INTRODUCTION

Combustion oscillations are a hot topic of research, whose process prediction is a challenge and is still in the development stage.\(^1\) Combustion oscillations occur in various combustion systems, such as, boilers,\(^2\) gas water heaters,\(^3\) gas turbines,\(^4,5\) ramjets,\(^6\) and rocket motors.\(^7,8\) Furthermore, they can cause structural vibration that increases the heat flux to the inner wall of the combustion chamber. This increases the content of nitrogen oxide in the flue gas, reduces the life of the equipment, and can also cause serious damage.\(^9\) Once the thermoacoustic coupling combustion oscillations occur in the high-performance propulsion systems, even a 1% change in the heat release rate can cause large pressure fluctuations in
the combustion chamber, and in extreme cases, they may lead to
disastrous effects.10,11

In the study of thermoacoustic coupling combustion oscillations, the accurate and rapid determination of the fluctuations in the flame heat release rate is crucial for stable combustion and control. However, the heat release rate cannot be obtained by direct measurement, and so it is necessary to select an indicator that can be used for characterization. One of the common methods used is to deduce the global heat release from the fluorescence emission of OH\textsuperscript{\*},12-17 CH\textsuperscript{\*},15-18 or C\textsubscript{2}\textsuperscript{\*}18 free radicals by means of a photomultiplier (PMT). A narrow-band filter can be used to remove the unwanted fluorescence radiation, and finally, the voltage signals proportional to the concentration of free radicals on the flame front can be obtained. Many researchers have used this method to measure the heat release rate fluctuations that can quickly quantify the flame description function (FDF).10-23 Another method used is to measure the flame front area.24-27 The intensified charge-coupled device (ICCD)\textsuperscript{17,26,27,19,25} and charge-coupled device (CCD)\textsuperscript{15,28} were employed to capture the chemiluminescence images. These images were then segmented and integrated to obtain the whole flame front area or a portion of it. Besides, a filter lens can be placed in front of the camera, which passes a certain wavelength according to the actual needs. However, the flame dynamics are ultimately independent of the filter lens.29 When the equivalence ratio remains fixed, the laminar flame propagation velocity is constant, indicating that the heat release rate is proportional to the fluorescence radiation intensity of the flame front. Although the second method used for the determination of the FDF is slower than the former, it can directly verify some of the theoretical studies based on the flame surface area. It can also visualize the interaction between the flame and the sound waves.26,27

The limitations imposed by the measuring instruments and the measurement methodologies make it difficult to measure the flame front area in a temporally resolved manner. It is found that the flame front area has been used for characterizing the heat release rate. In the burners featuring a single "V," "M," or conical flame case, and having low heat release rate fluctuations, small thermal load, and simple flame structures, the edge of the flame front is easy to detect. For a multipoint injection geometry burner, a burner with an array of parallel slots as the flame holes\textsuperscript{3} or a perforated plate premixed flame burner,23,26 the thermal load and the fluctuations are higher, making the edge of the flame front more difficult to define. Karimi\textsuperscript{29,30} used an ICCD camera to capture the instantaneous images of the flame and studied the interaction between the cone flame and the sound waves. The flame length was divided into 10 equal parts, and an intensity threshold algorithm was used to detect the position of the flame front. The algorithm was developed in MATLAB. However, an approximate calculation was made for calculating the flame front area. Li\textsuperscript{27} used an ICCD camera equipped with different interference filters to examine the acoustic forcing response. A color CCD camera was employed to select the pixel value in the flame zones of the image to characterize the heat release rate fluctuations. However, it did not effectively separate the flame front from the surrounding gas. Hartung\textsuperscript{31} used the Canny edge detection algorithm for the OH\textsuperscript{-}-PLIF (planar laser-induced fluorescence) image to identify the flame contour from the maximum gradient in the OH\textsuperscript{\*} field. The accuracy is higher than the constant intensity threshold algorithm. But the disadvantage of this method is that the beam profile and OH\textsuperscript{\*} concentration inhomogeneity affect the signal-to-noise ratio of the images. Yu\textsuperscript{32} and Wiseman\textsuperscript{33} employed a high-speed camera equipped with an intensifier and several fiber bundles to capture the CH\textsuperscript{\*} chemiluminescence from different views. The three-dimensional (3D) heat release rates were obtained using the computed tomography of chemiluminescence (CTC) technique. An iso-surface function in MATLAB was applied to the reconstructed emission fields, but the results depend on the accuracy of the constructed flame front.

There is no proper flame front recognition process available in the literature. Therefore, in this paper, a constant intensity threshold algorithm is used to detect the flame front and to carry out rapid measurement without using expensive instruments. Although this method is less accurate than the PLIF and the CCD camera fitted with an image intensifier measures the heat release rate of the flame, it provides a quick measurement method of the heat release rate fluctuations under relatively rudimentary laboratory conditions, using a high-speed camera. Single and multiple-cone flames are taken as the research objects, and a MATLAB program is developed to identify the flame front area. In particular, a method is proposed to deal with the impact of noise during combustion. Verifying with the PMT signals, it is found that there is good consistency between the normalized area and the heat release rate fluctuations.

2  |  EXPERIMENTAL CONFIGURATIONS

2.1  |  Experimental setup

A schematic view is displayed in Figure 1. The air from the surge tank enters a premixing pipeline after pressure adjustment, filtering, and metering. The methane is supplied to a gas distribution system from a high-pressure fuel tank and is injected into the premixing pipe in the opposite direction. The reactive mixture flows up to the head of the piston and enters into the resonance cavity through six evenly distributed round holes, each having a diameter of 5 mm. The piston head is smooth and flat to ensure that the sound reflection
boundary conditions are satisfied in the resonance cavity. The gap between the piston and the inner wall of the resonance pipe is sealed with nitrile butadiene rubber. The piston can slide up and down, which changes the length of the resonance cavity (84 mm–602 mm) and modifies the burner acoustic characteristics. The inner diameter of the resonant cavity is 68 mm, which is the same as the diameter of the perforated plate’s central part. The mixture flows downstream in the resonance cavity and finally produces conical flames at the nozzle. The first burner featuring a single-cone flame and operating like a Helmholtz resonator (HRB) is equipped with a convergent nozzle having a 10 mm exit diameter, the other burner uses a perforated plate instead of the convergent nozzle, and the flames are shaped in an ellipse as shown in the figure, the multiple flame burner behaving like an organ pipe resonator (OPR). The perforated plate is fixed at the end of the resonance cavity and is shown in Figure 2A,B. This specific plate is made from cold-rolled steel and has a diameter of 106 mm. Holes are machined in a hexagonal pattern at the center, and the pattern has a diameter of 68 mm. The number of holes, the elementary hole diameter, the hole pitch, and the perforated plate thickness are 397, 2 mm, 3 mm, and 3 mm, respectively. The perforated plate’s porosity is 0.34, which is the ratio of the flow passing through the surface to that passing through the central portion of the perforated plate. Both the burners contain a honeycomb to produce a laminar flow; the length of resonant cavities is, respectively, 0.26 and 0.3 m.

The main technical parameters of the test instruments are shown in Table 1. In the experiment, a gas roots flowmeter and a high-precision gas distribution system were used to control the flow of the air and the methane, respectively, to determine the equivalence ratio. As shown in Figure 1, the PMT equipped with a filter lens was used to measure the fluorescence radiation intensity of the CH∗ free radical and to estimate the heat release rate fluctuations. A high-speed camera was employed to continuously capture the flame images to observe the dynamic changes in the flames and to analyze the heat release rate fluctuations. The microphone M1 measured the sound pressure at a distance of 14 cm from the burner axis and at a distance of 30 mm above the plane of the convergent nozzle outlet and the perforated plate. The other microphone M2 recorded the pressure fluctuations in the resonant cavity. The signals were collected by a collecting device that was connected by a terminal block and a shielded cable. In this experiment, a LABVIEW-based program was
used for the synchronous triggering of the camera, the PMT, and the microphones. Finally, all the collected data were sent to a computer. The measuring instruments related to this article are displayed in Figure 1, and the instruments related to external excitation are not included.

2.2 | Measurement techniques

A PMT was employed to measure the global instantaneous CH* free mission from the flame, placed approximately 38 cm away from the burner. It consists of a bare tube and a tube base that is side-on type with a diameter of 28 mm. The measurable spectral response range can meet experimental requirements. The compact tube holder (C12597-01) is used in conjunction with the PMT. In the experiment, the output control voltage of the PMT is 4.3 V. A small current output was recorded without the flame in a dark environment, whose value was subtracted from the measurement results. Because the signals collector cannot directly collect the current signals, they are to be converted into voltage signals using a parallel resistance box. A CH* filter (430 ± 4 nm) was located between the PMT and the flame. The height of the filter could be adjusted according to the actual needs. The experiment was operated during the night to avoid interference from outside light, and the CH* filter and the PMT were placed inside a sealed box with a hole facing the flame direction to collect flame intensity signals, as shown in Figure 2C.

Instantaneous images of the flame were captured using a digital high frame rate camera that was based on a CMOS

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**TABLE 1** Test instruments

| Name                  | Model                  | Main technical parameters                                                                 |
|-----------------------|------------------------|-------------------------------------------------------------------------------------------|
| Gas roots flow meter  | FLRZ-G10-1A42          | Flow range: 0.5-10 m³/h, Accuracy grade: 1.5                                               |
| Gas distribution system | GCGB-41V              | Gas flow meter model: S48 28/HMT (5-100 L/min), precision: ±1.0%FS                         |
| PMT                   | Hamamasu-R928          | Spectral response range: 185-900 nm                                                        |
| CH* Filter            | 431 ± 4 nm             |                                                                                             |
| High-speed camera     | IF005C                 | Frame rate (Tint = 20 μs): >500FPS@800 × 600, Responsivity: ISO1500, Analog gain: 1-4      |
| Microphone            | CHQ2255                | Sensitivity (1000 Hz): 52.5 mV/Pa                                                             |
| Collecting device     | NI-PCI6251             | Resolution: 16-bit, Input range: ±0.1±10V, Maximum sampling rate: 1.25 MSa/s                |
| Terminal block        | NI-SCB-68              | 68-Pin I/O Connector                                                                         |
| Shielded cable        | NI-SHC68-68-EPM        | Conductor: 30AWG 7/38 tin-plated copper, 0.12 inch diameter                               |
image sensor and was equipped with a Nikon AF macro lens (60 mm f/2.8D). In order to ensure the visualizations and the signal-to-noise ratio of the images while maintaining high-speed shooting, the frame rate of the high-speed camera was set to 200 Hz. The exposure time and the acquisition period were set as 5 ms and 1 µs, respectively. Higher frequencies are also available but will reduce the signal-to-noise ratio. The peak signal-to-noise ratios (PSNRs) of the two flame images were approximately calculated to be 41 and 34, respectively. A lower camera gain was chosen in the snapshots and only a small area around the flame was shot to reduce the size of the imaging plane and to improve the effective resolution. The spatial resolution of the image is 0.265 mm. Because the Nikon macro lens has a fixed focus, the distance between the camera and the flame needs to be slightly adjusted to ensure sufficient picture clarity. An external synchronization acquisition mode was employed to carry out the synchronous triggering of the PMT and the microphones. The synchronization delay was zero. There were 2500 instantaneous pictures of the flame for each experimental condition.

The color image sensitivity (ISO) of the camera is up to 1500. The sensitivity of the camera can be adjusted with a brightness curve that has four nodes as shown in Figure 3. The brightness curve has a larger slope and a higher sensitivity. As the experiment was carried out in a dark environment, a brightness curve with a higher sensitivity was selected.

In the experiment, the distance between the measuring port of the microphone and the downstream end of the resonance cavity is 64 mm. Although insulation wool was placed between the convergent nozzle (perforated plate) and the resonance cavity, the temperature around the measuring port was still high. If the microphone is directly installed to the measuring hole, it will not only affect the measurement results, but can cause damage to the instrument. Also, it will induce cavity resonance when the microphone is close to the outer wall of the resonance cavity. Therefore, a semi-infinite pressure pipe method is used in the experiment. As shown in Figure 4, this method is composed of a pressure tube, a three-way connection, and a hose. The length of the pressure tube is 0.15 m, whose main function is to reduce the pressure disturbances in the resonance cavity. A microphone is installed on the three-way connector to form a "T" connection. The length of the hose is about 20 m in which the energy of sound waves can be attenuated to zero, so that there are only traveling waves in the hose. This method eliminates the resonance effect of the tube cavity and avoids reflection of the sound waves during the propagation process. In addition, compared with the measurement pore at the connection of the resonant cavity, the measurement spot of the microphone 2 is farther from the flame, thus there’s a lower ambient temperature, which would have a positive effect on the measuring accuracy and the protection of the instrument.

2.3 Instrument calibration and Error estimates

The signal generator was directly connected to an oscilloscope for verifying the output signal. The microphone was placed facing the loudspeaker. The signal generator was dual-channel output that provided a harmonic signal to the loudspeakers. The collecting device recorded the generator and the microphones output signals that were used for comparison. The results showed that the waveform and the frequency were completely consistent. The loudspeaker was placed at the bottom of the premixing tube and provided a harmonic signal of fixed-frequency to disturb the flow field in the resonance cavity. The PMT was employed to measure the flame heat release fluctuations, the high-speed camera simultaneously captured the flame images, and the fast Fourier transform was applied to process the data. Their dominant frequency is the same as the output signal of the loudspeaker. The gas flow meters were calibrated with the master meter method to meet the accuracy-level requirements.

To check the repeatability of the entire system, the same experiment was performed on different dates. However, due to the influence of the flow setting, the alignment of the optical components, and the influence of the external environmental
conditions, it was found that the flame images, the PMT, and the microphone signals were different. The second source of error is the background noise generated due to the residual energy on the CMOS image sensor and the rise in the operating temperature (the device has been operating for too long). This noise can be recorded on the captured images, and so a single tone (black) image is used as an indicator to observe the background noise that is subtracted from the final results. But it should be noted that background noise cannot be completely eliminated using any other methods. In addition, the diversity of the digital signal transmission is sensitive to the optical fibers and the limited number of samples causes uncertainties. To compare the results and to reduce the uncertainty caused by the above specific factors, the data were normalized with the mean value. In the current measurements, a compromise was made between the accuracy and the feasibility of the experimental setup.

3 FLAME IMAGE PROCESSING

The RGB image based on a Cartesian coordinate system consists of red, green, and blue color components. In order to reduce the amount of calculation and to further process the image, the original color image is converted into a grayscale image by weighting and summing the pixel values of each layer. An imagesc function performs the component processing on the RGB images in MATLAB. Figure 5B–D show the results of processing the RGB image with this function, where \( m_c \) and \( m_a \) designate the methane and air mean mass flow rate, respectively, \( \phi \) is equivalence ratio. The function uses linear mapping instead of direct mapping, which transforms the element values in the matrix into corresponding colors, increasing the contrast of the flame front with respect to the surrounding background and by highlighting the edge of the flame front.

The camera makes digital noise in the process of shooting and transmitting the images. The operating status of the internal components of the camera is affected by various objective conditions. When the camera captures the flame images, the external environment and the operating conditions of the internal sensors result in background noise on the image and it cannot be completely eliminated by any other methods. When the images are transmitted between the camera and the computer, either through a wired medium or through a wireless channel, factors such as light, atmospheric, and the surrounding instruments interfere with the transmission process, adding noise to digital images. Generally, the noise characteristics are the same for each color channel, but that has different effects on the image. The difference in the illumination intensities of the color channels produces images with different noise levels. For example, an IR filter can reduce the radiation intensity of the external light illuminating the infrared sensor, which is a source of noise with low illumination. As shown in Figure 5A–D, the red component in the image is often a source of noise when compared to the other two image components. Therefore, it is necessary to remove this noise signal from the digital image; otherwise, it will directly affect the image segmentation and the pattern recognition processes.

In addition, Figure 5E–L displays the flame with impact noise shot during the experiment. This phenomenon occurs occasionally with the single burner's flame. It contains less energy and is highlighted in the shape of an ellipse in the RGB image. However, it often occurs with a multiple flame burner, especially when the power of the burner is large. Uneven mixing of methane and air, low air cleanliness, loss of anticorrosion coating on the inner wall of gas storage tanks, pipes, and equipment, etc., may cause impact noise. Impact noise must be eliminated to reduce its adverse effect on the experimental measurement results. It can be known from the color component images of the three channels shown in Figure 5H,L that the blue channel has little impact noise. It can also be observed that the grayscale values of their corresponding positions are smaller than the other two channels and the surrounding background. In the combustion flame with methane as fuel, the fluorescence emission with CH* and C2* free radicals is mainly in the visible spectrum. The CH* free radical fluorescence wavelength is in a blue spectral range and the radiation intensity is much stronger than the other free radicals. The value of the blue pixel in the images is much higher than the values of red and green pixels. The quantitative relationship can be compared with the PMT measurement results. For the green channel, as shown in Figure 5K, the impact noise in the interior region has different colors, and the pixel value is higher than the edge region. However, in the corresponding region of the blue channel, there is only a slightly difference in the pixel value of the edge region, the pixel value of the inner region is zero. If the green channel is used to eliminate the impact noise, the maximum pixel value in the inner region must be selected as a threshold, but this threshold is much larger than the pixel value of the flame's front position, which will cause the entire flame region to disappear. Therefore, a blue channel image is selected for further processing to obtain the area of the flame front. According to this characteristic, the specific process of filtering out the impact noise and the process of identifying the flame front will be described below.

In order to reduce the amount of data in the image and to highlight the target contour of the image for later processing, it is necessary to convert the blue channel image into a binary image. The key is to select an appropriate threshold to effectively separate the flame from background. The pixels in the grayscale image with values greater than or equal to the threshold will be judged as the target areas; otherwise, they will be treated as background noise and are excluded.
from the target regions. It should be noted that the choice of threshold must be appropriate. A smaller threshold will lead to improper segmentation and it also creates noise, thereby, affecting the accuracy of the binary transformation. If the threshold is set too large, signals that are not noise may be filtered out by mistake, causing the objects in the image to disappear after the binary transformation. In this paper, the pixels corresponding to the impact noise are usually determined according to background noise. The data cursor is used in MATLAB to perform random estimation. To avoid large differences in the entire group of pictures, a corresponding estimation mode is provided in the program. Since the probability of having the impact noise in the images of a single-flame burner is very low, images corresponding to a multiple flame burner are used to illustrate the elimination of impact noise. The program is mainly divided into two parts, determining the threshold of impact noise and flame front position, and the formal calculation.
First, the program enters the debug mode and determines whether there is an impact noise after observing all flame images. Images containing impact noise, which are small in number converted into blue channel images. Since the pixel value at the edge is greater than the internal pixel value, the data cursor in the MATLAB is employed to select several different positions along the edge of impact noise to determine their pixel values. The largest pixel value is selected as the impact noise threshold for this image. The program is rerun to check whether the impact noise in all images has been eliminated. If some of the images still contain the impact noise, the above steps are repeated to select the threshold. If none of the images have impact noise, the threshold in the program is set to zero. The method of determining the flame front position’s threshold is slightly different from the above method. Due to the large number of flame images, they are randomly selected for each experimental condition. After the grayscale image of the processed image and the binary image of the blue channel are superimposed, the data cursor is employed to determine the pixel values at different positions along the edge of the flame front, and their mean value is taken as the threshold for this image. The same method is used to determine the flame front thresholds for other images. Finally, the mean value of all these thresholds is taken and is set as the flame front threshold. The image processing step selects the multiflame burner flame image to illustrate, $m_c = 0.036 \text{ g/s}$, $m_a = 0.769 \text{ g/s}$, and $\phi = 8$. Figure 6 shows the impact noise threshold; pixels having values greater than 12 in the blue channel are selected to form a binary array, as shown in Figure 7. The red region in Figure 7 indicates that there is no impact noise and the filtering is effective. If the image has no impact noise, it will almost be red, as shown in Figure 15A. Next, the original image is converted to a grayscale image (Figure 8). The pixel value of the red area in Figure 7 is superimposed with the pixel value located at the same position in Figure 8 to obtain Figure 9. This image is free from impact noise. As shown in Figure 10, the pixel value of the pixel with impact noise is zero. In other words, Figure 7 is a binary image that consists of logical values 0 and 1. Logical value 1 is needed, and logical value 0 must be eliminated as it contains impact noise. Figure 8 is a grayscale image consisting of the pixel values. After multiplying the corresponding data points in the two-dimensional array, the unnecessary data points are eliminated, and the final image is the grayscale image shown in Figure 9. The purpose of this step is to convert the blue channel binary image into the grayscale image without impact noise, the next step is to determine the flame front threshold, and the binary image has only logical values 0 and 1 that cannot determine this threshold. Similarly, the method of random estimation is also used to determine the pixel value of the flame front. As shown in Figure 11, the pixel value of the flame front edge is 21, which is used as a threshold for determining the flame front.

Figure 12 is obtained from the binarized Figure 11, but it is found that there are pixel particles, holes, and gullies near the outline of the flame front. Thus, the flame front needs to be further processed with morphological theory to smooth the flame contour, bridge the narrow discontinuities, elongate gullies, eliminate smaller holes, and fill in the breaks in
the contour lines. Finally, Figure 13 displays a binary image of the flame front. Figure 14 depicts the working flow diagram in MATLAB.

The results of processing for a single-cone flame image can be obtained that use the same method, as shown in Figure 15. It can be noticed that there is no impact noise in the flame. The binary image of the blue channel is almost all red. The imagesc function is also used during the image processing, which can automatically fill the colors corresponding to the pixel values. Therefore, the grayscale images have different background colors between the two burners, and the pixel value of a single-flame front position is higher than the multiple small flames. In addition, the different versions of MATLAB may also cause different background colors, but that will not affect the final calculation results.

4 | DISCUSSION

According to the final results from the procedure, the red regions shown in Figures 13 and 15F are actually the number of pixels. The pixel resolution on the flame image under the same set of working conditions remains unchanged. Therefore, the number of pixels is directly proportional to the flame front area and the total chemiluminescent emission. In order to verify the recognition results corresponding to the flame front area, two experimental working conditions and combustion regimes were chosen, and the experimental operating parameters are shown in Table 2. The experimental instruments were preheated before one hour to reduce the adverse effects on the measurement results, and the measurement was performed when the flame is stable for thirty minutes after ignition. Hence, it was ensured that the whole system was under thermal equilibrium. The output signals of a PMT and two microphones were recorded at a sampling frequency of $f_s = 16,384$ Hz for one second, resulting in a frequency resolution of 1 Hz and a time resolution of 0.061 ms.

The single-cone flame burner under this working condition is in a stable combustion regime. According to the above developed calculation program, time series of normalized area can be obtained, as shown in Figure 16A. The fuel-rich single-cone flame is that part of the fuel makes diffusion combustion. Although the figure shows only the flame front area of the inner cone, it does not affect the result of the final heat release rate fluctuation. The literatures even select the part of the flame front area to analyze the fluctuations of the heat release rate. The flame front area data were further processed to eliminate the direct current component. A spectrum Figure 16B can be obtained from the fast Fourier transform (FFT), and the dominant frequency of the flame front fluctuations is 2.32 Hz. However, it is found from the graph shown in Figure 16A that the normalized area exhibits random fluctuations, and these fluctuations do not obey any law. According to the dominant flame front fluctuation frequency the change in the flame shape in a period can be obtained, as shown in Figure 17. The flame shape is basically unchanged, and the high-speed camera can perceive little brightness changes. By comparing the images of high-frequency oscillation conditions, the flame brightness is dim. Under this working condition, the fluctuating pressure propagates, reflects, and attenuates in the resonance cavity, resulting in an initial distribution of the pressure, but the heat release rate
FIGURE 14  The flowchart for eliminating impact noise and calculating flame front area

FIGURE 15  Results of image processing for a single-cone flame image. A, Binary image of the blue channel. B, The original grayscale image. C, Grayscale image after stacking. D, A pixel value of the flame front edge. E, Binary image of the flame front area. F, Morphology processed binary image. $m_i = 0.007$ g/s, $m_s = 0.096$ g/s, and $\phi = 1.26$
fluctuations are not coupled with the pressure fluctuations, the pressure is not strengthened and has little effects on the flame that manifests as small random fluctuations. Figure 18A displays that there is a time delay between the pressure in the resonance cavity and output signals of a PMT due to the different measurement positions. Figure 18B–D presents the spectrogram of the microphones and the PMT. According to the spectrogram information shown in Figure 18B, the dominant frequency of the resonant cavity’s pressure fluctuation is 319 Hz. In addition to the harmonics containing the dominant frequency of the flame image fluctuations (2.32 Hz), it also contains other harmonics such as 52 Hz, 83 Hz, 480 Hz, etc. The dominant frequency of the fluctuations in the flame heat release rate as measured by the PMT is 240 Hz, and it contains harmonics such as 52 Hz, 319 Hz, 480 Hz, etc, as shown in Figure 18C. Figure 18D displays the sound pressure near the flame measured by the microphone M1. It contains a large number of harmonics, and there is no obvious dominant frequency except for the frequency of 52 Hz, which has higher energy. Also, the amplitude is much lower than that of the microphone M2, which may be attributed to the significant background noise present in the environment. The measurement of the microphone M2 adopts the semi-infinite pressure tube method, which can shield some of the harmonics with smaller energy, and can show the dominant frequency. The reason for the low peak frequency may be that a honeycomb is added to the burner outlet in the resonant cavity, which improves the stability of the laminar flow. Also, the experimental conditions of the burner are also much lower than the thermal load and flow velocity of similar burners. In addition, the single-flame burner is in a stable combustion regime, the flame area is basically stable, there are only small random fluctuations in the flame surface, the frequencies of the pressure and the heat release rate are different, which may also cause small peaks. Based on the above analysis, when the system operates in this regime, the dominant frequency of the fluctuations measured by the PMT is different from that measured by the microphones. When there is no coupling and mutual excitation between the combustion and the acoustics, the flames take a classic conical shape during combustion, and the sound pressure level measured by the microphone M1 is 54.1 dB, which is almost the same as the background noise.

A combustion condition of the multiple flame burner is selected with an equivalence ratio of 0.8 that makes an unstable case in this paper. Calculating all flame images under this working condition can get the normalized area displayed in Figure 19A. It can be seen from the zoomed graph that the normalized area has obvious fluctuations law. Figure 19B shows the FFT analysis results of the flame front area, the dominant frequency is 19 Hz, and the oscillation period is about 52.632 ms. The dominant frequency of the flame image fluctuation is 319 Hz, which may be attributed to the significant background noise present in the environment. The measurement of the microphone M2 adopts the semi-infinite pressure tube method, which can shield some of the harmonics with smaller energy, and can show the dominant frequency. The reason for the low peak frequency may be that a honeycomb is added to the burner outlet in the resonant cavity, which improves the stability of the laminar flow. Also, the experimental conditions of the burner are also much lower than the thermal load and flow velocity of similar burners. In addition, the single-flame burner is in a stable combustion regime, the flame area is basically stable, there are only small random fluctuations in the flame surface, the frequencies of the pressure and the heat release rate are different, which may also cause small peaks. Based on the above analysis, when the system operates in this regime, the dominant frequency of the fluctuations measured by the PMT is different from that measured by the microphones. When there is no coupling and mutual excitation between the combustion and the acoustics, the flames take a classic conical shape during combustion, and the sound pressure level measured by the microphone M1 is 54.1 dB, which is almost the same as the background noise.

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**Table 2** Experimental operating parameters. (25°C, 1 atm)

|                      | Single-flame burner | Multiple flame burner |
|----------------------|---------------------|----------------------|
| Air volume flow (g/s)| 0.096               | 0.769                |
| Methane volume flow (g/s)| 0.007           | 0.036                |
| Equivalence ratio    | 1.26                | 0.8                  |
| Thermal load (kW)    | 0.33—a              | 1.7—a                |

*aThe methane of lower heating value is 34 MJ/m³.*

**Figure 16**

A, Time-resolved measurements of the normalized area.
B, Spectra analysis of the flame front. 
\( m_c = 0.007 \text{ g/s}, m_a = > 0.096 \text{ g/s}, \text{ and } \phi = 1.26 \)

**Figure 17** Instantaneous images of the flame during one cycle. 
\( m_c = 0.007 \text{ g/s}, m_a = > 0.096 \text{ g/s}, \text{ and } \phi = 1.26 \)
fluctuations is consistent with the PMT and the microphones (Figure 20A–C). Consistent frequency is a necessary feature that causes the thermoacoustic coupling oscillation, and the Rayleigh index is often quoted as a criterion to indicate the necessary condition for instability, that is, 

\[ \frac{1}{T} \int_0^T q' p' dt > 0, \]

where \( q' \) and \( p' \), respectively, stand for the heat release rate and the pressure fluctuations; \( T \) is time taken for the completion of one combustion oscillation cycle. Rayleigh index for the experimental operating conditions is 0.612. This is consistent with the definition of the thermoacoustic instability stated by the Rayleigh criterion. The heat release rate and the pressure fluctuations in the flame region are mutually excited. The sound pressure level measured by the microphone \( M_1 \) is 72.6 dB; the noise during combustion oscillation is much higher than that of stable combustion. Finally, the sound energy radiation and the loss induced by the dissipation effects in the perforated plate are balanced with the energy release of the flame, the system forms a limit cycle, and the disturbance amplitude saturates.

Figure 20D presents the time-resolved measurements of the microphone \( M_2 \) and the PMT. They have a fixed phase difference and they form a positive feedback, which meets the determination conditions for thermoacoustic coupling in the Rayleigh criterion. However, the time resolution of the high-speed camera is different from the time resolution of the PMT. It is impossible to directly compare the two signals, but the high-speed camera is triggered synchronously with the microphones and the PMT. It can be known from the frame rate of the camera that there are about eleven flame images in one cycle. By matching the output signals of the PMT with the camera exposure time, the normalized flame area and the heat release rate fluctuations curves are obtained in the time domain and are displayed in Figure 21A. The changing trends of the two curves are almost the same.
and the Pearson correlation coefficient is 0.953, which is a very strong correlation. The reason for the slight deviation between the curves is that external environment has a different influence on the camera and on the PMT. While selecting the photoelectric signal corresponding to the camera exposure time, the photoelectric signal is replaced by the data closest to the time point due to a different time resolution. The introduction of morphological theory also has a negative effect on the accuracy. In this paper, for the single-flame burner, \( m_c = 0.007 \, \text{g/s}, m_a => 0.096 \, \text{g/s}, \) and \( \phi = 1.26 \). The flame front and impact noise threshold are set to 34 and 32, respectively. Based on the binary image after removing the impact noise, the maximum error after processing with morphological theory is 0.042. The multiple flame burner has, \( m_c = 0.036 \, \text{g/s}, m_a => 0.769 \, \text{g/s}, \) and \( \phi = 0.8 \).

**FIGURE 20** Spectrum analysis of (A) the microphone M1, (B) the microphone M2, and (C) the PMT. (D) Time-resolved measurements of the microphone M2 and the PMT signals. \( m_c = 0.036 \, \text{g/s}, m_a => 0.769 \, \text{g/s}, \) and \( \phi = 0.8 \).

**FIGURE 21** A, Time-resolved analysis of the normalized area and the heat release rate. B, Time-resolved analysis of the normalized area and the grayscale. \( m_c = 0.036 \, \text{g/s}, m_a => 0.769 \, \text{g/s}, \) and \( \phi = 0.8 \).

**FIGURE 22** Instantaneous flame images in one cycle. \( m_c = 0.036 \, \text{g/s}, m_a => 0.769 \, \text{g/s}, \) and \( \phi = 0.8 \).
and the maximum error is 0.037. It is worth noting that the calculation results of the flame images captured by the high-speed camera indicate the fluctuations of the local heat release rate in the flame, while the measurement results of the PMT are the fluctuations of the global heat release rate. The scale factors between the two measurement results and the actual heat release rate are different, but this does not affect the comparison of the calculation results. In addition, the normalized area and gray curves of the flame are also identical in the time domain, as shown in Figure 21B.

The flame images taken at regular time intervals are illustrated in Figure 22. The flame image at 45.009 ms was removed so that the layout could be more convenient. The brightness of the flame images is higher than the stable combustion regime. As the flame under this operating condition is a fully premixed flame, the flame height is smaller, the camera angle is poor, etc, and the change in the flame shape is not obvious. However, according to the spectrum analysis, it is found that the dominant frequency of the flame front oscillations, the heat release rate oscillations, the sound pressure oscillations near the flame, and the pressure oscillations during the resonance are completely consistent; there is a strong correlation between the fluctuations of the flame front area and the heat release rate. The flame front area and the heat release rate follow the same law of fluctuations. The heat release rate fluctuations phase is similar to the pressure fluctuations in a resonance cavity, which is completely consistent with the results in the literature.40,41 It shows that it is completely feasible to use the results of calculation from the flame front recognition program to indirectly characterize the heat release rate fluctuations.

5 | CONCLUSIONS

The visual measurement of the flame has become a key technology that achieves combustion diagnosis and control. It not only characterizes the heat release rate fluctuations, but it also intuitively reflects the flame dynamics. This article used a high-speed camera to capture the instantaneous images of the flame. A MATLAB-based flame front recognition program was developed to eliminate the impact noise in the flame. The edge position of the flame front was detected with an appropriate threshold and it was effectively segmented from the background. The flame front image was further optimized by the morphological theory, and the normalized surface area fluctuations of the flame front were obtained. Detailed experimental investigations were performed to measure the response of the self-excited oscillations of the flame. In this paper, the single-flame burner is in a stable combustion regime. The area of the flame front displays random fluctuations, and the dominant frequency of the microphones is different from the PMT, which contain a lot of harmonics. However, the multiple flame burner produces thermoacoustic coupling combustion oscillations. The dominant frequency of the flame front fluctuations is consistent with the output signals from all the instruments. Pearson correlation analysis shows that there is a strong correlation between the flame front area fluctuations and the PMT output signals, verifying the accuracy of the flame front recognition program. In summary, the flame images taken using the high-speed camera to analyze the fluctuations law of flame heat release rate is an effective method for the study of thermoacoustic coupling combustion oscillations.

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