Deformation Behavior of Liquid-Packaging Bags under Drop Impact

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Abstract
The deformation behavior of liquid-packaging bags containing liquid subjected to drop impact was observed using a high-speed camera and the relationship between the behavior and the pressure of the bags measured using pressure sensors was investigated. Results indicated that the liquid-packaging bags have characteristic constriction and bulging, whose degrees vary with time, and the variation in the shape of the bags can be explained using the variation in the pressure of the bags estimated on the basis of the water hammer theory.

Key words
Liquid-Packaging Bag, Plastic Film Bag, Drop Impact, Deformation, Bulging, Liquid, Water Hammer Theory, Experimental Mechanics

1. Introduction
Many plastic and paper containers for liquid products, such as tea and soy source, have been used in recent years. However, there exist problems, such as an increase in the amount of plastic garbage. Under such circumstances, a reduction in the volume of plastics is required to minimize the adverse effect. Furthermore, paper containers consisting of paper made from 100% virgin pulp laminated with sheets of polyethylene film are considered to be the cause of problems, such as the consumption of paper resources because of difficulty in the recycling of paper. Therefore, the use of paper without laminate film and easy to recycle paper containers is desired.

To fulfill these requirements, the authors have developed a new container that consists of a paper case and a liquid packaging bag. The paper case is made of a sheet of recycled paper and the liquid packaging bag is made of plastic film for which the amount of plastic used is about 1/8 of that of plastic containers. The degree of bulging of the new container subjected to static pressure is about 1/8 of that of plastic containers. The liquid consisted of water and ethanol. Polyethylene particles of about 3 mm diameter were placed in the liquid to visualize the movement of liquid in the bag [3-5]. Ethanol was used to equalize the specific gravity of the liquid to that of the particles. Sample B contained sample A in the container consisting of a case made of transparent plastic sheets of 0.5 mm thickness, as shown in Fig. 1(b). Instead of a sheet of recycled paper. Two miniature pressure sensors (PS-5KC, Kyowa Electronic Instruments Co. Ltd.) were placed at 5 mm from the inner top and bottom surfaces of the bag, as shown in Fig. 1(a). The bags cooled or heated at temperatures \( T = 0, 25 \) and 80 °C were used.

Figure 2 shows the free-drop testing equipment. The samples were held at heights \( h = 0.2, 0.3, 0.4 \) and 0.5 m using two lengths of kite strings and pulleys and freely dropped onto a wood flooring of 12 mm thickness on a

2. Experimental Procedure
The samples used for free-drop tests are shown in Fig. 1. Sample A was a liquid-packaging bag made of nylon-polyethylene laminate film of 67 \( \mu \)m thickness, as shown in Fig. 1(a). Four sides of the bag were heat-sealed using a heat sealer. The bag contained about 1,000 ml of liquid. The liquid consisted of water and ethanol. Polyethylene particles of about 3 mm diameter were placed in the liquid to visualize the movement of liquid in the bag [3-5]. Ethanol was used to equalize the specific gravity of the liquid to that of the particles. Sample B contained sample A in the container consisting of a case made of transparent plastic sheets of 0.5 mm thickness, as shown in Fig. 1(b), instead of a sheet of recycled paper. Two miniature pressure sensors (PS-5KC, Kyowa Electronic Instruments Co. Ltd.) were placed at 5 mm from the inner top and bottom surfaces of the bag, as shown in Fig. 1(a). The bags cooled or heated at temperatures \( T = 0, 25 \) and 80 °C were used.

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concrete floor. The bottom drop was carried out for drop tests. Side images of the samples during free drop and rebound were captured using a high-speed camera (FASTCAM-Net Max, Photron Ltd.). A frame rate of 1,000 fps and a shutter speed of 1/1,000 s were used to photograph the samples. The pressure was measured with a pressure interface, as shown in Fig. 2, and the obtained data were fed into a computer.

3. Experimental Results and Discussion

3.1 Deformation of liquid packaging bag and behavior of liquid

Figures 3 and 4 show examples of the variation in the shape of the liquid-packaging bags with time subjected to drop impact at \( h = 0.5 \) m and \( T = 25 \) °C for samples A and B, respectively. In the figures, \( t = 0 \) s indicates the moment when the bottom of the container contacts the flooring. For sample A, the bulging of the lower sides of the bag started immediately after the bag contacted the flooring, as shown in Fig. 3(b), and increased in degree with time, as shown in Fig. 3(c). After the degree of bulging became maximum at \( t = 7 \) ms, bulging moved upwards accompanying the constriction of the lower part of the bag and the bag started to rebound from the flooring at \( t = 15 \) ms, as shown in Fig. 3(d). The bag completely left the flooring at \( t = 35 \) ms, as shown in Fig. 3(h). During the rebound of the bag, the degree of bulging was lower and the longitudinal length of the bag was larger than that immediately after the rebound, as shown in Fig. 3(k). Then, the bag dropped onto the flooring, as shown in Fig. 3(n). For sample B, as shown in Fig. 4, rebounding started at \( t = 15 \) ms. The degrees of bulging and constriction were smaller than those for sample A. This is because the case reduced the bulging of the bag for sample B.

The liquid in the bag swirled at the lower part immediately after the impact of the bag to the flooring and then moved considerably upwards at the upper part, at \( h = 0.5 \) m and \( T = 25 \) °C for sample A, as shown in Fig. 5. For sample B, the liquid did not move pronouncedly. This is because the case reduced the bulging of the bag, as described above, and consequently limited the movement of liquid.

Figure 6 shows the flow speed of liquid with swirling at the lower part of the bag and the speed of rising flow at the upper part of the bag.

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the upper part, compared with the theoretical speed at the impact of the bag to the flooring, as a function of the drop height at $T=25\, ^\circ\text{C}$ for sample A. These speeds were measured from the movement of polyethylene particles. The average speed of liquid with swirling was lower than the theoretical drop speed and approximately constant independent of the drop height. The maximum swirl speed was approximately equal to the theoretical one. This may indicate that the movement of liquid at the lower part was three-dimensional. The average rising speed was proportional to the drop height and approximately equal to the theoretical one as the drop height increased.

Figures 7 and 8 show the variations in widths $W_l$, $W_m$ and $W_u$ with time at $h=0.5\, \text{m}$ and $T=25\, ^\circ\text{C}$ for samples A and B, respectively. The width $W_l$ of the bag corresponds to the location $H=H_l$ (=20mm), at which the width became a maximum at the lower part of the bag. The width $W_u$ corresponds to the location $H=H_u$ (=270mm), at which the width became a maximum at the upper part, and the width $W_m$ corresponds to the midpoint of $H=H_l$ and $H_u$. For sample A, the widths were measured in the $t$ range of 0 - 15 ms during the bag’s contact with the floor. For sample B, they were measured in the $t$ range of 0 - 48 ms. For sample A, the width $W_l$ at the lower part became maximum at about 7 ms and then decreased to the value obtained before contact with the floor. After $W_l$ became maximum, $W_m$ and $W_u$ became maximum. For sample B, $W_l$, $W_m$ and $W_u$ gradually increased and then decreased to the value obtained before contact with the floor.

The curves shown in Fig. 7 were similar to a pressure variation caused by a water hammer phenomenon. The water hammer phenomenon is caused by a rapid valve closure and is accompanied by pressure change and fluid vibration. This occurs owing to a rapid change in fluid momentum [7]. In this study, the impact of the bag to the floor rapidly increased in pressure, and this high pressure propagated upwards as a pressure wave. The pressure propagation speed in a circular tube can be calculated using

$$a = \frac{K}{\rho} \left( 1 + \frac{Kd}{Et} \right)$$

where $K$ is the bulk modulus of water, $\rho$ is the mass density of water, $E$ is the Young’s modulus of the bag, $d$ is the diameter of an equivalent round bag with the same cross-sectional area as the maximum cross-sectional area of the bag, and $t$ is the thickness of the bag [7]. After substituting $K=2.25\, \text{GPa}$, $\rho=997.1\, \text{kg/m}^3$ [8], $E=2.0\, \text{GPa}$ [9], $d=62.6\, \text{mm}$ and $t=67\, \mu\text{m}$ to Eq. (1), $a$ was calculated to be 46.3 m/s. From this pressure propagation speed, the maximum
bulging at the lower part of the bag was estimated to occur at $t=6\text{ ms}$, and the maximum constricting at $t=12\text{ ms}$. The estimated time at which the maximum bulging occurs is approximately coincided with that shown in Fig. 7, and the estimated time at which the maximum constriction occurs was longer than that shown in Fig. 7. This longer time, which indicates the reduction in pressure propagation speed, may be due to the effect of friction between the bag and the liquid and the variation in the cross-sectional shape of the bag which is caused by the flow of liquid in the bag, which reduces the amount of energy.

The degrees of bulging and constricting for sample B, as shown in Fig. 8, greatly differed from those for sample A. This is because for sample B, the plastic case suppresses the bulging of the bag, as described above.

Figure 9 shows the variations in the widths $W_{t,0}$, $W_{t,25}$, and $W_{t,80}$ of the bag at the location at which the width is maximum at the lower part of the bag at $T=0, 25$ and $80 \degree C$ for sample A. These results indicated that the pressure propagation speed decreases with an increase in the temperature of the bag and liquid in the bag. This is mainly due to a reduction in the Young’s modulus of the plastic film of the bag.

### 3.2 Maximum pressure

Figure 10 shows an example of the time variations of the pressure in the bags measured using pressure sensors. Table 1 shows a list of the maximum pressures $p_{\text{max}}$ at the lower and upper parts of the bag at $h=0.3$ and $0.5$ m and $T=25 \degree C$ for sample A. The pressure at the upper part was approximately 1/7 times lower than that at the lower part. This pressure reduction may be due to a reduction in the amount of energy caused by the deformation of the bag.

In section 3.1, it was found that the deformation of the bag subjected to drop impact could be explained on the basis of the variation in the pressure of the bag estimated using the water hammer theory. Therefore, the maximum pressures were compared with the impact pressure $p_{\text{impact}}$ calculated using Eq. (2) [7, 10], which was induced by the water hammer theory.

$$P_{\text{impact}} = v_0 \sqrt{\frac{\rho K}{1 + (Kd/E_t)}}$$

In Eq. (2), $v_0$ is the drop speed at $h=0$ m when the bag drops from $h=0.3$ and $0.5$ m. The theoretical impact pressures for $h=0.3$ and $0.5$ m were 114 and 148 kPa, respectively. The measured pressures were lower than the calculated pressures. Their discrepancies may be caused by the variation in the cross-sectional shape of the bag which is due to the flow of liquid in the bag and the presence of heat-sealed areas, which act as a damper to impact, as shown in Fig. 1.

![Fig. 9 Variations in widths, $W_{t,0}$, $W_{t,25}$, and $W_{t,80}$ with time $t$ for Sample A](image)

![Fig. 10 Time variations of the pressure in the bags measured by pressure sensors at the lower and upper parts of the bags at $h=0.3$ and $0.5$ m and $T=25 \degree C$ for sample A](image)

### Table 1 Relationship between drop height $h$ and measured maximum pressure $p_{\text{max}}$ at the lower and upper parts of the bag at $T=25 \degree C$ for sample A

<table>
<thead>
<tr>
<th>$h$ (m)</th>
<th>$p_{\text{max}}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower part</td>
<td>Upper part</td>
</tr>
<tr>
<td>0.3</td>
<td>72.6</td>
</tr>
<tr>
<td>0.5</td>
<td>86.0</td>
</tr>
</tbody>
</table>

### 4. Conclusions

In this study, the deformation behavior of liquid-packaging bags containing liquid subjected to drop impact was observed using a high-speed camera and the relationship between the behavior and the pressure of the bags measured using pressure sensors was investigated. The results were as follows:

1. The liquid-packaging bags had characteristic bulging and constriction, whose degrees vary with time. The deformation of the bag was larger than that of the bag in a case. The variation in the shape of the bags could be explained on the basis of the variation in the pressure of the bag estimated using the water hammer theory.
2. The deformation behavior of the bag was affected by the temperature of the bag and liquid because of the temperature dependence of pressure propagation speed.

### References


