The two high pressure pumps (HSF-300, Haskel) were linked in parallel to stably supply fuel to the common-rail system. The AVL research engine was connected to the compact test bed, which consists of a torque meter, a cooling water and oil conditioning system, and a dynamometer. The AC dynamometer (AMK DW 13-170-4, AVL) is a liquid-cooled three-phase asynchronous motor that allows for control of the engine speed and torque with the PUMA system.

The in-cylinder pressure was measured by a piezoelectric pressure transducer (AVL SL31D) coupled to a compact amplifier (AVL micro IFEM Piezo Module 4P3×). The combustion pressure was sampled over 300 cycles at 0.1 C.A. intervals to reduce the effects of variations between cycles. The AVL Indicom acquired the combustion data and calculated the rate of heat release in conjunction with the encoder signal to analyze the combustion characteristics under each test condition. The exhaust emissions (NO<sub>x</sub>, HC, CO and CO<sub>2</sub>) were measured by a HORIBA MEXA-554JKNOx exhaust gas analyzer under steady state conditions. The soot concentration in the exhaust gas was achieved by an AVL Micro Soot Sensor with high sensitivity and a wide range (5 µg/m<sup>3</sup> – 50 mg/m<sup>3</sup>).

In the present study, a combustion visualization system, the AVL Visioscope, was used to identify the combustion behavior at the in-cylinder under different fuels and test conditions. The visualization system consisted of a CCD camera, an endoscope (M10, AVL), an illumination device and the AVL-ThermoVision software. The endoscope was equipped with the CCD camera installed on the cylinder head and to show the combustion chamber upper view. The high-speed camera and light unit were synchronized with a crank angle encoder (AVL 365C, AVL) to capture the combustion images at the exact timings. The AVL-ThermoVision program calculated the flame temperature and the radiation of the diffusion flame (sooting flame) from the original combustion images.

**Table 1**  
Engine specifications.

| Description                            | Specification                   |
|----------------------------------------|---------------------------------|
| Engine type                            | Single-cylinder DI diesel (*NA) |
| Bore × stroke (mm)                     | 85 × 90                         |
| Displacement volume (cm <sup>3</sup> ) | 510.7                           |
| Compression ratio                      | 17.1                            |
| Fuel injection system                  | BOSCH common-rail type          |
| Number of nozzle holes                 | 5                               |
| Nozzle hole diameter (mm)              | 0.180                           |
| Spray angle (deg.)                     | 142                             |

<sup>a</sup> NA: naturally-aspirated.

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