

Simultaneous Reduction of Pressure Rise Rate and Emissions in a Compression Ignition Engine by Use of Dual-Component Fuel Spray

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ABSTRACT

Ignition, combustion and emissions characteristics of dual-component fuel spray were examined for ranges of injection timing and intake-air oxygen concentration. Fuels used were binary mixtures of gasoline-like component i-octane (cetane number 12, boiling point 372 K) and diesel fuel-like component n-tridecane (cetane number 88, boiling point 510 K). Mass fraction of i-octane was also changed as the experimental variable. The experimental study was carried out in a single cylinder compression ignition engine equipped with a common-rail injection system and an exhaust gas recirculation system. The results demonstrated that the increase of the i-octane mass fraction with optimizations of injection timing and intake oxygen concentration reduced pressure rise rate and soot and NO_x emissions without deterioration of indicated thermal efficiency. Numerical investigation into the pressure rise rate reduction mechanism was also performed by use of a multi-component fuel model developed by the authors. The calculated result showed that the pressure rise rate was reduced due to the difference in the vapor concentrations between two components which have difference reactivity.

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INTRODUCTION

Premixed charge compression ignition (PCCI) using early or late direct injection, high pressure injection and exhaust gas recirculation (EGR) offers promise for reducing particulate matter (PM) and NO_x emissions while keeping diesel-like thermal efficiency [1,2,3]. However, several technical issues still must be resolved. Among these, controlling the combustion duration and hence the pressure rise rate is a major issue to extend the applicable operation range. It is generally agreed that the important parameters impacting the pressure rise rate are the combustion phasing and the charge stratification [4,5,6], although the combustion phasing retard is restricted by misfire or by deterioration of the thermal efficiency while the charge stratification often increases CO and NO_x emissions [7]. Currently, as a realistic means, Shimazaki et al. [8] has proposed a dual mode combustion concept, in which engine is run with premixed charge operation from low till medium loads while diesel

mixing-controlled combustion is adapted for high load operation at which emissions are reduced by aftertreatment device.

To expand the load range of premixed charge operation and to achieve low emissions combustion at a high load, the authors have developed a combustion control method by use of physical and chemical properties of dual-component fuels [9, 10]. As schematically shown in Fig.1, a dual-component fuel consisting of different reactivity and volatility components provides a mixture in which two components are stratified due to the difference in the evaporation rate [11,12,13]. This so-called batch-distillation phenomenon can yield spatial-temporal difference in the ignition and combustion progress, associated with slowing of global combustion rate, and hence the premixed charge operation can be applied to higher load. Nevertheless, by increasing fuel loading, the range of the premixed charge operation could be limited by the increment of the combustion rate, so that mixing-controlled combustion would be employed



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because of its ability to control the combustion rate. Although a major drawback of conventional mixing-controlled combustion is a trade-off relation between PM and NO_x , mixing less reactive component increases lift-off length which is generally defined as a distance from nozzle tip to active combustion zone [14]. An increased lift-off length reduces the equivalence ratio in the diffusion flame, because the amount of entrained air increases with distance to nozzle, and hence reduces PM emissions [15].

Thus, in the present study, engine tests were carried out at a low load, focusing on the effect of mixing gasoline-like component into diesel-like component on pressure rise rate and emissions during premixed charge operation. In addition, to develop an understanding of the pressure rise rate reduction mechanism, a numerical investigation was also performed by use of a multi-component fuel model.

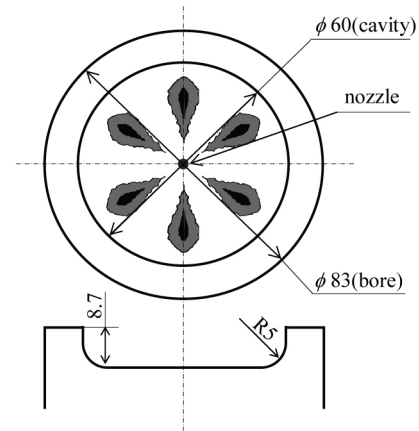


Figure 2. Appearance of piston and its cavity geometry.

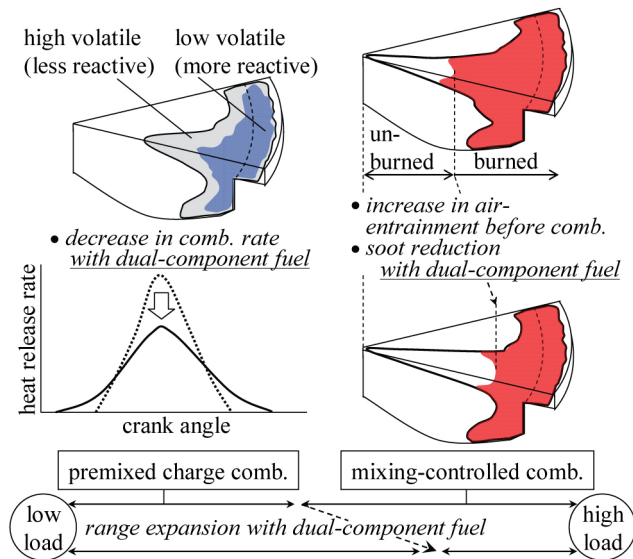


Figure 1. Schematic illustration of controlled combustion rate and low emissions combustion strategy using dual-component fuel.

EXPERIMENTS

Experimental Setup and Conditions

Experiments were carried out in a single cylinder, direct injection, water-cooled 4-stroke compression engine. The appearance of a piston is illustrated in Fig. 2. Specifications of the test engine and operating conditions are listed in Table 1. The test engine has dishshaped combustion chamber with the cavity diameter of 60 mm. The bore and the stroke are 83 mm and 85 mm, respectively. Temperatures of intake air, coolant water and lubricant oil were kept constant during the operation.

Table 1. Engine specification and experimental condition.

Bore × Stroke	[mm]	83 × 85
Compression ratio	[-]	16.6
Engine speed	[rpm]	800
Intake air temperature	[K]	313 ± 1
Lubricant oil temperature	[K]	353 ± 1
Water temperature	[K]	353 ± 1
Injection pressure	[MPa]	70
Injection quantity, Q_{inj}	[mg/cycle]	8.6
Injection pulse timing, θ_{inj}	[deg.CA ATDC]	from -25 to -5 as a step of 5 deg.CA
Intake oxygen concentration, X_{O_2}	[vol.%]	21 and from 17 to 14 as a step of 1 vol.%
Operating limitation		$dp/d\theta_{max} < 1.2 \text{ MPa/deg.CA}$ COV of IMEP < 6 %

A flush-mounted piezoelectric pressure transducer (KISTLER: 6125C01) was installed to measure in-cylinder pressure. The pressure data as well as injection pulse signal were recorded for 120 cycles, every 0.5 crank angle degree (deg.CA), based on the electric pulse from a rotary encoder. Exhaust gas concentrations of total-hydrocarbons (THC), CO, CO_2 and NO_x were measured by an exhaust analyzer (HORIBA: MEXA-9100D). To measure the mass of particulate matter (PM) according to filter weighting method, the exhaust gas was diluted through a full-dilution tunnel before PM was collected on a Teflon filter. Soxhlet extractor was used to isolate soluble organic fraction (SOF) from PM, and then insoluble fraction (ISF) which is predominantly composed of soot was evaluated.

Intake oxygen concentration (X_{O_2}) was changed as an experimental variable by recirculating a portion of engine exhaust gases back to the cylinder and the X_{O_2} was measured by the above exhaust gas analyzer. Before leading the gases to intake manifold, PM emissions were removed through a

diesel particulate filter and gases temperature was lowered to around intake air temperature by an EGR cooler.

A commercially available common-rail fuel injection system was used for direct injection. Fuel temperature was kept around 293 K with heat exchanger to suppress bubble release in the fuel line. The injector nozzle has 6 orifices with an umbrella angle of 145 degree (17.5 degree down-angle from the bottom surface of the cylinder head and their nominal diameter is 0.16 mm. Five different injection pulse timings (θ_{inj}) from -25 deg.CA ATDC to -5 deg.CA ATDC were selected.

An injected fuel quantity was 8.6 mg/cycle. This corresponds to global equivalence ratio of 0.26 without taking into account exhaust gas recirculation. Though the resulting indicated mean effective pressure (IMEP) varied according to the experimental condition, the maximum IMEP for all the experiments was about 0.33 MPa.

Fuels Tested

N-tridecane (n-C₁₃H₂₈) which is more reactive (cetane number 88) and high boiling point (boiling point 510 K) was used as a diesel-like component. By mixing i-octane (i-C₈H₁₈) which is less reactive (cetane number 12) and low boiling point (boiling point 372 K) into n-C₁₃H₂₈, the effect of a gasoline-like component was examined. The present study set the mass fraction of i-C₈H₁₈ (M_{iC8}) as 0 (pure n-C₁₃H₂₈), 50, 70 and 80 wt.%. As denoted above, the global equivalence ratio was 0.26. As for M_{iC8} of 50, 70 and 80 wt.%, the equivalence ratios of n-C₁₃H₂₈ were 0.13, 0.08 and 0.05, and those of i-C₈H₁₈ were 0.13, 0.18 and 0.21, respectively.

MULTI-COMPONENT FUEL MODEL

The multi-component fuel model has been developed based on KIVA3V [16]. Since more detailed description is found in the literatures [13, 17], essential points are described here.

Droplet Breakup and Evaporation

In order to accurately predict liquid phase penetration, the Kelvin-Helmholtz and Rayleigh-Taylor (KH-RT) model [18] was incorporated as a droplet breakup model. Same KH-RT model constants were adopted despite the fuels.

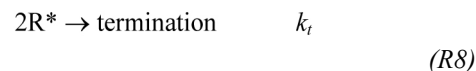
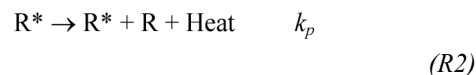
To evaluate the effects of interaction between molecules, high-pressure and non-ideal gas on phase properties and droplet evaporation process, a source code of SURERTRAPP [19] developed in National Institute of Standards and Technology was incorporated into KIVA3V. The SUPERTRAPP code calculates vapor-liquid equilibrium and gives phase compositions with Peng-Robinson equation of state. The solubility of ambient gas in the droplet was taken into account, while omitting internal circulation of the liquid and temperature gradient within the droplet.

Estimation of Physical Properties

Due to the difference in the evaporation rate among components, the mixture fraction within the droplet is changed as time goes by. Thus, all the fuel properties of droplet parcels were updated in every numerical timestep with taking into account both temperature and pressure effects as well as mixing fraction. The SUPERTRAPP code calculates thermodynamic and transport properties based on extended corresponding states. The more details on the prediction method are found in the literatures [17, 20].

Ignition and Combustion Models

The oxidation reaction lower than 1000 K was solved by the multistep kinetics Shell ignition model [21]. It includes eight reaction steps between five generalized species, specified as:



where RH indicates the fuel, R* is the generalized radical, Q is an unstable intermediate agent, B is the branching agent, and P denotes oxidized products such as CO, CO₂ and H₂O. The rate terms f_i are expressed as follows:

$$f_i = A_{f_i} \cdot \exp\left(\frac{-E_{f_i}}{R \cdot (T - T_x)}\right) \cdot [O_2]^{x_i} \cdot [RH]^{y_i} \quad (1)$$

where R is universal gas constant, T is cell temperature and T_x is a correction for temperature described below. The kinetic parameters, k_q , k_b and k_t , are expressed in the Arrhenius form as:

$$k_i = A_i \cdot \exp\left(\frac{-E_{f_i}}{R \cdot (T - T_x)}\right)$$