平成 24 文

主論文

Comparison of PRF and Toluene/n-heptane Mixture in the Mechanism of Compression Ignition Using Transient Species Measurements and Simplified Model Analysis

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Contents

First Chapter

Introduction

1.1 Research Background

1.1.1 Heat Engine

A heat engine is known as a mechanical system that uses thermal energy came from combustion and changes it into mechanical energy. An easy definition is that, a heat engine changes thermal energy into mechanical energy that can help us in daily life. A heat engine can be defined as external combustion engines and internal combustion engines by the method of heating the working fluid. An internal combustion engine gets the energy directly using heat energy generated by the combustion in the interior of the working fluid. On the other hand, an external heat engine is a heat engine where an (internal) working fluid is heated by combustion in an external source, through the engine wall or a heat exchanger. The fluid then, by expanding and acting on the mechanism of the engine, produces motion and usable work. The fluid is then cooled, compressed and reused (closed cycle), or (less commonly) dumped, and cool fluid pulled in (open cycle air engine). The advantages of an internal combustion engine are;

- Good thermal efficiency because of less heat loss.
- Engine system light and small.
- Least cost if it is not high output engine like power plant engine that uses internal combustion engine.

On the other hand, the advantages of external combustion engines are;

- Not good in thermal efficiency compared to the internal combustion engine.
- Widely used for high output engine such as power plant, and solar thermal rocket(externally heated rocket).
- Fuels in any kind of state (solid, liquid, gas) can be used and this can reduce the fuel cost [1].

Table1-1 shows classifications and usage of both internal and external combustion engines [2].

Table1.1 Classification of Thermomotor

Working liquid pressurizing method	Exchange method	Representatives examples	Main use examples
External Combustion engine	Volume type	Steam engine, Stirling Engine	Steam vehicles
	Speed type	Steam turbine	Generator, large vessels
Internal combustion engine	Volume type	Otto Cycle and Diesel Engine	Cars and ships
	Speed type	Gas Turbine and Jet Engine	Ships and Aircraft

1.1.2 History of Internal Combustion Engine

More than 120 years ago, Nicolaus Otto has been succeeded in making internal combustion engine into reality. Since 20th Century, internal combustion engines have been widely produced.

Research on Internal Combustion Engine has been improved up until 1970's. However, as oil shock happens and pollutions problems came ahead, the research has moved on mainly towards engine efficiency and environmental friendly. This trend doesn't stop up until now and rule on exhaust gas has been more strict years by years. However, CO_2 has caused global warming problem and depletion of petroleum throughout the world has been critically until now.

These days gasoline engines and diesel engine has been widely used as an internal combustion engines. However, these two engines have disadvantages and one of the solutions is Homogeneous Charge Compression Ignition engine or known as HCCI engine. Research on HCCI engine has increased up until now. However nowadays, most engine researchers did not consider developing pure HCCI engine. Instead of that, they tend to develop a gasoline engine or a diesel engine that can be operated in HCCI mode. Below is the classification of internal combustion engine with fuel injection system and ignition system in table 1.2.

Table1.2 Classification of Reciprocated Engine

	Fuel Injection system	Ignition system	Consumption rate	Exhaust
Gasoline Engine	Pre-injection	Spark ignition	×	○
Diesel Engine	Direct injection	Charge Compression	○	×
HCCI Mode Engine	Pre-Injection	Charge Compression	○	△

Engines based on the four-stroke ("Otto cycle") have one power stroke for every four strokes (up-down-up-down) and employ spark plug ignition. Combustion occurs rapidly, and during combustion the volume varies little ("constant volume"). They are used in cars, larger boats, some motorcycles, and many light aircraft. They are generally quieter, more efficient, and larger than their two-stroke counterparts.

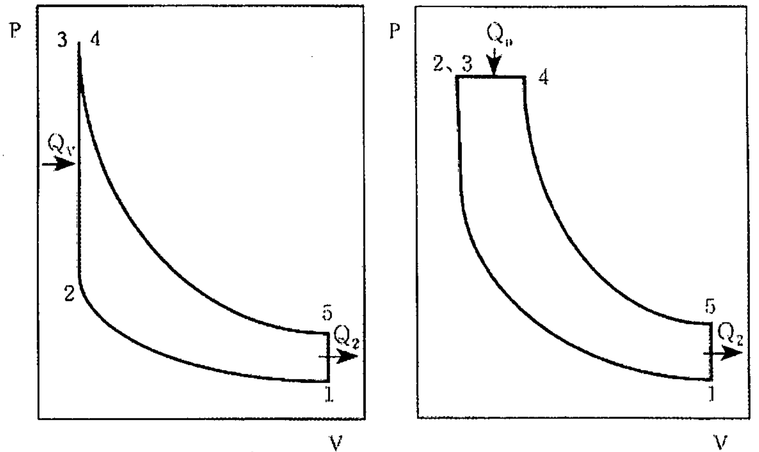
The steps involved here are:

1. Intake stroke: Air and vaporized fuel are drawn in.
2. Compression stroke: Fuel vapor and air are compressed and ignited.
3. Ignition: Fuel combusts and piston is pushed downwards.
4. Exhaust stroke: Exhaust is driven out. During the 1st, 2nd, and 4th stroke the piston is relying on power and the momentum generated by the other pistons. In that case, a four-cylinder engine would be less smooth than a six- or eight-cylinder engine in condition of total displacement are same.

A PV diagram of the Otto cycle is shown in Fig.1-1, the theoretical thermal efficiency is given as follows [3]

$$\eta_{th} = 1 - \frac{1}{\varepsilon^{\kappa-1}} \quad (\kappa : \text{Specific heat ratio}, \ \varepsilon : \text{Compression ratio}) \qquad (1\text{-}1)$$

For homogeneous air-fuel mixture, to obtain a significant change in specific heat ratio is difficult as for as air-fuel mixture is used as the working fluid. Gasoline fuel for instance has combustion limit of air-fuel ratio around, 10～18 and because of knocking limit, upper limit of compression ratio is around 9～12.5. Here, the air fuel ratio (A/F) is the ratio of air mass to fuel mass while the equivalence ratio is fuel air ratio divided by stoichiometric fuel air ratio. Further, in low load range, it is necessary to decrease air intake through a throttle valve. Because of this, minus work due to pumping loss happens during air intake, lowering indicated thermal efficiency of the otto cycle engine and this is a major cause of worse fuel consumption of this kind of engine. To overcome these problems, Lean Burn Engine which can achieved air fuel ratio more than 30 has been realized [4,5]. This type of engine can prevent from knocking and it is close to diesel engine in term of fuel consumption. Direct Inject Gasoline Engine [6], and Miller cycle are examples of various technology that has been produced to improve pumping loss [7].



Otto cycle

diesel cycle

Fig. 1-1 P-V curve of Otto-cycle and diesel-cycle .

On the other hand, regardless of the power load to the engine, a diesel engine has no intake throttle. Air is introduced to the cylinder at full load and the fuel is injected at around the end of compression stroke. The high pressure and temperature leads the fuel to ignite. Below is the equation of theoretical thermal efficiency for diesel cycle, η_{th} ;

$$\eta_{th} = 1 - \frac{\rho^{\kappa} - 1}{\varepsilon^{\kappa-1}\kappa(\rho - 1)} \qquad (\rho = V_4 / V_3 \text{ : Constant Pressure Expansion Ratio}) \qquad (1\text{-}2)$$

Because of the diesel cycle is very near to the air cycle, specific heat ratio is higher than that of stoichiometric mixture. Moreover, the high pressure ratio (ε=18~23) makes the thermal efficiency higher. However, the air-fuel mixture is inhomogeneous, in which the mixture is over concentrated in the center of fuel injection. The consequent, production of soot and NOx is the serious problem of diesel engine. As the countermeasures, using optimum fuel, delaying the injection timing, and exhaust gas recirculation (EGR) are performed. The delayed injection and EGR reduce combustion temperature, and EGR reduces oxygen concentration which lead to lower NOx production [8,9] . The NOx and soot regulation has been finally achieved by developing after-treatment techniques of the exhaust gas applicable to diesel engines, in this decade, although the cost is higher than that for gasoline engines [11].

1.1.3 HCCI Engine

HCCI has characteristics of the two most popular forms of combustion used in SI (spark ignition) engines- homogeneous charge spark ignition (gasoline engines) and CI engines: stratified charge compression ignition (diesel engines). As in homogeneous charge spark ignition, the fuel and oxidizer are mixed together. However, rather than using an electric discharge to ignite a portion of the mixture, the density and temperature of the mixture are raised by compression until the entire mixture reacts spontaneously. Stratified charge compression ignition also relies on temperature and density increase resulting from compression, but combustion occurs at the boundary of fuel-air mixing, caused by an injection event, to initiate combustion.

The defining characteristic of HCCI is that the ignition occurs at several places at a time which makes the fuel/air mixture burn nearly simultaneously. There is no direct initiator of combustion. This makes the process inherently challenging to control. However, with advances in microprocessors and a physical understanding of the ignition process, HCCI can be controlled to achieve gasoline engine-like emissions along with diesel engine-like efficiency. In fact, HCCI engines have been shown to achieve extremely low levels of Nitrogen oxide emissions (NOx) without an after-treatment catalytic converter. The unburned hydrocarbon and carbon monoxide emissions are still high (due to lower peak temperatures), as in gasoline engines, and must still be treated to meet automotive emission regulations.

Recent research has shown that the use of two fuels with different reactivities (such as gasoline and diesel) can help solve some of the difficulties of controlling HCCI ignition and burn rates. RCCI or Reactivity Controlled Compression Ignition has been demonstrated to provide highly efficient, low emissions operation over wide load and speed ranges

Advantages

- HCCI provides up to a 30-percent fuel savings, while meeting current emissions standards.
- Since HCCI engines are fuel-lean, they can operate at a Diesel-like compression ratios (>15), thus achieving higher efficiencies than conventional spark-ignited gasoline engines.
- Homogeneous mixing of fuel and air leads to cleaner combustion and lower emissions. Actually, because peak temperatures are significantly lower than in typical spark ignited engines, NO_x levels are almost negligible. Additionally, the premixed lean mixture does not produce soot.
- HCCI engines can operate on gasoline, diesel fuel, and most alternative fuels.
- In regards to gasoline engines, the omission of throttle losses improves HCCI efficiency.

Disadvantages

- High in-cylinder peak pressures may cause damage to the engine.
- High heat release and pressure rise rates contribute to engine wear.
- The autoignition event is difficult to control, unlike the ignition event in spark ignition (SI) and diesel engines which are controlled by spark plugs and in-cylinder fuel injectors, respectively.
- HCCI engines have a small power range, constrained at low loads by lean flammability limits and high loads by in-cylinder pressure restrictions.
- Carbon monoxide (CO) and hydrocarbon (HC) pre-catalyst emissions are higher than a typical spark ignition engine, caused by incomplete oxidation (due to the rapid combustion event and low in-cylinder temperatures) and trapped crevice gases, respectively.

1.2 Process of compression ignition in hydrocarbon fuels

1.2.1 Reaction mechanism of compression ignition

Fig.1-2 shows in-cylinder pressure institutions, heat generation and temperature profiles for HCCI engine with normal heptanes (nC_7H_{16}) as a fuel. From the figure, generally there are two-stage of heat generation from ignition mechanism of hydrocarbons. Relatively, around 700K there is small heat generation called “Cool Ignition” while around 1000K, there is a large heat generation as main combustion flame called “Hot Ignition”. This Hot ignition is dominated and influenced by the Cool Ignition.

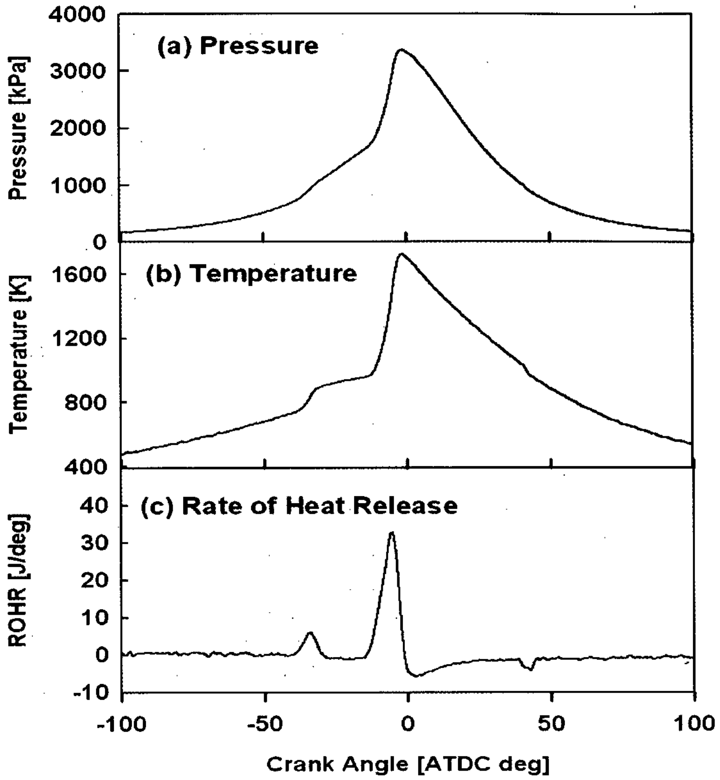


Fig.1-2 Observed pressure(a), temperature (b) and rate of heat release (c) in n-heptane fueled HCCI engine.(φ= 0.43, intake gas temperature = 413K)

According to Westbrook, hydrogen peroxide reaction as shown below, has significant impact in hot flame oxidation reaction [17].

$H_2O_2 + M = 2OH + M$ (R. 1-1)

Moreover, from Ando et al. suggested that there is H_2O_2 loop reaction that dominates hot ignition in the region between hot and cool ignition called “Region for Heat ignition preparation reaction”. This H_2O_2 loop reaction helps the heat generation as shown in Fig. 1-3 [18].

The overall reaction of H_2O_2 loop reaction is,

$2HCHO + O_2 \rightarrow 2H_2O + 2CO + 473KJ$ (R. 1-2)

Not H_2O_2, HCHO acts as the consumer and all of the reactions in the entire loop has a large heat and has an important role in the ignition preparation region.

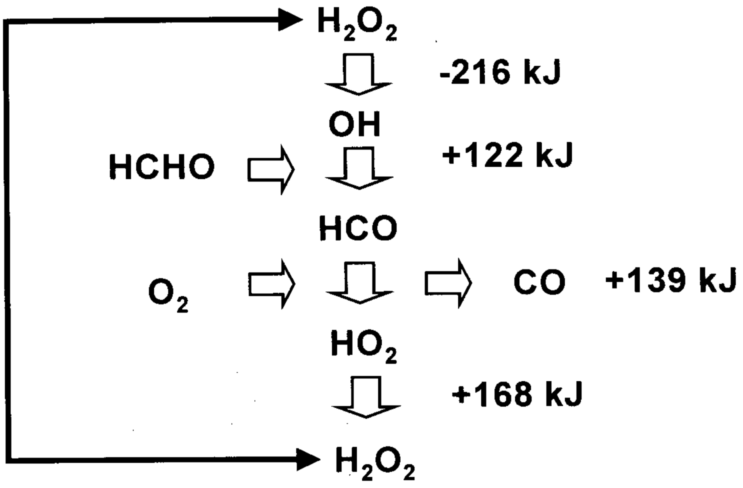


Fig.1-3 H_2O_2 loop reaction effective in the hot ignition preparation period.

Below indicates the reaction pathways for hot flame oxidation.

$RH + OH \rightarrow C + H_2O$ (R. 1-3)

$R(+M) \rightarrow H, CH_3 + Q$(olefine etc.) (R. 1-4)

$H + O_2 \rightarrow OH + O$ (R. 1-5)

$O + RH \rightarrow OH + R$ (R. 1-6)

$H + O_2(+M) \rightarrow HO_2(+M)$ (R. 1-7)

From loop (R.1-3) until (R.1-6) is a proliferative reaction of OH, reaction rate for chain branching reaction is rate-limited by (R.1-5), and stops at reaction (R.1-7). Here, k5 as the reaction rate constant for reaction (R.1-5) must win reaction rate constant k7 [M] as the prerequisite to achieve hot ignition. Although k5 has significance temperature dependence, while not in k7, k7[M] is dependent on the total pressure. Therefore, conditions to achieve heat hot flame are determined by temperature and pressure.

Heat generation for low temperature oxidation and thermal ignition preparation period has significant influence to the time when the temperature reached for the occurrence of hot flame. In addition, by supplying OH reactant into H_2O_2 presence reaction can accelerate the generation of hot flame. Therefore, to understand and control low temperature oxidation reaction that has dominated cool flame that cause the hot flame as the main combustion becoming important task in realizing HCCI engine. Fig.1-3 shows schematic diagram of the low temperature oxidation reaction in hydrocarbon fuel.

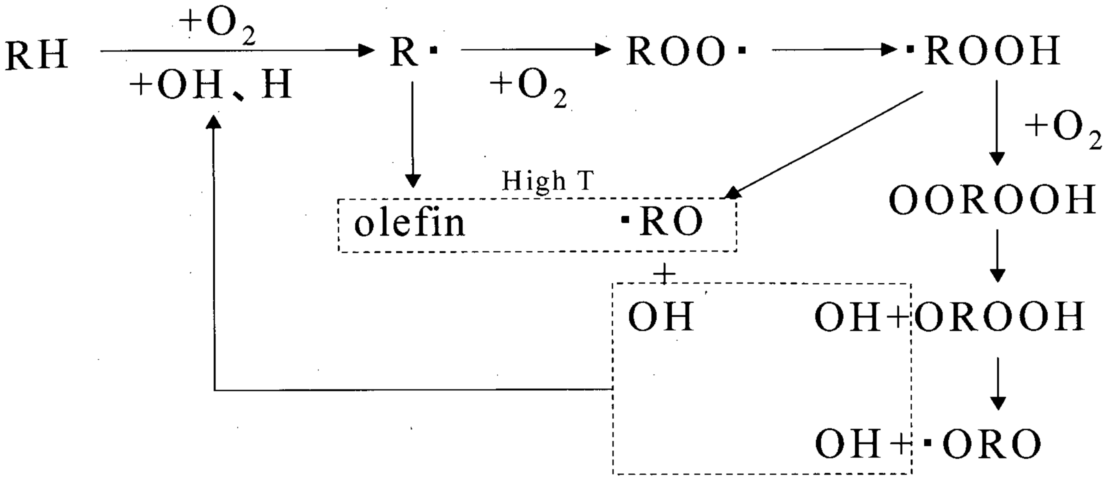


Fig1-3 General Oxidation Scheme for hydrocarbon at low and high

Apparently, Hydrogen Oxide produced by thermal decomposition. This reaction generates 2 OH radicals in low temperature oxidation that leads to fuel consumption through acceleration of hot flame. On the other hand, the fuel follows a complex reaction pathways is highly dependent on the fuel structure in the low temperature oxidation. In general, Hydrocarbon fuel (RH) in the low temperature range (R) of cool flame firstly reacted with oxygen molecules O_2 and H atom are withdrawn to generates Alkyl radicals (R).

$$RH + O_2, H, OH \rightarrow R + HO_2, H_2, H_2O \qquad \text{(R.1-8)}$$

Then, O_2 is added to one of the following reaction of R which is generated in the process of generating Alkyl Peroxyl Radical (ROO).

$$R + O_2(+M) \Leftrightarrow ROO(+M) \qquad \text{(R.1-9)}$$

And also, R is causing β-scission by carbon atom coupled (C-C) being thermally decomposited resulting Alkyl radical Rs that has C atoms fewer than alkenes (R1=R2) and R being generated.

$$R \rightarrow R1{=}R2 + Rs \qquad \text{(R.1-10)}$$

However, to achieve reaction (R.1-10), hydrocarbon must be equal or greater than 850K [19], if less than that, energy is not enough to get this reaction and because of that, in the early period of low temperature oxidation, (R.1-9) is mainly occurs.

There are many reactions that responsible in generating ROO but, the most important reaction in radical chain reaction in the stage before ignition is the reaction of hydroperoxyl alkyl radical that generates an internal isomerization reaction. In this reaction O atom as a radical center pulled out H atom in the molecule.

$$\mathrm{ROO} \Leftrightarrow \mathrm{ROOH} \qquad \text{(R.1-11)}$$

At this time, the H atom abstraction occurs through the structure ring members. Hydrocarbon structure in which the reactions take place via 6-membered ring structure is most likely to occur, followed by 7-membered ring and 5-membered ring structure.

4 reactions below are the main reactions that produce ROOH.

$$\mathrm{ROOH} \rightarrow \mathrm{RO} + \mathrm{OH} \qquad \text{(R1-12)}$$
$$\mathrm{ROOH} \rightarrow \mathrm{olefine} + \mathrm{HO_2} \qquad \text{(R.1-13)}$$
$$\mathrm{ROOH} \rightarrow \mathrm{olefine} + \mathrm{Carbonyl} + \mathrm{OH} \qquad \text{(R.1-14)}$$
$$\mathrm{ROOH} + \mathrm{O2} \Leftrightarrow \mathrm{OOROOH}$$

In the atmosphere of excess oxygen, O_2 second addition is most likely to occur to ROOH molecule. Thereafter, reactions that generated Hydroperoxyl Alkyl Peroxyl Radical OOROOH are,

$$\mathrm{OOROOH} \rightarrow \mathrm{OROOH} + \mathrm{OH} \qquad \text{(R.1-16)}$$
$$\mathrm{OROOH} \rightarrow \mathrm{ORO} + \mathrm{OH} \qquad \text{(R.1-17)}$$

From these reactions, 2 or more active OH has been generated. Generated OH causes a series of low temperature oxidation reaction by reacting with the fuel again. In this way, reaction that produces plurality of reactive molecules from the reaction of one active molecule is called "Chain Branching Reaction" and Low temperature Oxidation became active because of this reaction. From this chain reaction, temperature risen, as been expressed by reaction (R.1-12) and (R.1-14), one active molecule being consume while another being reproduce as called chain propagation reaction gradually become dominant. Moreover, reverse reaction in (R.1-9), by means ROO being decomposed and R being reproduced again as in (R.1-11). This kind of reaction most likely to occur [20], so-called chain termination reaction that does not produce reactive molecules leads to higher branching ratio. From this, temperature has risen up and negative reaction is suppressed and called negative temperature coefficient:NTC) moreover, when the temperature risen, makes the change in composition in low temperature oxidation that leads to high temperature oxidation.

Because of the problems in operating range and controlling ignition timing in HCCI engine, lately researchers began to pursue their studies from the chemical reaction inside this kind of engine. Although certain level of results has been acquired, results on low temperature oxidation is hardly known.

1.2.2 Research on Cool Flame inside HCCI Engine

In order to control ignition timing for HCCI engine, study on reactions happen in cool flame is very important.

From Yamada et al., with DME has been used as a fuel in HCCI Engine with hot flame suppressed condition, gas analysis experiments have been done. From the results, show that DME fuel consumption in cool flame regardless of the equivalence ratio, relative production rate to the amount of HCHO fuel input is constant. Fig.1-4 shows graph result from Fourier Transform Infra-Red (FT-IR) from Otomo et al. The result shows same conclusion with Yamada et al. [21].

Below is simplified reaction mechanism for DME in hot flame suppressed condition.

$$\mathrm{DME} + \mathrm{OH} \rightarrow \alpha\mathrm{OH} + \beta\mathrm{HCHO} + \mathrm{other} \qquad \text{(R.1-18)}$$

$$\mathrm{HCHO} + \mathrm{OH} \rightarrow \mathrm{HCO} + \mathrm{H_2O} \qquad \text{(R.1-19)}$$

These two expressions are the summarized version from (R.1-8) until (R.1-17) in term of OH group consumption and regeneration. In cool flame, DME reacts with OH radical reactant, through various reactions, and OH radical been reproduce, then produce a product such HCHO. Within the equation,α and βeach acts as reaction rate constant and primary temperature function, with depending on pressure and oxygen concentration. At the early stage of low temperature oxidation, α value exceeds 1 makes reaction grows reactant OH that leads to an accelerated reaction. Then, temperature risen makes α value decrease, in addition HCHO accumulated as the trend of branching ratio goes to (R.1-19). Because of that, overall amount of OH production rate decrease, and at certain temperature low temperature oxidation stops. It has been found that HCHO as an intermediate product produced in low temperature oxidation plays an important role as reaction suppression.

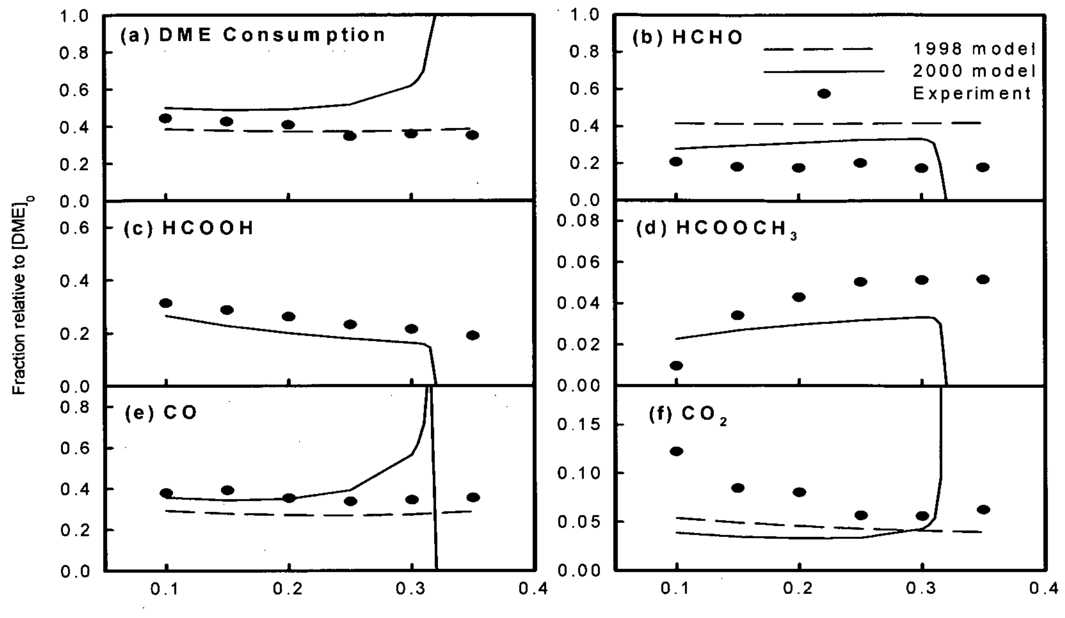


Fig.1-3 Fraction relative to initial DME concentration as a function of equivalence ratio. (a)Consumed DME, (b)HCHO, (c)HCOOH, (d)HCOOCH3, (e)CO, (f)CO2. Intake gas temperature = 373K

In addition, the experimental results done by Sakanashi et al. using Laser-Induced Fluorescence Method (LIF) in-cylinder engine by concentration measurement for the time variation of HCHO shows that HCHO is generated by the cool flame and being consumed by hot flame. The result is shown in Fig. 1-5 [22].

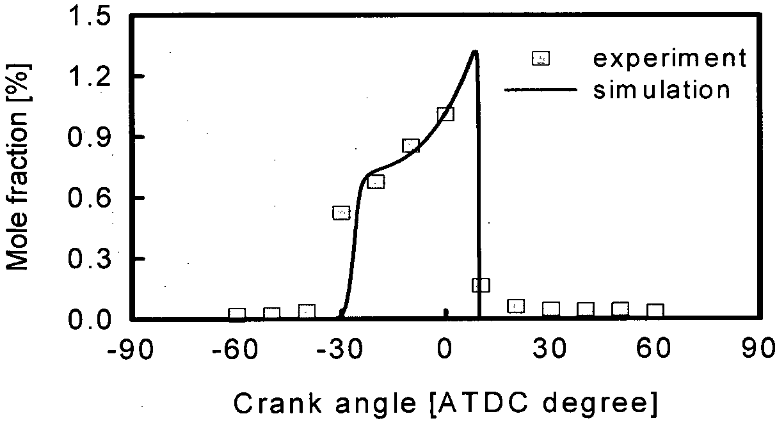


Fig.1-5 Crank angle resolved profile of HCHO mole fraction. Equivalence ratio = 0.25, intake gas temperature = 480K

According to Chung et al., when methanol and natural gas being added to DME, both of these gas has been the cause of ignition in HCCI combustion and proven to be DME's low temperature oxidation reaction suppression throughout experimental results. Between these two gases, methanol has been proven to have more effect of suppression compared to natural gas [23].

From Huang et al., 0 dimensional HCCI engine combustion model analyses has been done using n-heptane as a fuel. It showed that in low temperature oxidation reaction in order to achieve high temperature oxidation, the accumulation of H2O2 is very important for OH radical production. In addition, if the production of H2O2 is insufficient in low temperature oxidation, condition of misfire can be easily happened [24].

Moreover, according to Yoshii et al., development of high speed open-close pulse valve being used to get direct sampling in the cylinder method and measuring chemical species time to time in the cylinder by mass spectrometer have been succeeded [25]. This the method of which collecting gas for each angle if each nine rank in the cylinder and able to obtain time profile of a various chemical species by using a mass spectrometer. More than that, from the differences data of valve opening time, we can differentiate, and discriminates dead volume and boundary volume effects to get data of core volume inside the cylinder. Furthermore, by adding the gas directly to the mass spectrometer, made it possible to make measurements in a very short time, and H_2O_2 measurements analysis that has been too difficult until now becomes possible.

Time-resolved sampling method that has been done by Kasai et al, experimentally revealed the effect of adding methanol (CH_3OH) into DME, and also adding Ozone (O_3) into DME fuel [26]. Furthermore, Kasai et al also achieved in obtaining data result for low temperature oxidation fuel consumption and HCHO production time profiles by using n-heptane fuel that is very much near to the practical use fuel, Octane based fuel (Primary Reference Fuel: PRF). About H_2O_2, in the case of DME, because of the product is less, same mass of O_2 isotope in atmosphere makes different effect is large. By considering the ratio of its existence, time profile of H_2O_2 production can be obtained (Fig. 1-5), and experimental and simulation result shows almost same result.

From this method of time-resolved measurements technique, composition of cool flame when achieving hot flame can be shown same with exhaust gas composition when hot flame is generated. However, since the measurement is performed in the mass spectrometer, materials with close mass number value are hard to be identified such as CO, HCOOH as predicted intermediate products. Therefore, exhaust gas analysis method has been used to evaluate intermediate products in low temperature oxidation reaction. Compared to the time-resolved measurement method, this method has no limit on such as the number of mass, and can be evaluated more qualitative and quantitative exhaust components. However, getting generation profile for each products that have short period existence are difficult.

According to Leppaed et al, exhaust gas analysis was done by using GC (Gas Chromatography) to CRF Engine and Parrafin against Olefin's C4, C5,C6, considering the formation of the intermediate product and the consumption of each fuel against compression ratio show that each Paraffi and Olefin has different reaction pathway [27].

Also report from Miyashita et al, FT-IR gas analysis for HCCI engine with hot flame suppressed condition shows that not only PRF0 (n-heptane), but also 2 dimensional fuel, PRF50 (n-heptane 50%, iso-octane 50%) found that iso-butene iC_4H_8 as unique product from iso-octane. As an Olefin, it is one of the product of β-scission of hydrocarbon radicals, but C_2H_4 is specific to straight chain alkane like n-heptane. Iso-octane, as a branched alkane, preferably produces C3-C4 olefins including isobutene [28].

Another report from Kosaki et al, existence of Benzyldehyde C_6H_5CHO was confirmed in n-heptane+toluene fuel (NTF) after a procedure eliminating superimposed absorption of other aldehydes from raw FT-IR spectrum[kosaki].

1.3 Research Objectives

- In this research, we aimed to further clarify the contrast between iso-octane and toluene on the effect to n-heptane through the composition during hot ignition suppressed condition.
- Finally the essential mechanism affecting the ignition property of n-heptane is discussed by developing a simplified model reproducing the experimental results.

Second Chapter

Experimental Apparatus

2.1 Experimental Apparatus

Diagram of experimental apparatus that has been used in this research shown in Fig。 2-1.. A single cylinder, 4 cycle engine (displacement 541 cm^3, compression ratio 8.0) is externally driven by an electric motor for constant speed operation regardless of internal power generation, where the standard speed is 600 rpm. Liquid fuel is injected into the intake port, evaporated and mixed with preheated air to form combustible mixture gas. Crank angle resolved cylinder pressure is measured by a mounted pressure gauge and recorded at every crank angle degree indicated by a rotary encoder. A part of exhaust gas is introduced in an optical cell of 3 m path length at the pressure of 10 kPa, and the chemical composition is analyzed by a Fourier transform infrared spectrometer (FT-IR, Shimadzu IR Prestige-21). Tubing to the cell is heated to 70~80℃ to avoid condensation by ribbon heater installed along the sample line.

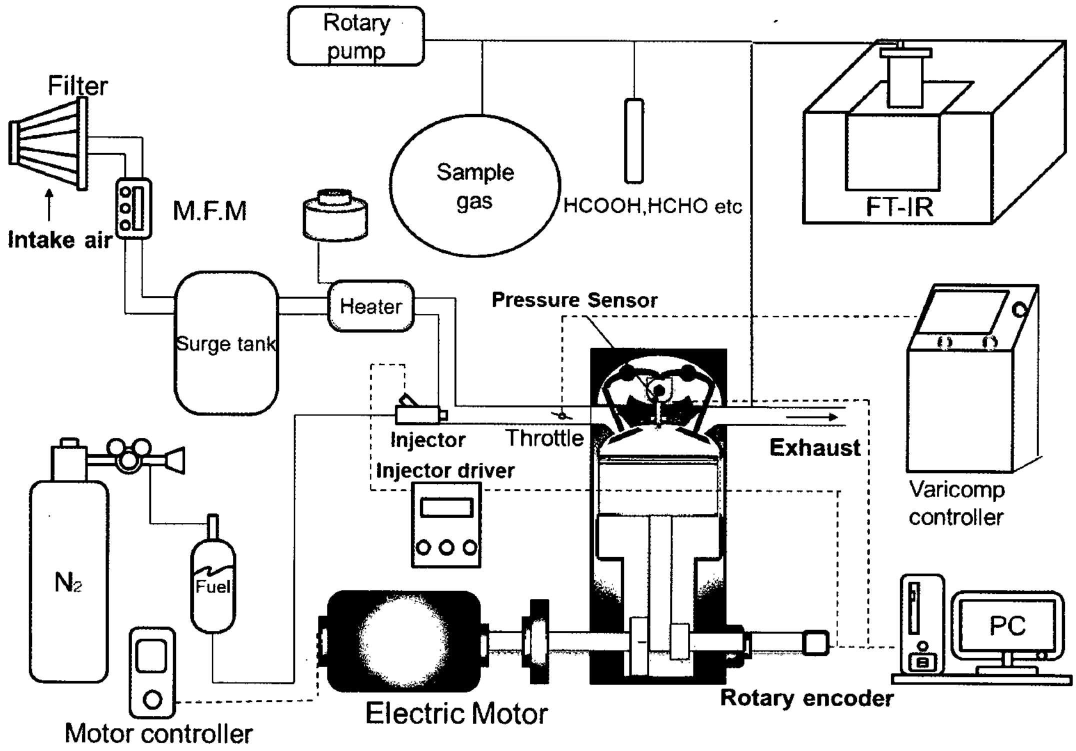


Fig. 2-1 Experimental apparatus

2.1.1 Engine System

VARICOMP Engine

Table 2-2 shows the specifications of the engine used in this study.

Table 2-2 Specification sheet of variable compression engine

Model System	4 stroke gasoline/diesel engine
Valve mechanism	Overhead cam
Cooling system	Water cooling system
Bore	90(mm)
Stroke	85(mm)
Connection rod ratio	3.41
Emissions	541 cc
Number of cylinder	Single cylinder
Compression ratio	Variable 4:1～17.5:1

By raising and lowering the engine head and cylinder, fixed by hydraulic pressure, by changing the clearance volume in combustion chamber of VARICOMP, compression ratio can be change in the range of 4.0 to 17.5. In this study we fixed the compression ratio to 8.

Originally, vertical displacement sensor was installed to the engine head to sense displacement into head engine, but because of insufficient in the resolution, Height gauge was installed onto the head of cylinder to measure the vertical displacement and decide compression ratio.

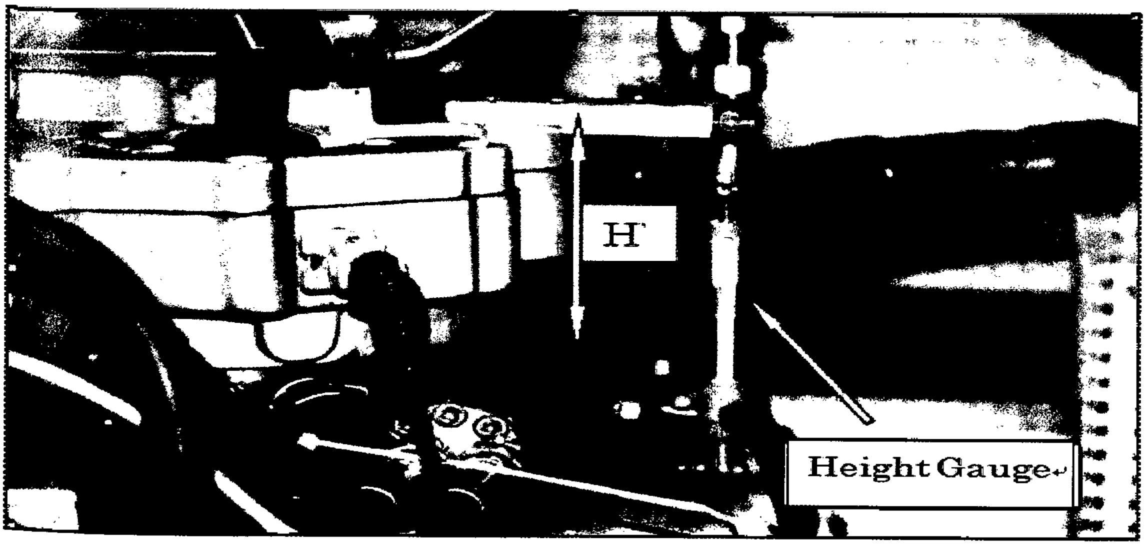


Fig. 2-2 position engine head (H') for compression ratio change

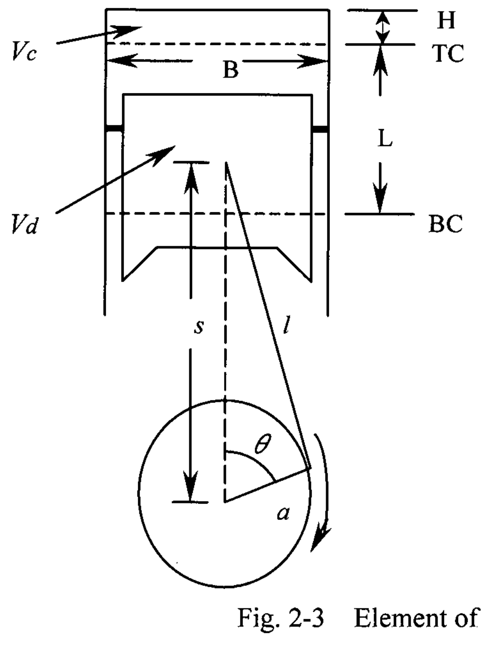
In this case, when engine head situated at the lowest point, compression ratio is calculated as 17.5, we can determine the position of engine head at each of the compression ratio value. As shown in Fig. 2-3, in-cylinder clearance volume is V_c , swept volume is V_d, and compression ratio isε, following equation is given,

$$\varepsilon = \frac{V_c + V_d}{V_c}$$

Then, when the position of cylinder head is lowest, by means compression ratio of 17.5, clearance volume V_0 (cc) , Bore piston of B (cm), cylinder head displacement of H (cm), equation of compression ratio over H is given below.

$$\varepsilon = \frac{V_0 + B^2 \times (1/4) \times \pi \times H + V_d}{V_0 + B^2 \times (1/4) \times \pi \times H} = \frac{573.52 + 2.025 \times 10^{-3} \times \pi \times H}{32.773 + 2.025 \times 10^{-3} \times \pi \times H}$$

Fig.2-4 shows graph of relation between compression ratio and the position of cylinder head from calculation



B=bore
L=stroke
l=connecting road length
a=crank radius
θ =crank angle
Vc=clearance volume
Vd=swept volume

Fig. 2-3 Element of the VARICOMP Engine

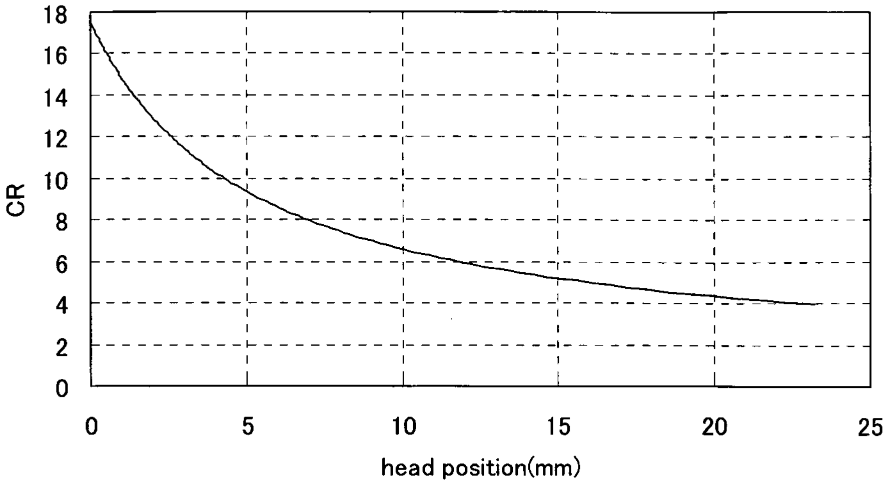


Fig. 2-4 Correlation between compression ratio and head position.

2.1.2 Intake Air System

Hot-wire flow meter are attached to measure intake air onto the VARICOMP but, due to the instability of the display of engine speed at 600 rpm, sufficient accuracy to determine the equivalence ratio cannot be obtained. Therefore, more accurate mass flow meter (manufactured by Yamatake Co., MCF015, flow range: 0 ~ 500L/min) is installed, and further, in order to smooth the intake flow rate, surge tank with the drums was made.

In order to obtain a stable ignition, intake air heater installed before intake port, heated by the heater to control the intake air temperature. Essentially, to achieve compression ignition, preheating is required. In addition, it is necessary to promote vaporization of liquid fuel in the intake port. Note that, intercooler used in automobiles being wrapped with ribbon heater makes intake air heater, while thermocouple installed onto the intake air port measures intake air temperature, transformer was used to control voltage, and heated by 3 ribbon heater (100V-150W×2, 100V-200W). Right now, to make intake air temperature to 130℃, 125V of voltage is needed. Because of that, in the future, ribbon heater need to be improved to get higher intake air temperature with low voltage.

2.1.3 Fuel Supply

Liquid fuel is inserted inside tank gas that can be pressurized. Then, N_2 gas was used to pressurize the fuel and injected to the intake port by injector.

Injector is controlled by Micro-Computer got from Fuji Heavy Industries by controlling injectior timing and injector valve opening period. Range for valve opening period is 1500μs~6500μs. In order to mix vaporized fuel and intake air, injection timing take the output from rotary encoder right after intake valve is closed at BTDC 115°.

Flow test was done to make sure injector working properly. This test The test was performed by pressurize the fuel tank by N_2 gas to 4 and 5 gauge pressure,

Below are the results for the test:

Table 2-5 Flow test parameters

Fuel type	PRF 50
Rotation value	500rpm
Injection duration	4 minutes
Pressure	4 & 5 atm

Table 2-6 Flow test with 4atm gauge

Injection Duration (μs)	1st try	2nd try	Average	Injection quantity (g/cycle)
1500			0	0
2000			0	0
2500			0	0
3000	1.1022	0.7281	0.91515	0.00091515
3500	4.3264	4.3114	4.3189	0.0043189
4000	5.5011	5.7022	5.60165	0.00560165
4500	6.9323	6.4982	6.71525	0.00671525
5000	7.5218	7.7795	7.65065	0.00765065
5500	8.188	8.2845	8.23625	0.00823625
6000	9.0685	9.102	9.08525	0.00908525
6500	9.817	9.889	9.853	0.009853