博士論文

SPRAY COMBUSTION
WITH SMALL AMOUNT OF HYDROGEN

（少量の水素を添加した噴霧燃焼）

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ABSTRACT

Spray combustion has been used very widely as engine energy, especially in the worldwide development of transportation, providing high performance of aircrafts and diesel engines. Oil-fired furnaces also employ spray combustion. In the hydrocarbon spray combustion, there is a problem on exhaust emission: large amount of NOx is exhausted if the combustion is enhanced, but CO and THC emissions are increased if NOx emission is reduced by some method. Hydrogen is one of the promising alternative fuels. Hydrogen has no carbon content, faster flame speed and smaller quenching distance, thus incorporating hydrogen should improve the combustion performance without deterioration of the exhaust emission characteristics. Since the heating value of hydrogen is about three times as large as that of diesel fuel, the addition of small amount of hydrogen also has a possibility to improve hydrocarbon fuel spray combustion.

In the present research, the experiments were carried out in three steps. The first step is to investigate basic characteristics of combustion and exhaust emission from spray combustion, the second step is to understand the influence of hydrogen addition method on the spray combustion, and the third step is to confirm the effect of hydrogen addition in the emulsion fuel.

As a preliminary test for hydrogen addition to rich-premixed spray-jet combustion, two hydrogen addition methods were compared using n-decane as a fuel; hydrogen addition to the spray jet and near the flame base. The method of hydrogen addition to the spray jet has a limitation in the amount of hydrogen. Beyond the threshold, the fire back occurs. The method of hydrogen addition near flame base allowed more hydrogen addition than the method of hydrogen addition to the spray jet. Thus, the effect of hydrogen on rich-premixed spray-jet combustion was investigated with hydrogen addition near flame base. The internal flame disappears by H_2 addition in the most cases. The heat generated by H_2 combustion enhances droplet vaporization and causes rich mixture over the rich flammability limit, resulting in the disappearance of the internal flame. Hydrogen addition also makes the flame higher. EICO and EITHC decrease by increasing hydrogen fraction. Since the internal flame produces much CO and dilution gases of CO_2 and H_2O, which slower the CO oxidation at the external flame, the disappearance of the internal flame leads to lower CO. The heat generated by H_2 combustion also enhances vaporization of droplets passing through the external flame and leads to lower THC. The trends of emission indexes with diesel fuel as a practical fuel are similar to those with n-decane.

In the first experiment, basic characteristics of spray combustion and exhaust emission were investigated by n-decane as fuel. Data of the flame height, and exhaust gas emission were taken for different equivalence ratios of the spray jet and different atomization conditions. The result shows that the spray flame consist of the internal flame and the external flame. The height of internal flame increase with decreasing spray jet equivalence ratio, while the height of external flame decreases. When the portion of internal flame in the external flame is higher, i.e., at smaller spray-jet equivalence ratio, CO emission is higher at the same atomizing air flow rate if the combustion efficiency is high enough. Since the internal flame is a rich premixed flame, much CO is produced at the internal flame. CO_2 and H_2O are also produced at the internal flame. CO_2 and H_2O act as dilution gases and slow CO oxidation reaction at the external flame, resulting in much CO emission. This is more significant when the portion of the internal flame in the external flame is greater. CO oxidation and NO production at the external flame are enhanced by the combustion enhancement at higher atomizing air flow rate and/or higher spray-jet equivalence ratio.

The second experiment was conducted with n-decane as a pure fuel and diesel fuel as a practical fuel to investigate the effect of hydrogen addition. As a preliminary test for hydrogen addition to rich-premixed spray-jet combustion, two hydrogen addition methods were compared using n-decane as a fuel; hydrogen addition to the spray jet and near the flame base. The method of hydrogen addition to the spray jet has a limitation in the amount of hydrogen. Beyond the threshold, the fire back occurs. The method of hydrogen addition near flame base allowed more hydrogen addition than to the spray jet method. Thus, the effect of hydrogen on rich-premixed spray-jet combustion was investigated with hydrogen addition near flame base. The internal flame disappears by H_2 addition in most cases. The heat generated by H_2 combustion also enhances vaporization of droplets passing through the external flame and leads to lower THC. The trends of emission index with diesel fuel as a practical fuel is similar to those with n-decane.

The third experiment was done to investigate combustion and emission characteristics with hydrogen added to emulsion fuel spray combustion. The water percentage of 5 vol% in W/O emulsion fuel was used. The content of water in the emulsion fuel leads to the lower combustion temperature, resulting in low NO emission but high CO and THC. The dependencies of emission index with the emulsion fuel on hydrogen fraction are also similar to those with n-decane. By adding a small amount hydrogen, CO and THC emission decrease significantly, while NO emission is still less than that with diesel fuel.

概要

噴霧燃焼はエンジンの燃焼技術として広く利用されており，特に世界的に輸送機器の発展が期待されている中で，高い性能を持つ航空機やディーゼルエンジンを世にもたらしている．同様に，油焚きバーナも噴霧燃焼を採用している．炭化水素燃料を用いた噴霧燃焼では，燃焼状態が活発であると大量のNOxが排出されるが，何らかの手段によりNOx排出量を削減すると逆にCOやTHCの排出量が増加してしまうという問題を抱えている．水素は代替燃料として有望な燃料の1つである．水素は炭素を含まず火炎伝播速度が大きく消炎距離が小さいために，燃焼場への水素添加は排気特性の悪化無しに燃焼状態を改善することができる．また，水素の発熱量は軽油と比較して約3倍であるため，少量の水素添加でも炭化水素燃料の噴霧燃焼を改善する可能性がある．

本研究では三段階に分けて実験を行った．まず，第一段階目として噴霧燃焼における基本的な燃焼・排気特性を調査した．その後第二段階目として噴霧燃焼への水素添加方法が与える影響の理解を行い，最後に第三段階目としてエマルジョン燃料における水素添加効果の確認を行った．

実験装置として，気体燃料を用いる際に用いられるブンゼンバーナを噴霧燃焼に適用した過濃予混合噴霧バーナを採用した．液体燃料はバーナ下部に設置された2流体噴射弁から微粒化用空気によって微粒化し，その燃料噴霧と微粒化用空気・補助空気を混合することで過濃予混合噴霧流を形成した．噴霧流の微粒化状態の制御は微粒化用空気流量の変更によって行った．補助空気は異なる微粒化状態において噴霧流当量比を一定に保つために供給した．噴霧流当量比は燃料流量の変更によって制御した．周囲空気は火炎の外側より拡散燃焼を完了させる目的で供給した．噴霧火炎はビデオカメラを用いて観察し，排気ガス成分であるCO，THC，NO，CO_2は自動車排気ガス分析装置を用いて計測した

はじめに，正デカンを燃料として噴霧燃焼およびその排気ガス成分について基本的な特性の調査した．噴霧流当量比および微粒化状態を変更し，火炎長や排気特性のデータを収集した．その結果，噴霧火炎は内部火炎と外部火炎とから成る二重火炎構造であり，噴霧流当量比が減少するにしたがって内部火炎の火炎長が増加すると同時に外部火炎長が減少した．また，燃焼効率がある程度高い場合には，噴霧流当量比の減少に伴い外部火炎内に占める内部火炎の割合が大きくなり，CO排出量は増加した．これはまず内部火炎が過濃予混合火炎であるため，多量のCOが内部火炎領域で生成したためである．同様にCO_2およびH_2Oも内部火炎領域にて生成されている．これらのCO_2およびH_2Oは拡散火炎中にて希釈ガスとして作用しCOの酸化反応を遅延させるために，結果としてCOが外部火炎から多量排出される．これは多量にCOを排出する条件である，内部火炎が外側の拡散火炎内に占める割合が大きい場合に特に重要な現象である．ただし，微粒化空気流量が大きいか噴霧流当量比が大きいほど燃焼が促進され，外部火炎でのCOの酸化，あるいはNOの生成も促進される．

次に，正デカンを純粋燃料，軽油を実用燃料として，それら噴霧火炎への水素添加効果の調査を行った．過濃予混合噴霧燃焼への水素添加の予備実験として，正デカンを燃料として，噴霧流に直接水素を添加する方法と噴霧火炎基部に水素を添加する方法の2つの水素添加方法の比較を行った．本予備実験により，噴霧流への直接の水素添加方法は逆火が生じる危険があるために，水素添加量の制限が存在することが分かった．噴霧火炎基部に水素を添加する方法では，前者の方法よりも多量の水素を添加できることが判明したため，以降の実験では後者の水素添加方法を用いて実験を行った．噴霧火炎に水素を添加した多くの条件において内部火炎は消失した．水素の燃焼により発生した熱に

より，外側の拡散燃焼火炎を通過した燃料液滴の蒸発が促進され，THC排出量の低減につながった．軽油における排気特性も，正デカンの排気特性と同様の傾向を示している．

最後に，エマルジョン燃料を用いた噴霧火炎に水素を添加した場合の燃焼・排気特性を調査した．含水率5 vol%のW/O型エマルジョン燃料を実験で利用した．本実験より，エマルジョン燃料内の水分により燃焼温度が低下したため，結果として軽油と比較してNO排出量が抑えられるが，COおよびTHC排出量が著しく増加した．排気ガス濃度の水素添加割合依存性は正デカンの場合と同様であった．少量の水素を添加することにより，COおよびTHC排出量は著しく減少した．その一方，NO排出量は軽油を用いた場合よりも少なくできた．

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CHAPTER 1. INTRODUCTION

1.1. RESEARCH BACKGROUND

Spray combustion has been used very widely as engine energy [1]. Especially in the worldwide development of transportation, providing high performance of aircrafts and diesel engines [2]. Oil-fired furnaces also employ spray combustion [3]. Combustion is mass and energy conversion processes during the chemical bond energy transformed into the thermal energy. The fuel reacts with an oxidizer to form products which have a lower formation enthalpy or reference enthalpy, than the reactants. Spray combustion is a complicated dynamic process that caused by interacting between chemical process and physical processes, such as liquid fuel atomization, droplet vaporization and mixing of fuel vapor and oxidizer.

A problem of hydrocarbon utilization to the spray combustion is the exhaust gas emission. Beside CO_2 emission, a large amount of NOx is exhausted when the combustion is enhanced. CO and THC (total unburned hydrocarbon) emissions are increased, however, if NOx emission is reduced by some methods. For example, if oil-water emulsion fuel is used, NOx and smoke are reduced but CO and THC are increased. NOx which mainly consists of NO and NO_2 produced from the reaction of nitrogen and oxygen in air at high-temperature region over 1500 K. NO_2 can produce ground-level ozone through photochemical reaction and therefore photochemical smog, giving a negative effects to the human body, such as damage the lung tissue, irritates the respiratory tract and eyes, NOx also reacts to form nitrate particle, and acid aerosols, which both cause respiratory problems. Nitric acid (HNO_3), formed when NOx reacts with water, can cause acid rain and deterioration water quality, which effect to the agricultural production. Acidic gases along with airborne particles cause visibility impairment and lower air quality. Nonetheless, other emissions are also dangerous for the survival, such as CO_2, CO and THC. CO_2 is a greenhouse gas and contributes to the global warming. CO is poisonous to humans and severely limits of the blood ability to transport oxygen to the tissues. That is caused dizziness, headaches, impaired coordination and the fatal risk. Unburned hydrocarbons also contributes to production of photochemical smog.

Contrary to the hydrocarbon fuels, hydrogen combustion does not emit CO_2, CO, THC and smoke but NOx. Therefore, hydrogen is a one of potential alternative fuels. Since the heating value of hydrogen is about three times as large as that of hydrocarbon fuels, such as diesel fuel, the addition of small amount hydrogen also has a possibility to improve hydrocarbon fuel spray combustion. Recently, Miyamoto et. al. [4] experimentally showed possibilities of improvement of the exhaust emission characteristics of a diesel engine with addition of small amount of hydrogen to the intake air. However, the effect of hydrogen on spray combustion has not been elucidated using spray-jet burners.

The present research investigated combustion and exhaust emission characteristics of spray-jet combustion with small amount of hydrogen. The experiments were conducted at three steps. The first step is to investigate basic characteristics of combustion and exhaust gas emission from spray combustion without hydrogen addition, to examine the flame structure with internal flame and relationship between the flame structure and emission characteristics. The second step is to understand the influence of hydrogen addition method on the spray combustion, to show H_2 addition limitation to the spray jet, to examine how the flame structure changes with H_2 addition near flame base and to examine the exhaust emission changes with H_2 addition near flame base. Third step is to confirm the effect of hydrogen addition in the emulsion fuel spray combustion.

The next section surveys previous researches related to the present research.

1.2. PREVIOUS RESEARCHES

1.2.1. Spray-jet Combustion

There have been many researches on spray combustion in relation with diesel engine and gas turbine. In such practical spray combustor, the liquid spray is naturally or artificially mixed with an oxidizer prior to combustion. However, there are not many basic researches on premixed-spray-jet combustion.

Tsushima et. al. [5] studied combustion characteristics of droplet clusters in a premixed-spray flame by simultaneous monitoring of planar spray images and local chemiluminescence. Multi-color Integrated Cassegrain Receiving Optics (MICRO) were applied to a premixed-spray flame. By observing the droplet cluster and local chemiluminescence simultaneously in the premixed-spray flame, it was confirmed that some portions of the spray stream disappear very rapidly due to preferential flame propagation, while other portions of the spray steam survived over a long period to form droplet clusters.

Mikami et. al. [6] studied combustion of partially premixed spray jets. Liquid spray was mixed with an oxidizer prior to combustion and injected continuously. A rich premixed spray is called “partially premixed spray”. A fuel spray and an oxidizer, diluted with nitrogen, was injected into the air. In the present burner, the mean droplet diameter of the atomized liquid fuel could be varied without varying the overall equivalence ratio of the spray jet. Two combustion modes with and without an internal flame were observed. As the mean droplet diameter was increased or the overall equivalence ratio of the spray jet was decreased, the transition from spray combustion only with an external group flame to that with the internal premixed flame occurred. The results suggest that the internal flame was supported by flammable mixture through the vaporization of fine droplets, and the passage of droplet cluster deformed the internal flame and caused internal flame oscillation. The existence of the internal premixed flame enhanced the vaporization of droplets in the post-premixed-flame zone within the external diffusion flame.

Nakamoto et. al. [7] studied burning behavior of rich premixed-spray jets with different fuel volatilities. n-Octane, n-decane, and n-tridecane were used as a liquid fuel, with the spray-jet equivalence ratio fixed to 12 and with almost the same atomization condition (about 100 μm in Sauter mean droplet diameter d_{32}), burning behavior depended on the fuel type. An internal flame was observed for n-tridecane. When the spray-jet equivalence ratio and atomization condition were varied, an internal flame appeared for some conditions of the spray-jet equivalence ratio and atomization condition even for n-octane and n-decane.

Nakachi et. al. [8] studied the effect of atomization condition on flame structure and emission characteristics of burning rich-premixed spray jets. Two combustion modes with and without an internal flame were observed. As Sauter mean droplet diameter became larger than a specific value, the internal flame appeared inside the external group flame. The existence of the internal flame was affected by the equivalence ratio of premixed spray jet. Exhaust emission characteristics were also affected by Sauter mean droplet diameter and an equivalence ratio of premixed spray jet. As Sauter mean droplet diameter was increased, the emission index of CO (EICO) increased. EICO concentration showed low values without the internal flame.

1.2.2. Effect of Hydrogen on Hydrocarbon-fuel Combustion

Many researches have revealed the advantage of hydrogen assist the combustion. Hydrogen enrichment retards the combustion phasing and reduces the combustion duration, increase the power output and fuel conversion efficiency, and improves the combustion stability [9]. Hydrogen-enriched with the natural and landfill gas yields the particularly attractive characteristic of a monotonic decrease in combustion irreversibility. With an increasing hydrogen content of the fuel, the efficiency is increased [10]. Several researchers have applied hydrogen as a fuel to the engine. The acquired results show that a hydrogen fueled engine has a higher heat transfer rate than a methane fuel engine. This is because hydrogen fuel has a higher heating value, faster flame speed and a smaller quenching distance [11]. However, hydrogen enrichment may narrow the operational compression ratio range and increase the knocking tendency in the engine. There is also a problem in storage at large volume. To overcome the problems, a little amount of hydrogen is added into the spray combustion which gives an optimum effect. The flame behavior is expected more establish.

Juste [12] studied injection of small quantities of hydrogen in a hydrocarbon-fueled gas turbine burner. Hydrogen was injected in the primary zone, where the fuel was premixed with air. The results showed that there were possible positive effects of additional hydrogen to the hydrocarbon combustion.

Miyamoto et. al. [4] experimentally investigated the performance and emission characteristics of the diesel engine with hydrogen added to the intake air at late diesel-fuel injection timings. NO showed a minimum at specific hydrogen fraction. The maximum rate of in cylinder pressure rise also showed a minimum at 10 vol % hydrogen fraction. Implemented EGR with 3.9 vol % hydrogen addition, the smoke emission value was 0%, NO emission was low, the cyclic variation was low, and the maximum rate of in cylinder pressure rise was accepted under a nearly stoichiometry condition without sacrificing indicated thermal efficiency.

Nguyen et. al. [13] studied the effect of hydrogen added to intake air on combustion noise from a diesel engine. The dependences of engine noise on the diesel-fuel injection timing for different hydrogen fractions were discussed considering the characteristics of maximum combustion impact energy for each frequency. The main conclusions are that hydrogen addition of 10 vol % of the intake air contributed greatly to the decrease in combustion noise at late diesel-fuel injection timings.

As explained above, there are some researches on combustion in practical combustors with hydrogen addition. However, the effect of hydrogen on spray combustion has not been elucidated well using laboratory-scale spray-jet burners.

1.2.3. Emulsified-fuel Combustion

The theme of Attia and Kulchitskiy [14] experiment is the influence of the structure, water-in-fuel emulsion on diesel engine performance. In this work the effect of the structure of Water-in-diesel Fuel Emulsion (WFE) on a three cylinder diesel engine performance was investigated. The results showed that emulsions with the large size of water droplets resulted in greater reduction in NOx emissions up to 25%. While, emulsions with finer droplets not only gave reductions in engine smoke and unburned hydrocarbons of values greater than 80% and 35% respectively, but also resulted in an increase of the engine effective efficiency up to 20%.

Yang et. al. [15] studied the impact of emulsion fuel with nano-organic additives on the performance of diesel engine. This work introduced a novel emulsion fuel with 82.4% diesel, 5% water and 12.6% nano-organic additives by volume. NOx emissions were reduced because of the presence of water, which brought down the peak flame temperature. The emulsion fuel can increase the efficiency of the engine since the ignition delay of emulsion fuel is slightly longer than pure diesel, thus, the combustion duration is shorter.

Although there are many researches on emulsion fuel combustion in addition to the above mentioned researches, there is no knowledge of hydrogen addition effect on emulsion fuel combustion.

1.3. RESEARCH OBJECTIVES

The objectives of this research are:

1. To study spray flame structure with the internal flame, exhaust gas emission characteristic, and relationship between the flame structure and emission characteristics using a laboratory spray burner.
2. To investigate the effect of hydrogen addition on the flame stabilization, flame structure and exhaust emission characteristics of spray combustion for different spray jet equivalence ratio and different atomization conditions.
3. To study the application of a hydrogen addition method to emulsion fuel spray combustion.

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CHAPTER 2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1. EXPERIMENTAL OUTLINE

The present research investigated flame and exhaust emission characteristics of spray-jet combustion with small amount of hydrogen. The experiments were conducted in three steps. The first is to investigate basic characteristics of spray-jet combustion and exhaust gas emission from the spray-jet combustion, the second step is to understand the influence of hydrogen addition on the spray-jet combustion, and the third step is to confirm the effect of hydrogen addition in the emulsion fuel spray-jet combustion.

The experimental apparatus employed at a rich-premixed spray burner similar to the Bunsen burner which used for gaseous fuels. The liquid fuel was atomized by the atomizing air throughout a twin-fluid atomizer which was placed below the exit of the burner. The fuel spray, atomizing air and supplementary air was mixed to generate a rich-premixed spray jet which was issued from the burner exit. The atomization condition was varied by the atomizing air flow rate. The supplementary air was supplied to keep the equivalence ratio of the spray jet constant for different atomization conditions. The equivalence ratio of the spray jet was varied by the fuel flow rate. The ambient air was supplied to the outside of the flame to complete diffusion combustion. The spray flame was observed using a video camera. Exhaust gas components, CO, THC, NO and CO_2 were measured using a motor exhaust gas analyzer.

In the first experiment, basic characteristics of spray combustion and exhaust emission were investigated using n-decane. Data of the flame height, exhaust gas emissions, combustion efficiency, and exhaust gas temperature were taken for different equivalence ratios of the spray jet and different atomization conditions. The second experiment investigated the effect of hydrogen addition to the spray combustion. First, two hydrogen addition methods were compared for n-decane spray; hydrogen addition to the spray jet and hydrogen addition near the flame base. Then the best method was applied to both n-decane and diesel fuel experiments. The third experiment was done to investigate combustion and emission characteristics with hydrogen added to emulsion fuel spray-jet combustion. The water percentage of 5 vol% in W/O emulsion fuel was used. Hydrogen was supplied near the flame base. The hydrogen addition methods are explained in Chapter 4.

2.2. EXPERIMENTAL APPARATUS

Figure 2.1 show the general experimental apparatus. It consists of premixed spray-jet burner with a twin-fluid atomizer, combustion chamber, gas supply system and exhaust gas analyzer.

2.2.1. Premixed Spray Burner Setup

Figure 2.2 shows premixed spray-jet burner. There is a twin fluid atomizer (1/8 JJ type, Spraying System, Co., Ltd.) as shows in Figure 2.4. This atomizer device makes a liquid fuel into a small droplet. When the liquid fuel flow throughout the extended pipe, the supply of liquid fuel is driven by a gas jet entered. Because the pressure of gas jet to the liquid fuel is high, thus the fuel becomes atomized due to a shear force.

Figure 2.3 shows the tail pipe of premixed spray burner. The outer diameter of spray nozzle extension pipe is ø 12.7 mm and the length is 300 mm. Solid cone sprays with angle formed 18° is used in this equipment. The twin-fluid atomizer is mounted to the burner with inner diameter and outer diameter of ø 16.7 mm and ø 21.7 mm, respectively. The tip of the nozzle is placed 18 mm below the exit of the burner. The liquid fuel is atomized and sprayed from the nozzle at the end of the pipe. The ambient air is issued into the quiescent atmosphere to complete the diffusion combustion. The atomizing air flow rate (Q_{atom}) was varied in order to vary the droplet size distribution. As the ambient air flow rate is increased, mean droplet diameters decrease [1-3]. Supplementary air (Q_{supp}) was issued to keep the total air flow rate in the premixed spray as a constant value (Q_{SJ}).

The atomizing air and supplementary air are supplied from compressed air cylinders. The flow rates are controlled by mass flow controllers (SEC-E40MK3, HORIBA) and controller units (PE-D20, HORIBA). The fuel tank is placed about 5 meter above the spray nozzle and using drop method to supply fuel. The fuel flow rate is also controlled by a mass flow controller (SEC-E40MK3, HORIBA) and controller unit (PE-D20, HORIBA). The ambient air flow is supplied from an oil-less air compressor (Handicon T08P6S03, Amadera Kuatsu Kogyo Co., Ltd.), and the air flow rate is controlled by a flow meter with precision needle valve (RK1250, KOFLOC).

From the end of the combustion chamber stack, an exhaust analyzer sampling probe and thermocouple (Handy Thermoterminal AM-2001, Anritsu Meter Co., Ltd.) are inserted for the measurement of exhaust gas components and temperature. The remaining of exhaust gas is blown away.

2.2.2. Combustion Chamber Setup

Figure 2.5 shows combustion chamber. A silica glass tube is used as a lower part of combustion chamber. The extended of combustion chamber is a chimney made of stainless steel tube. Silica glass tube inner diameter is ø 144.4 mm and the glass thickness is 3.8 mm, the length is 320 mm. Stainless steel tube inner diameter is ø 160 mm and the thickness is 5 mm, the length is 830 mm. Chimney exit diameter is ø 81.1 mm and is equipped with a cap with opening diameter of ø 40 mm. This cap is mounted for limiting the temperature and the composition effect from an outside system.

2.2.3. Pilot Burner Setup

Figure 2.2 shows propane and air line for the pilot burner in the premixed spray burner. In this research, the propane pilot flame is used only for the first ignition phase and to prevent flame extinction at the worming up processes. The flow rate of propane gas is set Q_{prop} = 150 mL/min. Propane is issued from 16 pilot burner holes, with a diameter of each hole of ø 1.2 mm. The pilot burner outer diameter is ø 42.7 mm and inner diameter is ø 16.7 mm. Stainless steel wool is installed inside the small slot air-propane mixing chamber of the pilot burner to prevent fire back into the propane and air line.

2.3. EXPERIMENTAL PROCEDURE

2.3.1. Spray Flame Observation

For spray flame observation, single-lens reflex digital camera (EXILM EX-F1, Casio) is used. As the photographing conditions for the experiment of n-decane without hydrogen addition, the camera shutter speed is set to 1/60 with ISO 800 and F-number = 2.7, and pictures are taken at 300 fps. For n-decane and diesel fuel with hydrogen addition, also emulsion fuel experiment, the camera shutter speed is set to 1/250 with ISO 400 and F-number = 3.3, and pictures are taken at 300 fps (frame per second).

2.3.2. Exhaust Gas Component Measurement

Exhaust gas components are measured using a motor exhaust gas analyzer (MEXA-1500D, HORIBA Co., Ltd.). The probe is placed on the vertical axis of z = 1150 mm from the burner exit. Before starting the measurement, the burner is warmed up for 30 minutes. At the warming up, atomizing air flow rate is setting 3.0 L/min. The concentration of exhaust gas components, CO (carbon monoxide), THC (total unburned hydrocarbon), CO_2 and NO (nitric oxide), are measured in volume fraction. Emission Index (EI) for 1 MJ total heating value of the fuels is calculated. If hydrogen is added, the heating value of hydrogen is also considered in calculation of the total heating value.

2.4. GENERAL EXPERIMENTAL CONDITION

There were three types of fuels used in this experiment, n-decane as a pure fuel, diesel fuel (JIS K2204 No.2) as a practical fuel and emulsion fuel consisting of diesel fuel, rheodol and water. Furthermore, hydrogen was used to enhance the combustion performance.

The atomizing air flow rate, Q_{atom} was varied as 2.0 L/min, 2.5 L/min, 3.0 and L/min. The supplementary air, Q_{supp} was supplied to keep the total air flow rate in the premixed spray jet as 5.0 L/min, $Q_{\mathrm{SJ}} = Q_{\mathrm{atom}} + Q_{\mathrm{supp}}$. The ambient air flow rate, Q_{ambi} was 35 L/min.

The following formula is the general equation for calculating the equivalence ratio,

$$\phi = \frac{(\mathrm{F/A})}{(\mathrm{F/A})_{\mathrm{st}}} \tag{2.9}$$

where each symbol is defined as follows:

ϕ : equivalence ratio

F : fuel mass flow rate [kg/s]

A : air mass flow rate [kg/s]

$(\mathrm{F/A})_{\mathrm{st}}$: stoichiometric fuel-air ratio

Since the fuel spray and air are premixed and are issued as a rich-premixed spray jet in the present burner, spray jet equivalence ratio can be defined at the exit of burner without ambient air as the following equation,

$$\phi_{\mathrm{SJ}} = \frac{(Q_{\mathrm{F}}\rho_{\mathrm{F}})/\{(Q_{\mathrm{atom}}+Q_{\mathrm{supp}})\rho_{\mathrm{air}}\}}{(\nu_{\mathrm{F}}\mathrm{W}_{\mathrm{F}})/(\nu_{\mathrm{O_2}}\mathrm{W}_{\mathrm{O_2}}/\mathrm{Y}_{\mathrm{O_2}})} \tag{2.10}$$

where each nomenclature is defined as follows:

ϕ_{SJ} : spray jet equivalence ratio

ϕ_{all} : overall equivalence ratio

Q_{F} : liquid fuel flow rate [mL/min]

Q_{atom} : atomizing air flow rate [L/min]

Q_{supp} : supplementary air flow rate [L/min]

ρ_{F} : liquid fuel density

$\rho_{n-\mathrm{decane}}$: n-decane density = 730 [kg/m^3]

$\rho_{\mathrm{diesel\ fuel}}$: diesel fuel density = 832 [kg/m^3]

ρ_{air} : air density = 1.2041 [kg/m^3]

ν_{F} : fuel stoichiometric coefficient = 1

$\nu_{\mathrm{O_2,n-decane}}$: oxygen stoichiometric coefficient at n-decane reaction = 15.5

$\nu_{\mathrm{O_2,diesel\ fuel}}$: oxygen stoichiometric coefficient at diesel fuel reaction = 24.5

$\mathrm{W_F}$: fuel molecular mass

$\mathrm{W_{n-decane}}$: n-decane molecular mass = 142 [kg/kmol]

$\mathrm{W_{diesel\ fuel}}$: diesel fuel molecular mass = 226 [kg/kmol]

$\mathrm{W_{O_2}}$: oxygen molecular mass = 32 [kg/kmol]

$\mathrm{Y_{O_2}}$: oxygen mass fraction in dry air = 0.232

The internal flame characteristics are related to the spray-jet equivalence ratio. ϕ_{SJ} was set higher than 5.

Since the spray jet equivalence ratio is larger than unity, the ambient air is supplied to complete diffusion combustion. The overall equivalence ratio is the equivalence ratio in the whole combustion chamber, including ambient air, which is expressed as,

$$\phi_{\mathrm{all}} = \frac{(Q_{\mathrm{F}}\rho_{\mathrm{F}})/\{(Q_{\mathrm{atom}}+Q_{\mathrm{supp}}+Q_{\mathrm{ambi}})\rho_{\mathrm{air}}\}}{(\nu_{\mathrm{F}}\mathrm{W_F})/(\nu_{\mathrm{O_2}}\mathrm{W_{O_2}}/\mathrm{Y_{O_2}})} \tag{2.11}$$

where Q_{ambi} is the ambient air flow rate. ϕ_{all} was set less than unity for complete combustion.

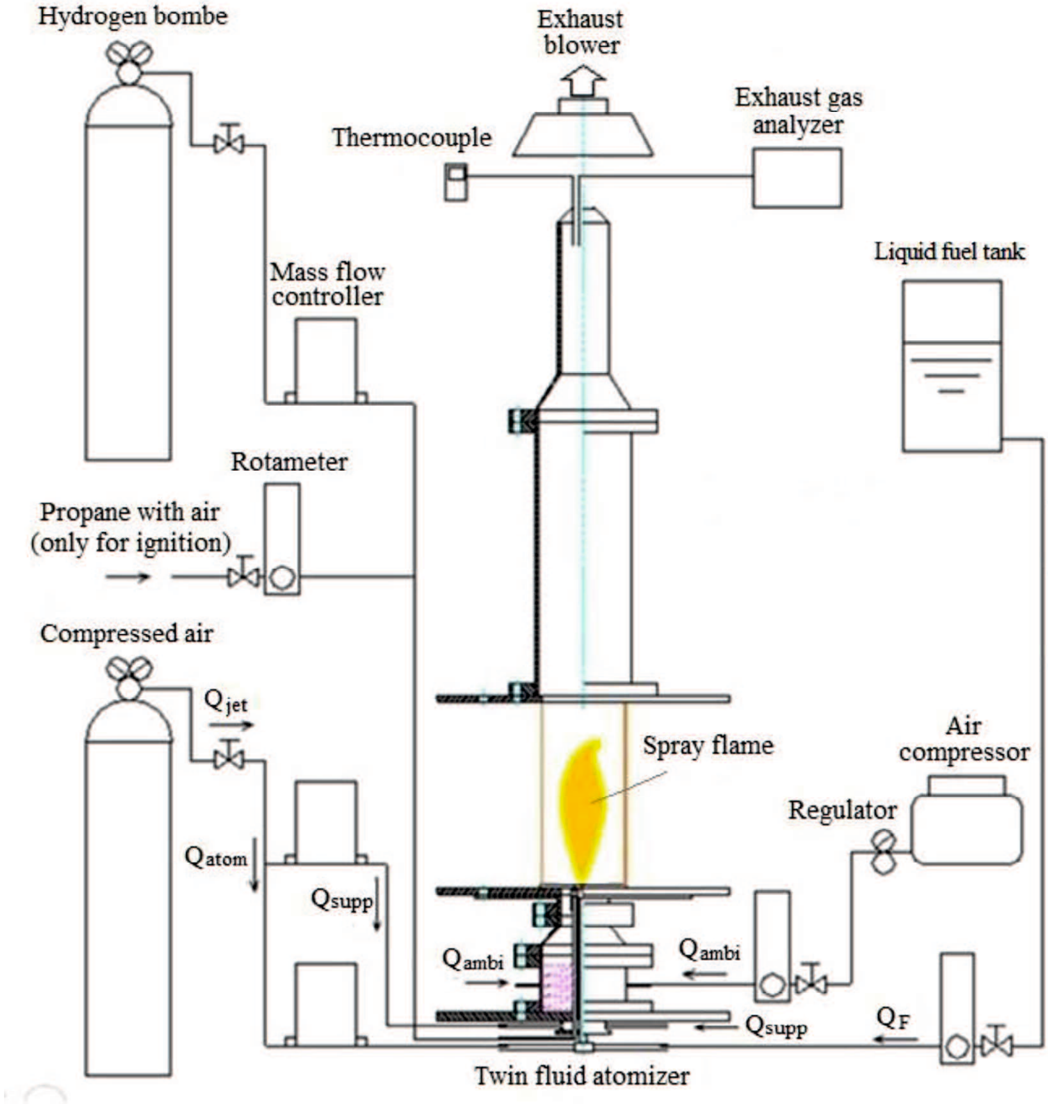

Fig. 2.1. General experimental apparatus

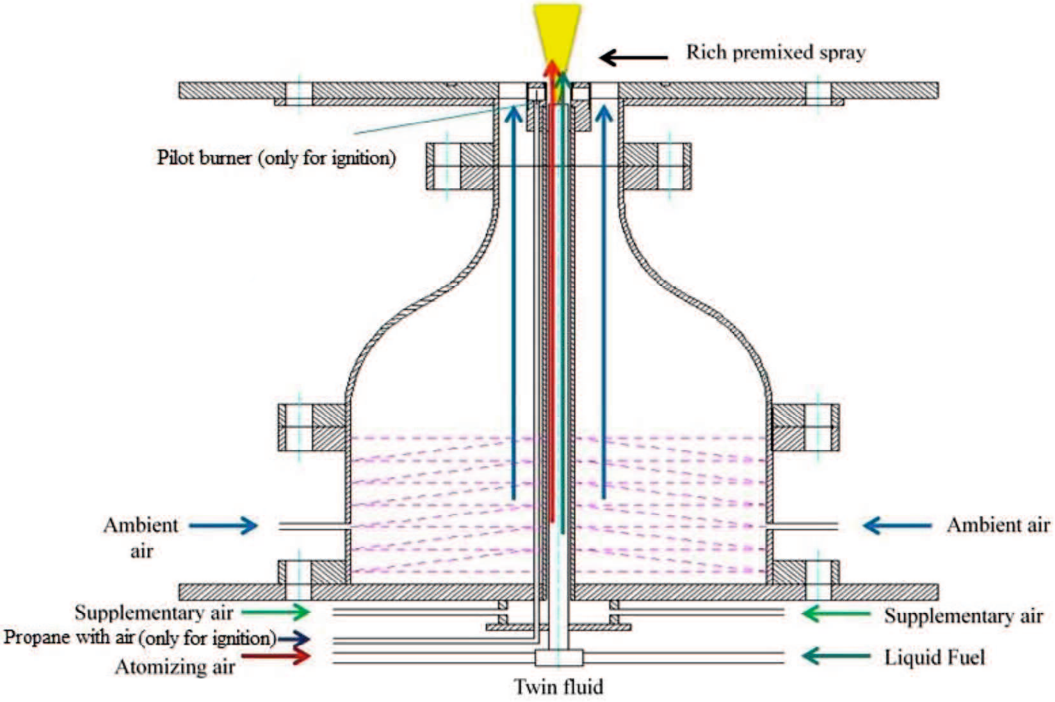

Fig 2.2. Premixed spray burner

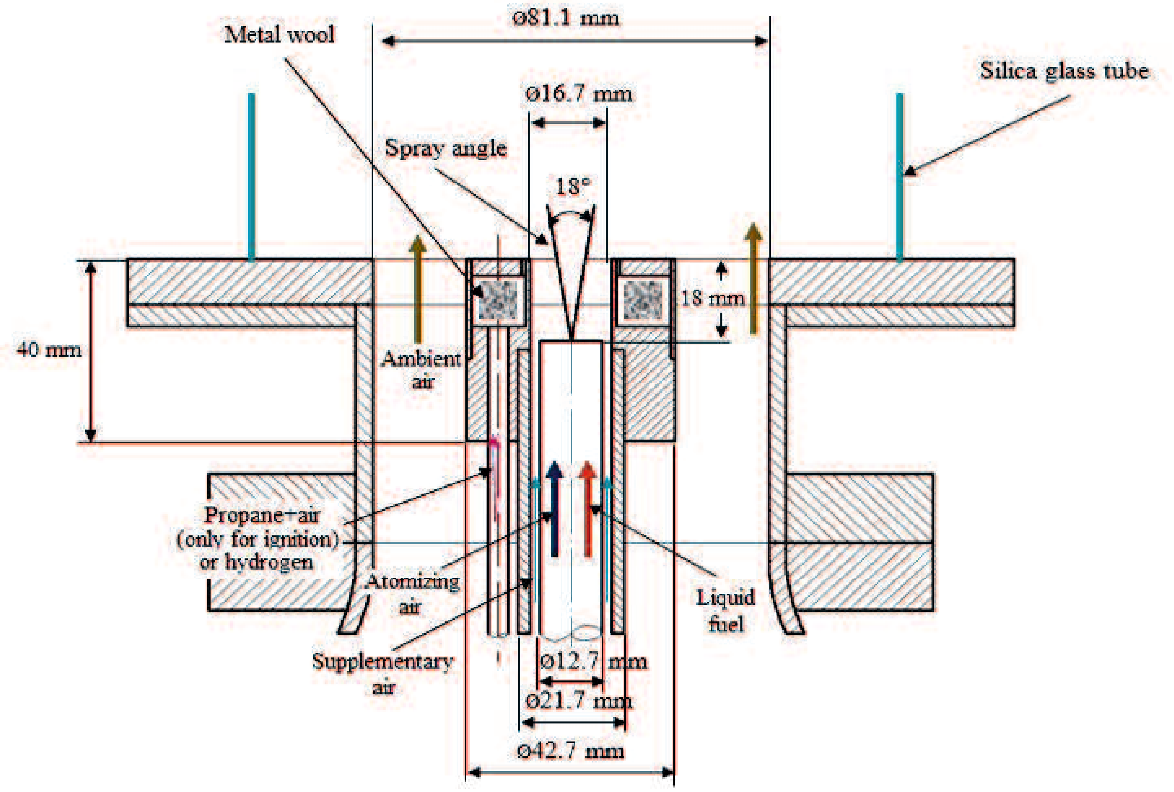

Fig. 2.3. Premixed spray burner end

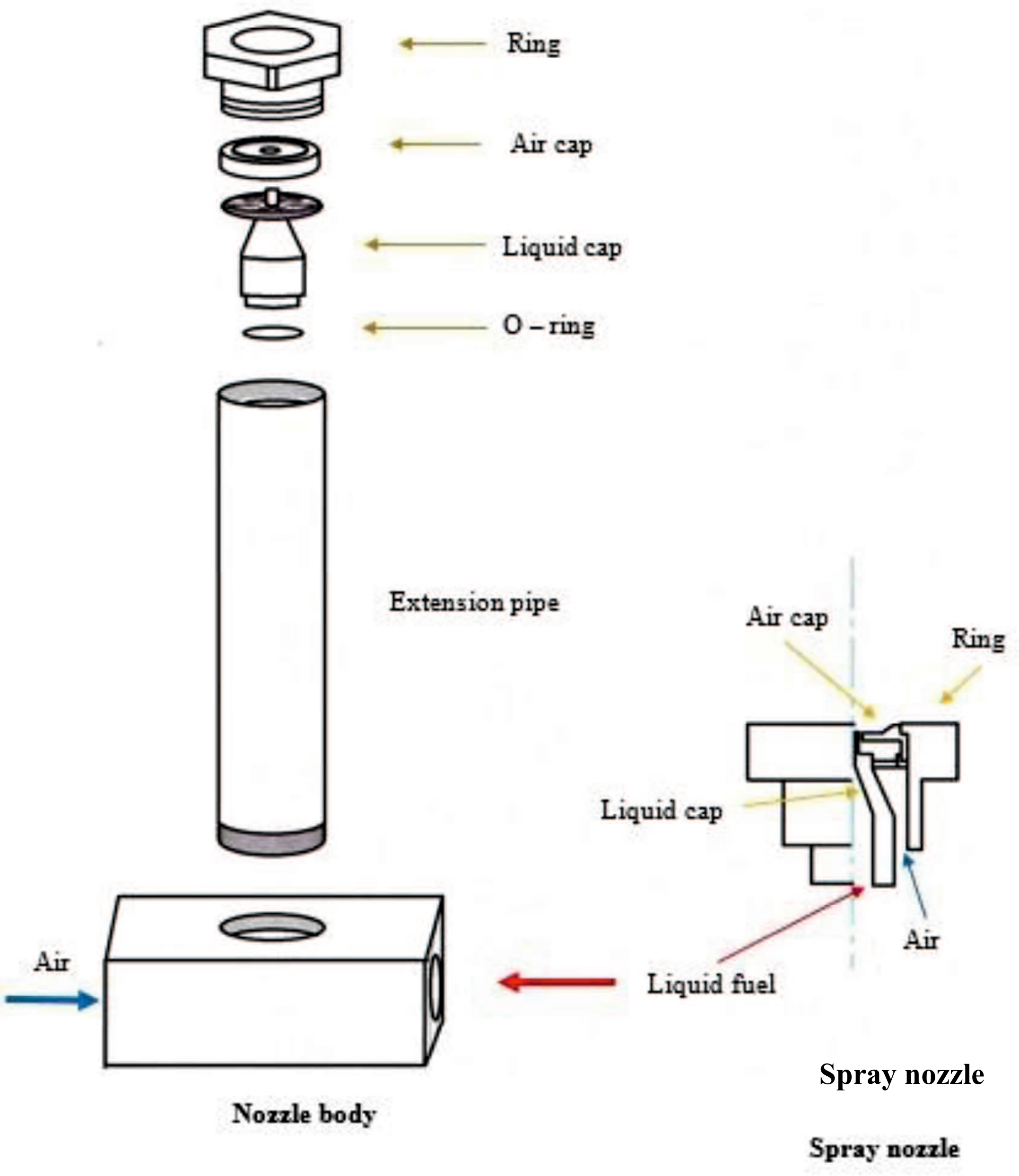

Fig. 2.4. Twin fluid atomizer

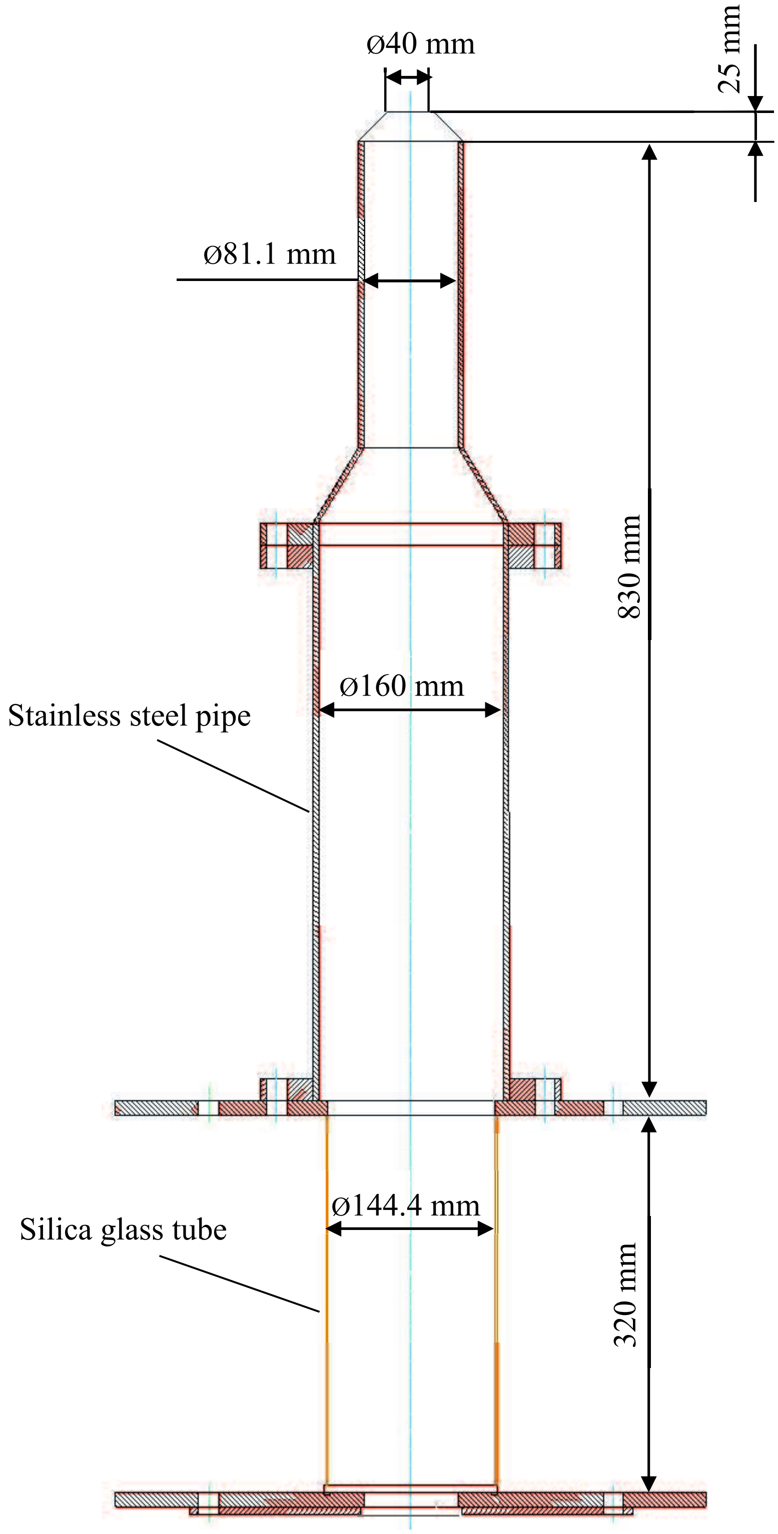

Fig. 2.5. Combustion chamber

References

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[2] Nakamoto, K., Kikuchi, Y., Moriue, O., Mikami, M., *A study on burning behavior of rich premixed-spray jets with different fuel volatilities*, 5th Asia-Pacific Conference on Combustion, 2005, pp. 217-220, Australia.

[3] Nakachi, N., Mikami, M., Kojima, N., *Effects of atomization condition on flame structure and emission characteristics of burning rich-premixed spray jets*, Proceedings of HT2007-32757, ASME-JSME Thermal Engineering Summer Heat Transfer Conference, 2007, Canada.

CHAPTER 3

N-DECANE PREMIXED SPRAY JET COMBUSTION

3.1. INTRODUCTION

In order to introduce the basic understanding of spray-jet combustion phenomena before showing the effect of hydrogen addition on spray-jet combustion, the experiment in Chapter 3 conducted the premixed spray-jet combustion using a burner which is principally similar to the Bunsen burner with a gaseous fuel. The liquid fuel and atomizing air were premixed near the exit of twin fluid atomizer and further premixed with supplementary air to generate a rich-premixed spray jet at the end of the spray nozzle. The ambient air was supplied to complete the diffusion combustion.

The experiments were conducted using n-decane as a pure fuel. The data, including flame structure and exhaust gas emission index, were taken for different atomizing air flow rates and spray jet equivalence ratios. The double-flame structure with the internal flame is presented and roles of the internal flame in exhaust emission are discussed.

3.2. EXPERIMENTAL CONDITION

Table 3.1 shows the setting condition of n-decane spray-jet combustion the fuel flow rate, atomizing air flow rate, total air flow rate in the premixed spray jet and ambient air flow rate. The total air flow rate in the premixed spray jet (the summation of the atomizing air flow rate and supplementary air flow rate) was kept constant at 5.0 L/min. The atomization condition depends on the atomizing air flow rate Q_{atom} and Mean droplet diameters decrease with increasing Q_{atom} [1]. Nakachi et al. [2] performed the same type of experiments with n-decane flow rate of 4.7 mL/min and showed Sauter mean droplet diameter, d_{32}, was 94 µm at Q_{atom}=2.0 L/min, 79 µm at Q_{atom}=2.5 L/min, and 71 µm at Q_{atom}=3.0 L/min. Since the fuel flow rate is close to that in Nakachi et al [2], Sauter mean droplet diameter for each Q_{atom} would show a close value.

Table 3.2 lists the values of spray jet equivalence ratio and overall equivalence ratio of n-decane spray-jet combustion. Since the spray jet equivalence ratio is larger than unity, this spray jet is a rich-premixed spray jet. The spray jet equivalence ratio was varied with the fuel flow rate under the constant total air flow rate in the premixed spray jet. While the ambient air flow rate was kept constant, the overall equivalence ratio was also varied with the fuel flow rate.

3.3. FLAME STRUCTURE WITH INTERNAL FLAME

Figure 3.1 show direct images of n-decane spray-jet combustion with spray jet equivalence ratio of 5.48 and atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. In order to visualize the flame structure clearly, the brightness and contrast of each raw image in this chapter were increased from the raw image. For the atomizing air flow rate of 2.0 L/min, a yellow luminous flame is observed. There is a small blue flame near the flame base. Therefore, the flame consists of the external flame and the internal flame. As the atomizing air flow rate is increased, the area of the yellow luminosity decreases. Only blue flames are observed for the atomizing air flow rate of 3.0 L/min. The yellow luminosity suggests that soot is generated inside the external flame. The external flame height decreases with increasing the atomizing air flow rate, meanwhile the internal flame height increases.

Figure 3.2 show direct images of n-decane spray-jet combustion with spray jet equivalence ratio of 6.39 and atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. As can be seen in Fig. 3.1, the double flame structure is observed in Fig. 3.2. As the atomizing air flow rate is increased, the area of the yellow luminous flame decreases but yellow luminosity is still observed even at 3.0 L/min atomizing air flow rate. The external flame height decreases with increasing the atomizing air flow rate, meanwhile the internal flame height increases.

Figure 3.3 show direct images of n-decane spray-jet combustion with spray jet equivalence ratio of 7.30 and atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. The double flame structure is observed as can be seen in Figs. 3.1 and 3.2. The external flame height decreases with increasing the atomizing air flow rate, meanwhile the internal flame height increases.

Figures 3.4, 3.5 and 3.6 show the direct images of n-decane spray-jet combustion with different spray-jet equivalence ratio at atomizing air flow rates 2.0 L/min, 2.5 L/min and 3.0 L/min respectively. The external flame height increases, otherwise the internal flame height decrease with increasing the spray jet equivalence ratio for a constant atomizing air flow rate. The area of the yellow luminosity, i.e., sooting region, increases with the spray-jet equivalence ratio for a constant atomizing air flow rate.

Figure 3.7 displays the enlarged images of flame near the flame base of spray-jet combustion for atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min and the spray-jet equivalence ratios of 5.48, 6.39 and 7.30. The pictures of flame have adjustment on the brightness and contrast to enhance the visualization of internal flame. Figure 3.7 shows that the internal flame height increases with increasing atomizing air flow rate with constant spray-jet equivalence ratios and decreases with increasing spray jet equivalence ratio with constant atomizing air flow rates. The luminosity of the internal flame is greater for higher atomizing air flow rate but does not vary very much with the spray-jet equivalence ratio.

Figure 3.8 shows the dependencies of the external flame height and internal flame height on the atomizing air flow rate at $\phi_{SJ} = 5.48$, 6.39 and 7.30. As an overall trend, the external flame height decreases with increasing atomizing air flow rate, but the internal flame height increase a little.

Figure 3.9 shows dependencies of the external flame height and internal flame height on the spray jet equivalence ratio at $Q_{\mathrm{atom}}= 2.0$, 2.5 and 3.0 L/min. The external flame height increases with increasing the spray jet equivalence ratio, but the internal flame decreases a little.

Figure 3.10 depicts the structure of flame of rich-premixed spray jet and combustion mechanism. The present spray flame consists of the internal flame and external flame. Since n-decane is a low-volatility fuel, any flammable mixture is not formed in the premixed spray at room temperature. Droplet vaporization occurs in high-temperature region near the internal flame. At the internal flame, fuel vapor is oxidized to a mixture of CO, CO_2 and H_2O by O_2 in the premixed spray. The internal flame is a rich premixed flame and thus much CO is produced here. NO is also produced here through oxidation of N_2 in the premixed spray. Since the internal flame generates heat in addition to the generation of CO, CO_2 and H_2O, droplet vaporization is enhanced in the post internal flame region. Since the mixture in the post internal flame region is a fuel rich mixture, some of NO is reduced to N_2. Contrary to the internal flame, the external flame is a diffusion flame. At the external flame, the fuel vapor and CO are oxidized by O_2 from the ambient air. NO is also produced at the external flame. As the internal flame generate CO_2 and H_2O, the fuel vapor and CO are diluted by CO_2 and H_2O in addition to the dilution by N_2. The CO_2 and H_2O dilution slows fuel and CO oxidation and NO production reaction, resulting in much CO emission and low NO emission.

3.4. EXHAUST GAS EMISSION CHARACTERISTICS

Figure 3.11 shows the emission index EICO of carbon monoxide (CO) from n-decane spray-jet combustion at atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. EICO decreases with increasing atomizing air flow rate at the spray-jet equivalence ratios of 6.39 and 7.30 but attains maximum at the spray-jet equivalence ratios of 5.48. As explained in Fig. 3.10, CO is produced at the internal flame first and is oxidized to CO_2 at the external flame. Although CO_2 and H_2O dilution slow CO oxidation at the external flame, enhanced vaporization with smaller droplet size and higher droplet velocity at higher atomizing air flow rate also enhances combustion at the external flame and thus causes less CO emission at higher atomizing air flow rate for the spray-jet equivalence ratios of 6.39 and 7.30. As shown later in Fig. 3.13, the combustion efficiency is low due to generation of relatively large droplets at the atomizing air flow rate 2.0 L/min and penetration of such large droplets through the external flame, especially for the spray-jet equivalence ratio of 5.48 and therefore, CO also becomes a lower value.

Figure 3.12 shows the emission index EITHC of total unburned hydrocarbon (THC) from n-decane spray-jet combustion at the atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. EITHC decreases with increasing the atomizing air flow rate. If droplets penetrate the external flame, such droplets contribute to THC emission. As explained in Section 3.2, mean droplet diameters increases with decreasing the atomizing air flow rate and the number of large droplets penetrating the external flame also increases, resulting in larger value of EITHC.

Figure 3.13 shows the emission index $EICO_2$ of carbon dioxide (CO_2) from n-decane spray-jet combustion at atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. $EICO_2$ increases with increasing the atomizing air flow rate. As explained above, mean droplet diameters increases with decreasing the atomizing air flow rate and the number of large droplets penetrating the external flame also increases, resulting in larger value of EITHC shown in Fig. 3.12 and smaller value of $EICO_2$ shown in Fig. 3.13.

Figure 3.14 shows the emission index EINO of nitric oxide (NO) from n-decane spray-jet combustion at atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. Three data points are plotted in the same conditions. EINO increases with increasing the atomizing air flow rate except for one data point at each of the atomizing air flow rates of 2.0 L/min and 3.0 L/min.

Figure 3.15 shows EICO from n-decane spray-jet combustion at $\phi_{SJ} = 5.48 \sim 7.30$. EICO decreases with increasing spray-jet equivalence ratio for the atomizing air flow rate of 3.0 L/min. As can be seen in Fig. 3.13, the combustion efficiency becomes highest for the atomizing air flow rate of 3.0 L/min. In such a case, EICO decreases with increasing spray-jet equivalence ratio because the CO oxidation at the external flame is enhanced by the increase in flame temperature through the increase heat generation. As can be seen later in Fig. 3.17, the combustion efficiency becomes lower for smaller spray-jet equivalence ratio with the atomizing air flow rate of 2.0 L/min. In such a condition, the amount of fuel converted into CO also smaller. If the combustion efficiency were high enough for the atomizing air flow rate of 2.0 L/min, EICO would decrease from a higher value with increasing the spray-jet equivalence ratio.

Figure 3.16 shows EITHC from n-decane spray-jet combustion at $\phi_{SJ} = 5.48 \sim 7.30$. EITHC decreases with increasing the spray jet equivalence ratio due to the increase in flame temperature through the increase heat generation leading to the rapid of vaporization.

Figure 3.17 shows $EICO_2$ from n-decane spray-jet combustion at $\phi_{SJ} = 5.48 \sim 7.30$. $EICO_2$ gradually increases with increasing ϕ_{SJ}.

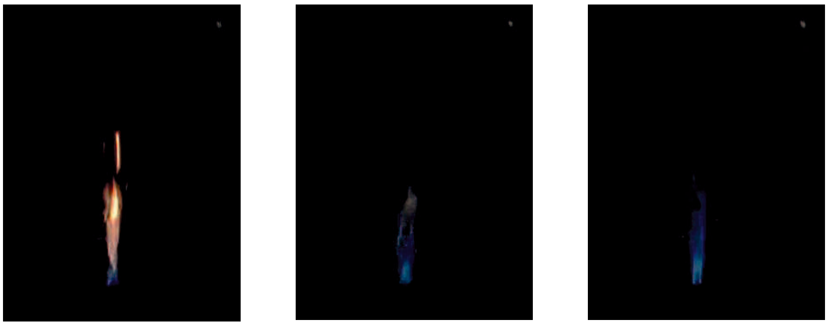
Figure 3.18 shows EINO from n-decane spray-jet combustion at $\phi_{SJ} = 5.48 \sim 7.30$. EINO increases with increasing spray jet equivalence ratio due to the increase in flame temperature through the increase heat generation. As explain in Fig. 3.14, there were exceptions at one of three data points for each of the atomizing air flow rates of 2.0 L/min and 3.0 L/min.

Table 3.1. Experimental conditions for n-decane spray-jet combustion

Description	**Conditions**
n-decane flow rate, Q_F [mL/min]	3.0, 3.5, 4.0
Atomizing air flow rate, Q_{atom} [L/min]	2.0, 2.5, 3.0
Supplementary air flow rate, Q_{supp} [L/min]	3.0, 2.5, 2.0
Total air flow rate in spray jet, Q_{SJ} [L/min]	5.0
Ambient air flow rate, Q_{ambi} [L/min]	35

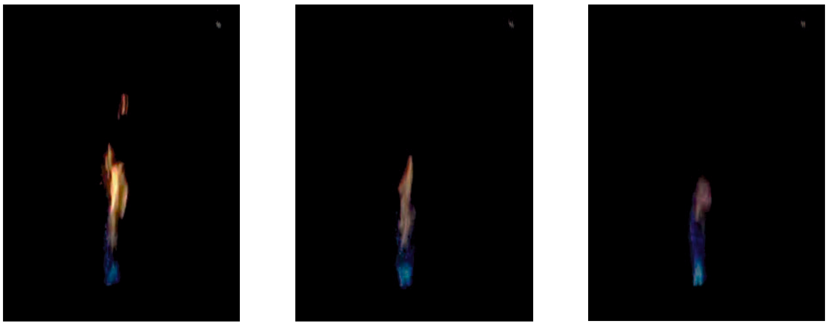
Table 3.2. n-Decane spray jet equivalence ratio and overall equivalence ratio

n-decane, flow rate [mL/min]	Spray jet equivalence ratio ϕ_{SJ}	Overall equivalence ratio ϕ_{all}
3.0	5.48	0.68
3.5	6.39	0.80
4.0	7.30	0.91



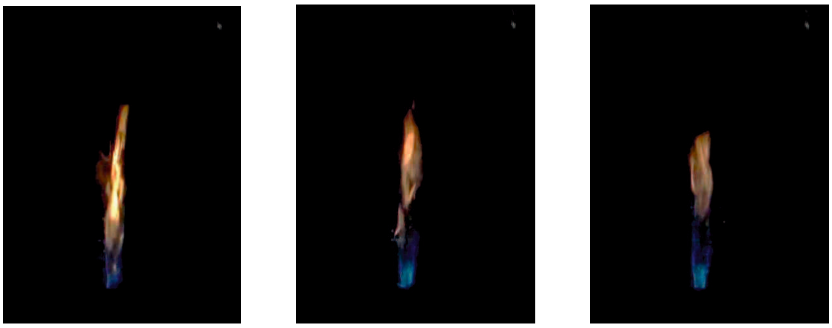
$Q_{atom} = 2.0$ L/min $Q_{atom} = 2.5$ L/min $Q_{atom} = 3.0$ L/min

Fig. 3.1. n-decane spray-jet combustion without H_2 addition at $\phi_{SJ} = 5.48$



$Q_{atom} = 2.0$ L/min $Q_{atom} = 2.5$ L/min $Q_{atom} = 3.0$ L/min

Fig. 3.2. n-decane spray-jet combustion without H_2 addition at $\phi_{SJ} = 6.39$



$Q_{atom} = 2.0$ L/min $Q_{atom} = 2.5$ L/min $Q_{atom} = 3.0$ L/min

Fig. 3.3. n-decane spray-jet combustion without H_2 addition at $\phi_{SJ} = 7.30$

$\phi_{SJ} = 5.48$
$\phi_{all} = 0.68$

$\phi_{SJ} = 6.39$
$\phi_{all} = 0.80$

$\phi_{SJ} = 7.30$
$\phi_{all} = 0.91$

Fig. 3.4. n-decane spray-jet combustion without H_2 addition at $Q_{atom} = 2.0$ L/min

$\phi_{SJ} = 5.48$
$\phi_{all} = 0.68$

$\phi_{SJ} = 6.39$
$\phi_{all} = 0.80$

$\phi_{SJ} = 7.30$
$\phi_{all} = 0.91$

Fig. 3.5. n-decane spray-jet combustion without H_2 addition at $Q_{atom} = 2.5$ L/min

$\phi_{SJ} = 5.48$
$\phi_{all} = 0.68$

$\phi_{SJ} = 6.39$
$\phi_{all} = 0.80$

$\phi_{SJ} = 7.30$
$\phi_{all} = 0.91$

Fig. 3.6. n-decane spray-jet combustion without H_2 addition at $Q_{atom} = 3.0$ L/min

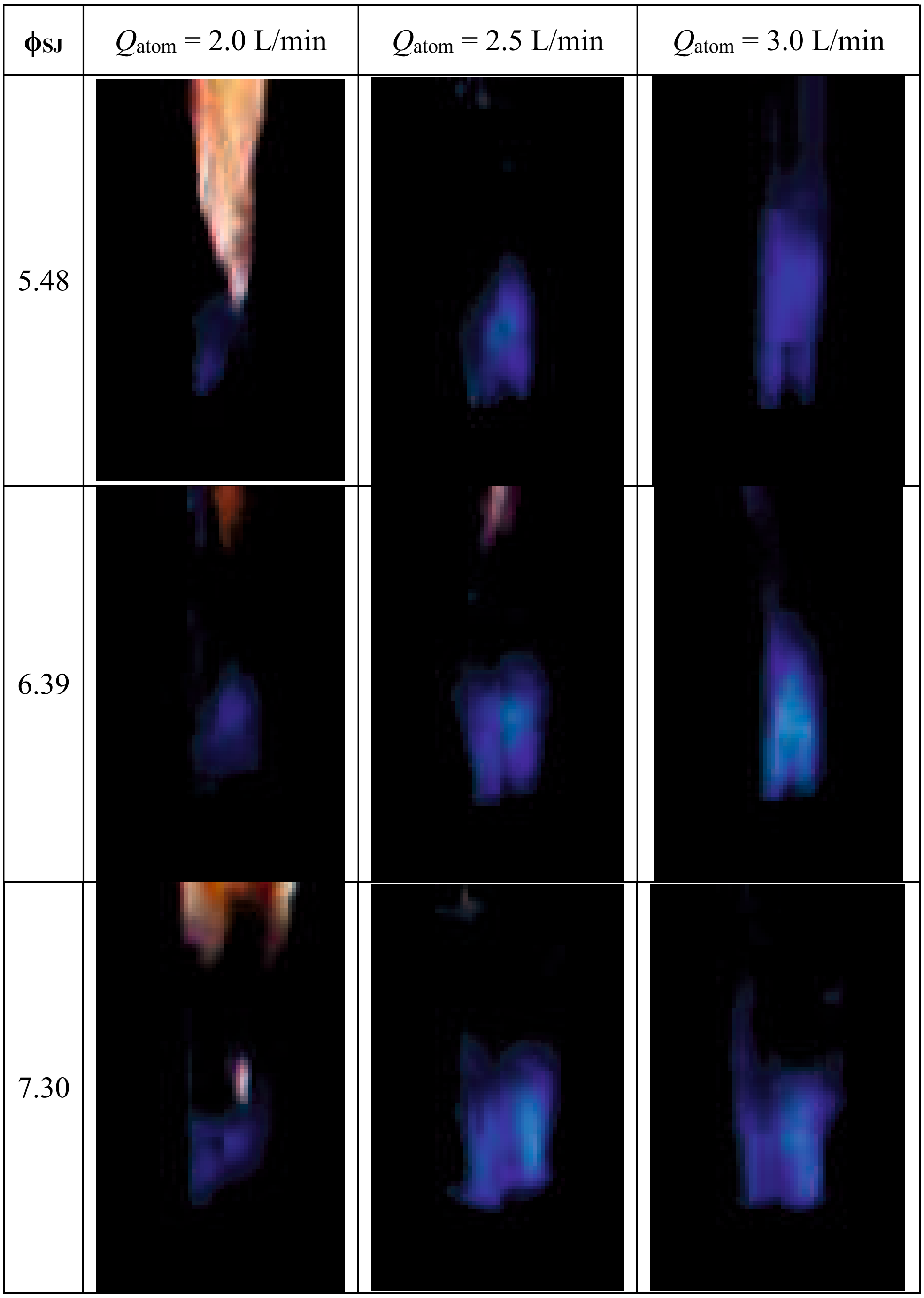


Fig. 3.7. The enlarged images around the internal flame region

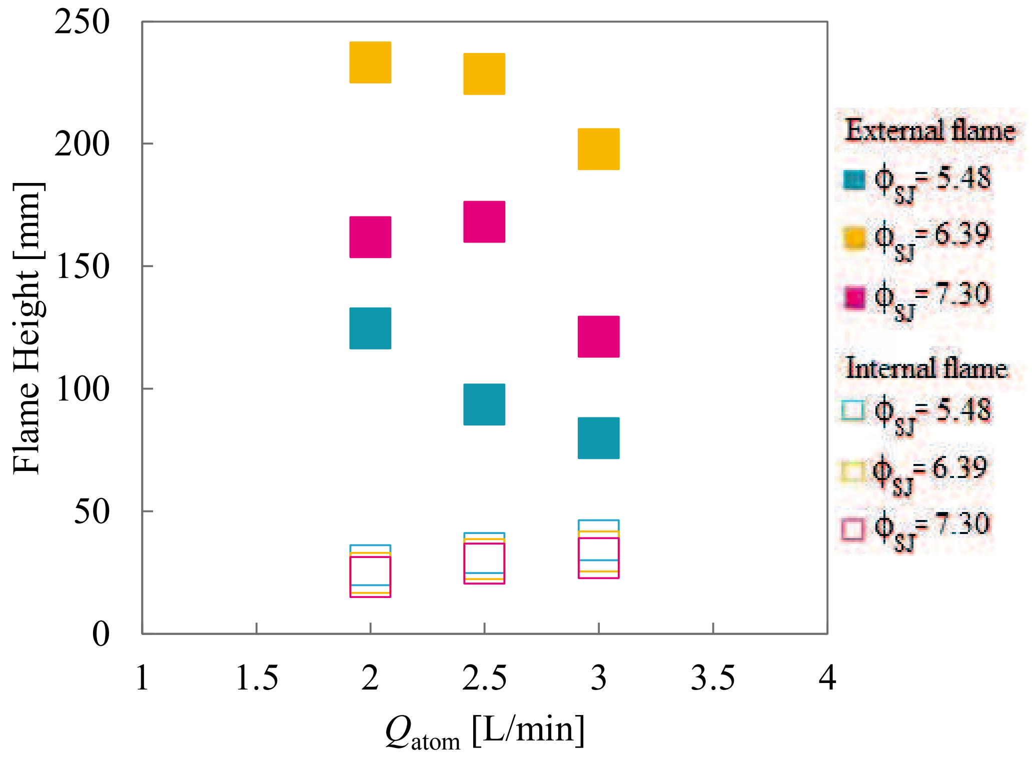


Fig. 3.8. External and internal flame heights at different Q_{atom}

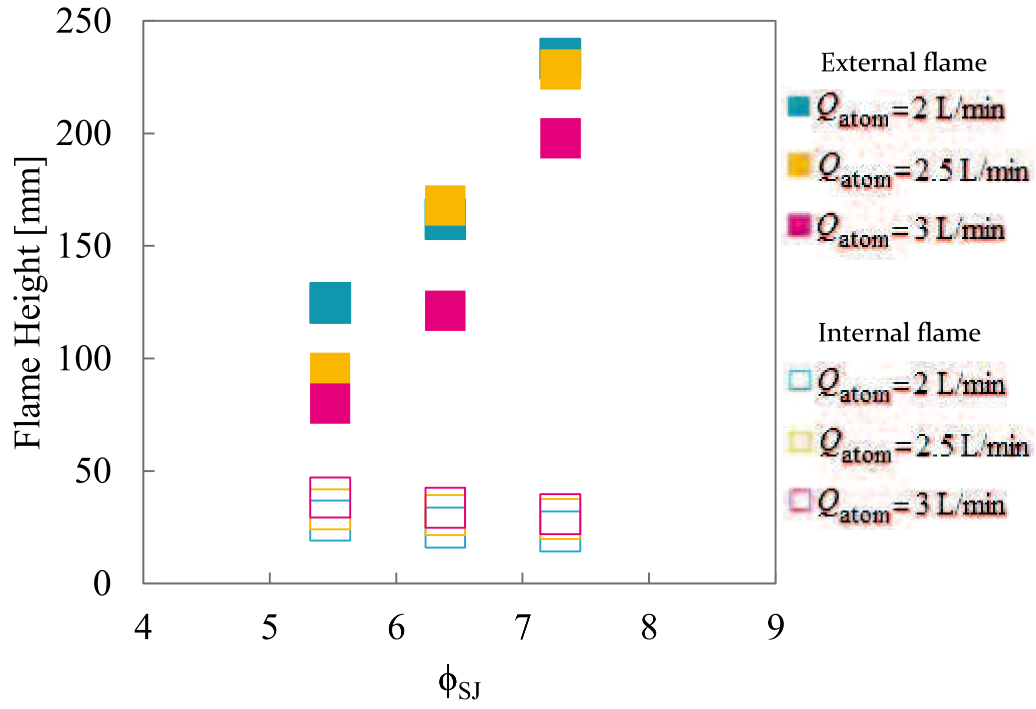
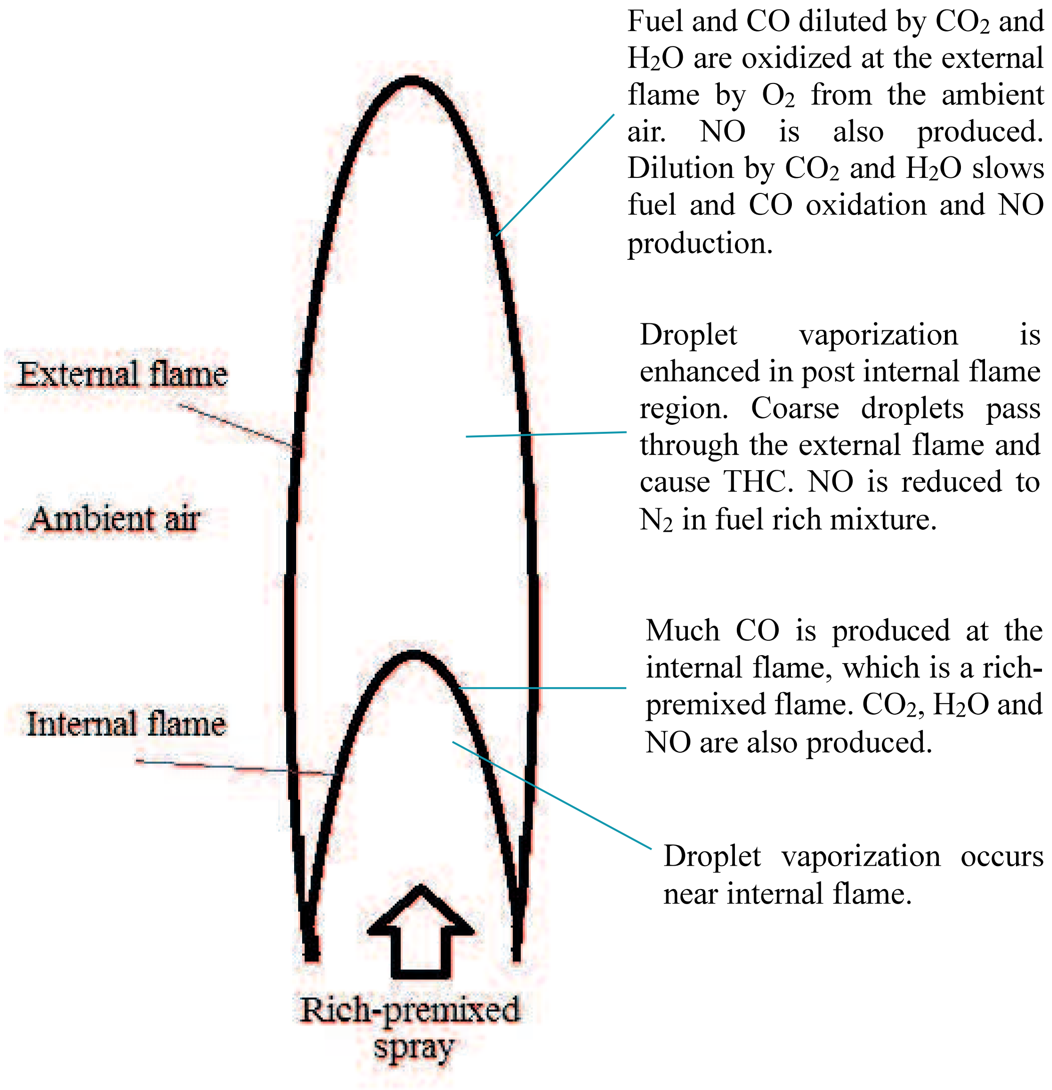


Fig. 3.9. External and internal flame heights at different ϕ_{SJ}



Fuel and CO diluted by CO_2 and H_2O are oxidized at the external flame by O_2 from the ambient air. NO is also produced. Dilution by CO_2 and H_2O slows fuel and CO oxidation and NO production.

Droplet vaporization is enhanced in post internal flame region. Coarse droplets pass through the external flame and cause THC. NO is reduced to N_2 in fuel rich mixture.

Much CO is produced at the internal flame, which is a rich-premixed flame. CO_2, H_2O and NO are also produced.

Droplet vaporization occurs near internal flame.

Fig. 3.10. The structure of flame and combustion mechanism with internal flame in rich-premixed spray jet combustion

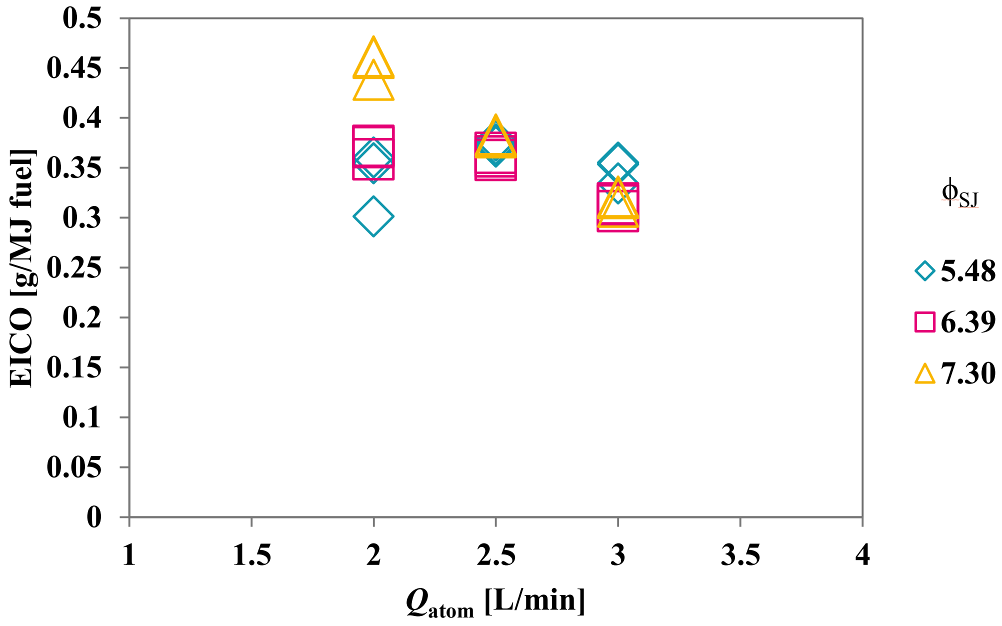


Fig. 3.11. The dependencies of EICO to the Q_{atom} at different ϕ_{SJ}

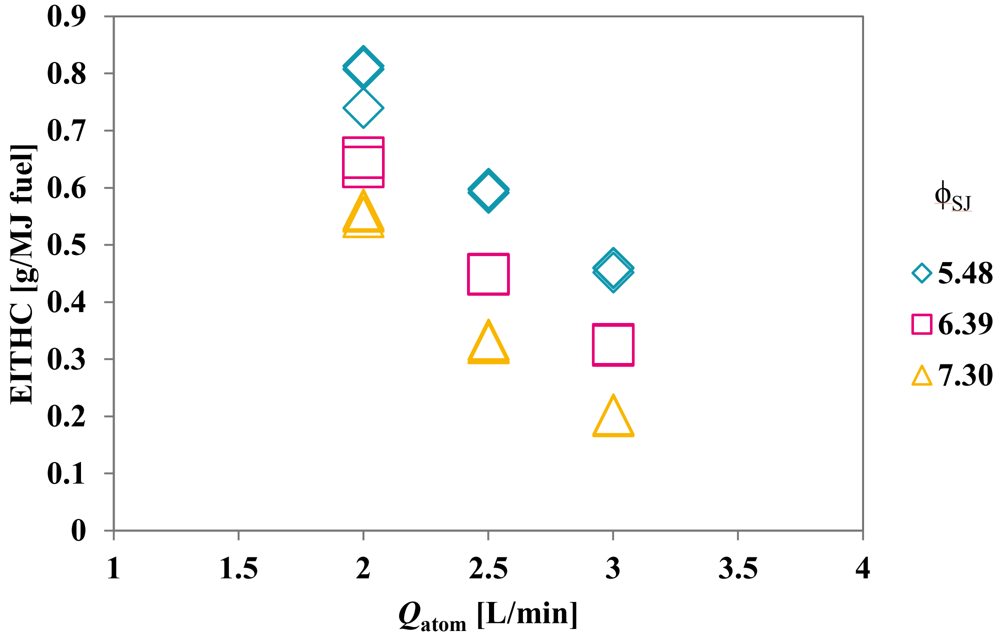


Fig. 3.12. The dependencies of EITHC to the Q_{atom} at different ϕ_{SJ}

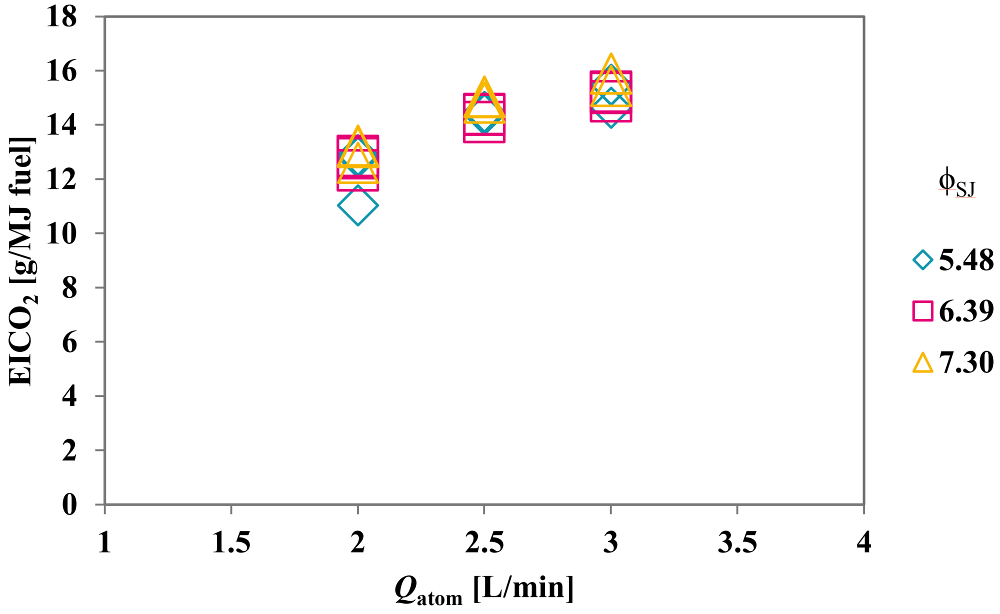


Fig. 3.13. The dependencies of EICO$_2$ to the Q_{atom} at different ϕ_{SJ}

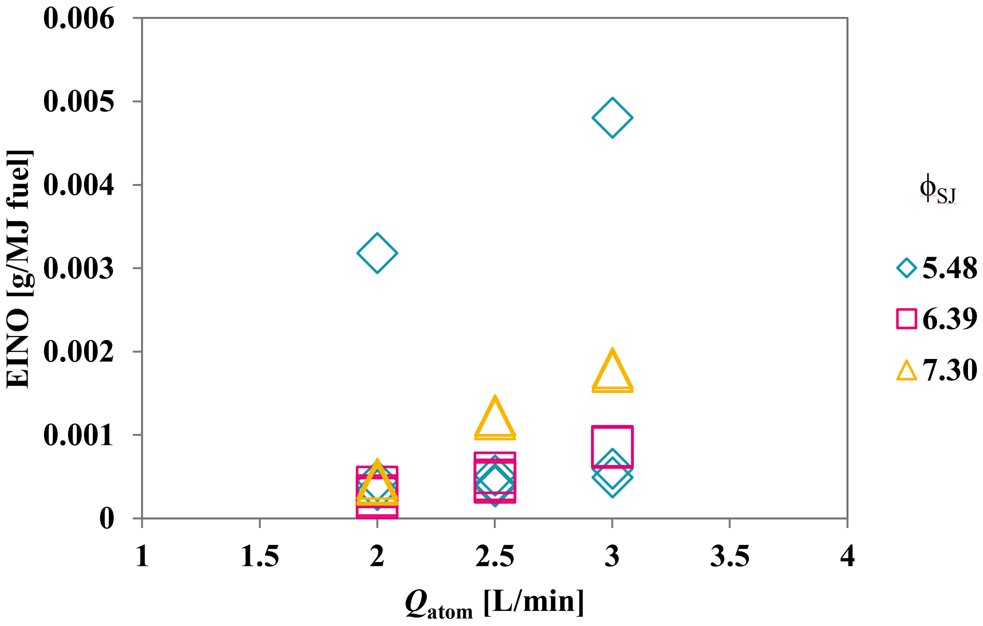


Fig. 3.14. The dependencies of EINO to the Q_{atom} at different ϕ_{SJ}

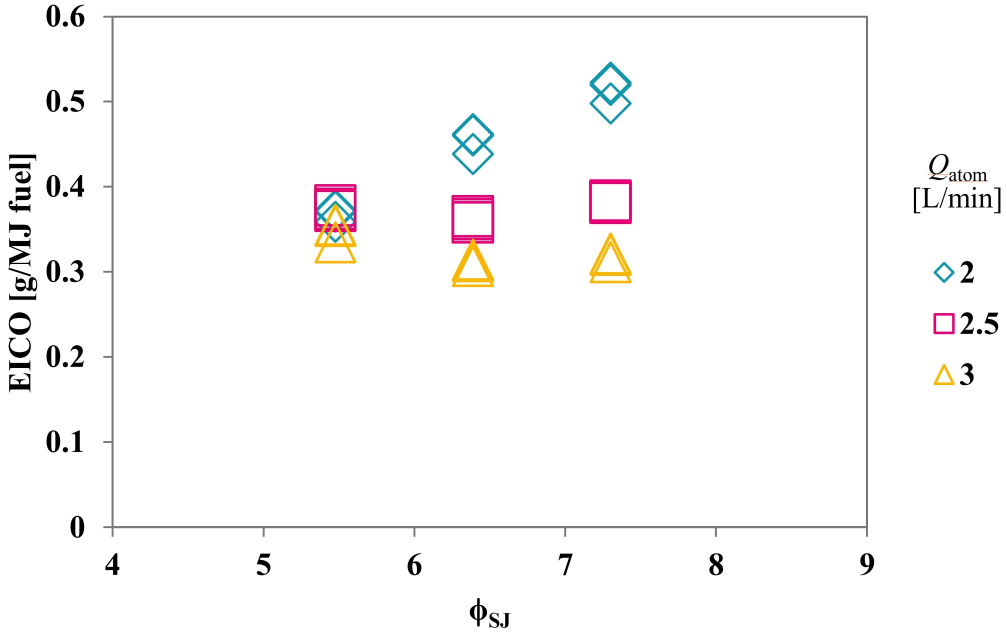


Fig. 3.15. The dependencies of EICO to the ϕ_{SJ} at different Q_{atom}

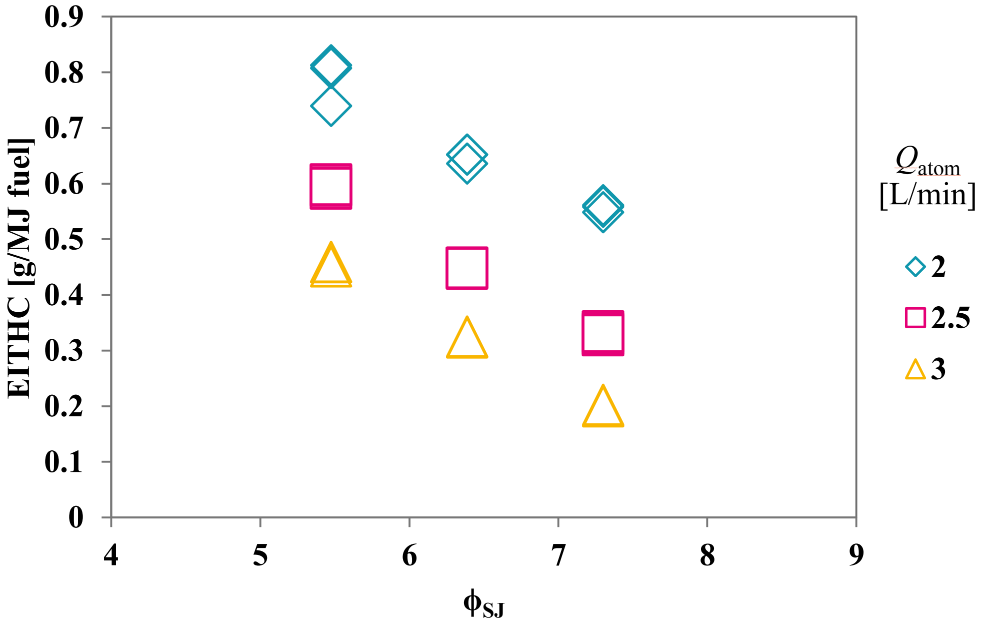


Fig. 3.16. The dependencies of EITHC to the ϕ_{SJ} at different Q_{atom}

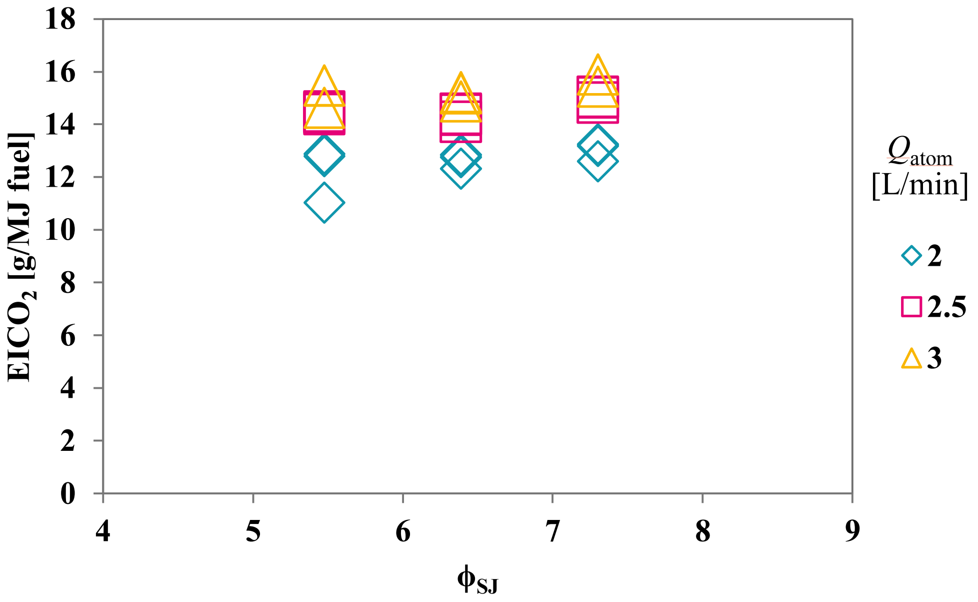


Fig. 3.17. The dependencies of EICO$_2$ to the ϕ_{SJ} at different Q_{atom}

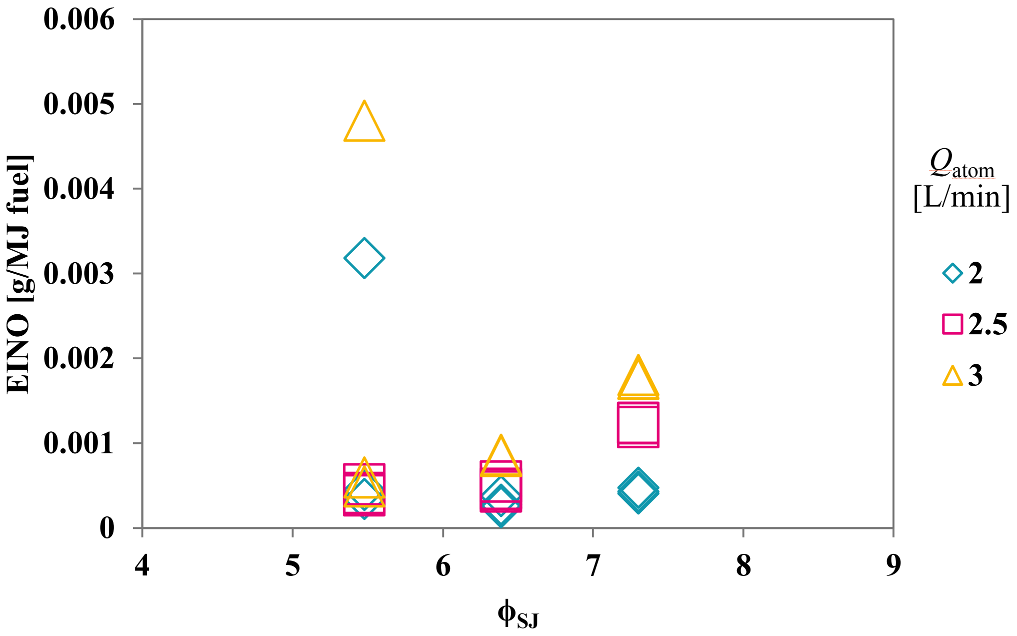


Fig. 3.18. The dependencies of EINO to the ϕ_{SJ} at different Q_{atom}

References

[1] Mikami, M., Yamamoto, K., Moriue, O., Kojima, N., *Combustion of partially premixed spray jets,* Proceeding of the Combustion Institute 30, 2005, pp. 2021-2028.

[2] Nakachi, N., Mikami, M., Kojima, N., *Effects of atomization condition on flame structure and emission characteristics of burning rich-premixed spray jets,* Proceedings of HT2007-32757, ASME-JSME Thermal Engineering Summer Heat Transfer Conference, 2007, Canada.

CHAPTER 4. SPRAY JET COMBUSTION WITH SMALL AMOUNT OF HYDROGEN

4.1. INTRODUCTION

Hydrogen is considered as a clean alternative fuel without carbon. Hydrogen has a potential to improve the combustion performance without deterioration of the exhaust emission characteristics. Since the heating value of hydrogen is about three times as large as that of diesel fuel, the addition of small amount of hydrogen also has a possibility to improve hydrocarbon fuel spray-jet combustion characteristics. In this chapter, combustion and exhaust emission characteristics of spray-jet combustion with small amount of hydrogen were investigated with n-decane as a pure fuel and diesel fuel as a practical fuel. First, two hydrogen addition methods were compared for n-decane spray jet combustion; hydrogen addition to the spray jet and hydrogen addition near the flame base. Then, the exhaust gas emissions characteristics were investigated with hydrogen additions near the flame base for n-decane spray combustion. Lastly, the effect of hydrogen addition was confirmed for the diesel fuel spray-jet combustion.

4.2. COMPARISON OF TWO DIFFERENT HYDROGEN ADDITION METHODS

4.2.1. Hydrogen Addition Methods

Figures 4.1 and 4.2 depict schematics showing two different hydrogen addition methods to the spray burner where rich-premixed spray are generated. One is a method of hydrogen addition to the spray jet as shown in Fig. 4.1. The other is a method of hydrogen addition near the flame base.

In the first method shown in Fig. 4.1, hydrogen is premixed with the supplementary air first and then is mixed with the atomizing air and fuel spray in the post nozzle region. The experimental procedure is as follows: After the spray jet is ignited by the pilot flame of propane/air mixture, the ambient air flows into the combustion chamber, then the supplementary air is supplied. After the spray flame is established, the propane/air mixture-line is closed, and then H_2 supplied into the supplementary air. Since hydrogen is mixed with the supplementary air, the fire back may occurs, H_2 line is closed immediately.

In the second method shown in Fig. 4.2, hydrogen is supplied near the flame base through the 16 holes through which the propane/air mixture is supplied in the ignition phase. The sequence from the initial ignition to establish the rich-premixed spray burning is similar to the process in the first method. After the spray flame is established, the propane/air mixture line is closed, and then H_2 is supplied to the some 16 holes. In this method, only H_2 is issued, without air inside the line. This method should be safer because there is no oxidizer in the driveway of hydrogen.

4.2.2. Experimental Condition

The experimental conditions are described in Tables 4.1, 4.2, and 4.3. Table 4.1 represents common experimental conditions of H_2 addition to the spray jet and H_2 addition near flame base, which consists of the fuel flow rate, atomizing air flow rate, supplementary air flow rate, total air flow rate in the premixed spray jet and ambient air flow rate. Tables 4.2 and 4.3 explain the spray jet equivalence ratio and overall equivalence ratio of n-decane spray-jet combustion for H_2 addition to the spray jet and near flame base, respectively.

This experiment is intended to reinforce the phenomena occurrence and hydrogen addition limit for H_2 addition to the spray jets and H_2 addition near flame base.

4.2.3. Hydrogen Addition Limit

Figure 4.3 shows the flames with H_2 addition to the spray jet at Q_{atom} = 2.5 L/min. Over than the hydrogen fraction of 0.5 vol%, a back fire and then extinction occurred

In the case of H_2 premixed with supplementary air, the fire back occurred due to imbalance between the velocities of H_2/supplementary air mixture with the burning velocity of H_2/supplementary air mixture (S_L). When the burning velocity becomes faster than the mixture velocity, the flame will show fire back. Since the mixture of H_2/supplementary air is in lean condition, the laminar burning velocity increases with increasing the fraction of H_2. This condition results in the fire back occurrence over the limit of H_2 addition.

Another method is H_2 addition near flame base. In this case, H_2 is issued without being mixed with air. Figure 4.4 shows direct images of the flame with H_2 addition near flame base from 0 ~ 8%. Flame height increases with addition of H_2. Even at 8% H_2 added near the flame base, the flame is established. Therefore, this method is better than the first method in view of safety and possible range of H_2 fraction. In the following sections, the effect of hydrogen on rich-premixed spray-jet combustion was investigated with the method of hydrogen addition near the flame base.

4.3. FLAME STRUCTURE AND EMISSION CHARACTERISTICS FOR SPRAY-JET COMBUSTION WITH HYDROGEN ADDITION NEAR FLAME BASE

Section 4.2 reveals that the method of H_2 addition to the spray jet method has the limitation of H_2 addition, meanwhile the addition of H_2 near flame base shows the flame is established with a wider range of hydrogen fraction. The following experiment aims to observe the flame behavior and exhaust gas emissions with H_2 addition near flame base at different atomizing air flow rates.

4.3.1. Experimental Condition

The experimental condition described on Tables 4.4 and 4.5. Table 4.4 lists the experimental condition of n-decane spray-jet combustion with H_2 addition near flame base at different atomizing air flow rates, which consists of the fuel flow rate, atomizing air flow rate, supplementary air flow rate, total air flow rate in the premixed spray jet, ambient air flow rate and hydrogen fraction. Table 4.5 explains the spray jet equivalence ratio and overall equivalence ratio of n-decane spray-jet combustion or different H_2 fraction. This experiment used n-decane as a pure fuel. The atomizing air flow rate was varied as 2.0 L/min, 2.5 L/min and 3.0 L/min.

4.3.2. Effect of Hydrogen Addition on Flame Structure

Figure 4.5 show the direct images of the flame at different atomizing air flow rates and hydrogen fractions. The flame height and flame luminosity increase with increasing H_2 addition. The heat generated by H_2 combustion increases the flame temperature, enhances droplet vaporization and reduces the number of large droplets penetrating the external flame, resulting in the increase in the height of the external flame and luminosity. The flame height and flame luminosity decrease with increasing atomizing air flow rate. The effect of the atomizing air is similar to that without H_2 explained in Chapter 3.

The appearance of double-flame structure with the internal flame and the external flame for H_2 of 0% as can be seen in Fig. 4.5. The characteristics of these flames are explained in Chapter 3. Figure 4.6 displays the enlargement part of the flame near the flame base to judge whether the internal flame exits or not. For H_2 0%, there is a blue internal flame for each atomizing air flow rate. However, the internal flame disappears by H_2 addition in most cases. Figure 4.7 shows the mode map in view of the flame structure.

Figure 4.8 depicts the structure of flame of rich-premixed spray jet and combustion mechanism with and without hydrogen addition. The present spray flame consists of the internal flame and external flame without hydrogen addition. If hydrogen is added over a specific value, the internal flame disappears. As explained in Chapter 3, the internal flame is a rich-premixed flame. If hydrogen is added, the heat generated by H_2 combustion enhances droplet vaporization and caused rich mixture over the rich flammability limit, resulting in the disappearance of the internal flame. As the internal flame also generate CO_2 and H_2O, the fuel vapor and CO are diluted by CO_2 and H_2O addition to the dilution by N_2. The CO_2 and H_2O dilution slows fuel and CO oxidation, resulting in much CO emission. Therefore, the disappearance of the internal flame leads to lower CO. The increased flame temperature also enhances droplet vaporization and reduces the number of large droplets passing through the external flame, resulting in the decrease in THC emission and the increase in the height of the external flame. The effect of hydrogen addition on exhaust emissions shown in Fig. 4.8 is confirmed in Section 4.3.3.

4.3.3. Effect of Hydrogen Addition on Exhaust Gas Emission

The dependencies of EICO, EITHC, $EICO_2$ and EINO on the H_2 fraction are shows in Figs 4.9, 4.10, 4.11 and 4.12 respectively. EICO and EITHC decrease with increasing hydrogen fraction, nevertheless $EICO_2$ increases and also EINO increases but the value is insignificant.

Figure 4.9 shows the EICO of n-decane spray-jet combustion with H_2 addition near flame base from 0 ~ 6%. Without H_2 addition, EICO is very high. As H_2 fraction is increased, EICO decreases significantly until H_2 addition 4% and slightly decreases until H_2 addition 6%. As explained in the previous section, the disappearance of the internal flame leads to lower CO since the internal flame produces much CO and dilution gases of CO_2 and H_2O, which slower the CO oxidation at the external flame. EICO shows relatively high value for 2% H_2 and the atomizing air flow rate of 2.0 L/min probably because there is the internal flame in this condition.

Figure 4.10 shows the dependencies of EITHC on the H_2 fraction at Q_{atom} = 2.0 L/min, 2.5 L/min and 3.0 L/min. EITHC for 0% H_2 has larger value for smaller atomizing air flow rate because mean droplet diameters increases with decreasing the atomizing air flow rate and the number of large droplets passing through the external flame also increases, resulting in larger value of EITHC as explained in Chapter 3. As H_2 fraction is increased, the increased flame temperature enhances droplet vaporization and reduces the number of large droplets passing through the external flame, resulting in the decrease in THC emission.

Figure 4.11 shows the dependencies of $EICO_2$ on the H_2 fraction at Q_{atom}=2.0 L/min, 2.5 L/min and 3.0 L/min. $EICO_2$ increases with increasing H_2 addition until H_2 fraction 4% because the combustion efficiency is increased due to the decrease in THC and CO and the increase in the flame temperature. If the combustion efficiency is high enough, $EICO_2$ will decrease with increasing H_2 fraction since the combustion of H_2 produces heat but does not produce CO_2. This trend is unclear due to the experimental error.

Figure 4.12 shows the dependencies of EINO on the H_2 fraction at Q_{atom} = 2.0 L/min, 2.5 L/min and 3.0 L/min. EINO increases with increasing H_2 addition because the flame temperature is increased.

4.4. EXHAUST EMISSION CHARACTERISTICS FOR DIESEL FUEL SPRAY-JET COMBUSTION WITH HYDROGEN ADDITION NEAR FLAME BASE

4.4.1. Experimental Condition

The effect of hydrogen addition investigated in Section 4.3 with n-decane as a fuel was confirmed for the diesel fuel spray-jet combustion in this section. Tables 4.6 and table 4.7 list the experimental condition of diesel fuel spray-jet combustion with H_2 addition near flame base. The atomizing air flow rate varied at 2.0 L/min, 2.5 L/min and 3.0 L/min. Table 4.6 shows the experimental conditions for hydrogen addition near flame base of diesel fuel spray-jet combustion at different atomizing air flow rates. Table 4.7 shows the spray jet equivalence ratio and overall equivalence ratio of diesel fuel spray-jet combustion with H_2 addition near flame base.

4.4.2. Exhaust Gas Emission

Figures 4.13, 4.14, 4.15 and 4.16 show dependences of EICO, EITHC, $EICO_2$ and EINO on the H_2 fraction at the atomizing air flow rate of 2.0 L/min, 2.5 L/min and 3.0 L/min. The trends of EICO, EITHC, $EICO_2$ and EINO are basically the same as n-decane spray-jet combustion with H_2 addition near flame base.

EICO decreases with increasing H_2 addition. EITHC also decreases with increasing H_2 fraction. The effect of the atomizing air flow rate on EITHC is more significant than on EICO.

Unlike n-decane spray-jet combustion, $EICO_2$ decreases with increasing the hydrogen fraction. As expected in Section 4.3, if the combustion efficiency is high enough, $EICO_2$ decreases with increasing H_2 fraction since the combustion of H_2 produces heat but does not produce CO_2.

EINO increases with the hydrogen fraction until 5% except for an irregular point for H_2 of 2% and shows relatively low value for 6% H_2. A further investigation is required to figure out the reason why the EINO shows relatively low value for 6% H_2 in diesel fuel spray-jet combustion.

Table 4.1. Experimental condition for both H_2 addition methods: H_2 addition to the spray jet and H_2 addition near flame base

Description	**Values**
n-decane flow rate, Q_F [mL/min]	3.5
Atomizing air flow rate, Q_{atom} [L/min]	2.5
Supplementary air flow rate, Q_{supp} [L/min]	2.5
Total air flow rate in premixed spray jet, Q_{SJ} [L/min]	5.0
Ambient air flow rate, Q_{ambi} [L/min]	35

Table 4.2. ϕ_{SJ} and ϕ_{all} for n-decane spray-jet combustion with H_2 addition in the case of H_2 addition to the spray jet

n-decane flow rate [mL/min]	**H_2 fraction [vol%]**	**Spray Jet equivalence ratio ϕ_{SJ}**	**Overall equivalence ratio ϕ_{all}**
3.5	0	6.39	0.80
3.5	0.1	6.41	0.80
3.5	0.2	6.43	0.80
3.5	0.3	6.45	0.81
3.5	0.4	6.47	0.81
3.5	0.5	6.49	0.81

Table 4.3. ϕ_{SJ} and ϕ_{all} for n-decane spray-jet combustion with H_2 addition in the case of H_2 addition near flame base

n-decane, flow rate [mL/min]	**H_2 fraction [vol%]**	**Spray Jet equivalence ratio ϕ_{SJ}**	**Overall equivalence ratio ϕ_{all}**
3.5	0	6.39	0.80
3.5	1	6.39	0.82
3.5	2	6.39	0.85
3.5	3	6.39	0.87
3.5	4	6.39	0.90
3.5	5	6.39	0.92
3.5	6	6.39	0.95
3.5	7	6.39	0.98
3.5	8	6.39	1.01

Table 4.4. The experimental conditions for hydrogen addition near flame base at different atomizing air flow rates

Description	**H_2 addition near flame base**
n-decane fuel flow rate, Q_F [mL/min]	3.5
Atomizing air flow rate, Q_{atom} [L/min]	2.0, 2.5, 3.0
Supplementary air flow rate, Q_{supp} [L/min]	3.0, 2.5, 2.0
Total air flow rate in premixed spray jet, Q_{SJ} [L/min]	5.0
Ambient air flow rate, Q_{ambi} [L/min]	35
H_2 fraction [vol%]	2.0, 4.0, 6.0

Table 4.5. Hydrogen fraction of n-decane spray-jet combustion

Hydrogen addition near the flame base, vary Q_{atom}			
Hydrogen fraction [vol%]	Hydrogen flow rate, Q_{H2} [L/min]	Spray Jet equivalence ratio ϕ_{SJ}	Overall equivalence ratio ϕ_{all}
0	0	6.39	0.80
2	0.82	6.39	0.85
4	1.67	6.39	0.90
6	2.55	6.39	0.95

Table 4.6. The experimental conditions for hydrogen addition near the flame base of diesel fuel spray-jet combustion at different atomizing air flow rates

Description	**H_2 addition near flame base**
Diesel fuel flow rate, Q_F [mL/min]	3.0
Atomizing air flow rate, Q_{atom} [L/min]	2.0, 2.5, 3.0
Suplementary air flow rate, Q_{supp} [L/min]	3.0, 2.5, 2.0
Total air flow rate in premixed spray jet, Q_{SJ} [L/min]	5.0
Ambient air flow rate, Q_{ambi} [L/min]	35
H_2 fraction [vol%]	0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0

Table 4.7. Hydrogen fraction for diesel fuel spray-jet combustion

Hydrogen addition near the flame base			
Hydrogen fraction [vol%]	Hydrogen flow rate, Q_{H2} [L/min]	Spray jet equivalence ratio ϕ_{SJ}	Overall equivalence ratio ϕ_{all}
0	0	6.19	0.77
1	0.40	6.19	0.79
2	0.82	6.19	0.82
3	1.24	6.19	0.85
4	1.58	6.19	0.88
5	2.11	6.19	0.90
6	2.55	6.19	0.93

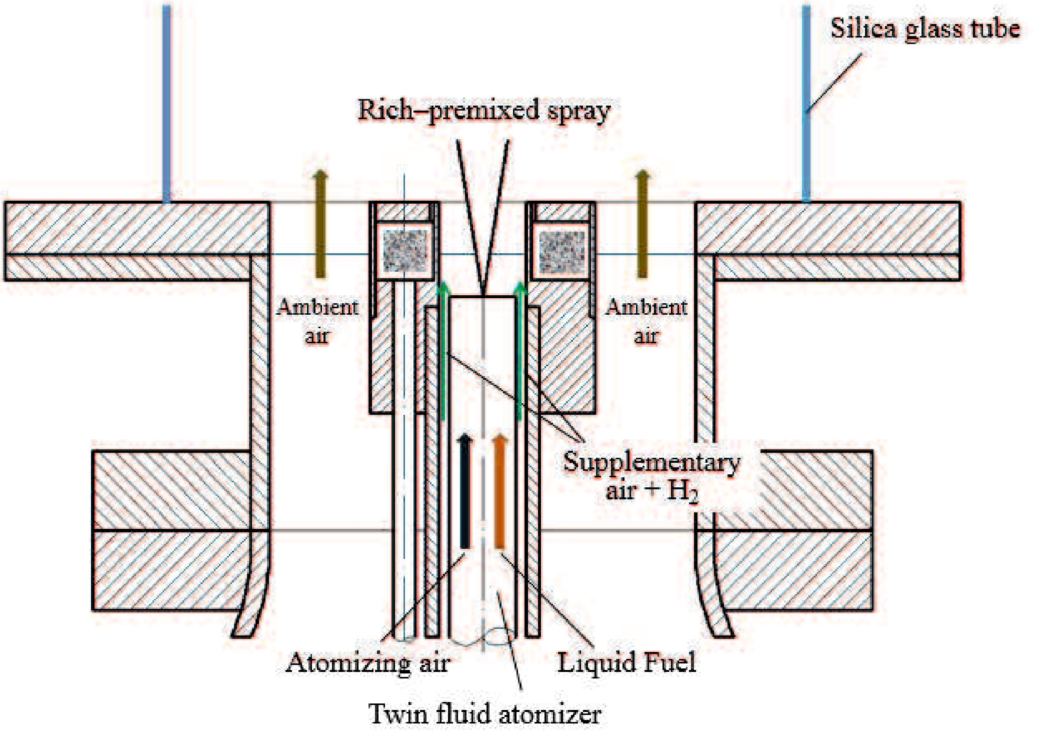


Fig. 4.1. Schematic of spray burner with H_2 addition to the spray jet

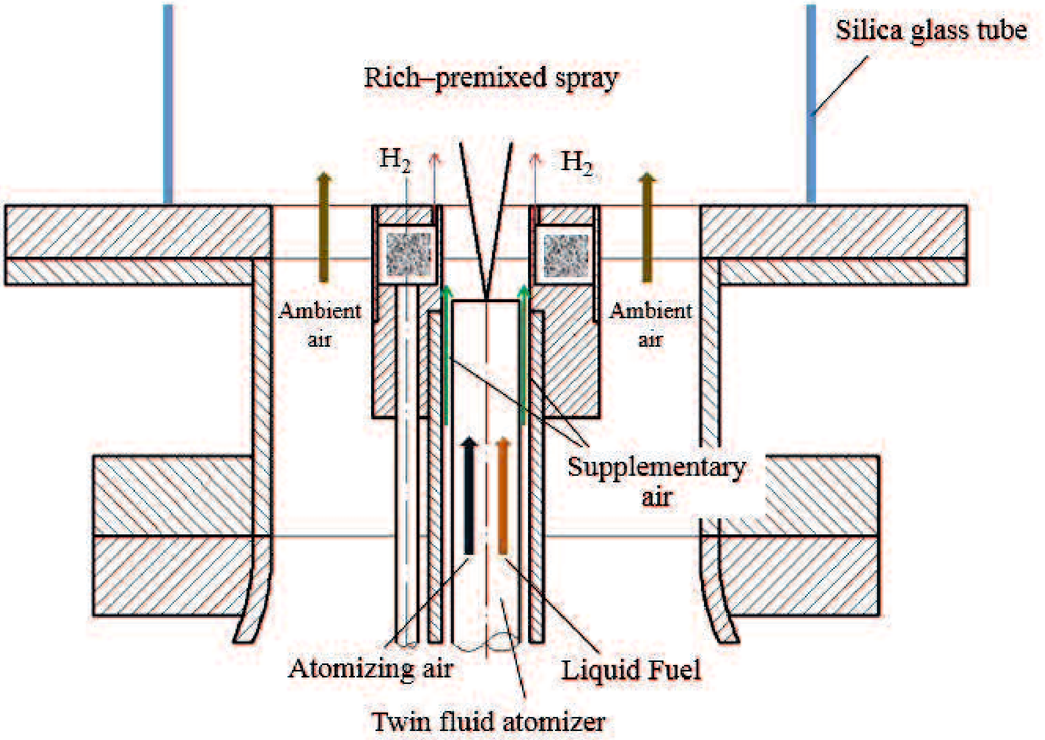


Fig. 4.2. Schematic of spray burner with H_2 addition near flame base

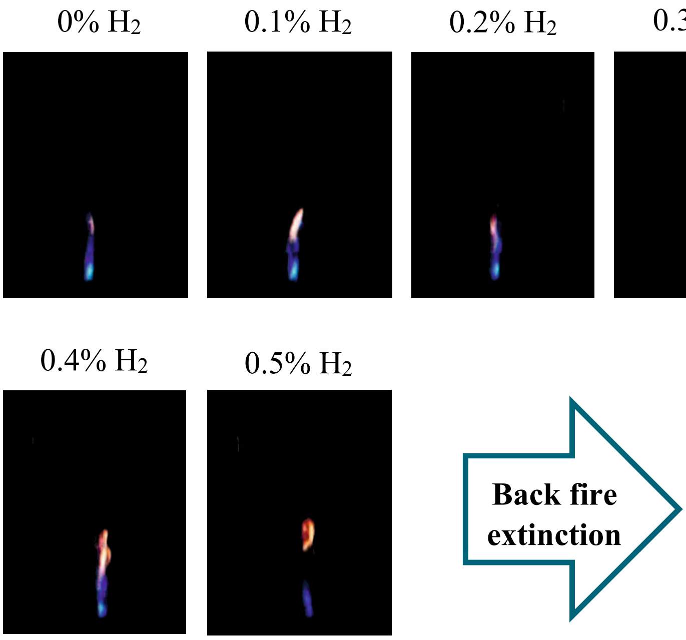


Figure 4.3. Direct images of n-decane spray-jet combustion with H_2 addition to the spray jet at Q_{atom} = 2.5 L/min.

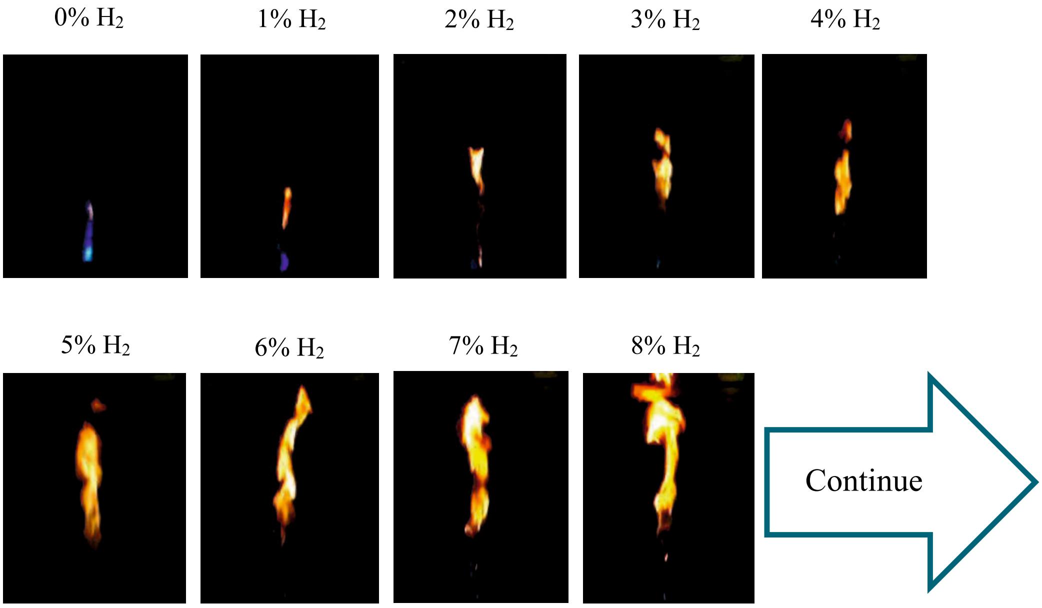


Figure 4.4. Direct images of n-decane spray-jet combustion with H_2 addition near flame base at Q_{atom} = 2.5 L/min

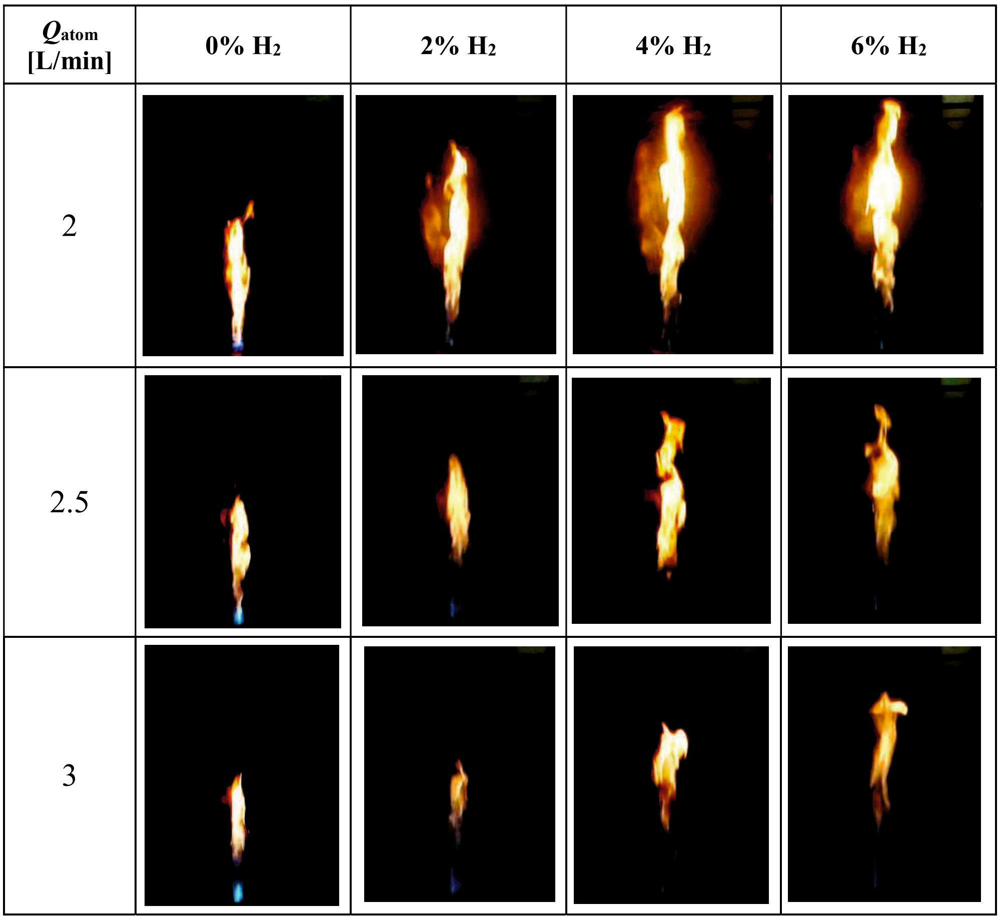


Fig. 4.5. Direct images of n-decane spray-jet combustion with H_2 addition near flame base at different Q_{atom} and $\phi_{SJ} = 6.39$

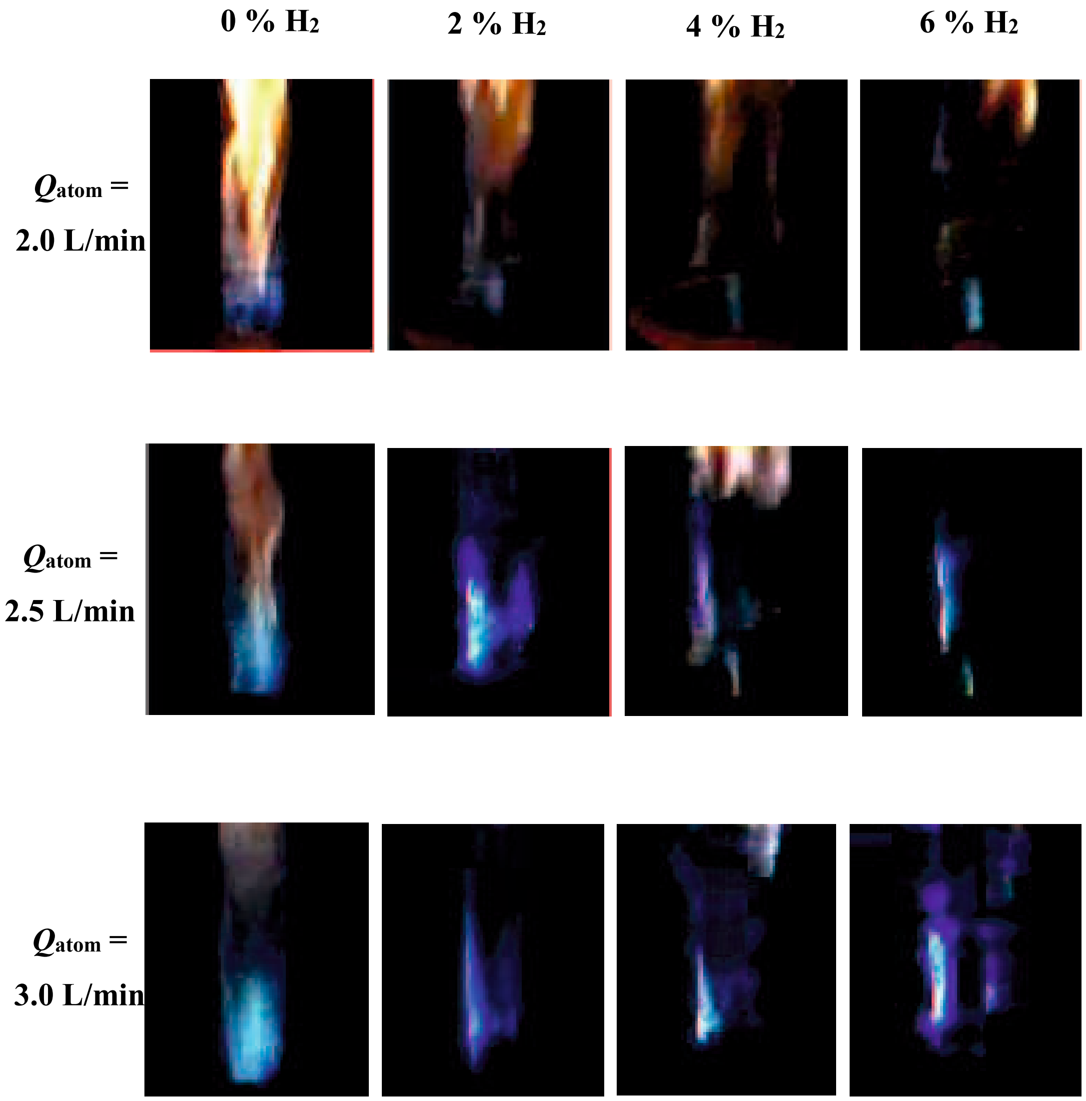


Fig. 4.6. The enlarged images near the flame base for n-decane spray-jet combustion with H_2 addition near flame base at different Q_{atom}.

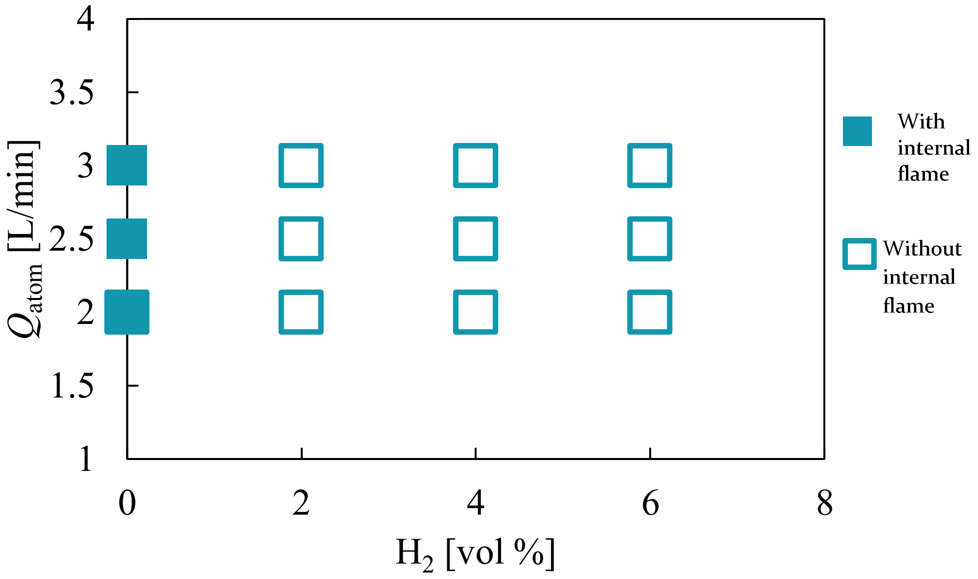
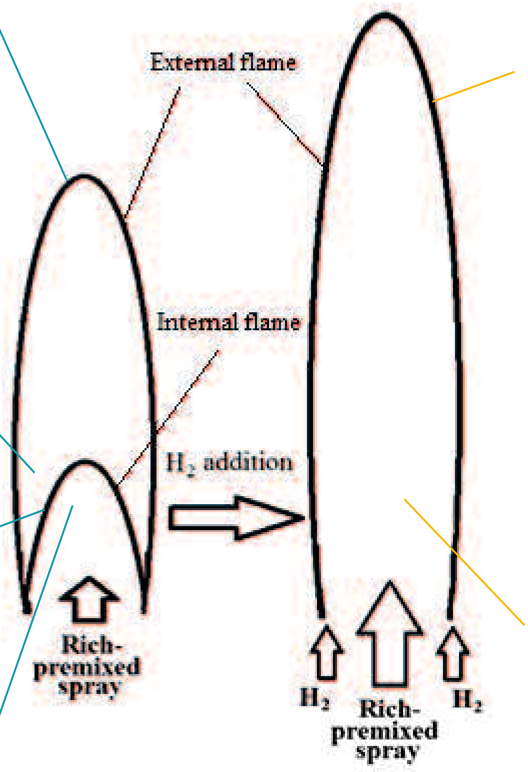


Fig. 4.7. Mode map of burning n-decane premixed spray-jet with hydrogen addition for ϕ_{SJ}=6.39



Fuel and CO diluted by CO_2 and H_2O are oxidized at the external flame by O_2 from the ambient air. NO is also produced. Dilution by CO_2 and H_2O slows fuel and CO oxidation and NO production.

Droplet vaporization is enhanced in post internal flame region. Coarse droplets pass through the external flame and cause THC. NO is reduced to N_2 in fuel rich mixture.

Much CO is produced at the internal flame, which is a rich-premixed flame. CO_2, H_2O and NO are also produced.

Droplet vaporization occurs near internal flame.

Heat generated by H_2 combustion increases the flame temperature, enhances droplet vaporization and reduces the number of coarse droplets passing through the external flame, resulting in the decrease in THC emission and the increase in the height of the external flame.

Heat generated by H_2 combustion enhances droplet vaporization and results in the disappearance of the internal flame.

Fig. 4.8. The influence of H_2 addition on rich-premixed spray-jet combustion

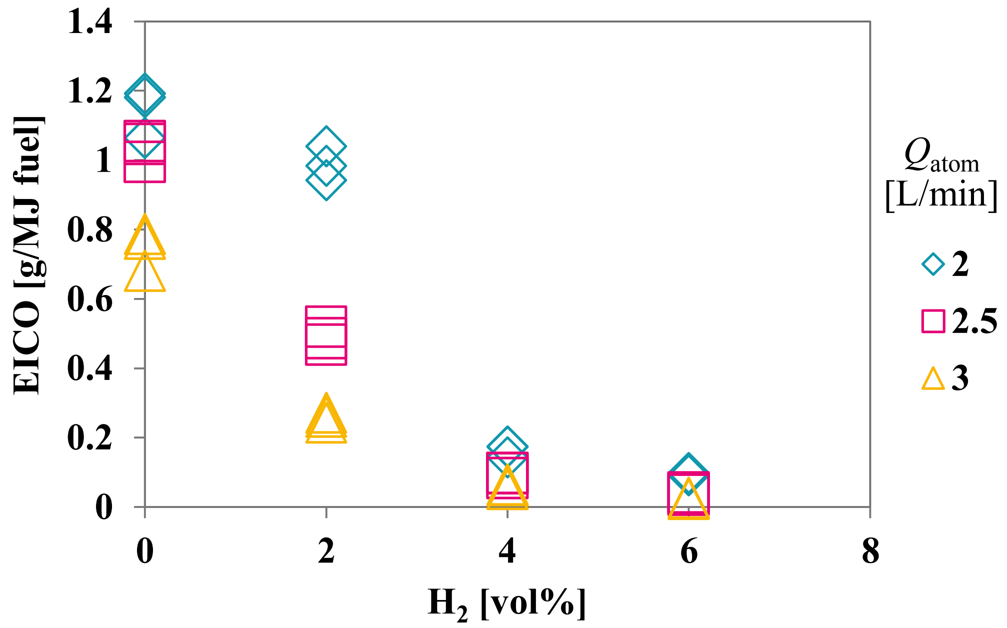


Fig. 4.9. The dependencies of EICO to hydrogen fraction at different atomizing air flow rates, for n-decane spray-jet combustion with ϕ_{SJ}=6.39

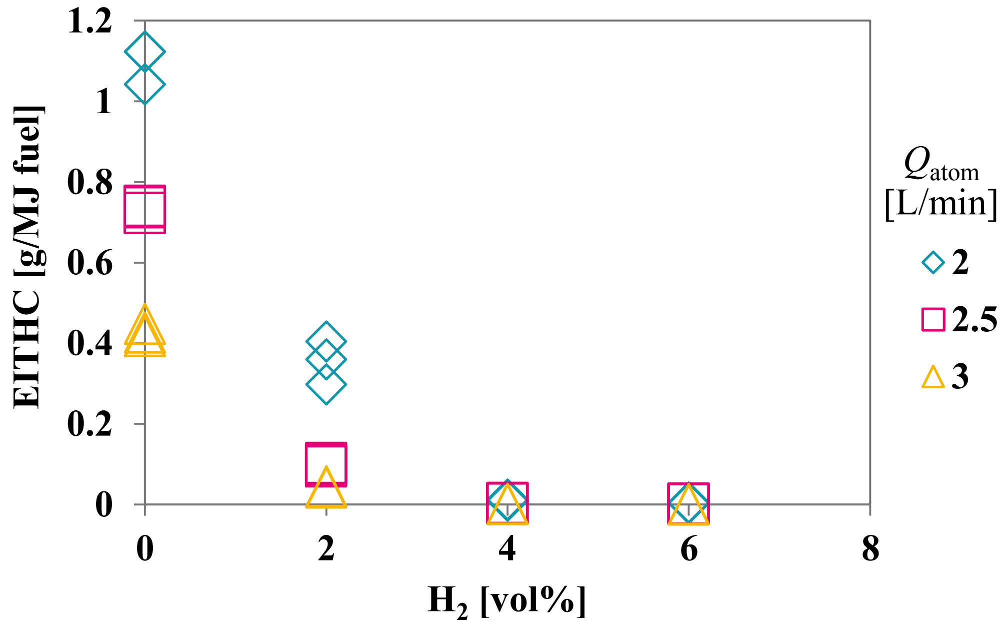


Fig. 4.10. The dependencies of EITHC to hydrogen fraction at different atomizing air flow rates, for n-decane spray-jet combustion with ϕ_{SJ}=6.39

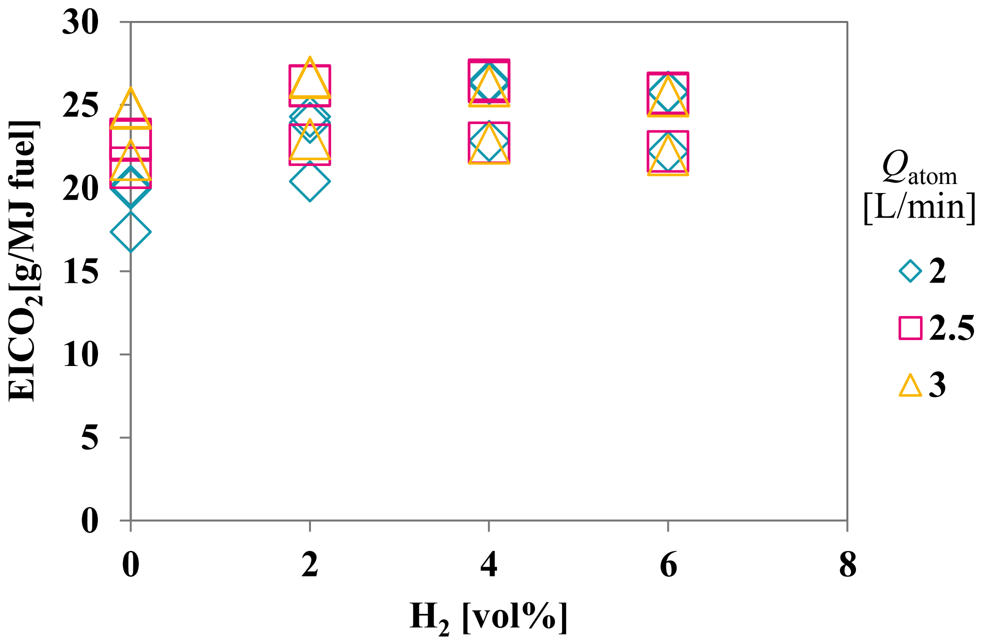


Fig. 4.11. The dependencies of $EICO_2$ to hydrogen fraction at different atomizing air flow rates, for n-decane spray-jet combustion with ϕ_{SJ}=6.39

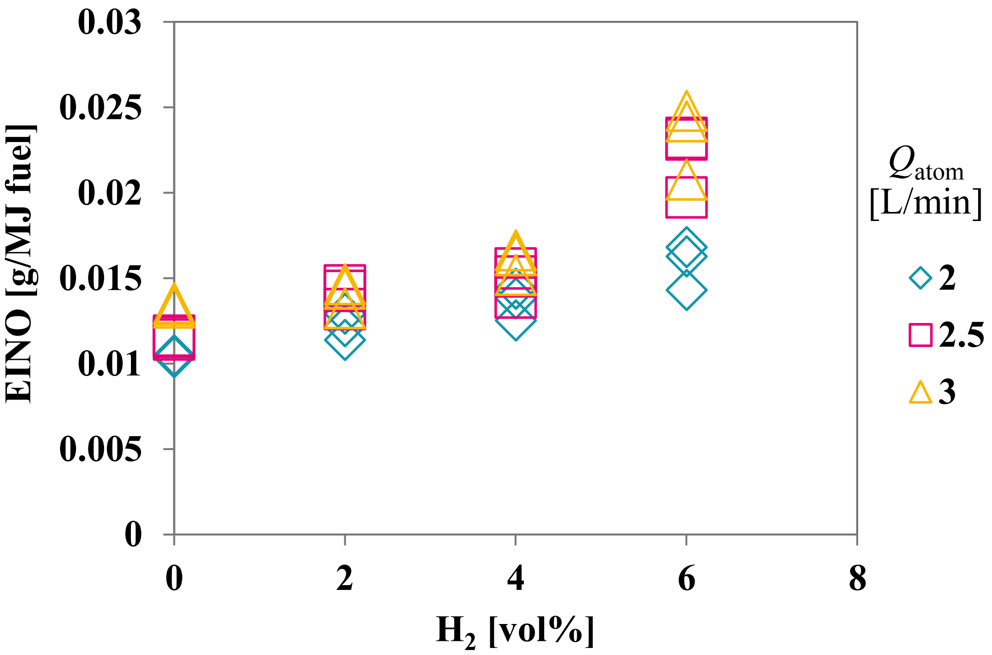


Fig. 4.12. The dependencies of EINO to hydrogen fraction at different atomizing air flow rates, for n-decane spray-jet combustion with ϕ_{SJ}=6.39

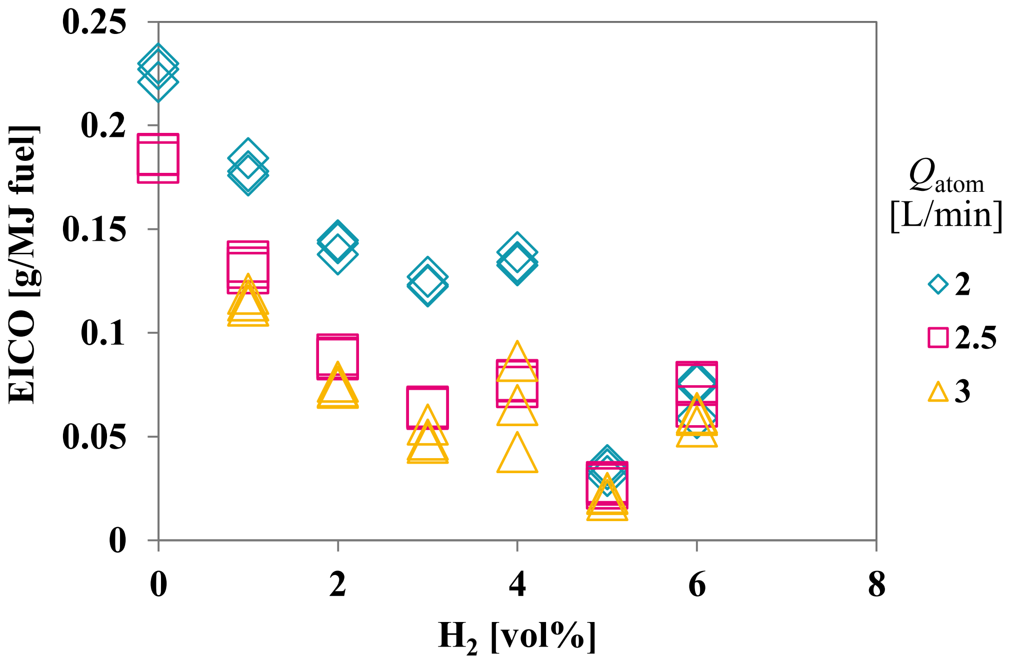


Fig. 4.13. The dependencies of EICO to hydrogen fraction at different atomizing air flow rates, for diesel fuel spray-jet combustion with ϕ_{SJ}=6.19

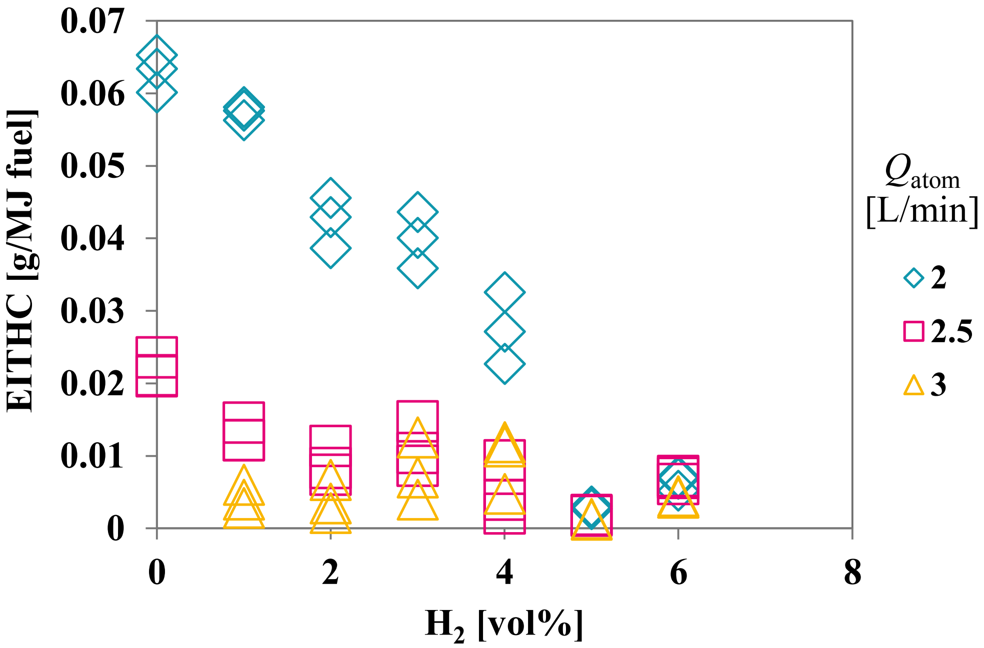


Fig. 4.14. The dependencies of EITHC to hydrogen fraction at different atomizing air flow rates, for diesel fuel spray-jet combustion with ϕ_{SJ}=6.19

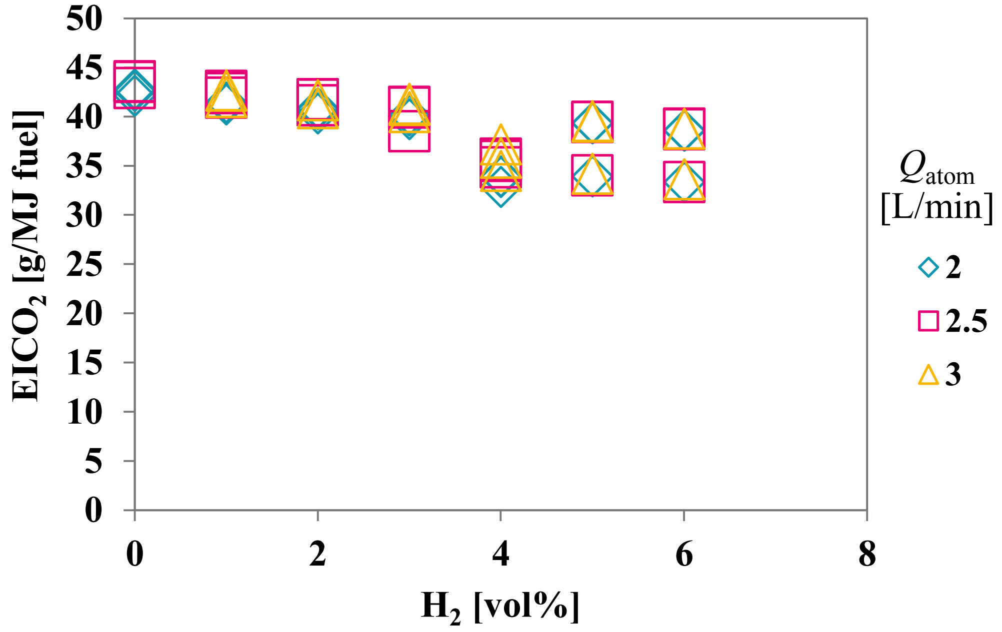


Fig. 4.15. The dependencies of EICO$_2$ to hydrogen fraction at different atomizing air flow rates, for diesel fuel spray-jet combustion with ϕ_{SJ}=6.19

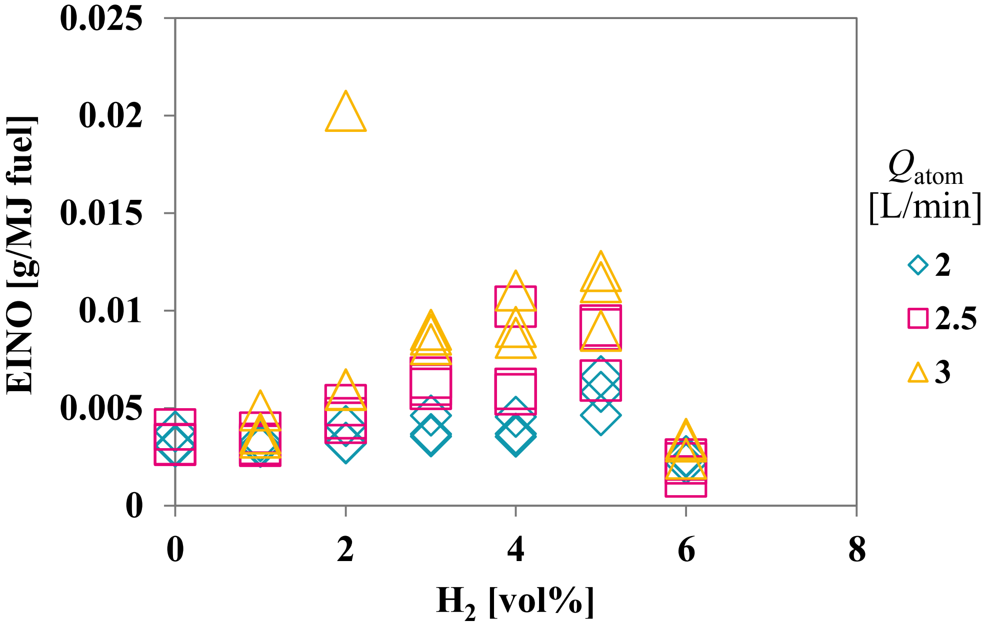


Fig. 4.16. The dependencies of EINO to hydrogen fraction at different atomizing air flow rates, for diesel fuel spray-jet combustion with ϕ_{SJ}=6.19

CHAPTER 5. APPLICATION OF HYDROGEN ADDITION TO EMULSION FUEL SPRAY-JET COMBUSTION

5.1. INTRODUCTION

The emulsion fuel utilization in spray combustion has benefits of potential control of the simultaneous lower NOx emission [1] and enhancement of combustion due to secondary atomization [2], which is produced as a consequence of the disruptive evaporation of the water droplets contained in oil droplets [3]. Even though low combustion temperature leads to a low NO emission but CO and THC emissions would be high. One of the ways to overcome this issue is supplying a small amount of hydrogen to the emulsion fuel spray-jet combustion. In this experiment, the effect of hydrogen fraction was investigated up to 6% H_2 on spray-jet combustion with W/O emulsion fuel. The hydrogen was added near the flame base as tested in Chapter 4.

5.2. BURNING BEHAVIOR IN EMULSION FUEL SPRAY-JET COMBUSTION

Diesel fuel (JIS K2204 No.2) was used as the main fuel, and Rheodol SP-O10V HLB 4.3 (KAO Corporation) surfactant as an emulsifier. The water content was 5 vol%. The stirring speed of the homogenizer (T 10 basic, IKA) was sets at 8000 RPM with the mixing time of 30 minutes. Table 5.1 shows the experimental condition of emulsion fuel spray-jet combustion with variation on the atomizing air flow rate. Table 5.2 shows the spray jet equivalence ratio and overall equivalence ratio of the emulsion fuel spray-jet combustion for the present experiment.

Figure 5.1 displays direct images of the flame. The hydrogen fraction was varied at 0 ~ 6 vol% and spray jet equivalence ratio was set at 6.19.

At the atomizing air flow rate of 3.0 L/min, the flame could not be ignited for 0% and 1% hydrogen because the higher Q_{atom} makes higher droplet velocity and fuel spread wider. As H_2 fraction is increased over 2%, the flame height and flame luminosity increase. At Q_{atom} = 2.5 L/min, blow out occurred only with 1%

H_2 possible due to increased droplet velocity with hydrogen addition. As H_2 fraction is increased over 2%, the flame height and flame luminosity increase. Overall trends of the flame height and luminosity variation are similar to those with n-decane shown in Chapter 4.

Soot formation occurs when the mixture is rich of fuel and high combustion temperature. The yellow luminosity of a flame is due to soot particles in the flame. Lower flame luminosity shows lower soot formation during spray combustion and/or lower flame temperature. There is water gas shift reactions occurring before the combustion reaction occurs.

$$\mathrm{C} + \mathrm{H_2O} \rightarrow \mathrm{CO} + \mathrm{H_2} \ -131\ \mathrm{kJ/mol}$$

$$\mathrm{CO} + \mathrm{H_2O} \rightarrow \mathrm{CO_2} + \mathrm{H_2} + 41\ \mathrm{kJ/mol}$$

The first reaction reduces soot formation. The first reaction absorbs more energy. The phase change from liquid water to water gas absorbs latent heat from the surrounding. Both liquid water and water vapor need sensible heat during heating and vaporization. They cause the flame temperature lower than the case without water in fuel. The lower flame temperature affects not only the lower flame luminosity but also the lower flame height. Relatively large droplets penetrate the flame and the number of such coarse droplets becomes more with emulsion fuel due to lower flame temperature. As the hydrogen fraction is increased, the vaporization of coarse droplets is enhanced by increased flame temperature due to the heat of hydrogen combustion. Therefore the flame height is increased with increasing hydrogen fraction.

5.3. EXHAUST GAS EMISSION

Figures 5.2, 5.3, 5.4 and 5.5 respectively show dependences of EICO, EITHC, $EICO_2$ and EINO on the H_2 fraction at the atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. The trends of EICO, EITHC, $EICO_2$ and EINO are basically the same as n-decane spray-jet combustion with H_2 addition near flame base shown in Chapter 4.

Figure 5.2 shows the dependencies of EICO of emulsion fuel spray-jet combustion on the hydrogen fraction. EICO decreases with increasing H_2 fraction. The minimum value is at Q_{atom} = 3.0 L/min. Water, gas shift reaction leads lower combustion temperature at the emulsion fuel. It leads to the high EICO on the by-product. High EICO means too much fuel in the combustion system because cannot burn (not complete combustion). Hydrogen addition until 6% near flame base can reduce EICO significantly.

Figure 5.3 shows the dependencies of EITHC on the hydrogen fraction for emulsion fuels at different atomizing air flow rates. Hydrogen addition up to 6% reduces EITHC significantly. As explained above, as the hydrogen fraction is increased, the vaporization of coarse droplets is enhanced by increased flame temperature due to the heat of hydrogen combustion. Therefore, EITHC decreases with increasing the hydrogen fraction.

Figure 5.4 shows the dependencies of $EICO_2$ on the hydrogen fraction for emulsion fuels at the atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. $EICO_2$ increases with increasing the hydrogen fraction until 4% H_2 and stays constant or decreases over 4% H_2. This trend is similar to that with n-decane as shown in Fig. 4.10. If the combustion efficiency is high enough, $EICO_2$ decreases with increasing hydrogen fraction, as explained in Chapter 4. Since the flame temperature is relatively low with the emulsion fuel, the combustion efficiency is also lower for smaller hydrogen fraction and thus $EICO_2$ becomes lower. As the hydrogen fraction is increased, the flame temperature is increased and $EICO_2$ is increased. Further increase in the hydrogen fraction will reduce $EICO_2$ because hydrogen combustion supplies heat but no CO_2.

Figure 5.5 shows the dependencies of EINO on the hydrogen fraction of emulsion fuel at the atomizing air flow rates of 2.0 L/min, 2.5 L/min and 3.0 L/min. For the emulsion fuel spray-jet combustion, EINO by product is lower than that with diesel fuel. Even though H_2 addition up to 6% leads to EINO increase at the emulsion fuel spray-jet combustion due to the increased flame temperature, but the value is still low.

Table 5.1. The experimental condition of emulsion fuel spray-jet combustion

Emulsion Fuel 5 vol % water	**Value**
Emulsion fuel flow rate, Q_F [mL/min]	3.2
Water [vol% in emulsion fuel]	5
Surfactant Rheodol SP-O10V, HLB 4.3 (Kao Corporation) [vol% in emulsion fuel]	2
Atomizing air flow rate, Q_{atom} [L/min]	2.0, 2.5, 3.0
Supplementary air flow rate, Q_{supp} [L/min]	3.0, 2.5, 2.0
Total air flow rate in premixed spray jet, Q_{SJ} [L/min]	5
Ambient air flow rate, Q_{ambi} [L/min]	35

Table 5.2. Spray jet equivalence ratio and overall equivalence ratio with H_2 addition

Hydrogen fraction [vol%]	Hydrogen flow rate, Q_{H2} [L/min]	Spray jet equivalence ratio, ϕ_{SJ}	Overall equivalence ratio in combustion chamber, ϕ_{all}
0	0	6.19	0.76
1	0.4	6.19	0.78
2	0.82	6.19	0.81
3	1.24	6.19	0.83
4	1.67	6.19	0.85
5	2.11	6.19	0.88
6	2.55	6.19	0.91

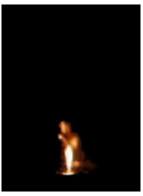
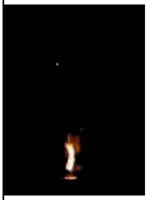
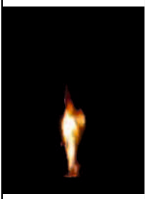
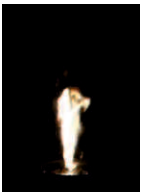
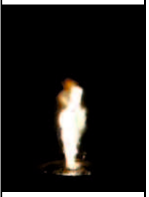
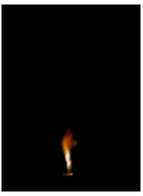
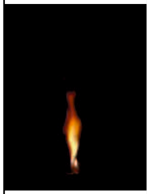
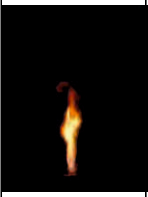
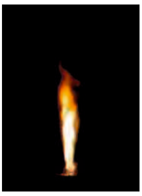
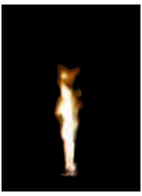
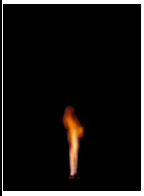
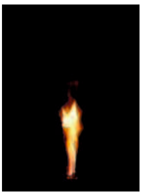
Emulsion fuel 5 vol %, with hydrogen addition near flame base							
Q_{atom} [L/min]	**0% H_2**	**1% H_2**	**2% H_2**	**3% H_2**	**4% H_2**	**5% H_2**	**6% H_2**
2							
2.5		Blow out					
3	Blow out	Blow out					

Fig. 5.1. Direct images of emulsion fuel spray-jet combustion with additional hydrogen from 0 to 6%, at $\phi_{SJ} = 6.19$

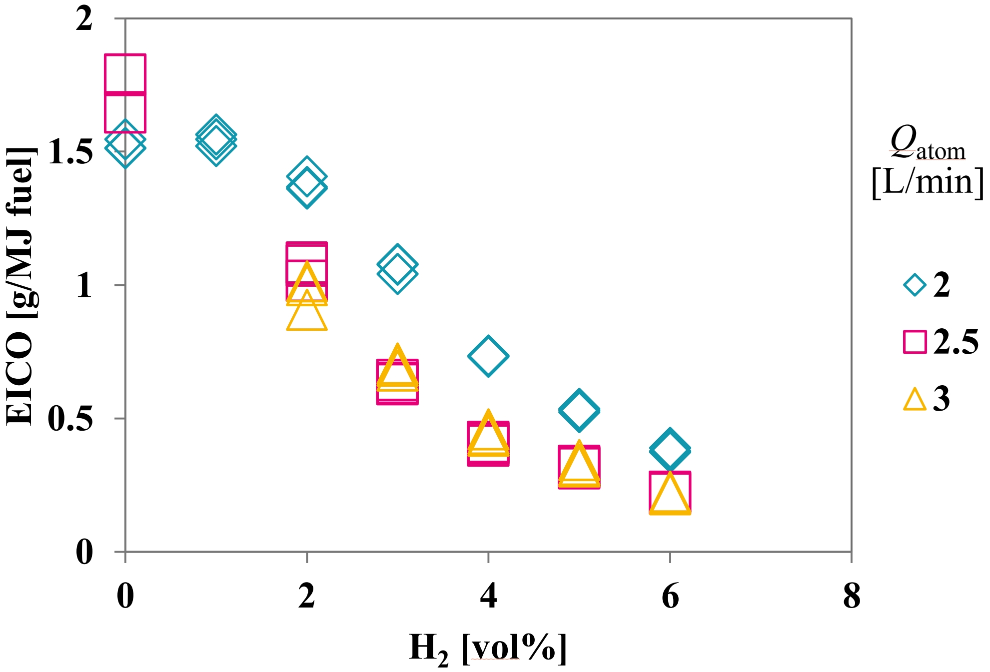


Fig. 5.2. Dependencies of EICO of emulsion fuel spray-jet combustion on the hydrogen fraction at $\phi_{SJ} = 6.19$

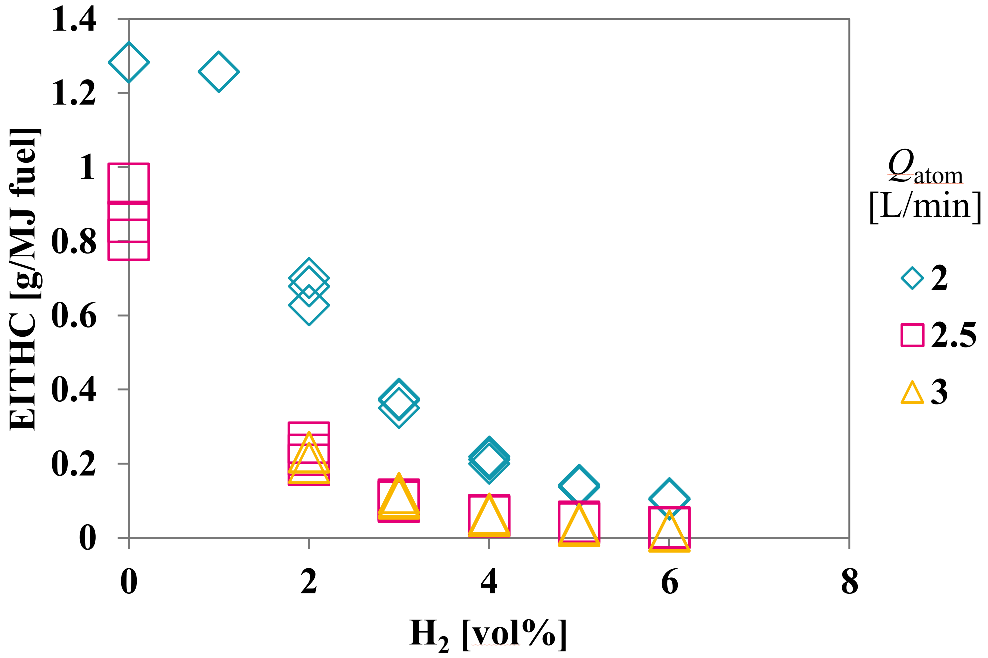


Fig. 5.3. Dependencies of EITHC of emulsion fuel spray-jet combustion on the hydrogen fraction at $\phi_{SJ} = 6.19$

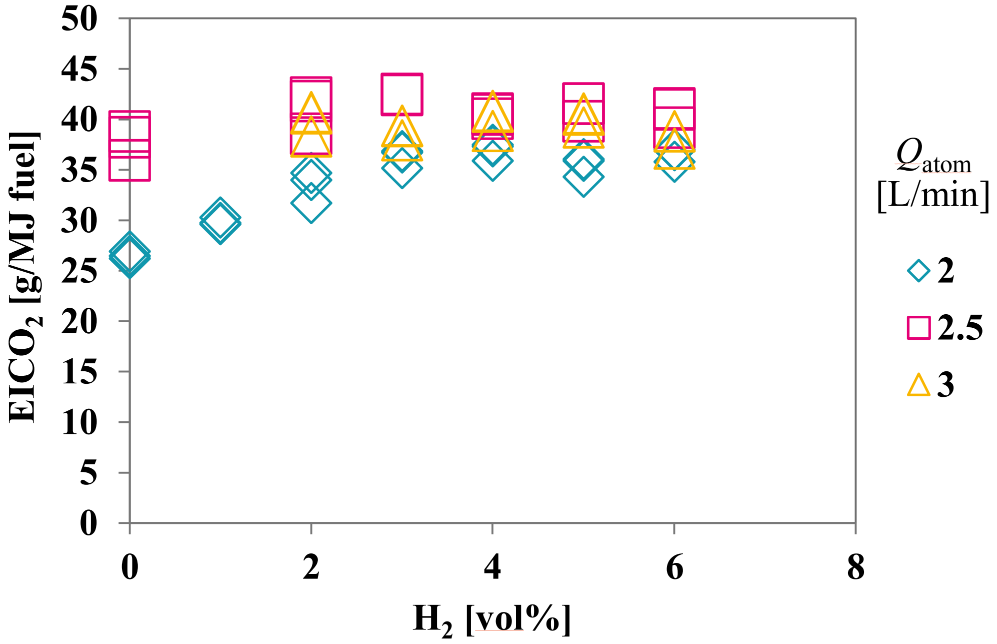


Fig. 5.4. Dependencies of $EICO_2$ of emulsion fuel spray-jet combustion on the hydrogen fraction at $\phi_{SJ} = 6.19$

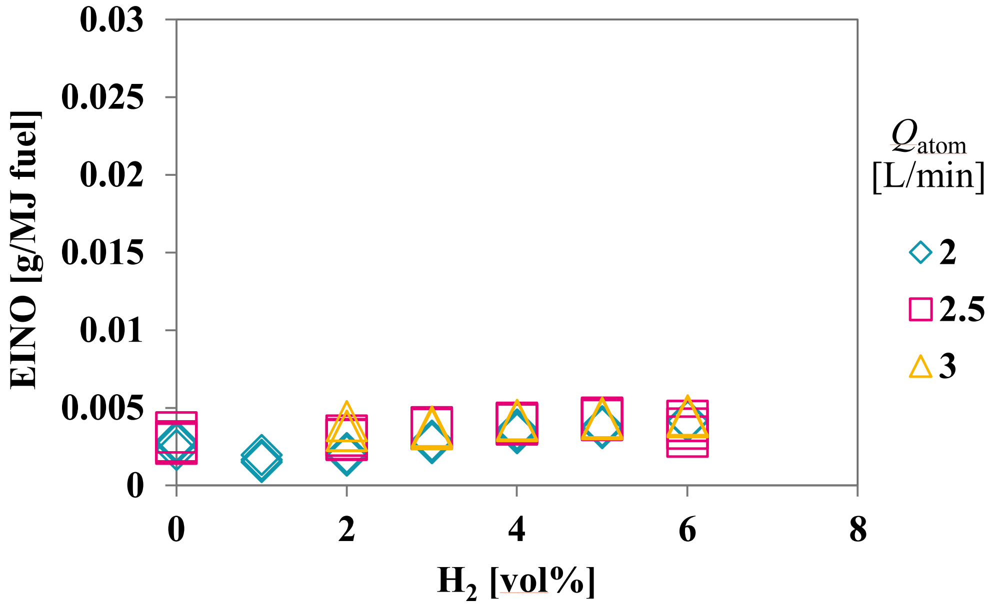


Fig. 5.5. Dependencies of EINO of emulsion fuel spray-jet combustion on the hydrogen fraction at $\phi_{SJ} = 6.19$

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[1] Qi, D.H., Chen, H., Matthews, R.D., Bian, Y. ZH., *Combustion and emission characteristics of ethanol-biodiesel-water micro-emulsions used in a direct injection compression ignition engine*, Fuel 89, 2010, pp. 958-964.

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[3] Ballester, J.M., Fueyo, N., Dopazo, C., *Combustion characteristics of heavy oil – water emulsion*, Fuel Vol. 75 No. 6, 1996, pp. 695 – 705.

CHAPTER 6 CONCLUSIONS

The present research investigated combustion and exhaust emission characteristics of spray combustion with small amount of hydrogen. Hydrogen is considered as a clean alternative fuel without carbon and sulfur content with larger heating value, about three times as large as diesel fuel. The experiments were conducted in three steps. The first step is to investigate basic characteristics of combustion and exhaust emission from spray combustion, to examine the flame structure with internal flame and relationship between the flame structure and emission characteristics without H_2 addition. The second step is to understand the influence of hydrogen addition method on the spray combustion, to show the limitation of hydrogen addition for two different hydrogen addition methods, to examine the structure of flame and exhaust gas characteristics by hydrogen addition near flame base. Third step is to confirm the effect of hydrogen addition on the emulsion fuel spray combustion.

The flame of n-decane rich-premixed spray-jet combustion consists of internal flame and external flame. The height of internal flame increases with decreasing spray jet equivalence ratio, while the height of external flame decreases. When the portion of internal flame in the external flame is higher, i.e., smaller spray jet equivalence ratio, EICO is higher at the same Q_{atom} if the combustion efficiency is high enough. Since the internal flame is a rich premixed flame, much CO is produced at the internal flame. CO_2 and H_2O are also produced at the internal flame. CO_2 and H_2O act as dilution gases and slow fuel and CO oxidation reaction at the external flame, resulting in much CO emission. This is more significant when the portion of the internal flame in the external flame is greater. NO is produced at the internal flame but is reduced to N_2 in fuel-rich post internal flame region. NO production at the external flame is also slowed by the dilution effect. CO oxidation and NO production at the external flame are enhanced by the combustion enhancement at higher atomizing air flow rate and/or higher spray-jet equivalence ratio.

As a preliminary test for hydrogen addition to rich-premixed spray-jet combustion, two hydrogen addition methods were compared using n-decane as a fuel; hydrogen addition to the spray jet and near the flame base. The method of hydrogen addition to the spray jet has a limitation in the amount of hydrogen. Beyond the threshold, the fire back occurs. The method of hydrogen addition near flame base allowed more hydrogen addition than the method of hydrogen addition to the spray jet. Thus, the effect of hydrogen on rich-premixed spray-jet combustion was investigated with hydrogen addition near flame base. The internal flame disappears by H_2 addition in the most cases. The heat generated by H_2 combustion enhances droplet vaporization and causes rich mixture over the rich flammability limit, resulting in the disappearance of the internal flame. Hydrogen addition also makes the flame higher. EICO and EITHC decrease by increasing hydrogen fraction. Since the internal flame produces much CO and dilution gases of CO_2 and H_2O, which slower the CO oxidation at the external flame, the disappearance of the internal flame leads to lower CO. The heat generated by H_2 combustion also enhances vaporization of droplets passing through the external flame and leads to lower THC. The trends of emission indexes with diesel fuel as a practical fuel are similar to those with n-decane.

The hydrogen addition method was applied to emulsion fuel spray combustion. Hydrogen was supplied near the flame base. The content of water in the emulsion fuel leads to the combustion with low flame temperature, low EINO but high EICO and EITHC. The trends of emission indexes with the emulsion fuel are also similar to those with n-decane. By adding a small amount hydrogen, EICO and EITHC decrease significantly, while EINO is still less than that with diesel fuel.

LIST OF RELATED PAPERS

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2. NYENYEP Sriwardani. OKAMOTO, Yuya. SEO, Takehiko· MIKAMI, Masato. “ Exhaust gas characteristics of diesel fuel spray combustion with additional hydrogen”, 第50回燃焼シンポジウム講演論文集原稿， 2012, Combustion Society of Japan, B321 pp. 452-453 (Related to Chapter IV).
3. Nyenyep Sriwardani. Yuya Okamoto, Takehiko Seo, Masato Mikami. “ The Influence of Hydrogen Addition to Diesel Fuel Spray Combustion For Different Atomization Conditions ”, Applied Mechanics and Materials Vol. 493 (2014) pp 33-38. (Related to Chapter IV).
4. 岡本 雄弥，Nyenyep SRIWARDANI，瀬尾 健彦，三上 真人. “ 軽油エマルジョン燃料の燃焼および排気特性に関する研究 （第2報，水素添加が噴霧燃焼に及ぼす影響）”. “Study of Combustion and Emission Characteristics of Diesel Fuel/Water Emulsion (2nd Report, Effects of Hydrogen Additon on Spray Combustion) “. Transactions of the JSME, in press. (Related to Chapter V)

NOMENCLATURE

Q_{F}	Liquid fuel flow rate	[mL/min]
Q_{atom}	Atomizing air flow rate	[L/min]
Q_{supp}	Supplementary air flow rate	[L/min]
Q_{SJ}	Total air flow rate in premixed spray jet (= $Q_{\mathrm{atom}}+Q_{\mathrm{supp}}$)	[L/min]
Q_{ambi}	Ambient air flow rate	[L/min]
$Q_{\mathrm{H_2}}$	Hydrogen flow rate	[L/min]
ϕ	Equivalence ratio	[-]
ϕ_{SJ}	Spray jet equivalence ratio	[-]
ϕ_{all}	Overall equivalence ratio	[-]
F	Fuel mass flow rate	[kg/s]
A	Air mass flow rate	[kg/s]
F/A	Fuel-air ratio	[-]
$(F/A)_{\mathrm{st}}$	Stoichiometric fuel-air ratio	[-]
ρ	Density	[kg/m^3]
ρ_{F}	Liquid fuel density	[kg/m^3]
$\rho_{\mathrm{n-decane}}$	n-decane density = 730	[kg/m^3]
$\rho_{\mathrm{diesel\ fuel}}$	Diesel fuel density = 832	[kg/m^3]
ρ_{air}	Air density =1.2041	[kg/m^3]
ν	Stoichiometric coefficient	[-]
ν_{F}	Fuel stoichiometric coefficient = 1	[-]
$\nu_{\mathrm{O_2,n-decane}}$	Oxygen stoichiometric coefficient at n-decane reaction = 15.5	[-]

$\nu_{O_2,\text{diesel fuel}}$	Oxygen stoichiometric coefficient at diesel fuel reaction = 24.5	[-]
W	Molecular mass	[kg/kmol]
W_F	Fuel molecular mass	[kg/kmol]
$W_{\text{n-decane}}$	n-decane molecular mass = 142	[kg/kmol]
$W_{\text{diesel fuel}}$	Diesel fuel molecular mass = 226	[kg/kmol]
W_{O_2}	Oxygen molecular mass = 32	[kg/kmol]
Y_{O_2}	Oxygen mass fraction in dry air = 0.232	[-]
EI	Emission index	[g/MJ]
EICO	Emission index of Carbon Monoxide	[g/MJ]
EITHC	Emission index of total unburned Hydrocarbon	[g/MJ]
$EICO_2$	Emission index of Carbon Dioxide	[g/MJ]
EINO	Emission index of Nitric Oxide	[g/MJ]

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