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Investigation of Bunsen-type Premixed Flame Response to Acoustic Excitation: Temperature and Flame Profile

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Summary

We aimed to characterize a Bunsen-type premixed flame subjected to various acoustic excitations with a range of frequencies and amplitudes. Various acoustic fields were imposed on a Bunsen-type flame. Two key properties of the flame, flame profile and temperature, were examined and analyzed in the experiment. We observed that flame tilt angle, flame height, and flame temperature were strongly influenced by excitation frequencies and amplitudes. The results provide possible interpretations of experimental observations. In agreement with most combustion theories, there was a correlation between these flame properties and excitation amplitude and frequency. It has been shown that higher frequencies and amplitudes cause greater tilt angles and shorter flame heights, while in terms of flame temperature, higher acoustic amplitudes lead to greater combustion instabilities, resulting in lower flame temperature. Higher frequencies, on the other hand, lead to higher flame temperatures.

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Introduction

The interaction between acoustic waves and premixed flames has long been recognized in combustion physics. A flame subjected to acoustic excitation is shown in **Figure 1A**. Such acoustic-flame interaction is considered a serious problem in combustion engines, in that the acoustic disturbance could alter the structure of the flame and thus lead to heat release perturbation and unsteady combustion. During instability, the heat release oscillation feeds energy into acoustic modes and amplifies the acoustic waves, which in turn, continue to affect combustion heat release. As a result, the combustion system mires in a vicious feedback loop that could ultimately cause high combustion instability and even system failure if the velocity and pressure amplitude are very high (1). In such a chaotic system, the shape of the flame and the combustion temperature can be greatly affected. Different characteristics of the acoustic waves, such as amplitudes and frequencies, may disturb the system, which would lead to the volatility of some combustion characteristics including temperature, combustion rate, particle velocity, and flame shape. However, very little is known about the specific correlation between these variables or the mechanism underlying the phenomena. Therefore, this paper aims to study the effect of flame-acoustic interaction upon temperature and profile of a premixed flame.

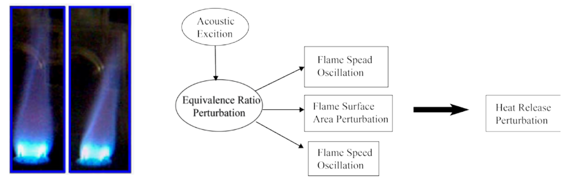

Figure 1: Acoustic Perturbations on Flame Response. A) Photograph of a stable flame and a flame subjected to acoustic disturbance, from ref. 2**.** B) Physical mechanisms of how acoustic excitation leads to flame heat release perturbation.

In order to investigate the acoustic-flame interaction during combustion, we need to first shed light on the mechanisms that cause flame oscillation and heat release perturbation. The interaction between various dynamics is demonstrated in **Figure 1B**. In combustion systems, the behaviors of reaction particles are associated with acoustic radiation forces in a uniform acoustic field. The expression for the force in the axial direction was developed by Hasegawa and Yosioka (3):

$$F_x = \pi a^2 E Y_p$$

where a is the particle surface area, E is the energy density of the acoustic wave, and Y_p is the radiation force function. Particularly, the amplitude of the acoustic wave is directly proportional to the density of acoustic potential energy:

$$E = \frac{pv}{c}$$

where p is the sound pressure measured by the sound amplitude, c is the speed of sound, and v is the particle velocity in the direction of propagation. Thus, a higher acoustic amplitude leads to a higher acoustic energy density and therefore produces a greater acoustic radiation force.

During combustion, these forces are directed away from the flame zone and could alter the flame structure and lead to equivalence ratio disturbance. (4). Consequently, the acoustic wave causes a series of changes in flame properties. As the acoustic radiation force changes the ionic structure of the flame, the equivalence ratio is first affected; combustion particles are dense in some part of the flame in comparison to others (**Figure 2**). As a result,

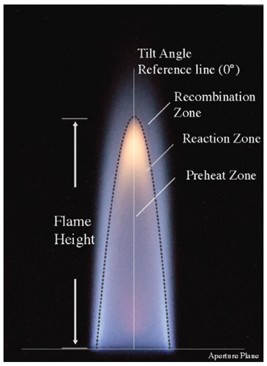

Figure 2: Schematic of a Typical Bunsen-type Flame, showing three distinctive combustion zones: recombustion zone, reaction zone, and preheat zone.

flame shape contorts, flame surface area changes, and the speed of the flame oscillates. According to the works of Lieuwen *et al.* (5), these disturbances would together lead to general heat release oscillation, thereby affecting the combustion flame temperature. This can also be seen by the global heat release rate of premixed flame developed by Fleifil (6) and Ducruix (7):

$$Q(t) = \int_s \rho S_1 \Delta h_R dA_{FL}$$

where ρ is the density of the air, Δh_R is the heat of reaction, S_1 is the instantaneous flame speed, and A_{FL} is the flame surface area. From the diagram and formulae, it is clear that amplitude and frequency can determine combustion temperature and flame shape during unstable combustion because of the acoustic-flame interaction.

The combustion theory previously developed by Lauvergne *et al.* (8) and Sankaran *et al.* (9) has led to a few insights on such phenomena. Through numerical investigations, these researchers concluded that in unsteady combustions, the flame heat release and instantaneous flame speed is a function of frequency. In addition, during unsteady combustions, the acoustic pressure could lead to flame pressure perturbation and thereby affect the heat release transfer function:

$$TF_p = \frac{q'/\bar{q}}{p'/\bar{p}}$$

where q' and p' refer to instantaneous heat release and pressure, respectively, and *q'* and *p'* represent the mean flame heat release and pressure, respectively. The equation illustrates that a higher amplitude acoustic excitation could lower the flame temperature and therefore generate high combustion instability.

In regards to the flame profile, the acoustic radiation force plays an important role. Previous work by Rivin *et al.* (10) has shown that an electric field can affect the flame profile through electric forces, attracting and repulsing some ions inside the flame and thus altering the shape and the ionic structure of the flame. It is reasonable to infer that an acoustic field may cause a similar effect upon the combustion particles and therefore affect the flame profile in this microscopic way.

Over the decades, the Bunsen-type flame has been widely studied. In a Bunsen burner, the fuel gas is released from the fuel orifice and interacts with the air from the adjustable intake port in the tube. After ignition, the subsequent reaction forms a premixed flame above the burner aperture (11). The burning temperature of a normal Bunsen-type laminar flame can reach up to 1300°C.

A typical Bunsen flame is presented in **Figure 2**. The structure of the flame is divided into three distinctive characteristic zones: the preheat zone, reaction zone, and recombination zone (11). In the present paper, the surface area of the flame is defined as the surface area of the parabolic-shaped reaction zone marked with a dashed line in **Figure 3**. The flame height refers to the

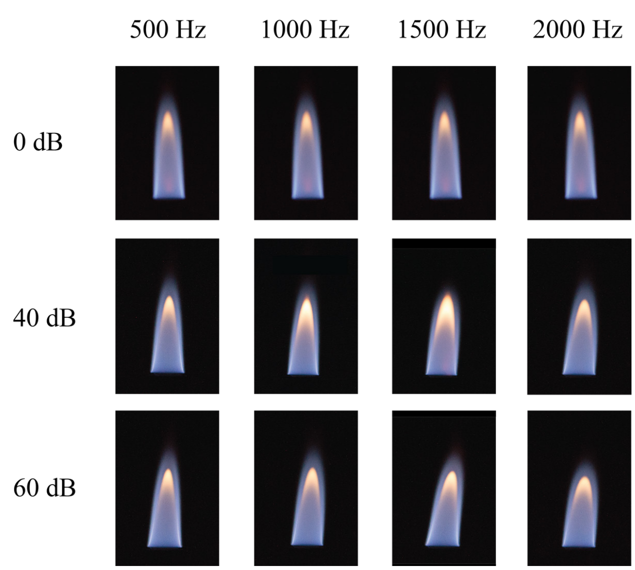

Figure 3: Flame Profile Under a Longitudinal Uniform Acoustic Field, showing the effect of frequency and amplitude.

Amplitude	f=500 Hz		f=1000 Hz		f=1500 Hz		f=2000 Hz	
	Angle	Height	Angle	Height	Angle	Height	Angle	Height
0 dB	0º	35.8 mm	0º	35.8 mm	0º	35.8 mm	0º	35.8 mm
40 dB	1.1º	34.7 mm	1.8º	34.4 mm	2.8º	33.5 mm	2.9º	32.5 mm
60 dB	2.3º	34.5 mm	3.8º	34.6 mm	5.2º	32.8 mm	4.9º	30.7 mm

Table 1: Flame tilt angles and heights for cases shown in Figure 3.

Frequency	p =0	p =40 dB	p =60 dB	$T_{40} - T_{60}$
200 Hz	1507.1 K	1492.2 K	1422.4 K	69.8 K
400 Hz	1507.1 K	1491.6 K	1380.3 K	111.3 K
600 Hz	1507.1 K	1467.3 K	1378.9 K	88.4 K
800 Hz	1507.1 K	1509.8 K	1432.5 K	77.3 K
1000 Hz	1507.1 K	1502.1 K	1455.8 K	46.3 K
1200 Hz	1507.1 K	1561.2 K	1479.1 K	82.1 K
1400 Hz	1507.1 K	1543.5 K	1474.3 K	69.2 K
1600 Hz	1507.1 K	1567.7 K	1460.2 K	107.5 K
1800 Hz	1507.1 K	1581.3 K	1486.0 K	95.3 K
2000 Hz	1507.1 K	1562.5 K	1497.7 K	64.8 K

Table 2: Flame temperatures under acoustic fields with different frequencies and amplitudes.

distance between the peak of the reaction zone and the peak of the surface of the aperture. In the experiment, we investigated the flame height and the tilt angle as the flame profile under various acoustic fields. Some of the results can be well explained by the theories and models previously built by others, while some experimental results still lack proper theoretical interpretation. This is because several different mechanisms are involved in a chaotic combustion system. Among these mechanisms, vorticity and convective motion, chemical kinetics, and heat transfer play significant roles in combustion instabilities (12). The interactions between them make the combustion system difficult to model. This paper does not provide any numerical investigations about the interaction among these variables but will draw a few conclusions based on experimental results.

Results

A Bunsen-type flame was placed under various acoustic frequencies and amplitudes generated by a speaker. The images of flames subjected to various acoustic excitations are presented in **Figure 3**. Based on the images, Table 1 gives the numerical measurements of tilt angles and flame heights. The tilt angle was nearly zero when no acoustic waves were generated (P=0 dB), while in the presence of an acoustic field, the acoustic waves tended to direct the flame away from the original flame position. The results illustrate that both frequency and amplitude of acoustic waves could alter the flame profile. At high frequencies and amplitudes, the tilt angles appeared to be greater, indicating a stronger force applied in the flame zones. The effect was quite obvious at the first three frequency intervals (0–1.5 kHz); however, at a higher frequency range, the flame showed little response to the increasing acoustic frequency. For P=60 dB, the increase of frequency from 1.5 kHz to 2 kHz even showed a slight drop in flame tilt angle.

The flame height decreased with increasing frequency and amplitude, although the effect was subtle at the lower frequencies (**Table 1**). The small fluctuation of flame heights in the low frequency range was likely due to the disturbance of background noise and flow noise with similar low frequencies, which intervene in the crowding effect of acoustic fields(13). We can observe from **Figure 3** that as flame height drops, the flame surface area shrinks, which indicates that the combustion heat release was, to some extent, affected.

Under high amplitude acoustic excitation, the flame displayed a greater response to change in acoustic frequency. Under a 40-dB acoustic field, shifts from 1 kHz to 1.5 kHz and from 1.5 kHz to 2 kHz resulted in a 2.6% and 3.0% decrease in flame height, respectively, while under a 60 dB acoustic field, the drops were 5.2% and 6.4%. With regards to tilt angles, the increases in the first two frequency intervals were 0.7º and 1º for a 40-dB acoustic field, yet 1.5º and 1.4º for a 60 dB acoustic field. Unfortunately, based on current combustion literature, the reason for such phenomena is still unclear.

Table 2 presents the temperatures of flames subjected to different acoustic excitations. It's necessary to note that all these data bear some uncertainties, and under a high temperature over 1000 K, the measurement error of a Type-K thermocouple can reach up to 0.75% (14), which is around 10–12 K in this set of data. In addition, as the tip of the flame is not always stationary during combustion, variability in the flame position may increase uncertainty while collecting the data. However, these minor errors don't greatly affect the overall trend.

The range of flame temperature under a 40-dB acoustic field was about 1450–1600 K, and about 1350–1500 K under 60-dB acoustic field. The combustion temperature under no acoustic excitation (0 dB) was 1503.1 K (**Table 2**). In order to further observe the relationship between the variables, the data was then processed by Matlab and plotted on a scatter diagram. **Figure 4** shows that the flame temperature under a 40-

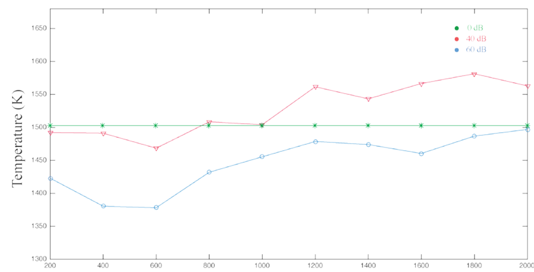

Figure 4: Flame Temperatures under Various Acoustic Excitations. Showing the relation to acoustic frequencies and amplitudes.

dB acoustic field was overall higher than that under 60 dB at all frequency domains. While comparing flame temperatures in a 40-dB and 0-dB acoustic field, the temperature was similar at the lower end of the frequency domain (0-1000 Hz), but the gap increased as the frequency shifted to the higher end. The gaps between the temperatures under 40-dB and 60-dB acoustic fields are shown in **Figure 5A**. The temperature difference fluctuated in a range of 46.3–111.3 K with a mean of 81.2 and standard deviation of 19.04. The data, as plotted in the graph, did not show a clear trend as frequency increased.

There were strong temperature fluctuations as frequency increased, likely due to flame heat release perturbation caused by acoustic excitation, and a slightly upward trend was observed. **Figure 5B** and **Figure 5C** show the best linear fitting curves of the two sets of data (40 dB and 60 dB) in a linear model, y=ax+b, given by the curve-fitting tool. For a 40-dB acoustic field, the results were a=0.05817, b=1464 with an adjusted R^2 of 0.7696. For a 60-dB acoustic field, the coefficients were a=0.05959, b=1381 with an adjusted R^2 of 0.7007. The values of adjusted R^2 for both cases indicate that the linear model can roughly explain the observed variation in the experiment. The positive values of coefficient a suggest a positive correlation between the flame temperature and acoustic excitation frequency. The slopes for both curves were nearly identical.

Discussion

This paper describes the physical characteristics of a Bunsen-type flame subject to various acoustic excitations in the 0–2 kHz frequency range and 40 dB/60 dB acoustic amplitude. The images collected from the experiments confirm the effect of acoustic waves upon flames.

Through detailed analysis, we were able to draw a few conclusions about the experimental observations. First, the acoustic excitation caused the flame to wrinkle and shrink. The increase of frequency and amplitude led to a greater flame tilt angle and smaller flame height. Under high-frequency excitations, the flame response was greater for flame height, but smaller for tilt angle. Secondly, under high-amplitude excitation, the flame profile response to acoustic excitation was generally greater than lower amplitude excitation. Finally, analysis of flame temperatures showed a significant effect of the flame-acoustic interaction upon combustion heat release. Higher amplitude acoustic excitation generally generated high combustion instability and led to a lower flame temperature. We also noticed that the gap between temperatures at different dB levels was fairly consistent. The results also showed a positive correlation between frequency and flame temperature.

Yet, these pictures warrant some more specific investigations. In order to get a better understanding of the above-mentioned correlations, measurements are needed for a broader range of frequencies, equivalence ratios, and amplitudes to investigate more specific flame responses to acoustic excitations. More advanced equipment may be used in future investigations to improve the accuracy of measurements. A more complicated model involved with multi-dimensional excitations may be examined, as sound interference

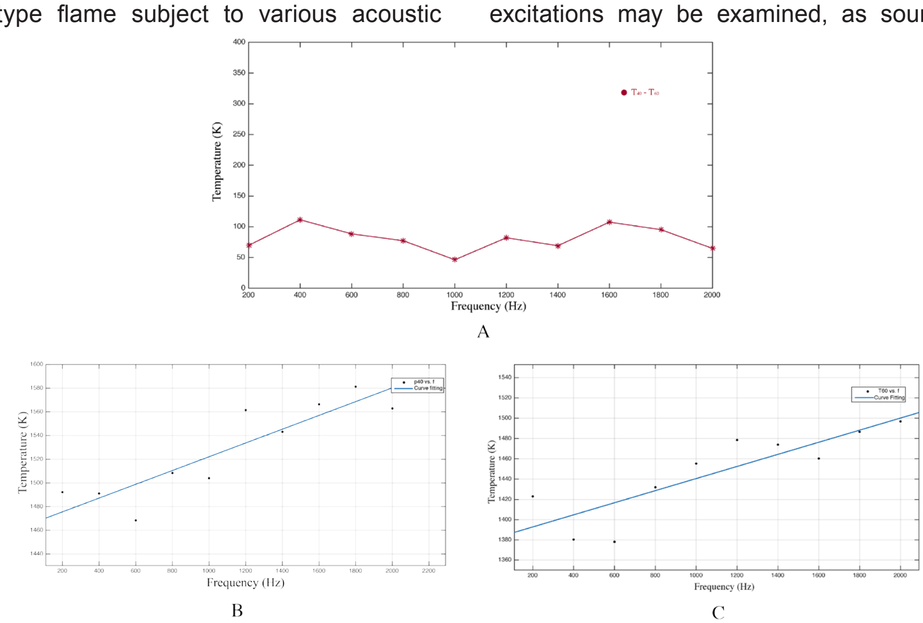

Figure 5: Comparing Flame Temperatures under 40 and 60 dB Fields. Showing the relation to acoustic frequencies and amplitudes. A) Difference between flame temperatures under a 40-dB and 60-dB acoustic field with different frequencies. B) Correlation between temperature and acoustic excitation frequency under a uniform 40-dB acoustic field. C) Correlation between temperature and acoustic excitation frequency under uniform 60 dB acoustic field.

is inevitable in real acoustic propagation. Based on the future investigations, we may be able to establish detailed theoretical models between different dynamics to interpret these phenomena and apply them to real situations.

Methods

The experiment setup is shown in **Figure 6**. A natural gas-air premixed flame was stabilized on a Bunsen burner tube with a 15-mm aperture. As the fuel and air flowed together in the burner tube, they were mixed in an adjustable air-fuel ratio. All experimental data were attained at a main burner equivalence ratio of ϕ=0.89. Acoustic disturbances were generated by a Phillips Speaker with an 85-mm diameter set 20 cm to the left of the burner. The speaker was connected to a PC to generate different tones. Frequencies and amplitudes were measured in units of Hertz and Decibel (SPL), respectively. Data was obtained at driving frequencies of 0–2 kHz and amplitudes of 0 dB, 40 dB (2 µpa), and 60 dB (20 µpa), which is the typical sound sourced from people's daily activities (16). At these amplitudes and frequencies, the nonlinear interactions were negligible. In the experiment, the acoustic radiation was spread directly to the flame at angles of 0–20 degrees.

In order to avoid other environmental factors that may have affected the results, the experiment was conducted in a closed lab with very little air flow. All other equipment was turned off to avoid any sound interfering with the one generated from the speaker and any electric field attracting or repulsing ions inside the flame, thus affecting the flame height and tilt angle.

During combustion, the flame temperatures under different acoustic fields were recorded at the peak of the flame reaction zone by a Type-K thermocouple. The measurements were taken three times for each trial, and the mean temperatures of the flames were plotted in a scattergram in Matlab. The data was then processed by the curve fitting tool in Matlab to determine the correlations between the variables (flame temperature, frequency, and amplitude). In addition, as instantaneous air disturbance can sometimes cause a greater tilt in flame angle and change the shape of the flame, for each selected excitation frequency and amplitude, a total number of five images were taken by a Nikon D7100 Camera with 50-mm lens. The best images for each amplitudes and frequencies were selected for comparison. Based on the images, we were able to measure the tilt angle and flame height of each flame and compute an average value.

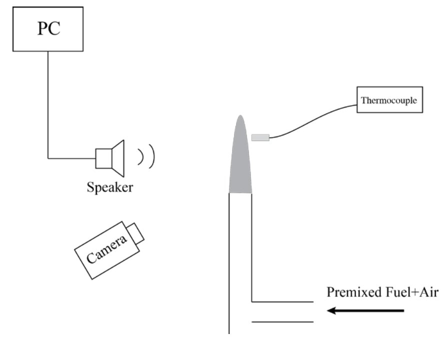

Figure 6: Experimental Setup. Sound was focused on a pre-mixed air Bunsen flame. Images and thermocouple measurements were taken.

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