FORMATION OF GAS-IN-LIQUID COMPOUND DROPS

Shy-Ya Lin 1, Sheng-Lin Chiu 1, Rong-Horng Chen 2, Jen-Yung Pu 1 and Ta-Hui Lin 1

1 Department of Mechanical Engineering, National Cheng Kung University, Taiwan, R.O.C, thlin@mail.ncku.edu.tw
2 Department of Mechanical Engineering, Southern Taiwan University of Technology, Taiwan, R.O.C.

ABSTRACT An experimental method to generate stable, controllable and periodic gas-in-diesel compound drops by coaxial compound jets is presented. The compound jet can be categorized into bubbling and jetting regimes in the upstream or into bubbling and compound drop regimes in the downstream. The characteristics of a compound jet nozzle strongly depend on the actual sizes of the needles and the flowrates. According to experimental results, steady and periodical compound drops could be produced for Weber number less than 7 and velocity ratio within 0.2 ~ 0.45. As the outer liquid velocity increases, the compound drop generation frequency goes down. In the compound drop regime, the satellite grows with increasing velocity ratio.

Keywords: compound drop, compound jet, frequency, diesel

1. INTRODUCTION

Drop formation plays an important role in many industrial applications, such as the processes of food products, chemical industries, medicine industries, fuel injection, spray cooling, and so on. A lot of efforts have been made by previous researchers for the purpose of understanding the characteristics of drop formation. As a pioneer of this field, Rayleigh [1] first considered the instability of an inviscid jet in a vacuum and gave a detailed analytical explanation of this phenomenon. He theorized that a jet is always stable except when the external disturbance is axisymmetric and has a wavelength longer than the circumference of the jet. This instability causes the jet to breakup into drops. Later, this phenomenon was examined and described in the experiments by Donnelly and Glaberson [2], Goedde and Yuen [3] and many others.

Besides drops of single liquid, a special kind of drop, which is made of a core of a certain fluid surrounded by another liquid or solid, called a compound drop, has been of particular significance in food industry for encapsulation of food additives [4] and has also been an active research area in material science, membrane, chemical, and biochemical technologies for extraction, separation, and fermentation [5].

The substance of the core of a compound drop may be either gas [6] or liquid [7-9]. For the gas core, there are several types of compound drops with reference to their the different structures. According to Florence and Whitehill [6], three types of compound two-phase drops, namely Type-A, Type-B and Type-C were defined.

For the liquid core compound drop, many different methods for the generation of compound drop have been presented. In 1983, Hertz and Hermanrud [7] first developed a liquid-in-liquid compound jet, which consisted of a central primary jet surrounded by a sheath of secondary fluid for application in ink-jet printer. By means of the Rayleigh breakup, they produced compound drops successfully and looked into the mechanism of the compound jet
quantitatively and found that the compound jet exhibited three different types of instabilities for varied jet velocities. In 2002, Loscertales et al. [8] reported an electrical method to generate steady coaxial jets of immiscible liquids. They found that the breakup process and the drop size were strongly dependent on the liquid viscosities and on the ratio of the liquid flow rates. On the other hand, a common mechanism to produce a stable liquid drop stream is the use of a piezoelectric plate driven by a signal generator and an amplifier to give the jet a periodic excitation and then induce the jet breakup. By using this technique, a water-in-diesel compound jet was issued from a concentric nozzle into still air and disintegrated into uniform-sized compound drops in the work of Chiu and Lin [9].

So far, no detailed experimental investigation on the formation of a gas-in-liquid compound drop has been discussed. In the present work, we performed an experiment on the breakup of a nitrogen-in-diesel compound jet. With careful control of the flow rates of the nitrogen and diesel oil, many types of breakup mechanism of the compound jet were observed and the formation of a nitrogen-in-diesel compound drop was examined.

2. EXPERIMENTAL SETUP AND MEASUREMENT

The nozzle for the generation of compound drops, shown in Figure 1, was coaxially constructed with a reducing glass outer-nozzle carrying diesel oil and an inner stainless steel hypodermic needle carrying nitrogen gas. The geometrical characteristics of the inner and outer nozzles and the properties of the fluids supplied are separately listed in Table 1 and Table 2.

![Figure 1: Nozzle of gas-in-liquid compound drops.](image1)

Table 1 Sizes of the nozzle.

<table>
<thead>
<tr>
<th></th>
<th>Inner diameter of outer glass nozzle tip</th>
<th>Inner and outer diameters of the stainless needle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(D_o=0.061) cm</td>
<td>(D_o=0.03) cm (D_i=0.017) cm</td>
</tr>
</tbody>
</table>

Due to pressure head, the high-lifted liquid tank provided stable liquid flow, with the metering valve controlling the flow rate of the liquid. From the compressed nitrogen cylinder, we linked the pressure regulator and flow-meter to supply a controllable and stable gas flow. Image recording was achieved with a stroboscope (~ 200 Hz) and a camera. The complete experimental set-up is shown in Figure 2.

![Figure 2: Experiment setup.](image2)

The velocity of the outer flow can be calculated by dividing the flow rate by the corresponding exit cross-sectional area as follows

\[
U_o = \frac{\dot{Q}_o}{\frac{\pi}{4}(D_o^2 - D_i^2)}
\]
Similarly, the velocity of the inner flow is

$$U_i = \frac{Q}{\frac{\pi}{4}D_i^2}$$  \hspace{1cm} (2)

Note that the outer flow rate was measured by a measuring cylinder, and the inner flow rate by a bubble meter since the gas was too small to be measured by a float meter.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In our experiment procedure we first specified the initial gas flow and then gradually enlarged the liquid flow while observing the images nearby the exit of the nozzle and the downstream of the jet from the display. The gas-in-liquid compound jet was carefully observed and categorized according to either its upstream or downstream patterns. A typical set of patterns are presented with photos and represented by various symbols in Figure 3.

<table>
<thead>
<tr>
<th>We=9.08</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>u=</td>
<td>0.063</td>
<td>0.070</td>
<td>0.073</td>
<td>0.120</td>
<td>0.184</td>
<td>0.196</td>
<td>0.203</td>
<td>0.208</td>
</tr>
<tr>
<td>Upstream of the compound jet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>◆</td>
<td>◆</td>
</tr>
<tr>
<td>Downstream of the compound jet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>△</td>
<td>○</td>
<td>○</td>
<td>△</td>
<td>●</td>
<td>●</td>
<td>●</td>
<td>◇</td>
</tr>
</tbody>
</table>

Figure 3 Upstream and downstream patterns for different velocity ratios at a constant We.

In Figure 3, the Weber number We, defined as $\rho U_i^2 D_i / 2\sigma$, was 9.08 and the evolution of the compound jet with increasing velocity ratio $u$, defined as $U_o/U_i$, is shown. For $u = 0.063$, the inner jet broke up periodically and stably at the exit of the nozzle to produce the bubbling jet, in the upstream, denoted by □; this bubbling jet remained unbroken in the downstream, denoted by △. As the velocity ratio was raised to 0.07 or 0.073, the inner jet broke up as before, but the bubbles merged together rapidly after going out the exit of the nozzle to become a larger one, then the bubble retracted into a sphere by its surface tension. Note that in the upstream the symbol □ denotes a quick breakup of the inner gas jet into bubbles and the symbol ◆ denotes a persistent inner gas jet. Through the waves of the outer
surface, the bubbling jet broke up regularly to produce gas-in-liquid compound drops, denoted by ○. For higher (u = 0.120) velocity ratio, the bubbles in the bubbling jet did not merge together anymore and the downstream part of the bubbling jet did not break up by the outer surface wave; this is again denoted as △. If we carried on adding the velocity ratio, the inner jet broke up stably, and the bubbling jet broke up by the outer surface wave to create compound drops in the downstream. This behavior is denoted as ●. It is noteworthy that satellites would appear and became larger with increasing velocity ratio. When the velocity ratio went up to 0.208, the inner jet did not break up near the nozzle exit but remained a jet for quite a long distance (denoted by ◆). The inner jet eventually broke randomly by Rayleigh breakup instability, and then the bubbling jet broke up unstably by the wave of the outer surface in the downstream; this is denoted by ◇.

Note that we have divided Figure 3 into two parts, the upstream and the downstream of the compound jet. For the upstream, it is easy to distinguish the bubbling regime and jetting regime, i.e. for u up to 0.196, the inner gas jet broke near the exit, while for u > 0.203 the gas jet remained unbroken for quite a long distance. The appearance of the upstream compound jet is related to the Weber number and the velocity ratio. We compared our results with Sevilla et al. [10] in Figure 4 and brought out some points: the tendency of the transition from the bubbling to jetting instability was very similar, but the major difference in our study from theirs is that the ratio of the inner and outer nozzle in our study was too small to ignore the interaction of the outer flow with the stagnated air and the interaction between the inner gas stream and the outer liquid shell. In Figure 4, the solid line was the theoretical criterion for bubbling/jetting transition, i.e. on the left of the solid line, the upstream of the compound jet will appear as a bubbling jet; while on the right, a compound jet (the inner gas flow would remain a jet) results. It is quite apparent that this criterion is affected strongly by the hardware, i.e. the sizes of the needles. Table 3 listed the needles used by Sevilla et al. and us. Our needle sizes were much smaller than theirs. In Figure 4, we can see that as the needle size was reduced, the criterion moved to the left, i.e. to smaller u. It is clear that the geometry of the nozzle played an important role in the bubbling-jetting transition. From the observation that the smaller geometry of the nozzle the more departure of the theoretical transition, we can reasonably deduced that there is more than one parameter to control the transition.

<table>
<thead>
<tr>
<th>Needle</th>
<th>Dii(mm)</th>
<th>Dio(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sevilla et al. I</td>
<td>1.66</td>
<td>1.194</td>
</tr>
<tr>
<td>Sevilla et al. II</td>
<td>1.27</td>
<td>0.838</td>
</tr>
<tr>
<td>Ours</td>
<td>0.3</td>
<td>0.17</td>
</tr>
</tbody>
</table>

For the phenomena in the downstream we focus on the composition of the compound drops and map the We-u diagram first as Figure 5, where the double dot chainline (—·—·) represents the bubbling/jetting transition as in Fig.4 and dashed line (— — — —) represents the transition from bubbling to compound drops, and we found that, when velocity ratio was between 0.2~0.45 and Weber number was lower than 7, gas-in-liquid compound drops were composed. For a velocity ratio larger or smaller than this criterion, the compound jet and bubbling jet are respectively composed. Furthermore, the larger Weber number, the more difficult for the jet to break up into compound drops.

![Figure 4 Comparison our upstream bubbling/jetting transition with these of Sevilla et al.](image)
Figure 5 Mapping the We-u diagram for downstream gas-in-liquid compound drops.

Now let us focus our attention on the compound drop regime, after recording the images of the gas-in-diesel compound drops, we can measure the outer diameters of the compound drops \(d_o\) by image tool and figure out the sizes of the bubbles \(d_i\) in the compound drops by the outer diameter \(d_o\), the outer flow rate \(\dot{Q}_o\), and the frequency of the compound drops \(f\), since the compression of the bubble in the compound drop is small and negligible. The relation between the parameters is expressed by:

\[
\frac{\pi}{6} (d_o - d_i) = \frac{\dot{Q}_o}{f} \Rightarrow d_i = \frac{\pi}{6} \frac{\dot{Q}_o}{f}
\]

(3)

where the frequencies of compound drops are calculated by the equation shown below, and modified by the frequency of the stroboscope \(f_s\). Note \(N\) is an integer.

\[
f = \frac{\dot{Q}_o + \dot{Q}_i}{\pi d_o^3} = Nf_s
\]

(4)

When the compound jet is monodispersed into a uniform compound drop stream, the composition of the compound drop is only related to the ratio of the inner and outer flow rate, i.e.

\[
\frac{d_o}{d_i} = \frac{\dot{Q}_o}{\dot{Q}_i} + 1
\]

(5)

It means that we can control the ratio of the inner and outer flow rates to change the composition of the compound drop. However, in the process of enlarging the velocity ratio, the satellites began to appear, then we have to account for the effects of the satellites and the equation is modified as

\[
\frac{d_o}{d_i} = \frac{\dot{Q}_o}{\dot{Q}_i} \left( \frac{d_o}{d_i} \right)^3 + 1
\]

(6)

where \(d_s\) is the diameter of the satellite. In Figure 6, the horizontal axis is the outer diameter of the compound drop, the vertical axis is the frequency, and different symbols represent different inner velocities. We only choose \(U_i = 16.7, 17.5, 18.3\) to map the f-do diagram because these data were more stable. In Figure 6, it is easy to observe that the outer diameter and the frequency of compound drop closely depend on each other no matter what the inner velocity is.

In Figure 7, the horizontal axis is the outer velocity and...
the vertical axis is the frequency of the compound drop, and the different symbols represent the different inner velocities. Roughly speaking the larger the outer velocity, the lower frequency of the compound drop would be, and it corresponds reasonably the larger outer diameters of compound drops. Note that the type of the data in Figure 7 correspond to $We \approx 2$ in the compound drop regime in Figure 5.

5. ACKNOWLEDGEMENT

The authors acknowledge the supports provided by the National Science Council, R.O.C. under the contract NSC94-2815-C-006-045-E.

6. REFERENCES