ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-14-1

THE STUDY OF SPRAY STRUCTURE BY NUMERICAL SIMULATION - THE EFFECT OF INTERACTION BETWEEN DROPLETS ON SPATIAL INHOMOGENEITY -

Shimpei HAYAKAWA[1], Shintaro OKAJIMA[2], and Naochika TOKUOKA[3]

[1]Keio University Graduate School, Japan
[2] TonenGeneral Sekiyu K.K., Japan
[3]Department of Mechanical Engineering, Keio University, Japan

ABSTRACT

Purposes of atomization are to accelerate physical phenomena by increasing surface of droplet. Though diffusion and a mixing process of spray, interaction between drops and ambient airflow forms spatial inhomogeneity of drop distribution. This gives effects on the results technology using spray. This paper aims at clarifying the effect of different sized drops on spatial inhomogeneity in the mixing and diffusing processes of multi-dispersed spray. In order to obtain the three dimensional space state and also to eliminate the atomizer characteristics, we analyzed by numerical simulation. We used CFD, and selected LES model for the turbulence model of ambient airflow and Lagrange evaluate system model for drops. And then we used the two-way coupling method for considering the exchange of momentum between continuous phase and discrete phase. The spatial inhomogeneity is expressed by inhomogeneity index that is based on volume and indicates deviation of the position and volume of drops. Multi-dispersed spray which has normal distribution diameters of drops was analyzed. The spatial inhomogeneity was evaluated by volume based inhomogeneity index. As results, it is ascertained the spatial inhomogeneity of multi-dispersed spray has relationship with Stokes number of drop with mode diameter.

1. INTRODUCTION

1.1 Purpose

The purposes of atomization are to accelerate physical phenomena or chemical reaction by increasing surface of droplet. Various inhomogeneity like drop size distribution, density, concentration, the spatial arrangement, etc. exist in spray. Especially spatial inhomogeneity of droplet distribution that formed interaction between droplets and ambient airflow though diffusion and a mixing process of spray, affects on both accelerating and obstructing the intentioned phenomena. So this gives effects on the results of technology using spray such as combustion, painting, etc. For example, spatial inhomogeneity greatly influences the flame propagation in the ignition phenomenon on the initial stage of the spray combustion in fuel lean condition. Therefore, it is important to analyze spatial inhomogeneity of spray for high efficiency use.

In this study, it aims to make clear the effect of drop size distribution on the structured inhomogeneity in spray flow.

1.2 Specific Objectives

In the past, some of authors conducted the structure of spray flow and transition of inhomogeneity in fuel spray and air mixture experimentally [1]. In that study, two-dimensional distribution of droplets was analyzed by recording the vertical cross section of spray by CCD camera. However, the spatial distribution of droplets and the ambient airflow are three dimensional phenomena.

And it was proved that spatial inhomogeneity of droplet forms the anisotropic structure toward flow direction. So in order to clarify this spatial spray structure, it needs to record the three-dimensional spatial distribution of droplets.

Moreover in the experimental way, it is quite difficult to eliminate the atomizer characteristics and to measure the diameter and the spatial distribution of droplets at the same time. Therefore, it is difficult to consider the spray which has wide range of diameter distribution. On the other hand, the analysis by numerical simulation is possible to analyse three-dimensionally and spray with drop size distribution.

In this study, the spray-air flow that spray with various characteristics was injected into airflow, calculated by numerical simulation and analyzed the transition of inhomogeneity three-dimensionally. The inhomogeneity was evaluated by 'Inhomogeneity Index'. The modeling software FLUENT 6.3 (ANSYS Inc.) was used for numerical simulation. We modelled the field by setting up a turbulent lattice in the upstream. Surface injection was set up to inject drops uniformly in order to eliminate the effect of the atomizer to spatial inhomogeneity.

2. FORMER RESEARCH

Authors have reported the effects of interaction between droplets on inhomogeneity of air-particle flow [2][3]. In the report, mono-dispersed spray, mixture of two or three mono-dispersed sprays with different sizes are injected into air flow and the transition of inhomogeneity was discussed. The results related to this study are summarised. In that report, inhomogeneity was evaluated by the Inhomogeneity Index based on drop number because of mono-dispersed spray. The tendency of one based on drop number H_n and on drop volume H_v is similar.

2.1 Spatial Inhomogeneity in Mono-Dispersed Spray

Transition of spatial inhomogeneity along the stream with different sized droplets in mono-dispersed spray is shown in Fig.1. 5μm and 20μm drop's Inhomogeneity Index slightly decreases with mixing time. Then 50μm and 70μm drop's one become constant with mixing time. It is because they have small Stokes Number St less than 1, and follow the airflow which turbulent intensity slightly decreases along the stream, too. It is thought that these droplets are in the fully developed stage at the diffusion and mixing process of spray. On the other hand, in case of 100μm drops, viscosity of air and inertia force of drops is balanced or inertia force is slightly dominant and as a result Inhomogeneity Index increases as the diffusion process proceeds. Further more, 100μm droplets take the maximum value. This indicates that droplets which behave unstable since the air viscosity and drop inertia force influence equally (St=1), form the most inhomogeneous spatial distribution. Since 140μm and 200μm droplets have large St more than 1, they are under inertia force dominant condition. Then they flow with the initial state because they move independently from ambient airflow.

To conclude, the formation of the spatial inhomogeneity in spray can be divided into three patterns as Stokes Number. When St is less than 1, transition of spatial inhomogeneity is greatly influenced by ambient airflow state. On the contrary, when St is larger than 1, it is independent from ambient airflow state. Moreover, when St is around 1, spatial inhomogeneity is formed the most uneven by both effect of airflow and inertia force.

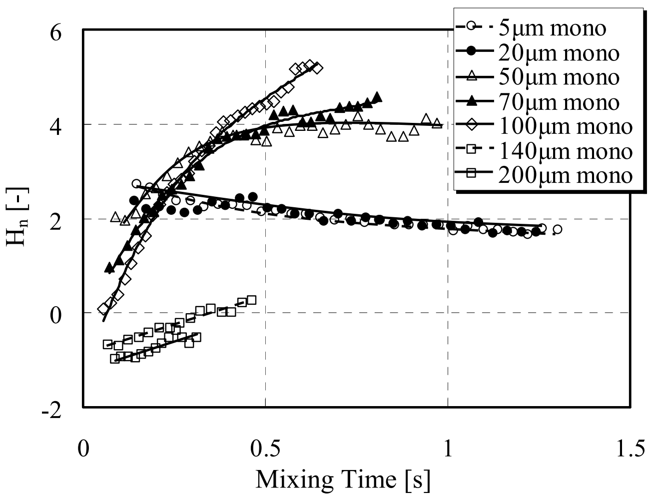


Fig.1 Transition of Inhomogeneity Index (Mono-Dispersed Spray)

2.2 Spatial Inhomogeneity in Bi-Modal Mono-Dispersed Spray

For study of the interaction of drops, bi-modal mono-dispersed spray was analyzed the behaviour of each sized drop individually. The result was shown with the case of mono-dispersed spray only. Comparison of transition of Inhomogeneity Index between mono-dispersed spray and bi-modal mono-dispersed spray are shown in Figures 2 and 3.

In case of 50-100μm bi-modal mono-dispersed spray, 50μm droplets in bi-modal mono-dispersed spray is more uneven than 50μm droplets in mono-dispersed spray. On the other hand, 100μm droplets in bi-modal mono-dispersed spray is more uniform than 100μm droplets in mono-dispersed spray. The reason for this is the exchange for kinetic energy of drops and ambient airflow. 50μm ones follow ambient airflow more than 100μm ones. So 50μm ones follow turbulent of ambient airflow that is formed by 100μm ones, and become more uneven. And 100μm ones is more uniform because kinetic energy of them is deprived by ambient airflow.

In case of 100-200μm bi-modal mono-dispersed spray, 100μm droplets in bi-modal mono-dispersed spray is more uneven than 100μm droplets in mono-dispersed spray. However, the spatial inhomogeneity of 200μm ones in bi-modal mono-dispersed spray is the almost same as 200μm ones in mono-dispersed spray. The inhomogeneity index of 100μm ones in bi-modal mono-dispersed spray that their St is around 1 is influenced from turbulence of airflow is formed by 200μm ones, and increases as compared with 100μm ones in mono-dispersed spray. On the contrary, 200μm ones aren't affected by turbulence of airflow since they move under inertia force dominant condition. And spatial inhomogeneity of them is practically constant as they move together same diameter drops and even various diameter drops either.

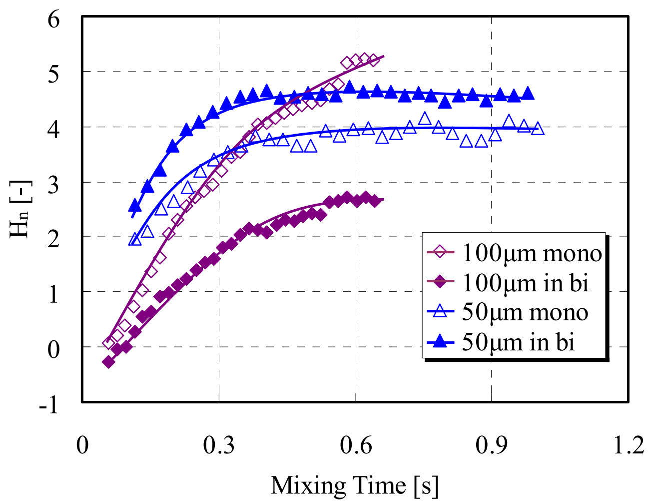


Fig.2 Transition of Inhomogeneity Index (50-100μm Bi-modal Mono-Dispersed Spray)

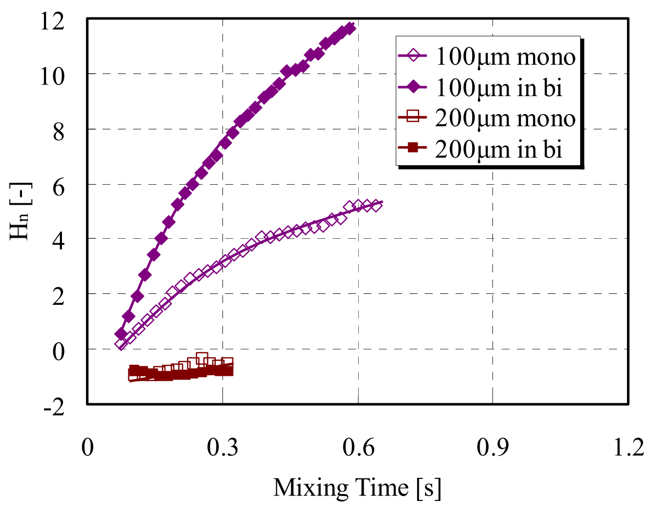


Fig.3 Transition of Inhomogeneity Index (100-200μm Bi-modal Mono-Dispersed Spray)

3. ANALYSIS AND MODELLING

3.1 Inhomogeneity Index

The spatial inhomogeneity of spray is estimated by using the Inhomogeneity Index defined by Czainski [4].

The Inhomogeneity Index means spatial droplets dispersion normalized by random state. The Inhomogeneity Index H is expressed as follows:

$$H = \frac{h - E(h)}{\sigma_h} \quad (1)$$

Czainski's Inhomogeneity Index is based on droplet number. In this study, however, drop size of spray has distribution. So we transformed this Index H_n into the Inhomogeneity Index H_v that is based on total volume of droplets [5]. Each value of Equation (1) of index H_v is expressed as follows:

$$h = \mu / E(\mu) \quad (2)$$

$$\sigma_h = \left(\frac{2\left(V - \pi D_{32}^3 / 6\right)}{V(\kappa - 1)} \right)^{1/2} \quad (3)$$

Where,

$$\mu = \sum_{i=1}^{\kappa} \left(v_i - \frac{V}{\kappa} \right)^2 \quad (4)$$

$$E(\mu) = V(\kappa - 1) / \kappa \quad (5)$$

Inhomogeneity index indicates lager than 0 when droplets distributes more uneven than one being random. On the contrary, drop size distribution is more uniform than the case of being random, inhomogeneity index becomes smaller than 0. If the droplet distribute at random, inhomogeneity index is 0.

Inhomogeneity index is estimated by droplet number or volume of droplets in each cell that the analysis volume is divided equally into any size. The size of cell is called 'cell size' and used as measurement scale. Especially, when the cell size becomes equal to the characteristic scale of droplet cluster, the inhomogeneity index indicates maximum. This cell size is defined as Characteristic Scale CS that signifies the cluster scale.

From the property of inhomogeneity index, the inhomogeneity index increases with the increase of total volume of droplets in analysis volume. Therefore, it is important to keep the volume same when the inhomogeneity indices obtained at deferent conditions are compared.

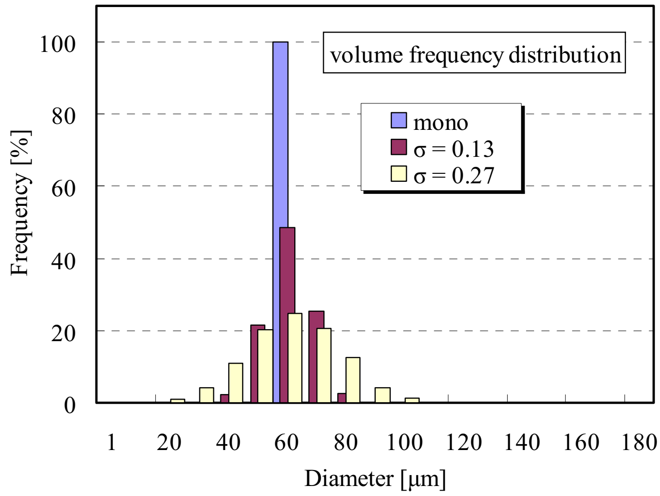
3.2 Drop Size Distribution

Therefore, it aims to make clear the effect of drop size distribution on inhomogineity in spray flow because general spray has drop size distribution. It is well known that the spray can be expressed by the log-normal distribution in most cases. However, the normal distribution is adopted because it is easy to deal with and can be indicate the span of distribution by deviation. The normal drop size distribution function *f(d)* is expressed as follows:

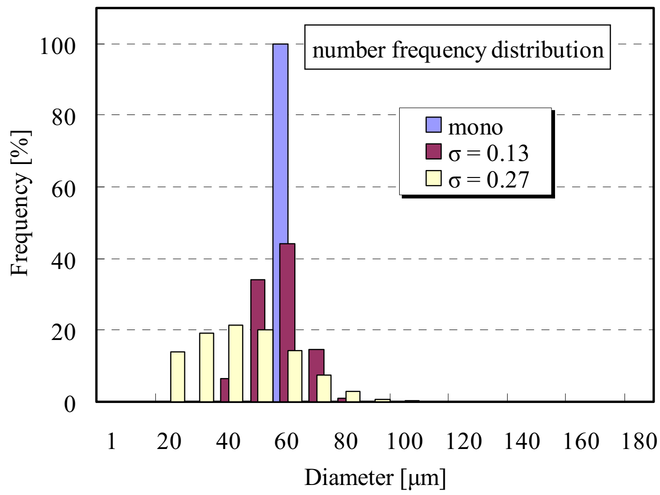
$$f(d) = \frac{1}{\sqrt{2\pi}\sigma / D} \exp\left(- \frac{(d - D)^2}{2(\sigma / D)^2} \right) \quad (6)$$

The effect of drop size distribution on inhomogeneity is estimated by changing σ and D.

Figure 4 shows the distribution with D_{mode}=60μm as an example. The upper one is volume frequency distribution and the lower number one. Droplet volume distribution is assumed to be the normal distribution. Therefore, the number of smaller droplets increases when it is converted to the droplet number distribution. The deviation σ and the mode diameter D_{mode} are different in other cases as shown in Table 2.



(a) volume frequency distribution



(b) number frequency distribution

Fig.4 Drop Size Distribution (D_{mode}=60μm)

3.3 Modelling

Table 1 shows the calculating conditions. We used LES model for the turbulence model and Lagrange evaluate system model (called DPM model) for droplets (discrete phase). The exchange of momentum between continuous phase and discrete phase are considered by two-way coupling method. Moreover, the breakup and collision of droplets, the heat and mass exchange and evaporation were ignored because the volume fraction of droplets is less than 0.01% and the temperature is not high. It is known that the interaction between droplets can not be disregarded when the volume fraction is less than 10% [5].

Modelling for calculation is shown in Fig.5. The upper surface of a rectangular parallelepiped chamber (60×60mm) is defined as the inlet with air velocity of 0.25 m/s and bottom surface as the outlet with 0 Pa in gage pressure. Side surface is defined as periodic boundary in order to ignore the effect of wall. Turbulent lattice of 10 mm in diameter and 20 mm in interval was sat upstream for producing turbulent. In order to eliminate the effect of the atomizer on spatial inhomogeneity, Injected volume of droplets is uniform over cross section at injecting surface Z=0.

Test volume is 40×40×40mm. The spatial inhomogeneity index is evaluated by the average value of 100 samples. The t=0 is defined the time when droplets are injected into airflow at Z=0 and the transition of inhomogeneity index from upstream to downstream are measured the relation between mixing time and spatial inhomogeneity are examined.

Table 1 Analysis Conditions

Turbulent Model	LES(Smagorinsky-Lilly Model)
Multiphase Model	DPM(Random Walk Model)
Continuous Phase	Air
Discrete Phase	Water droplets
Calculating Volume	60×60×530 [mm^3]
Number of Cells	30×30×265
Time Step	0.004 [s]
Analysis Volume	40 mm Cube [mm^3]
Calculating Flow Time	20 [s]
Sampling Number	100

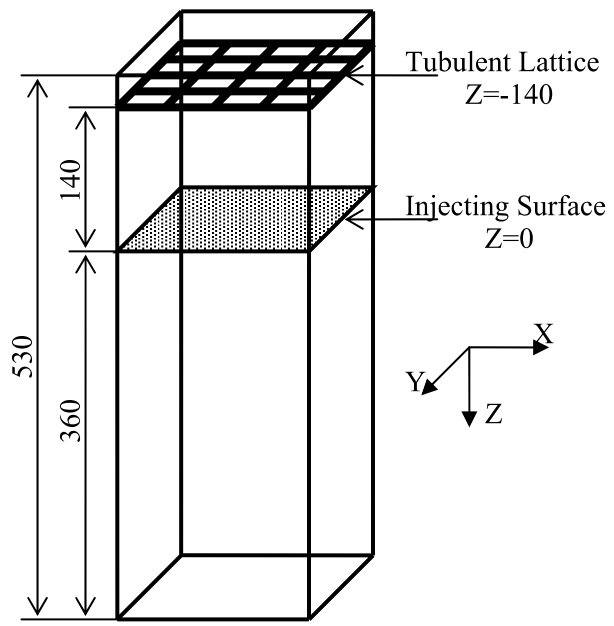


Fig.5 Modeling for calculation

3.4 Calculation Conditions

Table 2 shows the conditions of spray. D_{mode} and σ are the mode drop size and the standard deviation based on drop volume distribution respectively. σ=0 means mono-dispersed spray. Surrounding air velocity is xx m/s and drop velocity is the theoretical terminal one to eliminate the effect of change of relative velocity between droplet and airflow. Furthermore, the total volume of droplets keeps equal at each experiment because of inhomogeneity index depends on total volume.

Table 2 Condition of Spray

D_{mode} [μm]	σ [μm]
60	0.0(mono), 0.13, 0.27
100	0.0(mono), 0.15, 0.35
140	0.0(mono), 0.07, 0.14

4. RESULT AND DISCUSSION

4.1 Effect of Drop Size Distribution on Inhomogeneity

The inhomogeneity index H_v of spray with D_{mode}=60, 100, 140μm are shown in Figs.6 to 8 respectively.

In case of D_{mode}=60 μm, inhomogeneity index converges some value with mixting time and is nearly equal even if the deviation σ increases. As shown in Fig.1, the inhomogeneity index indicates maximum at 100μm that Stokes number is nearly 1 and decreases with the increase of deviation from 100μm. In case of mixture of larger droplets and smaller one, inhomogeneity of smaller droplets increases and of larger one decreases by interaction. In case of Fig.6, the change of inhomogeneity is canceled each other though inhomogeneity of droplets less than D_{mode} increases and one of more than D_{mode} decreases. Consiquentry, inhomogeneity index becomes even if the deviation of distribution increases. Futhermore, Stokes number of 60μm droplet is around 0.3 and follows dasily to air flow. As a result, inhomogeneity index of small droplets is influenced hardly by drop size distribution.

In case of D_{mode}=140μm, inhomogengeity index increases with the increase of mixing time and σ as shown in Fig.7. The tendency of behaivior of smaller droplet and larger one comparing with 140μm are same as the case of D_{mode}=60 μm. With respect to interaction of each different size droplets, smaller droplet becomes more uneven by effect of larger droplet. Larger droplet, however, moves independently because its stokes number is large. As a result, inhomogeneity index increases with the increase of σ.

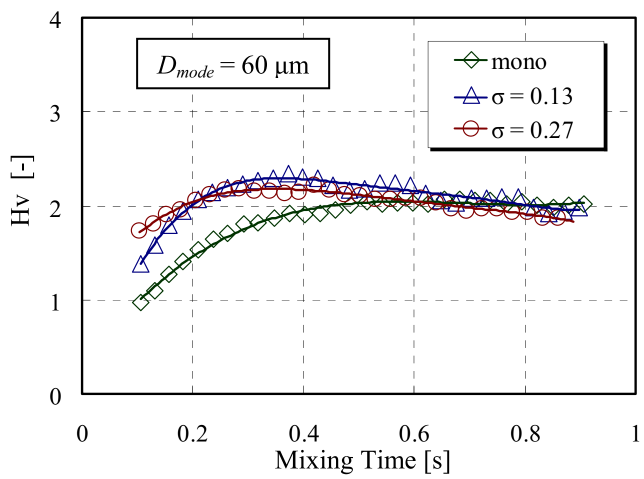


Fig.6 Transition of Inhomogeneity Index (D_{mode}=60μm)

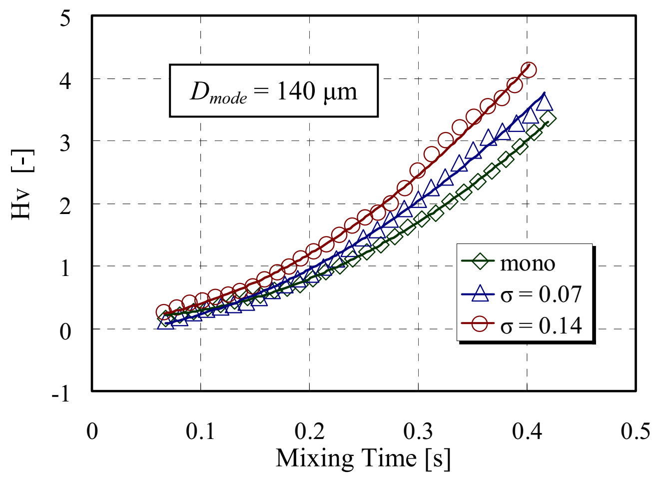


Fig.7 Transition of Inhomogeneity Index (D_{mode}=140µm)

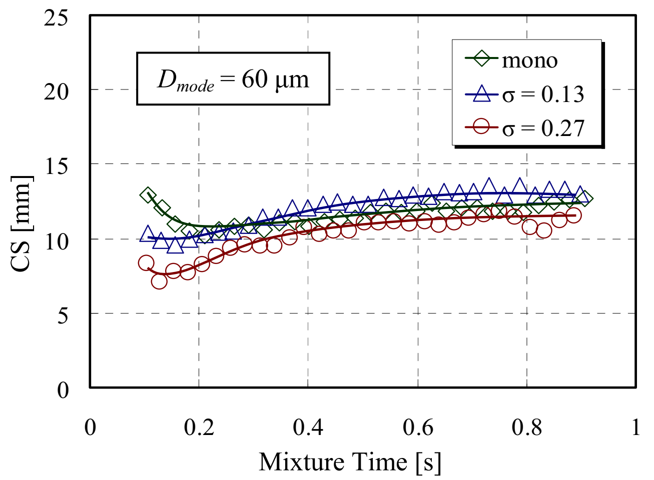


Fig.9 Transition of Characteristic Scale (D_{mode}=60µm)

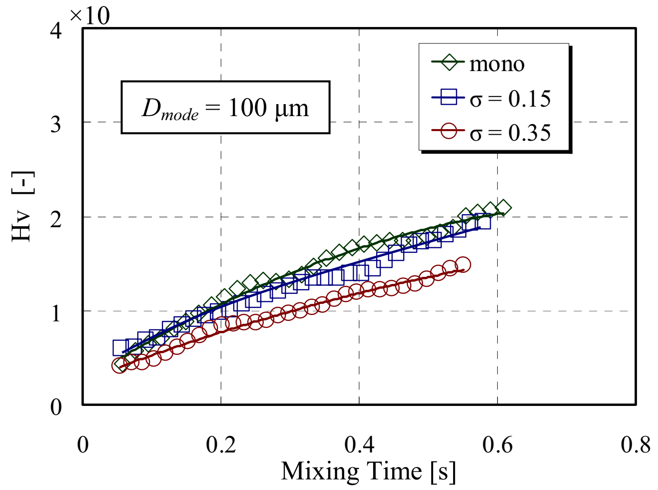


Fig.8 Transition of Inhomogeneity Index (D_{mode}=100µm)

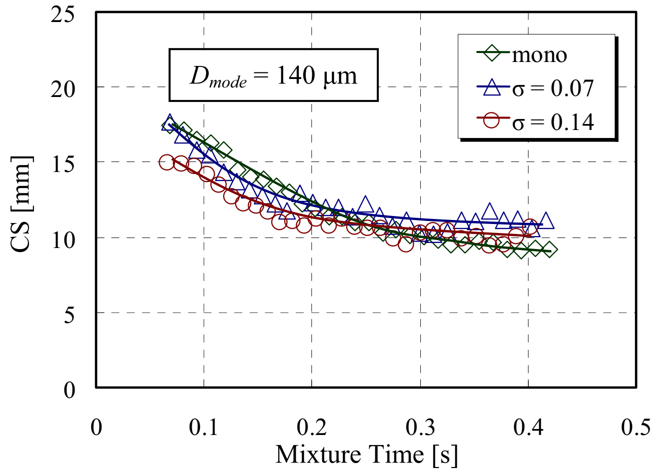


Fig.10 Transition of Characteristic Scale (D_{mode}=140µm)

The behaivior of spray with D_{mode}=100µm is shown in Fig.8. It is inportant to pay attension that inhomogeneity index is 10 times larger than other cases.

In this case, inhomogeneity index increases with the increase of mixing time and decreases with the increase of σ. As shown in Fig.1, inhomogeneity of around 100µm droplet becomes the largest and larger or smaller droplet than 100µm behaives more even. The effect of interaction is cancelled. Concequently, inhomogeneity index decreases with the increase of σ.

It is estimated that the intensity of interaction between droplets depends on the momentum of smaller droplets and larger one. Therefore, the effect of drop size distribution gives effects on the results.

Those results are applicable to spray of which drop volume distribution is asumed to be the normal distribution.

4.2 Effect of Drop Size Distribution on Characteristic Scale

The transition of characteristic scale is shown in Figs 9 to 11. In all cases, characteristic scale approaches around CS=10mm. This results suggest that characteristic scale is scarcely affected by drop size distribution and interaction between droplets and strongly by turbulent scale of surounding air flow.

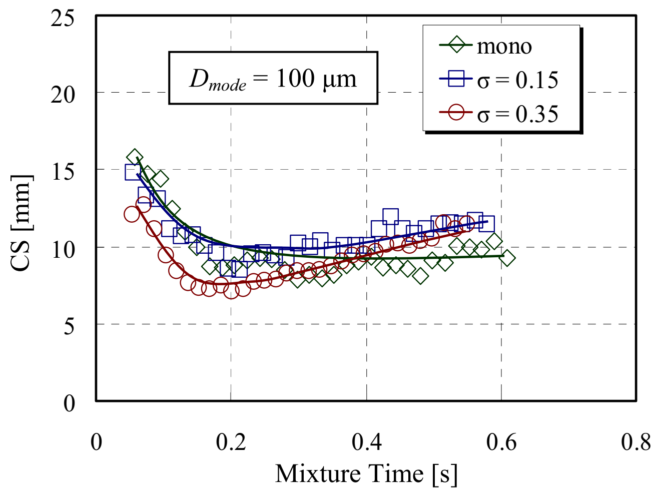


Fig.11 Transition of Characteristic Scale (D_{mode}=100µm)

5. CONCLUSION

In this paper, the effect of drop size distribution and the interaction between droplets on inhomogeneitu of air spray flow are analyzed three-dimensionally by using numerical simulation. The spatial inhomogeneity is evaluated by the inhomogeneity index based on volume of droplets. Droplets were injected uniformly into the airflow with turbulence to eliminate the atomizer characteristics. And the droplet volume distribution is assumed to be normal distribution.

The results are summarized as follows:

1. The spatial inhomogeneity of poly-dispersed spray is affected by the standard deviation of distribution and the representative diameter.

2. Spatial inhomogeneity is settled by the combination of Stokes number of each droplet and interaction between droplets.
   In case of drop size distribution based on drop volume being normal distribution, the spatial inhomogeneity of spray is affected scarcely in the range of Stokes number of mode diameter is $St<1$, increases with the increase of standard deviation in the region of $St>1$ and decreases with the increase of standard deviation in the range of $St \sim 1$.

3. It is estimated that the characteristic scale *CS* affected scarcely by drop size distribution and strongly by turbulent scale of surounding air flow.

REFERENCES

[1] K.Kuno, M.Kuramochi, S.Okajima, K.Terashima and N.Tokuoka, Transition of Spatial Inhomogeneity of Mono-Sized Spray –Transition of Inhomogeneity of Bi-Modal Mono-Dispersed Spray, ICLASS-2006, Aug. 2006.

[2] S.Okajima and N.Tokuoka, The Study of Spray Structure by Numerical Simulation –Spatial Inhomogeneity of Droplets in Spray, ILASS Europe 2007, Sep. 2007.

[3] S.Okajima and N.Tokuoka, Analysis of Spatial Inhomogeneity of Spray using CFD, The 16th ILASS-Japan, Dec. 2007, (in Japanese)

[4] A.Czainski, Quantitative Characterization of inhomogeneity in Thin Metallic Films Using Grancarek's Method, J.Phys.D:Appl.Phys.27, pp.616-622, 1994.

[5] FLUENT 6.3 User7s Guide, ANSYS Inc.