Springer

Journal of Mechanical Science and Technology 22 (2008) 148~156

Journal of Mechanical Science and Technology

www.springerlink.com/content/1738-494x

Characteristics of auto-ignition and micro-explosion behavior of a single droplet of water-in-fuel

Incheol Jeong[1], Kyung-Hwan Lee[2,*] and Jaesoo Kim[3]

[1]*Graduate school, Sunchon National University, Sunchonsi, Chonnam 540-742, Korea*
[2]*School of Mechanical and Aerospace Engineering, Sunchon National University, Sunchonsi, Chonnam 540-742, Korea*
[3]*Department of Aerospace Engineering, Chosun University, Gwangju, 501-759, Korea*

(Manuscript Received February 7, 2007; Revised July 2, 2007; Accepted July 19, 2007)

Abstract

The characteristics of auto-ignition and micro-explosion behaviors of a single fuel droplet have been investigated experimentally with varying droplet sizes, ambient temperature, and water content. The fuel used for this experiment was pure n-decane, which was emulsified with several water content varied from 10% to 30% to compare the effects of water content in the emulsified fuel. Imaging with a high-speed digital camera was adopted to measure the ignition delay and flame life-time, as well as to observe micro-explosion behavior. The increase of droplet size and furnace temperature causes a decrease of the ignition delay time. The flame life-time is augmented as the droplet size increases, however it doesn't seem to be affected by the ambient temperature relatively. As the water content increases, the ignition delay increases and the micro-explosion behavior is strengthened. The start timings of micro-explosion and fuel puffing are compared for different droplet sizes and the amount of water content.

Keywords: Droplet; Diesel engine; Auto-ignition; Micro-explosion; Emulsion

1. Introduction

The liquid fuels used currently are forming an ever-greater part of energy resources. The current oil crisis is thought to be more serious than the oil shocks of the 1970s and getting worse due to the growing demands on oil without new and sufficient basins to have a global impact. The unstable oil market is likely to lead to a radical and tremendous increase in the price of oil, before physical shortages begin to appear in the 21st century.

Environmental pollution due to fossil fuels is also another important issue for the future of the earth and human existence. Even though there are many ideas and researches for improving and alleviating these problems, still there is no powerful way to improve this situation directly. Many researches have been made in an effort to develop more efficient use in oil and improve the fuel economy in combustion systems. One of those researches is how to apply low volatile fuels, which was not welcomed due to its high boiling point, difficulties in vaporization and ignition, and serious exhaust emissions, especially high soot concentrations. It is necessary to improve the fuel atomization and evaporation to ignite a low volatile fuel properly to expand the use of these fuels. One of the efficient methods to stimulate the evaporation of low volatile fuel is to mix some water with these liquid fuels, which can emulsify the fuel with water and result in a micro-explosion [1]. The micro-explosion is known to accelerate the evaporation of a liquid fuel droplet, mixing of fuel with air, and consequently combustion of the droplet. It is also well known that emulsified fuels can reduce the emission of soot and NOx from diesel engines without any deterioration of

*Corresponding author. Tel.: +82 61 750 3822, Fax.: +82 61 750 3820
E-mail address: khlee@sunchon.ac.kr
DOI 10.1007/s12206-007-1018-5

specific fuel consumption [2-4].

The aim of this research is intended to investigate the auto-ignition characteristics and combustion behavior of a single droplet of low volatile fuels with some emulsification experimentally. The ignition delay and life-time of single droplets with various water contents and droplet sizes are compared with various ambient temperatures(T_a). The micro-explosion phenomena are also observed and analyzed for different operating conditions.

2. Experimental apparatus and method

The experimental apparatus used in this work is illustrated in Fig. 1. An electric furnace with temperature controller was used as a combustion chamber to keep a constant temperature from 920K to 1070K for the auto-ignition of a single droplet. A fuel supply system with a micro-liter syringe whose volume is 50μl and operated by 4-axis stepping motors can generate a single droplet. It can adjust the droplet size and transfer the droplet into the combustion cham ber. It also detects the location of the suspender in

Table 1. Properties of tested fuel.

Fuel	n-decane
Symbol for element	$CH_3(CH_3)_8CH_3$
Manufacture	Junsei Chemical co
Assay(GC)	Min 95.0%
Lot No	2C2101
Melting point(℃)	-30℃
Boiling point(℃)	174℃
Density	0.73cm^3/g

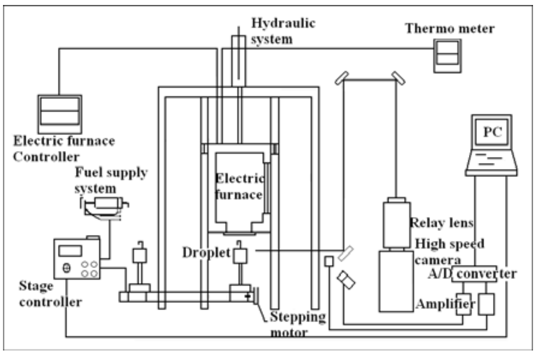


Fig. 1. Schematic diagram of experimental apparatus.

the beginning and feeds the exact amount of fuel. The supplied fuel was suspended at the end of silica fiber suspender. All these movements by stepping motors were controlled with PC and stepping motor controller.

The base fuel used for these experiments is n-decane(n-$C_{10}H_{22}$). The addition of water into the fuel is not easy due to its difficulties in mixing and separation. With some surfactant and stirrer, emulsified fuel can be obtained instead of the ultrasonic wave, which can increase the temperature of the emulsified fuel. The actual shape of the suspended droplet was elliptical and an equivalent diameter of droplet D is expressed as the cubic root of the product of the droplet width squared and droplet length, i.e.,

$$D = (D_1^2 \times D_2)^{1/3},$$

where D_1 and D_2 indicate the droplet width and droplet length [5, 6].

The hydraulic driving system is applied to move up and down the electric furnace to the location of single fuel droplet. The size of the hydraulic cylinder is φ50 mm x 700 mm and its stroke is 380 mm. The moving velocity of that plunger can be adjusted from 1 to 18 cm/s. If the electric furnace moves down over the speed of 18 cm/s, the droplet on the silica fiber suspender can fall due to the air stream, which makes it

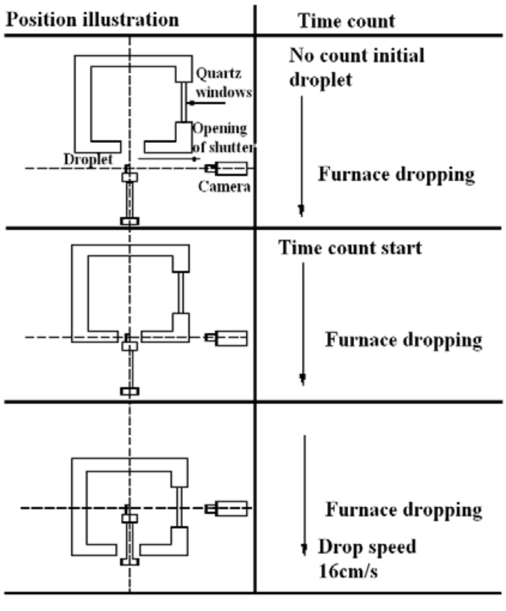


Fig. 2. Illustration of time count.

impossible to take pictures. In this experiment it was fixed as 16 cm/s. It is designed that the high speed camera starts to operate when the bottom of the electric furnace meets the location of droplet, as shown in Fig. 2. If the drop speed of the electric furnace is below 16 cm/s, the ignition can start while the electric furnace moves down due to the heat transfer from the furnace before the camera start to capture the image, which makes it difficult to determine the ignition delay and life-time of the droplet. The diameter of the silica fiber suspender is approximately 150$\pm$10 μm and its end is fabricated with about 300$\pm$10 μm to attach the droplet easily.

A high speed video camera (PASTCAM, X1280PCI) is applied to measure the ignition delay and flame life-time. The frame speed of camera is set as 250-500 f/s to observe the proper behavior of flame stretching and micro-explosion behaviors. The personal computer is used to control the stepping motors and capture the video image. Fig. 2 shows an illustration of time count to measure the ignition delay, life time, and start timing of micro-explosion. The time count and video camera start to operate automatically by a sensor as the bottom of the electric furnace aligns to the center of the droplet. All the measurements were performed under atmospheric conditions.

3. Results and discussions

The size and volatility of a fuel droplet can seriously affect its ignition time and the ignition time of a single droplet can be expressed as an evaporation time and chemical reaction time [6]. For a large droplet or low volatile fuel, most of the fuel cannot be evaporated until the surface temperature of the fuel reaches the boiling point. The mixing and chemical reaction time is negligible since the evaporation becomes vigorous once this evaporation starts.

Typical images of combustion behavior for fuel droplets by a high speed video camera are shown in Fig. 3 for 970 K of ambient temperature and 1.25 mm of droplet diameter. The first figures through (a)-(d) show the starting time of main combustion, that is the ignition delay(I/D). Although the ignition delay seems to be slightly delayed as the water content increases, the differences in ignition delay for each case are not thought to be significant. In the case of pure n-decane as shown in (a), the micro-explosion cannot be seen, but puffing of fuel only. The second figures of (a), (b), and (c) show the droplet puffing due to the boiling of fuel. However, as shown in (b)-(d) the micro-explosion behavior was observed with a little faster combustion consequently as the water content increased. In the case of (b), whose water content is 10%, a weak micro-explosion started to occur at 1.07 sec approximately after the droplet was exposed to the high ambient temperature. A relatively stronger micro-explosion with vigorous flame spread can be observed for the case of (d) whose water content is 30%. From these figures it is seen that the micro-explosion started at around 0.94-1.1 sec after the emulsified n-decane droplet with 1.25 mm of diameter was exposed to the 970K of ambient temperature. It is also found that the intensity of micro-explosion gets stronger as the water content increases.

3.1 Effect of ambient temperature and water content on ignition delay

The air temperature in the combustion chamber increased from 920 K to 1070 K by 50 K intervals and the water content also varied from 10% to 30% by 10% to investigate the effect of ambient temperatures and water content on ignition delay. Figs. 4(a) to (c) show that the water content of emulsified fuels can affect ignition delay with ambient temperature and droplet size. The ignition delay appears to range from 1.1 sec to 1.2 sec in the case of d=0.75 mm, and from 1.0 sec to 1.1 sec for d=1.0 &1.25 mm by approximately 0.1sec as shown in Fig. 4(a), which is thought to show the apparent effect of water concentration on ignition delay at lower ambient temperature. For 1020 K, as shown in Fig. 4(b), the trend in ignition delay is almost the same as for 920K with a reduced ignition delay relatively. As the ambient temperature increases, the ignition delay decreases distinctly regardless of droplet size and water content. There also don't appear serious differences in the ignition delay with the water content at higher temperature as shown in Fig. 4(c); it is thought that the fuel and water evaporated almost simultaneously without any significant differences in the ignition delay at high ambient temperature conditions.

It is also found that a droplet smaller than 0.75 mm under an ambient temperature of 920 K is difficult to ignite; it is thought that the vaporized fuel is dissipated due to the long ignition delay and cannot form

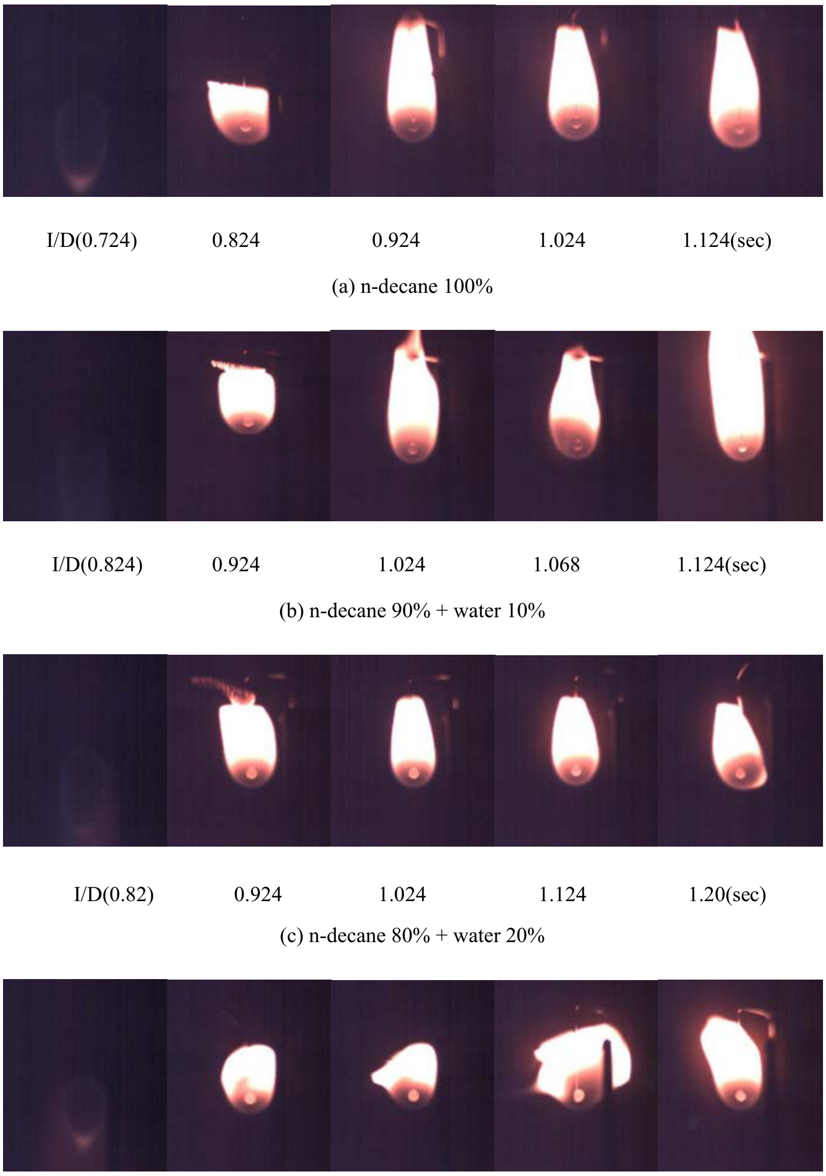
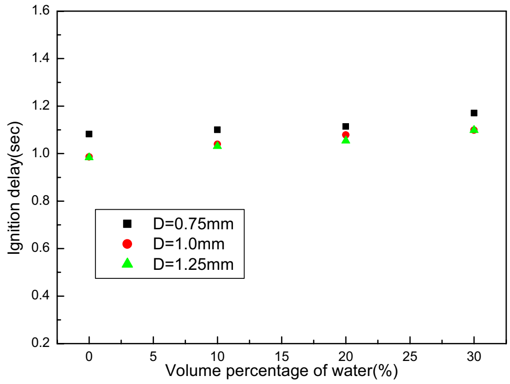


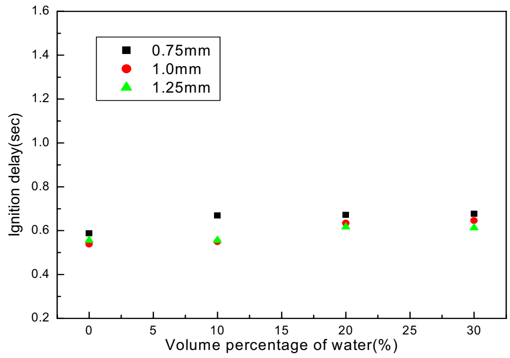
Fig. 3. Direct photographs of combustion behavior for emulsified n-decane droplets(D=1.25 mm, Ta=970 K).

an ignitable mixture. The case of 0.75 mm in droplet diameter shows a little longer ignition delay than other droplet sizes regardless of water content and ambient temperature, which is thought to be due to the extended chemical reaction time as the mass flux of vapor increases rapidly. The ignition delay of pure n-decane seems to be apparently shorter than that of emulsified n-decane at the ambient temperature lower than 1070 K. However, the ignition delay of pure n-decane at an ambient temperature of 1070 K doesn't show any significant differences with the emulsified n-decane regardless of water content, as shown in Fig. 4(c).

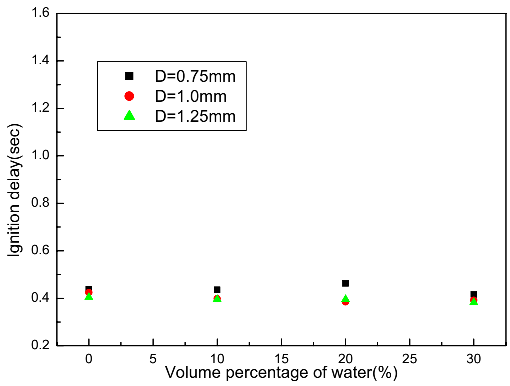
The dependency of ambient temperature on igni-



(a) T_a=920 K



(b) T_a=1020 K



(c) T_a=1070 K

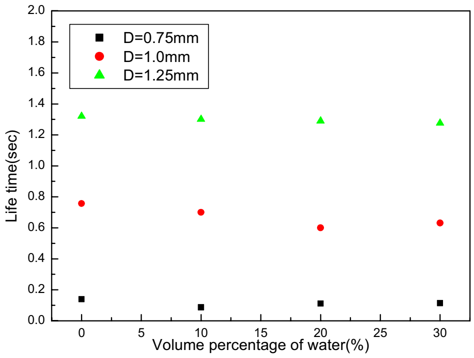
Fig. 4. Effect of droplet size and water contents on ignition delay for the ambient temperatures.

tion delay was also investigated. For 920 K the ignition delay for all droplet sizes and water content ranged from 1.0-1.2 sec, while 0.7-0.9 sec for 970 K, 0.5-0.7 sec for 1020 K, and 0.4-0.5 sec for 1070 K, respectively. That is, the ignition delay of water-in-fuel droplet decreases almost linearly with an increase in ambient temperature, which is consistent with the general trend.

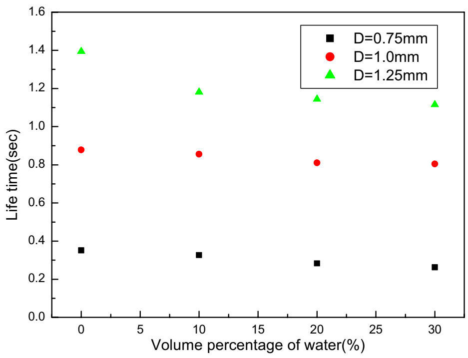
For smaller droplet sizes, as the mass flux of vapor increases rapidly, the chemical reaction time is extended. It is found that a droplet smaller than 0.75 mm under an ambient temperature of 920 K cannot ignite; the thinking here is that the vaporized fuel is dissipated due to the long ignition delay which makes it difficult to ignite because it cannot form an ignitable mixture due to the too-lean mixture ratios. Consequently, in the case of a relatively high volatile fuel with smaller diameter of droplet, the ignition timing can be rather delayed with the excess evaporation, which is consistent with the previous research [6].

3.2 Effect of ambient temperatures and water contents on life-time and full combustion time.

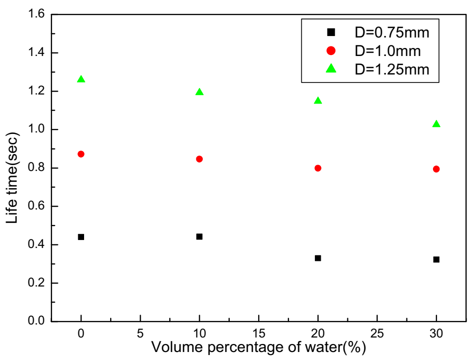
The life-time of an emulsion droplet, which is defined as the time interval between the ignition delay and the completion of combustion, was compared to understand the effect of ambient temperature and water content on the combustion of an emulsified fuel droplet. As seen in Fig. 5(a), at lower ambient temperature(920 K) the life-time doesn't change so much with an increase in water content regardless of droplet size. However, with higher ambient temperatures, as shown in Fig. 5(b) & (c) the life-time of emulsion droplets decreases with the increase in water content, which is thought due to a micro-explosion. When the droplet size is small(D=0.75 mm), the life-time of the emulsion droplet is not seen affected significantly by water content, possibly because the micro-explosion is not strong enough to affect the main combustion duration with smaller droplet. However, with the bigger droplet size the life-timeis decreased slightly as the water content in emulsified droplet increases. This result indicates that a stronger micro-explosion with an increase in water content can shorten the duration of combustion for the emulsion droplet. As the droplet size increases, it indicates that the life-time of a droplet is affected by the water content at higher ambient temperature, as shown in Fig. 5(b) and (c). For the same droplet size, as the water content increases the life-time of the droplet gets shorter, which is thought to be due to the micro-explosion of emulsified fuel droplet, but the effect of ambient temperature is not so significant.



(a) T_a=920 K

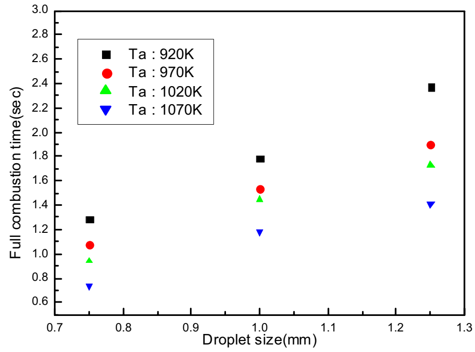


(b) T_a=1020 K

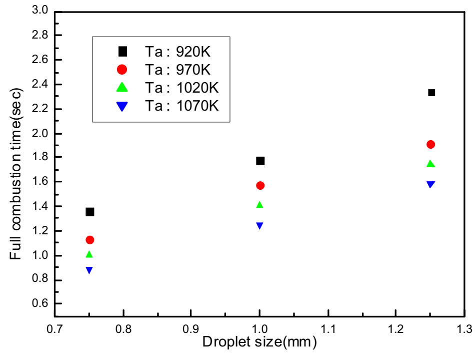


(c) T_a=1070 K

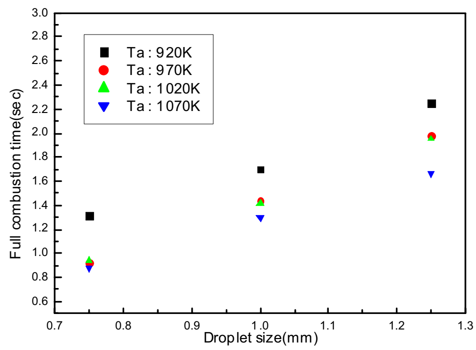
Fig. 5. Effect of droplet size and water contents on lifetime for the ambient temperatures.



(a) Decane 70%+Water 30%



(b) Decane 80%+Water 20%



(c) Decane 100%

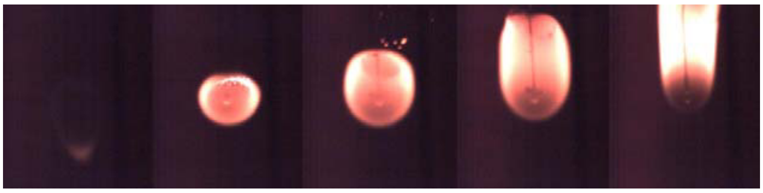
Fig. 6. Effect of droplet size and ambient temperature on full combustion time.

The full combustion time defined as the total of ignition delay and life-time was also examined to compare the effect of water content and ambient temperature for different droplet sizes, as shown in Fig. 6. From this figure it is found that the trend of changes in full combustion time for the emulsified fuels with the variation in ambient temperatures gets longer generally as the droplet size increases regardless of ambient temperature. It is clear that the full combustion time increases as the droplet size increases due to the increase in mass to be burnt regardless of ambient temperature and water content as generally known [7]. It is also confirmed that the full combustion time is strongly dependent on the ambient temperature. The full combustion time increases regardless of water content due to the longer ignition delay and less change in the life-time of the droplet as the ambient temperature gets lower. At relatively lower ambient temperature the trend in full combustion time shows a little increase as the water content increases; however, at a higher temperature such as 1070 K the full combustion time decreases a little as the water content increases. It is thought that the life-time decreases due to the strong micro-explosion with the higher water content even though there is not much change in ignition delay, which causes a reduction in full combustion time.

3.3 Micro-explosion starting time

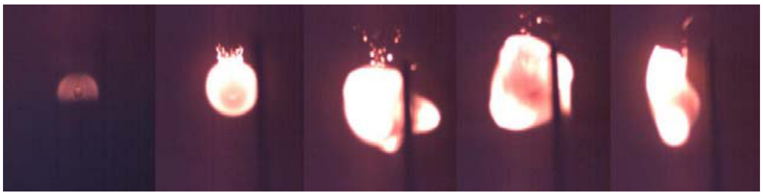
In an emulsified fuel droplet with water, the water droplets encased within a fuel droplet can instantaneously vaporize as the temperature of the droplet increases. As the temperature exceeds the homogeneous nucleation temperature of a fuel component, this leads to the formation and growth of a vapor bubble in the droplet. This rapidly growing vapor bubble ultimately shatters the surrounding liquid fuel envelope into smaller fragments that burn more efficiently because of their increased surface area [8].

A typical image of micro-explosion behavior for water-in-fuel droplets by a high speed video camera is shown in Fig. 7 for different water content with 1.0 mm in droplet diameter and 1070 K of ambient temperature. In the case of n-decane, a micro-



I/D(0.46) 0.56 0.66 0.76 0.86(sec)

(a) n-decane 100%

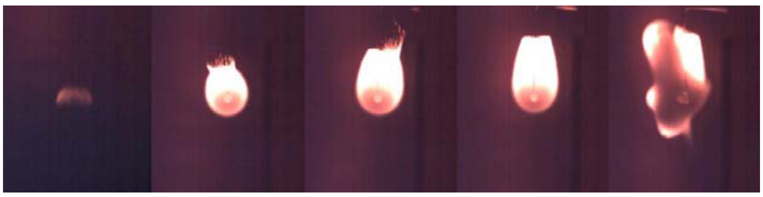


I/D(0.394) 0.492 0.564 0.592 0.804(sec)

(b) n-decane 90%+Water 10%

I/D(0.41) 0.516 0.564 0.624 0.824(sec)

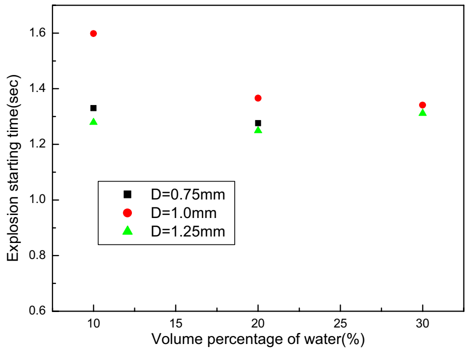
(c) n-decane 80%+Water 20%



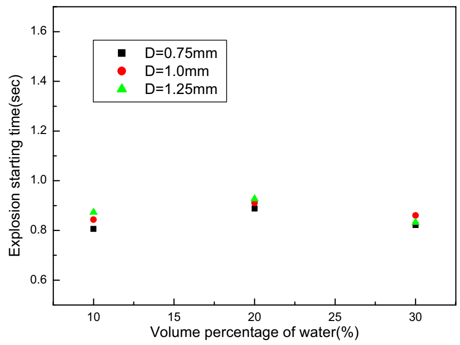
I/D(0.4) 0.54 0.64 0.74 0.8(sec)

(d) n-decane 70%+Water 30%

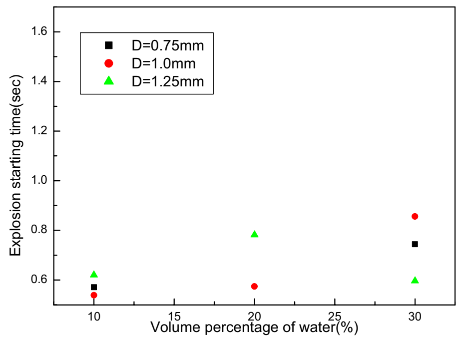
Fig. 7. Direct photographs of micro-explosion behavior for emulsified n-decane droplets(D=1.0mm, Ta=1070K).



(a) T_a =920 K



(b) T_a =1020 K



(c) T_a =1070 K

Fig. 8. Micro-explosion starting time with respect to droplet size and water contents.

explosion cannot be seen, but puffing of fuel only. However, as the water content increases stronger micro-explosion, vigorous flame, and consequently faster combustion can be seen.

As shown in Fig. 8, when the droplet size is 0.75 mm and T_a is 920 K, the case of 30% water content doesn't show any micro-explosion phenomena. In the case of higher temperature with the same droplet size, the micro-explosion occurs at the case of 10% and 30% of water content. From this result it is conjectured that for a smaller droplet it is sometimes difficult to have a micro-explosion due to its extended chemical reaction time as the mass flux of vapor increases rapidly. The effect of water content on the start of a micro-explosion doesn't show any typical trend when it is compared with the same droplet size. It was also found that as the ambient temperature increases, generally the micro-explosion occurs earlier regardless of droplet size and water content, as shown in Fig. 9. That is, the starting time of the micro-explosion seems to be linearly dependent on the ambient temperature. With the increase in water contents the intensity of the micro-explosion seems to be stronger and combust more vigorously, especially at higher temperature.

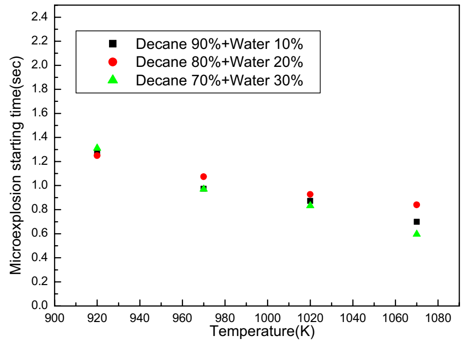


Fig. 9. Micro-explosion starting time with respect to ambient temperature and water contents(D=1.25mm).

4. Conclusion

The ignition delay and life-time of a single droplet of low volatile fuel with various water content and droplet size were experimentally compared with some ambient temperatures. The flame behavior in a micro-explosion was also observed and analyzed for micro-explosion starting time for the different operating conditions. Even though there are some limitations on the experimental conditions of droplet sizes and ambient temperatures, these results show the some trends in the combustion behavior of an emulsified fuel droplet. However, the case of smaller droplet sizes or higher ambient pressures and droplet array needs to be compared in order to apply the obtained results to a more realistic combustion system, that is, the internal combustion engine, in the future. From this investigation the following conclusions are made:

(1) The ignition delay of an emulsified fuel droplet is related to the ambient temperature and droplet

size significantly. When the droplet size is too small, a rapid increase in mass flux causes a delay of auto-ignition timing.

(2) Ignition appears to be delayed apparently at lower ambient temperatures by the effect of water concentration. However, higher temperatures don't show serious differences in ignition delay due to water content; it is thought that the fuel and water evaporate almost simultaneously.

(3) The droplet life-time is affected by the water content as the droplet size increases. For the same droplet, the life-time of the droplet was affected more by the increase of water content rather than the ambient temperature, which is thought to be due to the micro-explosion.

(4) The full combustion time increases regardless of water content due to the longer ignition delay and less changes in life-time of droplet as the ambient temperature gets lower.

(5) As the ambient temperature increases, generally the micro-explosion occurrs earlier and proceeded more vigorously regardless of droplet size and water content.

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