รายงานการวิจัยฉบับสมบูรณ์

การศึกษาคุณลักษณะการเผาไหม้ของเชื้อเพลิง HVO และเชื้อเพลิง HVO ผสมเชื้อเพลิงดีเซลในห้องเผาไหม้ปริมาตรคงที่ ภายใต้เงื่อนไขกระบวนการนำไอเสียกลับมาใช้ใหม่และการเผาไหม้ที่อุณหภูมิต่ำ

COMBUSTION CHARACTERISTICS OF HYDROTREATED VEGETABLE OIL (HVO) AND DIESEL BLENDED FUELS IN CONSTANT VOLUME COMBUSTION CHAMBER (CVCC) UNDER EGR CONDITIONS AND LOW TEMPERATURE COMBUSTION (LTC)

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RESEARCH REPORT

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ชื่อโครงการ การศึกษาคุณลักษณะการเผาไหม้ของเชื้อเพลิง HVO และเชื้อเพลิง HVO ผสมเชื้อเพลิงดีเซลในห้องเผาไหม้ปริมาตรคงที่ภายใต้เงื่อนไขกระบวนการนำไอเสียกลับมาใช้ใหม่และการเผาไหม้ที่อุณหภูมิต่ำ

Combustion Characteristics of Hydrotreated Vegetable Oil (HVO) and Diesel Blended Fuels in Constant Volume Combustion Chamber (CVCC) under EGR conditions and Low Temperature Combustion (LTC)

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ABSTRACT

Hydrotreated vegetable oil (HVO), a modern alternative fuels. HVO is a second generation biofuel that produce from vegetable oil by using hydrotreating process. HVO is a mixture of normal paraffin and isomerized paraffin, which has superior advantages such as low sulfur and aromatics, high cetane number, high heating value and narrow distillation temperature range. From this reason, it offers significant improvement in performance and exhaust gas emissions of diesel engines. The objective of this research is to investigate effects diesel and HVO blending percentage on characteristics of ignition and spray combustion in constant volume combustion chamber (CVCC) under low ambient oxygen concentration and different ambient temperature using heat release analysis and to visualize combustion process of diesel and HVO blends in order to describe effects of fuel properties of HVO on spray development and flame development using shadowgraph technique. The experiment carried out using CVCC, four test fuels were tested: commercial diesel, two commercial diesel-HVO blends by mass: 20% (H20), and 50% (H50) and 100% HVO with single-hole injector, 0.2 mm in nozzle orifice diameter, 2.5 ms in energizing time. The injection pressure was kept constant at 100 MPa. The ambient oxygen concentration was varied between three discrete values from 21%, 15% and 10% to simulate effect of EGR conditions. The ambient temperature was varied at 1100 K, 900 K and 700 K to study effect of ambient temperature. The results showed that at low oxygen concentration 15% and 10%, the rate of combustion pressure decreased 9.08% and 29.58%, the integral heat release decreased 2.76% and 0.96% due to its lower oxygen availability. At low ambient temperature 900 K and 700 K, the rate of combustion pressure increases 6.77% and 6.46% because of longer ignition delay

promotes available time for mixing to obtain better mixture formation. A decrease of oxygen concentration results in an insignificant effects on spray development due to the same ambient air density and temperature, but the ignition delay is changed with oxygen concentration as seen as the luminous flame. At the 10% oxygen concentration, the flame luminosity is not observed due to the lack of oxygen, which results in a slow chemical reaction. The HVO is easier to vaporize and distribute in the chamber due to its lower density, viscosity and distillation temperature at T90. A decrease of ambient temperature effects on fuel-air mixing by providing a longer mixture formation time, resulting in later luminous flame with higher peak heat release rate. At 700 K of ambient temperature, the flame luminosity of only HVO is observed because of its higher cetane number provides high reactivity at low temperature. As the results, The HVO can be recommended to use in the diesel engine with EGR application as well, but it is necessary to optimize the engine when using in low temperature combustion such as reducing the compression ratio

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Nowadays, the renewable energy technologies are built, developed and distributed worldwide because of the public climate change and global warming. Many countries try to make abundant contribution of clean energy into building a clean environment and protecting public health. As a result, many researchers have been developed a new clean energy for the vehicles, for instance, fuel cell, battery electric, and also plug-in electric. From this reason, in order to replace conventional vehicles by those energy technologies, it is very difficult because of the production cost, well to wheel. However, the internal combustion engines and hybrid engines still play a role of light-duty vehicles at least 30 years (Council, 1994) .

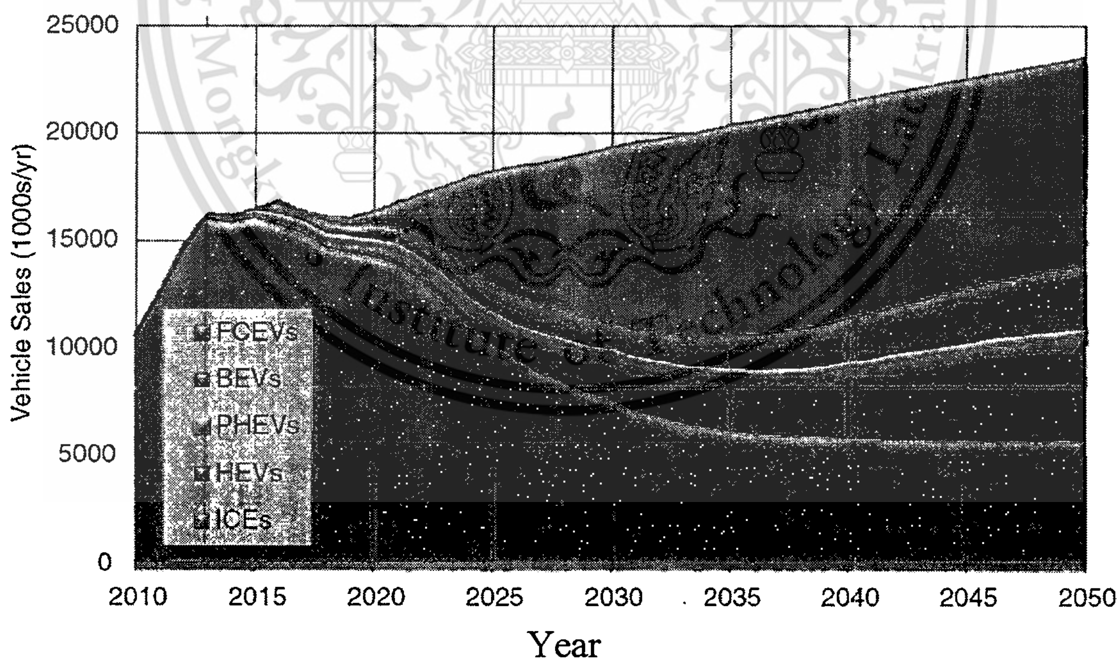


Figure 1.1 Vehicle sales by vehicle technology for midrange technologies and policies (Council, 1994)

Diesel engines provided higher thermal efficiency than spark ignition engines. However, diesel engines still have serious pollutant problems. Pollution is one of the many environmental challenges facing the world today (Tatsuo et al., 2008). Many researchers have been employed various techniques for reducing in exhaust gas emissions such as after-treatment systems (i.e. DOC, SCR, DPF, etc.) (Murtonen et al., 2009), engine combustion control (i.e. common-rail, swirl mixing, EGR, etc.) (Agarwal et al., 2013a, 2013b; Liu et al., 2013). On the other hand, researchers have been researched, invented and introduced alternative fuels to use in the diesel engine. An alternative fuels have not only sustainable but also friendly, respect with the environment. Therefore, a sustainable energy has been researched for applying into diesel engines such as biodiesel (i.e. FAME, SME, RME, etc.) and Hydrotreated Vegetable Oil (HVO).

Biodiesel is a first generation biofuel that produce from vegetable oil by using transesterification process (Hoekman and Robbins, 2012). Biodiesel has been widely utilized and used, as it can be directly used or blending used with diesel in the engines without no modification. However, it still has some disadvantages to the engines like high density and viscosity that make larger droplet size distribution, poor fuel-air mixing processes and mixture formation in the combustion process (Gao et al., 2009; Mohan et al., 2014), with low heating value (Qi et al., 2010), which resulted a decrease in engine power and increase fuel consumption due to loss of heating value (Xue et al., 2011). In addition, the use of biodiesel and blends can reduce exhaust gas emissions such as Hydrocarbon (HC), Carbon monoxide (CO) due to its higher cetane number and oxygen content, and Particulate matter (PM) due to lower aromatics and sulfur content (Xue et al., 2011). While Nitrogen Oxides (NO_x) emissions of biodiesel showed increase due to higher oxygen content that making a higher combustion temperature and flame temperature (Hoekman and Robbins, 2012; Xue et al., 2011).

From these reason, Hydrotreated vegetable oil (HVO) is attended and contributed into diesel engines from many researchers. HVO is the second generation biofuel, which can produce from many kinds of vegetable oil by using hydrotreating process. Due to HVO has potential benefits so that HVO can be promised alternative fuels as one of a candidate to replace diesel due to its more advantages in comparison with other alternative diesel fuels. The first one shows about production. It has variety of bio-feedstock, better oxidation stability. The second one is better fuel properties in the term of physical and chemical properties, for instance, low density, viscosity, low sulfur and aromatics, high cetane number, high heating value, and similar chemical composition to diesel (Lapuerta et al., 2011; No, 2014). From this reason, it offers significant improvement in engine performance and exhaust gas emissions and fuel consumption. However, HVO still have limitation to use in diesel engines as it shows very high cetane number and low lubricity, so researchers suggested that HVO would not be blended over 50% (Lapuerta et al., 2011).

However, in order to utilize HVO into diesel engines, it is necessary to understand effects of fuel properties on mixture formation, ignition and combustion as illustrated in Figure 1.2. From this figure shows the sub-processes in diesel engine mixture formation and combustion. The particular sub-processes proceed largely simultaneously and interact with each other. Generally, the conventional diesel engine combustion process is characterized by heterogeneous mixture formation and combustion. In direct-injection diesel engines, the air is induced into the combustion chamber and then compressed under compression stroke to generate high pressure and temperature, fuel is directly injected under high pressure and temperature in the combustion chamber. The liquid fuel entering the combustion chamber is atomized into small droplets, evaporated and is mixed with hot air, resulting in a heterogeneous mixture of fuel and air. Combustion is initiated by sufficient the high temperatures and pressures by an auto-ignition process. (Merker et al., 2012).

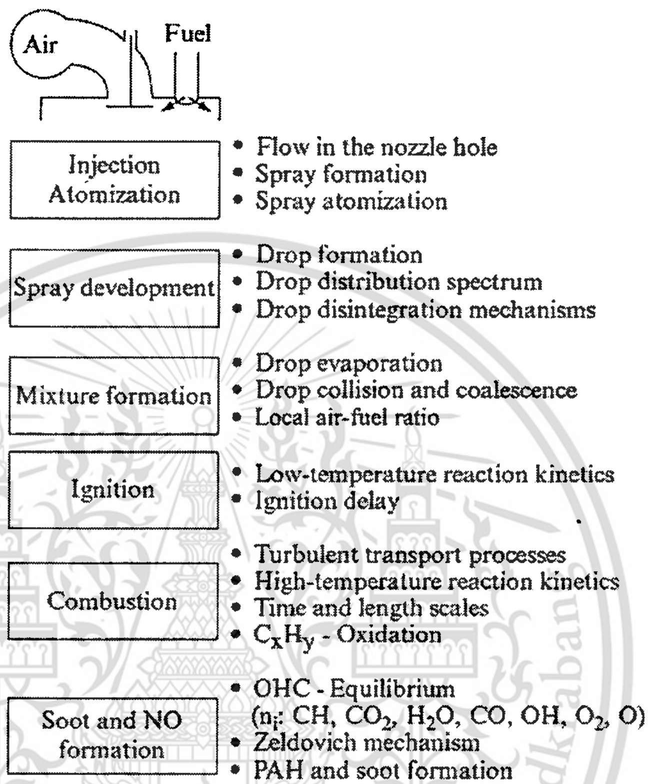


Figure 1.2 Sub-processes of mixture formation and combustion in diesel engines (Merker et al., 2012)

The employment of exhaust gas recirculation (EGR) is able to reduce NO_x emission. EGR causes a lower combustion temperature and keeps a lower flame temperature (Bedar and Kumar, 2016; Brijesh and Sreedhara, 2013; Sorathia et al., 2012). On the other hand, EGR decreases heat release due to decreased combustion pressure and combustion reaction intensity (Zhang et al., 2013).

In a moment, the low temperature combustion (LTC) strategies have been widely influenced to engine performance and emission characteristics of diesel engines because LTC is effective method to reduce flame temperature and combustion pressure that related to NO_x and soot emissions (Junjun et al., 2009; Zhang et al., 2012, 2013). LTC is very important field research to meet future regulated emissions of modern diesel engines by applying large amount of EGR ratio, low compression ratio as low ambient temperature. From previous research showed that LTC has potentially simultaneous reduction of NO_x and soot emissions under various low temperature combustion conditions (Imtenan et al., 2014; Kook et al., 2005; Zhang et al., 2012).

Previous research showed that the employment of HVO can improve engine performance and exhaust gas emissions of diesel engines. HVO has better in production and fuel properties compare to diesel. However, few researches have been performed the influence of diesel and HVO blend percentage on characteristics of the ignition delay and spray combustion by using heat release analysis under low oxygen concentration and different ambient temperature. Especially, the discussion on effects of diesel and HVO blend percentage on the combustion visualization by using shadowgraph technique, for instance, spray development and flame development have not clearly explained yet.

1.2 Research objective

1.2.1 To investigate effects diesel and HVO blending percentage on characteristics of ignition and spray combustion in constant volume combustion chamber under low oxygen concentration and low temperature combustion.

1.2.2 To visualize combustion process of diesel and HVO blends in order to describe effects of fuel properties of HVO on spray development and flame development.

1.3 Scope of work

In this experiment investigated spray combustion characteristics under low oxygen concentration and different ambient temperature in constant volume combustion chamber (CVCC) using heat release analysis and shadowgraph technique. The heat release analysis is applied to study the characteristics of ignition delay and combustion such as heat release rate, cumulative heat release, ignition delay, and integral heat release. The shadowgraph technique is used to visualize spray combustion process as spray development, flame development and capture combustion process by using a high speed video camera. The oxygen concentration was varied between three discrete values from 21%, 15% and 10% to simulate the effect of EGR conditions in the combustion chamber. The ambient temperature was varied from 1100 K, 900 K and 700 K to simulate the effect of ambient temperature.

CHAPTER 2

LITERATURE REVIEW

2.1 Conventional diesel engine

The conventional diesel engine combustion process is characterized by heterogeneous mixture formation and combustion. In direct-injection diesel engines, the air is induced into the combustion chamber and then is compressed under compression stroke to generate high pressure and temperature, fuel is directly injected under high pressure and temperature in the combustion chamber. The liquid fuel entering the combustion chamber is atomized into small droplets, evaporated and mixed with hot air, resulting in a heterogeneous mixture of fuel and air. Combustion is initiated by sufficient the high temperatures and pressures by an auto-ignition process. Therefore, the physical and chemical properties of fuel are dominated factors for the ignition process of diesel combustion (Heywood, 1988).

2.1.1 Diesel engine operation

There are four principle state of the diesel four-stroke engine operations; firstly, the air is induced into combustion chamber during the intake stroke, then is compressed under isentropic process to a higher pressure and temperature during the compression stroke. The injector inject the liquid fuel, fuel evaporated and mixed with hot compressed air, and burnt rapidly due to the auto-ignition process during the power stroke. The exhaust gas is push out by piston movement during the exhaust stroke.

The four-stroke diesel engine consists of, the intake stroke, the compression stroke, the power stroke, and the exhaust stroke as illustrated in Figure 2.1 (Heywood, 1988).

1. Intake stroke: The piston move down from top dead center (TDC) to bottom

dead canter (BDC) during intake valve open and exhaust valve close. The fresh air is induced into cylinder due to the difference in the pressure.

2. Compression stroke: The piston move up from BDC. The air is compressed, the air temperature and pressure increase during intake valve and exhaust valve are close.

3. Power stroke: Piston moves down from TDC due to the high combustion reaction of fuel injected. The liquid fuel is injected continuously into combustion chamber during power stroke. The in-cylinder pressure increase from combustion that converting into mechanical energy through the piston to the crankshaft.

4. Exhaust stroke: Piston move up from BDC to TDC during intake valve close and exhaust valve open. The exhaust gas is flow out of combustion chamber due to the different pressure between in-cylinder and ambient.

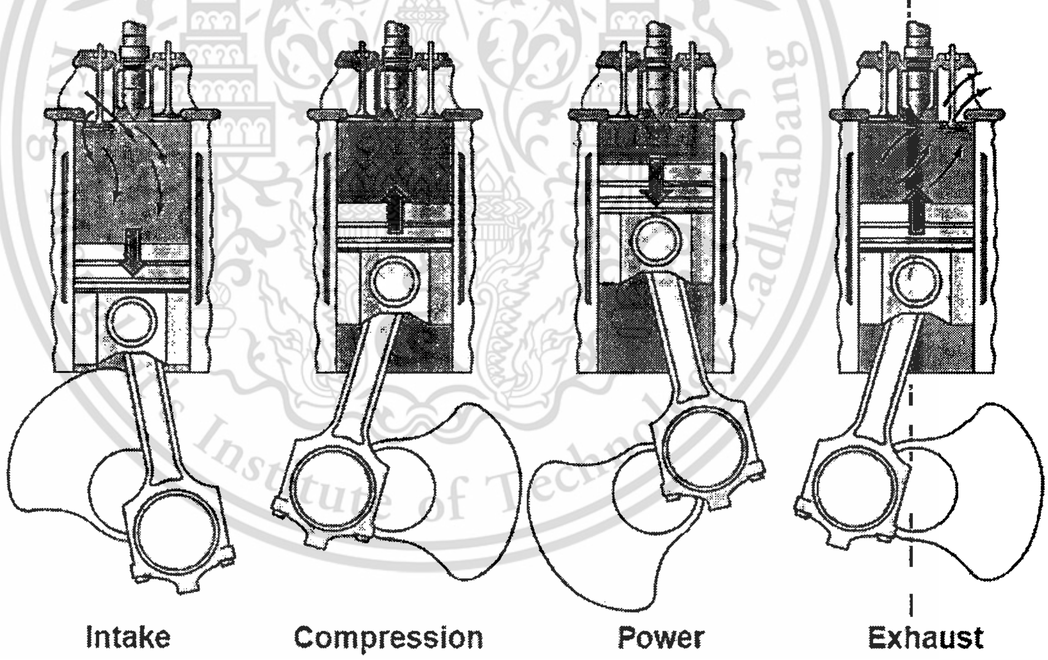


Figure 2.1 Four-Stroke diesel engines operation (Bennett, 2012)

2.2 Combustion of diesel direct-injection

2.2.1 Diesel combustion process

In diesel engine, the liquid fuel is injected directly into combustion chamber before TDC. However the fuel will not immediately combustion. Mixing time of fuel and air are required to be a mixture formation prior the ignition and combustion process as illustrated in Figure 2.3.

Ignition delay (a to b) is defined as the interval time between the start of injection (SOI) to start of combustion (SOC) where the heat release rates recovers from negative value due to heat absorption of fuel.

Premixed combustion (b to c) is defined as a rapid heat release rate. In this phase, combustion of fuel has already mixed with air during the ignition delay period occurs rapidly in a short time.

Mixing controlled combustion (c to d). When fuel and air are mixed during the ignition delay have been consumed, the heat release rate is controlled by the rate at which mixture becomes available for burning. While several processes are involved liquid fuel atomization, vaporization, mixture formation, and chemical reaction the rate of burning is controlled in this phase primarily by the mixture of fuel and air. The heat release rate may or may not reach a second peak in this phase; it decrease as this phase progresses.

Late combustion (d to e). Heat release continues at lower rate. There are several reasons for this phenomena. A small fraction of the fuel may not yet have burned. A fraction of the fuel energy present in soot and fuel rich combustion product. The cylinder charge mixing in this period promotes more complete combustion and less dissociated gases. The kinetics of the final burnout process become slower as the temperature of the cylinder gases fall.

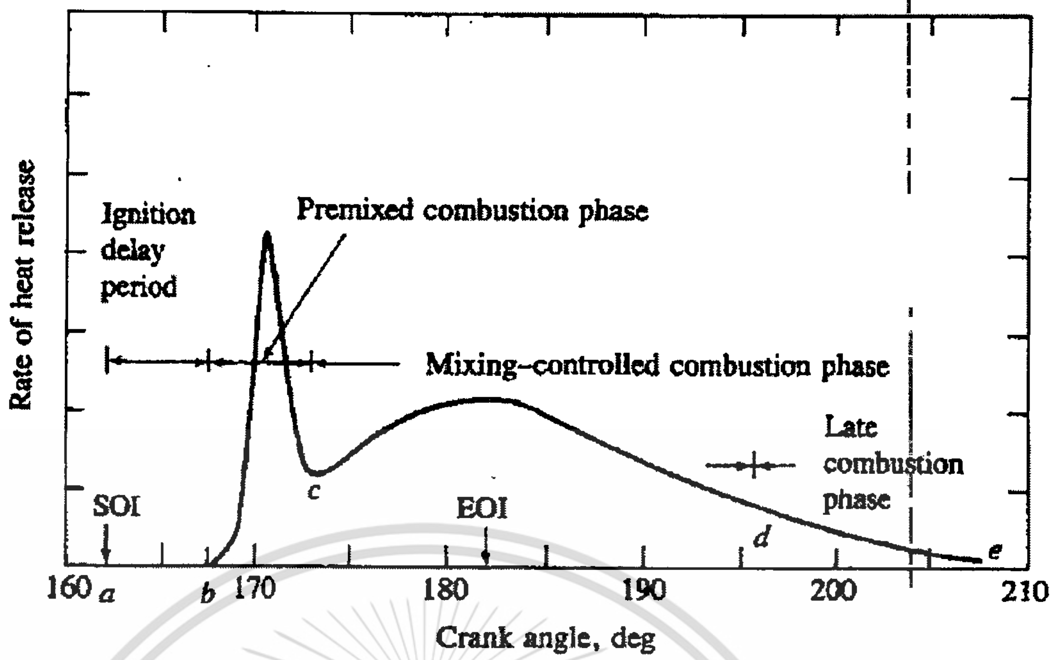


Figure 2.3 Combustion process of diesel direct-injection (Heywood, 1988)

2.3 Simulation of diesel engine combustion condition

In order to observe the combustion phenomena and to access diesel spray flame inside the combustion chamber of diesel engine is very difficult because combustion of diesel engine is very complicated. However, researcher has used many approaches and experimental equipment to access the combustion, for instance, the optical research engine (ORE), the rapid compression expansion machine (RCEM), constant pressure flow rigs (CPFR), constant volume hot cells (CVHC) and constant volume pre-combustion cell (CVPC) or constant volume combustion chamber (CVCC). As a result, the operation rage of CVCC can cover full range of diesel combustion condition. The CVCC has been widely used to study diesel spray combustion (Fujimoto et al., 2005; Kitamura et al., 2005; Nguyen et al., 2010). The CVCC can simulated a wide range of ambient gas pressure and temperature prior fuel injection. The simulated ambient gas pressure and temperature of CVCC in this research are linked to the pressure and temperature of diesel engine during the end of compression stroke. The operation of the experimental equipment were summarized by Baert *et al.* (Baert et al., 2009) as shown in Figure 2.4.

Table 2.1 shows the comparison of different experimental equipment. It can concluded that even though the ORE shows that most similarity to the real diesel engine situation, the CVCC is more suited and contributed for studying basic research of free spray combustion because it can give a wide operating range and large volume for diesel spray.

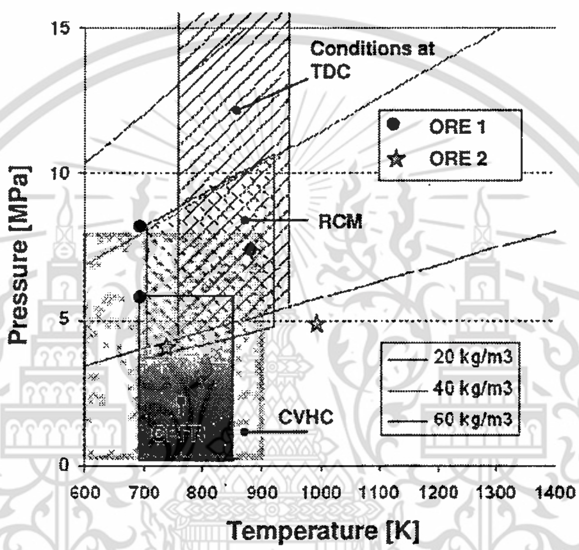


Figure 2.4 In-cylinder conditions prior injection of diesel engine compared to the operating range of different experimental equipment (Baert et al., 2009)

Table 2.1 The comparison of different experimental equipment; ORE, RCEM, CVFR and CVPC or CVCC (Baert et al., 2009).

Type of optical test rig	ORE	RCM	RCYM	CPFR	CVHC	CVPC
Optical accessibility	0	0	++	++	-	+
Similarity to the real engine situation	0	-	--	--	--	--
Free spray penetration distance	0	+	+	+++	++	++
Control on trapped gas p / T	0	+	0	++	++	++
Control on trapped gas composition (i.e. EGR)	0	-	0	+	++	+++
Flow field impact on combustion	--	-(-)	-	0	-	-
Test facility volume	0	+	0	0	++	++
Time to switch between operating conditions (i.e. T)	0	0	0	0	--	++
Time between tests [s] (*)	1	120-600	1	1-3	60	600

Note: mostly relative: 0 = neutral, + = better, - = worse

2.4 Fuel injection system

The high injection pressure system or called "common rail system" as shown in Figure 2.6 has been developed for the modern diesel engines in order improve fuel atomization, mixture formation, combustion efficiency, and also engine-out emissions of diesel engines. There are nine main parts; (1) Supply pump is used to supply high pressure fuel into (2) the common rail, which is equipped with pressure sensors; (3) Pressure sensor is used control fuel pressure inside the rail to suit with the engine operating conditions; (4) Electronic Control Unit (ECU) is used to control operating the common rail system based on information from various sensors, such as (5) pressure limiter, the crankshaft positioning sensor, the throttle positioning sensor, the intake temperature; (6) Electric Driver Unit (EDU) receive information from ECU to control injector suit with load and speed of the engine. ECU also controls the suction control valve (SCV) of supply pumps to match with engine operation; (7) Injector is used to inject fuel; (8) Fuel filter and (9) Fuel tank.

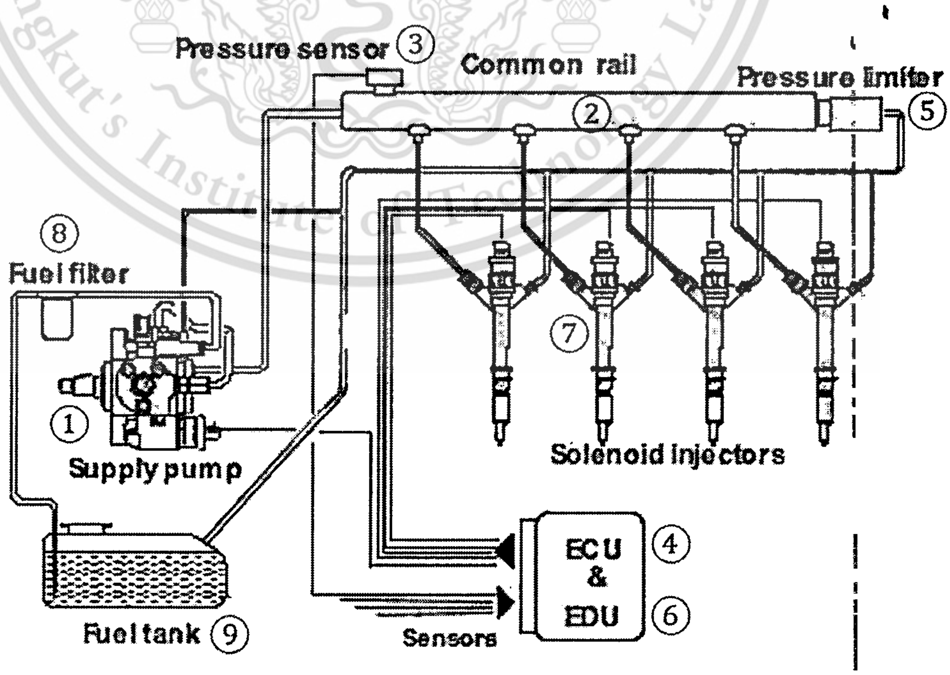


Figure 2.6 Main component of common rail system (Densoautoparts, n.d.)

2.5 Hydrotreated Vegetable Oil

Hydrotreated vegetable oil (HVO) is a second generation biofuel that produce from vegetable oil by using hydrotreating process, the triglyceride is hydrogenated in the first step and broken down into various intermediates, mainly monoglycerides, diglycerides, and carbonxylic acids. These intermediates are then converted into alkanes by different pathways: decarboxylation, decarbonylation (both removing a carbon atom), and hydrodeoxygenation (with no carbon remove) at the temperatures above 300–360 °C and pressure at least 3 MPa. Propane, water, carbon monoxide and carbon dioxide are produced as side-products (No, 2014).

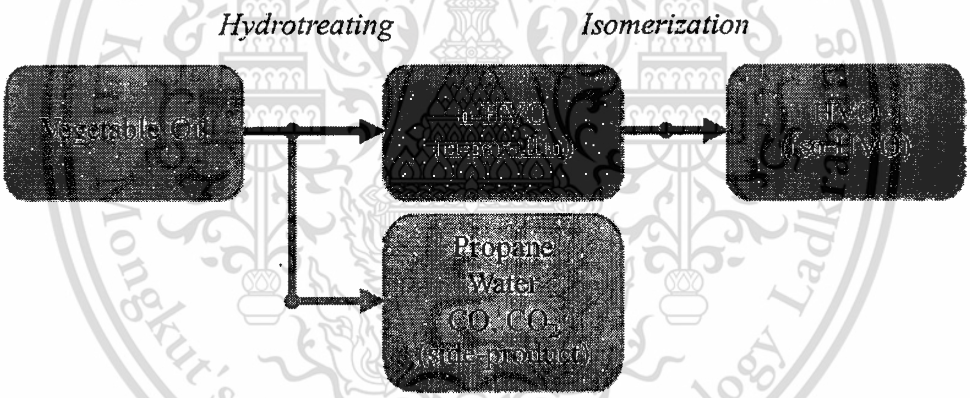


Figure 2.7 Schematic diagram of HVO production (No, 2014)

HVO is a mixture of normal and iso-paraffin with straight chain-length (Caprotti et al., 2011; No, 2014). The properties of HVO are beneficial to use into the diesel engine such as high cetane number, high heating value and narrow distillation temperature range. However, there are some disadvantages that may limit to use HVO from previous study such as poor low-temperature properties, as displayed by cloud point, pour point and cold filter plugging point (CFPP) (No, 2014). Therefore, an improvement process as isomerization process is may be use to solve that problem then HVO would be iso-HVO.

2.6 Effect of HVO on combustion and emissions characteristics

Sugiyama *et al.* (Sugiyama et al., 2011) carried out HVO on the engine and chassis dynamometer. The engine was 4-cylinders diesel direct-injection engine, 2.2 liter turbocharged with common rail system. The results from the engine test showed that heat release rate of HVO exhibited more advance with shorten ignition delay due to the high cetane number for both single and pilot-injection cases. HVO is early start of combustion for low, medium and high engine load at engine speed of 2000 rpm. The exhaust gas emissions and fuel consumption of HVO can decrease 4.97% in nitrogen oxide (NO_x), 34.54% in hydrocarbon (HC), 37.79% in carbon monoxide (CO) and 3.21% in fuel consumption.

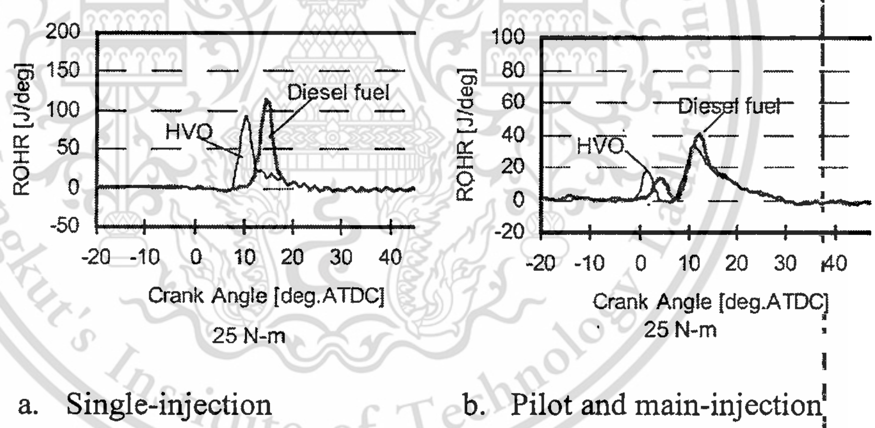


Figure 2.8 Results of rate of heat release using HVO with low engine load (Sugiyama et al., 2011)

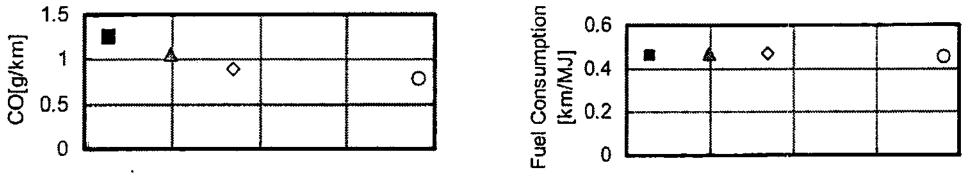


Figure 2.9 Results of exhaust gas emissions and fuel consumption using HVO in the vehicle test (Sugiyama et al., 2011)

Jaroonjitsathian *et al.* (Jaroonjitsathian et al., 2014) studied effects of HVO, GTL, HVO and GTL blend with diesel 50% on engine performance and emission characteristics. The experiment conducted with 4-cylinders common-rail direct injection engine, 2.5 liter. This study was performed using pilot and main injection at engine speed of 1170 rpm. The results revealed that ignition delay of HVO was shorter than diesel by 7.0% for pilot injection condition, and 7.5% for without pilot injection due to a high cetane number as shown in Figure 2.10, the shorter combustion duration by 8.46% for pilot injection, and 4.96% for without pilot injection as shown in Figure 2.11 due to narrow distillation range and lower distillation temperature at T90, which provided better vaporization and good mixture formation.

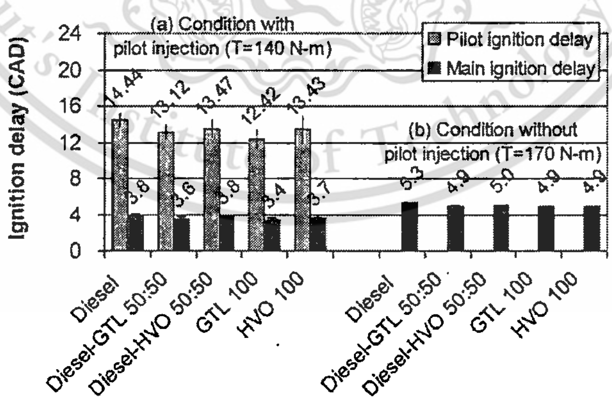


Figure 2.10 Comparison of the ignition delay (Jaroonjitsathian et al., 2014)

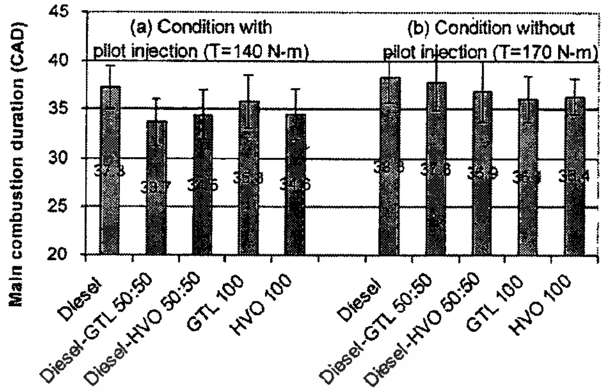
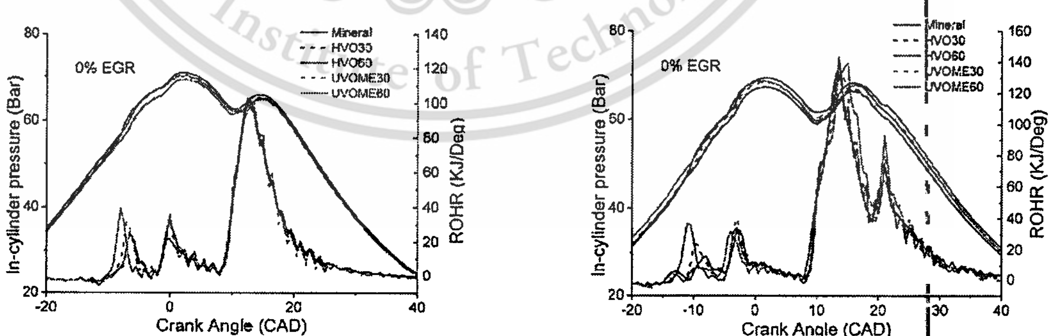
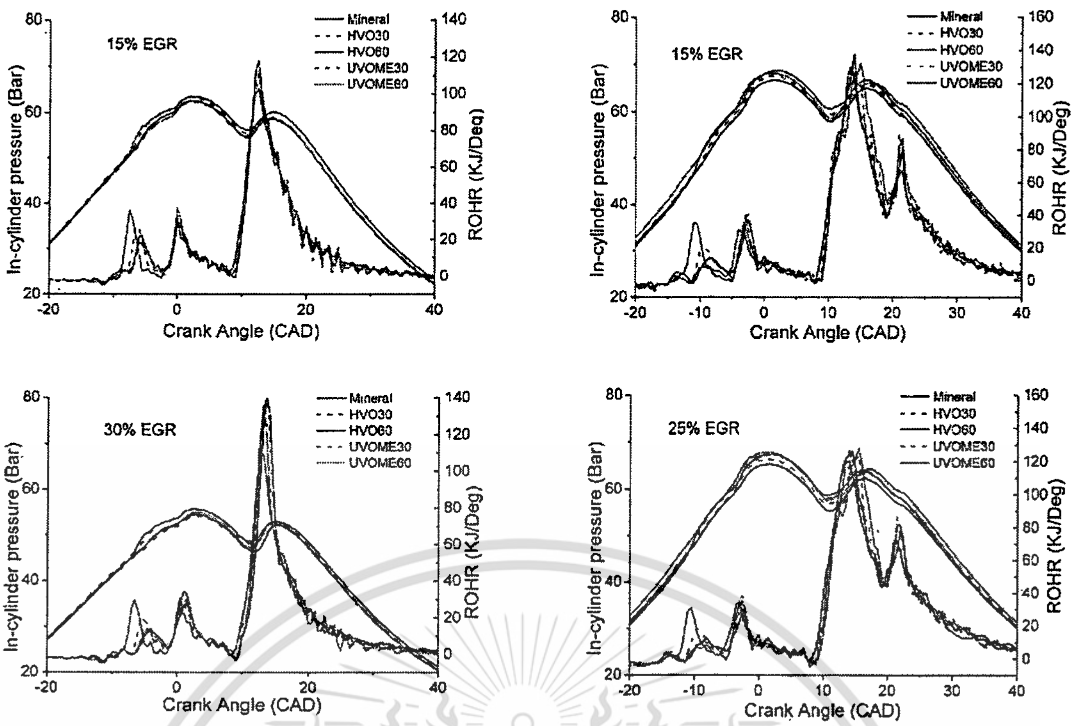


Figure 2.11 Comparison of combustion duration (Jaroonjitsathian et al., 2014)

Liu *et al.* (Liu et al., 2013) studied effects of HVO blends on combustion characteristics by using 6-cylinders diesel engine, turbocharger 3.0 liter. The engine was performed under EGR conditions with low and high engine load at 1500 rpm. The results concluded that combustion pressure and heat release rate of HVO showed slightly higher than diesel, moreover the shorter ignition delay and combustion duration were observed with high EGR rate due to its higher cetane number, higher amount energy per unit volume, and the straight chain-length of HVO is easier to broken up than diesel fuel.





1500RPM, 72Nm. (a)0% EGR, (b)15% EGR, (c)30% EGR

(b) 1500RPM, 143Nm. (a)0% EGR, (b)15% EGR, (c)25% EGR

Figure 2.12 Results of In-cylinder pressure and rate of heat release (Liu et al., 2013)

Millo *et al.* (Millo et al., 2015) investigated HVO blend by using 4-cyliders diesel direct-injection engine, turbocharger 1.2 liter at 1500 RPM@ 2 bar BMEP This experiment concluded that HVO blend with diesel 30% showed increase of engine performance by increasing fuel conversion efficiency and lower brake specific fuel consumption (BSFC) with various advance start of injection (SOI). In addition, HVO blend can increase fuel conversion efficiency and reduce BSFC with using EGR simultaneously at low engine load with SOI = 5.7 deg bTDC.

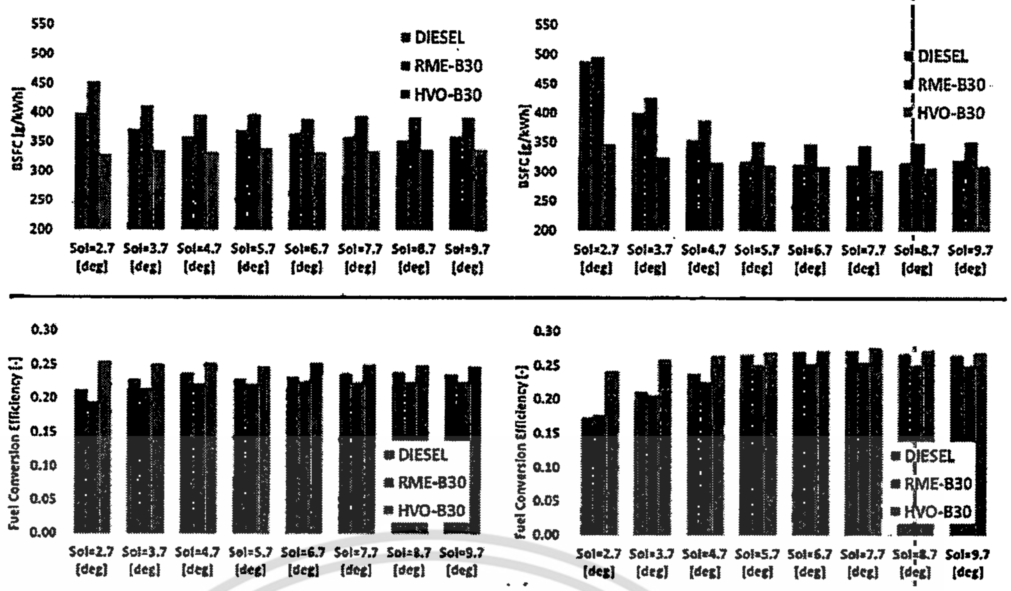


Figure 2.13 In-cylinder pressure, heat release rate, mass fraction burned, and injector signal (Millo et al., 2015)

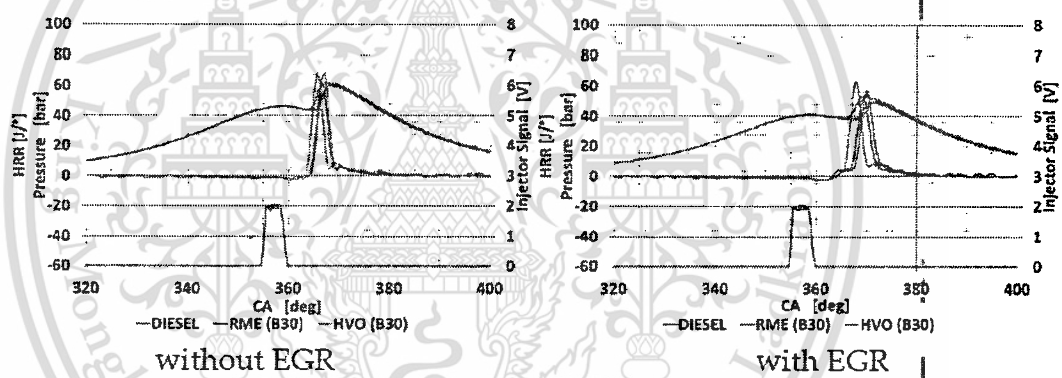


Figure 2.14 In-cylinder pressure, heat release rate, mass fraction burned, and injector signal (Millo et al., 2015)

Armas *et al.* (Armas et al., 2015) carried out HVO on chassis dynamometer to performance, combustion and emission characteristics under New European Driving Cycle (NEDC) by using 4-cylinders diesel direct-injection engine. The results showed that HVO exhibited 9.74% lower specific fuel mass consumption, 9.21% lower heat release rate, and shorter ignition delay due to its higher cetane number. In addition, exhaust gas emissions also decreased.

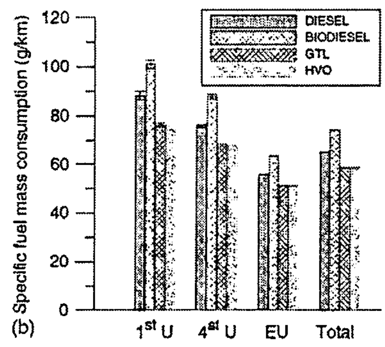


Figure 2.15 Results of specific mass consumption (Armas et al., 2015)

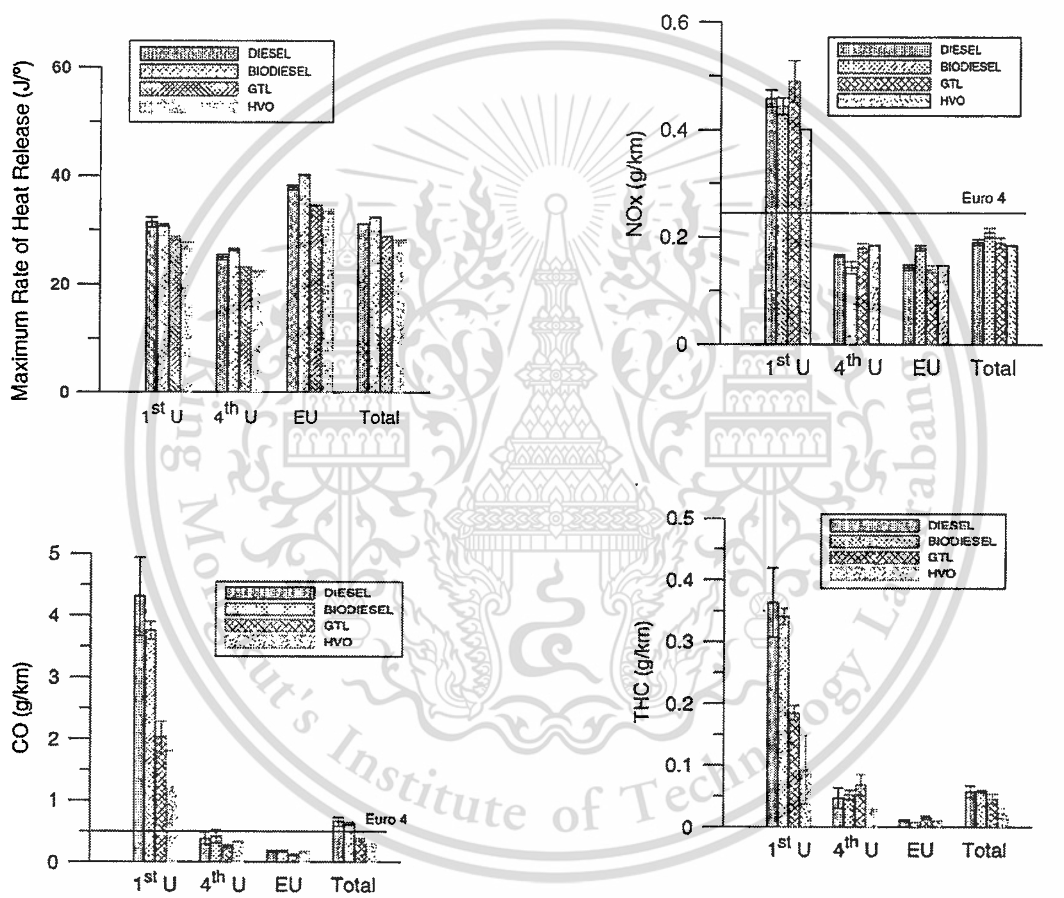


Figure 2.16 Results of heat release rate and specific NO_x, CO and HC emissions (Armas et al., 2015)

From previous researches have been done on combustion and emission characteristics, so these can be summarized that HVO provided a shorter ignition delay, similar heat release rate trend (Jaroonjitsathian et al., 2014; Millo et al., 2015;

Sugiyama et al., 2011), and lower exhaust gas emissions (Aatola et al., 2008; Jaroonjitsathian et al., 2014), for instance, HC and CO emissions because HVO is more complete combustion due to its better ignition quality then provide better combustion efficiency.

2.7 Exhaust gas recirculation

Exhaust gas recirculation (EGR) is one of today's most common engine control system that used to suppress NO_x formation. The exhaust gas are introduced to mix with fresh air into the combustion chamber, diluting oxygen concentration and increasing its heat capacity in combustion chamber (Bedar and Kumar, 2016; Zheng et al., 2004). Therefore, the diluted oxygen availability caused the lower combustion temperature and reduced flame temperature, then reduced NO_x formation.

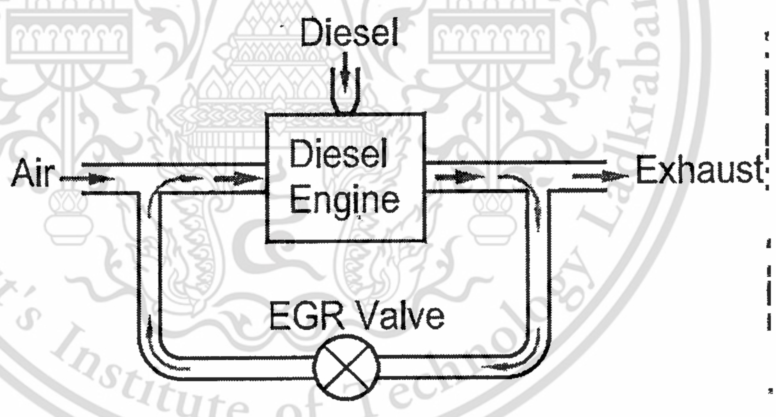
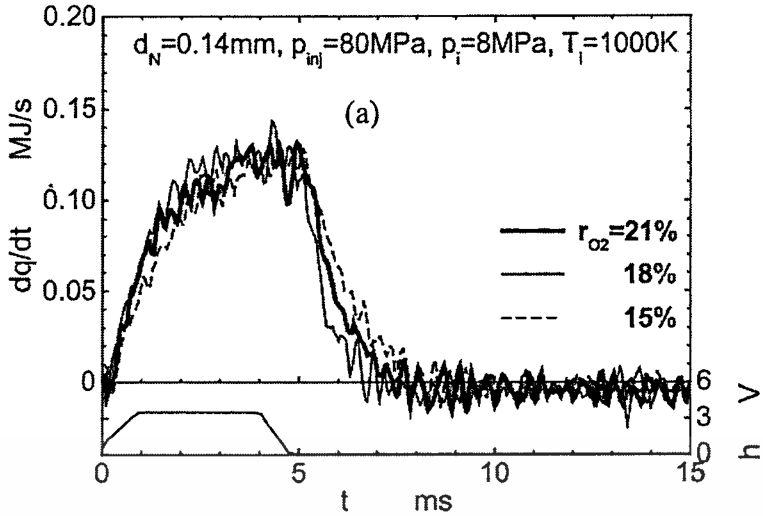


Figure 2.17 Exhaust gas recirculation (EGR) (Zheng et al., 2004)

Kitamura *et al.* (Kitamura et al., 2005) experimentally investigated effects of oxygen concentration on diesel combustion in constant volume combustion chamber (CVCC) under simulated diesel combustion condition. The results showed that the decreased oxygen concentration to 18% and 15% had not affected to heat release rate, but it largely affected to NO_x emission as shown in Figure 2.18.



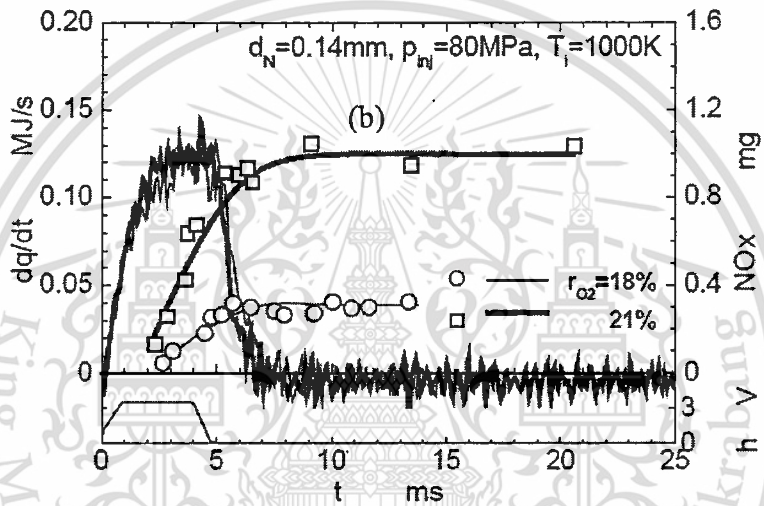


Figure 2.18 Effect of oxygen concentration on (a) heat release rate and (b) NO_x emission (Kitamura et al., 2005)

Zhang *et al.* (Zhang et al., 2013) investigated effect of oxygen concentration by change oxygen concentration 21%, 18%, 15% 12% and 10% in CVCC. The results showed that the lower oxygen concentration extended ignition delay and reduced heat release rate due to decrease in combustion reaction intensity as shown in Figure 2.20. Moreover, decreasing reaction intensity is explained in function of OH* chemiluminescence as shown in Figure 2.21.

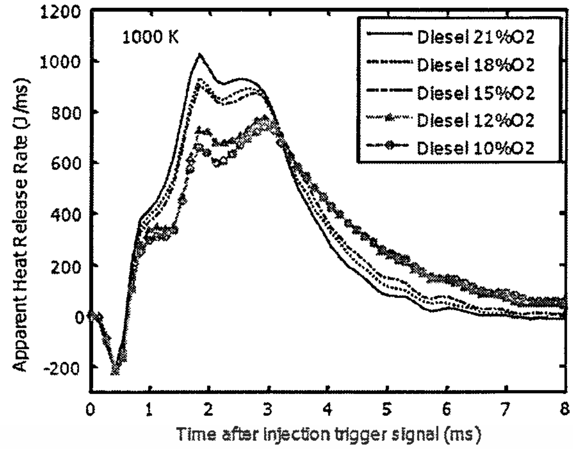


Figure 2.20 Effects of oxygen concentration on heat release rate (Zhang et al., 2013)

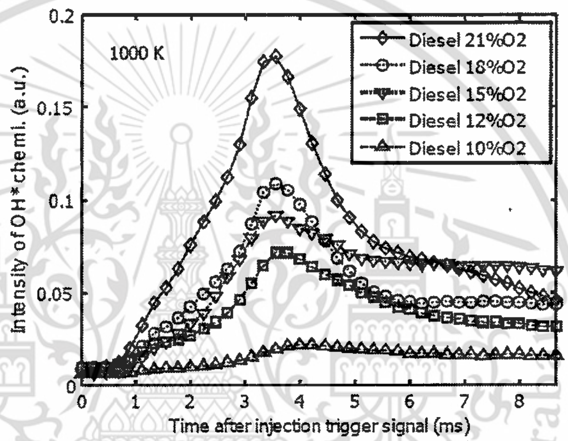


Figure 2.21 Effects of oxygen concentration on OH* chemiluminescence (Zhang et al., 2013)

Ewphun *et al.* (Ewphun et al., 2017) investigated effects of oxygen concentration and supercharged conditions on the combustion characteristics of HVO-diesel blends in Rapid Compression Expansion Machine (RCEM). The results showed that the employment of HVO and blends decreased the ignition delay, the flame temperature, the soot concentration and the NO_x concentration simultaneously. In addition, heat release rate at oxygen concentration of 10 % dramatically dropped due to a shortened ignition delay. The heat release rate, flame temperature, and NO_x concentration were decreased when the oxygen concentration was reduced due to decreasing reaction intensity. The results of reducing in oxygen concentration conditions showed that an increase in heat release rate, flame temperature, decrease in ignition delay and soot concentration.

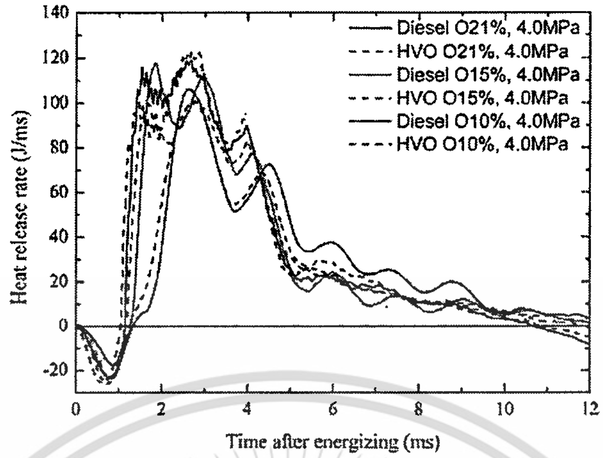


Figure 2.23 Heat release rate under reduce oxygen concentration (Ewphun et al., 2017)

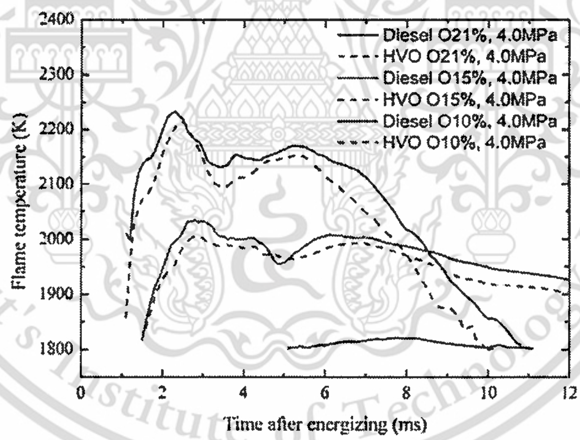


Figure 2.24 Flame temperature under reduce oxygen concentration (Ewphun et al., 2017)

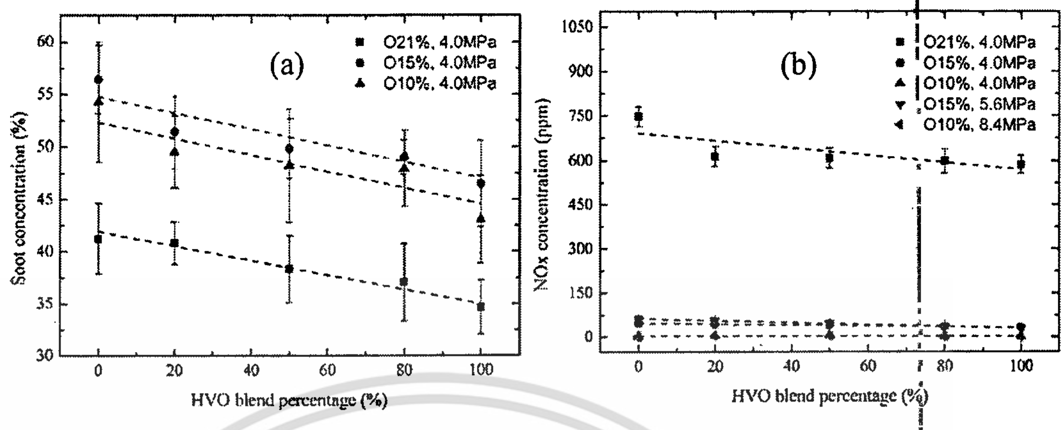


Figure 2.25 (a) Soot and (b) NO_x concentration under reduce oxygen concentration (Ewphun et al., 2017)

2.8 Low temperature combustion

A main benefits of using low temperature combustion (LTC) is to reduce NO_x and soot emissions simultaneously as lowering local temperature range (Imtenan et al., 2014; Kook et al., 2005; Neely et al., 2005), From previous research, there are two categories of LTC (Imtenan et al., 2014; Kook et al., 2005). First, the combustion phasing is decoupled from injection timing and combustion is dominated by the chemical reaction, the mixture is near homogenous like homogenous charge compression ignition (HCCI) as an equivalence ratio is less than 1. In the second category, using the injection event, pre-mixing occurs between the fuel injection and start of combustion event, but significant regions exist where the equivalence ratio is greater than unity at the start of the combustion like premixed charge compression ignition (PCCI).

The main objective of these strategies is to keep a flame temperature low by using low compression ratio, large amount of cooled EGR, and using retarded injection timing (Kook et al., 2005). Therefore, LTC can achieved a lower flame temperature that leaded to decrease simultaneously in NO_x and soot emissions at expressed in Figure 2.26.

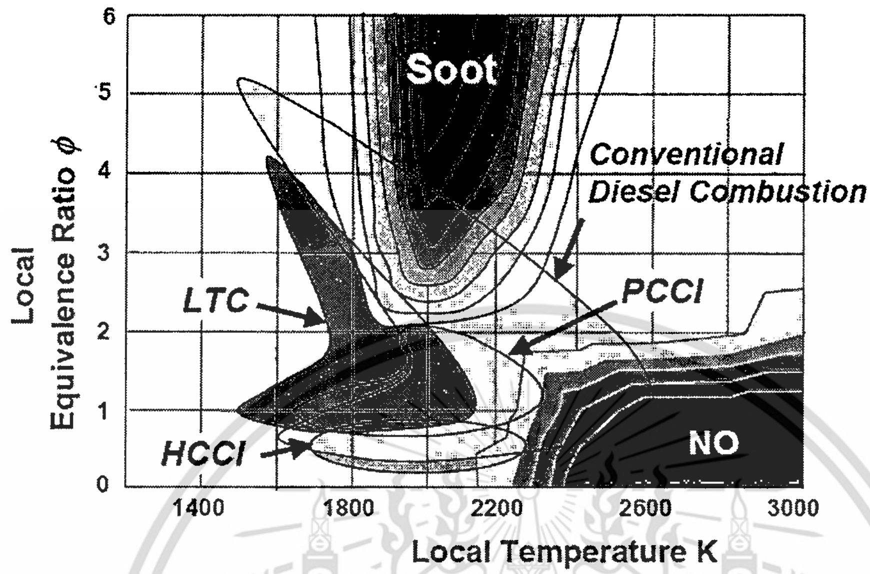
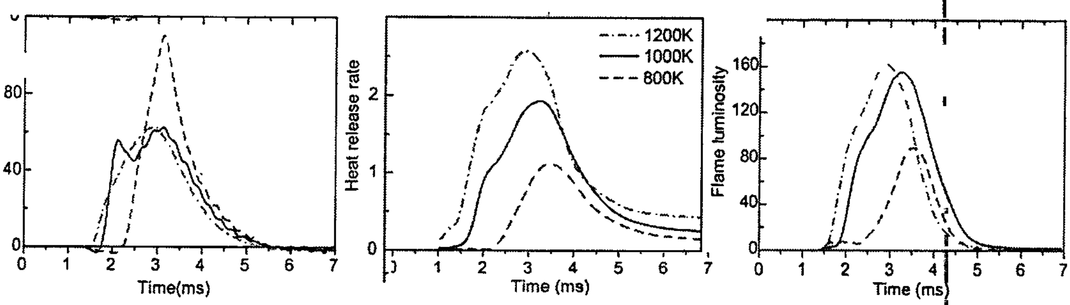


Figure 2.26 Local equivalence ratio and local temperature map (Neely et al., 2005)

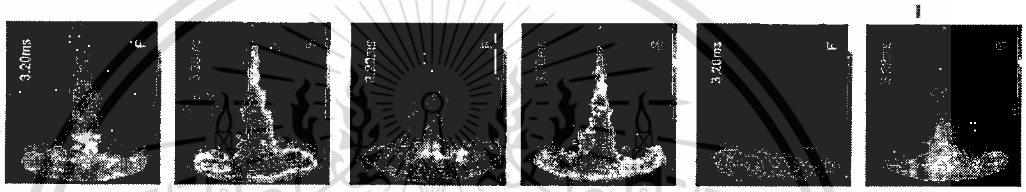
Xu *et al.* (Xu and Lee, 2004) studied effects of ambient temperature and oxygen concentration on soot evaluation in constant volume optical spray chamber. The ambient temperature was 1200 K, 1000 K and 800 K. The oxygen concentration was varied at 21% to 15%. The conclusions showed that a decrease of ambient temperature caused longer ignition delay with higher heat release rate. The fuel burnt is increased with portion of premixed combustion. In addition, decreasing ambient temperature is beneficial to less soot form during combustion as shown by soot mass, and reduced flame luminosity. Lower oxygen concentration caused lower flame luminosity, while having the same soot level. In addition, the combustion process is basically not changed with changing oxygen concentration, but longer combustion duration and lower heat release rate. The lower heat release rate resulted lower flame temperature, which might contribute to reduce NO_x emission.



Heat release rate　　Flame luminosity　　Total soot mass

Figure 2.27 Heat release rate, Flame luminosity and Total soot mass under various ambient temperature (Xu and Lee, 2004)

Flame　Soot　Flame　Soot　Flame　Soot



At 1200 K　　At 1000 K　　At 800 K

Figure 2.28 Flame luminosity and soot distribution images under various ambient temperature (Xu and Lee, 2004)

Zhang *et al.* (Zhang et al., 2012) studied the transient flame structure by high speed imaging of natural luminosity and OH* chemiluminescence of diesel under low oxygen concentration and low temperature combustion in CVCC. The results showed that at the same ambient temperature, 15% O_2 concentration provides a shorter ignition delay with higher heat release rate compared to 10% O_2 concentration due to a higher oxygen availability in the chamber. At the same O_2 concentration, decreasing ambient temperature provides a longer ignition delay with higher heat release rate due to improved mixture preparation, also resulting in higher burning rate. The intensity of natural luminosity (NL) showed that decreasing O_2 concentration decreased the level NL as decrease flame temperature. Decreasing ambient temperature decreased OH* chemiluminescence as reduce combustion intensity. This lead to reduce soot form.

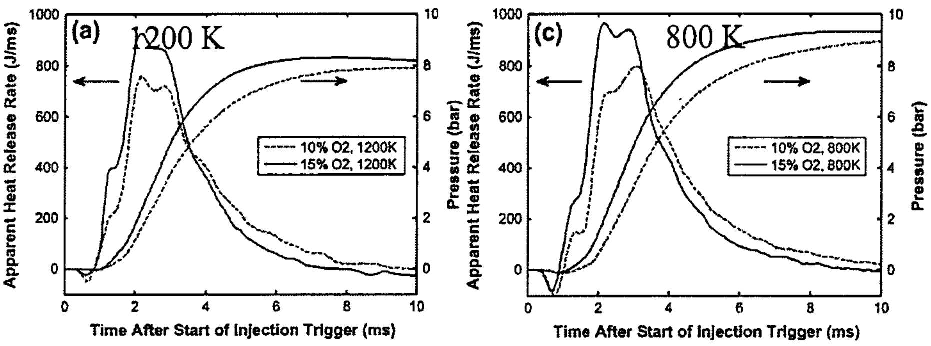


Figure 2.29 Heat release rate at 15% and 10% O_2 concentration and ambient temperature of 1200 K and 800 K (Zhang et al., 2012)

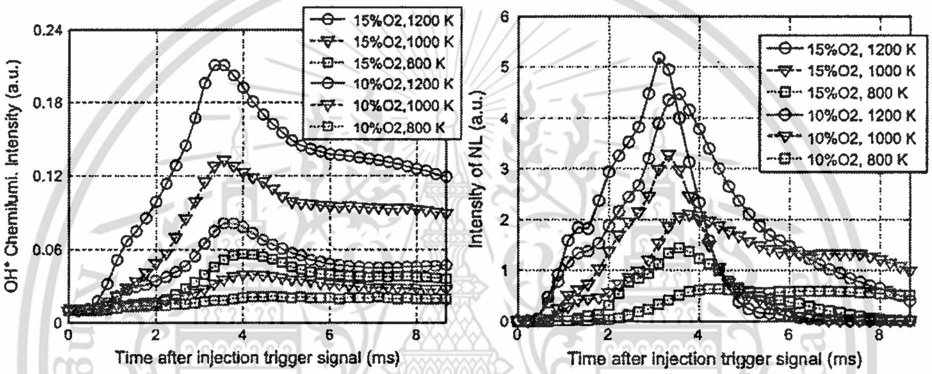


Figure 2.30 OH* chemilumi. and natural intensity at 15%, 10% O_2 concentration and ambient temperature of 1200 K, 1000 K, 800 K (Zhang et al., 2012)

2.9 Research gap

The advantages of properties of HVO, as displayed by low sulfur and aromatics, narrow distillation temperature range, lower T90 distillation temperature, and higher cetane number, which might contribute to improve combustion under low oxygen concentration and low temperature. In addition, to meet the further stringent emissions, the EGR method as decreasing oxygen concentration is the most effective method to control NO_x emissions. LTC strategy is beneficial technique to suppress the formation of NO_x and soot particles simultaneously due to lower flame temperature.

Currently, few researches have been concluded the influence of diesel and HVO blend percentage on the characteristics of the ignition delay and spray combustion by using heat release analysis and shadowgraph technique. Especially, the discussions on effects of diesel and HVO blend percentage on the combustion visualization such as spray development and flame development have very limited data. Therefore, the fundamental data of ignition delay, combustion and the visualization of combustion are helpful information to optimize and to develop the further design in diesel operating combustion conditions by utilizing HVO.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Heat release analysis in constant volume chamber

Heat release rate (Heywood, 1988) can be determined from pressure rise after burning injected fuel based on the first law of thermodynamics of the system, as shown in Equation (3.1).

$$\frac{dQ}{dt}=\frac{\gamma}{\gamma-1}\cdot P\cdot\frac{dV}{dt}+\frac{1}{\gamma-1}\cdot V\cdot\frac{dP}{dt} \tag{3.1}$$

Where,

γ	Ratio of specific heat
dV/dt	Chamber volume change with time, m^3/s
dP/dt	In-chamber pressure change with time, Pa/s
P	In-chamber pressure, Pa
V	Chamber volume, m^3

In this study, the heat release analysis was studied in constant volume chamber where the chamber volume is kept constant then the *dV/dt* term can be deleted (Mayo and Boehman, 2015). Hence, heat release rate is expressed as follows:

$$\frac{dQ}{dt}=\frac{1}{\gamma-1}\cdot V\cdot\frac{dP}{dt} \tag{3.2}$$

3.2 Ignition delay determination

The ignition delay characterized into physical delay, which is associated with fuel atomization, vaporization and mixing. This depend on the physical properties such as fuel viscosity, density, and distillation temperature. While chemical delay is associated with chemical composition and structure, temperature, pressure, and oxygen mole fraction. In this study, the ignition delay is defined as the interval time between start of injection (SOI) to start of combustion (SOC) where heat release rate recover from the negative value due to heat absorption. This has been widely used to determine ignition delay (Ewphun et al., 2017; Heywood, 1988; MUNSIN, 2014; Nguyen et al., 2010; Srichai, 2016) as described in Figure 3.1.

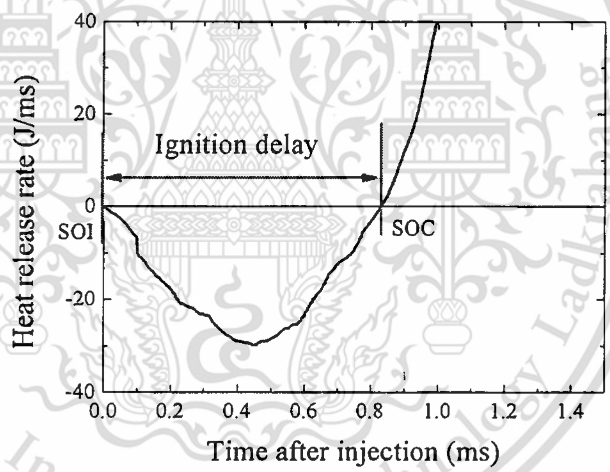


Figure 3.1 Definition of ignition delay (Nguyen et al., 2010)

3.3 Experimental setup

Figure 3.3 shows the schematic diagram of spray combustion characteristics experiment using CVCC. The schematic diagram in this experiment consists of three parts: (1) the high pressure fuel injection system was used to generate high injection pressure, the three-phase motor was used to drive a second generation common-rail pump to generate high fuel pressure by the inverter controller; (2) the gas system was used to allow to introduce into combustion chamber in order to simulate ambient gas condition; (3) the CVCC, the heater, the ignition system, the data acquisition and controller. The CVCC was a circular cylinder with 80 mm in diameter, 100 mm in depth. The two quartz windows were equipped in this chamber for optical assessment.

There are six main parts of combustion chamber system as shown in Figure 3.4: (1) an intake valve was used to control partial pressure of premixed gaseous mixture of acetylene (C_2H_2), oxygen (O_2) and nitrogen, (N_2); (2) an exhaust valve was used to remove burnt-gas after combustion is ended; (3) the conventional spark plug was used to ignite gaseous mixture to generate high pressure and temperature; (4) the mixing fan was used to run 25 second before spark-ignition for maintaining uniform gas distribution throughout the combustion of fuel; (5) a dynamics pressure transducer (Kistler 6053CC60) and charge amplifier (Kistler 5011) were used to measure pressure rise of combustion, and (6) a single-hole injector was installed at the top of combustion chamber to inject tested fuel. The pressure rise of auto-ignition was recorded by oscilloscope (RIGOL DS1052E) with sampling rate $5x10^5$ S/s.

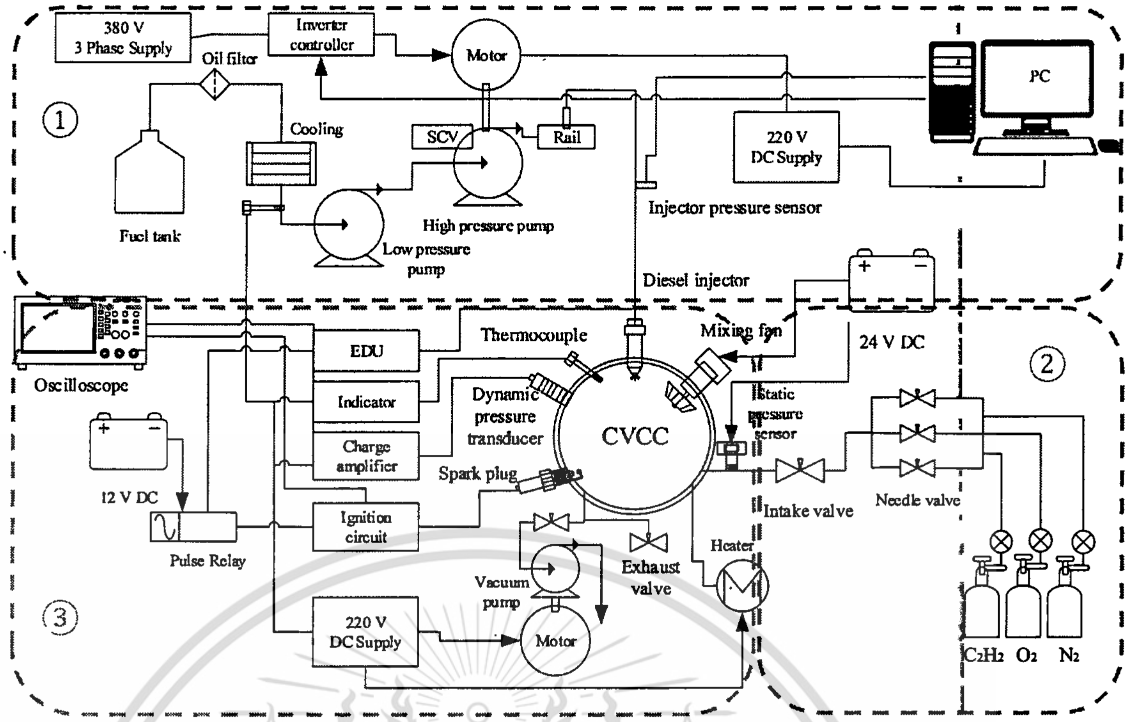


Figure 3.3 Spray combustion characteristics experiment using CVCC

Figure 3.4 Constant volume combustion chamber system

3.4 Bulk gas temperature

The bulk gas temperature is used to calculate the relationship of ambient gas temperature and pressure as shown in Figure 3.5. From this figure, the ambient temperature is calculated based on the initial premixed gas of 1.5 MPa and the percentage of oxygen concentration of 21%. The ambient gas temperature and pressure were assumed to be uniform at each steps of ignition in this chamber. The ambient gas temperature data was used to precisely evaluate for cool down time, time after ignition where is start of injection. The equation can be expressed as follows (Mayo and Boehman, 2015; MUNSIN, 2014; Srichai, 2016):

$$T_{bulk}=T_{init}\left(\frac{P_{bulk}}{P_{init}}\right)M \tag{3.3}$$

Where,

T_{bulk} Bulk gas temperature of combustion products, K

T_{init} Initial temperature of the premixed gas, K

P_{bulk} Bulk gas pressure of combustion products, N/m^2

P_{init} Initial pressure of the premixed gas, N/m^2

M Ratio of molecular weights of the combustion products and the premixed gas

To simulate ambient oxygen concentration of 21%, 15% and 10% and ambient temperature of 1100 K, 900 K and 700 K, it is essential to control precisely the percentages of oxygen concentration by controlling the initial pressure. The gas composition in the chamber was evaluated prior spark-ignition and at start of fuel injection. The ambient gas temperature was calculated and evaluated to obtain the time of fuel injection in the combustion chamber. The ambient temperature was calculated by using Equation 3.3. The ambient temperature in this research is linked to the top dead center of diesel engine at the end of compression stroke. The percent of oxygen concentration remain as shown in Table 3.1.

This has been widely used to study combustion in constant volume chamber (Jing et al., 2013; Zhang et al., 2012, 2013).

Table 3.1 Percent of oxygen concentration at the time of fuel injection and reactants prior to spark ignition

Percentage of oxygen concentration	Gas composition [mol%] (Composition before spark ignition)			Gas composition [mol%] (Composition at start of injection)			
	C_2H_2	O_2	N_2	O_2	N_2	H_2O	CO_2
21%	3.5	29.3	67.2	21.0	67.2	3.5	7.1
15%	3.5	23.4	74.4	15.0	74.4	3.5	7.1
10%	3.5	18.5	79.4	10.0	79.4	3.5	7.1

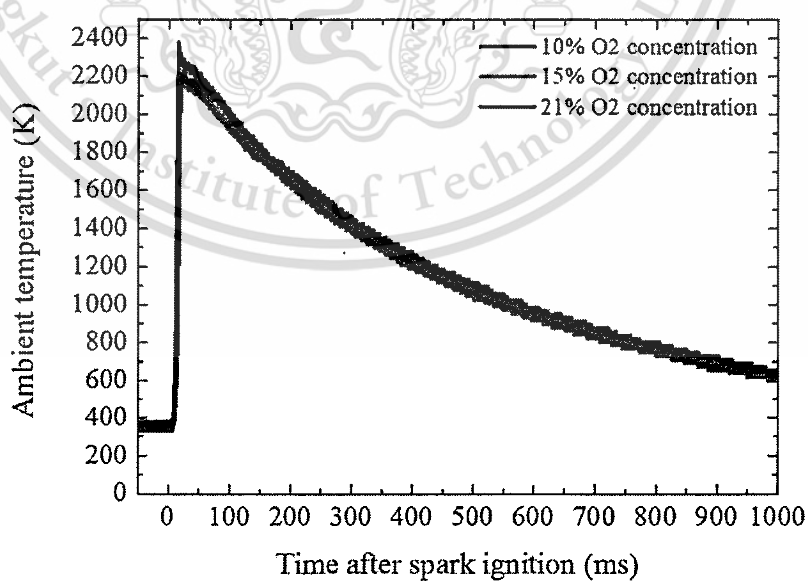


Figure 3.5 Ambient gas temperature of initial premixed gas of 1.5 MPa and 21% oxygen concentration

3.5 Experimental procedure

The spray combustion characteristics were investigated under simulated diesel combustion conditions in CVCC by using two-step combustion as illustrated in Figure 3.6. The first step was using spark plug to generate high-pressure and high-temperature ambient gas by burning the premixed gas of C_2H_2, O_2 and N_2 as premixed burning period. Before the second step, in-chamber pressure and temperature were decreased to reach diesel combustion condition due to the heat transfer as cool down process. The second step was fuel injection into combustion chamber, then injected fuel was continuously burnt as combustion of fuel.

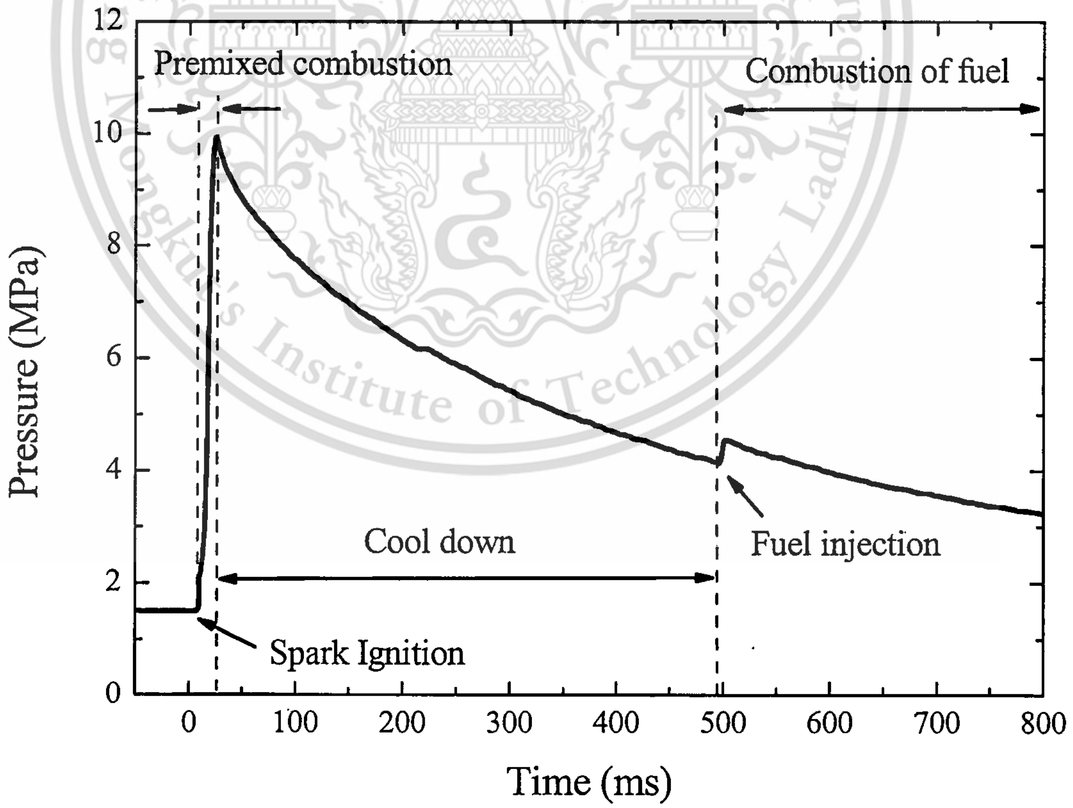


Figure 3.6 In-chamber pressure of two-step combustion

3.6 Visualization of combustion

Figure 3.7 shows schematics diagram of spray combustion experiment using the shadowgraph technique. The shadowgraph technique was used to visualize spray combustion in this research. The shadowgraph technique is a useful technique to study the macroscopic of diesel flame (Pastor et al., 2013). The concave mirror allowed to reflect the light from the Xenon lamp light source that passes through the combustion chamber. The high speed video camera (FASTCAM MINI UX-100) with 10,000 frame per second (fps) was used to capture high speed video combustion, and a resolution of 640 x 480 pixels, and shutter speed of 10.2 μs (Photron, n.d.).

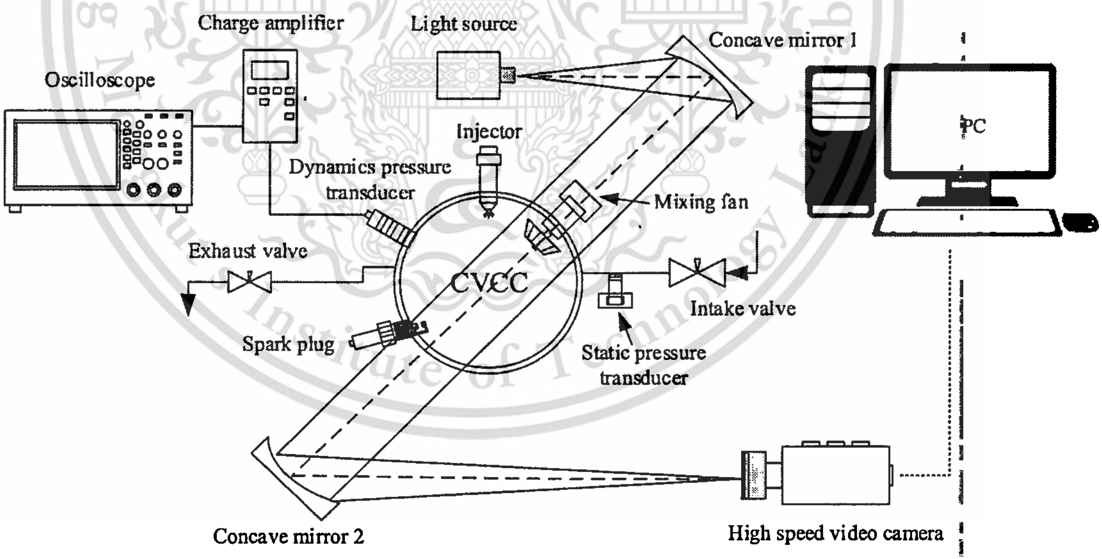


Figure 3.7 Schematics diagram of spray combustion experiment using shadowgraph technique

3.7 Test fuels

Table 3.2 shows fuel properties of test fuels. In this study, four different fuels were commercial diesel grade, commercial diesel blended HVO by mass: 20% (H20), 50% (H50) and pure HVO. The properties of test fuels were determined prior to the study of spray combustion. From this table, the viscosity of H20, H50 and HVO have lower than diesel by 4.62%, 10.49% and 18.52%, with lower density than diesel by 1.21%, 2.91% and 5.58%. But higher heating values by 0.39%, 0.11% and 2.18%. In addition, one of important property in this study is distillation temperature that describes the evaporation characteristics of fuel. At T90 distillation temperature, H20, H50 and HVO have lower than diesel by 0.21%, 0.70% and 16.77%, as shown in Figure 3.8. If fuel has lower distillation temperature, it will show fast evaporation and mixing with ambient air. The cetane index is used to estimate the cetane number of fuel, which calculated from fuel density, T10, T50 and T90 distillation temperature. According to the larger difference of density, T50 and T90 of H20, H50 and HVO compared to diesel so that the cetane index of H20, H50 and HVO are higher than diesel by 4.86%, 13.05% and 27.23% due to its lower density, T50 and T90, respectively.

Table 3.2 Fuels properties

Properties	Standard	Diesel	H20	H50	HVO
Density @ 30°C (g/cm^3)	ASTM D4052	0.824	0.814	0.800	0.778
Kinematic viscosity @ 40°C (mm^2/s)	ASTM D445	3.24	3.09	2.90	2.64
Heating value (MJ/kg)	ASTM D240	45.86	46.04	46.38	46.86
Carbon content (%)	ASTM D5291	85.73	85.43	84.98	84.24
Hydrogen content (%)	ASTM D5291	13.22	13.59	14.14	15.05
Oxygen content (%)	ASTM D5599	0.00	0.00	0.00	0.00
Distillation T10 (°C)	ASTM D86-11b	207.7	210.7	216.3	227.4
Distillation T50 (°C)	ASTM D86-11b	287.9	284.5	281.4	278.2
Distillation T90 (°C)	ASTM D86-11b	352.3	345.2	327.4	293.2
Cetane index	ASTM D4737	60.43	63.37	68.32	76.89

Auto-ignition temperature (°C)	ASTM 659	288	-	-	288

3.8 Experimental condition

Table 3.3 shows the experimental condition in this research. Four test fuels were tested: commercial diesel, two commercial diesel-HVO blends by mass: 20% (H20), and 50% (H50) and 100% HVO. The experiment was carried out using constant volume combustion chamber (CVCC) with single-hole injector, 0.2 mm in nozzle orifice diameter, 2.5 ms in energizing time. The injection pressure was kept constant at 100 MPa. The ambient temperature were varied at 1100 K, 900 K and 700 K to study effects of ambient temperature. The oxygen concentration was varied at 21%, 15% and 10% to simulate effects of EGR conditions. All test were repeated 10 times per each test conditions.

Table 3.3 Experimental condition

Parameters	Conditions
Test fuels	Diesel, H20, H50, HVO
Nozzle orifice diameter	Single hole 0.2 mm
Energizing time	2.5 ms
Injection pressure	100 MPa
Ambient temperature	1100 K, 900 K, 700 K
Oxygen concentration	21%, 15%,10%
Repeat	10 Times / Condition

CHAPTER 4

RESULTS AND DISCUSSION

This research on the combustion characteristics of diesel and HVO blend percentage under low oxygen concentration and low temperature combustion were derived into two parts. In the first part, combustion pressure, combustion temperature, heat release rate, cumulative heat release, ignition delay and integral heat release were presented and discussed. In the second part, focusing on the shadowgraph images, which used to describe effects of physical and chemical properties on the spray development, ignition and the flame development.

4.1 Combustion characteristics

The experimental results of combustion characteristics were presented in terms of heat release rate, cumulative heat release and ignition delay.

4.1.1 Heat release rate

Figure 4.1 shows the effect of oxygen (O_2) concentration on the heat release rate into diesel and HVO as representative under constant injection pressure and ambient temperature. Heat release rate is determined from pressure rise by using Equation 3.2 as described in Chapter 3. The peak heat release rate of 21% and 15% O_2 concentration of HVO is lower than diesel due to its higher cetane number, which makes a shorter ignition delay (Ewphun et al., 2017). Both 21% and 15% O_2

concentration exhibit a single-stage ignition, which is hot flame (Heywood, 1988), premixed combustion phase, and following by diffusive combustion phase, respectively. Lower O_2 concentration produced the slowed combustion rate, indicating by the change of heat release rate slope and lower peak heat release rate (Nguyen et al., 2011). Heat release rate of 10% O_2 concentration shows the lowest peak heat release due to the lower flame temperature caused by the diluted ambient gas (Azimov et al., 2008; Ewphun et al., 2017). At 10% O_2 concentration exhibits the two-stage ignition. The two-stage ignition is commonly observed in the diesel combustion, the first-stage ignition is "low temperature heat release (LTHR)" and the second stage is "high temperature heat release (HTHR)" due to a slow combustion process (Heywood, 1988). The LTHR were relatively similar with different O_2 concentration. On the other hand, The HTHR is shifted with different O_2 concentration (Mayo and Boehman, 2015).

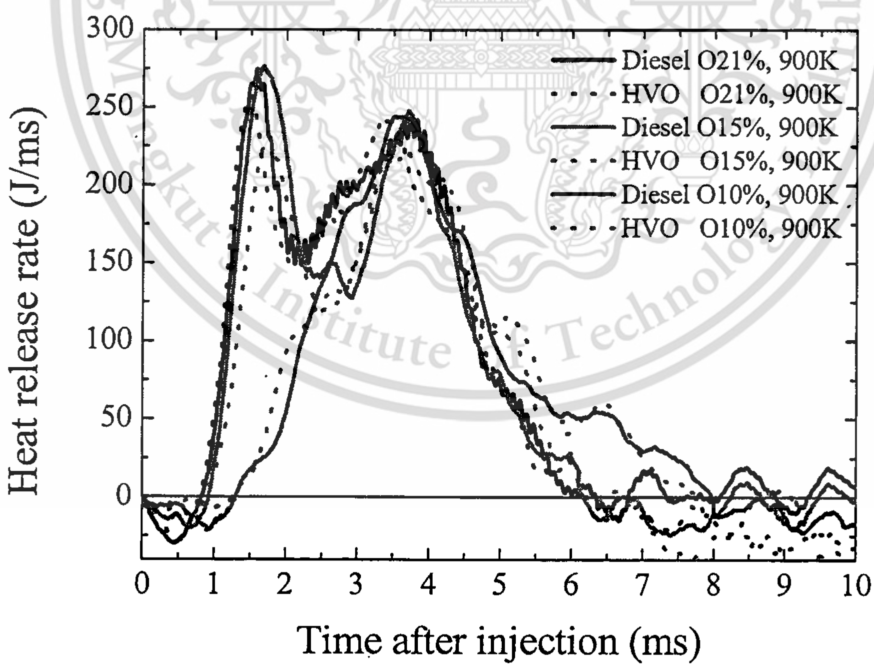


Figure 4.1 Effect of oxygen concentration on heat release rate of diesel and HVO as representative

Figure 4.2 shows the effect of ambient temperature (T_{amb}) on the heat release rate into diesel and HVO as representative under constant injection pressure and oxygen concentration. The heat release rate at T_{amb} = 1100 K exhibits the lowest heat release rate because fuel and air are fast vaporized and mixed during the ignition delay period (Nguyen et al., 2010) as seen as the dip of heat absorption (Zhang et al., 2012). The peak heat release rate decreases with increasing T_{amb} to 1100 K due to a less time of fuel-air mixing. In addition, the shorter ignition delay is observed with T_{amb} = 1100 K, resulting in suppress the premixed combustion period and lengthen the diffusive combustion period (Junjun et al., 2009). At T_{amb} = 700 K, the heat release rate increases rapidly in the premixed combustion phase because of fuel and air well mixed and distributed during the ignition delay period (Azimov et al., 2008, 2009). The heat release rate of HVO exhibits the highest heat release rate due to the improved mixing of fuel and air (Azimov et al., 2009). From the results, the conclusion is that HVO promotes shorter ignition delay in the combustion chamber at low ambient temperature and contributes to use in the diesel engine at low engine load, cold engine conditions (Lapuerta et al., 2011; Millo et al., 2015) and low compression ratio (Kook et al., 2005).

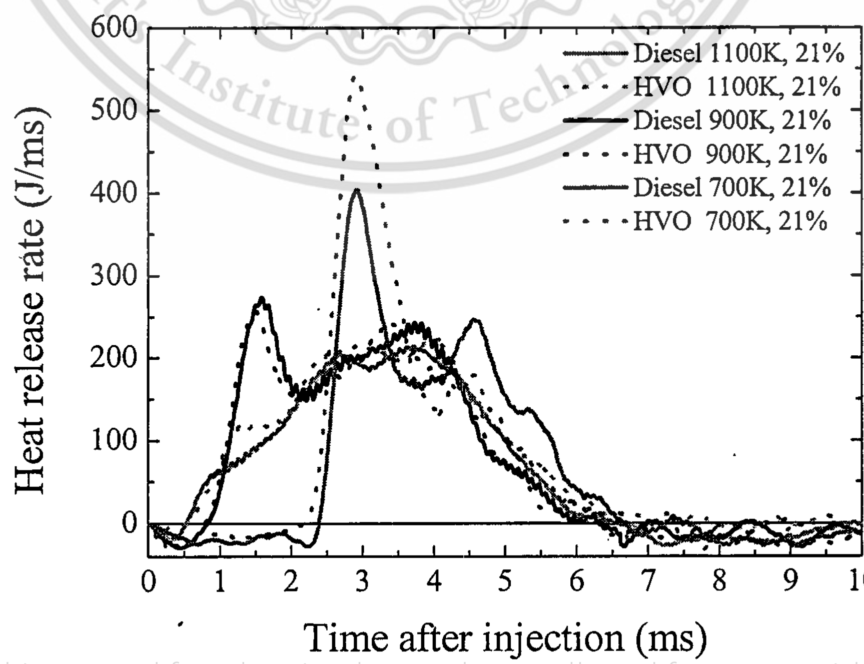


Figure 4.2 Effect of ambient temperature on heat release rate of diesel and HVΘ as representative

4.1.2 Cumulative heat release

Figure 4.3 shows the effect of oxygen (O_2) concentration on the cumulative heat release into diesel and HVO as representative under constant injection pressure and ambient temperature. The 21% O_2 concentration shows the highest value of cumulative heat release at 6 ms after injection because a higher oxygen availability causes an increase in the burning rate (Zhang et al., 2012), indicating by the change of cumulative heat release slope. The 21% and 15% O_2 concentration show similar cumulative heat release and begin to decrease at 7 ms time after injection. On the other hand, cumulative heat release of 10% O_2 concentration still slowly increases due to slow burning rate.

Figure 4.4 shows the effect of ambient temperature (T_{amb}) on the cumulative heat release into diesel and HVO as representative under constant injection pressure and oxygen concentration. T_{amb} = 1100 K observed early increase in cumulative heat release due to a shorter ignition delay. Burning rate of T_{amb} = 1100 K exhibits similar trend to T_{amb} = 900 K, but at T_{amb} = 700 K exhibits a higher burning rate due to promoting long mixing time that makes better mixture formation at lower temperature (Ewphun et al., 2017).

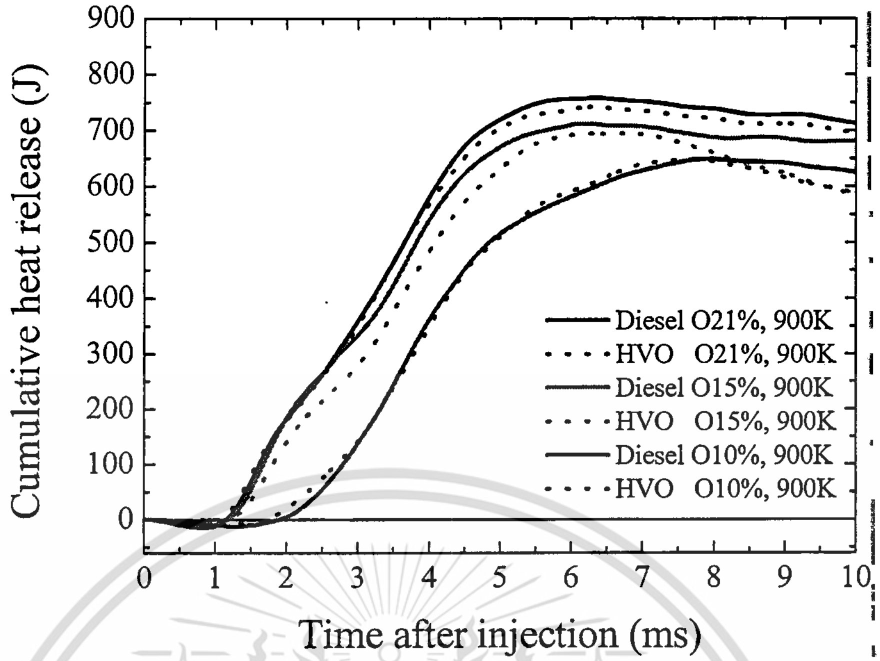


Figure 4.3 Effect of oxygen concentration on cumulative heat release of diesel and HVO as representative

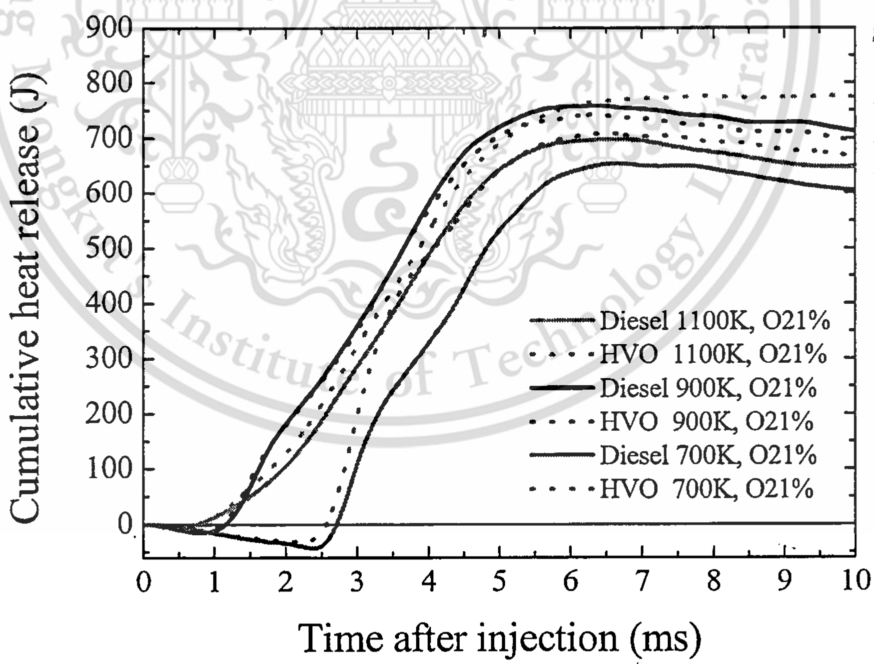


Figure 4.4 Effect of ambient temperature on cumulative heat release of diesel and HVO as representative

4.1.3 Ignition delay

Figure 4.5 shows the effect of oxygen (O_2) concentration on the ignition delay into diesel and HVO blend percentage under constant injection pressure and ambient temperature. From this figure, the ignition delay of 21% and 15% O_2 concentration exhibit similar trend for all test fuels. On the other hand, the 10% O_2 concentration shows the longest ignition delay because of the slowed chemical kinetics due to the less of oxygen availability (Azimov et al., 2009; Ewphun et al., 2017). The ignition delay of H20, H50 and HVO exhibit 0.72%, 6.0% and 6.24% shorter than diesel at O_2 concentration of 21% due to its higher cetane number (Jaroonjitsathian et al., 2014; Liu et al., 2013; Millo et al., 2015; Nguyen et al., 2011; Sugiyama et al., 2011) and lower T90% temperature (Nguyen et al., 2010; Oo et al., 2015). The ignition delay of HVO exhibits shorter than diesel by 6.24%, 5.42% and 9.63% at O_2 concentration of 21%, 15% and 10%, respectively. The conclusion is that decreasing oxygen concentration results in increasing ignition delay due to the less of oxygen availability. Increasing HVO blend percentage leads to shortening ignition delay for all test condition due to its higher cetane number.

Figure 4.6 shows the effects of ambient temperature (T_{amb}) on the ignition delay into diesel and HVO blend percentage under constant injection pressure and oxygen concentration. From this figure, the ignition delay of T_{amb} = 1100 K and 900 K exhibit similar trend for all test fuels. On the other hand, T_{amb} = 700 K ambient temperature shows the longest ignition delay because fuel slowly evaporated, mixed with the ambient air (Nguyen et al., 2011; Zhang et al., 2012, 2013). The ignition delay of HVO exhibits shorter than diesel by 2.26%, 6.24% and 8.84% at T_{amb} = 1100 K, 900

K and 700 K, respectively due to its higher cetane number (Jaroonjitsathian et al., 2014; Liu et al., 2013; Millo et al., 2015; Nguyen et al., 2011; Sugiyama et al., 2011). The conclusion is that decreasing ambient temperature results in increasing ignition delay due to a lower fuel evaporation process.

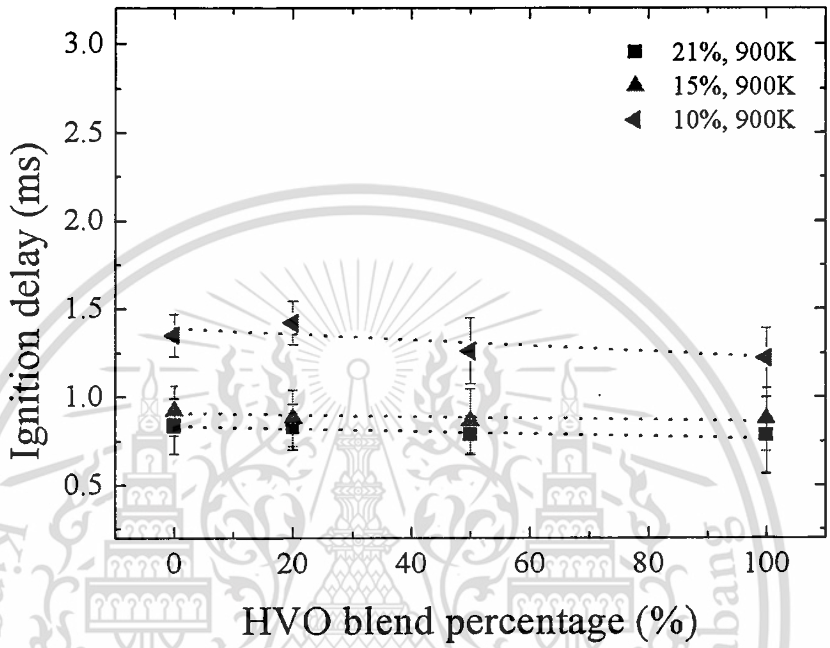


Figure 4.5 Effect of oxygen concentration on ignition delay of diesel and HVO blend percentage

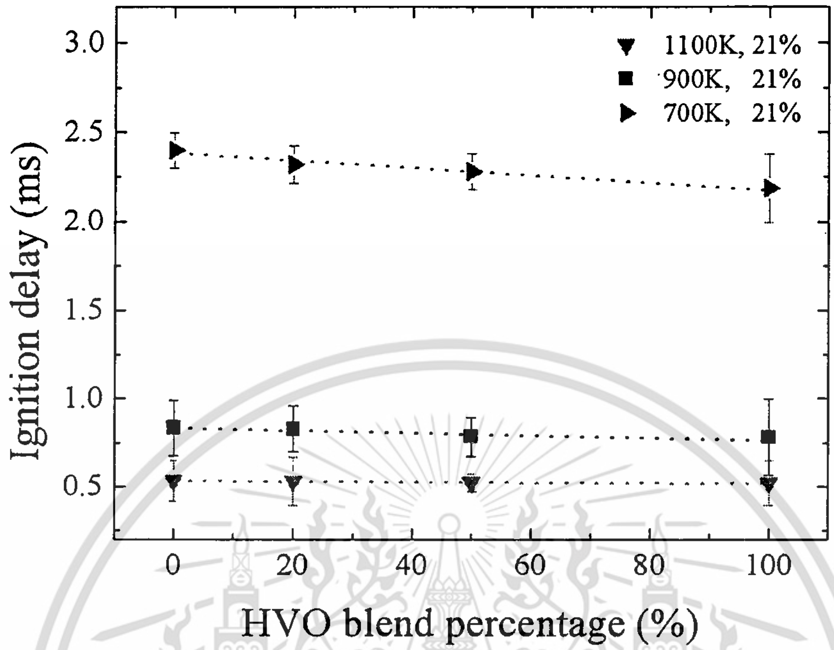


Figure 4.6 Effect of ambient temperature on ignition delay of diesel and HVO blend percentage

4.2 Combustion visualization

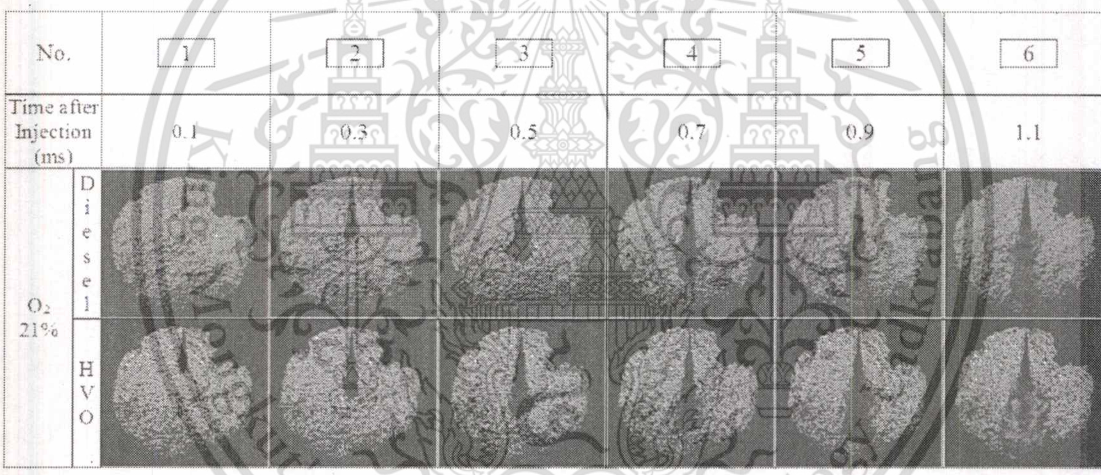
In this part, focusing on the combustion visualization of fuel. Result of combustion visualization were presented; first, the shadowgraph image of spray development describes effect of ambient conditions and fuel properties on the mixture formation and the ignition delay, second, the shadowgraph images of combustion progress describe effect of ambient conditions on the flame development. The sequence shadowgraph images of spray combustion in this research were captured by using the high-speed video camera, and analyzed by using Photron Fastcam Viewer program. Diesel and HVO were selected to present the combustion visualization as representative.

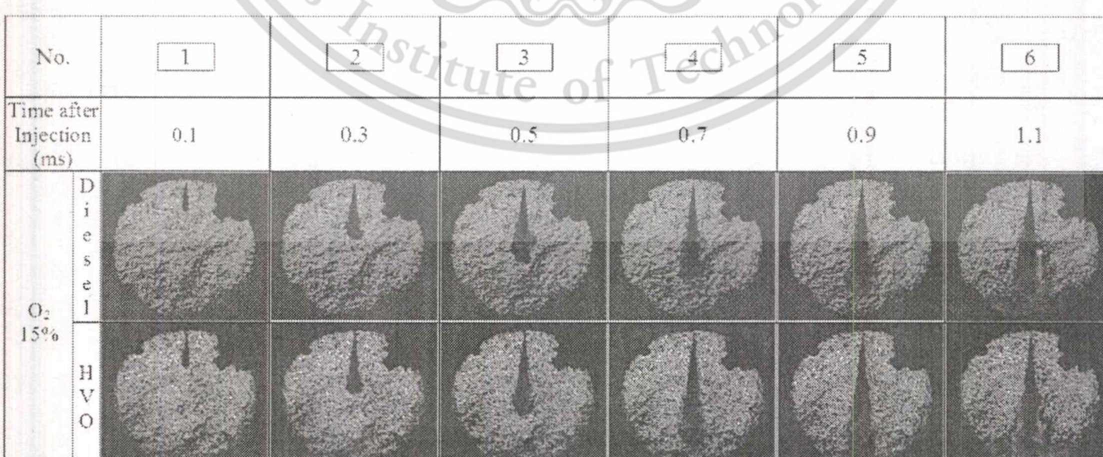
4.2.1 Spray development

1. Effect of oxygen concentration

Figure 4.7 illustrates shadowgraph images of spray development of diesel and HVO as representative under effect of oxygen (O_2) concentration. All tested fuel continue to penetrate, evaporate and distribute with the ambient gas in the chamber. The effect of O_2 concentration has an insignificant on spray penetration due to the same of ambient gas density and temperature (Hulkkonen et al., 2011; Sugiyama et al., 2011). The 21% O_2 concentration exhibits early ignition as seen as the luminous flame at 0.9 ms after injection due to oxygen enhancement that caused a higher combustion rate as displayed by larger slope increase in heat release rate curve. This result is agreement with previous research (Nguyen et al., 2010). The 15% O_2 concentration exhibits similar spray penetration to 21% O_2 centration case, but it required more time of mixing, distribution, and ignition because its oxygen availability is lower than the O_2 concentration of 21% as observed during 0.7 ms to 0.9 ms after injection (Ewphun et al., 2017; Nguyen et al., 2011). However, the 10%

O_2 concentration cannot obtain a luminous flame 0.1 ms to 2.1 ms after injection due to the slowed combustion reaction rate (Nguyen et al., 2011). The evaporation of HVO is quicker than diesel as it observed larger vaporized fuel around the tip of spray during 0.5 ms to 0.9 ms after injection at 21% and 15% % O_2 concentration due to its lower viscosity, density, and distillation temperature at T90, resulting in easier fuel atomized, distributed and mixed with the ambient air (Jaroonjitsathian et al., 2014; Nguyen et al., 2010; Oo et al., 2015). In addition, from previous research, HVO is a mixture of paraffin and iso-paraffin with straight chain-length (Caprotti et al., 2011; Koyama et al., 2007; Liu et al., 2013; No, 2014), which might contribute to easier broken up and ignition compared to diesel.





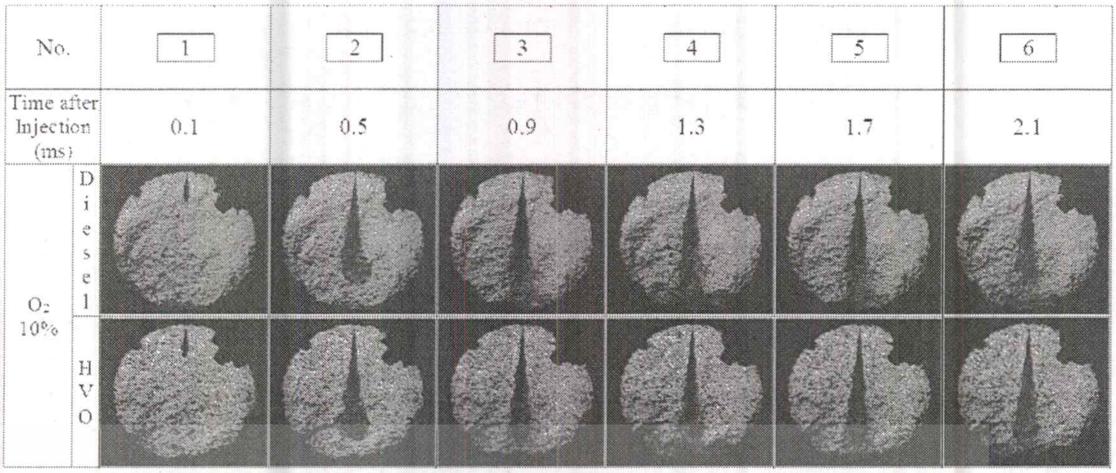
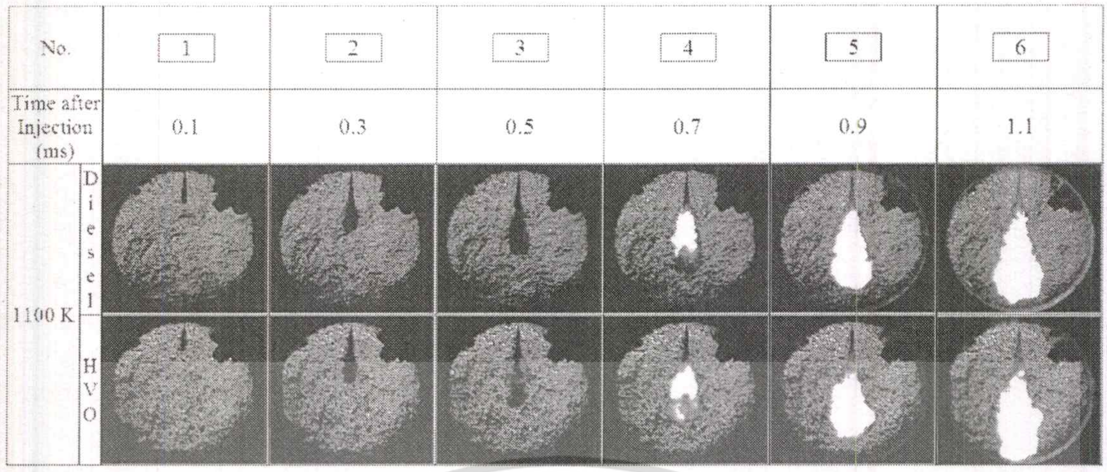


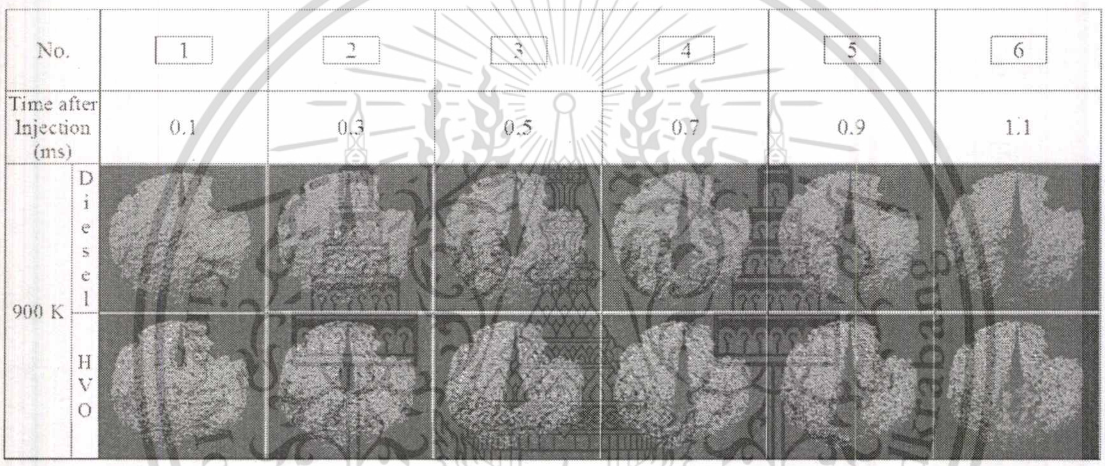
Figure 4.7 Shadowgraph images of spray development of diesel and HVO as representative (a) O_2 = 21% (b) O_2 = 15% and (c) O_2 = 10%

2. Effect of ambient temperature

Figure 4.8 illustrates shadowgraph images of spray development and ignition process of diesel and HVO under effect of ambient temperature (T_{amb}). From this figure, the effect of ambient temperature has largely impacted on spray penetration due to different ambient gas density and temperature. The T_{amb} = 1100 K exhibits early ignition at 0.7 ms after injection due to a rapid fuel evaporation (Oo et al., 2015), a less time of fuel-air mixing and higher combustion rate (Nguyen et al., 2010, 2011). Lower ambient temperature has more time for spray mixing, more ambient air entrained into fuel spray, resulting in higher the peak heat release rate and later luminous flame at 1.1 ms for T_{amb} = 900 K, and 2.1 ms after injection for T_{amb} = 700 K, respectively (Azimov et al., 2009; Nguyen et al., 2011; Xu and Lee, 2004). The comparison between HVO and diesel on spray development and ignition process can be explained that HVO exhibits faster evaporate, distributed and mixed with ambient air compare to diesel for all ambient temperature as observe larger fuel evaporated around the tip of spray at 0.5 ms after injection for T_{amb} = 1100K, and 0.7 ms for T_{amb}

= 900 K and 700 K.





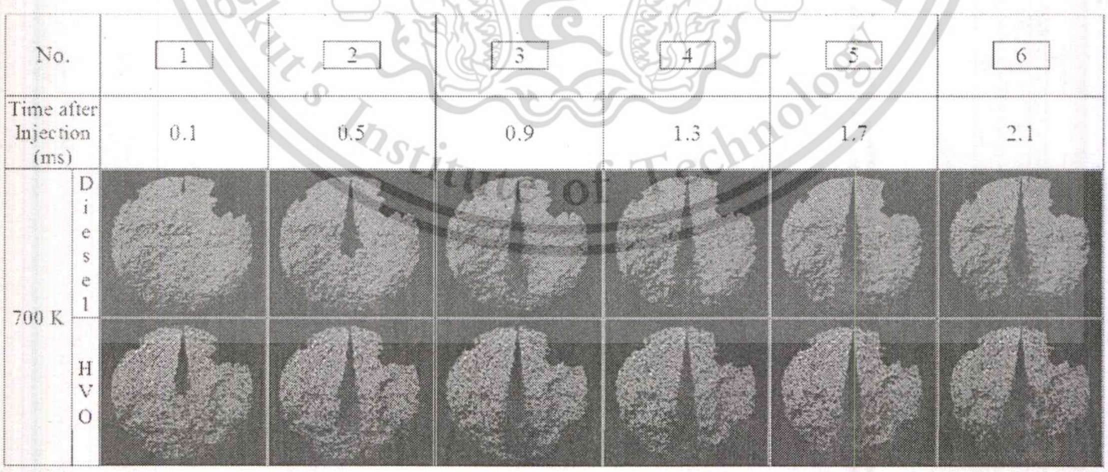
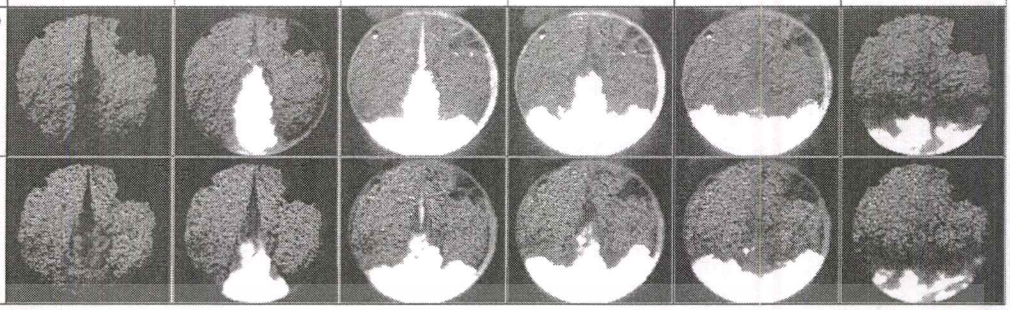


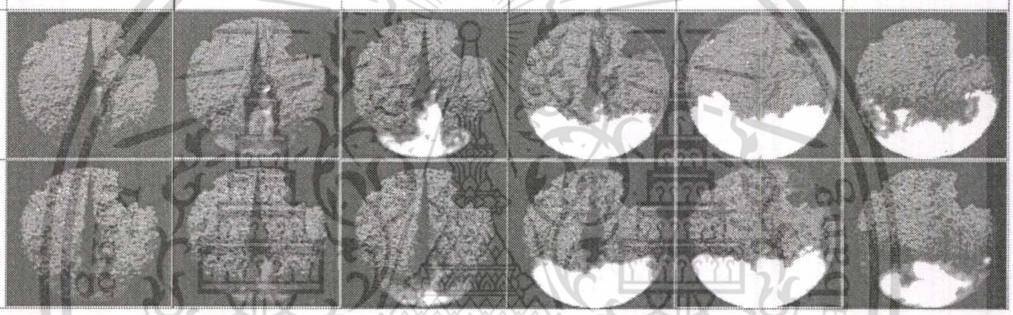
Figure 4.8 Shadowgraph images of spray development of diesel and HVO as representative (a) T_{amb} = 1100 K (b) T_{amb} = 900 K and (c) T_{amb} = 700 K

4.2.2 Combustion progress

1. Effect of oxygen concentration

Figure 4.9 illustrates shadowgraph images of flame development of diesel and HVO under effect of oxygen (O_2) concentration. The 21% O_2 concentration exhibits early the luminous flame at 1.1 ms after injection due to a higher oxygen availability in the chamber (Nguyen et al., 2011) at the premixed combustion period. At 15% O_2 concentration, the luminous flame is observed around 1.6 ms after injection at premixed combustion phase. The brighter flame luminosity is observed during 2.6 ms to 4.6 ms after injection for 21% O_2 concentration, and during 3.6 ms to 4.6 ms after injection for 15% O_2 concentration at the diffusive combustion period. The luminous flame is not observed at 10% O_2 concentration due to the lack of oxygen, which results in the slowed chemical reaction (Azimov et al., 2009) and decreasing combustion reaction intensity (Zhang et al., 2012, 2013). The comparison of flame luminosity between HVO and diesel can be explained that HVO exhibits faster flame development compared to diesel due to smaller droplet size distribution (Chen et al., 2013), which made fuel-air interaction very well during ignition delay through combustion process as seen as the flame at 21% and 15% O_2 concentration. This result is agreement with previous research (Xu and Lee, 2004).

No.	1	2	3	4	5	6
Time after Injection (ms)	1.1	1.6	2.6	3.6	4.6	5.6
O_2 21% Diesel / HVO						

No.	1	2	3	4	5	6
Time after Injection (ms)	1.1	1.6	2.6	3.6	4.6	5.6
O_2 15% Diesel / HVO						

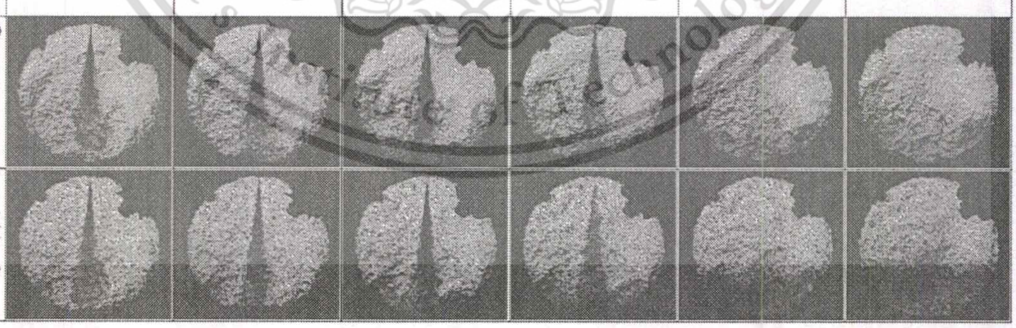
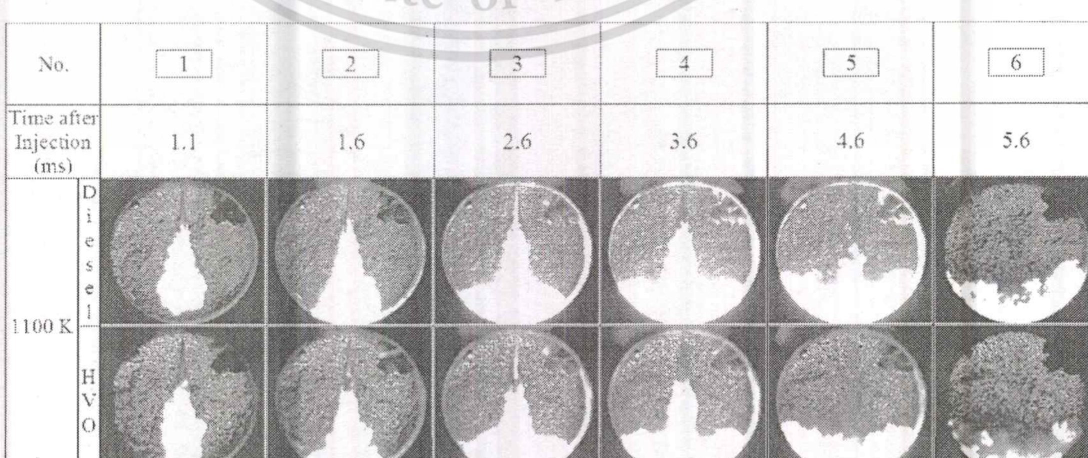
No.	1	2	3	4	5	6
Time after Injection (ms)	1.1	1.6	2.6	3.6	4.6	5.6
O_2 10% Diesel / HVO						

Figure 4.9 Heat release rate and shadowgraph images of flame development of diesel and HVO as representative (a) O_2 = 21% (b) O_2 = 15% and (c) O_2 = 10%

2. Effect of ambient temperature

Figure 4.10 illustrates shadowgraph images of flame development of diesel and HVO under effect of ambient temperature (T_{amb}). The T_{amb} = 1100 K is observed the brighter flame compared to T_{amb} = 900 K and 700 K at 1.1 ms to 4.6 after injection due to the rapid fuel evaporation and distribution in the chamber. The flame luminosity of T_{amb} = 900 K exhibits later than 1100 K due to lower temperature. The comparison of flame luminosity between HVO and diesel can be explained that the flame luminosity of HVO is weaker than diesel during 1.6 ms to 4.6 ms after injection for T_{amb} = 1100 K and 900 K. On the other hand, at T_{amb} = 700 K, the flame luminosity appears only in case of HVO because increasing cetane number provides high reactivity at low temperature (Jaroonjitsathian et al., 2014; Mayo and Boehman, 2015). In addition, HVO exhibits the luminous flame of T_{amb} = 700 K at downstream spray because it has better mixture formation due to its higher cetane number and lower distillation temperature at T90.



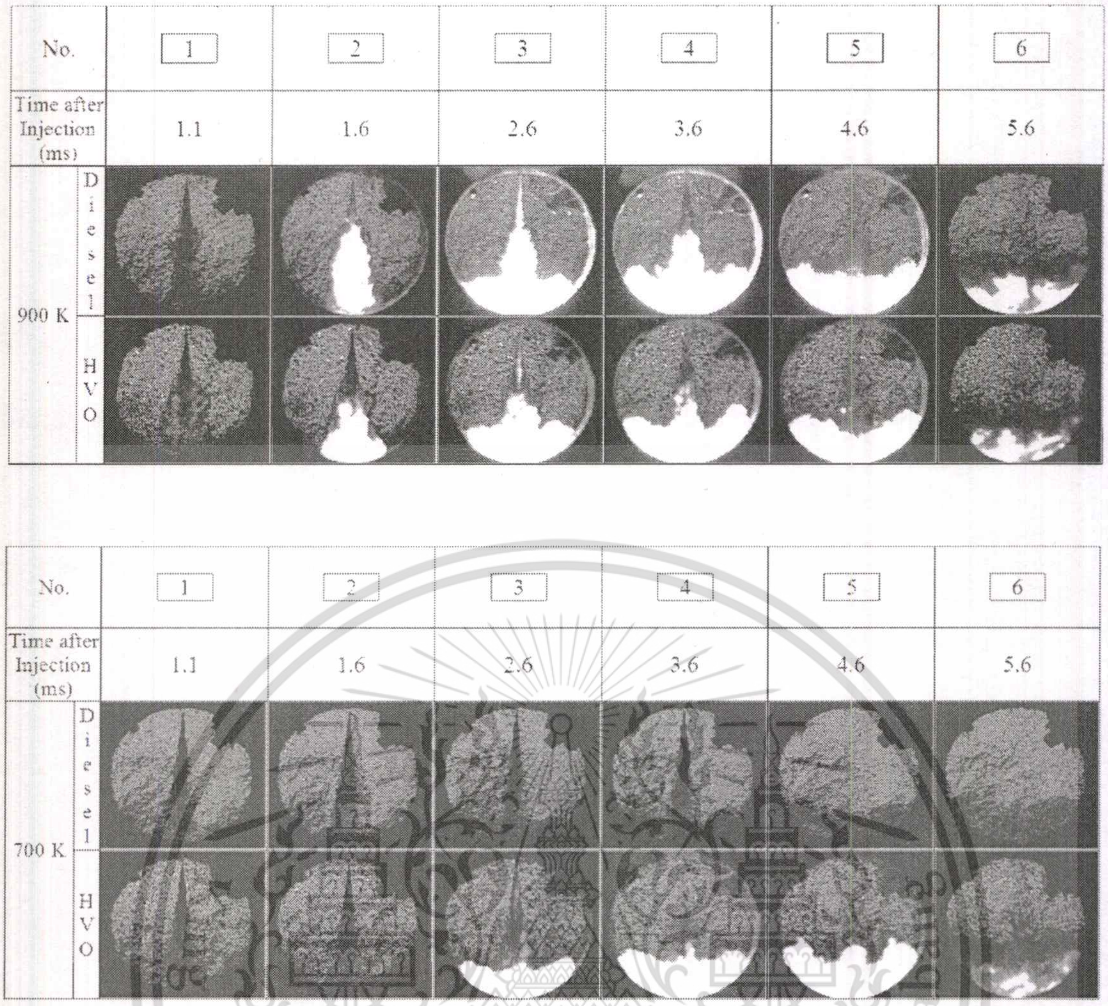


Figure 4.10 Heat release rate and shadowgraph images of flame development of diesel and HVO as a representative (a) T_{amb} = 1100 K (b) T_{amb} = 900 K and (c) T_{amb} = 700 K

CHARPTER 5

CONCLUSIONS

5.1 Conclusions

This research investigated effect of Hydrotreated vegetable oil – diesel blend percentage on spray combustion characteristics under low oxygen concentration and low temperature condition. The conclusion were derived into two parts. In the first part, heat release rate, cumulative heat release and ignition delay were presented. In the second part, focusing on the shadowgraph images of spray development and flame development.

5.1.1 Combustion characteristics

1. Decreasing oxygen concentration from 21% to 15% and 10% results in 9.08% and 29.58% decreasing the rate of combustion pressure due to the diluted ambient gas, but decreasing ambient temperature from 1100 K to 900 K and 700 K results in 6.77% and 6.46% increasing the rate of combustion pressure due to improving fuel-air mixing.

2. Decreasing oxygen concentration from 21% to 15% does not significant affect to the combustion process, but at 10% oxygen concentration, combustion process exhibits two-stage ignition and dominates by large premixed combustion period because of a lower oxygen availability, leading to a slow combustion rate. A decrease of ambient temperature results in a higher peak heat release rate due to a better fuel-air preparation during the ignition delay. HVO exhibits the higher heat release rate at 700K due to its higher cetane number, which improves mixing of fuel and air at low temperature.

3. Decreasing oxygen concentration causes a decrease in burning rate due to a

lower oxygen availability, indicating by the slope of cumulative heat release. Decreasing ambient temperature exhibits a higher burning rate because the longer ignition delay promotes available time for mixing that makes a better mixture formation at low temperature.

4. Decreasing oxygen concentration results in a longer ignition delay due to a slow chemical reaction. Decreasing ambient temperature results in a longer ignition delay due to the slowed fuel evaporation and mixing with the ambient air in the chamber. However, increasing HVO blend percentage provides a shorter ignition delay as 6.24%, 5.42% and 9.63% at 21%, 15%, and 10% oxygen concentration, with 2.26% and 8.84% at 1100 K and 700 K ambient temperature due to its higher cetane number.

5. Decreasing oxygen concentration results in the lower integral heat release due to the lower combustion rate and a higher heat capacity in the chamber. Decreasing ambient temperature results in an increase of integral heat release due to improved mixing during a longer ignition delay. Increasing HVO blend percentage provides a lower 2.38%, 2.76% and 0.94% at 21%, 15%, and 10% oxygen concentration.

5.1.2 Combustion visualization

1. A decrease of oxygen concentration results in an insignificant effects on spray development due to the same ambient air density and temperature, but the ignition delay is changed with oxygen concentration as seen as the luminous flame. At the 10% oxygen concentration, the flame luminosity is not observed due to the lack of oxygen, which results in a slow chemical reaction. The HVO is easier to vaporize and distribute in the chamber due to its lower density, viscosity and distillation

temperature at T90.

2. A decrease of ambient temperature effects on fuel-air mixing by providing a longer mixture formation time, resulting in later luminous flame with higher peak heat release rate. At 700 K of ambient temperature, the flame luminosity of only HVO is observed because of its higher cetane number provides high reactivity at low temperature. As the results, The HVO can be recommended to use in the diesel engine with EGR application as well, but it is necessary to optimize the engine when using in low temperature combustion such as reducing the compression ratio.

5.2 Recommendations and Future Studies

1. Using needle lift sensor to clearly determine the needle lift opening and closing of injector for evaluating the injection delay and the ignition delay.

2. Investigation on effect of HVO to combustion characteristics by using High speed imaging of OH* chemiluminescence and natural luminosity to clearly understand the chemical reaction, flame luminosity.

3. Investigation on effect of HVO to combustion characteristics by using two-color method to measure flame temperature and KL factor to obtain soot concentration.

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APPENDIX A: Measurement specifications

KISTLER
measure. analyze. innovate.

Miniature Measuring Probe

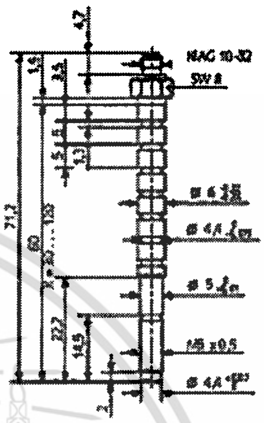
Type 6053CC...

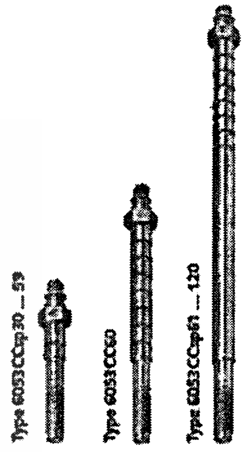
for Non-Cooled Cylinder Pressure Measurement, M5 Thread

Patent No. US 6,105,434

The miniature measuring probe with very small dimensions and M5x0,5 mounting thread is particularly suitable for direct installation in small-capacity combustion engines with more than two valves per cylinder. The measuring element is identical to the standard sensor Type 6052C... .

- Good temperature stability of the sensitivity
- Acceleration-compensated
- Needs only 6 mm mounting bore
- Low thermal shock error and long life thanks to the front seal
- Very high sensitivity





Description

Type 6053CC... uses a new type of PiezoStar® crystal which achieves high sensitivity in conjunction with an extremely small sensor structure. The sensitivity drifts by a maximum of ±0,5 % over the temperature range of 200 ±50 °C. The passive acceleration compensation patented by Kistler keeps the influence of engine vibrations to a minimum.

The front seal allows very good heat dissipation and thus briefly a maximum operating temperature of 400 °C. The diaphragm, optimized by finite element calculation, produces good measuring results and ensures a long service life.
The shape of the probe allows mounting with a very small access bore. The cable connection has to be outside the cylinder-head, in an area free of oil mist. O-rings also permit mounting through coolant passages. The probe can be manufactured in custom lengths between 30 and 120 mm.

Application

The sensor Type 6053CC... is an excellent all-rounder. Its rugged construction makes it suitable for measurements at the knock limit as well as for thermodynamic investigations. This sensor is used mainly on multi-valve engines, motor cycle and other small engines and for combustion analysis.
This sensor should be used when there is insufficient mounting space available for the Type 6052C... .
At high speeds (vibrations), the Type 6053CC...U40 should be used. For applications mainly in the knocking range or at very high peak pressures, use of Type 6053CC...U20 with reinforced diaphragm (heavy duty version) is recommended.
The probe is supplied without a cable. See Accessories for the various cables available for different applications.

Technical Data

Measuring range	bar	0 ... 250
Calibrated sub-ranges	bar	0 ... 50, 0 ... 100, 0 ... 150, 0 ... 250
Overload	bar	300
Sensitivity	pC/bar	≈–20
Natural frequency, nominal	kHz	≈160
Linearity in all ranges (at 23 °C)	%/FSO	≤±0,3
Acceleration sensitivity		
axial	bar/g	<0,0002
radial	bar/g	<0,0005
Operating temperature range	°C	–20 ... 350
Temperature min./max	°C	–50 ... 400
Connector	°C	200

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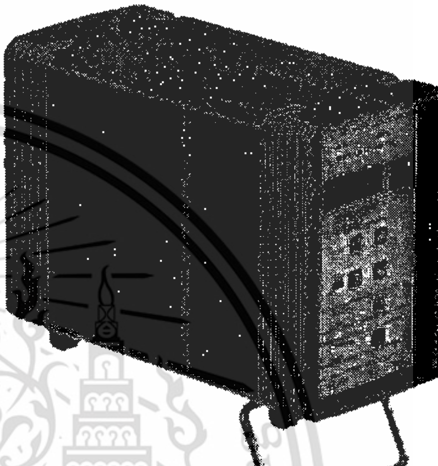
KISTLER
measure. analyze. innovate.

Charge Amplifier

Type 5011B...

Single-channel multi-range laboratory charge amplifier

The mains-operated, microprocessor controlled single-channel charge amplifier Type 5011B... converts the electrical charge produced by piezoelectric sensors into a proportional voltage signal.



- Large measuring range
- Wide frequency range
- Automatic zero correction
- Adjustable low-pass filter and time constant
- Various options and versions provide optimum adaptation to the measuring problem
- Conforming to CE

Description

The main features of the instrument are its continuous measuring range adjustment range from ±10 ... ±999 000 pC and convenient adjustment of the parameters with a two-line LC display. The values entered are retained in the event of an interruption in the power supply.

A built-in IEEE-488 parallel interface or a serial RS-232C interface is available as an option. This enables all set values to be entered or queried. Transmission of data measured is not possible.

The version ...Y50 additionally has a drift compensation and is used in engine measuring technology with uncooled sensors

Application

This amplifier serves mainly to measure mechanical quantities, e.g. pressure, force or acceleration.

The instrument dimensions are DIN standardized and it can be supplied in a desktop or rack mount case.

The principle measurement without calculation:
- Set sensor sensitivity
- Select display scale
- Sensor sensitivity and scale are displayed
- Set the signal output of the data acquisition unit (recorder, oscilloscope...), for example to 1 V/unit (1 V/cm)
- The display appears directly in mechanical units according to the display scale selected

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ALAVA INGENIEROS

FASTCAM Mini UX100

COMPACT HIGH-SPEED CAMERA SYSTEM

Preliminary Datasheet

PRODUCT FEATURES:

Frame Rate Performance Examples:

- 4,000fps at 1280x1024 pixel resolution.
- 5,000fps at 1280x1000 pixel resolution.
- 6,250fps at 1280x800 pixel resolution.
- 8,000fps at 1280x624 pixel resolution.
- 20,000fps at 1280x248 pixel resolution.
- 200,000fps at 1280x24 pixel resolution.
- 800,000fps at 640x8 pixel resolution.

Compact and Lightweight:
120mm x 120mm x 90mm Camera Body
Weight: 1.5Kg

Dynamic Range (ADC):
12-bit Monochrome, 36-bit Colour.

High Light Sensitivity:
Unique image sensor technology combining high light sensitivity and small pixel size.

Global Electronic Shutter:
Minimum Shutter Speed 3.76μs to 1μs dependent on frame rate selection.

Gigabit Ethernet Interface:
Provides reliable system communication and fast image download.

Recording Memory Options:
To meet all application requirements:
4GB, 8GB and 16GB.

1 inch C-mount Compatible Sensor Size and integrated Nikon G type lens mount:
Allowing operation with both current Nikon DSLR F/G type lenses and full compatibility with 1 inch C-mount lenses at all image resolutions.

Photron
High-Speed Imaging Solutions

Compact and light weight camera system offering outstanding performance and ease of use in a wide-range of high-speed imaging applications

The Photron FASTCAM Mini UX100 high speed camera provides outstanding high speed imaging performance in a small and lightweight camera design. Providing 1.3 Megapixel image resolution (1280x1024 pixels) at frame rates up to 4,000fps frames per second and 1 Megapixel resolution (1280x800 pixels) at 6,250fps, the Mini UX-100 system offers both impressive high speed imaging performance and convenience of use.

Housed within a 120mm x 120mm x 90mm camera body weighing just 1.5kg, the FASTCAM Mini UX-100 is ideally suited for use in a wide range of scientific and industrial applications. The camera is available with recording memory options up to 16GB providing extended recording times and triggering flexibility.

Using innovative proprietary CMOS image sensor technology, the FASTCAM Mini UX-100 achieves high light sensitivity from a sensor having a 10μm pixel size fitted with a micro lens. At full image resolution, the image sensor size is compatible with readily available 1" C mount lenses allowing the user a wide choice of small, low cost and very high aperture (up to f0.95) objectives to use with the system and may also be coupled to scientific microscopes and borescopes. In addition, the camera is supplied with a Nikon F mount lens fitting fully compatible with G type Nikon DSLR objectives.

FASTCAM Mini UX-100 is fitted with a high speed Gigabit Ethernet interface providing reliable system control and fast image download. The system is supplied with intuitive and feature rich Photron FASTCAM Viewer (PFV) software and Photron Device Control SDK (software development kit), allowing integration with user-specific software. Alternatively, the camera can be controlled as a device within a MATLAB or LabVIEW environment.

Asst.Prof.Dr.Preechar Karin

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Work Experience

- 2010-Present — Assistant Professor of Automotive Engineering Program, International College, King Mongkut's Institute of Technology Ladkrabang
- 2007-2010 — Research Assistant, Multidisciplinary Education and Research Center for Energy Science, Tokyo Institute of Technology, Japan
- 2007-2010 — Honors Scholarship for Privately Financed International Students (JASSO), Rotary Yoneyama Memmorial Foundation Inc., Japan
- 1997-2006 — Vehicle Design Engineer, Isuzu Technical Center of Asia Co.,Ltd., Isuzu Motor Ltd., Japan

Education

- D.Eng. (Mechanical Engineering), Tokyo Institute of Technology, Japan

Research Experience

- The Thailand Research Fund (TRF), Renewable Bio-oxygenated Fuel Particle Emission Trapping and Oxidation Behaviors inside Ceramic Micro-porous of Diesel Particulate Filters (2014-2016)
- The Thailand Research Fund (TRF), Renewable Bio-oxygenated Fuels Particulate Matter Trapping and Oxidation Behaviors (2012-2014)
- ASEA-UNINET Staff Exchange, One Month Scholarship, Engine After-treatment Technology for Particle Emissions Reduction (1-31 May 2013)
- International College, King Mongkut's Institute of Technology Ladkrabang, Physical and Chemical Characterization of Diesel Particulate Matter (March-September 2011)

Management Experience

- Committee and Secretary of Automotive Engineering Program, International College, King Mongkut's Institute of Technology Ladkrabang (2010-Present)
- Program Director of Automotive Engineering Program, TAIST-Tokyo Tech (King Mongkut's Institute of Technology Ladkrabang, King Mongkut's University of Technology Thonburi, National Science and Technology Development Agency and Tokyo Institute of Technology (2010-Present)
- Committee and Secretary of Thai Society of Mechanical Engineers (TSME) (2015-Present)
- Committee of Thai Society of Automotive Engineers (TSAE) (2014-2015)

International Journal Publications

- P. Karin, J. Boonsakda, K. Siricholathum, E. Saenkhumvong, C. Charoenphonphanich and K. Hanamura, "Morphology and Oxidation Kinetics of CI Engine's Biodiesel Particulate Matters on Cordierite Diesel Particulate Filters using TGA", International Journal of Automotive Technology, Vol. 18, No. 1, pp. 31–40, 2017.
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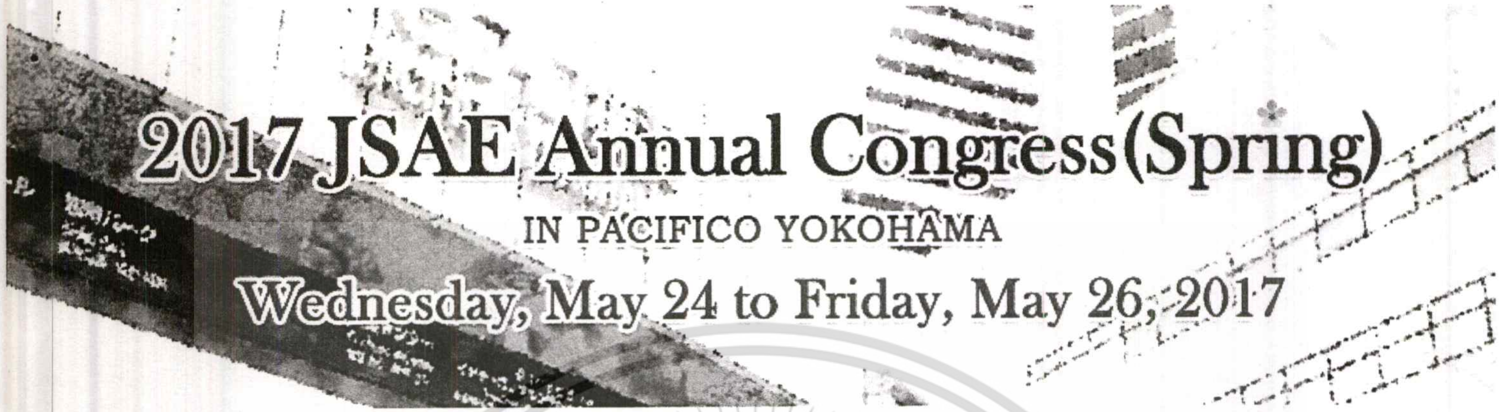
- H. Oki, P. Karin and K. Hanamura, (2011) "Visualization of Oxidation of Soot Nanoparticles Trapped on a Diesel Particulate Membrane Filter", SAE International Journal of Engines, SAE International, Vol. 4 no. 1 pp.515-526.
- P. Karin and K. Hanamura, (2010) "Particulate Matter Trapping and Oxidation on Catalyst-Membrane", SAE International Journal of Fuels and Lubricants, SAE International, Vol.3 No.1 pp.368-379.
- P. Karin and K. Hanamura, (2010) "Microscopic Visualization of Particulate Matter Trapping and Oxidation Behaviors in a Diesel Particulate Catalyst-Membrane Filter", Transactions of Society of Automotive Engineers of Japan, Society of Automotive Engineers of Japan Inc, Vol.41, No.4, pp.853-858.
- P. Karin and K. Hanamura, (2010) "Microscopic Visualization of PM Trapping and Regeneration in a Diesel Particulate Catalyst-Membrane Filter (DPMF)", Transactions of Society of Automotive Engineers of Japan, Society of Automotive Engineers of Japan Inc, Vol. 41, No. 1, pp.103-108.
- P. Karin, L. Cui, P. Rubio, T. Tsuruta and K. Hanamura, (2009) "Microscopic Visualization of PM Trapping and Regeneration in Micro-Structural Pores of a DPF Wall", SAE International Journal of Fuels and Lubricants, SAE International, Vol.2 No.1, pp.661-669.
- K. Hanamura, P. Karin, L. Cui, P. Rubio, T. Tsuruta, T. Tanaka and T. Suzuki, (2009) "Micro- and macroscopic visualization of particulate matter trapping and regeneration processes in wall-flow diesel particulate filters", International Journal of Engine research, Professional Engineering Publishing, Vol.10, No.5/2009, pp.305-321.
- L. Cui, P. Rubio, P. Karin, T. Tsuruta and K. Hanamura, (2009) "Microscopic Visualization of Particulate Matter Trapping and Regeneration in Microstructural Pores on Diesel Particulate Filter Wall", Transactions of Society of Automotive Engineers of Japan, Society of Automotive Engineers of Japan Inc, Vol. 40, No. 1, pp.153-158.

APPENDIX B: Publications

Society of Automotive Engineers of Japan

Japanese page ▶

Page Top | Outline | Program | Important Dates | Geneneral Information for Participants | Guidance for Speaker



TOPICS

2017.05.18 up Final program is now available. NEW

2017.03.10 up Early Bird Registration is now open.

2016.10.07 up Presentation registration is now open.

2016.8.01 up 2017 JSAE Annual Congress (Spring)

Period : Wednesday, May 24 to Friday, May 26, 2017 Venue : PACIFICO YOKOHAMA

Technical Paper Presentation of JSAE Annual Congress is open to (and welcomes) international speakers/audiences:

- Technical Session is organized regardless of the presentation language.
- The language of Technical Paper Presentation material is in English.

Experimental Investigation on Spray Combustion Characteristics of Hydrotreated Vegetable Oil (HVO)-Diesel Blends in Constant Volume Combustion Chamber (CVCC)

Sombat Marasri [1] Pop-Paul Ewphun [1] Prathan Srichai [2] Sukit Saeo [1] Vo Tan Chau [2] Chinda Charoenphonphanich [2] Preechar Karin [1] Manida Tongroon [3] Hidenori Kosaka [4]

1) International College, King Mongut's Institute of Technology Ladkrabang Ladkrabang, Bangkok, 10520, Thailand
2) Faculty of Engineering, King Mongut's Institute of Technology Ladkrabang Ladkrabang, Bangkok, 10520, Thailand
3) National Metal and Materials Technology Center (MTEC), National Science and Technology Development Agency (NSTDA), Klong Luang, Pathumthani, 12120, Thailand
4) Department of System and Control Engineering, Tokyo Institute of Technology 1-44-18 Hayamiya, Nerima-ku, Tokyo, 179-0085, Japan

ABSTRACT: Hydrotreated vegetable oil (HVO) is one of candidate to replace diesel fuel due to its superior properties such as high cetane number and heating value. The objective of this paper is to investigate effects of HVO and diesel blends on combustion characteristics using heat release analysis and shadowgraph technique. Four test fuels were tested: diesel, four diesel-HVO blends by mass: 20%(H20), and 50%(H50) and 100% HVO(H100) in constant volume combustion chamber (CVCC) with single-hole injector. The results show that increasing HVO fraction provide shorter ignition delay and slightly lower heat release rate.

KEY WORDS: **Heat engine, Hydrotreated vegetable oil (HVO), Combustion characteristics, Heat release rate,** Shadowgraph technique. (A1)

1. INTRODUCTION

Diesel engines (DI) engines provide higher thermal efficiency than spark ignition (SI) engines, however DI engines still have serious pollutant problems. Many researchers have been employed various techniques for reducing in exhaust gas emissions such as after-treatment systems (i.e. DOC, SCR, DPF, etc.) [1], engine combustion control (i.e. common-rail, swirl mixing, EGR, etc.) [2,3]. On the other hand, research on the alternative and renewable fuels are searching to employ for proper way, which have not only sustainable, but also friendly, respect with the environment. Therefore, alternative fuels as sustainable energy have been researched for applying into diesel engines such as biodiesel (i.e. FAME, SME, RME).

Biodiesel which is a first generation of biofuel can be produced by transesterification process. Biodiesel have been widely used, as it can be directly used or blending used with diesel in the engines without no modification. However it still have some disadvantages to the engines such as low heating value [4] and high density and viscosity that make larger droplet size distribution, poor fuel-air mixing processes and mixture formation [5,6]. However, HVO is more advantage than biodiesel such as high cetane number, similar density and viscosity to diesel that can make small atomization, better mixture formation.

HVO is a second generation of biofuel that can be produced from many kinds of vegetable oil by using hydrotreating process. HVO is a mixture of normal paraffin and iso-paraffin [7]. HVO is promising alternative fuels as one of candidate to replace diesel due to its more advantages in comparison with other alternative diesel fuels. The first one shows about production. HVO has variety of bio-feedstock, better oxidation stability. The second one is better fuel properties such as low aromatics and sulfur, high cetane number, high heating value, similar density, viscosity, chemical structure to diesel [8]. From this reason, it offers significant improvement in engine performance and exhaust gas emissions. However, HVO still have limitation to use in diesel engines as it shows very high cetane number and low lubricity, so researchers suggested that HVO would not be blended over 50% [9].

Effects of HVO on combustion characteristics have been performed by many researches in the diesel engines. Sugiyama et al [10] carried out HVO on the engine and concluded that heat release rate of HVO exhibited more advance with shorten ignition delay to improve combustion which resulted decreasing in fuel consumption, Hydrocarbon (HC) and Particulate Matter (PM) emissions. Liu et al [11] concluded that combustion pressure and heat release rate of HVO showed slightly higher than diesel, moreover the shorter ignition delay and combustion duration were observed with high EGR rate due to its higher cetane number, higher amount energy per unit volume, and the long chain paraffin is easier to broken up than diesel fuel. Jaroonjitsathian et al [12] experimentally investigated HVO and HVO blended fuels on combustion characteristics and engine performance, concluded that HVO and blends provided shorter ignition delay, combustion duration, and better combustion efficiency, consequently overall engine efficiency and specific energy consumption can be improved by HVO. Sugiyama et al [10] and Armas et al [13] carried out HVO on chassis dynamometer to performance, combustion and emission characteristics under New European Driving Cycle (NEDC) and showed that HVO exhibited low fuel consumption, higher heat release rate, shorter ignition delay due to its higher cetane number. In addition, exhaust gas emissions also decreased.

From previous researches have been done on combustion so these can be summarized that HVO provided shorter ignition delay, slightly higher heat release rate, and low exhaust gas emissions due to its better ignition quality that provide better combustion efficiency. Therefore, HVO showed the better the evaporation characteristics, smaller droplet size distribution that make its better mixture formation. However, a few work have been performed the influence of diesel and HVO blend percentage on characteristics of the ignition delay and spray combustion by using heat release analysis. Especially, the discussions effects of diesel and HVO blend percentage on the combustion visualization such as spray evaporation and flame development have not clearly explain yet.

The objective of this paper is to investigate effects diesel and HVO blend percentage on the heat release rate, the ignition delay and the integral heat release in constant volume combustion chamber (CVCC) under simulated diesel combustion condition using heat release analysis. Moreover, the shadowgraph technique was to visualize combustion processes of fuel in order to describe effects of fuel properties of diesel and HVO blend percentage to fuel evaporation processes, and flame development. Therefore, the fundamental data of ignition delay, combustion and the visualization of combustion are helpful information to optimize designing in diesel engines by HVO.

2. METHODS

2.1 Heat release analysis

Heat release rate can be determined from pressure rise after burning injected fuel based on the first law of thermodynamics of the system, as shown in Equation (1) [14].

$$\frac{dQ}{dt}=\frac{\gamma}{\gamma-1}\cdot P\cdot\frac{dV}{dt}+\frac{1}{\gamma-1}\cdot V\cdot\frac{dP}{dt} \qquad (1)$$

Where γ is ratio of specific heat, dV/dt is chamber volume change with time, dP/dt is in-chamber pressure change with time, P is in-chamber pressure, V is chamber volume

In this paper, the heat release analysis was studied in constant volume combustion chamber where the chamber volume was kept constant then the dV/dt term could not be considered. Hence, heat release rate for this study is express as follows:

$$\frac{dQ}{dt}=\frac{1}{\gamma-1}\cdot V\cdot\frac{dP}{dt} \qquad (2)$$

The ignition delay is defined as the time from start of injection (SOI) to the start of combustion (SOC) where heat release rate recover from the negative value due to heat absorption [14, 15] as illustrated in Figure 1. The total heat release can be integrated from the heat release rate curve area from the start of combustion to the end of combustion (EOC) where heat release rate decrease to the negative value.

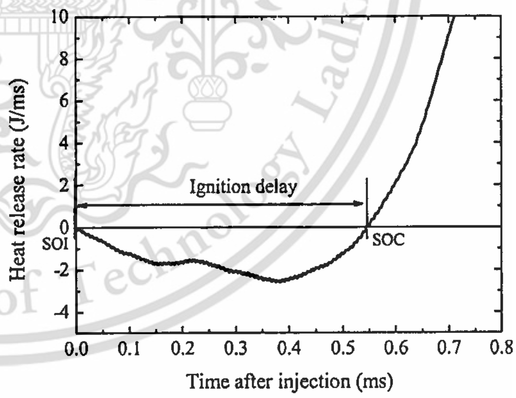


Fig. 1 The definition of the ignition delay

3. EXPERIMENTAL SETUP AND PROCEDURES

3.1 Experimental setup

Figure 2 shows the schematic diagram of spray combustion characteristics experiment using CVCC with shadowgraph technique. The CVCC was a circular cylinder with 502.65 cm^3 in volume. The combustion chamber has 80 mm in diameter, 100 mm in depth, the quartz window were equipped in this chamber for optical assessment. There are six main parts of combustion chamber: an intake valve was used to control partial pressure of the premixed gaseous mixture of acetylene (C_2H_2), oxygen (O_2) and nitrogen, (N_2), an exhaust valve was used to remove burned-gas, the spark plug was used to ignite gaseous mixture to generate high pressure and temperature, the mixing fan was used to run 25s gaseous mixture before spark-ignition for maintaining uniform gaseous distribution throughout the combustion of fuel, a dynamics pressure transducer (Kistler 6053CC60) and charge amplifier (Kistler 5011) were used to measure pressure rise of combustion of fuel , and a single-hole injector was installed at the top of combustion chamber to inject tested fuel. The 3-phase motor was used to drive a second generation common-rail pump to obtain high fuel injection pressure by the inverter controller. The pressure rise of auto-ignition was recorded by oscilloscope (RICOL DS1052E) with sampling rate $5x10^5$ S/s.

The shadowgraph technique was used to visualize spray combustion. The concave mirror allowed to reflecting the light from the Xenon lamp that passing through combustion chamber. The high speed video camera (Phantom Miro 3a10 Camera) with 10,000 frame per second (fps) was used to capture high speed video combustion, and a resolution of 512 x 464 pixels.

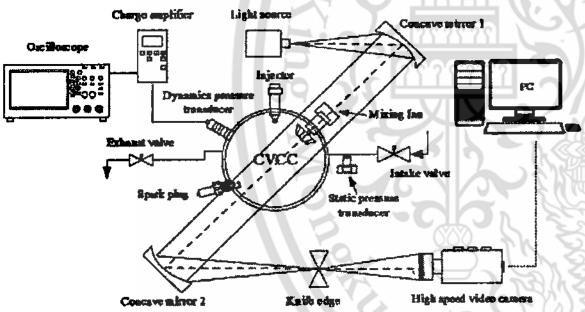


Fig. 2 Schematic diagram of spray combustion characteristics experiment using CVCC with shadowgraph technique

3.2 Experimental condition

Table 1 shows the experimental condition in this experiment. Four test fuels were tested: diesel, two HVO-diesel blends by mass: 20%(H20), and 50%(H50) and 100% HVO in constant volume combustion chamber (CVCC) with single-hole injector, 0.2 mm in nozzle orifice diameter, 2.5 ms in energizing time. The injection pressure was kept constant at 100 MPa. The ambient pressure and temperature were controlled at 4.0 MPa and 900 K that refer to diesel combustion conditions at the end of compression stroke.

Table 1. Experimental condition

Parameter	Conditions
Test fuels	Diesel, H20, H50, HVO
Nozzle orifice diameter	Single hole 0.2 mm
Energizing time	2.5 ms
Injection pressure	100 MPa
Ambient pressure	4 MPa
Ambient temperature	900 K
Oxygen concentration	21%
Repeat	10 times / condition

3.3 Test fuels

Table 2 shows fuel properties. In this study, four different fuel were diesel, H20, H50 and HVO. The properties of test fuels were determined prior to the study of spray combustion characteristics. From this table, H20, H50 and HVO have lower viscosity by 4.62%, 10.49% and 18.52%, respectively, with lower density than diesel by 1.21%, 2.91%a and 5.58%, respectively. But higher heating values by 0.39%, 0.11% and 2.18%, respectively. Moreover, one of important property in this study was distillation temperature that describes the evaporation of fuel. At T90, H20, H50 and HVO have lower distillation temperature than diesel by 0.21%, 0.70% and 16.77%, respectively. If fuel has lower distillation temperature that will be show fast evaporation and well-mixed with surrounding air dramatically. The cetane index is calculated from fuel density, T10, T50 and T90 distillation temperature that used to estimate the cetane number of fuel. The cetane index of H20, H50 and HVO are higher than diesel by 4.86%, 13.05% and 27.23% due to its lower T10, T50 and T90, respectively.

Table 2. Fuel properties

Properties	Standard	Diesel	H20	H50	HVO
Kinematic viscosity (40°C, cSt)	ASTM D445	3.24	3.09	2.90	2.64
Density (30°C, kg/m^3)	ASTM D4052	824	814	800	778
Heating value (MJ/kg)	ASTM D240	45.86	46.04	46.38	46.86
Distillation T10 (°C)	ASTM D86-11b	207.7	210.7	216..3	227.4
Distillation T50 (°C)	ASTM D86-11b	287.9	284.5	281.4	278.2
Distillation T90 (°C)	ASTM D86-11b	352.3	345.2	327.4	293.2
Cetane index	ASTM D4737	60.43	63.37	68.32	76.89

3.4 Experimental procedure

The spray combustion characteristics were investigated under simulated diesel combustion conditions in CVCC by using two-step combustion that can be illustrated in Figure 3. The first step was using spark plug to generate high-pressure and high-temperature ambient gas by burning the premixed gas of C_2H_2, O_2 and N_2 as premixed combustion period. Before the second step, in-chamber pressure and temperature were decreased to reach diesel combustion condition due to the heat transfer as cool down process. The second step was fuel injection into combustion chamber, then injected fuel was continuously burnt as combustion of fuel.

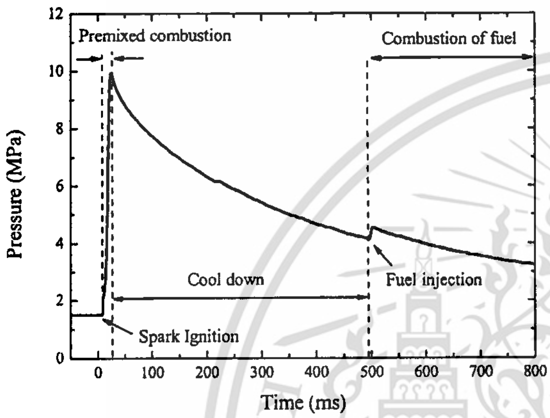


Fig. 3 Pressure history in combustion chamber

4. RESULTS AND DISCUSSIONS

The investigation on the spray combustion characteristics of diesel and HVO blend percentage under simulated diesel combustion were derived into two parts. In the first part, the heat release rate, the ignition delay, and the integral heat release were discussed. In the second part, we focused on the shadowgraph images that describe effects of fuel properties on the spray evaporation, ignition delay and flame development.

4.1 Heat release rate

Figure 4 show the effects of diesel and HVO blend percentage on the heat release rate. This study calculated the heat release rate in CVCC based on the first law of thermodynamics [14]. HVO and blends show that it early observed SOC as early observed heat release rate recover from SOI due to its high cetane number that make its short ignition delay [11,12], In addition, HVO and blends show slightly higher the peak of heat release rate than diesel due to its higher heating value Therefore, the employments of an increase in HVO blend percentage are to improve ignitability of fuel and to increase heat release rate.

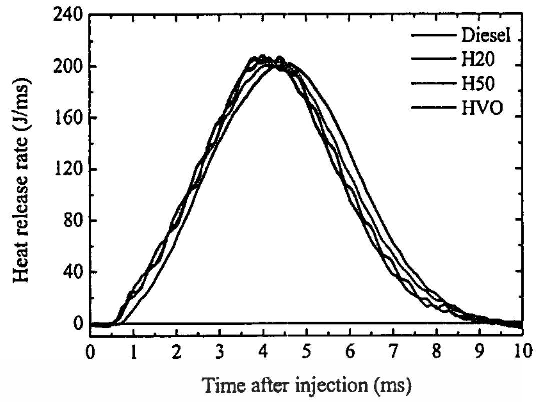


Fig. 4 Heat release rate

4.2 Ignition delay

Figure 5 show the effects of diesel and HVO blend percentage on the ignition delay. The ignition delay in this study defined as the period from SOI to SOC where heat release rate recover from the negative value due to heat absorption. The ignition delay was significantly decreased with increasing HVO percentage by 14.27%, 19.28% and 34.48%, respectively compare to diesel due to its higher cetane number. Another reason for shorter ignition delay of HVO and blends is the lower distillation temperature which make its faster evaporation with surrounding air in the chamber, and it might contribute to small droplet size distribution [15,16], which is related to a better mixture formation. The conclusion in effects of HVO and blends on the ignition delay is that increasing HVO blend percentage lead to a decrease in ignition delay so that combustion can be improved.

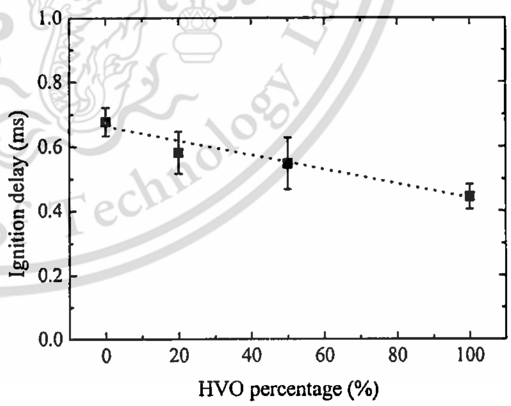


Fig. 5 Ignition delay

4.3 Integral heat release

Figure 6 shows the integral heat release as total amount of heat release where emitted from combustion of fuel, which is calculated from the integration under heat release rate curve area from SOC to EOC. The integral heat release in this study describes as the heat of combustion of injected fuel. The results showed that increasing HVO blend percentage show insignificant effect on the integral heat release due to similarity of energy input [17].

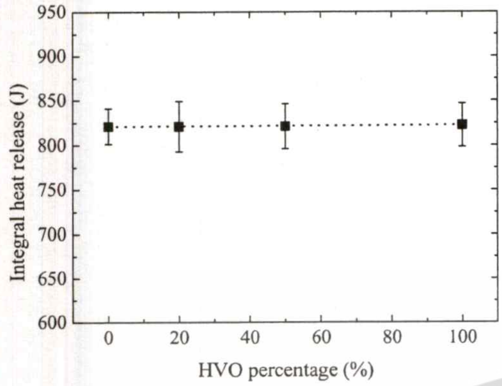


Fig. 6 Integral heat release

4.4 Combustion visualization and shadowgraph images

The sequence shadowgraph images of spray combustion of this study were capture by using the high speed video camera. The discussion on the effects of diesel and HVO as a representative on the fuel evaporation, the mixture formation and the combustion progress, such as viscosity, density and distillation temperature were illustrated in Figure 7.

In this figure, the first column indicated time after energizing, the second and the third column indicated diesel and HVO as a representative. At 0.5 ms, HVO observed slight long spray penetration and wide spray angle than diesel. At the time of 0.7 ms, HVO observed shorter liquid phase as it shows small dark spray, fast spray vaporization and well-mixing with surrounding air compare diesel as it observed larger fuel evaporated around the tip of spray due to its lower density, viscosity and distillation temperature at T90% by 18.52%, 5.58% and 16.77%, respectively, which might contribute to small droplet size distribution, lead to reducing in fuel-air mixing time. At 0.9 ms, Both diesel and HVO have already ignited as shown as flame luminosity. After 0.9 ms, diesel and HVO have continuously burnt as seen as flame development, and reach to chamber wall around 1.4 ms. The combustion progress of diesel and HVO show similar due to difference of flame luminosity area by 1.31%. But after the flame reach to the wall at 1.4 ms, the flame luminosity area of HVO show significant lower than diesel by 12.31%, 6.45%, 18.17% and 21.03%, respectively following the time after energizing of 1.9 ms, 2.9 ms 3.9 ms and 4.4 ms, respectively. This possibility is that diesel has generated more soot form than HVO, as displayed by larger flame luminosity area which emitted from the thermal radiation of soot particles [18], that agreement with previous research [7-8, 10, 12-13].

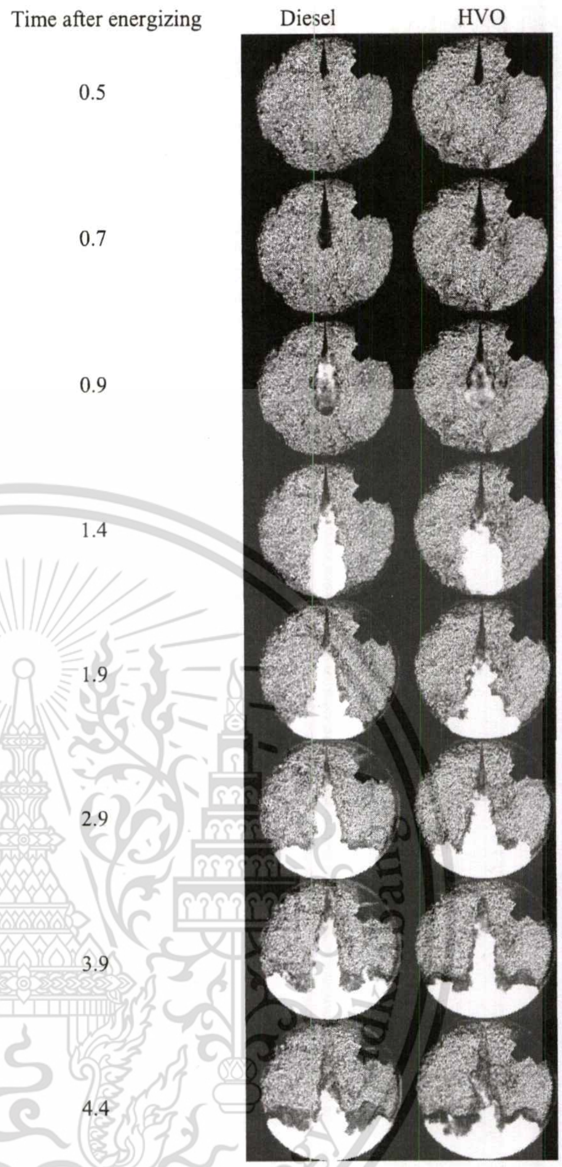


Figure 7 Shadowgraph images of combustion processes of diesel and HVO at ambient pressure of 4 MPa and ambient temperature of 900 K

5. CONCLUSIONS

The effects of HVO-diesel blend fuels on the ignition delay and spray combustion characteristics in CVCC under simulated diesel combustion condition were investigated using heat release analysis and shadowgraph images. The heat release rate, the ignition delay, the integral heat release and shadowgraph images were summarized as follows:

(1) The heat release rate of HVO and blends show similar results to diesel under constant injection pressure, ambient pressure and temperature.

(2) Increasing HVO blend percentage lead to decrease the ignition delay due to its higher cetane number and lower distillation temperature.

(3) Increasing HVO blend percentage shows insignificant improvement in the integral heat release due to the same of energy input.

(4) On the shadowgraph images of combustion processes, HVO can reduce time of mixing processes that make better mixture formation as more fuel vaporize, and fuel-air interaction inside combustion chamber very well during combustion phase due to its better evaporation characteristics.

(5) The combustion process of diesel and HVO show slight difference as seen as flame development. In addition, diesel shows larger flame luminosity area than HVO that might generate high soot formation.

6. ACKNOWLEDGEMENT

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