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Classification of diesel and gasoline dual-fuel combustion modes by the analysis of heat release rate shapes in a compression ignition engine

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ABSTRACT

Reactivity controlled compression ignition (RCCI) is one of representative dual-fuel combustion concepts for low NOx, soot emissions and high thermal efficiency. Overall lean and highly premixed auto-ignition combustion make low combustion temperature and the reduction of heat transfer loss. Although premixed compression ignition (PCI) combustion using a single fuel, i.e., diesel, also shows low emissions and higher thermal efficiency, combustion characteristics of RCCI (dual-fuel PCI) are different from single-fuel PCI due to reactivity gradient from two different fuel characteristics as well as local equivalence ratio due to the fuel distribution. Therefore, it is necessary to know the influence of above two factors on the dual-fuel combustion characteristics for better understanding of dual-fuel combustion and its effective utilization. In this research, the characteristics of dual-fuel combustion are evaluated comparing to single-fuel combustion. Also, dual-fuel combustion modes are classified according to the analysis of heat release rate (HRR) shapes. Major factors in the classification of dual-fuel combustion modes are the degree of fuel reactivity gradient and the local equivalence ratio in the cylinder. Thus, the diesel injection timing, diesel and port injected gasoline fuel ratios and the overall equivalence ratio were selected as the main variables to characterize each dual-fuel combustion mode. The result emphasizes that the dual-fuel combustion could be classified as three types by HRR shapes, and it was mainly affected by reactivity gradient and overall equivalence ratio.

1. Introduction

The major research in internal combustion engines is focused on the clean air and energy resource conservation. For the atmospheric environment, internal combustion engine research is related to strict emission regulations in the passenger vehicles. EURO-6, one of the newest emission regulations, has been enforced since September 2014. EURO-6 prescribes that nitrogen oxide (NOx) and particulate matter (PM) emissions should be reduced to 80 and 4.5 mg/km respectively, in the new European driving cycle (NEDC) mode. The emission test for driving cycle will become more severe when the worldwide harmonized light vehicles test procedure (WLTP) takes action replacing the new European driving cycle (NEDC) in 2017. WLTP covers broader operating range, and additionally real driving emissions (RDE) will be applied to challenge the test mode that is executed under real road conditions.

It is challenging to reduce engine-out emissions without modifying the conventional powertrain system. Currently, many diesel vehicles have been equipped with emission after-treatment systems such as the diesel particulate filter (DPF), lean NOx-trap (LNT) and selective catalytic reduction (SCR). However, these systems inevitably cause an increase in the manufacturing cost. Thus, the clean combustion concept for the reduction of engine-out NOx and PM emissions in engines needs to be investigated.

Additionally, the depletion of fossil fuels has become a major problem. For this reason, alternative fuels such as biodiesel and oxygenated fuel have introduced to internal combustion engines. However, because most of the alternative fuel has a low energy density compared to those of diesel and gasoline, changing fuel is not a fundamental solution for the energy crisis. Therefore, improving the efficiency of internal combustion engines is important. Although the diesel engine has a superb thermal efficiency compared to that of gasoline spark ignition (SI) engine, there is a possibility for a greater increase in thermal efficiency with the reduction in energy losses such as combustion loss, heat transfer

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loss to the cylinder wall and exhaust loss from high temperature exhaust gas.

To achieve these two purposes simultaneously (the implementation of the clean and high thermal efficiency in diesel combustion), the introduction of a premixed combustion concept for a compression ignition (CI) engine system is desirable. Conventional diesel combustion is based on the combination of premixed and mixing controlled combustion phases [1]. Because the mixing controlled combustion phase is based on the heterogeneous mixture between air and fuel, most of the NOx and PM emissions occur during this period [2,3]. In addition, the duration of the mixing controlled combustion period is usually longer than the duration of the premixed combustion period so that heat transfer loss becomes worse and effective work during the expansion stroke is decreased [1]. The mixing controlled combustion phase usually has adverse effects on the aspects of engine-out emissions and thermal efficiency. Therefore, as mentioned above, it is necessary to increase the premixed combustion phase while reducing the mixing controlled combustion phase.

The most effective methods for increasing the premixed combustion phase in diesel engines are application of early diesel injection during the compression stroke and usage of a heavy exhaust gas recirculation (EGR) rate. These methods are related to the ignition delay. Period from the start of injection (SOI) to the start of combustion (SOC) gives time for the air and fuel mixture to be premixed well. These strategies could be classified as a premixed compression ignition (PCI). PCI combustions are different from the conventional diesel combustion aspect which indicates the large amount of premixed combustion phase while mixing controlled combustion phase is decreased.

These two PCI concepts shows effective emission reduction results compared to conventional diesel combustion, but there was a problem with the limitation of the operating range [4]. If the amount of diesel fuel was increased or the engine speed increased, there was a lack of premixing time between the air and diesel fuel. As a result, there was an obvious limitation to the extension of the operating range by using only diesel fuel.

For this reason, dual-fuel combustion, which uses two different types of fuel injection equipment (FIE), was introduced. Reactivity controlled compression ignition (RCCI) is a representative dual-fuel combustion that can be implemented by supplying a high fraction of low reactivity fuel such as gasoline and natural gas to the intake port with an early diesel injection strategy [5–7]. Because most of the low reactivity fuel was premixed due to the port fuel injection system, the premixed air-fuel mixture condition improved, and the small amount of diesel fuel became the ignition source. Thus, the characteristics of RCCI combustion were similar to the characteristics of homogeneous charge compression ignition (HCCI), as the entire combustion scheme was based on the premixed combustion phase. In previous research, Xingcai Lu et al. suggested the HCCI combustion using diesel and gasoline fuel blending in the cylinder [8]. The results showed that more controllable HCCI combustion which had the potential of low emissions with high gross indicated thermal efficiency (GIE) was possible by using dual-fuel combustion.

However, simultaneous premixed auto-ignition by dual-fuel combustion increased the maximum in-cylinder pressure rise rate problem usually under higher load conditions [9,10]. Additionally, a diesel injection strategy created unstable combustion too fast because the local fuel reactivity in the cylinder became lower as the reactivity stratification was small. As a result, the characteristics of dual-fuel combustion need to be known prior to making an improvement in these challenges of the dual-fuel combustion.

While only the local equivalence ratio was important for the conventional diesel combustion because it used a single fuel, the gradient of the fuel reactivity stratification in the cylinder was also important for the dual-fuel combustion. The reactivity stratification influenced on the reactivity gradient in the cylinder which could control the combustion duration. The reactivity gradient came from the different characteristics of two fuels and it is similar with the concept of 'primary reference fuel (PRF)' [5,7]. The local equivalence ratio and the reactivity stratification might be the major factors in defining the dual-fuel combustion modes.

As a result, in this research, the characteristics of dual-fuel combustion were investigated by comparing to the single-fuel, i.e., diesel, combustion. Especially, the classification of the dual-fuel combustion modes was discussed deeply by the experimental analysis of the heat release rate (HRR) shape with a single cylinder CI engine. Diesel and gasoline were selected as high and low reactivity fuels. The main variables were an overall-equivalence ratio, diesel injection timing and the ratio of the gasoline to the total amount of fuel. In the result part, there were three types of dual-fuel combustion as different fuel reactivity gradients which were affected by above three main factors.

2. Experimental setup

2.1. Experimental apparatus

A high-speed direct injection (HSDI) single-cylinder diesel engine with a 395 cc displacement based on the EURO V standard was used for these experiments. A solenoid diesel injector with a spray pressure of up to 180 MPa was equipped with a common rail system. Also, two solenoid gasoline port fuel injectors were equipped on the intake port with a fuel pressure of 0.5 MPa. The ratio between diesel and gasoline was calculated by each mass. More detailed specifications of the engine are introduced in Table 1. To control the engine, a 37 kW DC dynamometer was adopted To measure the fuel flow rates, a mass burette type flowmeter (ONO SOKKI, FX-203P) for diesel and a mass flow meter (AVL, 7030 flow meter) for gasoline were used. The concentrations of NOx, total hydrocarbon (THC), CO, CO_2 and O_2 were measured using an exhaust gas analyzer (Horiba, MEXA 7100DEGR), and the soot emission was measured by a smoke-meter (AVL, 415S). To measure the pressures, an absolute pressure transducer (Kistler, 4045A5) was used, and a relative pressure transducer (Kistler, 6055Bsp) with a glow-plug type adaptor was adopted for in-cylinder pressure. Signals from the pressure transducers were recorded using a scale of one crank angle per 100 cycles per case using a data acquisition (Kistler, KiBox To Go 2893 with integrated charge amplifier 5064B) system. The experimental setup is depicted in Fig. 1. Additionally, the diesel and gasoline properties are presented in Table 2.

2.2. Combustion analysis

From the measured values of the in-cylinder pressure, HRR and gross indicated mean effective pressure (gIMEP) were calculated. As a calculation model of HRR, the single-zone model, which uses the Woschini correlation for the wall heat transfer, was used. GIE was calculated by below equations (Eq. (1)) and low heating value (LHV) of diesel was 42.5 MJ/kg and that of

Table 1
Engine specifications.

Engine type	Single cylinder (four-stroke) compression ignition
Displacement [cc]	395
Bore [mm]	77.2
Stroke [mm]	84.5
Connecting rod [mm]	140
Compression ratio	14