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Acoustic flame extinction by the sound wave or speaker-induced wind?

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ABSTRACT

Many literature studies explored acoustic-driven flame extinction via different experimental techniques, but the interpretation of results and the underlying mechanism are still unclear. In this work, a candle flame (20 W) is tested in two kinds of sound fields, one developing freely and the other guided by a cylindrical tube. Results show that the flame exhibits completely different fluctuations at the same sound pressure, indicating the observed flame extinction is irrelevant to sound waves (particle velocity ~10^{-2} m/s at 100 dB). The oscillating airflow (~0.5 m/s at 100 dB) generated by the vibration of the speaker diaphragm is the real cause of flame fluctuation and extinction. Moreover, using a cylindrical tube can enhance the diaphragm-induced airflow and promote flame extinction.

1. Introduction

Fire suppression technology has always been a topic deserving the enthusiasm and energy of the firefighting community [1–3]. The sound, which is essentially a longitudinal pressure wave, recently shows its potential to be an effective fire extinguisher. Due to the many advantages, such as simple operation and being free of environmental pollution, this technology is of both scientific interest and practical importance. Thus, many studies have recently designed different experiments for applying sound to extinguish flames [4–13].

McKinney and Dunn-Rankin [4] carried out one of the earliest experiments using speakers and sound to cause extinction. They chose the upward fast-moving droplet flame as the target and revealed a positive correlation between the extinction sound pressure and frequency. This positive correlation was then confirmed by a comprehensive investigation carried out by DARPA [5], which argued that the necessary condition under which acoustic extinction can appear is enough flame displacement from the fuel. To seek the mechanism behind acoustic extinction, Friedman and Stoliarov [6] applied low-frequency acoustic field to extinguish the alkane-fueled diffusion flames. They formulated an extinction model involving the influence of acoustic perturbations, where the competition between the fuel heating by flame and the fuel cooling by acoustic flow plays an important role. This mechanism received further support from Niegodajew et al. [7]. In all these existing works, the sound field generated by the speaker was always transmitted to flame via a cylindrical tube. Such a tube can guide the sound and help keep a safe distance between the flame and the speaker.

In our recent works [8–10], the freely developed sound fields (without a guided tube) have also been proved to cause the extinctions of dripping flame, flaming firebrand, and gas-burner flames. Fundamentally, the observed flame extinctions inside sound fields are caused by a strong flame fluctuation induced by a fluctuating airflow (or wind), which can be explained by a critical Damköhler number and flame strain rate [8–10,14]. Then, one key question is raised: if the sound wave can induce an airflow strong enough to blow out a flame, why do we never feel this flow when hearing any sound or music? In other words, is the sound wave the real cause of acoustic extinction? Besides, will the use of the guided tube affect the extinction mechanism? This work aims to answer these questions.

2. Experimental methods

2.1. Target flame

The target flame is a candle flame produced by a 3-mm candle with a 1-mm wick. This is because the candle flame has no buoyancy-induced puffing [15], and it has a stable burning rate. On the other hand, the wick connects the flame and the candle, so the flame will not regress into the wax and can be fully exposed to external sound, see Fig. 1a. When burning stably, the flame keeps a width of 5 mm and a height of 15 mm, and its power (or heat release rate) is about 20 W, as measured previously [9].

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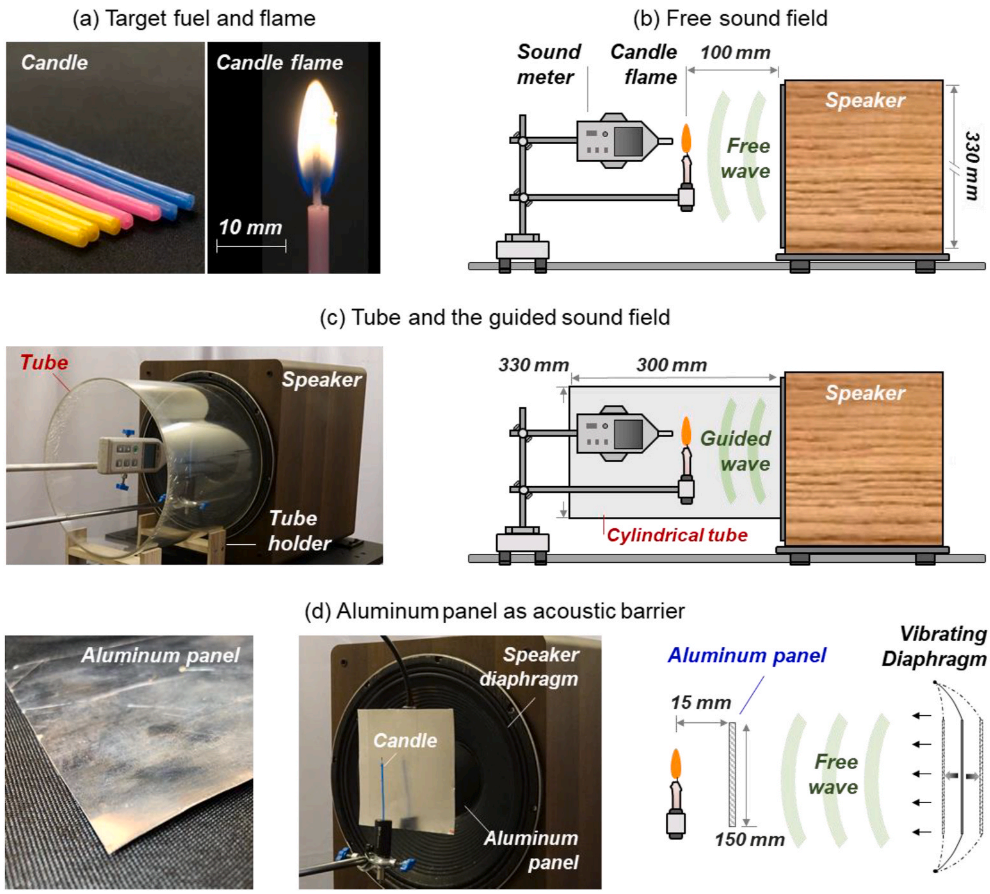

Fig. 1. (a) The target candle and flame, (b) a free sound field, (c) the tube and guided sound field, and (d) the aluminum panel used as wind barrier and its installation.

2.2. Sound source

The sound signal is initially produced from a wave generator, enhanced by a power amplifier, and finally being emitted by a speaker (Fig. 1b). The speaker has a diaphragm with a diameter of 330 mm. Since the diaphragm is much larger than the flame, and the diaphragm-flame distance is short, the spherical waves from the speaker can be approximated as planar waves at the flame. Thus, the whole flame can experience the same acoustical impact even it moves as the candle melts.

Two kinds of sound were used, including one developing freely (Fig. 1b) and the other guided by a tube (Fig. 1c). To produce the guided sound, a tube was installed in front of the speaker. This tube is made by plastic, with an inner diameter same as the diaphragm and a length of 300 mm. All experiments were conducted in a spacious room, so to minimize the sound reflections from sidewalls.

2.3. Experimental procedure

Before experiments, the flame was moved to a position 100-mm in front of the speaker diaphragm, with its base leveling with speaker center. The sound has a frequency of 60 Hz, which falls into the range of 30–140 Hz commonly used to cause extinction [10]. The sound pressure level (SPL) near the flame was measured by a TES-1352S sound level meter in a unit of dB. Note the pressure in Pa can be converted to dB by $dB = 20\lg[Pa/(2 \times 10^{-5})]$. To demonstrate the true cause of flame extinction in a sound field, a thin aluminum panel (see Fig. 1d) was used to separate the flame from the speaker. In all tests, the unstable flame behaviors were monitored by a 1,000-fps camera. All cases were repeated three times to reduce the uncertainty.

3. Results and discussion

3.1. The essence of acoustic extinction

Fig. 2a shows the flame fluctuation in a free sound field as the base case (i.e., Case I at 97.3 dB), where the flame is deflected far from the wick and kept fluctuating (Video S1). Then, keeping the sound source unchanged and placing the panel in front of the flame. Immediately, the flame fluctuation becomes very weak, and the flame is almost straight upward (Case II: upper of Fig. 2b and Video S2). However, before and after using the panel, the decreased SPL near the flame is only 1.0 dB, as measured by the sound meter. These phenomena depend not on the distance between the flame and the panel.

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To further confirm that the above disappearance of flame fluctuation is not caused by the decreased 1.0 dB, the panel was removed, and the sound pressure was reduced to the same level of 96.3 dB as the panel-weakened one (Case III: lower of Fig. 2b and Video S2). The flame fluctuation can still exist with obvious amplitude. Thus, the sound wave

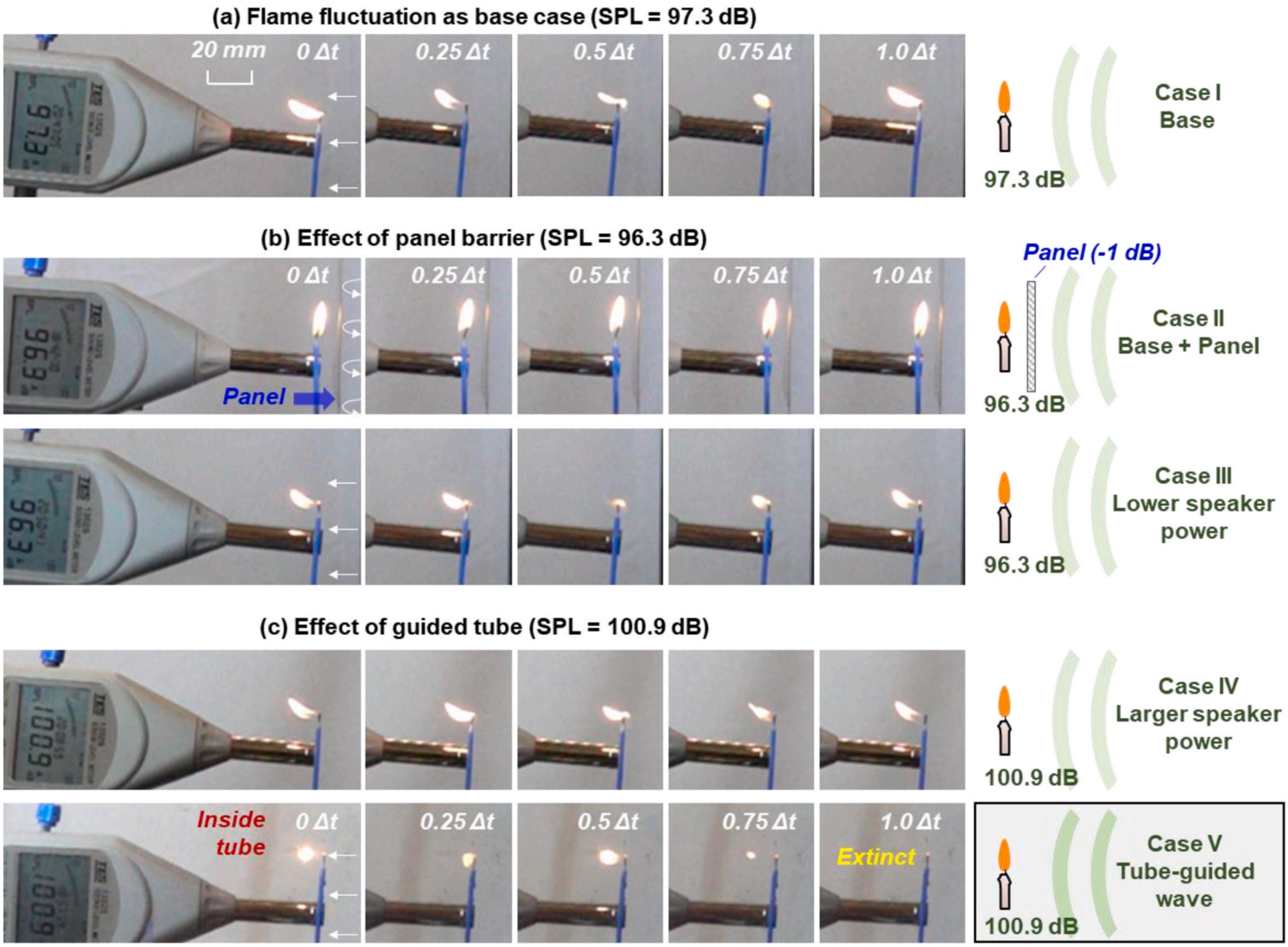

Fig. 2. (a) Flame fluctuation in a 60-Hz sound field at 97.3 dB as the base case in Videos S1 and (b) effect of panel barrier in Videos S2 and (c) effect of the cylindrical guided tube in Video S4; $\Delta t = 16.7$ ms is the acoustic cycle.

cannot be the factor to dominate flame fluctuation, let alone cause flame extinction. The above experiments prove that at least two flows are generated from an activated speaker, including 1) a longitudinal pressure oscillating flow, which is the sound we hear, and 2) an oscillating airflow that acts as a background flow, which is the wind we feel. The latter should be responsible for flame fluctuation and extinction.

Then, what can be the cause of the background airflow? Re-examining the experiment, the flame fluctuation is consistent with the vibration of the speaker diaphragm (see Video S3). Thus, Table 1 compares the displacements of flame fluctuation and diaphragm vibration, obtained via video processing (see more details in Ref. [10]). Also, the pure displacement (δ) of sound-particle (air medium) for transmitting sound wave [16] is given by

$$\delta = \frac{P}{2\pi f \rho c} \tag{1}$$

where P is sound pressure in Pa; $f = 60$ Hz is sound frequency; $\rho = 0.43$ kg/m^3 and $c = 566$ m/s are air density and sonic speed at 800 K (the average of flame temperature and room temperature). For example, the sound-particle displacement in the base case is $\delta = 1.47/(2\pi \times 60 \times 0.43 \times 566) = 1.6 \times 10^{-5}$ m. Comparing three displacements in Table 1 shows that the displacements of flame fluctuation and diaphragm vibration are comparable (~1 mm), which are two orders of magnitude larger than that of sound-particle (~10^{-2} mm). Hence, the background airflow is produced by diaphragm vibration, not by sound wave.

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To further confirm that it is not the sound wave but the diaphragm-produced airflow (or wind) to control flame fluctuation, the root-mean-square (RMS) velocities of flame fluctuation and diaphragm vibration are measured [10]. Besides, a Testo 405i hot-wire anemometer measures the mean velocity of the local airflow at the flame position. For sound particles, its mean velocity can be given by

$$v = \frac{P}{\rho c} \tag{2}$$

For example, the sound-particle velocity in the base case is $v = 1.47/(0.43 \times 566) = 6.0 \times 10^{-3}$ m/s. Table 1 compares all these velocities, where velocities of flame fluctuation, diaphragm vibration, and local airflow are comparable (about 1 m/s), which are all two orders of magnitude larger than the sound-particle velocity (~10^{-2} m/s). Thus, it allows concluding that the essence of 'acoustic-driven flame extinction'

Table 1
Fluctuating displacements and velocities of flame, diaphragm, local airflow, and sound particle in a 60-Hz sound field, where the base SPL is 97.3 dB; the airflow is measured by an anemometer, and motions of sound-particle are calculated by Eqs. (1) and (2), where ± shows the uncertainty of measurement.

Sound Field		Free sound				Guided sound
Field elements (Case No.)		Base (I)	Base + Panel (II)	Base – 1 dB (III)	Base + 3.6 dB (IV)	Base + Tube (V)
SPL [dB]		97.3	96.3	96.3	100.9	100.9
Displacement [mm]	Flame fluctuation	3.1 ± 0.2	0.3 ± 0.1	3.0 ± 0.1	3.3 ± 0.3	>4 (Extinct)
	Diaphragm vibration	1.7 ± 0.2	1.7 ± 0.2	1.6 ± 0.2	2.2 ± 0.2	1.7 ± 0.2
	Sound-particle	1.6×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	2.4×10^{-2}	2.4×10^{-2}
RMS velocity [m/s]	Flame fluctuation	0.54 ± 0.03	0.08 ± 0.02	0.51 ± 0.02	0.55 ± 0.04	>0.6 (Extinct)
	Diaphragm vibration	0.64 ± 0.07	0.64 ± 0.07	0.57 ± 0.07	0.76 ± 0.07	0.64 ± 0.07
	Local airflow	0.46 ± 0.03	0.06 ± 0.01	0.44 ± 0.04	0.50 ± 0.03	0.58 ± 0.04
	Sound-particle	0.60×10^{-2}	0.54×10^{-2}	0.54×10^{-2}	0.91×10^{-2}	0.91×10^{-2}

is a ‘flame blowoff by diaphragm-driven wind.’ However, the diaphragm-produced airflow is easily dissipated by air friction, so we rarely feel it when hearing the sound.

3.2. The impact of guided tube on acoustic extinction

The cylindrical tube is commonly used to guide sound and promote extinction. Such a tube can enhance both 1) the local SPL and 2) the diaphragm-produced background airflow. To check which enhancement dominates extinction, additional experiments extended from the base case were carried out inside a tube. Before experiments, it has been tested that installing a tube can increase the local SPL from the base 97.3 dB to 100.9 dB, with an increase of 3.6 dB.

Then, to control the variable, the test is first conducted without the guided tube, and the speaker power is increased to generate a local pressure of 100.9 dB (Case IV). As shown in the upper of Fig. 2c and Video S4, the flame fluctuation increases, but extinction does not occur. The flame fluctuation displacement increases from the base 3.1 mm to 3.3 mm, and the diaphragm vibration displacement increases from 1.7 mm to 2.2 mm. Comparatively, the sound-particle displacement increases from 1.4×10^{-2} mm to 2.4×10^{-2} mm, which is negligible.

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Afterward, the speaker power is reduced to the same level as the base case, and the guided tube is installed to enhance the local SPL to 100.9 dB (Case V). As shown in the lower of Fig. 2c and Video S4, the flame fluctuation increases significantly, which successfully triggers extinction. Therefore, the enhanced local SPL by the tube is not the factor that causes extinction. Instead, the enhancement of the diaphragm-produced wind by the tube is the reason for flame extinction. As expected, the aluminum panel has the same effect in Case V, i.e., blocking wind and preventing the flame from extinction, and even stabilizing the flame, as observed in the experiment.

It is also found that the critical flame displacement for candle flame extinction is around 4 mm. If the sound-particle displacement (δ) reaches 4 mm to blow out this candle flame purely by sound, the required SPL is at least $P = 2\pi \times 60 \times 0.43 \times 566 \times 4 \times 10^{-3} = 367$ Pa, based on Eq. (1). Such a sound pressure equals 145 dB and is loud enough to damage human hearing and health. Thus, the flame extinction and firefighting by pure sound waves are more or less a “fantasy.”

3.3. Effect of sound frequency

To assess the effect of sound frequency, we expanded all measurements in Table 1 to other frequencies ranging from 55 to 75 Hz with the same sound pressure of 97.3 dB. Fig. 3 summarizes all the results, where the relative magnitudes of velocity and displacement maintain the same trend. Because both the flame displacement and wind velocity produced by the speaker diaphragm become larger at a lower sound frequency, the low-frequency “sound” can therefore extinguish the flame more easily.

Hence, two conclusions can be drawn: 1) the observed ‘acoustic extinction’ is a blowoff by the diaphragm-produced airflow, not by the sound wave, and 2) using a tube can facilitate flame extinction by enhancing the diaphragm-produced airflow and blowoff.

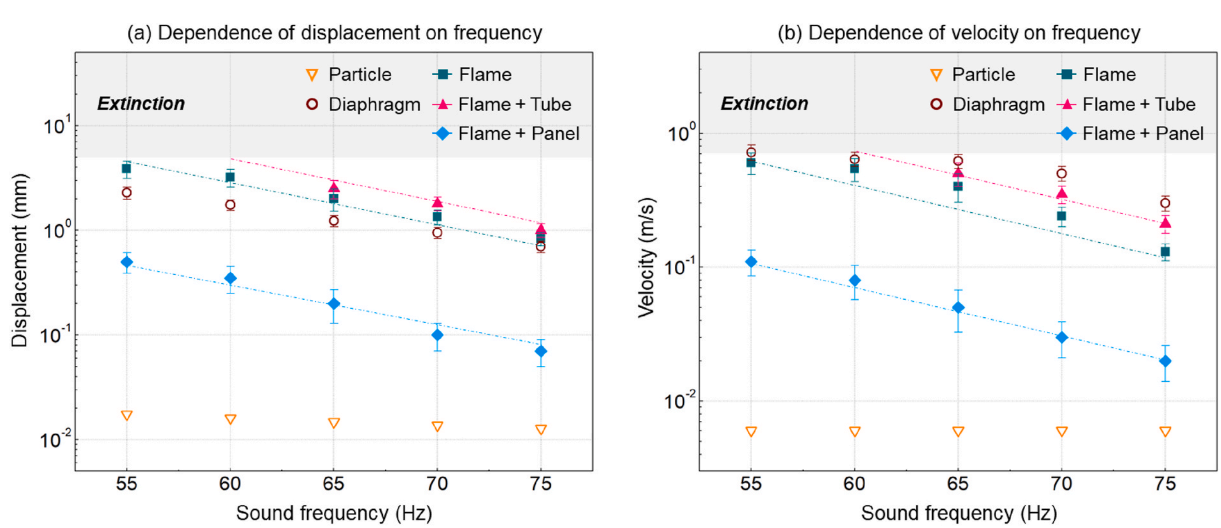

Fig. 3. Dependence of (a) displacement and (b) velocity of the flame, diaphragm, and sound-particle on sound frequency, where the SPL at the flame position keeps 97.3 dB, and extinction occurs in the shaded region.

CRediT author statement

Caiyi Xiong: Investigation, Methodology, Formal analysis, Writing - original draft.

Zilong Wang: Investigation, Resourcing.

Xinyan Huang: Conceptualization, Formal analysis, Methodology, Writing - review & editing, Supervision.

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.

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