PS02

灯芯拡散燃焼におけるフリッカリングの重力応答性

Gravity Response of Flickering in Wick Diffusion Flames

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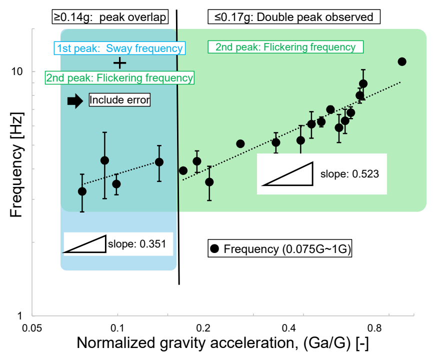

Abstract: The periodic oscillation of flame height, known as flame flickering, is a well-documented phenomenon that results from buoyancy-driven instabilities in laminar diffusion flames under normal gravity. While previous studies have established scaling relationships involving the Strouhal and Froude number, the precise gravity level at which flickering ceases, referred to as the critical gravity, has not been clearly identified. In this study, flickering behavior in a wick-fed flame was examined under partial gravity levels ranging from 1G to 0.075G. The gravity was controlled using the slope sliding method (SSMe), which allows repeatable and finely adjustable gravitational conditions in laboratory experiments. Temporal variations in flame height were recorded and analyzed using fast Fourier transform (FFT) to extract characteristic frequencies. The results indicate that the Strouhal–Froude correlation proposed by Hamins et al. is valid down to approximately 0.17G. In addition, the disappearance of flickering between 0.14G to 0G suggests that the critical gravity level lies within this interval. These findings enhance our understanding of buoyancy-driven flame dynamics under reduced gravity and support the development of combustion models applicable.

Keywords: Spirit flame, Partial gravity, Flickering, Buoyant flame

1. Introduction

1.1. Instability of flame behavior: "Flickering"

In relatively large-scale flames, such as those seen in large fires, the flame height often shows periodic up-and-down movement. This unstable behavior is generally called "flickering", and many studies have been conducted on this phenomenon[1-5]. **Figure 1** shows the behavior of flickering using a burner flame[1]. Hamins and others organized their own experimental results along with previous studies and showed that flickering can be plotted on a two-dimensional plane using the Strouhal number ($St=fd/v_f$) and the Froude number ($Fr=v_f^2/Gd$)[2](shown in **Fig. 2**). Here, f is the flickering frequency [Hz], d is the diameter of the fuel outlet [m], v_f is the fuel velocity [m/s], and g is the gravitational acceleration [m/s²]. Because gravity is included in the Froude number, this suggests that flickering is strongly affected by gravity.

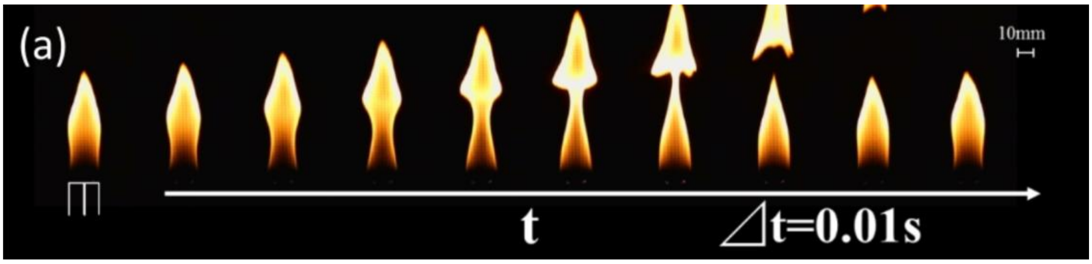

Figure 1. Flickering behavior on burner flame[1)]

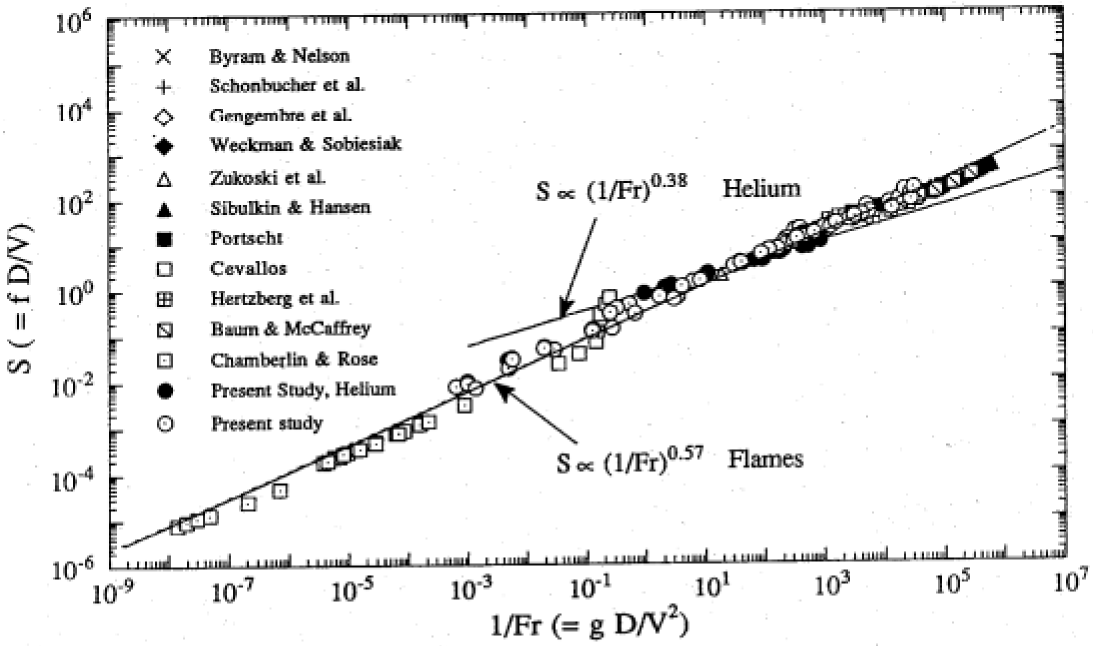

Figure 2. Relation of St-Fr^{-1} for flickering[2)]

1.2. Effect of gravity on flickering

As described above, flickering is considered to be strongly influenced by gravity, and many researchers have investigated how it depends on gravitational conditions. Sato et al. studied the flickering behavior under high-gravity conditions using a centrifuge and found that the flickering frequency increases steadily as gravity becomes stronger[3)]. On the other hand, Kato et al. conducted a microgravity experiment using a drop tower and found that flickering does not occur in microgravity[4)]. In this case, no characteristic frequency is observed, and the flame becomes steady. These results suggest that flickering is heavily influenced by natural convection, and that there may be a critical gravity level that determines whether flickering occurs. However, only a few studies have directly targeted this critical gravity value. One reason is that it is difficult to precisely control gravity in small increments between 0G and 1G (where G stands for the gravitational acceleration on Earth; 9.81 m/s^2)), and there are very few devices that allow for repeatable experiments under such conditions. Under these limitations, Yoshihara et al. used a counterweight based low gravity simulator at laboratory scale to study the behavior of pool fire[5)]. They performed experiments in the range from 1G to 0.55G and showed that the flickering frequency still correlates with the Froude number in this range. However, due to the limits of the device, they could not conduct experiments below 0.55G and therefore could not identify the critical gravity value.

1.3. Objective

To clarify the critical gravity value, it is necessary to use a partial gravity generator that can precisely control gravity between 0G and 1G. In this study, we used a method developed by the authors called the

"Slope-Sliding-Method environment 2 (SSMe2)"[5]. This method allows repeatable laboratory-scale experiments and can reproduce target gravity levels accurately, making it suitable for this study. The purpose of this study is to investigate the critical gravity for flickering, which is expected to exist in the range between 0G and 0.55G. The results are expected to help improve our understanding of combustion behavior under partial-gravity conditions, which is still a developing field.

2. Experimental design

2.1. Experimental device and protocol

Figure 3 shows a schematic of the experimental setup, and **Figure 4** shows direct photographs of the experimental setup.

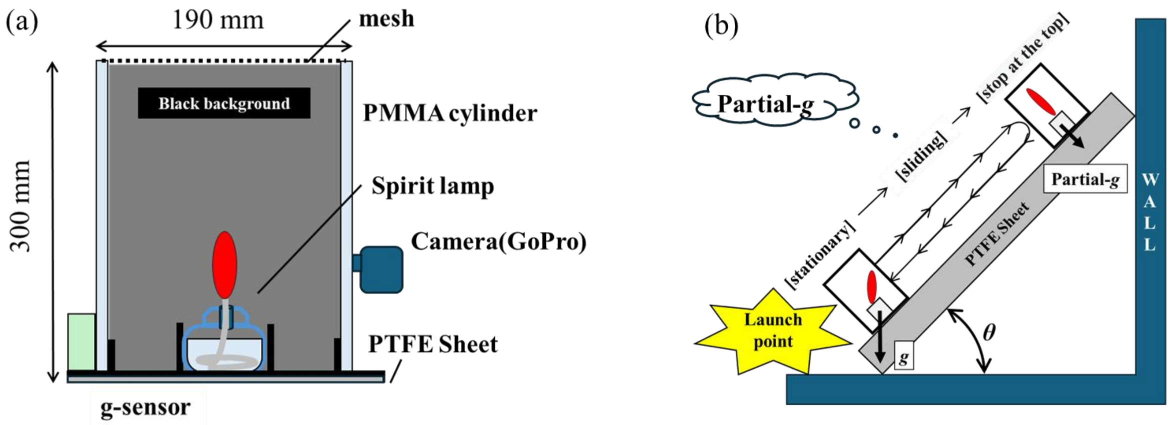

Figure 3. Schematic diagrams[5]: (a) experimental rack(without wings); (b) experimental concept.

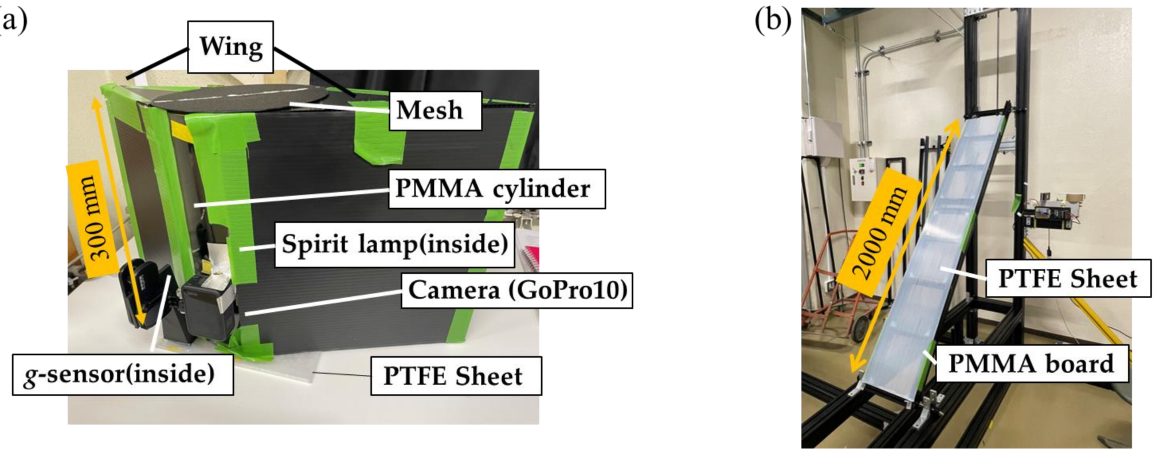

Figure 4. Pictures of adopted hardware: (a) experimental rack; (b) sliding board.

A flat PMMA board coated with a PTFE sheet (polytetrafluoroethylene: Chukoh ASF-110FR) was used as the low-friction surface, which served as the sliding slope base in this study. The longitudinal length of the slope was 2000 mm, and the angle was freely adjustable. In the present study, experiments were conducted at five prescribed angles: 45.0°, 47.5°, 50.0°, 52.5°, 55.0°, 57.5°, 60.0°, 62.5°, 65.0°, 70.0°, 75.0°, 78.0°, 80.0°, 81.5°, 83.0°, 84.5°, 85.0°, and 87.2° (corresponding to 0.703G ~ 0.075G). A cylindrical experimental rack with a height of 300 mm was equipped with a gravity (*g*) sensor (SRIC: G-men GR01, resolution: 0.02G) to record gravity throughout the experiment. Considering that the Ref 4 used liquid fuel, a spirit lamp, which is a suitable liquid fuel for the present experimental setup, was used in this study. A spirit lamp with a prescribed wick scale (dia.: 7 mm and length: 5 mm) was installed. It was set up to produce flickering under normal gravity (1G). A spirit flame fueled with a mixture of 85% methanol and 15% isopropyl alcohol was recorded with a camera (GoPro: HERO10: 3,840×2,160 pixels, ISO 200, shutter speed of 1/480 s, and high-speed mode of 120 FPS) during the sliding operations along the slope. Because both the lamp and camera were fixed to the rack, the vertical direction in the recorded images always corresponded to the normal direction relative to the slope surface. The camera was set 95 mm from the center plane along the wick axis to capture a full image of the flame. For better visibility, a black aluminum sheet was placed on the back side. The flame formed on the wick of a spirit lamp was recorded, and the flickering behavior was investigated by analyzing the flame height. The air drag acting on the cylindrical rack is known to affect both the acceleration and deceleration phases of the flow[6)]. To minimize this drag, a wing made of plastic corrugated board was attached to streamline the shape of the rack.

Note that liquid fuel is nearly 20% filled inside the ramp container (around 145 gram); therefore, the mass center of the liquid may be shifted temporary when a large acceleration is subjected (e.g. launching moment). The liquid does shake when g-jitter is presented, however, variation of the mass center caused by *g*-jitter is considered as negligibly small so that liquid motion during the sliding operation process will not affect largely on the flaming behavior in this study.

3. Results and Discussion

3.1. Time variation in flame height

As shown in **Fig. 5 (a)**, the definition of flame height (H_f) is from the top of the wick to the tip of the flame contour. Figure 5 (b) shows the temporal variation of flame height, where the time origin is set at the moment of launch (typical cases for a 55° slope: 0.60G). The flame begins to respond to gravity from 0 ms, and a certain time constant is observed until the flame height reaches a steady state. Accordingly, the period excluding this time constant was defined as the valid data region, and FFT analysis was performed on this interval.

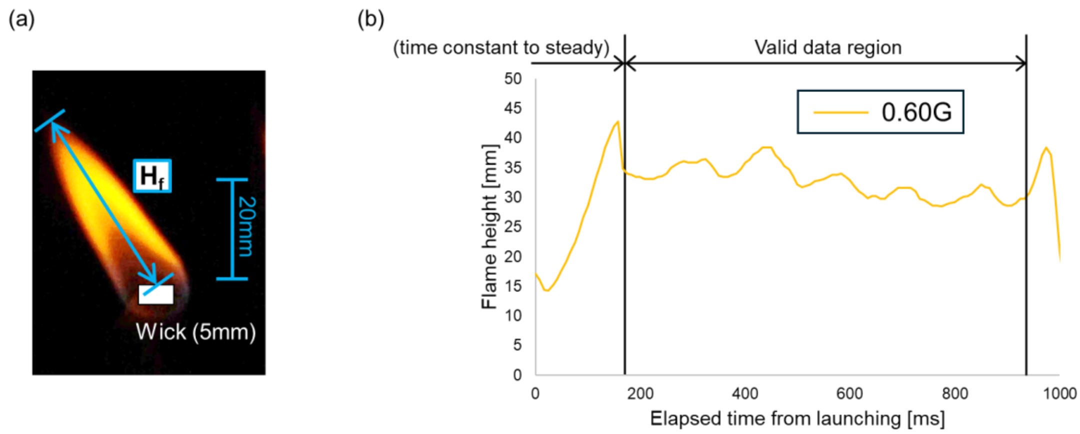

Figure 5. Typical cases for 55° slope (=0.60G): (a) Definition of flame height (H_f) in captured images ;(b) Time-sequence of the flame height.

Figure 6 shows sequential flame images under various gravity levels. Pronounced flickering is observed at 1G, while the oscillation appears somewhat suppressed at 0.73G. As gravity decreases, the oscillation diminishes proportionally, and at 0.099G, flickering seems to disappear entirely. This suggests that the critical gravity point may lie in this region. To verify this observation, FFT analysis was performed to identify the characteristic frequency components.

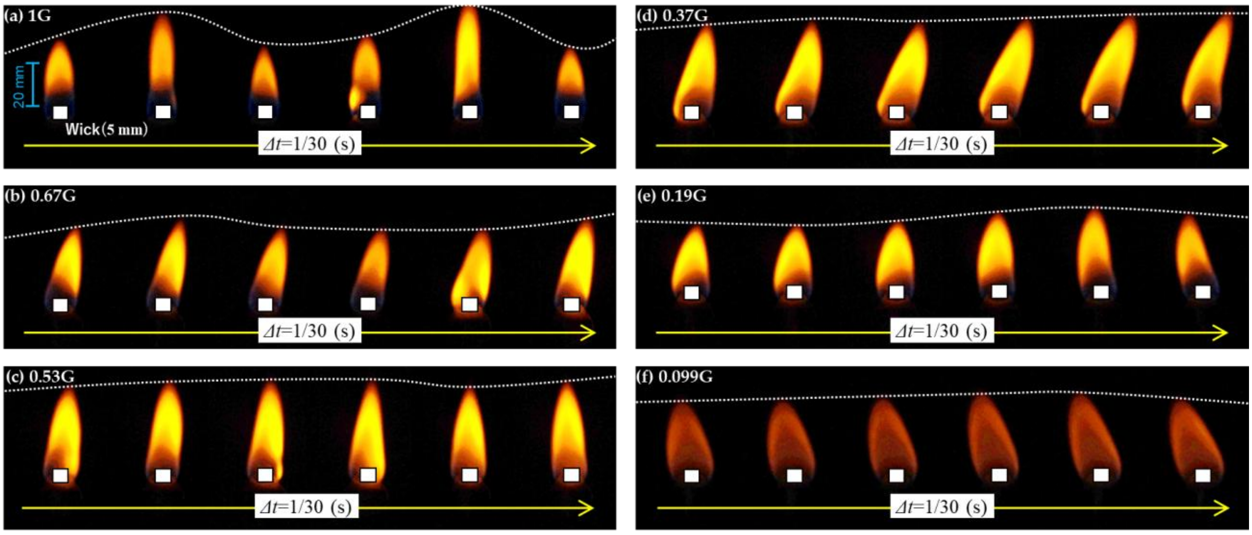

Figure 6. Sequential images of the flame appearance at various gravity levels during valid data region (adjust brightness +80%).

3.2. FFT Analysis

Figure 7 shows a three-dimensional plot of the FFT analysis results based on the recorded flame height data, where G_a is the net gravity acceleration subjected to the sliding object. The characteristic frequencies, presumed to be associated with flame flickering, are labeled above the spectral peaks. A clear trend is observed: the characteristic frequency decreases as the gravity level is reduced. This result indicates that flickering behavior is influenced by gravity, and that the characteristic frequency can serve as a quantitative indicator of this dependence.

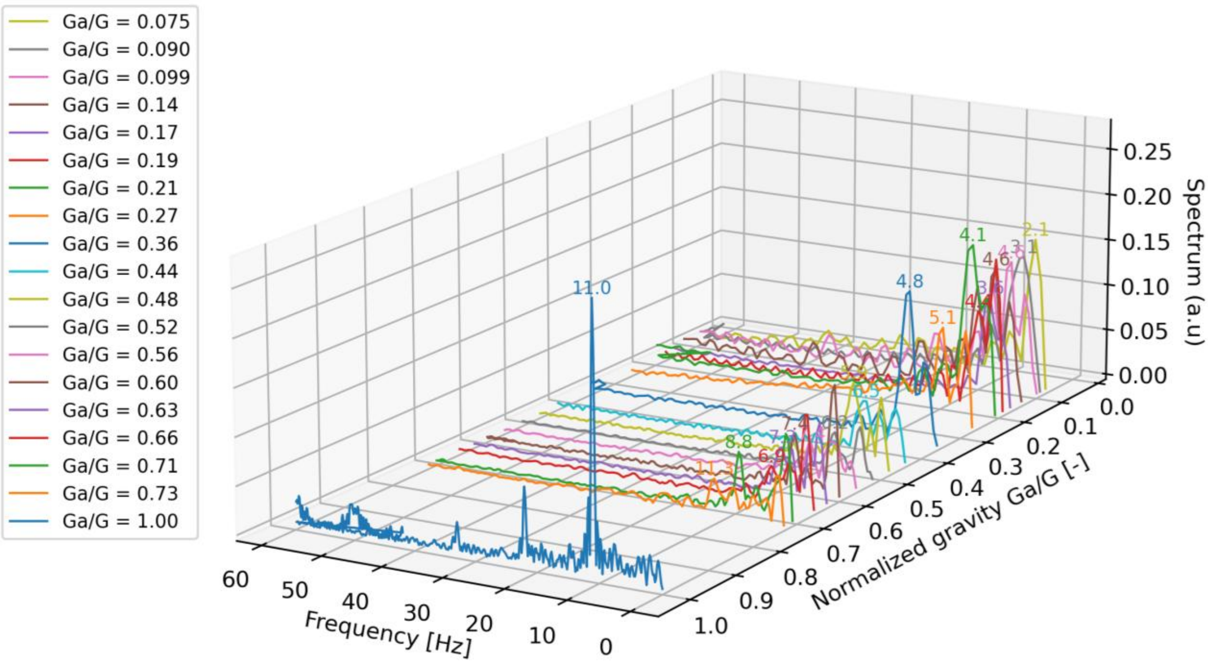

Figure 7. FFT analysis: Frequency components of the wick flame under various gravity levels (3D).

Figure 8 shows a two-dimensional graph constructed by extracting a portion of the FFT results presented in **Fig. 7**. Upon examining the results, it is observed that under 1G conditions, a single characteristic frequency, referred to as a "single peak," appears. In contrast, under reduced gravity conditions, two distinct frequency components become apparent, resulting in a "double peak" structure. These two peaks are treated as separate phenomena in this study. The first peak(corresponding to the blue area in **Fig. 8**), located in the range of approximately 1 to 2 Hz, is considered to result from the influence of the experimental setup. The second peak(corresponding to the green area in **Fig. 8**) closely matches the theoretically predicted flickering frequency and is therefore regarded as representing the flickering phenomenon itself.

At a gravity level of 0.14G, three peaks are observed, and two of them may overlap. As a result, it is difficult to pinpoint a single characteristic frequency at this level. Therefore, in the present study, the gravity range between 0.73G and 0.17G, where the double peak structure is clearly confirmed, is defined as the effective data area.

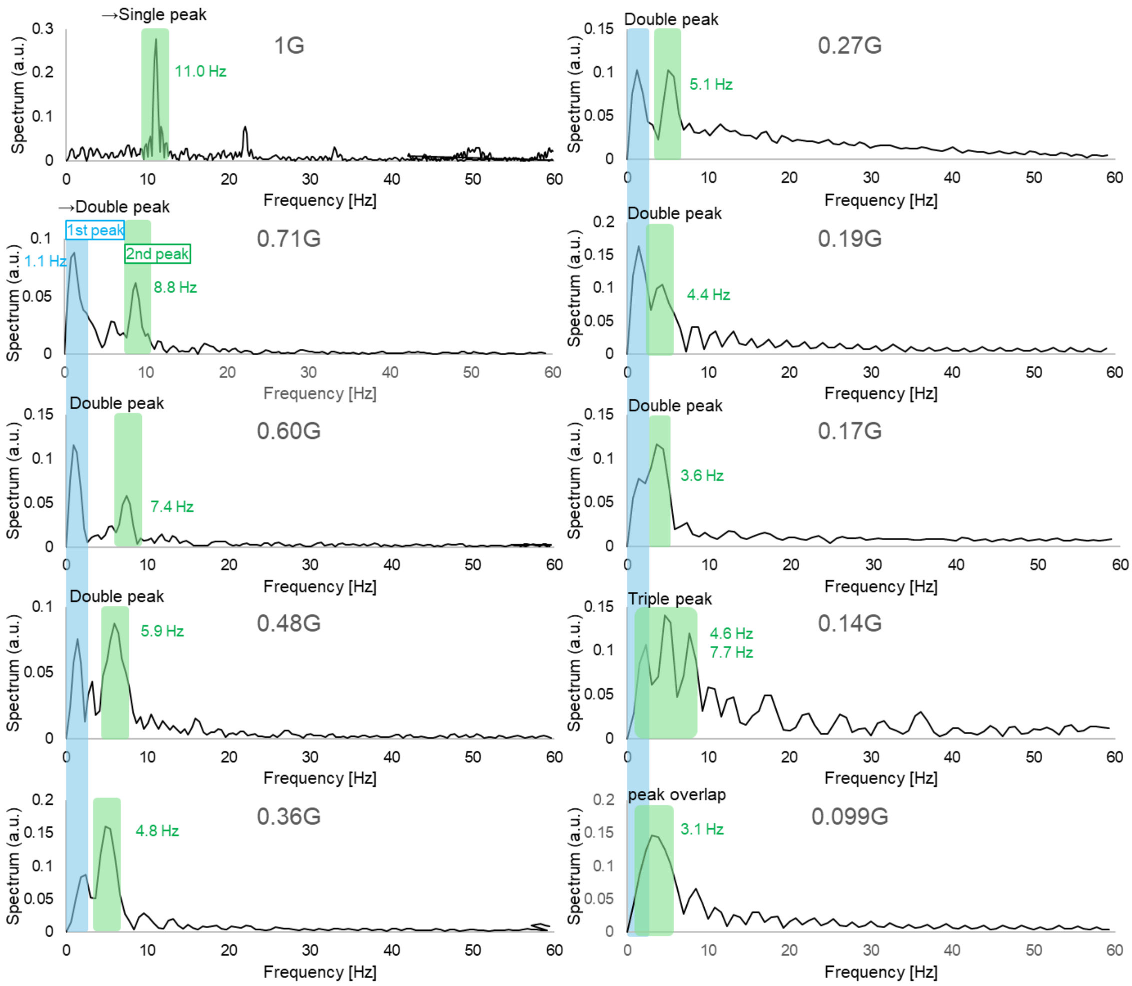

Figure 8. FFT analysis: Frequency components of the wick flame under representative gravity levels (2D).

Figure 9 shows the relationship between the characteristic frequency and gravity level. In the range from 0.17G to 1G, the obtained slope of 0.523 corresponds closely to the slope of 0.5 proposed in the frequency–gravity relationship[1]. This slope of frequency is formulated as follows:

$$f \propto G_a^{\frac{1}{2}}, \tag{1}$$

Here, f is the characteristic frequency [Hz]. This result is compared with the study on flame flickering in pool fires conducted by Yoshihara et al[4] (**Fig. 10**). In their reported experimental range of 1 G to 0.55 G, a slope of 0.502 was observed, which is in good agreement with the findings of the present study. This result indicates that the equation is valid for partial gravity environments above 0.17G. However, as discussed in Section 3.2., the frequency of lateral flame motion (1st peak, Figure10; blue area) and the flickering frequency (2nd peak, Figure10; green area) expected to appear in the gravity range below 0.14G may overlap, leading to an unacceptable level of error. In the present FFT analysis using a wick flame with the SSMe system, definitive confirmation of the point at which flickering ceases could not be obtained. Based on the experimental results, it is suggested that the critical gravity level lies within the range between 0.17G and 0G.

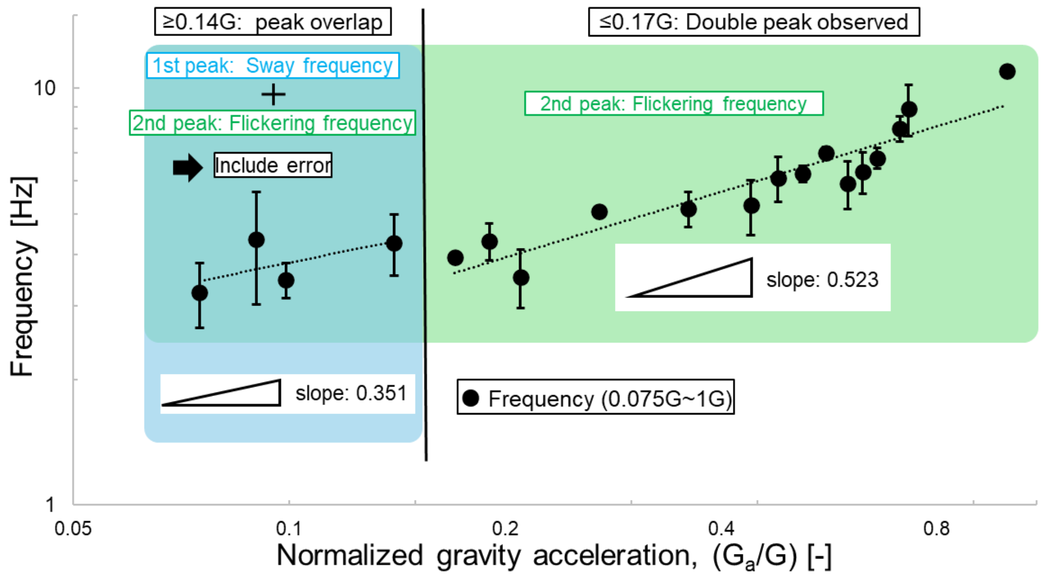

Figure 9. Characteristic frequencies under various gravity levels.

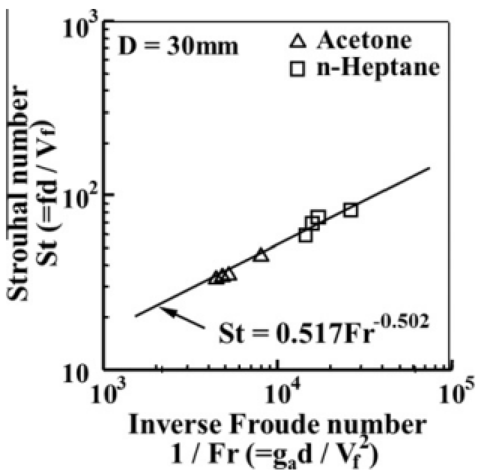

Figure 10. Characteristic frequencies under various gravity levels.(Yoshihara, Ito and Torikai)[4]

3.3 Peak frequency component

In Section 3.2., it was noted that the FFT results in this experiment exhibited a double peak. Here, we discuss the possible reasons for this phenomenon. **Figure 11 (a-1 to 3)** shows the flame behavior over time, which can be divided into three distinct phases. The first phase spans from the rack launch and the formation of the partial gravity flame until the onset of its inclination (approximately corresponding to the "climbing up operation"). The second phase extends from the initial moment of inclination to the point where the tilt stabilizes (approximately corresponding to the "turn over operation"). The third phase covers the period from the stabilization of the inclination to the end of the partial gravity interval (approximately corresponding to the "sliding down operation"). **Figure 11 (b-1 to b-3)** shows schematic diagrams of flame behavior for each operation. In the "climbing up operation" shown in **Fig 11 (b-1)**, the flame exhibits reciprocating motion between positions 1 and 2. In the "turn over operation" shown in **Fig 11 (b-2)**, lateral oscillation corresponding to the gravity direction **(1, 2, 3)** is observed. In the "sliding down operation" shown in **Fig 11 (b-3)**, reciprocating motion is again observed. However, an important distinction is that, when comparing positions **1** and **3**, position **3** is influenced by the lateral oscillation experienced at position **2**. As a result, the FFT analysis for each interval shown in **Fig 11 (c-1 to c-3)** reveals a double peak only in **c-3**, indicating the presence of low-frequency oscillation during the "sliding down operation."

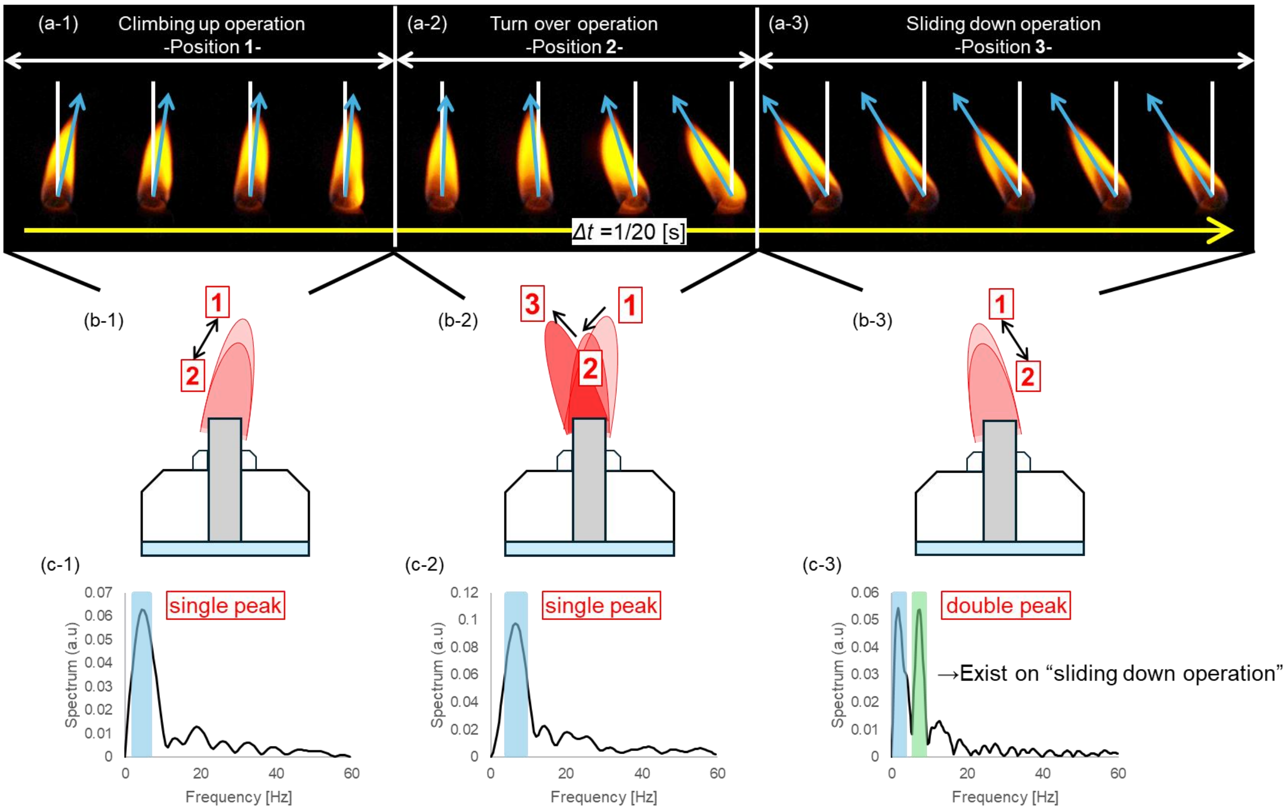

Figure 11. Temporal Analysis of Flame Behavior (Typical case for 0.60G): (a-1 to 3) Time evolution of flame behavior, (b-1 to 3) Schematic diagrams of flame behavior in each phase, (c-1 to 3) FFT results segmented by phase.

The reason for the presence of low-frequency oscillation of approximately 2 Hz during the "Position 3 (sliding down operation)" is examined. This phenomenon is considered to result from the lateral restoring motion experienced by the flame. **Figure 12** shows a schematic of the heat transfer process in wick combustion. In wick combustion, heat flux is transferred from the flame surface at flame temperature T_f to the wick, causing fuel evaporation and subsequent flame formation. Flame formation involves a time delay (τ), corresponding to the time required for heat to traverse the distance between the flame surface and the wick (δ). Consequently, the lateral disturbance component, after experiencing this delay, manifests as low-frequency flame oscillation at position **3**. As this originates from the delayed heat transfer inherent to alcohol lamp combustion, it is expected that employing a burner for flame formation would eliminate this effect.

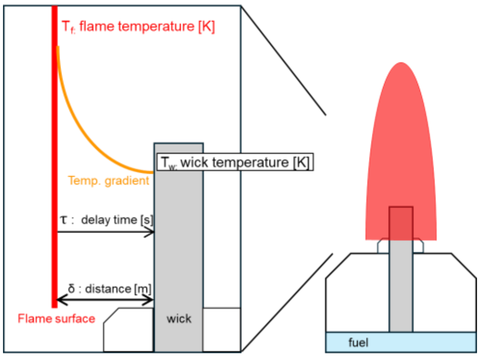

Figure 12. Schematic of the heat transfer process in wick combustion.

4. Concluding Remarks

In this study, the Slope Sliding Method (SSMe), which is feasible at the laboratory scale, was employed to conduct a detailed investigation of the flickering behavior of wick flames under a wide range of gravity conditions, from 1G down to 0.099G. Analysis of the temporal fluctuations in flame height using FFT confirmed that the relationship between the Strouhal number and the Froude number is applicable down to 0.17G. Furthermore, flickering disappeared in the gravity range between 0.17G and 0G, with no distinct peak observed, suggesting the existence of a critical gravity acceleration at which flame oscillations cease. The findings obtained in this study are significant for understanding the influence of gravity levels on combustion behavior and are expected to contribute foundational data for the safe fire control and prediction technologies in space and planetary environments in the future.

Acknowledgments

This study was partially funded by Suzuki Foundation. Technical assistance delivered by Mr. Ogawa (Toyohashi U Tech) was helpful in conducting the tests. We would like to express our sincere appreciation for this support.

Conflicts of Interest

The authors declared that there is no conflict of interest.

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