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THE EVOLUTION OF HEAVY LIQUID DROP SUSPENDED IN LIGHT LIQUID AFTER AN IMPACT

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ABSTRACT

An experimental investigation was carried out for the deformation and breakup of liquid drop suspended in an oil tank which is decelerated by an impact. The experiments were conducted in a specially designed drop tower, in which the oil tank can be lifted up to about 1.5 m high and dropped onto ground damper. A high speed camera was used to visualize the temporal development and breakup. Four recognizable different modes of the drop deformation have been found up to now from our experiments. The transitions between these modes appear to be related to the density ratio of the drop to the oil, the interfacial tension, the initial drop diameter and the impulse being generated by suddenly decelerating the oil tank. The deformation appears to be more severe if the density ratio, the initial drop diameter, or the impulse is increased, and vice versa. The interfacial tension between the drop and the ambient oil seems to play a suppression role against the drop deformation and breakup. The results of the transitions between these modes were summarized by "deformation and breakup maps" where different modes are shown in the H-D plane (H is the height of the tank falling freely and D is drop initial diameter) for different values of the density ratio and interfacial tension.

Keywords: Drop deformation and breakup; Impact; Liquid-liquid two phase; Interface

INTRODUCTION

The drop deformation and breakup are common phenomenon in a variety of scientific and engineering applications such as fuel injection, oil pipeline transport, etc.. Numerous experimental and numerical studies are interested in the case of liquid drop surrounded by gas phase, namely the liquid drop breakup in a liquid-gas two phase system. In early experimental works, Liu and Reits [5], for example, analyzed the distortion and breakup mechanisms of liquid drops into a transverse high velocity air jet. Hsiang [8] studied the drop deformation and breakup properties due to shock wave and steady disturbances. Numerical methods, including front-tracking method [4], direct numerical study [2], etc., have been developed to investigate the process of the drop interface movement. However, investigation in the deformation and breakup of liquid drop with ambient liquid is relatively quiescent, compared with liquid drop in the gas-liquid system. Although Niederhaus and Jacobs [3] used the drop tower to study the liquid-liquid two phase interface development, they focused on the Richtmyer-Meshkov instability and mixing process of the two liquids. The present work is concentrated on the liquid drop deformation in the liquid-liquid two phase system by an impact. The objective is to study the details of the liquid drop deformation and breakup after such a strong disturbance, as well as the key factors which dominate the deformation process.

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EXPERIMENTAL METHODS

The experiments are carried out in a drop tower system, as shown in Fig. 1. The facility mainly consists of a lifter, two pieces of 2.7 m long rails, a damping stopper, an oil tank, light source for the visualization, and high speed camera. The drop tower is so designed to allow the tank travels down along the rail in a free-fall way until it collides with the stopper. The lifter can produce magnetic force up to about 1000 N, which is enough to raise the tank. The tank with interior dimensions of 24 cm*24 cm*40 cm is jointed to both sides of the rails with ball bearing to reduce the friction at the joint, so that the tank is capable of falling freely. To observe and record the development of drop deformation, the high speed camera is set in the front of tank and captures images of the deformation and breakup at a resolution 512*1024 at 1000 frames per second, with the help of an intensity light source placed at the back of the tank.

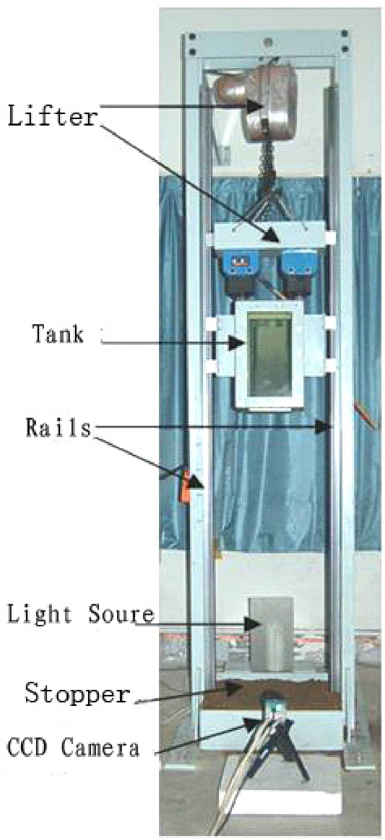


Fig. 1. Drop tower device

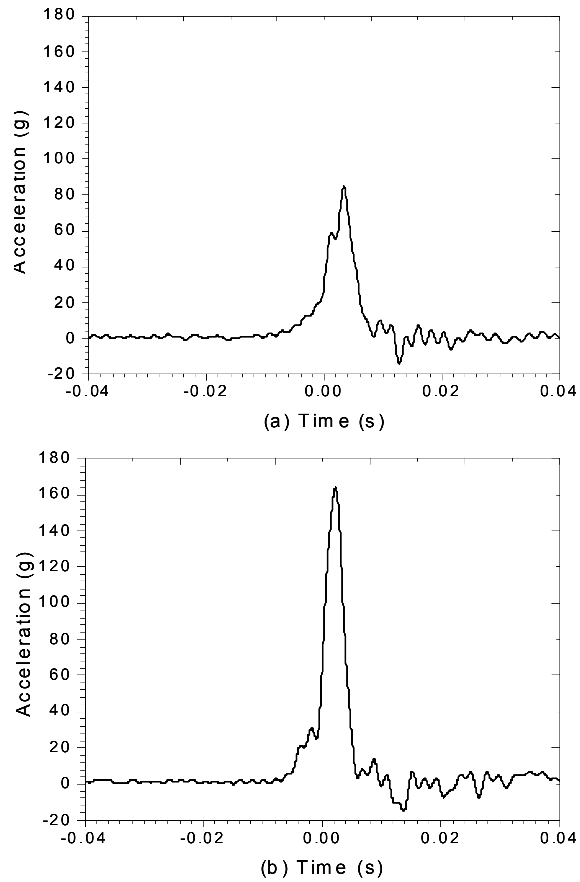


Fig. 2. The plots of acceleration versus time for typical experiments at different heights of the tank falling: (a) H=0.5 m, (b) H=1.45 m.

A drop holder is introduced for the generation of nearly ideal spherical drop with controllable volume. The liquid drop is generated by controlling the liquid injector, until the size of the drop reaches its required diameter. The drop is released from the holder just before the tank starts to fall, and it tends to become spherical due to interfacial tension. One important parameter is the impulse of the impact, which is a key factor of dominating the process of the drop deformation. The amplitude of the impulse is controlled by adjusting the free-falling height of the tank. In our experiments, we set the heights from 0.5 m to 1.45 m, and the stopper is made of 10 cm thick sand. Fig. 2 shows some typical acceleration behaviors of the tank during impacting process, from which an order of 5ms impact time duration and hundreds gs of acceleration were measured. To expand the properties of the fluids in our experiments, we add salt to the liquid to change the density ratio of the drop to the oil from 1.23 to 1.6 and add surfactant to the water to change the interfacial tension between the water and the oil from 5.1 mN/m to 33.7 mN/m.

The operation of the experiment is as follows: Firstly, the high speed camera is focused at the plane where the drop is located in the tank. Then, the tank is raised to the specified height, and a drop is created on the drop holder in the tank as mentioned before. Finally, the high speed camera start to record and the tank is released from the top of drop tower by cutting off the power supplied for the electromagnet device. The drop leaves off the drop holder just before the tank starts to fall, and dips in the surrounding oil nearly spherically, until it collides with the stopper. The drop begins to deform at the moment oil tank impacting at the stopper.

Table 1. Summary of the test conditions

Condition	$\rho_d(kg/m^3)$	ρ_d/ρ_o	$\sigma(mN/m)$	$D_d(mm)$	$H(m)$	Observation mode
1	1000	1.23	33.7	7.0	0.5	A
2	1000	1.23	33.7	9.2	0.7	B
3	1053	1.30	39.9	8.7	1.1	C
4	1296	1.60	46.3	9.1	1.1	D

The density of the oil was taken at normal temperature and pressure: $\rho_o = 810 kg/m^3$.

RESULTS AND DICUSSIONS

The typical modes of the liquid drop evolution

A typical mode evolution of liquid drop after the impact is shown in Fig. 4.a, with the experimental condition as shown in Table 1(1), which is for the case of weakest impact, and is called mode A in the paper. The acceleration pulse imparted to the tank in this case versus time is shown in Fig. 2 (a). It can be seen that an initial spherical liquid drop is flattened and forms nearly hemisphere shape (see the Fig. 4.a (5 ms)).The upper part of the drop inverts the shape and starts to penetrate the inner part of the drop as shown in Fig. 4.a (10 ms-20 ms). With the deformation continuously develops in the drop, more and more outside oil enters the drop and the bottom of the drop forms a liquid film (as shown in most images of Fig. 4.a, and also as sketched in Fig. 3), of which the thickness decreases during the early stage of the deformation. Furthermore, a circular rim (sketched in Fig. 3) is formed along the waist part of the drop, which rolls up and collects most volume of the water drop as shown in Fig. 4.a (10 ms-50 ms). Then as the time advances further, the interfacial tension seems to take over the action of impact, which tends to decrease the total surface area of the deformed drop and shrink it to smaller size (as shown in Fig. 4.a (60 ms-110 ms)). During the evolution, the drop breakup does not occur in this case because of small drop size and weak impulse. Note that there are two kinds of final destinations of this mode which were observed in our experiments: One is the recovery of a spherical drop after a process of non-separation deformation, which is pulled back by the interfacial tension; and the other is that during unstable process of deformation and recovery, the parent drop will break up into a couple of smaller child drops. The details of the breakup are not discussed for the time being.

In our experiments, three other typical modes, which are called mode B, C and D (as shown in Fig. 4 b-d), respectively, have be observed through various of test conditions, such as different ratio of the drop density to the oil, the interfacial tension, the drop diameter and the falling-height of the tank. From Fig. 4, we can find that the drops are flattened and form nearly hemisphere shape in all cases at the beginning of

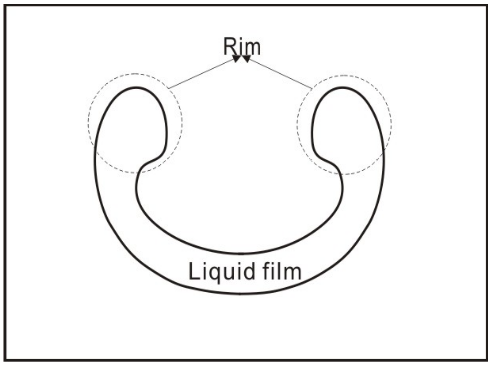
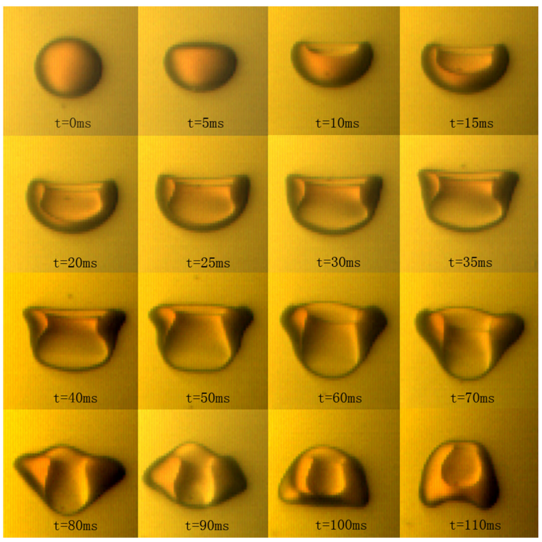
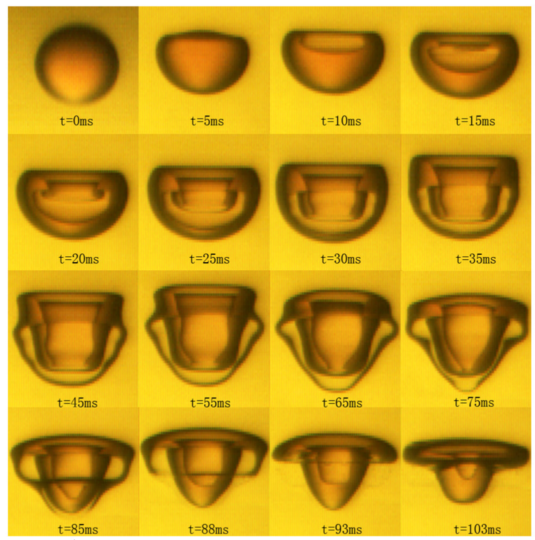


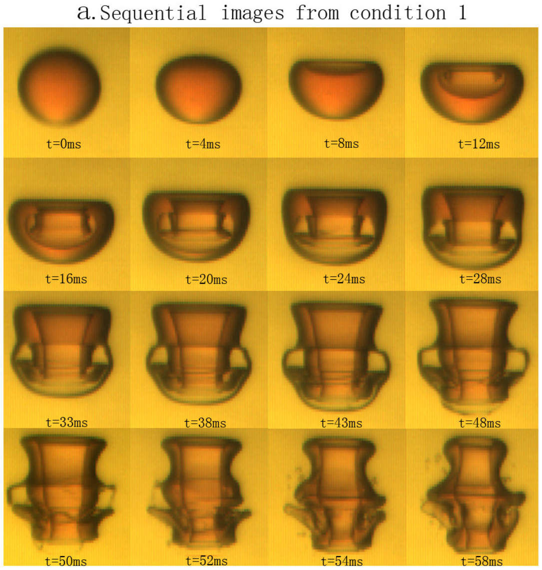
Fig. 3. The sketch map of the details of the early-stage drop deformation



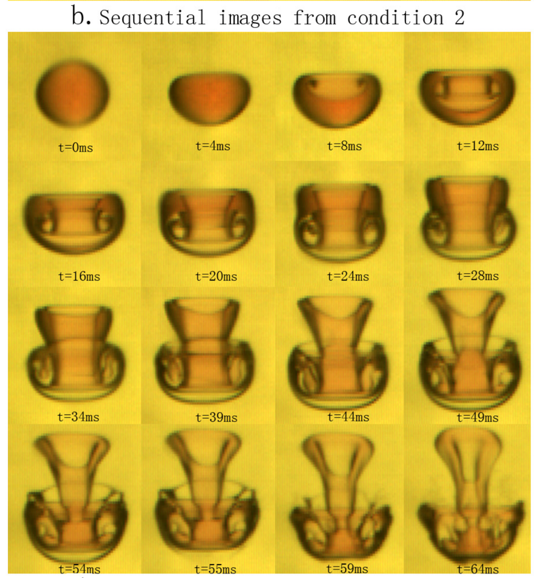
a. Sequential images from condition 1



b. Sequential images from condition 2



c. Sequential images from condition 3



d. Sequential images from condition 4

Fig. 4. A sequence of images from the experiments with the test conditions as Table 1. t=0ms is he beginning of the tank impacting at the stopper.

the impact, although the deformation deviate into different shapes later on, from which different modes are classified. There are two notable differences from the images shown in Fig. 4: One is the length variation caused by stretching the drop in the vertical direction. There is a little stretching in mode A and B as shown in Fig. 4.a and b, but in mode C and D as shown in Fig. 4.c and d, the vertical size is stretched several times longer than the initial drop diameter, of which the lower part forms a typical mushroom shape. The other notable difference is the rolling behaviors along the rim part (as sketched in Fig.3) during the deformation. These rolling behaviors seems to become more severe from mode A towards D, and it is because of the self induction of the strong vortex ring that stretches the size along the vertical direction in the cases mode C to D. Besides the two notable differences mentioned above, it is also observed that the thin liquid film at the bottom of the drop finally breaks up into very fine droplets. Comparing the four modes as shown in Fig. 4, we can easily find that the rate of drop deformation increases from A mode to D mode.

The regime maps of the drop deformation

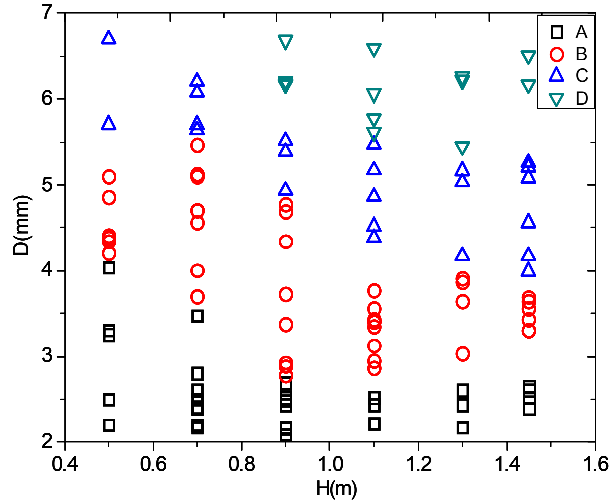
From our experiments, we find the density ratio of the drop to ambient oil (ρ_d/ρ_o), the interfacial tension (σ), the impulse related to the falling-height of the tank (H), and the initial drop diameter (D) have significant effect on the liquid drop evolution, but the drop viscous plays little role in the evolution. To summarize the results of the effect of the four parameters (ρ_d/ρ_o , σ , D, H) on the transitions between the four modes, the deformation and breakup transition maps are presented in Fig. 5 and Fig. 6.

Fig. 5 shows the experimental results with a given density ratio of ρ_d/ρ_o =1.23. Three maps (as shown in Fig. 5(a)-(c)) are corresponding to different interfacial tension. The map for a relatively small σ =5.1 mN/m (Fig 5(a)) shows that increasing the magnitude of D at a fixed H, such as H=0.9 m, results in the transitions fron mode A towards D. Changing H for a fixed D, we can find that the transitions do not happen until the drop diameter is large enough (more than 3 mm as shown in Fig. 5 (a)). We also observed that increasing H for fixed D leads to the transitions from A to D as shown in Fig. 5 (a). The same transitions can be observed in other two experimental situations (see the Fig. 5 (b) and (c)), so we can conclude that the rate of drop deformation will be enhanced when the magnitude of either H or D is increased. When σ is increased to 17.0 mN/m (Fig. 5 (b)) and 33.7 mN/m (Fig. 5 (c)), there are some differences in the boundaries between these modes with increasing D for fixed H. For example, the B mode, which can be observed at D=3 mm~5 mm in Fig. 5 (a), is now seen at D=6 mm~10 mm in Fig. 5 (b) and D=7 mm~11 mm in Fig. 5 (c), and the D mode can be observed at D>6 mm in Fig. 5 (a), but is no longer seen in Fig. 5 (b) and in Fig. 5 (c). The similar phenomenon can be observed in other falling heights of tank. Therefore, the interfacial tension suppresses the drop deformation.

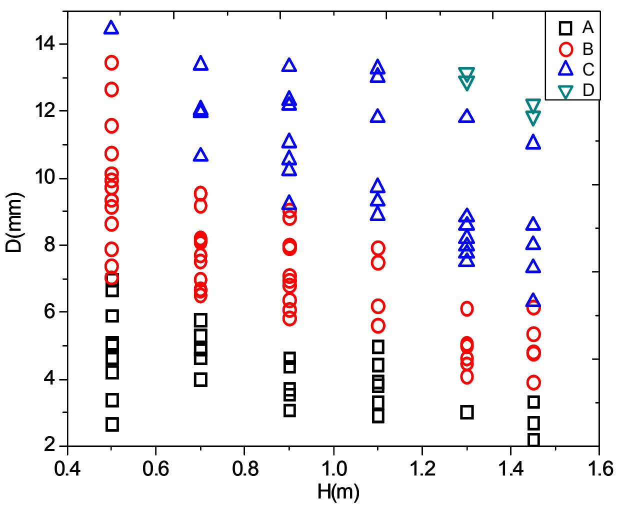
In Fig. 6, the regime maps are presented for drops with different density ratio. Three maps are shown in Fig. 6 (a) –(c), for density ratio of ρ_d/ρ_o =1.23, 1.4 and 1.6 respectively, and interfacial tension to be σ =33.7 mN/m, 41.3 mN/m and 46.3 mN/m. As shown in Fig. 6 (a), it displays the transitions from A to D for a fixed H as D is increased. The same transitions sequences can be observed in Fig. 6 (b) and (c), which again validates that increasing the drop diameter and impulse is to promote the evolution of drop deformation and breakup. In terms of conclusion obtained before, increasing the interfacial tension reduces the rate of deformation. However, even though the interfacial tension is increased from 33.7mN/m in Fig. 6 (a) to 46.3 mN/m in Fig. 6 (c), the development of deformation is still promoted by the density difference as shown in Fig. 6. Therefore, the density ratio of the drop to the ambient oil plays an important role for the drop deformation and breakup.

CONCLUSIONS

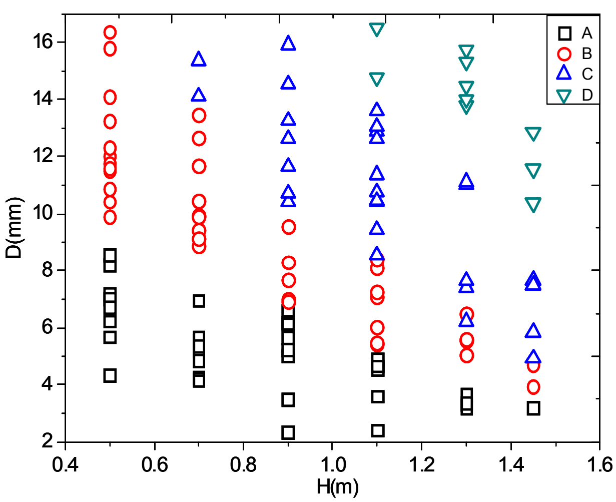
An experimental investigation was carried out for the deformation and breakup of liquid drop suspended in oil tank which is decelerated by an impact. Based on the results obtained from experiments



(a) $\rho_d/\rho_o = 1.23, \sigma = 5.1 mN/m$

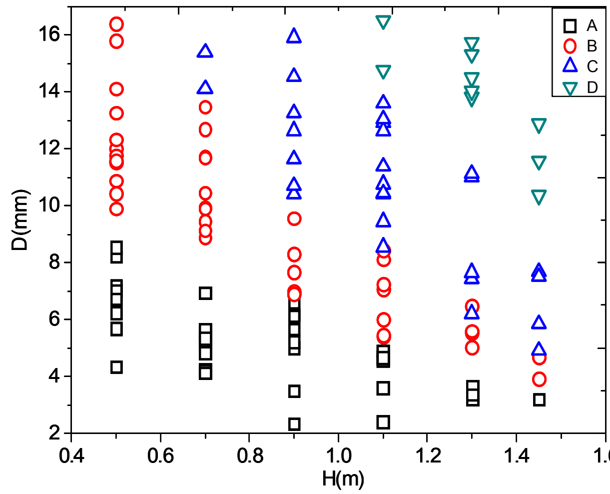


(b) $\rho_d/\rho_o = 1.23, \sigma = 17.0 mN/m$

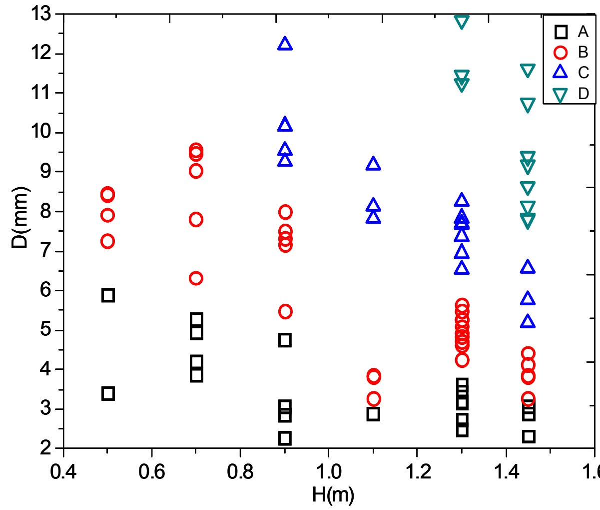


(c) $\rho_d/\rho_o = 1.23, \sigma = 33.7 mN/m$

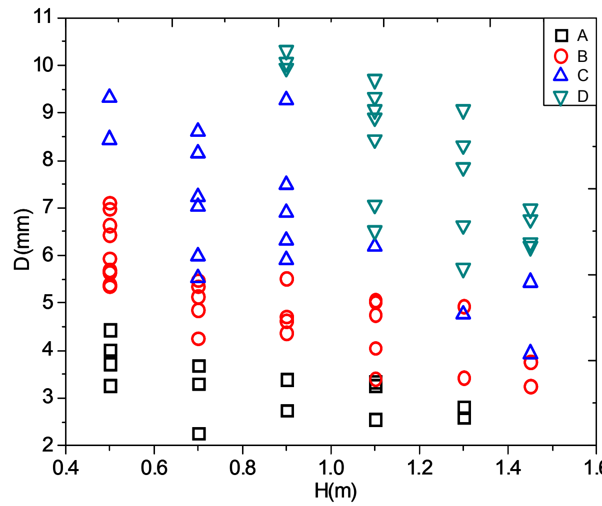
Fig. 5. Deformation and breakup regime maps for ρ_d/ρ_o =1.23. Three maps are shown for σ=5.1mN/m, 17.0mN/m, 33.7mN/m. In each map, the horizontal and vertical axes are H and D, respectively.



(a) $\rho_d/\rho_o = 1.23, \sigma = 33.7 mN/m$



(b) $\rho_d/\rho_o = 1.4, \sigma = 41.3 mN/m$



(c) $\rho_d/\rho_o = 1.6, \sigma = 46.3 mN/m$

Fig. 6. Deformation and breakup regime maps. Three maps are shown for ρ_d/ρ_o=1.23, 1.4, 1.6 and σ=5.1mN/m, 17.0mN/m, 33.7mN/m. In each map, the horizontal and vertical axes are H and D, respectively.

and the discussions mentioned above, the following conclusions can be summarized.

(1) The deformation and breakup process of liquid drops can be classified roughly into four typical modes from our experiments.

(2) The deformation appears to be more severe if the density ratio, the initial drop diameter, or the impulse is increased, and vice versa. The interfacial tension between the drop and the ambient oil seems to play a suppression role against the drop deformation and breakup.

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