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高校内における微小重力実験装置の開発と実験

Development of dropping experimental apparatus and microgravity experiments in high school

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1. Introduction

1.1. Background

The Zero-Gravity Experiment Team at Tokyo Gakugei University Senior High School has been continuously conducting microgravity experiments through drop experiments within school and has presented its results. Last year, the team participated in JAXA's "Asian Try Zero G 2023," where experiments on capillary action were conducted on the ISS, among other activities related to microgravity (see 5. Appendix for details). However, the traditional method of conducting experiments by dropping a cardboard box containing the experimental apparatus within a classroom does not allow precise microgravity experiments. Therefore, to conduct high-precision microgravity experiments within school, we have developed a drag shield-type drop experiment device (hereinafter referred to as TGμ-DS1).

Figure1 . TGμ-DS1

1.2. Objective

We have been conducting experiments to observe the behavior of gas and liquid in a horizontal acrylic tube under microgravity conditions. These experiments were conducted using the drop tower at the Faculty Industrial Technology, Nihon University. This drop tower can maintain a g-quality of 10^{-3}G for 1.2 seconds[1]. Under these conditions, we were able to observe changes in the behavior of gas and liquid within the horizontal tube, as shown in figure 2,3."

Next, we attempted a simple experiment at our high school by placing the experimental apparatus inside a single-layer cardboard box. However, in this setup, we were unable to observe any changes in the behavior of the gas and liquid within the horizontal tube.

From this, we concluded that the reason for the lack of observable behavior was due to the insufficient g-quality of the cardboard box experiment compared to the drop tower at Nihon University. Therefore, our goal is to replicate the g-quality obtained with the Nihon University drop tower within our high school setting.

Comparison of
Nihon University Drop Tower Experiment and Cardboard Box Experiment

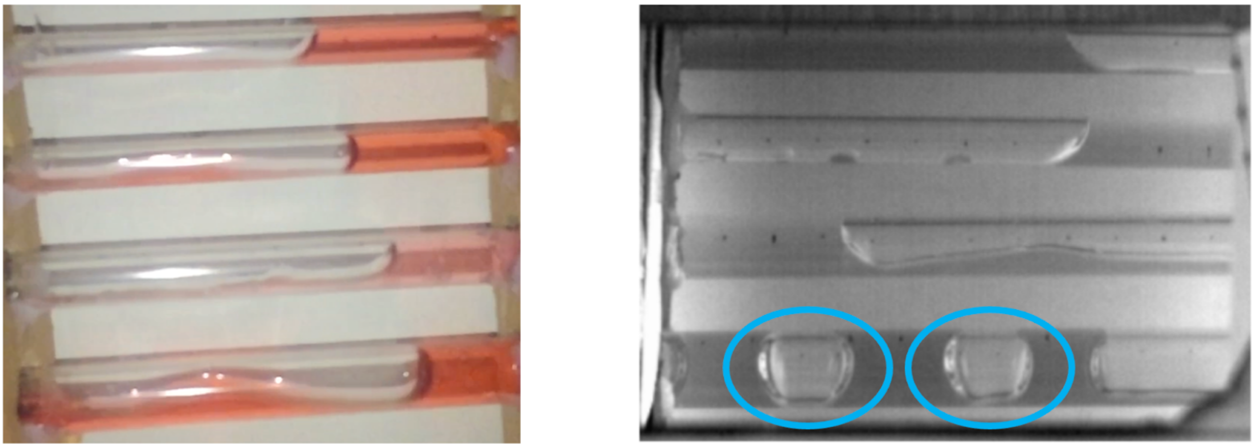


Figure 2 . Behavior of Gas and Liquid in a Horizontal Tube Observed in the Drop Tower at Nihon University[2] and in the Cardboard Box

2. Experimental Method

2.1. Experiment System

Our experimental setup can be primarily divided into two parts: the drop capsule TGμ-DS1 and the holding device TGμ-DD1. The setup allows for a drop distance of 10 meters from the third floor of the school building to the ground, creating a fall time of approximately 1 second. To ensure the procedures during the experiment are conducted accurately and safely, we have implemented various measures, including a procedure checklist and forbidden access to the drop area.

In pursuit of replicating the g-quality obtained at the Nihon University drop tower within our high school, we quantitatively measure the gravity levels using a Vernier wireless accelerometer (GDX-ACC E31-8200-08). This accelerometer can measure within a range of ±156.80 m/s^2 with an accuracy of ±0.01 m/s^2. Additionally, the experiment is recorded using the slow-motion function of an iPhone at 240 fps.

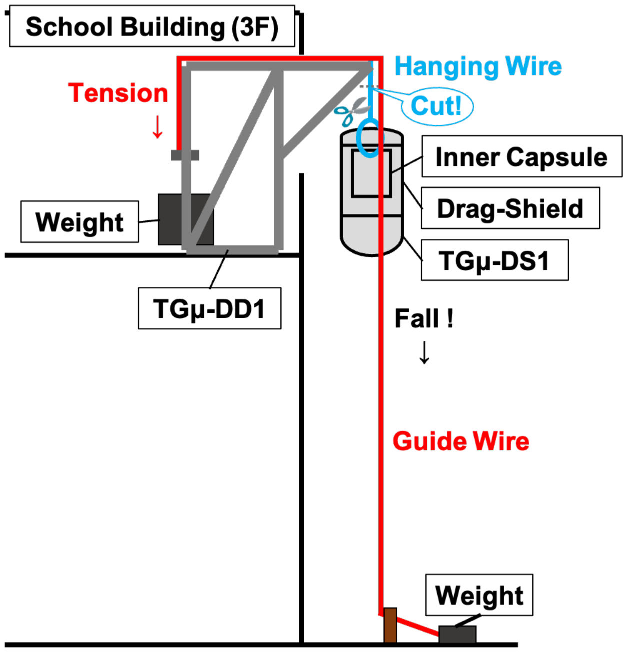


Figure 3. Side-view of the drop experiment using TGμ-DS1 and TGμ-DD1.

2.2. Drop Capsule

The TGμ-DS1 is a drop capsule that adopts a double-structure design. The outer capsule drag shield has a diameter of 380 mm, a total height of 800 mm, and weighs approximately 7 kg. The experimental space within the inner capsule measures 250 mm × 250 mm × 250 mm, and the inner capsule has a vertical movement range of 130 mm within the drag shield. The TGμ-DS1 is primarily constructed using an aluminum frame and wood, with some parts made with a 3D printer.

As shown in the figure, the TGμ-DS1 is hung using a hanging wire, and the drag shield and inner capsule are released at the same time for an independent free fall and independent free fall by cutting this wire. Scissors are generally used for cutting. Additionally, guide wires are passed through wire guides attached to the sides of the TGμ-DS1, preventing rotational motion during the fall and ensuring that the capsule does not fly off after the fall. The lower part of the TGμ-DS1 is equipped with a shock absorbing material and nose cone, “haack-kun” (figure 2).

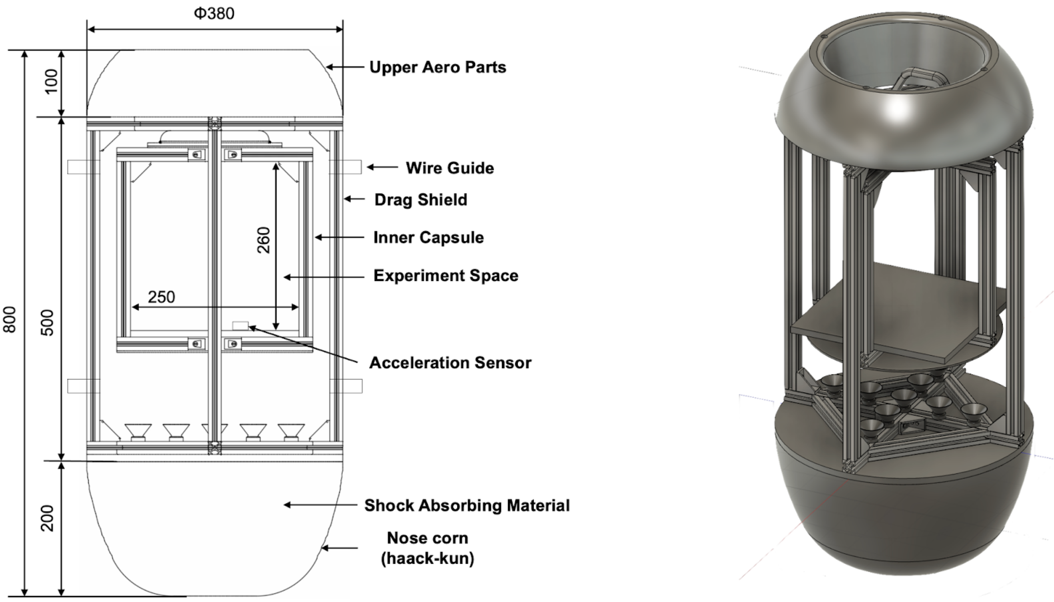


Figure 4. Structure of TGμ-DS1.

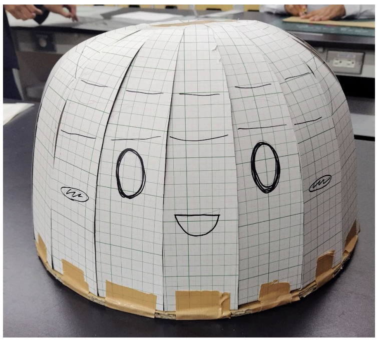


Figure 5. The nose cone named "haack-kun".

2.3. Drop Device

The TGμ-DD1 is a device used to hold the TGμ-DS1, which is a drop capsule, in place during its drop. This device is normally fixed to a wall using panel clamps. The device has a structure as shown in the figure, with a total length of 2000 mm, a total width of 500 mm, a height of 2000 mm, and a mass of approximately 75 kg. The TGμ-DD1 is primarily constructed from carbon steel using single-tube pipes.

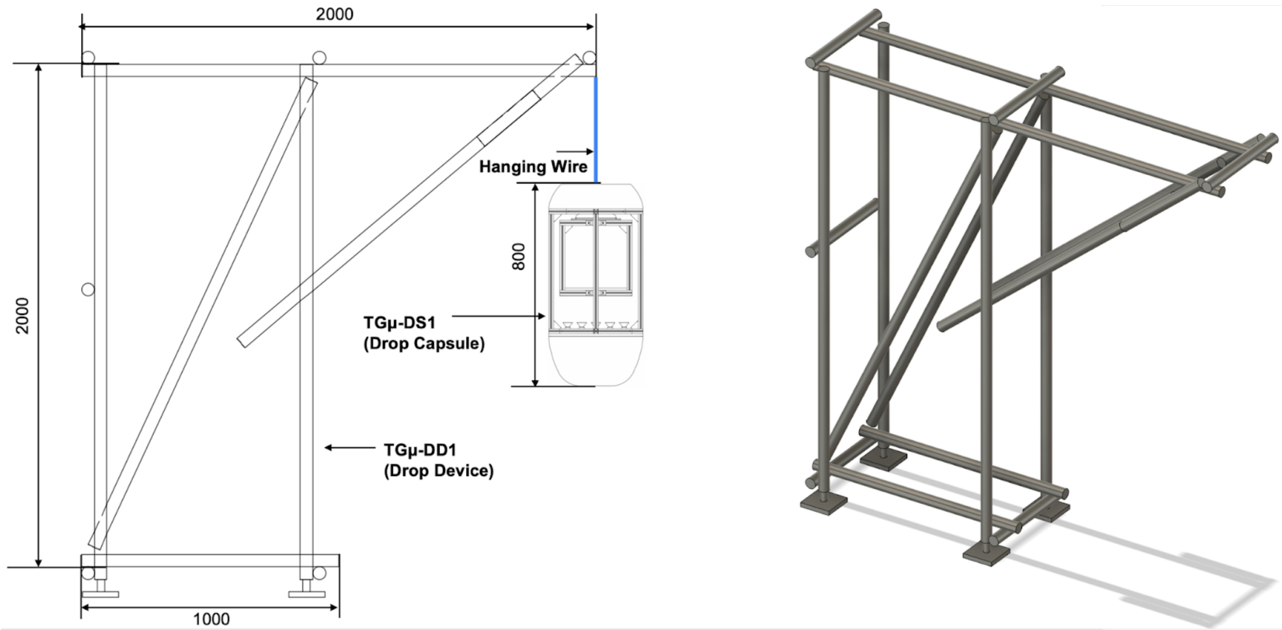


Figure 6. Structure of TGμ-DD1.

2.4. Conducted Experiments

2.4.1. Horizontal Tube Experiment (Experiment Ⅰ)

Experiment I was conducted to the g-quality of experiments using TGμ-DS1. The objective was to determine whether the same phenomena observed in the experiments conducted at the drop tower at Nihon University, as introduced in section 1.2, could be replicated using TGμ-DS1. At the time of this experiment, the TGμ-DD1 was still under development, and a simplified drop apparatus was used for the drop tests.

2.4.2. Experiments aimed at quantitative evaluation of g-quality (Experiment Ⅱ)

Experiment II was conducted to quantitatively evaluate the g-quality of experiments using TGμ-DS1. The TGμ-DD1 was used for this experiment. Five tests were conducted under the same condition. From the approximately 1.4 seconds of fall, a 1.0-second interval with the smallest standard deviation in the gravity level was extracted. The average and standard deviation of the gravity level in this interval were calculated. Data points with the maximum average gravity level and the initial data were removed as outliers. Additionally, graphs of the gravity levels for these data are also presented.

3. Results

3.1 Experiment Ⅰ

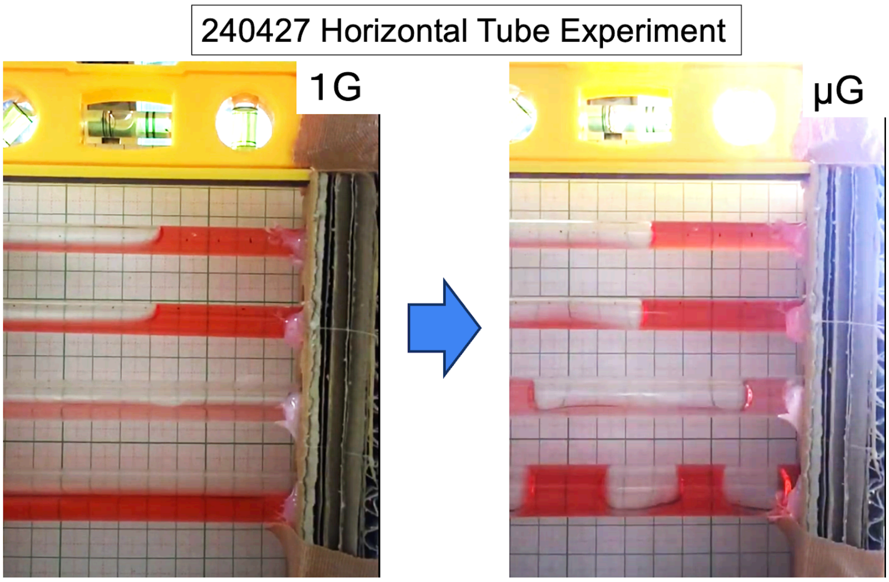
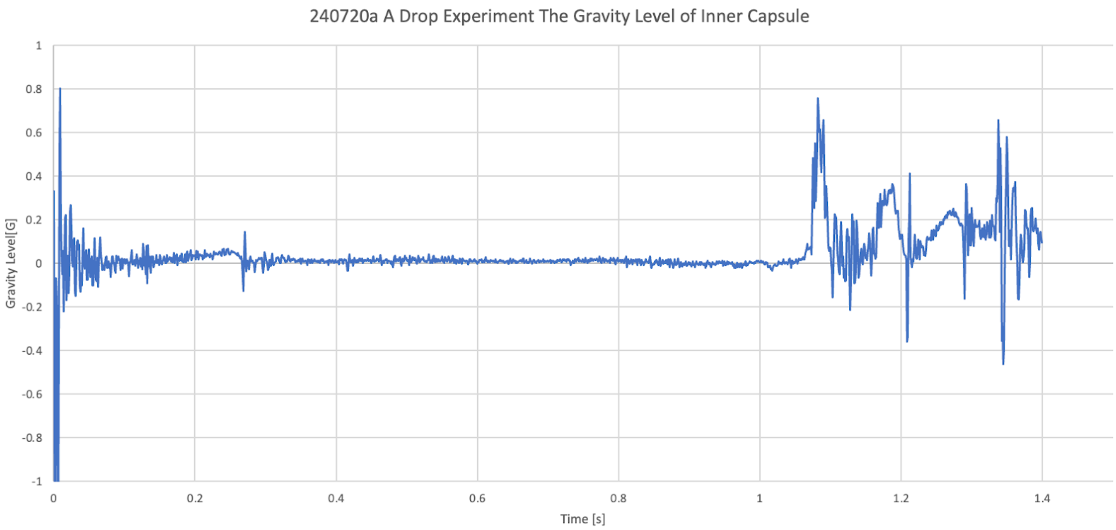


Figure 7. Horizontal tube experiment with TGμ-DS1.

In Experiment I, changes in the behavior of gas and liquid in a horizontal tube were observed.

3.2 Experiment II

In Experiment II, five experiments were conducted. The following are the results of the analysis performed using the method shown in 2.4.2.



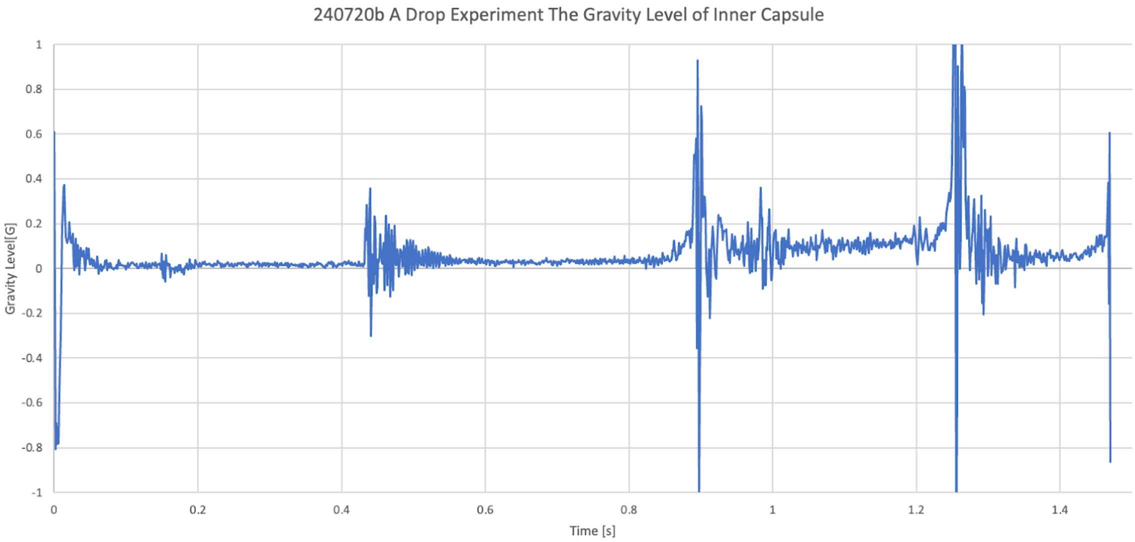


Figure 8. Typical graphs in Experiment II

Table 1. The result of Experiment II

Experiment code	Average Gravity Level [G]	Start Time [s]	Standard Deviation [G]
240720a	0.011	0.064	0.018
240720b	0.040	0.031	0.085
240720c	0.040	0.210	0.045
240720d	0.040	0.072	0.052
240720e	0.019	0.015	0.039

4. Discussion & Conclusions

4.1.1 Experiment 1 Discussion

The state of gas and liquid within the horizontal tube observed in Experiment I was more similar to the observations made during the experiments at the Nihon University drop tower than to those from the previous free-fall experiments conducted using the cardboard box. This suggests that the g-quality of experiments using TGμ-DS1 is closer to that of the Nihon University drop tower compared to the g-quality achieved with the cardboard box experiments.

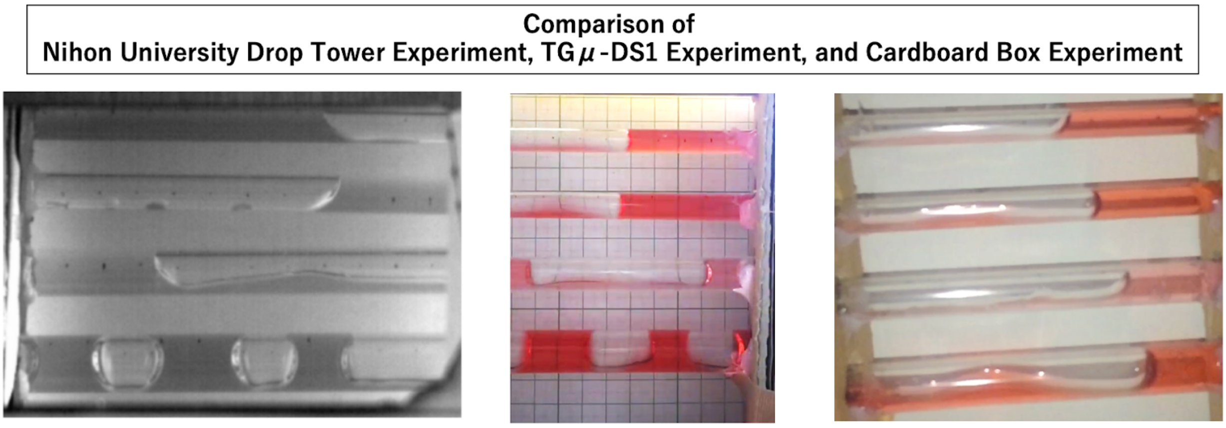


Figure 9. Comparison of three types of free fall experiments.

4.1.2 Experiment II Discussion

In Experiment II, the average gravity level during the 1.0-second interval of the approximately 1.4-second fall was 0.033G, with a standard deviation of 0.045G. Given that the gravity level in the cardboard box experiment was approximately 0.1G, it can be concluded that the g-quality of the experiments using TGμ-DS1 has improved compared to the cardboard box experiments. However, the graph from Experiment II shows that the gravity level fluctuates significantly during the fall. These fluctuations are believed to result from impacts when the inner capsule disrupted its orientation and collided with the drag shield, as observed in the video recordings of the inner capsule.

4.1.3 Discussion

Based on these findings, it can be qualitatively and quantitatively concluded that the g-quality of experiments using TGμ-DS1 is higher than that of the experiments using the cardboard box. However, the appearance of the horizontal tube in Experiment I differed from that observed in the experiments at the Nihon University drop tower, and the gravity levels achieved in Experiment II did not reach the target of 10^{-3}G as obtained at the Nihon University drop tower. Therefore, it can be said that the quality of microgravity experiments conducted within the high school could not be made equivalent to the quality of microgravity experiments conducted at the Nihon University drop tower.

4.2. Conclusion

Since changes in the behavior of the horizontal tube were observed with TGμ-DS1, it can be said that the g-quality of the experiments was improved using TGμ-DS1. This improvement has been confirmed quantitatively. However, the initial target of 10^{-3}G was not achieved, and significant vibrations during the fall were also observed. In the future, we aim to further enhance the g-quality by improving methods such as the separation of the inner capsule.

5. Appendix

We have been conducting several experiments using the apparatus we created.

5.1. Capillary action

The first experiment focuses on the capillary rise in a microgravity environment.

In March 2023, we conducted an experiment on capillary action under microgravity using the drop tower at Nihon University. The results showed that the rise speed of the liquid gradually decreased.

In August 2023, we needed to verify the capillary action using materials other than glass in preparation for experiments on the ISS. We tested various combinations of materials (acrylic, polycarbonate, ABS, fluororesin) and coatings (abrasives of 7 μm, 1 μm, 0.2 μm, and glass coating) using the drop tower at Nihon University. Among the tested conditions, acrylic with a 1 μm abrasive coating showed the best results.

In September 2023, an experiment was conducted using our school's drop tower to observe the capillary action under microgravity. The rise speed of the liquid resembled the Bosanquet equation ($\sqrt{t}$-(1-e^{-t}), approximately a linear function). Additionally, a narrower tube radius resulted in a greater rise per unit time.

In December 2023, we again conducted an experiment using our school's drop tower. The rise speed initially followed the Bosanquet equation (approximately a linear function) for the first 0.2 seconds, then it resembled the Lucas-Washburn equation ($\sqrt{t}$).

In March 2024, a further experiment was conducted, and the rise speed followed the Quéré equation ($t/\sqrt{2}$) for about 0.05 seconds, then the Bosanquet equation (approximately a linear function) until 0.5 seconds, after which it resembled the Lucas-Washburn equation ($\sqrt{t}$).

In summary, different trends were observed in each experiment, and we have not yet established a reproducible theoretical model.

5.2. Horizontal Tube

The second topic concerns the pitch (periodicity) of liquid plug formation in a horizontal tube under microgravity conditions.

Previous experiments have shown that when an acrylic tube containing air and tap water is subjected to microgravity, a liquid plug forms, and the gas-liquid interface becomes convex towards the liquid phase. It has also been determined that an inner diameter of approximately 12 mm is suitable for a simple free-fall experiment, with an appropriate gas volume fraction of about 0.5 to 0.4. Moreover, a previous study (Takamatsu et al., 1998) indicated that "the pitch of the liquid plug formation closely matches the most dangerous wavelength derived from the linear stability theory of the annular liquid film within the tube." However, the equation for the pitch of liquid plug formation in glass tubes, as given by Takamatsu et al. (1998)[3)]

$$\mathrm{X} = \lambda_d \approx 4.45 \times \phi \tag{1}$$

where x is the pitch, ϕ is the inner diameter of the tube, and λ_d is the most dangerous wavelength, does not hold for acrylic tubes.

The ultimate goal of this experiment is to derive an accurate equation to determine the pitch in acrylic tubes and to identify the factors that determine the length of the liquid plug. Currently, we are investigating the ease of plug formation and the pitch length in a tube with a 12 mm inner diameter, which is the most conducive to observing liquid plug formation, by varying the gas volume fraction.

5.3 Shock absorbing material

The third experiment focuses on the shock absorbing material used inside the nose cone part (haack-kun). The goal of this study is to develop shock absorbing material that can protect the TGμ-DS1 and its internal experimental apparatus from the impact of landing and reduce the bounce back after landing.

We primarily use cushioning materials such as bubble wrap and air pillow bag, polyethylene foam, and polyurethane foam as shock absorbing material.

In previous drop experiments, TGμ-DS1 and the internal experimental apparatus were basically undamaged, regardless of the material used, as long as the shock absorbing material had enough thickness. In particular, by using only air cushioning material, the height of the bounce could be reduced to about 0.2 m, one-fourth of the total length of TGμ-DS1.

Future research will focus on the difference in bounce height depending on the size and number of air cushioning material and the use of low rebound polyurethane foam as a shock absorbing material.

Currently, the challenge is that there is no method to evaluate the degree of shock absorption at landing other than analysis of the bounce height. We are also considering the use of honeycomb structures as a type of shock absorbing material.

References

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