Aerodynamic Breakup of Droplets Arrayed in Gas-flow Direction

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Abstract

In actual spray field, liquid droplets often fly in groups, and the aerodynamic droplet-breakup may be influenced by other droplets. In the present study, some attempts were made to gain insight into the phenomenon. The simplified systems of droplet group were employed, that water droplets of the same size were arrayed in air-flow direction. The breakup behavior of two droplets was examined in the range of dimensionless droplet-distance 3–15 and the range of Weber number 8–18. Based on the results, the breakup behavior of inline four droplets was investigated in the range of Weber number 9–28 and the cases of dimensionless droplet-distance of 15 and 24. The 1st droplet behaved like isolated droplet, but the 3rd and the 4th droplets showed different breakup manner. The breakup time and the acceleration of 3rd and 4th droplets differed much from those of 1st droplet, and the data were widely distributed. The breakup behavior of eight droplets arrayed in two flow-lines was also observed. It was shown that the droplet breakup was influenced much by the presence of upstream droplets. The influence was specified in this study. The data presented here will provide useful hints to develop more realistic numerical models of droplet breakup.

Introduction

Aerodynamic breakup of liquid droplet has been studied by numerous researchers [1-3]. Based on the results several numerical models of droplet breakup have been developed and utilized in numerical simulation of spray [4]. Most of the previous studies focused on the droplet breakup under ideal condition, that isolated liquid droplet was exposed suddenly to uniform steady gas-stream. Some of the previous studies focused on the droplet breakup in rather realistic flow field; shear gas-flow, transient gas-flow and turbulent gas-flow [3, 5-7]. However, basic data may be still insufficient to develop realistic breakup models. In actual spray field, liquid droplets often fly in groups of several droplets. That is, there are some other droplets in the upstream of droplet. The droplet breakup may be influenced by the presence of other droplets and the droplet may show different breakup behavior from isolated droplet. However, the influence has not been investigated sufficiently and has been disregarded in the numerical models.

Aiming to obtain insight into the phenomenon of aerodynamic droplet-breakup in droplet-group, experimental investigations were performed employing the simplified setups, that water droplets of the same size were arrayed in air-flow direction. The breakup behavior of two droplets was examined preliminary. In the range of dimensionless droplet-distance larger than about 7, the upstream droplet behaved like isolated droplet. The critical Weber number of downstream droplet was slightly higher than the upstream droplet, and the breakup of downstream droplet was delayed from the breakup of upstream droplet. However, the breakup of downstream droplet was affected not so much by the upstream droplet when the dimensionless droplet-distance was larger than about 15. It was suggested that the setup of two droplets is too simple to simulate the droplet-breakup in droplet-group. Based on the results, the breakup behavior of inline four droplets was investigated. The 1st droplet behaved like isolated droplet and the 2nd droplet broke up by almost similar manner to the 1st droplet. But the 3rd and the 4th droplets showed different breakup manner. The breakup manner altered every observation and the data of acceleration and breakup-time were widely distributed. The breakup behavior of eight droplets arrayed in two lines was also observed. Following were deduced: the aerodynamic droplet-breakup was influenced much by the presence of upstream droplets. One cannot predict determinately the acceleration during breakup, the breakup time, the breakup manner and the results of breakup, when there are some other droplets in the upstream. For more reliable numerical simulation of spray, it is encouraged to involve the influence into the breakup models. The statistical treatment should be necessary to do so.

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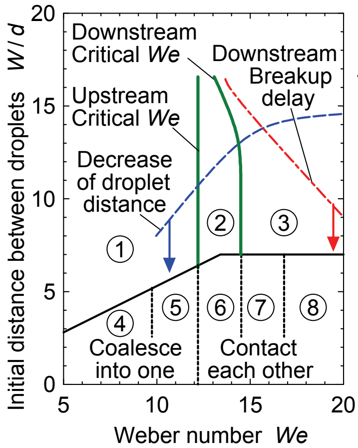


Zone	Breakup mode of droplets: Upstream	Downstream
①	No–breakup	
②	Bag type	No–breakup
③	Bag type	Bag type
④	Coalesce	
⑤	Coalesce -> Breakup	
⑥	Bag type	No–breakup
⑦	Bag type	Bag type or Vibrational
⑧	Bag type	Bag type

In–line two droplets
Water $d = 3.0$mm

Figure 1. Domains of typical interaction and breakup mode.

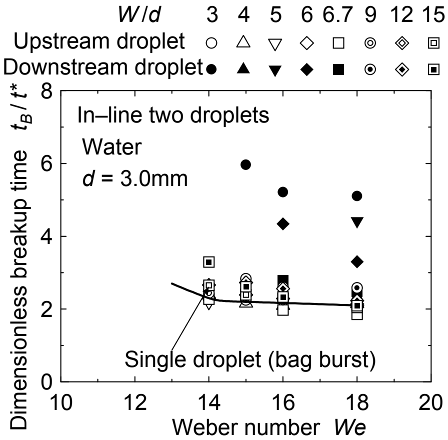


Figure 2. Breakup time of each droplet.

Breakup Behavior of Two Droplets Arrayed in Flow Direction

The breakup behavior of two droplets was examined preliminary. Two water droplets of the same size were generated simultaneously using PZT driven liquid injectors and were dropped into uniform air stream which blown out from horizontal wind tunnel. The droplets were arrayed in the air-flow direction. Experimental investigations were made within the range of the initial droplet-distance, *W*, from 9 to 45 mm and the air-flow velocity, U_g, from 13 to 19 m/s. The diameter, *d*, of droplets was 3.0mm. Weber number, *We*, was ranging from 8 to 18, Reynolds number, *Re*, of air flow around droplet was ranging from 2500 to 3800, and Ohnezorge number, *On*, was 2.2×10^{-3}.

The behavior of droplets was observed by high-speed video and flash photography. Fig. 1 shows the diagram of observed interaction and breakup mode in the coordinate of the dimensionless droplet-distance, *W*/*d*, and Weber number. The upstream droplet behaved like isolated droplet within the range of *W*/*d* above the solid black line in Fig.1. The critical Weber number of upstream droplet was about 12. At the smaller Weber numbers, the droplets seldom broke up. At the larger Weber numbers, the upstream droplet broke up mainly by bag mode; the droplet deformed into bag-like shape and the bag busted. The breakup of downstream droplet was affected by the upstream droplet. The critical Weber number of downstream droplet was slightly larger than the upstream droplet. The upstream droplet broke up but the downstream droplet did not disintegrate in zone (2). Both of two droplets broke up mainly by bag mode in zone (3). The distance between droplets tended to decrease with elapsed time. The decrease of droplet distance was not so obvious within the range of *W*/*d* above the dashed blue curve in Fig.1. More serious drop-drop interactions were observed within the range of *W*/*d* below the solid black line in Fig.1. The distance between droplets decreased rapidly, and the two droplets coalesced into one in zone (4) and (5). The upstream droplet deformed into bag-like shape and contacted with the downstream droplet before the burst in zone (6), (7) and (8).

Fig.2 shows the breakup time, t_B, of each droplet, which is defined as the elapsed time from air-flow exposure to burst of bag. The breakup time of upstream droplet almost agreed with that of isolated droplet. But the breakup time of downstream droplet was longer than that of upstream droplet. The smaller the value of *W*/*d* became, the longer the breakup delay of downstream droplet was. However, the breakup delay of downstream droplet was not so obvious within the range of *W*/*d* above the dash-dotted red curve in Fig.1.

The stream-wise length of wake-zone behind droplet should be about 3 times of droplet width or so [8]. Within this experimental range, the width of deformed droplet was about 2 times of droplet diameter just before the bag-formation and about 4 times of droplet diameter just before the bag-burst. That is, the length of wake-zone could be estimated at about 6 times of droplet diameter just before the bag-formation and about 12 times of droplet diameter just before the bag-burst. Therefore, it should be natural that the serious drop-drop interaction occurred only in the range of *W*/*d* below the solid black line in Fig.1 (*W*/*d* smaller than about 7), and that the breakup of downstream droplet was influenced not so much by the upstream droplet in the range of *W*/*d* larger than about 15. These results suggest that the setup of two droplets was too simplified to gain insight into the phenomenon of our interest.

Breakup Behavior of Inline Four Droplets

The breakup behavior of inline four water droplets was investigated. Schematic diagram of the experimental setup is shown in Fig.3(a). By enforcing axial vibration to four laminar water-jets, set of uniform droplets were generated periodically. Mean diameter, *d*, of the droplets was 2.54mm and the standard deviation was 0.09mm. Though

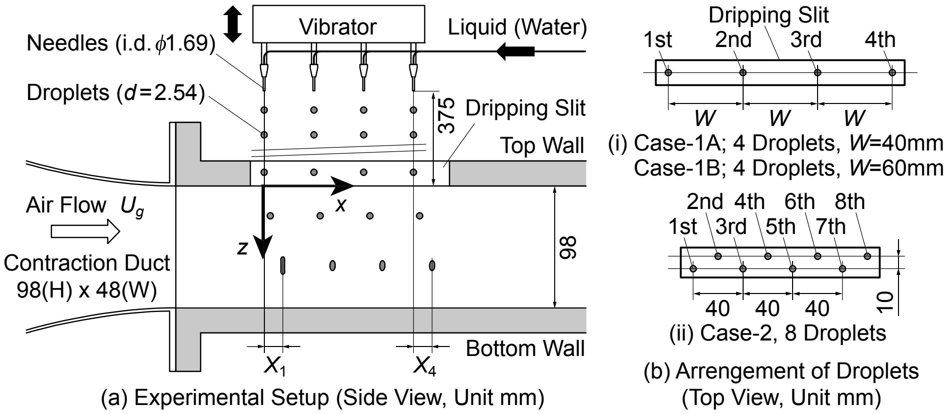


Figure 3. Schematic diagram of experimental setup and droplet arrangement.

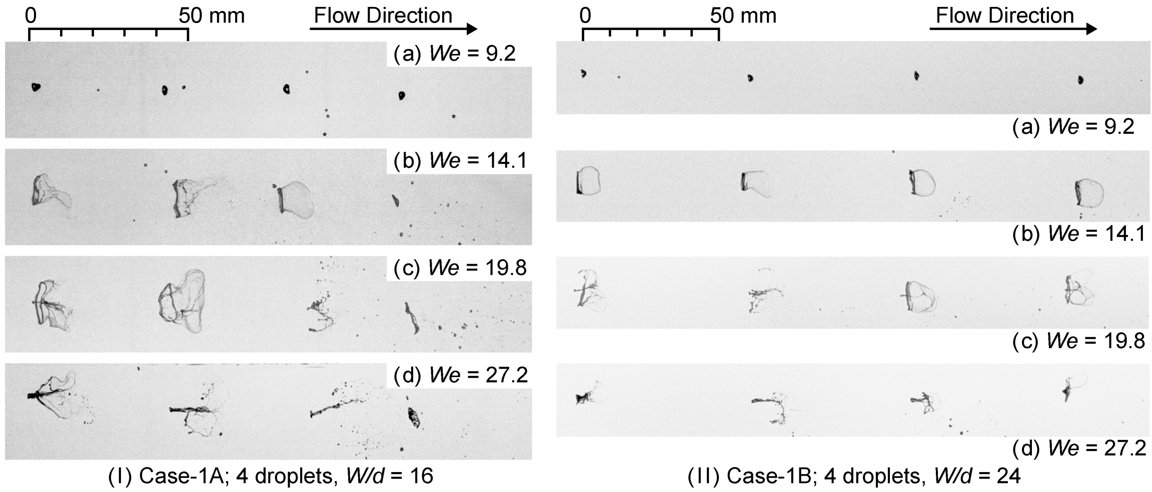


Figure 4. Typical flash photographs of four droplets during breakup.

tiny satellite droplets were also produced by the breakup of liquid jets, they were ignored in the investigations. The four droplets of about the same size entered almost simultaneously into the uniform air-stream of horizontal wind tunnel. The droplets were initially arrayed in the air-flow direction with the almost same distance, as shown in Fig.3(b)-(i). Two cases were examined; the initial droplet distance, *W*, was set to 40mm (W/d=16) in Case-1A and the distance was set to 60mm (W/d=24) in Case-1B. Experimental investigations were performed within the range of air-flow velocity, U_g, from 15 to 26 m/s. Weber number, *We*, was ranging from 9 to 28, Reynolds number, *Re*, of gas-flow around droplet was ranging from 2500 to 4400, and Ohnezorge number, *On*, was 2.4×10^{-3}.

Fig.4-(I) shows typical flash photographs of droplets during breakup in Case-1A. At Weber numbers smaller than the critical Weber number of isolated droplet, every droplet did not breakup, (a). At slightly larger Weber numbers, the 1st droplet broke up by the manner of bag mode similar to the isolated droplet, the 2nd and the 3rd droplets showed almost similar breakup manner to the 1st droplet, but the 4th droplet showed different manner, (b). At larger Weber numbers, the 1st droplet broke up by the manner of bag-jet mode, the 2nd droplet showed almost similar breakup manner to the 1st droplet, but the breakup manners of 3rd and 4th droplets differed from 1st droplet, (c) and (d). Fig.4-(II) shows typical photographs of droplets in Case-1B. The presence of upstream droplets seemed to influence not so much upon the breakup manner of 2nd and 3rd droplets. But the 4th droplet often showed different breakup manner from 1st droplet, especially at relatively large Weber numbers. It is remarkable that the breakup behavior of 4th droplet was affected by the upstream droplets in the case of sufficiently large W/d of 24.

It was found by repeated investigations that the breakup manner of droplets changed every observation, especially 3rd and 4th droplets in Case-1A. The occurrence frequency of each breakup mode was examined with changing Weber number. Fig.5-(I) shows the occurrence frequency distributions in Case-1A. For the 1st droplet, the occurrence frequency of each breakup mode was similar to that of isolated droplet, (a). The occurrence frequency distri-

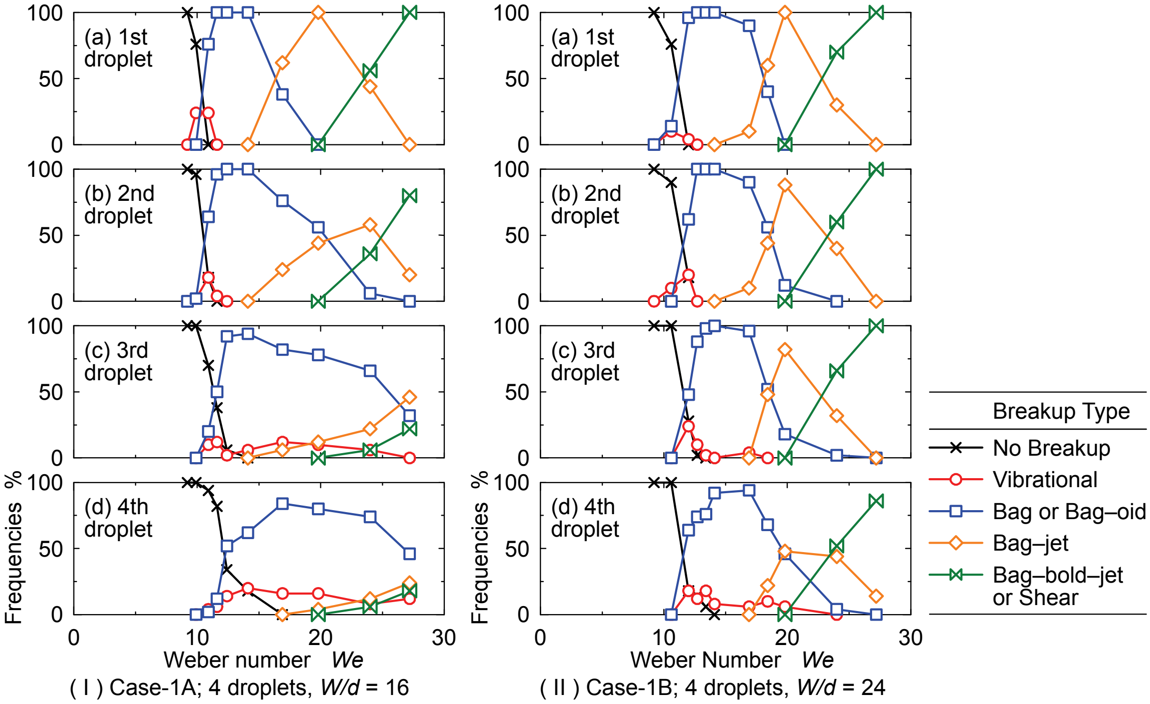


Figure 5. The occurrence frequency of each breakup mode.

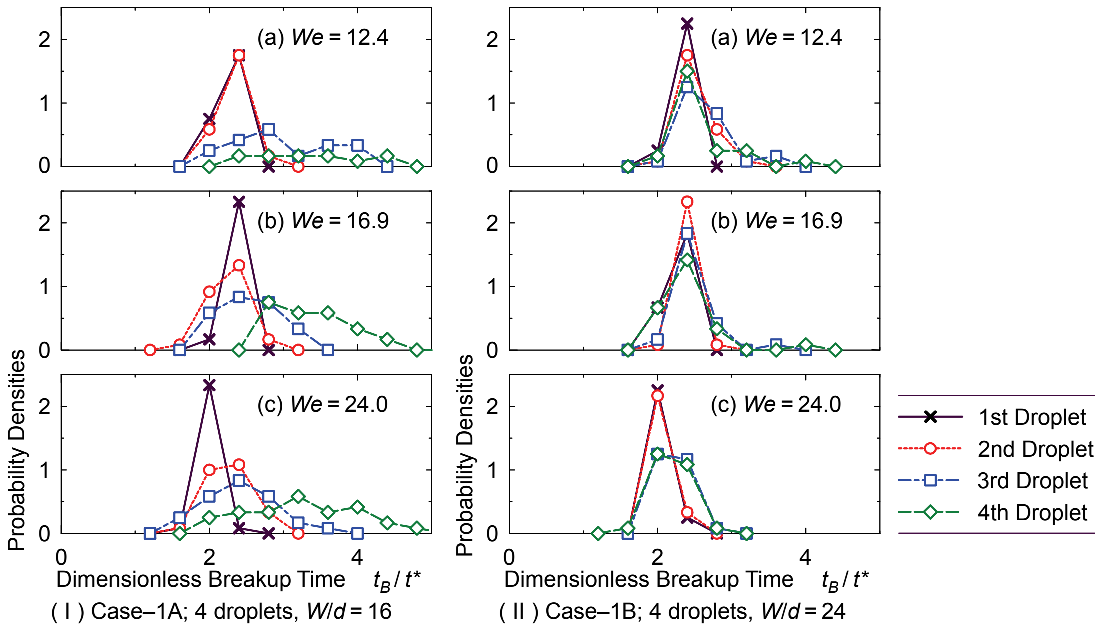


Figure 6. The probability density of dimensionless breakup time of each droplet.

butions of 2nd droplet resembled to those of 1st droplet, as could be easily predicted from the results of previous chapter. But the frequency of bag-jet-type breakup was smaller than 1st droplet at Weber number of about 20, (b). For the 3rd droplet, the frequency of bag-jet-type breakup became smaller at Weber number of about 20, the frequency of bag-bold-jet-type breakup became small at Weber number of about 25, and the frequency of bag-type or bag-oid breakup became large in the place, (c). For the 4th droplet, the frequency of bag-type breakup was obviously smaller than the upstream droplets at Weber number of 12-15, and the frequency of vibrational-type breakup and no-breakup became large in the place, (d). Considering that the air-flow behind deformed droplets should be perturbed

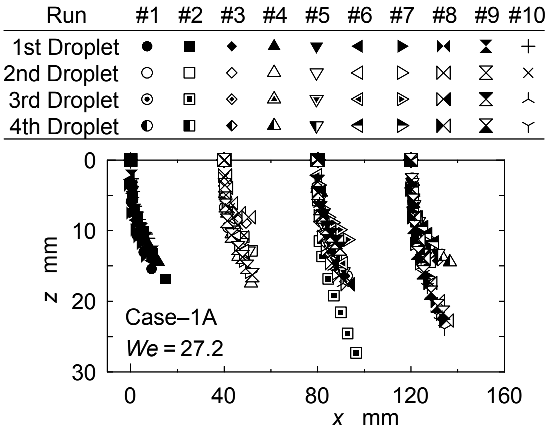


Figure 7. The trajectories of droplets in air-flow. (Results of 10 experimental runs are shown.)

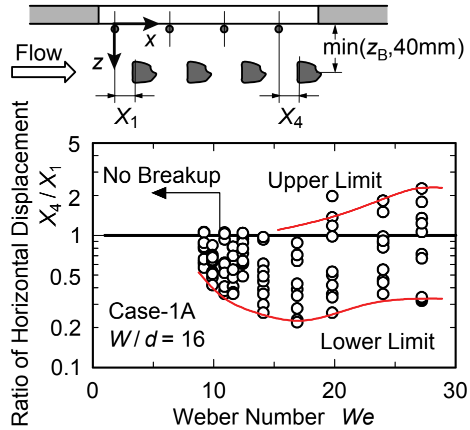


Figure 8. The ratio of horizontal displacement of 4th droplet to that of 1st droplet.

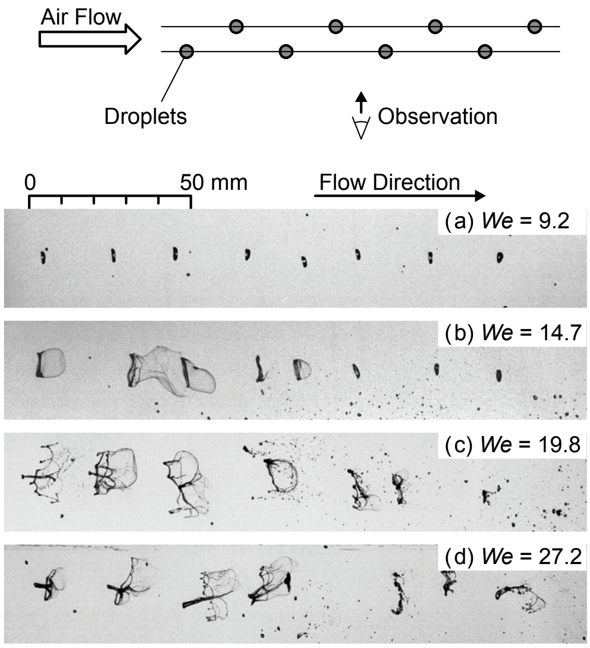
and that the downstream droplets should be exposed to the perturbed air-flow, the 3rd and the 4th droplets should alter their breakup manner owing to the flow perturbation. Fig.5-(II) shows the occurrence frequency of each breakup-mode in Case-1B. The frequency distributions of 2nd and 3rd droplets almost resembled to those of 1st droplet. However, the frequency distributions of 4th droplet differed from the upstream droplets, especially at Weber number of about 12 and 20. As mentioned above, the downstream droplets showed variety of breakup manners. The breakup manner cannot be predicted determinately when there are some other droplets in the upstream. The results of breakup cannot be predicted determinately neither, because the results of breakup should depend on the breakup manner.

The breakup time of each droplet was examined. Fig.6-(I) shows the probability densities of the dimensionless breakup-time, t_B/t^*, in Case-1A. The breakup time of 1st droplet was distributed within a narrow peak. The breakup time of 2nd droplet was distributed in a slightly wider peak than the 1st droplet, especially in the case of relatively large Weber number. For the 3rd droplet, the distribution of breakup time was extended to the right side in the figure (longer breakup-time). For the 4th droplet, the distribution extended wider and sifted more to the right side. Fig.6-(II) shows the probability densities of the dimensionless breakup-time in Case-1B. The influence of the upstream droplets upon the breakup time of 2nd droplet was not so obvious. However, the breakup time of 3rd and 4th droplets distributed in wider peak than the 1st droplet and the peaks shifted slightly to the right side in the figure. From these results, it is considered that the air-flow velocity around downstream droplets should decrease slightly due to the wake of upstream droplets. The breakup-time of downstream droplet should be distributed in wider range, because the amount of velocity decrease should change every experimental run due to the change of breakup manner.

During breakup, the droplets were falling gravitationally and accelerated horizontally by the air-flow. The trajectory of each droplet was investigated. Fig.7 shows typical example of the droplet trajectories. The results of 10 experimental runs are shown in the figure. The trajectories of 3rd droplet and 4th droplet changed every experimental run, although the trajectories of 1st droplet scarcely changed. To compare the aerodynamic accelerations between 1st droplet and 4th droplet, the ratio of horizontal displacement of 4th droplet to 1st droplet was examined. The results are shown in Fig.8. Data of 10 runs at each Weber number condition are plotted in the figure. At Weber number of about 10, the displacement-ratio was ranging from 0.5 to 1.0. The 4th droplet tends to be less accelerated than the 1st droplet. At Weber number of about 17, the plots of displacement-ratio were distributed in wider range, from 0.2 to 1.0. This should be due to the variety of breakup manners of upstream droplets. At the larger Weber numbers, the plots of displacement-ratio were distributed in wider range and the upper limit exceeded unity, i.e. the 4th droplet could be accelerated more than the 1st droplet occasionally. As mentioned above, the upstream droplets also influenced strongly upon the aerodynamic acceleration of downstream droplet during breakup.

Breakup Behavior of Eight Droplets

Experimental observations were made on the breakup behavior of eight droplets arrayed in two lines as a rather realistic model of droplet group. The experimental setup was similar to the previous chapter. The arrangement of droplets is shown in Fig.3(b)-(ii). The stream-wise distance of droplets was similar to Case-1A.Typical flash photographs are shown in Fig.9. The occurrence frequency of each breakup mode is shown in Fig.10. Comparing Fig.10 with Fig.5-(I), it is obvious that the breakup behavior of downstream droplets was affected more by the upstream droplets than Case-1A. The results mean that not only the droplets positioned rightly upstream but also the droplets



Case-2; 8 droplets, *W/d* = 16

Figure 9. Typical flash photographs of eight droplets during breakup.

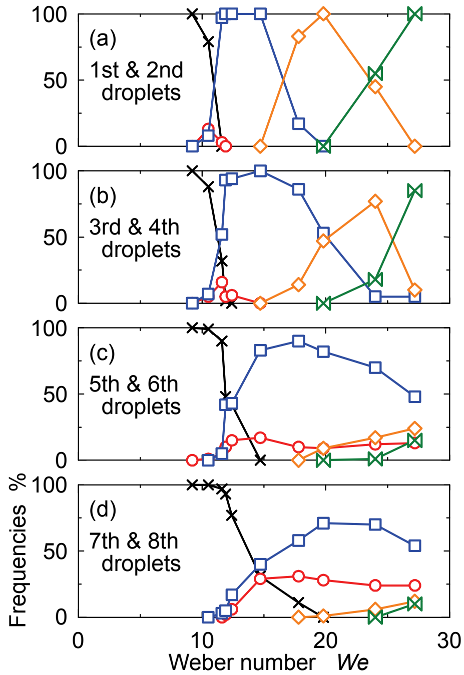


Figure 10. The occurrence frequency of each breakup mode. (see Fig.5 for key to symbols.)

positioned obliquely should influence on the breakup behavior of downstream droplet. That is, the droplet breakup should be affected by other droplets nearby in actual spray field, though they might not position rightly upstream.

Conclusions

The aerodynamic droplet-breakup in droplet-group was studied employing the simplified setups. Three situations were considered: two droplets arrayed in air-flow direction, four droplets arrayed in air-flow direction, eight droplets arrayed in two flow-lines. Following were deduced: the aerodynamic droplet breakup was influenced much by the presence of upstream droplets. One cannot predict determinately the aerodynamic acceleration during breakup, the breakup time, the breakup manner and the results of breakup, when there are some other droplets in the upstream.

Nomenclature

d diameter of liquid droplet
On Ohnesorge number ($On = \mu_l / (\rho_l d \sigma)^{1/2}$)
Re Reynolds number ($Re = \rho_g U_g d / \mu_g$)
t_B breakup time of droplet
t^* characteristic time ($= d (\rho_l / \rho_g)^{1/2} / U_g$)
U horizontal velocity
W droplet distance
We Weber number ($We = \rho_g U_g^2 d / \sigma$)

x-z coordinate
X_N horizontal displacement of N-th droplet
ρ density
μ viscosity
σ surface tension

Subscripts
g gas
l liquid

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