STUDY ON IGNITABILITY OF FUEL SPRAY

(EFFECT OF INHOMOGENEITY ON SPRAY IGNITION PHENOMENON)

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Ignition probability and the flame formation of the lean concentration fuel spray are affected by the spray characteristics, especially the inhomogeneity of fuel spray. In this study, it is aimed to clarify the effect of spatial inhomogeneity of fuel spray on ignition phenomenon, particularly the generation of luminous flame. As a result, the ignition probability is affected by the spatial inhomogeneity intensity of the fuel spray, and it is suggested that the existence of optimum intensity of spatial inhomogeneity of fuel spray for flame propagation and ignition. On the other hand, the flame propagation of the fuel spray is effected by the spatial inhomogeneity scale of the fuel spray, and it is suggested that the optimum scale exists for the formation of luminous flame.

1. Introduction

In understanding the ignition phenomenon of fuel spray, most studies can be divided roughly into two types, i.e. focused on macroscopic characteristic of fuel spray [1], and on each droplets in spray and their interactions [2]. It is indispensable to pay attention to fundamental characteristics of each droplet for clarifying the spray ignition phenomenon. However, droplets in spray exist un-uniform in space and the interaction of droplets is complicated. This inhomogeneity effects strongly on the ignition phenomenon and the flame formation. Therefore, it is unreasonable to apply the results obtained by such fundamental studies to real spray ignited. In this study, it is aimed to clarify the effect of spatial inhomogeneity of fuel spray on ignition phenomenon, especially on ignition probability, and the generation of luminous flame.

2. Experimental apparatus and methods

The schematic arrangement of experimental devices is shown in Fig.1 and the experimental conditions in Table 1. In order to clarifying the effect of spatial inhomogeneity, two different time-averaged fuel concentration conditions are carried out (see Table 1.) Mono-dispersed n-Decane spray is injected from atomizer that is on the top of mixing chamber. In order to simplifying the spray ignition phenomenon, we used mono-dispersed fuel spray. The spray is diffused spatially in a mixing chamber, and led to the ignition point. After measurements of time-average specification of fuel spray by PDPA, a large number of ignition trials were performed. Instantaneous concentration and droplet positions just before ignited are measured from the images obtained by CCD with pulse laser sheet. Inhomogeneity of fuel spray is calculated from this image. Luminous flame formation is also recorded by another CCD. In this experiment, the distribution of time-averaged spray concentration at any point within 30mm in diameter around spark electrodes is within more than 80wt% of maximum concentration. In addition, sufficient time for experiment conditions to return to a stationary state was vacated for each examination.

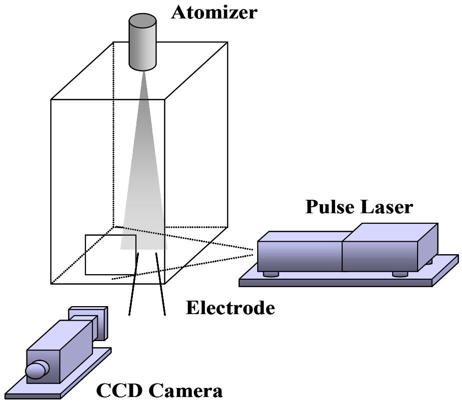

Fig.1 Experimental apparatus

Table 1 Experimental conditions

ITEM	Condition 1	Condition 2
Fuel	n-Decane	
Droplet diameter (D_{32})	113μm	115μm
Time-averaged fuel spray concentration	0.0082kg/m^3	0.0044kg/m^3
Spray velocity	0.210～0.241m/s	
Temperature / Pressure	Atmospheric Temperature/ Atmospheric Pressure	
Igniter and Discharge duration	Discharged spark system, 50ms (0.8J)	

3. Definition of ignition

It is difficult to apply the theoretical definition of ignition to experiment. In this study, the following criteria are defined to classify the flame propagation on ignitability.

(1) Flame propagated over 50mm in diameter.
(2) Flame propagated over 30mm in diameter.
(3) Flame propagated until around 30mm in diameter.
(4) Flame propagated, but the flame was extinguished within 30mm in diameter.
(5) Flame kernel was observed, but it did not propagate.
(6) Flame kernel was not observed.

Here, the flame patterns (1)-(3) are defined as successful ignition, (4)-(6) as failed ignition. The ratio of flame patterns (1)-(3) to (1)-(6) is defined as the ignition probability, the ratio of flame pattern (1)-(4) to (1)-(6) as small flame development ratio. As a result, the ratio of (1)-(3) to (1)-(4) is flame propagation ratio.

4. Definition of flame formation

The flames of fuel spray combustion can be divided roughly into two types from their structures, one is the group combustion, and the other is the formation of many small flamelets. Figures 2 and 3 show the typical structures.

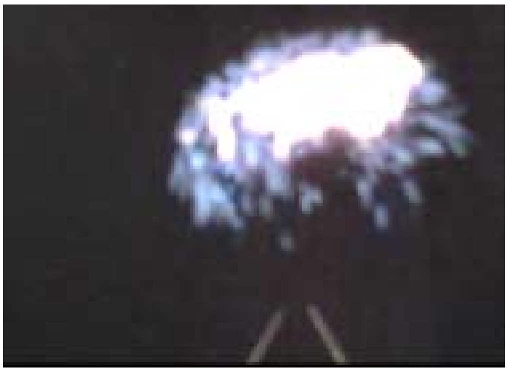

Fig.2 The structure of group combustion

Fig.3 The structure of many small flamelets

However, it is difficult to analyze flame structure quantitatively, because those two structures can not be classified clearly. From the flame structure point of view, the formation of a luminous flame is discussed in this study.

Flame formation is recorded 12 frames in every 30msec by CCD camera. Further, the most suitable threshold is determined through the image processing such as edge insistence, smoothing and acumination, and the luminous flames are extracted. Here, figures 4 and 5 show the flame image by CCD and result after image processing, respectively.

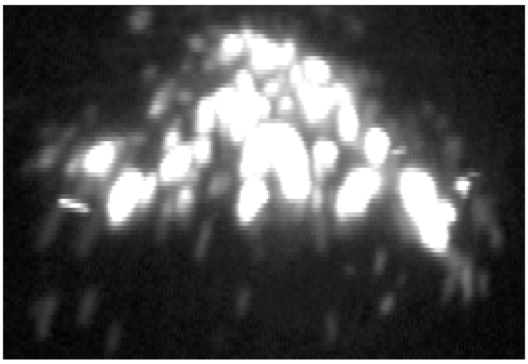

Fig.4 flame image by CCD

Fig.5 Processed image

The flame which is shown in processed image is defined as the luminous flame. And the processed image which is taken after 90 msec after ignition is used for analysis. The maximum area of a luminous flame is defined as the flame area which has maximum area in the processed image.

5. The definition of inhomogeneity index and evaluation by it

It is supposed easily that the spatial inhomogeneity of fuel spray gives the great influences on the flame propagation. In this study, inhomogeneity of fuel spray is estimated by the inhomogeneity index defined by Czainski [3].

The inhomogeneity index means the complexity of dispersion layer and is defined as the ratio of deviation of fuel droplets number in each cell to one of droplets distributed randomly. The inhomogeneity index H is expressed as follows:

$$H = \frac{h-1}{\sigma_h} \tag{1}$$

where,

$$h = \mu / \mu_{random} = \frac{\sum_{i=1}^{\kappa} \left(n_i - \frac{n}{\kappa} \right)^2}{n(\kappa - 1)/\kappa} \tag{2}$$

$$\sigma_n = \sqrt{\frac{2(n-1)}{n(\kappa - 1)}} \tag{3}$$

H : Inhomogeneity index

n : Number of total droplet

n_i : Number of droplet within ι_{th} cell

κ : Number of cells

(See Fig. 6)

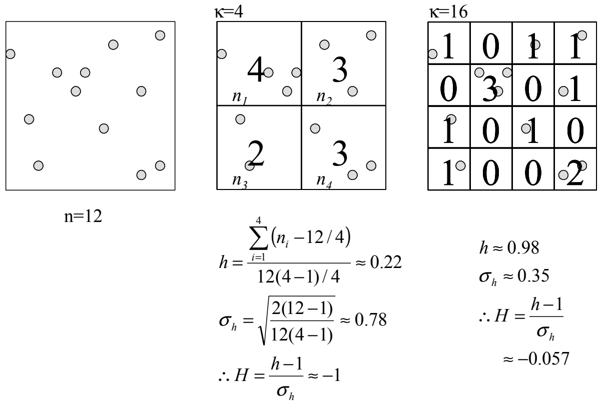

Fig.6 Example of calculation of the inhomogeneity index

In original definition [3], it was calculated with the projection area of the particles. However, it was calculated with the number of particles in this research since the spray droplets were sphere and almost uniform size. Moreover, it was calculated from the 2-dimentional distribution of droplets although the fuel spray distributed 3-dimensionally.
When the inhomogeneity index is larger than 0, droplet distribution is more uneven than one being randomly. On the contrary, when the inhomogeneity index is smaller than 0, droplet distribution is more uniform than the case being randomly. If the droplet distribute at random, inhomogeneity index becomes 0.
It is also possible to evaluate the scale of inhomogeneity from cell size. When the cell size is large, large scale of inhomogeneity is evaluated. When the cell size becomes equal to the characteristic scale of droplets cluster, the inhomogeneity index indicates maximum, because the difference of droplets number in each cell becomes maximum. The cell which has a maximum inhomogeneity index is defined as the characteristic scale, in this study.

6. Results and discussions

6.1 Effect of inhomogeneity of fuel spray on ignition probability

In order to clarify the effect of instantaneous fuel spray concentration on the ignition probability, more than 500 times of ignition trials were carried out for each time-averaged concentration condition. The relation between instantaneous fuel spray concentration and the ignition probability is shown in Fig.7. It is evidence from this figure that the instantaneous concentration of fuel varies widely even if the time-averaged concentration is same. The ignition probability increases with the increase of instantaneous fuel concentration. However, both of successful ignitions and failed one occur at same instantaneous concentration. Further, the ignition probability of condition 2 is higher than one of condition 1 at each instantaneous concentration. One of the differences between those two conditions is the inhomogeneity of spray (see Figs.13 and 14). Those facts suggest that the ignition phenomena are affected by not only instantaneous fuel concentration but also other factors such as distribution of fuel drops in space. Figures 8 and 9 show the small flame development ratio and flame propagation ratio against the instantaneous concentration of fuel spray respectively. When the instantaneous concentration is same, the appearance of small frame is same regardless of distribution of fuel drops but flame propagates more at condition 2. Those results suggest that the ignition probability is affected more by the frame propagation in those cases.

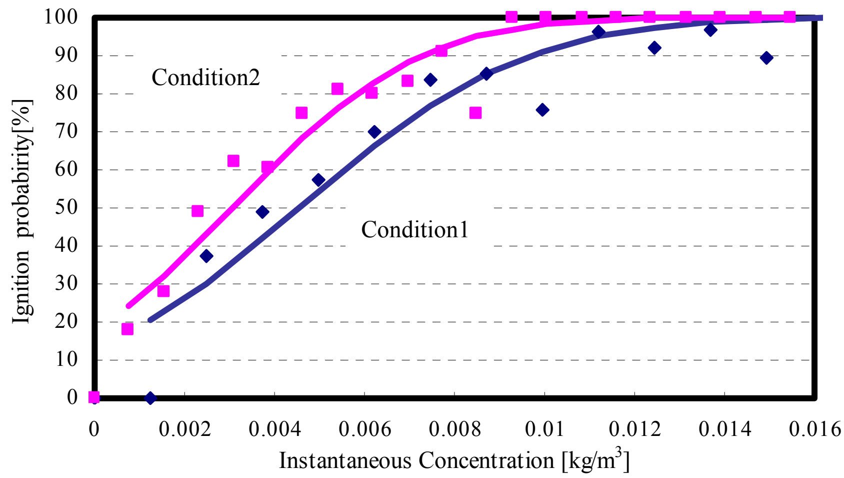

Fig.7 Ignition Probability of Test Spray

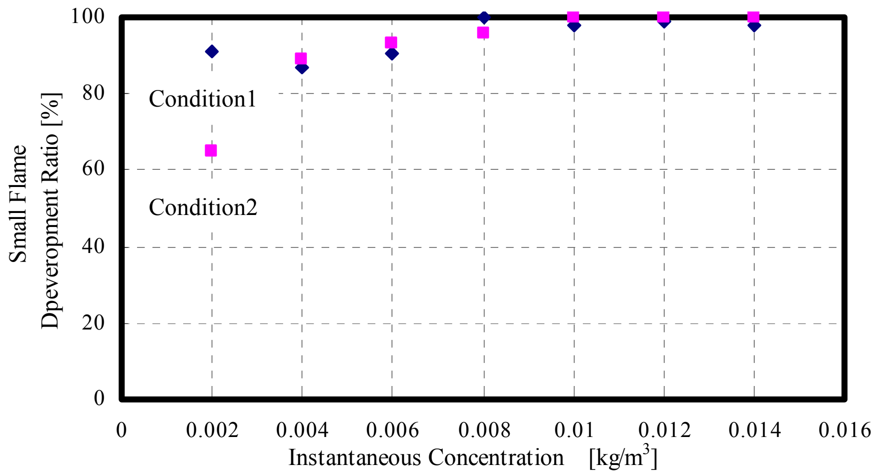

Fig.8 Variation of Small Flame Development Ratio

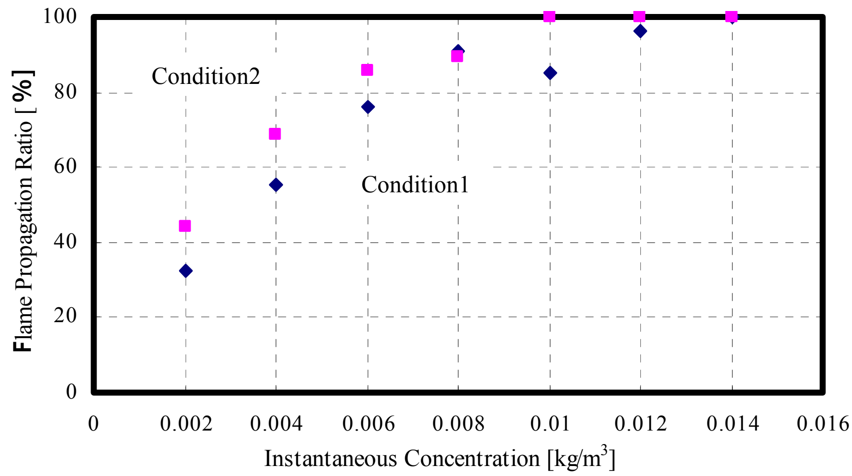

Fig.9 Variation of Flame Propagation Ratio

The spatial inhomogeneity of fuel spray in each condition is shown in Fig. 10. The keys show the average value of all examinations of each instantaneous concentration. And as is evident from Fig.10, condition 2 has weaker intensity of inhomogeneity than that of condition 1 at every observation scale.
The probability that a fuel particle exists in the circumstance becomes low in the condition which the intensity of inhomogeneity is too strong. As a result, the flame kernel cannot propagate, because of the insufficiency of fuel concentration for flame propagation. On the other hand, flame does not propagate if fuel particles are arranged completely homogeneously and distance between drops each other is equal to average distance, i.e. about 40-55 times of droplet diameter in those cases. These facts suggest that the optimum intensity of spatial inhomogeneity exists for flame propagation and ignition.

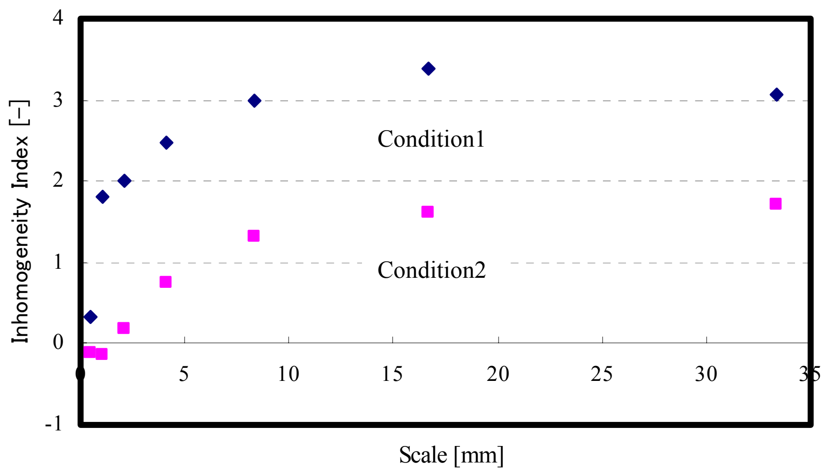

Fig.10 Inhomogeneity of Test Spray

6.2 Effect of inhomogeneity of fuel spray on flame formation

The maximum area of a luminous flame with the instantaneous concentration of fuel spray is shown in fig.11. The keys are the averaged values of maximum luminous frame area in each trial. The average of luminous frame area increases with the increase of instantaneous concentration of fuel spray. During the instantaneous concentration is rather lower, the values of condition 1 are larger but they are reversed at around 0.009kg/m^3 and one of condition 2 become larger. Considering that the flames of fuel spray change their formation by spatial arrangement of fuel drops, it is suggested that the difference among the values of the maximum luminous area is affected by the spatial inhomogeneity.
Fig.12 shows the relation between the characteristic scale and maximum area of a luminous flame. Here, the characteristic scale means the scale that the inhomogeneity index shows the maximum value at each trial. As is evident from Fig.12, the maximum area of a luminous flame indicates the maximum at some characteristic scale. It is suggested that the luminous flames are affected by the spatial inhomogeneity of fuel spray and the reverse in Fig.11 is caused by the effect of the scale of spatial inhomogeneity.

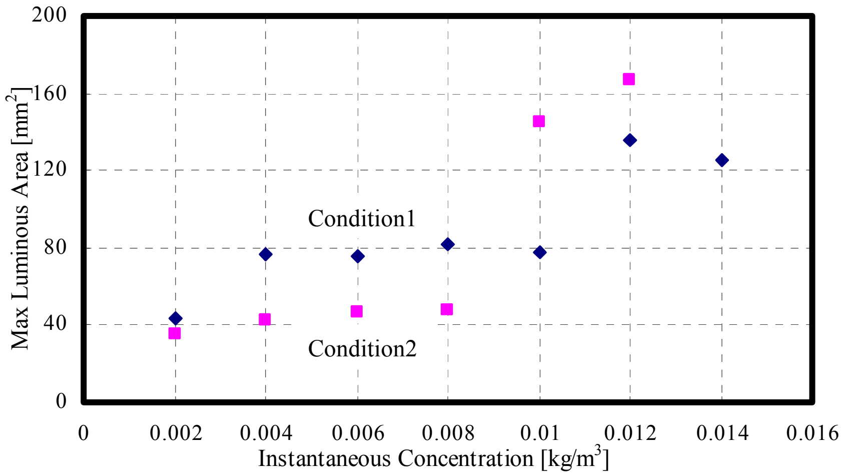

Fig.11 Relation between Max Luminous Area and Instantaneous Concentration

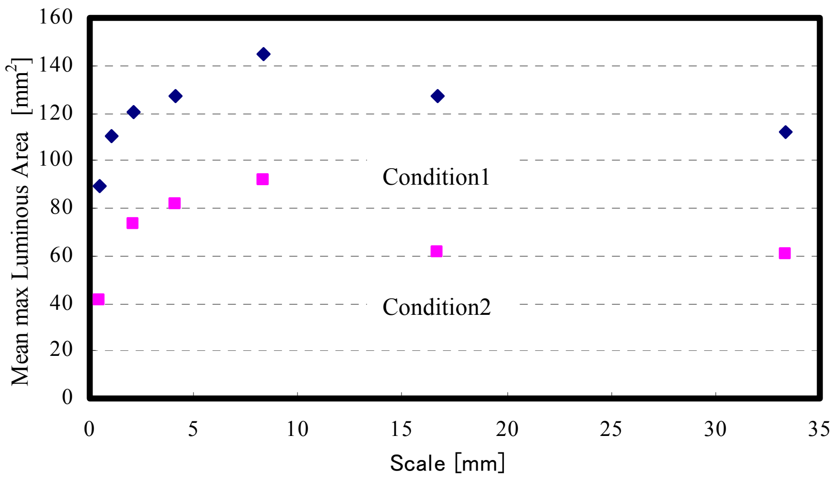

Fig.12 Relation between Max Luminous Area and Characteristic Scale

Figures 13 and 14 show the inhomogeneity of instantaneous concentration=0.008kg/m^3 spray and =0.010kg/m^3 one, respectively. At 0.008 kg/m^3, the maximum area of a luminous flame of condition 1 is larger than one of condition 2, but at 0.010 kg/m^3, one of condition 1 is smaller than one of condition 2 (see Fig.11). On the other hand, at 0.008 kg/m^3, the inhomogeneity index of condition 1 is always larger than condition 2, but at 0.010 kg/m^3, their inhomogeneity indexes are reversed around scale 7mm. This scale is very close to the value that the maximum luminous area shows maximum, i.e.8.3 mm (see Fig. 12). Those facts suggest that the maximum luminous area is affected by the inhoomogeneity index, and the optimum scale for the maximum area of a luminous flame exists.

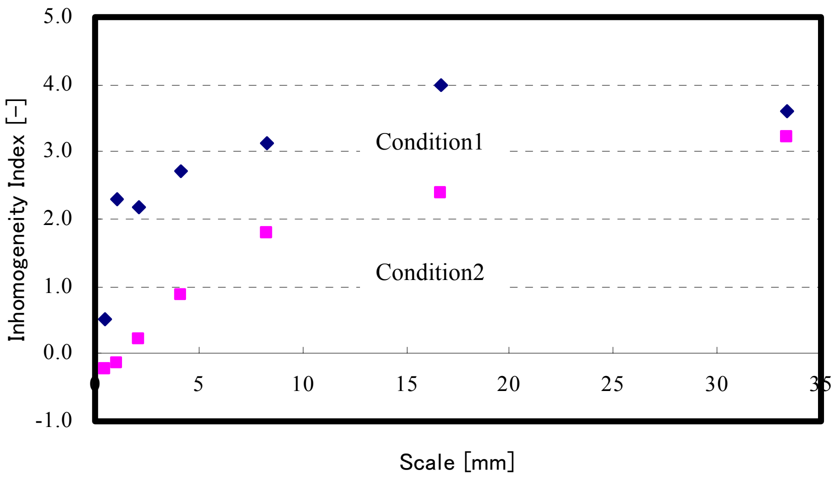

Fig.13 Inhomogeneity of Spray (0.008kg/m^3)

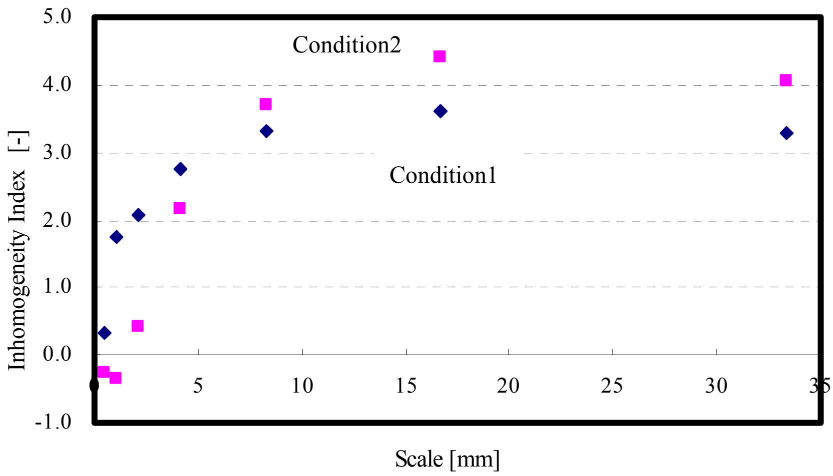

Fig.14 Inhomogeneity of Spray (0.010kg/m^3)

7. Conclusions

The influence of inhomogeneity of fuel spray on ignition phenomena was investigated. The results are summarized as follows;

(1) Spray ignition characteristics, especially ignition probability depends on intensity of the spatial inhomogeneity of fuel spray.

(2) The maximum area of a luminous flame depends on the scale of the spatial inhomogeneity of fuel spray.

From these results, it is suggested that the intensity and the scale of the spatial inhomogeneity of fuel spray affect the propagation of the flame and the luminous flame formation, and each one has the optimal value, when the instantaneous concentration is equal.

References

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