EFFECT OF DROP SIZE DISTRIBUTION OF FUEL SPRAY ON IGNITION PHENOMENON

***1 Koji TERASHIMA, *2 Naochika TOKUOKA**

***1 Brunel University, Uxbridge, Middlesex UB8 3PH, UK**
***2 KEIO Univ., 3-14-1 Hiyoshi Kohoku-ku Yokohama 223-8522, JAPAN**

ABSTRUCT

The effects of drop size distribution on ignitability of fuel spray are examined experimentally. Ignitability is evaluated under constant Sauter mean diameter and fuel spray concentration. Results clearly show that ignitability deteriorates with the increase of the span of drop size distribution. The effect of drop size distribution cannot expressed by any mean diameter. This result is not agree with related research. It may be caused by the deference of the definition of ignition. In addition, flame structure also changes by the drop size distribution. As the span of drop size distribution increases, the ratio of luminous flame area to total flame area decreases. It is supposed that the larger drops increase and it burnt insufficiently around electrodes.

INTRODUCTION

It is clearly that clarifying the ignition phenomenon is very important because it is the initial transient phenomena of combustion and plays an important role for successful combustion. Especially, fuel spray ignition is one of the unexplained combustion problems and is supposed to be elucidated in detail.

Mean diameter and drop size distribution are the common characteristic values of spray. However, those depend on the injection pressure that is the only control parameter in general continuous-type atomizer. Therefore, it is impossible to change those values independently. For the difficulty of drop size distribution control, most of researchers have ignored the effect of drop size distribution or tried to express the drop size distribution by mean diameter, although it is known that drop size distribution has significant effect on. For the point of view, some research projects have performed [1-4] as shown in Table 1. However, unified result has not been obtained yet and results are not agreed with each other.

In this research, it is aimed to clarify the effect of drop size distribution on spray ignition experimentally. Vibratory atomizer was used to produce sprays with various spans of drop size distribution under constant mean diameter. For controlling a spray, the drop size control technique developed by authors [5] was applied.

EXPERIMENTAL APPARATUS AND METHODS

Experimental Apparatus

Figure 1 shows the schema of the experimental apparatus and Table 2 shows the experimental conditions. The ignition trials were carried out more than 300 times for each condition. High-frequency discharged spark system was used as an ignition source to prevent from the fluctuation of ignition energy at each trial. Spray characteristics were measured by phase doppler particle anemometer (PDPA, TSI). Fuel spray concentration is measured by direct sampling method since it is difficult to measure spray concentration by any optical measurement methods. In this experiment, the distribution of time-averaged spray concentration at any local point within 30mm in diameter around spark electrodes was conditioned to be more than 80wt% of maximum concentration.

Table1 Recent researches for the effects of drop size distribution on spray ignition and combustion phenomenon

PERSON	OVERVIEW	RESULT
KIDO and MIZUTANI [1]	Comparison of flame propagation velocity between mono-dispersed and poly-dispersed sprays	Combustibility of mono-dispersed spray is higher than that of poly-dispersed spray
S.K.AGGARWAL and W.A.SIRIGNANO[2]	Numerical analysis of ignition delay and ignition energy of poly-dispersed decane spray	Sprays taht have same D_{20} can consider as same.
D.DIETRICH and I.NAMER[3]	Measurement of minimum ignition energy of nDECANE bi-dispersed spray	Sprays taht have same D_{32} can consider as same.
J.BOSSARD and R.PECK[4]	Measurement of combustion characteristics of poly-dispersed spray	Spray with narrower drop size distribution indicates higher combustion efficiency and heat release rate than those of wider one.

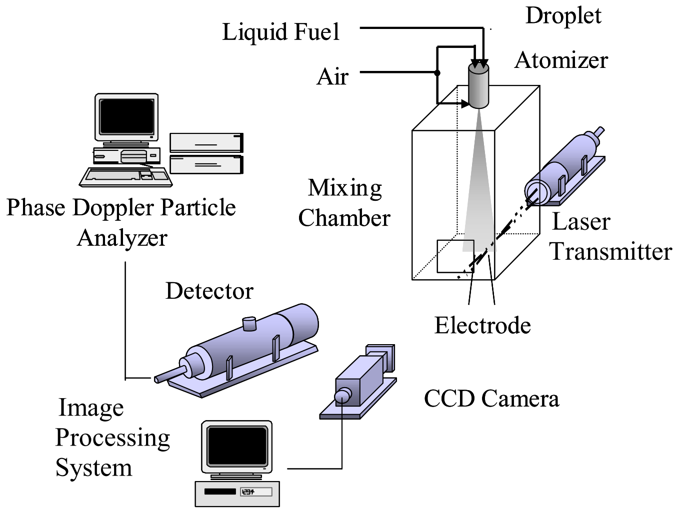

Fig.1 Experimental apparatus

Table.2 Experimental conditions

Experiment	Condition1	Condition2
Fuel	n-Decane	
Droplet diameter	D_{32}: 118 μm	D_{32}: 120 μm
Drop size distribution	σ =11.3~17.9 μm	σ =9.8~16.9 μm
Time-averaged fuel spray concentration	3.07×10^{-3} kg/m^3	2.49×10^{-3} kg/m^3
Mean spray velocity	0.28m/s	
Mean air velocity	0.10~0.11m/s	
Temperature Pressure	Atmospheric temperature Atmospheric pressure	
Igniter	High-frequency discharged spark System (25kHz, 50ms, 0.8J)	
Electrode	Gap: 3mm, Tip: slant-cut	
Ignition trial	300 times for each condition	

Fuel vapor concentration was also measured with direct sampling method and analyzed by gas chromatography. However, it was negrected since it was very lean and the effect of vapor may be little. Images of propagating flame after ignition were obtained by CCD and analyzed.

Drop Size Distribution Control

In this study, the impressed signal to the vibratory atomizer is controlled to produce the target spray. This control technique has been developed by authors [5]. The test atomizer is shown in Fig.2. A pair of piezoelectric ceramic vibrators is attached to the atomizer body and actively vibrates liquid jet. The signal with square wave whose frequency fluctuates periodically is impressed to the vibrators. Liquid jet disintegrates to drops according to the signal. Therefore, the characteristics of drops change periodically. Sprays with various combinations of drop size distribution and mean diameter can be generated by controlling characteristics of impressed signal. Produced drops are arrayed with narrow distances so that diffusion air is used to prevent drops from recombining each other. By this technique, the characteristics of spray change periodically. However, periodical change decays quickly during drops' flight process since drug force differs according to drop size. The variation of Ignition Probability by the periodicity is shown in Fig.3. In this case, the sweep time of impressed signal is 10ms, ignition point 500mm from atomizer and spark duration 50ms. Spark timing was synchronized with the spray's periodicity. Result clearly indicates that the periodicity does not affect to Ignition Probability in this test.

Drop size distribution is expressed by the relative standard deviation of drop size and Sauter mean diameter for mean diameter.

Figure 4 shows the drop size distributions of condition 1 (average fuel spray concentration 3.07×10-3kg/m3) as examples. It is clearly indicated that the span of drop size distribution can be changed gradually by this technique.

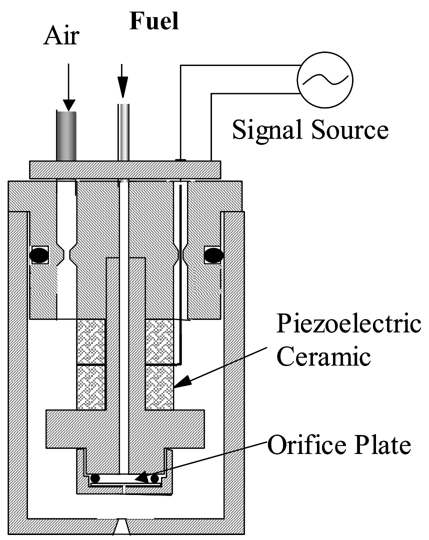

Fig.2 Drop size controllable atomizer

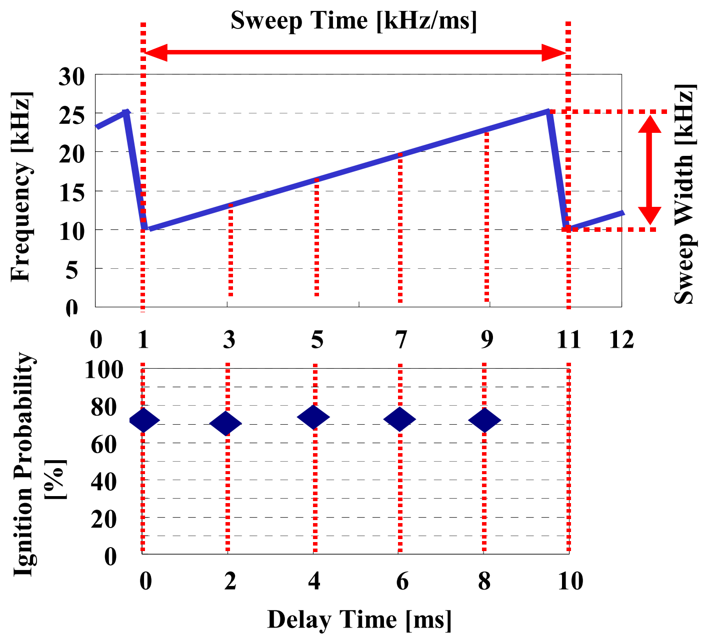

Fig.3 Variation of ignition probability with delay time

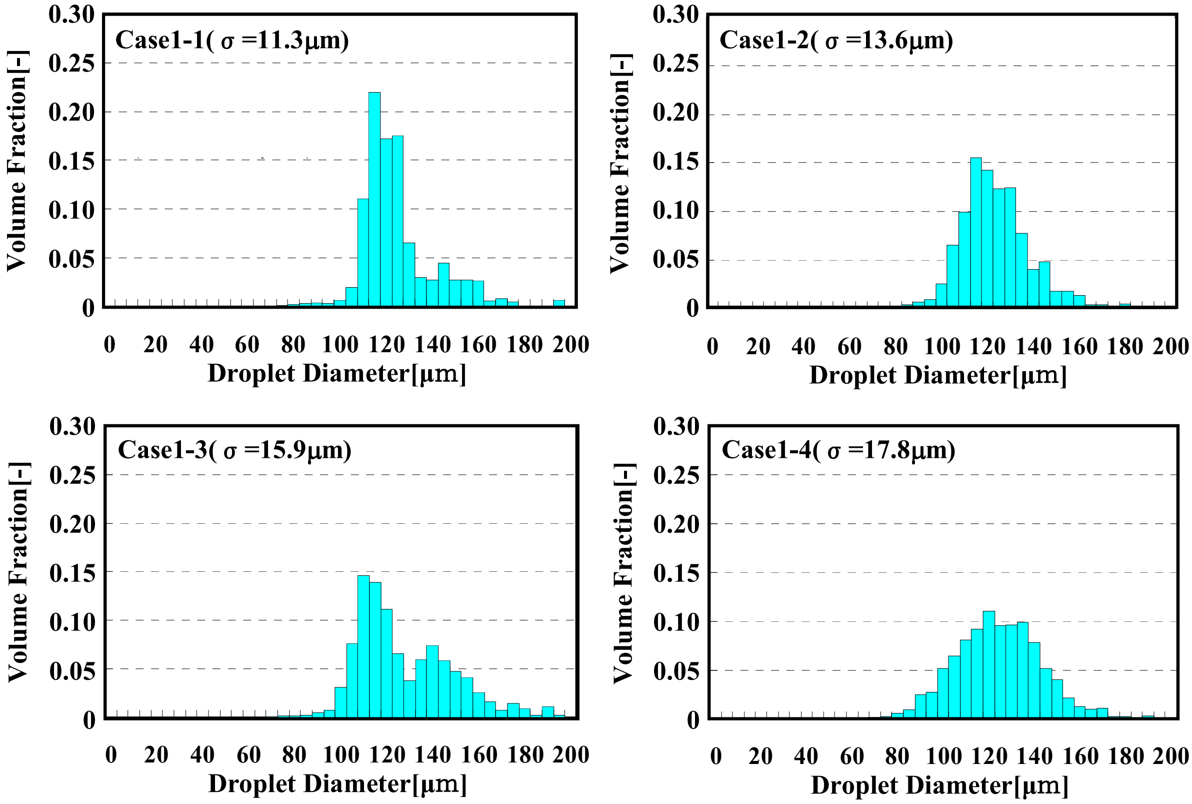

Fig.4 Typical drop size distributions (Condition1)

Definition of Ignition

A flame observed after ignition was classified into the following 5 patterns by visual observation.

(a) Flame propagated over 50mm in diameter.	(Flame Pattern 1)
(b) Flame propagated over 30mm in diameter.	(Flame Pattern 2)
(c) Flame propagated about 30mm in diameter.	(Flame Pattern 3)
(d) Flame propagated within 30mm in diameter, and is extinguished.	(Flame Pattern 4)
(e) Flame kernel was observed, but not propagated.	(Flame Pattern 5)

In this research, success ignition is defined that a flame is observed and it exceeds more than 30mm (Flame patterns 1-3). "*Ignition Probability*" is calculated as the ratio of nomber of Success to the one of trials. Likewise the cases that flame propagetes within 30mm (the Flame patterns 1-4) is called "*Small Flame Formation*" and that flame does not propagete (the flame pattern 5) "*Initial Flame Formation*". Each case was counted independently and their probabilities were calculated. In addition, the probability that small flame appears and it propagetes and exceeds more than 30mm is calculated and it is called "*Small Flame Propagete ratio*". Namely, it is the ratio of Ignition Probability to Small Flame Formation. Ignitability phenomena is discussed from the changes of these four evaluation parameters.

RESULTS AND DISCUSSIONS

Effect of Drop Size Distribution on *Ignition Probability*

In this study, the changes of evaluation parameters by the span of drop size distribution were discussed. The experiment was carried out under constant Sauter mean diameter and two kinds of average spray concentrations and 4 kinds of the spans of drop size distributions. Figure 5 shows the change of Ignition Probability. It is considered in general that ignitability depends on Sauter mean diameter and ignitability does not change by drop size distribution when both Sauter mean diameter and fuel spray concentration are constant. However, as a result, Ignition Probability decreases with the increase of the span of drop size distribution although Sauter mean diameter keeps constant. This tendency is remarkable when the average fuel spray concentration is high. This result also suggests that any other mean diameters calculated from Eq(1) are not suitable to represent ignitability of fuel spray because any other mean diameters changes little within the degree of change of drop size distributions in this study. Nevertheless, Ignition Probability degreases with the increase of the span of drop size distribution.

$$d_{xy} = \left(\frac{\sum_i d_i^x}{\sum_i d_i^y} \right)^{1/(x-y)} \quad \text{(x=0,1,2 or 3 , y=0,1,2 or 3)} \qquad (1)$$

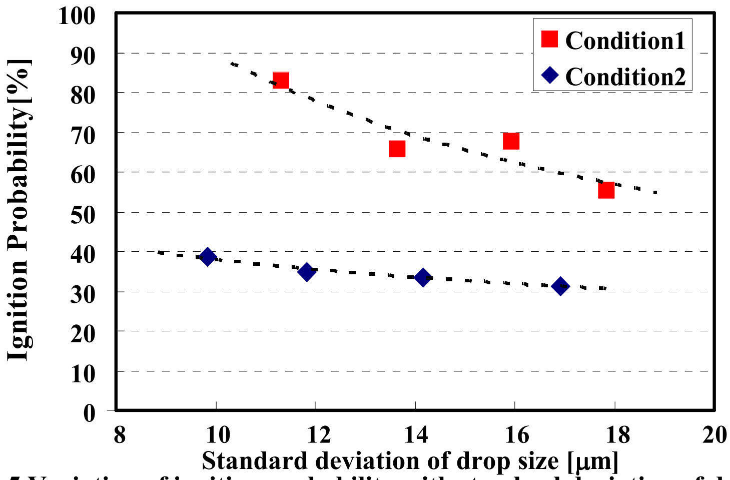

Fig.5 Variation of ignition probability with standard deviation of drop size

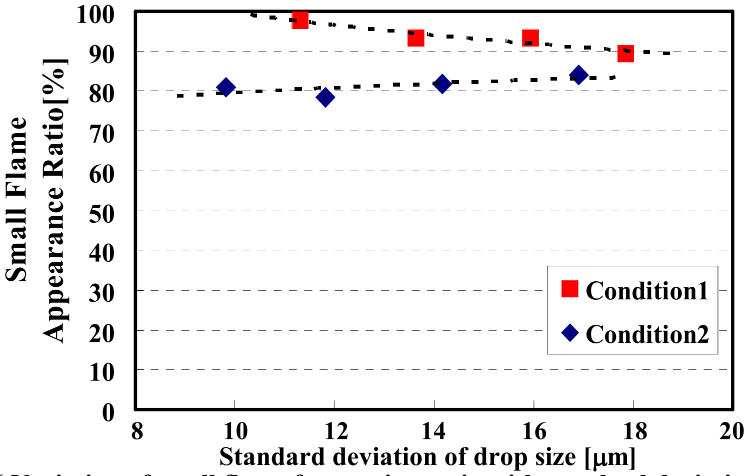

Fig.6 Variation of small flame foramation ratio with standard deviation of drop size

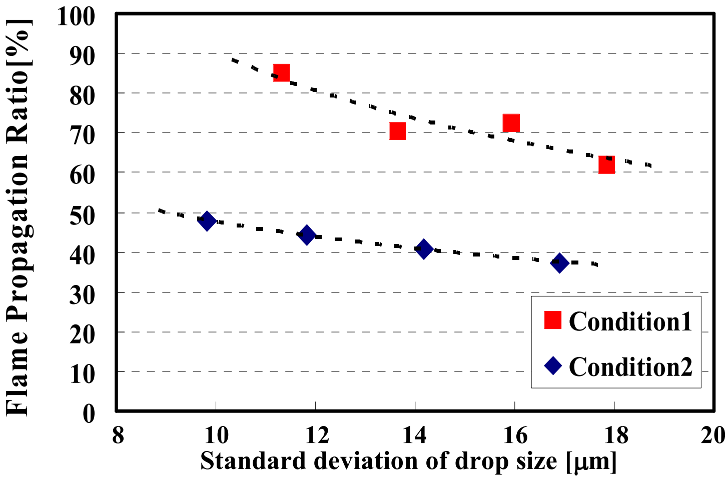

Fig.7 Variation of flame propagation ratio with standard deviation of drop size

The Effect of Drop Size Distribution on *Small Flame Formation Ratio* and *Small Flame Propagation Ratio*

The effect of drop size distribution on Small Flame Formation ratio and Small Flame Propagation ratio are shown in Figs.6 and 7, respectively. When the span of drop size distribution increases under constant average fuel concentration and Sauter mean diameter, number density slightly increases. The increase of number density causes the increase of ignitability. However, Small Flame Formation Ratio changes little as shown in Fig.6. It can be thought that the effects of drop size distribution and number density are cancelled each other.

On the other hand, Small Flame Propagation Ratio is evidently decreases with the increase of the span of drop size distribution as shown in Fig.7. This tendency is similar to Ignition Probability. That is to say, possibility of flame propagation is the dominant factor of ignitability.

Moreover, from the tendencies of those parameters, the difference between related research and us is caused by the definition of ignition. If Small Flame Formation was applied as definition for success ignition, our results would be same as result obtained by D.DIETRICH[3] or general consideration, in other words, the effect of drop size distribution can be considered with Sauter mean diameter. This presumption is supported by the fact that the diameter of their test section is about 20mm and fairly small when compared to our test device.

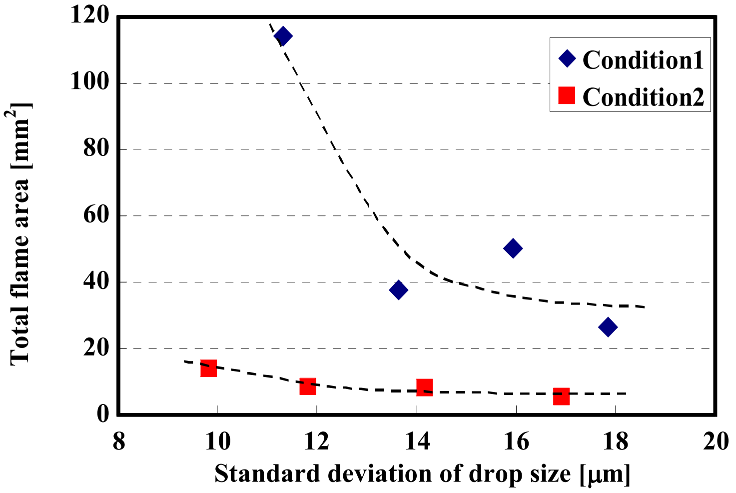

Fig.8 Variation of total flame area with standard deviation of drop size

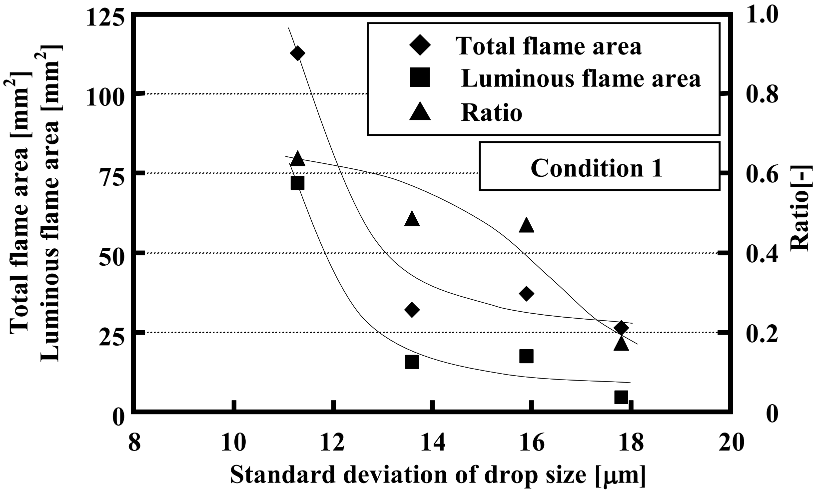

Fig.9 Variation of flame around luminous flame area of condition1 with standard deviation of drop size

The Effect of Drop Size Distributions on Flame Structure

The change of flame structure by the deference of drop size distribution is evaluated. In every ignition trial, flame image around spark electrodes was taken at 130ms after discharge. From those images, average projected areas of both total flame and luminous flame for successful ignition cases were measured. Here, luminous flame area is a part of flame, so that the total flame area includes the luminous flame area. The results are shown in Figs.8 and 9. Figure 8 shows the total flame area of Conditions 1 and 2 and Fig. 9 is the results of Condition 1. In case of Condition 2, luminous flame area is not indicated because it was hardly occurred. In both conditions, the total flame areas in both cases and luminous frame area of condition 1 decrease with the increase of the span of drop size distribution. In addition, the ratio of luminous flame area to total flame area also decrease with the increase of the span of drop size distribution. To consider this result, the formula of group combustion number[6] which is well known as an indicator of spray combustion condition is shown below.

$$G = 0.15\mathrm{Le} n_T^{2/3} / S \tag{2}$$

$$\begin{aligned} S &= (L/10d)/(1+0.276\mathrm{Sc}^{1/3}\,\mathrm{Re}^{1/2}) \\ &= (L/10d)/(\mathrm{Sh}/2) \end{aligned} \tag{3}$$

When G number is higher, drops burn as group combustion, so that the ratio of luminous flame area to total flame area increases.

By introducing assumptions (Le=1,Sh=2), Eq.(2) can be rewritten to,

$$G = 1.5V^{2/3} dN \tag{4}$$

$$N = (1/L)^3 \tag{5}$$

$$V = N / n_T \tag{6}$$

As the drop size distribution increases, the number density increases slightly and the cluster becomes larger because inhomogeneity of spray decreases. Therefore, the increase of the span of drop size distribution means the increase of luminous flame ratio. However, the result indicates opposite. To decrease G number, it can be a reason that larger drops that do not relate to spray combustion so much exist in spray. Larger drop needs much time and quantity of heat to evaporate and to burn than that of smaller drop. Thus larger drops burn insufficiently and combustion region in spray decreases and as a result, ignition probability decreases.

CONCLUSION

The effects of drop size distribution on ignitability of fuel spray are obtained experimentally. Ignitability is evaluated under constant sauter mean diameter and fuel spray concentrations. Results clearly show that ignitability deteriorates with the increase of the span of drop size distribution. And flame structure also changes by the drop size distribution. As the drop size distribution increases, the ratio of luminous flame area to total flame area decrease. In addition, the effect of drop size distribution cannot be expressed by any mean diameter. As a cause of this, the increase of larger drops can be suggested.

NOMENCLATURE

d	Drop size	[m]
G	Group combustion number	[-]
L	Distance between drops	[m]
N	Number density of spray	[1/m^3]
n_t	Drop number in cluster	
S	Non-dimensional drop distance	[-]
V	Cluster volume	[m^3]
i, x, y	Integral number	

REFERENCES

1 Y. Mizutani,S. Kido, Combustion Characteristics of Mono-dispersed and Poly-dispersed Spray (JAPANESE),Journal of JSME, 1978, pp47-49

2 S. K.AGGARWAL, W.A.SIRIGNANO,Ignition of Polydisperse Sprays: Importance of D20,Combustion science and technology, 1986,vol.46, pp.289-300

3 Dietrich,D.L., Cernansky,N.P., Somashekara,M.B., and Namer,I., Spark Ignition of a Bidisperse n-Decane Fuel Spray, Twenty-third Symposium (Int.) on Combustion, The Combustion Institute (1990), p.1383-1389

4 J.A.Bassard,R.E.Peck, Droplet Size Distribution Effect in Spray Combustion, Twenty-sixth Symposium(International) on combustion,Combistion institute,1996,pp.1671-1677

5 K. Terashima,D. Shinohara,M. Nakagawa,N. Tokuoka, Development of Drop Size Dstribution Control Technique, ICLASS2003

6 Chiu,H.H., Kim,H.Y., and Croke,E.J., Internal Group Combustion of Liquid Droplets, Nineteenth Symposium (Int.) on Combustion, The Combustion Institute (1982), p.971-980