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Extinguishing the dripping flame by acoustic wave

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ABSTRACT

Dripping of molten fuels is a widely observed phenomenon in the wire fire and façade fire, which promotes the fire spread and increases the fire hazard. The flame attachment to drip is a necessary condition for dripping ignition, so that extinguishing the dripping flame can effectively reduce the dripping fire hazard. In this work, we investigated the use of acoustic wave to extinguish the fast-moving dripping flame. Continuous drips, with a mass of 6.2 mg and a diameter of 2.6 mm, were produced from a burning polyethylene tube, and two fall heights, 0.3 m and 0.7 m with velocities of about 2 m/s and 3 m/s, were selected as the targets. The sound source varied in pressure from 80 to 114 dB and frequency from 90 to 110 Hz. Results showed that the effectiveness of flame extinction by acoustic wave decreases as the dripping velocity increases, so the acoustic wave is more effective to extinguish the dripping flame in the early stage. An extinction criterion was formulated based on a characterized Damköhler number to describe the underlying mechanism. This work provides important information on the acoustic effect on a moving flame and helps mitigate the fire hazard of dripping phenomena.

1. Introduction

Application of acoustic wave to control flame behavior has been an active research topic in combustion [1,2]. Different from the flame behavior in the airflow, flames under the acoustic environment are affected by a pressure gradient, so the sharp density gradient may promote the flame displacement from its original position [3,4]. Based on this mechanism, the extinction of flame could be expected when the two primary acoustic parameters, i.e., the sound pressure and frequency, are appropriately assigned. Several studies in the literature [5–10] have defined acoustic oscillation as an effective fire extinguisher.

The flame response to the sound varies with the applied frequency [11,12]. In the 'DARPA' project funded by the US Department of Defense [13], a positive correlation between the extinction pressure and the extinction frequency was found for a gas burner under the sound frequency from 35 to 150 Hz and pressure from 0.2 to 112 Pa (equals to 80–135 dB).[1] A similar effective acoustic suppression was confirmed by Niegodajew et al. [10] and demonstrated for the liquid line flame by Friedman and Stoliarov [9]. Recently, Yamazaki et al. [4] found a strong deformation to the non-premixed flame sheet around a sound frequency of 400 Hz. All these previous studies focused on the acoustic suppression on the flame produced by the stationary burner. Mckinney and Dunn-Rankin [14] investigated the effect of acoustic on the flame from tiny droplet (100–250 μm) with an upward velocity of 10 m/s, and found that under a large sound pressure, the droplet flame was extinguished due to the acoustic-driven flame displacement. This work, however, aims to extend the physical findings of previous studies that did not explore the potential use of acoustic wave to extinguish a moving flame in the fire.

Dripping of molten fuels is a widely observed phenomenon in the wire fire and the façade fire, which promotes the fire spread and increases fire hazards [15–19,26]. The most common example of dripping is the burning candle, where the molten wax flows downward and forms a drip without the flame attachment (Fig. 1(a)). In a realistic fire scenario, however, drips melted from wire insulation (Fig. 1(b)) and façade material (Fig. 1(c)) can often carry a flame, i.e. the dripping flame. Previously, the flame attachment is found to be the necessary condition for drips to ignite other fuels, providing the potential to enlarge the scope of fire [15]. Therefore, extinguishing the flame attached to the drip can significantly lower the fire hazard of dripping phenomena.

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[1] $dB = 20 \cdot \log_{10}[Pa/(2\cdot 10^{-5})]$.

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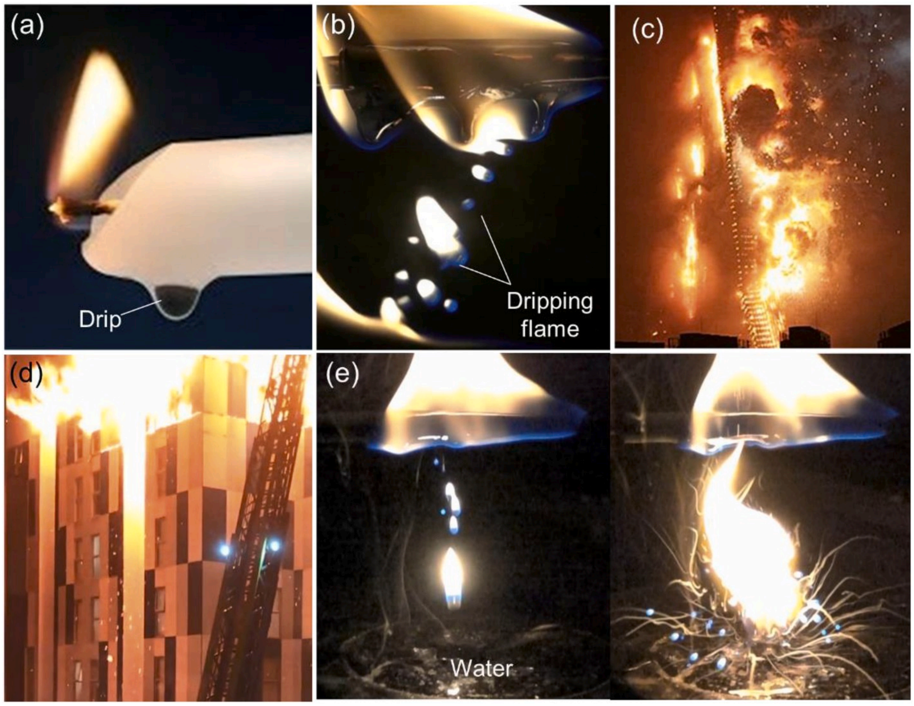

Fig. 1. (a) Drip from a candle flame, (b) dripping flame in wire fire, (c) dripping phenomena in 2017 Grenfell Tower fire, (d) 2019 Bolton façade fire, and (e) boil-over when dripping flame contacts water.

Nevertheless, conventional water-based fire suppression technologies are hard to track the fast-moving flame. Moreover, using water may not be suitable for extinguishing the dripping flame, because the hot drip of molten thermoplastics can interact with water, which causes a dangerous boil-over behavior [20] and a sudden increase in fire intensity, as shown in Fig. 1(e). Thus, a better fire strategy is desired to mitigate the fire risk of dripping flames, such as the use of acoustic wave.

As the drip is accelerated by gravity, the initial stable diffusion flame surrounding the drip will move behind, and eventually, develop to a stable flame-shedding structure after the fall height of 0.7 m and dripping velocity of about 3 m/s [15], as illustrated in Fig. 2. Such a flame-shedding process appears to the eye to be a blue chain of flame as a result of the persistence of vision (Fig. 2(a), see in Video S1). Moreover, such a flame shedding is very stable and could remain for a fall height of at least 2.6 m and reach a dripping velocity of 4 m/s. Since the dripping flame is essentially a burning specimen with subjecting the airflow, the associated acoustic extinction can be attributed to the combined effect of the acoustic wave and the dynamic flow which depends on different forms of dripping flame at different fall heights.

In this work, we conducted experiments to investigate the acoustic-driven extinction of the fast-moving dripping flames under various acoustic environments. Different forms of fast-moving dripping flame under different fall heights were investigated and compared with the stationary candle flame. Dripping flame behaviors before extinction were also analyzed to explore the underlying acoustic extinction mechanism.

2. Experimental method

2.1. Fuel and flame

Fig. 3(a) illustrates the experimental setup where drips were generated from a horizontally burning polyethylene (PE) tube. To better control the drip size and dripping rate, solid stainless steel (SS) rod was inserted into the PE tube to control the heat transfer of molten PE within the flame. This approach is analogous to previous dripping studies [15–17]. As the dripping fire hazard increases with the size of drip, the largest PE drip, with a diameter of 2.6 mm, the mass of 6.2 mg, and the flame width of about 3 mm, was used to demonstrate the effectiveness of acoustic suppression on the dripping flame.

The trajectory of the dripping flame was set to the vertical central place of the speaker and 16-mm away from the speaker surface. As the form of dripping flame changes with the drip speed during the falling process (Fig. 2), two fall heights ($H = 30$ and 70 cm) between the PE tube and the speaker axis, where the dripping velocities (V_{dr}) were measured to be about 2 m/s and 3 m/s, respectively, were taken as the research targets (see in Videos S2 and S3).

As a base case, the effectiveness of acoustic suppression was firstly examined with a stationary candle flame, which also helped explore the critical acoustic condition for extinguishing the dripping flame. The setup for the candle test is illustrated in Fig. 3(b). A thin candle, with a diameter of 3 mm and a length of 115 mm, was utilized to produce a stable flame, and this candle flame had the same size as the dripping flame. In order to ensure a similar sound regime to the dripping flame, the axis of candle overlapped with the trajectory of dripping flame, and its flame surface was positioned on the axis of the speaker center and the same 16-mm away from the speaker surface.

2.2. Sound source

Since the acoustic response of flame is the most prominent in the low-frequency range, a subwoofer was used as the speaker to emit uniform acoustic waves. The diameter of the speaker was 460 mm, and its maximum power limit was 800 W. This large speaker preferred to allow different drips to experience the same acoustic phase, and the residence time of dripping flame (about 0.2 s) was not too short [15].

The wave was generated by a wave generator, and the sound power was controlled by an amplifier. In the current setup, the flame had a most prominent response to the sound frequency of about 100 Hz. Therefore, the frequency band ranging from 90 to 110 Hz was studied in detail. Note that this frequency band is higher than that used commonly in previous works (30–60 Hz), which is attributed to the dependence of

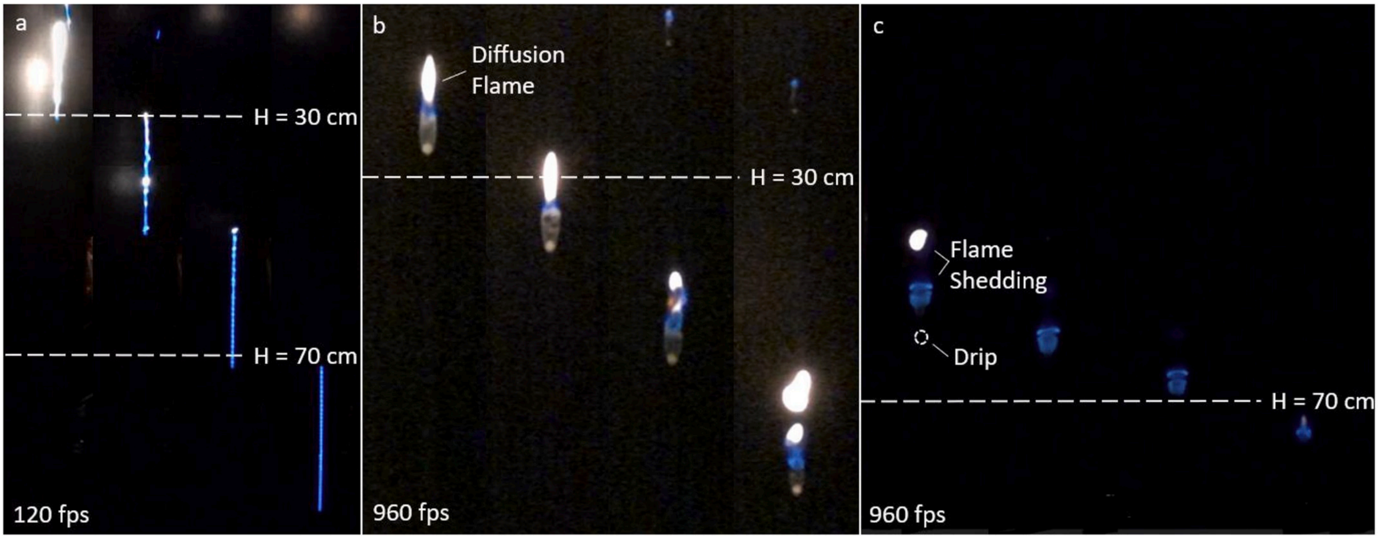

Fig. 2. Snapshots of dripping flames (a) from a burning PE wire under the shutter speed of 120 fps (see Videos S1) and (b) at the fall height of 30 cm and dripping speed of 2 m/s (Video S2), and (c) at the fall height of 70 cm and dripping speed of 3 m/s under the shutter speed of 960 fps (Video S3).

frequency response of flame on the speaker size. Actually, a 305-mm speaker was tested first, where a sensitive flame response resides in the frequency range of 40–80 Hz, but the phase impact cannot be avoided. For the current experimental set-up, the flame shows a reluctance to respond to the frequency lower than 90 Hz. Further increasing frequency higher than 110 Hz can also cause flame extinction, however, the required sound pressure would increase sharply and exceed the safe operating limit of the amplifier and speaker. To ensure that the sound field was developed naturally, the speaker center was placed 940 mm above the floor. Also, there was no sidewall nearby reflecting the sound waves.

The measurement of sound pressure was performed by a portable decibel meter, which works in the range of sound pressure level (SPL) from 30 to 130 dB with the accuracy of 0.1 dB and records data at every 1 s. Fig. 4 shows the measured horizontal and vertical SPL distributions from the centerline of the flame trajectory plane. Since the sound field was the most uniform within a region of 30-cm diameter (the blue region in Fig. 4), only the extinction events within the semi-uniform acoustic field were counted as the effective extinguishing.

For the candle flame, a sound-proof panel was placed between flame

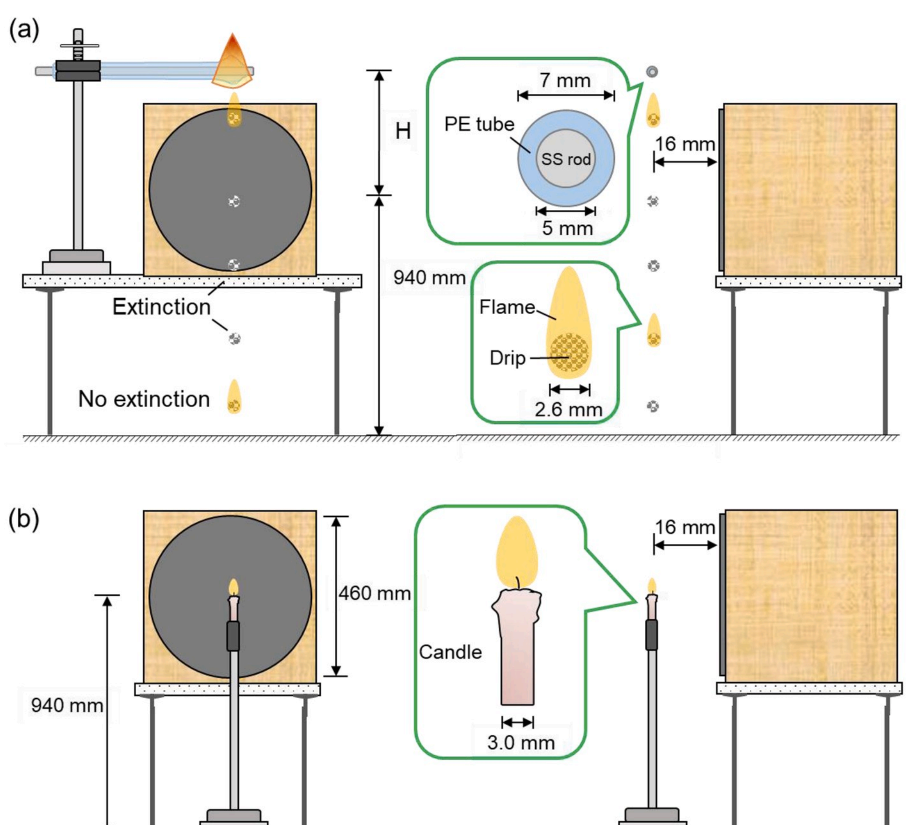

Fig. 3. Schematic of the experimental setups of (a) the dripping-flame test, and (b) the candle-flame test.

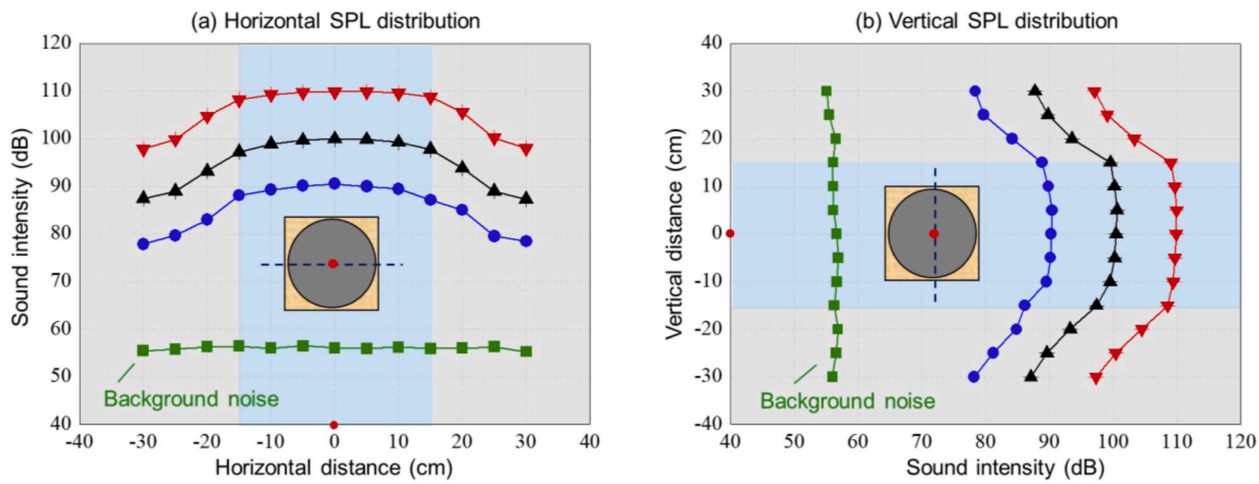

Fig. 4. Sound pressure distributions in (a) horizontal and (b) vertical directions on the plane 16 mm away from the speaker surface, where the irradiated frequency is 90 Hz.

and speaker before the activation of the speaker. Once the sound field reaches the assigned pressure and frequency, the panel was slowly removed to minimize the air perturbation. For the dripping flame, once a 10-cm PE tube was ignited, more than 300 drips could be produced to fall into the same acoustic field, so that the extinction probability could be estimated. At least three trials were repeated for each acoustic field to improve the accuracy of measurement. A high-speed camera was used to capture the extinction behaviors of different flames within the semi-uniform acoustic field.

3. Results

3.1. Extinguishing the stationary candle flame (base case)

To provide a suitable basis for the extinction of the dripping flame, the tested candle flame should be extinguished instantly when entering the sound field. Fig. 5 shows a typical extinction process of the candle flame subjected to the sound pressure of 110.4 dB and the frequency of 90 Hz, where sound waves enter the domain from the right to left (see Video S4 at 960 fps). It can be seen that near extinction, the flame does not strictly follow the direction of sound propagation, but waves from side to side. Specifically, the extinction of candle flame occurs within one acoustic cycle (about 11.1 ms), in which the flame is displaced from the wick. Based on arguments made in Ref. [9], this extinction may be attributed to the disruption of the flame-fuel-supply cycle by acoustic-driven flame displacement.

To confirm the stable burning behavior of the candle flame as a reliable base, the average mass loss rate without applying any sound field was recorded and shown in Fig. 6(a). Experiments were repeated three times, and the flame lasted for about 330 s before burnout. The stable mass loss rate, with a relative uncertainty of less than 5%, indicates that the candle flame is very stable and has a good repeatability. For the same reason, under a given sound field, the candle flame will always show the same behavior (sustained/extinguished), rather than showing a probability of extinction.

By varying the pressure and frequency of the sound source, the critical acoustic conditions for the extinction of candle flame were determined with at least three repeating tests. As plotted in Fig. 6(b), there is a positive correlation between the critical sound pressure and frequency for flame extinction, which agrees with those of other stationary flames in the literature [9,10].

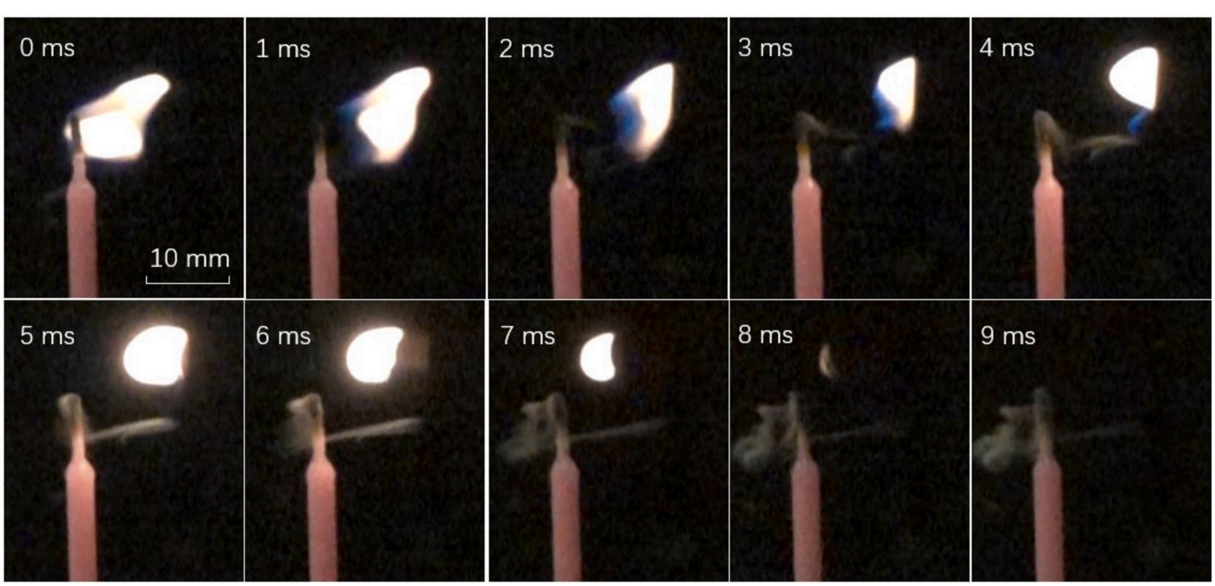

Fig. 5. The candle flame experiencing acoustic oscillation at a frequency of 90 Hz and pressure of 110.4 dB, where sound waves enter the domain from the right to left (Video S4 at 960 fps).

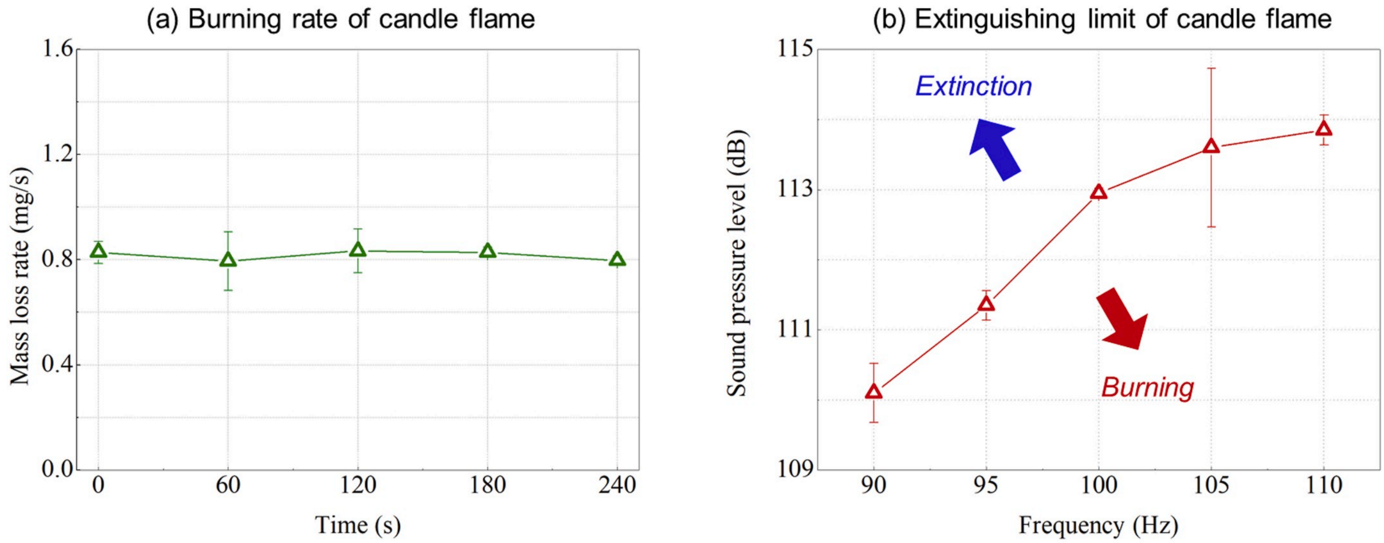

Fig. 6. (a) Time trace of the mass loss rate for the candle flame without applying any sound field, and (b) the extinction limit of the candle flame as a function of sound pressure and frequency.

3.2. Extinguishing the fast-moving dripping flaming

Fig. 7 shows a typical extinction process of the dripping flame. Note that the dripping extinction may start anywhere within the applied sound field, so the video snapshots presented here were arbitrarily chosen. In the early stage of dripping (Fig. 7(a)), the flame is constantly peeled off from the drip and behaves in a complex manner. The continuous ignition of fuel behind the drip still exists at this stage, which

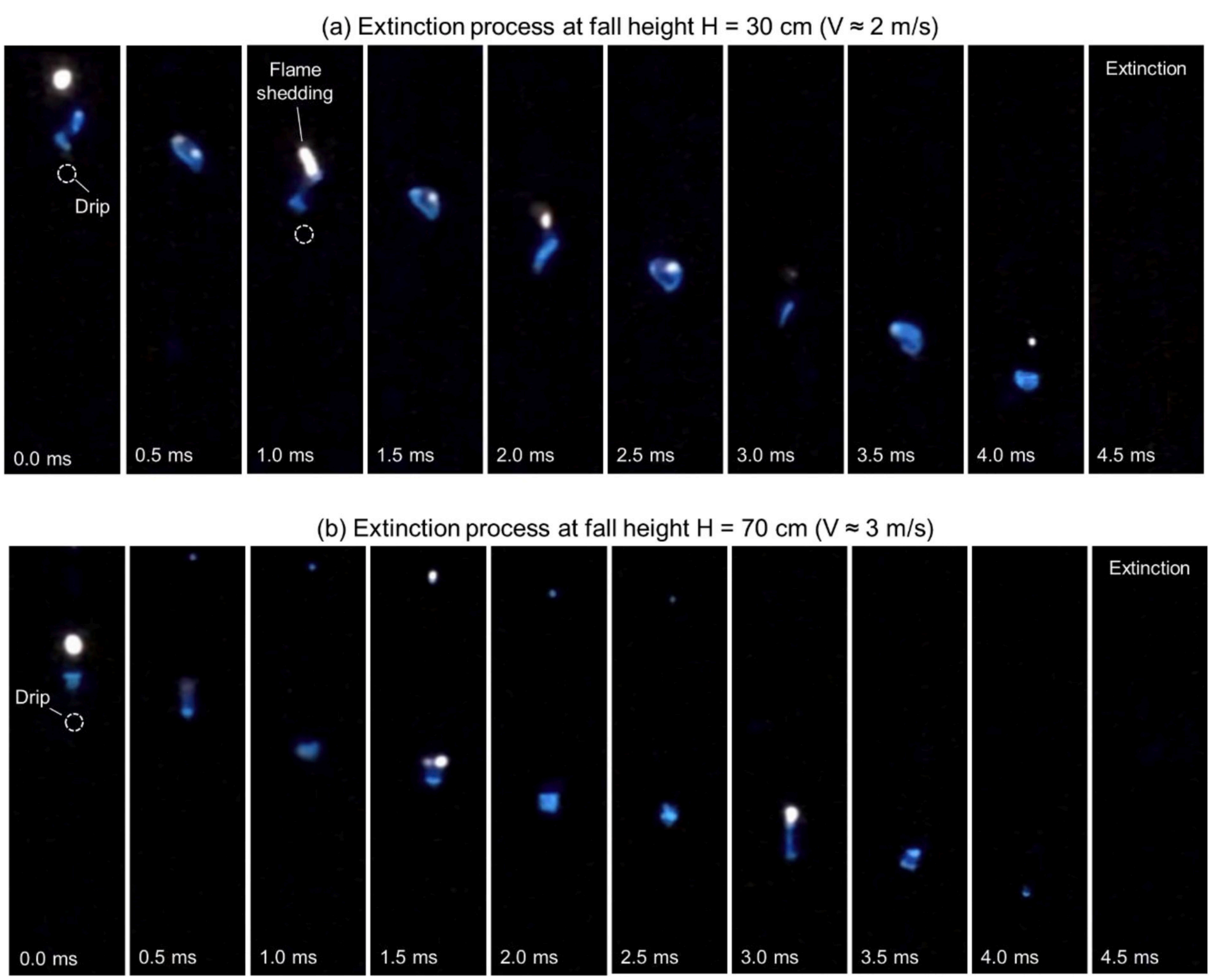

Fig. 7. High-speed imaging (960 fps) of the typical extinction process at (a) the fall heights of 30 cm and speed of $V_{dr} = 2$ m/s (Video S5), and (b) the fall heights of 70 cm and speed of $V_{dr} = 3$ m/s (Video S6).

is similar to the normal situation without additional sound (see in Fig. 2 (b)). However, the difference lies in that the flame sheet starts to shake in the stable acoustic field. Compared to the stationary candle flame, the dripping flame is not anchored at the fuel supplier, so the acoustic force can deflect flame more easily, resulting in a detrimental consequence in terms of fuel evaporation and eventually leading to extinction (see Video S5). Worthy to note that for both the dripping flame and candle flame, the residual white smoke (pyrolysis gas) after the flame being extinguished remains to shake around the parent fuel. This fact suggests that the observed extinction phenomenon is caused by acoustic streaming, i.e. the flow of sound propagation medium, rather than by the acoustic radiation pressure [4].

Comparison between Fig. 7(a) and (b) shows a difference in the suppression process associated with the drop distance (H). Indeed, there exists some possible factors, e.g. the state of fuel or the flame structure, that are responsible for this difference. Also, as the drip is accelerated by the gravity force, its residence time within a given sound field will be reduced. Based on our previous work [15], the most prominent difference between the dripping flames at the early and later stages is that the developed dripping flame has a structure similar to the classical von Kármán vortex street, i.e., the flaming shedding. In other words, in the coordinate referenced to a later-stage and fast-falling drip, the pyrolysis gas seems to be injected out from the top sphere, which leads to a rise of momentum for the fuel stream behind the drip [21]. This is evidenced by that the developed dripping case behaves similar to a lifted jet flame, as seen in Fig. 2(c). As a result, the flame shedding structure of the dripping flame shows a reluctance in response to the applied acoustic field (Fig. 7 (b), see Video S6).

The dripping flame has a large falling speed and continues to accelerate for about 1 s and 3 m before reaching the terminal velocity of 4–5 m/s [15]. Therefore, the flame attached to the moving fuel is not as stable as the candle flame or other stationary diffusion flames, and a small portion (5%) of dripping flames will self-extinguish under the background sound level of 56.6 dB without applying any additional sound field. Compared to the stationary flame, the fast-moving dripping flame only has a short residence time (about 0.2 s) in the applied sound field. Thus, a more stringent rule is applied to quantify the extinction of the dripping flame, that is, only the extinction events occurring within the uniform acoustic field were considered.

Referring to the past study on the hot-particle ignition [22,23], the extinction probability (P_{ex}) is defined as the ratio of the number of extinction (N_{ex}) to the total number of dripping flames (N_{tot}):

$$P_{ex} = \frac{N_{ex}}{N_{tot}} \times 100\% \tag{1}$$

The extinction probabilities for three sound frequencies varying with the sound pressure were plotted in Fig. 8(a–c). At least 500 drips were measured for each case. By defining the probability of 50% as the critical value, characteristic sound pressure can be identified in each case, which separates the low-risk and high-risk sound regimes for the

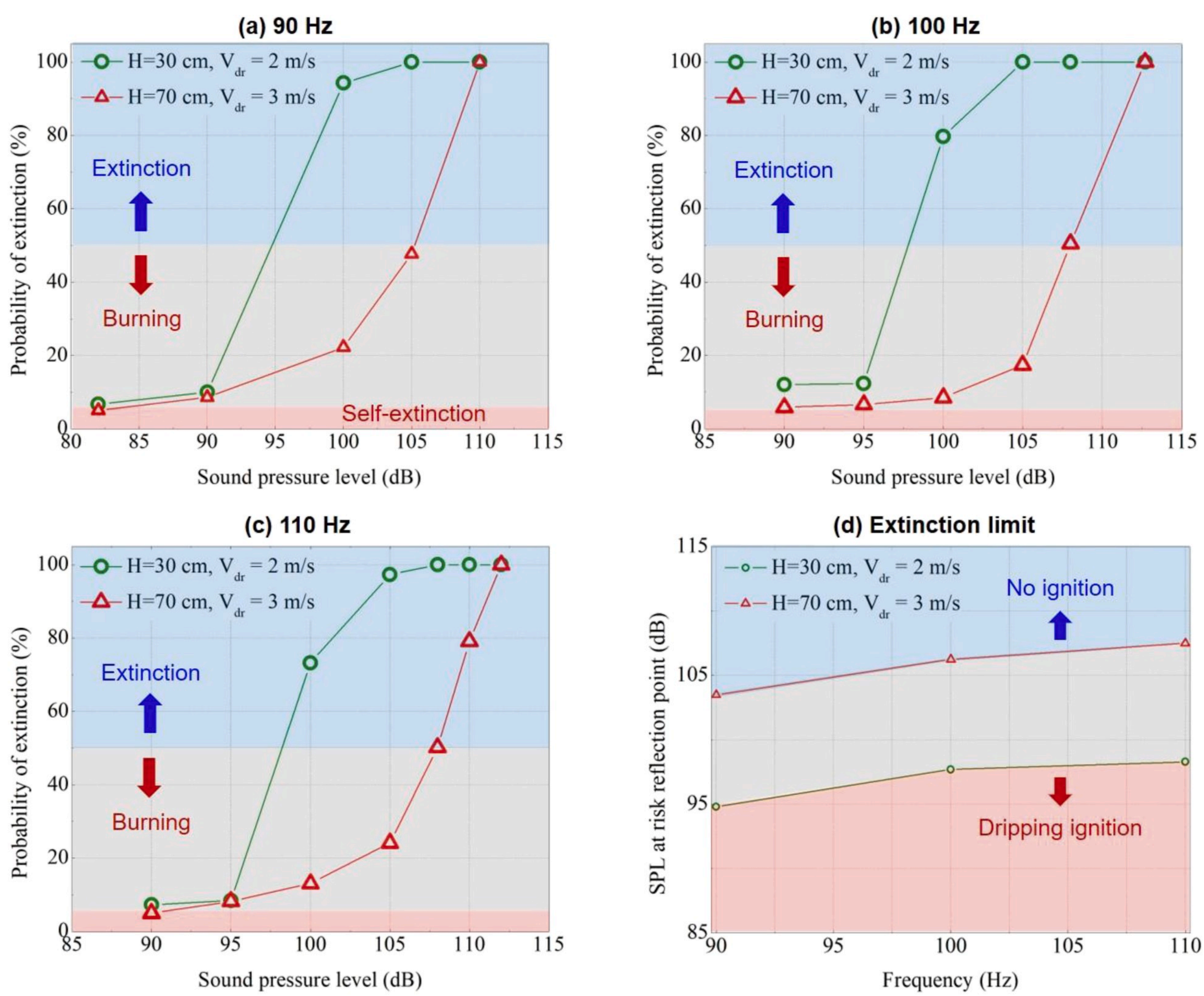

Fig. 8. The extinction probability for dripping flames under two fall heights (velocities) varying with sound pressure at (a) 90 Hz, (b) 100 Hz and (c) 110 Hz, and (d) the mitigation of dripping-ignition risk by sound wave.

dripping cases.

Under all three sound frequencies, the extinction probability shows the same trend for two forms of dripping flame, i.e., a higher probability of extinction under a larger sound pressure level. Moreover, the fully developed dripping flame with the structure of flame shedding shows a higher sound resistance than the case at the early stage. This is because for flame shedding, the momentum of the flame sheet inside the wake region behind the drip is larger, and the residence time in the sound field is smaller. Therefore, the developed dripping flame becomes more difficult to be suppressed. Note that the extinction probability in the early dripping case increases sharply as the sound level increases from 95 to 100 dB. This can be attributed to the enhanced flame deflection in this pressure range. Fig. 8(d) further demonstrated that as frequency increases, a higher sound pressure level is required to maintain fire safety.

To further evaluate the effectiveness of acoustic suppression on the fast-moving dripping flame, Fig. 9 compares the 100% extinction limit (or safe boundary) between the stationary candle flame and the fast-moving dripping flame. Note that the boundary condition to hold the flame is different in these two cases. Hence, only the variation trend of the extinction limit is qualitatively discussed here. In general, a similar trend is found between the stationary and fast-moving flame, that is, the limiting sound pressure level increases with the sound frequency. Moreover, when the dripping flame reaches the fall height of 30 cm and the velocity of 2 m/s, the acoustic environment required for dripping extinction occurs to be moderate. When the drip further accelerates to 3 m/s after falling for 70 cm and develops the structure of flame shedding, the acoustic suppression becomes difficult. However, a complete extinction can still be achieved by increasing the sound level. Therefore, it allows concluding that using acoustic wave can effectively suppress the dripping flame and significantly reduce the fire hazard of molten drip.

3.3. Extinction criterion

Since the dripping extinction relates closely to the competition between the acoustic streaming and the momentum of fuel stream behind the drip, a qualitative model was proposed to characterize the flame behavior before extinction. As illustrated in Fig. 10(a), a wake flame is attached to the falling drip, which has the same velocity as drip and continuously burns the pyrolysis fuel gas from the hot drip. It is, therefore, hypothesized that the acoustic extinction should be a blowoff phenomenon of the wake flame.

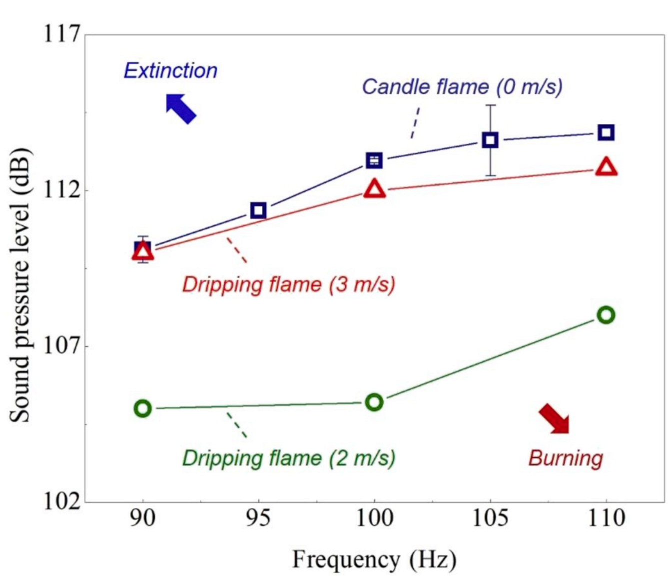

Fig. 9. Comparison of the 100% extinction limit (or safe boundary) between the stationary candle flame and the fast-moving dripping flame at different dripping height and speed.

Typically, the critical Damköhler (Da) number can be used to explain the blowoff limit [24]. Thus, a similar criterion was adopted for judging the acoustic extinction of the fast-moving flame, where the rate of gas motion should exceed the rate of gas consumption in flame. Then, a characteristic Da number was formulated, which describes the competing process by the ratio of the residence time of fuel gas (t_{re}) to the flame-chemistry time (t_{ch}).

$$Da = t_{re}/t_{ch} \tag{2}$$

In general, the gas-phase chemical time is short and of the order of ms [25]. Therefore, it is suggested that the flame-chemistry time t_{ch} remains constant and the flame residence should be the key factor that governs the extinction phenomenon.

There are two velocity components working on the wake flame, that is, (i) the vertical velocity of drip, V_{dr}, and (ii) the transverse offset velocity imposed by sound wave, U_s, as shown in Fig. 10(a). Since the drip size is far smaller than the wavelength of the low-frequency sound, the acoustic pressure is uniform around the dripping flame. Then, the sound-induced velocity can be estimated as $U_s = \sqrt{P/\rho}$, where P is the sound pressure in the unit of Pa and $\rho = 0.25$ kg/m^3 is the air density at 1400 K (the average of polymer flame temperature and pyrolysis temperature). For example, at a sound pressure level of 110 dB (6.3 Pa), the sound-induced velocity is $U_s = 5.0$ m/s, which is comparable to the dripping velocity.

With the overall velocity, the residence time can be calculated as $t_{re} = D_{dr}/\sqrt{U_s^2 + V_{dr}^2}$, where D_{dr} denotes the drip diameter. Thus, the critical Damköhler number (Da*) for extinction may be expressed as

$$Da^* = \frac{D_{dr}\Big/\sqrt{P_{ex}/\rho + V_{dr}^2}}{t_{ch}} \tag{3}$$

where a faster motion of dripping flame (V_{dr}) facilitates the flame extinction under a lower pressure limit (P_{ex}).

Fig. 10(b) shows the calculated Da* based on the measured extinction limits (P_{ex}) in Fig. 9, with the assumption that the candle and polymer are of the same chemical time. It was observed that the $Da^* \approx 1/2t_{ch}$ at the extinction limit, where the unit of t_{ch} is ms. Further, since the value of Da* is insensitive to the variation of sound frequency, it can be used to distinguish the extinction and no-extinction situations. This result also confirms the compensation between acoustic streaming and shedding momentum for flame extinction. With a strong sound, the flammable gas could not be held in the wake region, which prevents the flame from propagating and catching up with the falling drip. Note that the influence of sound frequency is not included in the extinction criterion, which needs further study in future work.

4. Conclusions

In this work, we experimentally studied the acoustically driven extinction of the fast-moving dripping flame. The target object was the burning molten-PE drip with a mass of 6.2 mg and a diameter of 2.6 mm. Two forms of dripping flame at the falling heights of 0.3 m (diffusion flame) and 0.7 m (flame shedding) were exposed to the transverse acoustic waves. The sound source varied in pressure from 80 to 114 dB and frequency from 90 to 110 Hz. The probability of extinction for the dripping flame was determined with a given sound field, and limiting conditions were defined at the extinction probability of 50%.

It was found that the positive correlation between extinction pressure and sound frequency applies equally to the dripping flame, just as that works for the stationary case. Moreover, the results showed that the acoustic wave is more effective to extinguish the dripping flame in the early stage because the flame is more easily deflected from the drip. As the drip accelerates with the fall height, the momentum of the flame

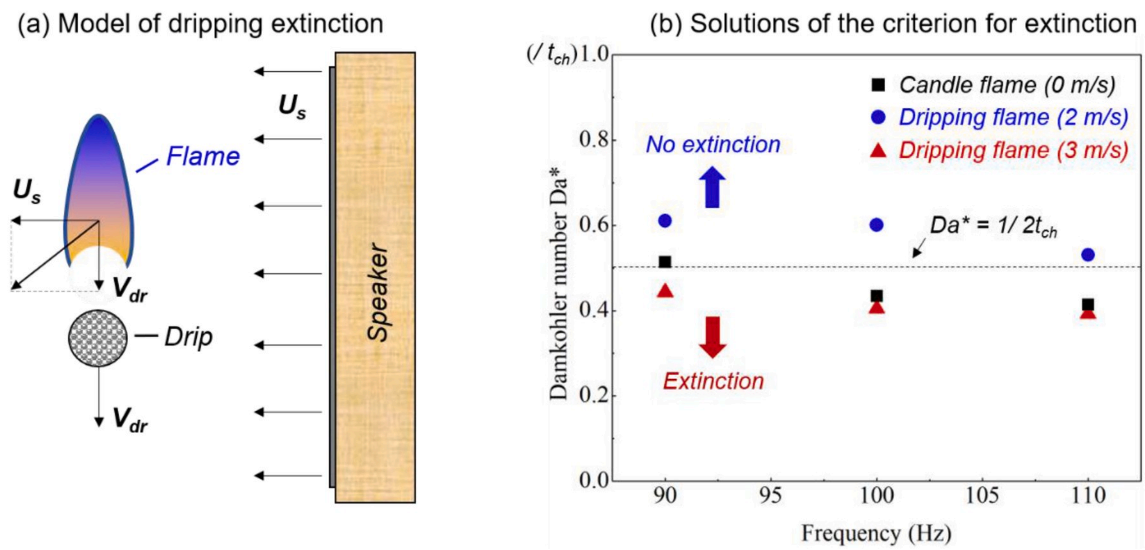

Fig. 10. (a) A model of flame behavior prior to extinction, and (b) the solutions of Da at extinction limits, where the unit of t_{ch} is ms.

sheet inside the wake region behind the drip is increased, and the residence time in the sound field is decreased, so that the dripping flame becomes more difficult to suppress. To qualitatively explain this acoustic extinction phenomenon, a criterion based on a critical Damköhler number was formulated to demonstrate the compensation between dripping velocity and acoustic streaming near the extinction limit.

This work provides important information on the acoustic effect on a moving flame, and it helps guide the design of new fire suppression technology to mitigate the fire hazard of the dripping phenomenon, e.g., an acoustic extinguishing system that shields the dripping flame can be installed on the existing combustible building façade. Further research is still needed on the influence of drip size and residence time to reveal more about the underlying extinction mechanism of dripping flame by acoustic waves.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Caiyi Xiong: Investigation, Writing - original draft, Formal analysis. **Yanhui Liu:** Investigation, Formal analysis. **Cangsu Xu:** Methodology, Resources. **Xinyan Huang:** Conceptualization, Supervision, Writing - review & editing.

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