Experimental Studies on Acoustic Oscillation Angles and Positions on Soot Suppression from Acetylene Laminar Diffusion Flames

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Abstract

In this study, the relation of acoustic oscillation angles (the angle between the acoustic oscillation direction and horizontal axis) and positions (the acoustic oscillation applied to the top, average, and bottom regions of the flame) with the soot suppression efficiency was investigated for acetylene laminar diffusion flames. The soot suppression efficiency depends on acoustic oscillation angles. With an increase in the flow rate, the angle required for optimum soot suppression increased. At the flow rate of 50 mL/min, the acoustic oscillation angle required for the optimum suppression efficiency was 0°. The angle increased to 15° when the flow rate increased to 70 mL/min. Further increase in the flow rate to 90 mL/min leads to an increase in the angle to 30°. Moreover, acoustic oscillation positions affect the soot suppression efficiency. When the acoustic oscillation acts on the top region of the flame, the effect of soot suppression is substantial. The top region of the flame is the soot oxidation zone. The bottom and average regions of the flame are soot formation and growth zones, respectively. The application of acoustic oscillations on the soot oxidation zone can effectively increase the soot oxidation reaction rate. Furthermore, when the acoustic oscillation is applied to the top region of the flame, the flame temperature is higher than that when the acoustic oscillation is applied to the average and bottom regions of the flame.

Keywords: *Angle, flame position, soot suppression, acoustic oscillation, oxidation zone*

I. Introduction

Combustion is widely used in energy conversion systems. Insufficient combustion can lead to soot generation [1, 2], which results in serious environmental pollution problems [3, 4], thereby affecting human health [5, 6]. The development of effective protocols for soot suppression is highly demanded. Several strategies are reported to effectively minimise soot emission. Js et al. [7] studied the characteristics of gaseous products and coke deposition during the pyrolysis of pure propane and methanol propane mixtures. The addition of methanol to propane leads to a considerable decrease in carbon depositions and particle diameters. Kalbhor et al. [8] studied the influence of hydrogen enrichment and water vapour dilution on soot formation in laminar ethylene counterflow flames through numerical simulations and showed that the fuel-side enrichment of hydrogen or oxidiser-side dilution of water vapours causes the suppression of soot formation through chemical effects.

Applying an electric field to diffusion flames can suppress soot generation [9, 10]. For instance, Wang et al. [10] experimentally studied the effects of electrode shapes, positions, strengths, and polarities on the flame morphology and soot deposition characteristics. Their results showed that the central electrode with positive charge can suppress soot particle emission. Moreover, the addition of catalysts to fuel is an effective approach to soot suppression [11, 12]. Yang et al. [11] developed a catalyst with potassium to effectively improve CO conversion and minimise soot-growth zone temperature. Furthermore, Yong et al. [13] achieved the suppression of soot, acetylene and propargyl by adding methanol to ethylene. With an increase in the methanol mole fraction, the average soot particle size linearly decreases. Consalvi et al. [14] numerically simulated laminar methane diffusion

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flames with different contents of n-heptane and isooctane in CO_2 dilution in air. Their results showed that soot production linearly decreases with an increase in the CO_2 molar concentration.

The application of acoustic oscillations is considered an effective approach to soot suppression. Satio et al. [15] reported that soot emission from acetylene laminar diffusion flames can be suppressed considerably by applying acoustic oscillations having different sound pressure levels (SPLs) and frequencies. Their results showed a soot suppression efficiency of >90% with the acoustic Reynolds number of >3000. By applying acoustic oscillations, which lead to the reoxidation of soot particles, the mixing of fuel gas with surrounding gas can be enhanced, and flame temperature can be increased. Jocher et al. [16] studied the interaction among flow, chemistry, and soot in acoustic-intensity wave co-flow flames and showed that with an increase in frequency, the maximum soot volume fraction decreases. At 40 Hz, the transient evolution of maximum soot production and forced fuel velocity almost synchronises. Oliveira et al. [17] investigated the soot suppression of the jet free diffusion flames of a liquefied petroleum gas under the acoustic oscillation condition. Soot suppression depends on the amplitude and frequency of oscillations acted at the flame formation region. Hirota et al. [18] applied 20-kHz high-frequency standing waves to a methane air lift jet flame base and found that the soot can be considerably supressed. We have applied acoustic oscillations for soot suppression [19, 20]. Ye et al. [20] investigated soot suppression by combining numerical and experimental studies and reported that with the development of acoustic oscillations, O_2 consumption substantially increases. The decrease in the surface growth rate is the main cause for soot suppression when air is pushed towards flames. Guo et al. [21] studied the effects of different waveforms on soot suppression. The relationship between acoustic parameters and the soot suppression rate is normalised through sound energy. The suppression efficiency reaches 50% when the fluctuation velocity is >2 m/s.

Santoro et al. [22-24] investigated the formation and growth of soot particles in a coaxial diffusion flame by measuring the soot particle size through laser scattering. The flame can be roughly divided into three regions (Figure 1). The top, average, and bottom regions are characterised by soot oxidation, dominant soot particle growth, and dominant soot particle formation processes, respectively.

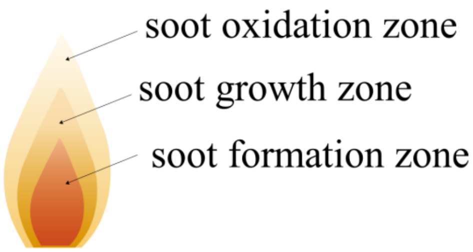

Fig. 1. Soot formation and consumption in laminar flames [22]

However, no study has investigated the effects of acoustic oscillation angles (the angle between the acoustic oscillation direction and horizontal axis) and positions (acoustic oscillations applied to the top, average, and bottom regions of the flame) on soot suppression. In this study, the relation of acoustic oscillation angles and positions with the soot suppression efficiency was investigated for acetylene laminar diffusion flames. With an increase in the flow rate, the angle required to achieve the optimal soot suppression increases. When acoustic oscillations are applied to the top region of the flame, the effect of soot suppression is significant.

II. Experimental Set Up

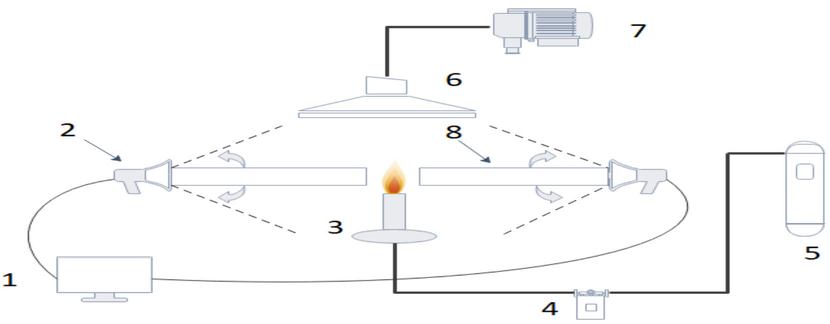

Fig. 2 Experimental setup

1. Computer; 2. Loudspeakers; 3. Bunsen lamp; 4. Flowmeter; 5. Acetylene cylinder; 6. Glass fibre filter; 7. Vacuum pump; 8. Quartz glass tube.

Table. 1. Technical characteristics of the experimental equipment

Serial number	Equipment	Technical characteristics
1	Computer	LabVIEW program on acoustic oscillation
2	Loudspeakers	Acoustic oscillation
C	Bunsen lamp	Acetylene diffusion flame
4	Flowmeter	The flow rate of acetylene gas
5	Acetylene cylinder	Acetylene gas
6	Glass fiber filter	Collect soot particles
7	Vacuum pump	Extraction of gas
8	Quartz glass tube	Channels for acoustic oscillation

Figure 2 shows the experimental setup. Table 1 shows the role of each experimental device in this project. Two loudspeakers (166.67-mm woofer, DL50TZF-30) were connected at both the ends of quartz glass tubes (outer and inner diameters of 35 and 30 mm, respectively). The length of quartz glass tube is 20 cm. The sine waves generated using the two loudspeakers were applied to the flame. The amplitude and waveforms generated using the loudspeakers were measured and calibrated using piezoelectric pressure sensors. SPL was measured using a sound-level meter. Before the experiment, the SPL was measured at both the ends of the loudspeaker. The frequency (f) and amplitude (A) of disturbance waves varied within 50–150 Hz and 0–0.14 V, respectively. Flame temperature (T) was measured by employing a high-speed two-colour pyrometer. Acetylene gas was utilised as fuel. The fuel flow rates (Q) were controlled at 50, 70, and 90 mL/min. The soot particles produced through acetylene diffusion flame were collected with a glass fibre filter. To ensure no moisture was present, before the experiment, the glass fibre filter was heated in an oven at 110 ℃ for >12 h. The soot particle mass collected on the glass fibre filter was measured using an electronic balance (artrius, bsa2245-cw) with an accuracy of 0.1 mg. Each collection time of soot particles was 1 min. The glass fibre filter was directly above the flame. All the burned gas flowed through the filter. The whole device formed a strong negative pressure. And it drove soot particles whose density is higher than the density of the gas to move upwards. The response time of the temperature pyrometer was 1 ms. And the accuracy was ±4 ℃ (±7.2 ℉) of the measured value.

All the experiments were performed on the same horizontal axis. To change the acoustic oscillation angle, the outer sides of the two quartz glasses were fixed, and the inner sides were elevated or lowered to certain degrees. The upward and downward angles of the quartz glasses were positive (+) and negative (−), respectively. The angle of the quartz glasses varied from −75° to 75°.

III. Results and Discussion

3.1 Effects of the acoustic oscillation angle on soot suppression

Figure 3 shows the effects of the acoustic oscillation angle on soot suppression with a fuel flow rate of 50 mL/min. Under this condition, the measured flame length is approximately 18.4 mm. The horizontal axis presented in Figure 1 is the acoustic oscillation angle. The longitudinal axis is the ratio of soot mass in pulsating combustion (M_1) to that in nonpulsating combustion (M_0). Figure 3a shows the relation between of the acoustic oscillation angle and soot suppression efficiency at the frequency of 50 Hz. With an increase in SPL, the soot suppression efficiency increases. The acoustic oscillation angle affects the soot suppression efficiency. The soot suppression efficiency is the highest at the angle of 0 °. The same results were obtained for the frequency of 70, 90, 110, 130, and 150 Hz (Figure 3b–f). Moreover, with the increasing frequency, SPL must be increased to achieve a high soot suppression efficiency. The results are consistent with a previous report [15].

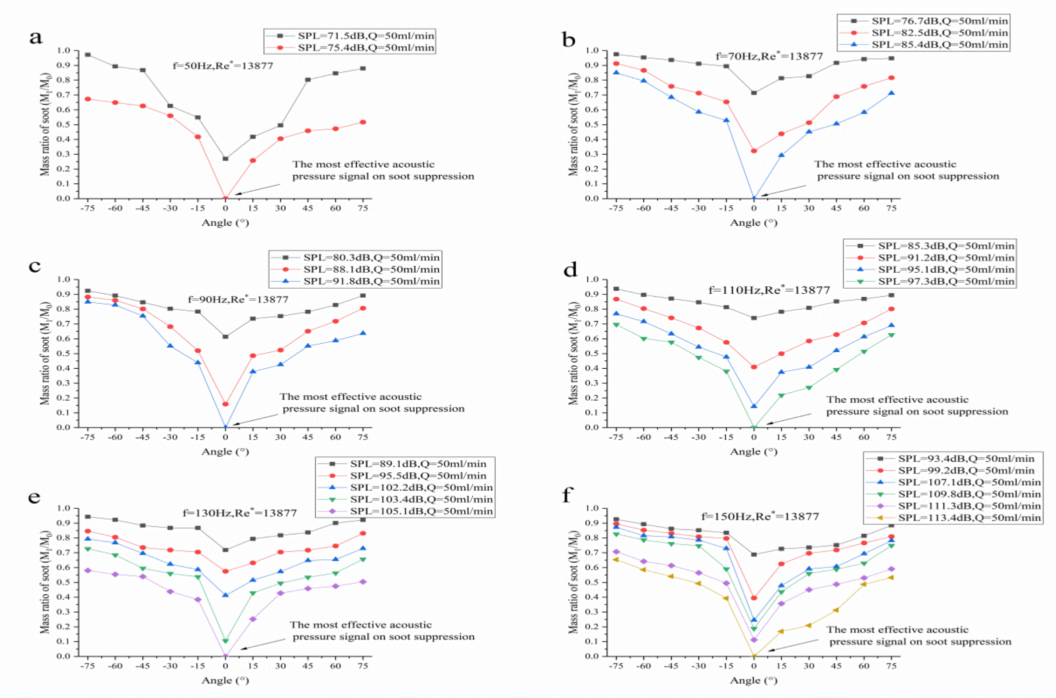

Fig. 3. Effects of the acoustic oscillation angle on soot suppression at a fuel flow rate of 50 mL/min

Figure 4 shows the effects of the acoustic oscillation angle on soot suppression at a fuel flow rate of 70 mL/min. Under this condition, the measured flame length is approximately 24.2 mm. Figure 4a shows the relation between the acoustic oscillation angle and soot suppression efficiency at the frequency of 50 Hz. With an increase in SPL, the soot suppression efficiency increases. The acoustic oscillation angle affects the soot suppression efficiency. The soot suppression efficiency is the highest at an angle of 15 °. The same results were obtained for the frequency of 70, 90, 110, 130, and 150 Hz (Figure 4b–f).

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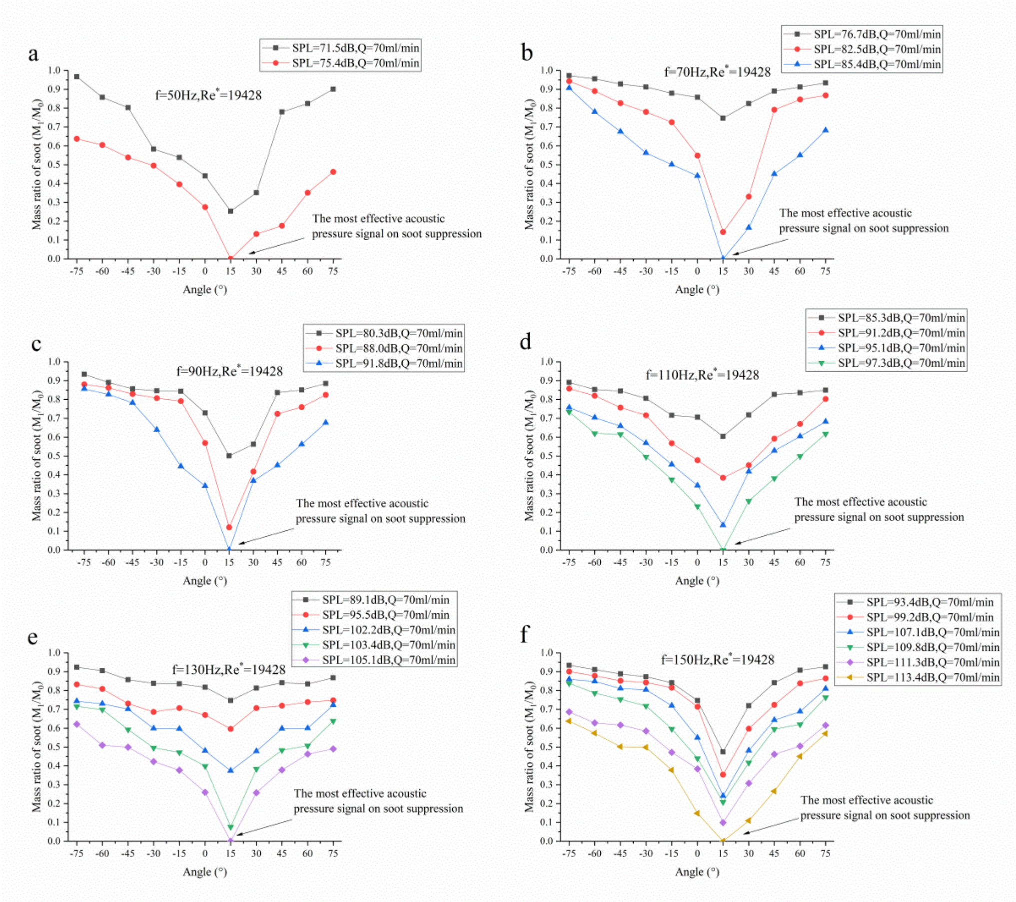

Fig. 4. Effects of the acoustic oscillation angle on soot suppression at a fuel flow rate of 70 mL/min

Figure 5 presents the effects of the acoustic oscillation angle on soot suppression at a fuel flow rate of 90 mL/min. Under this condition, the measured flame length is 35 mm. With an increase in SPL at a certain frequency, the soot suppression efficiency gradually increases. The acoustic oscillation angle affects the soot suppression efficiency. At the angle of 30 °, the soot suppression efficiency is the highest.

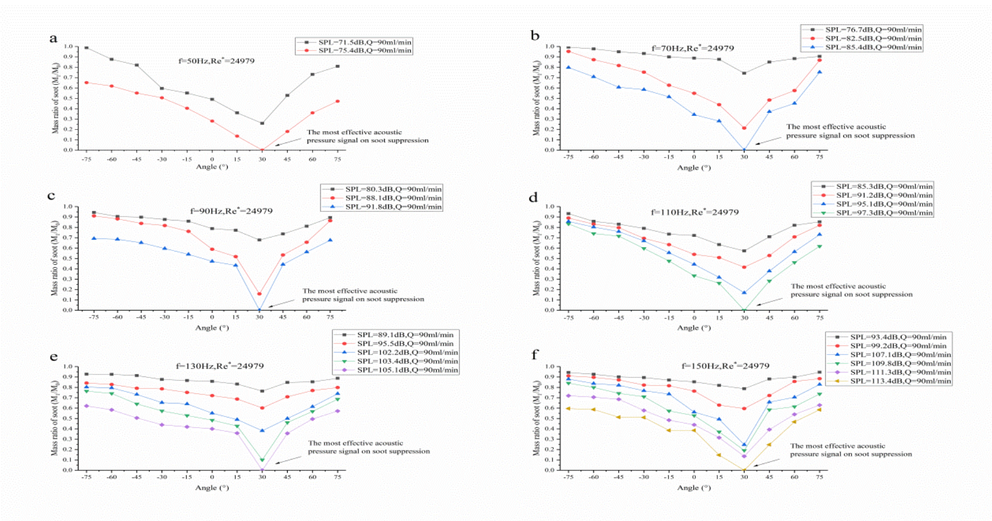

Fig. 5. Effects of the acoustic oscillation angle on soot suppression at a fuel flow rate of 90 mL/min

The flame length at the flow rate of 50 mL/min is approximately 18.4 mm. because the inner diameter of the glass tube is 30 mm, the flame is covered with the loudspeaker. When the acoustic oscillation angle is applied in parallel (acoustic oscillation angle of 0°), the aggregation point of the acoustic oscillation occurs at the top region of the flame, indicating that the oscillation is applied on this top region (Figure 6a and 6b). At the flow rate of 70 mL/min, the flame length increases to 24.2 mm. The acoustic oscillation with an angle of 15° was applied on the top region of the flame (Figure 6c and 6d). At the flow rate of 90 mL/min, the flame length increases to 35 mm. The acoustic oscillation with the angle of 30° is applied on the top region of the flame (Figure 6e and 6f). To achieve the highest soot suppression efficiency, acoustic oscillations should be aimed at the top region of the flame, that is, the soot oxidation zone [22-24].

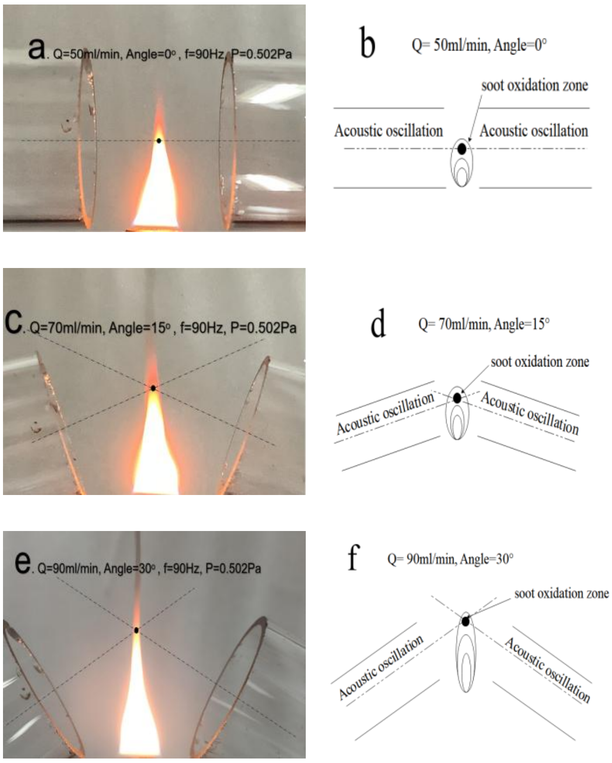

Fig. 6. Images and graphs of the aggregation point of the acoustic oscillation

3.2 Effects of acoustic oscillation positions on soot suppression

Figure 7 shows the parameters related to the acoustic oscillation position at the fuel flow rate of 50 mL/min. The flame length (H) is 18.4 mm. The interval difference is 10 mm. Figure 7a illustrates the acoustic oscillation applied at the top region of the flame (H_T). To apply the acoustic oscillation to the average and bottom regions of the flame, the Bunsen burner was moved upward by 10 mm (Figure 7b) and 20 mm (Figure 7c), respectively.

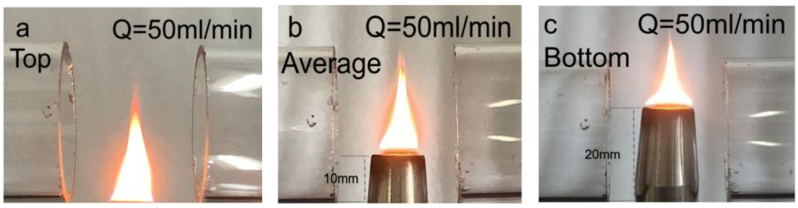

Fig. 7. Parameters related to acoustic oscillation position at the fuel flow rate of 50 ml/min

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Figure 8 shows the effects of acoustic oscillation positions on soot suppression at the fuel flow rate of 50 mL/min and acoustic oscillation angle of 0 °. It can be seen that, with the increase of amplitude, the soot suppression efficiency is increased, which is consistent with previous report [19, 20, 21]. Moreover, the soot suppression efficiency at the top region of the flame is the highest. The same results can be obtained when the fuel flow rates are at 70 mL/min and 90 mL/min (as shown is Figure 9 and Figure 10).

When the acoustic oscillation is applied on the top of the flame (soot oxidation zone), the soot suppression efficiency is highest. The application of acoustic oscillations on the soot oxidation zone causes the intensification of the mixing of the fuel gas and excess air. In such a situation, the boundary layer of soot particles can be decreased, which leads to the enhancement of mass transfer and reoxidation of soot particles in the oxidation zone [19-21].

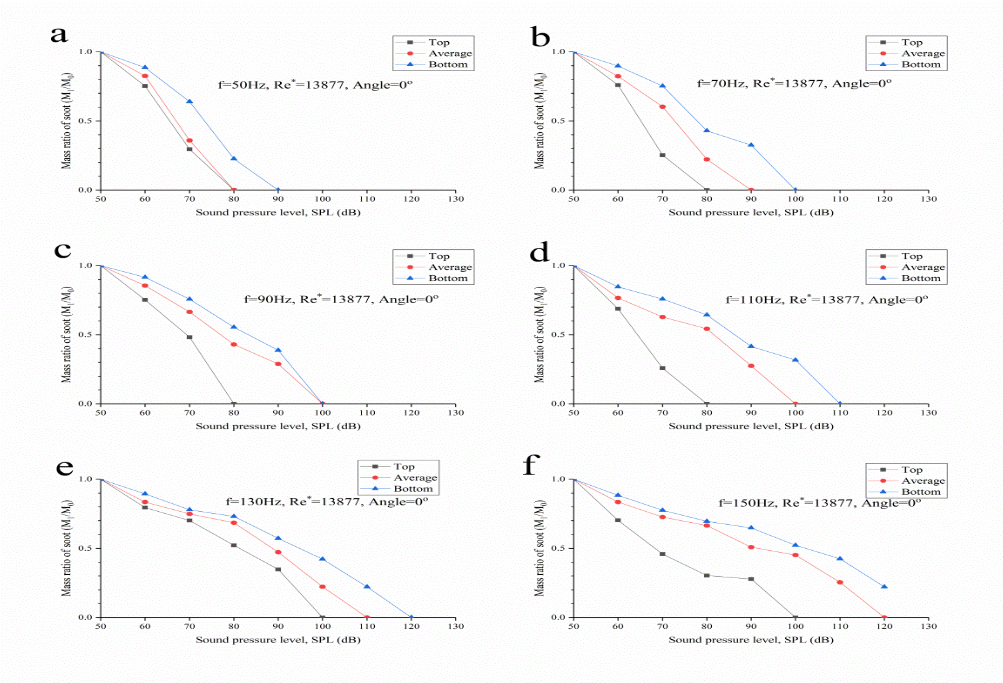

Fig. 8. Effects of the acoustic oscillation position on soot suppression at the fuel flow rate of 50 mL/min

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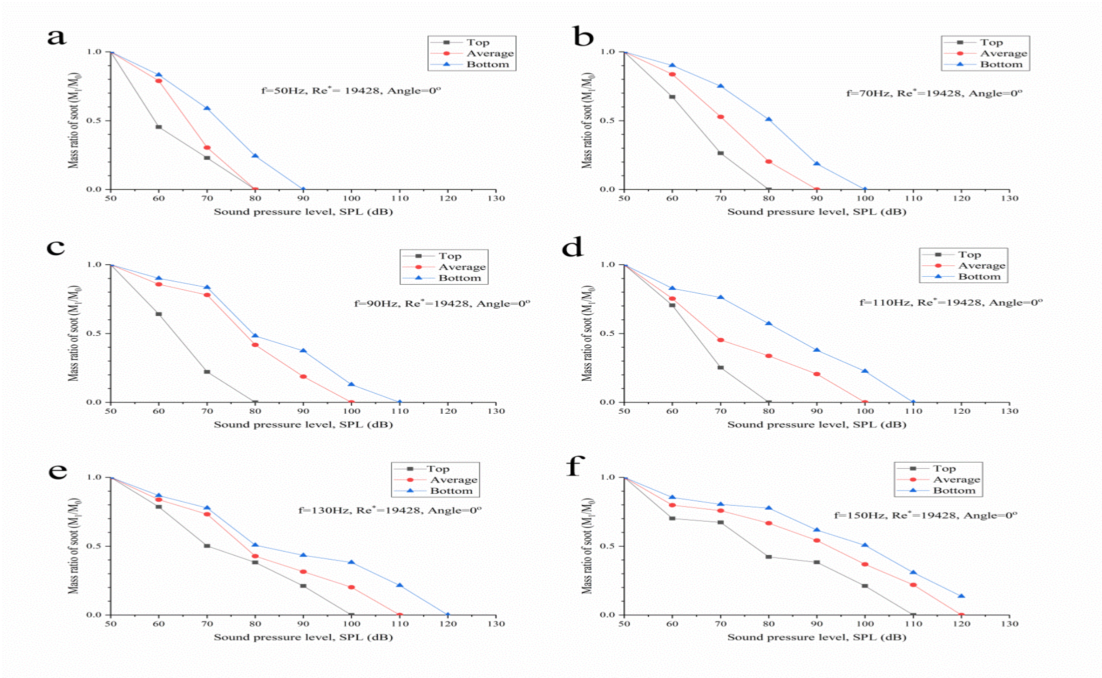

Fig. 9. Effects of the acoustic oscillation position on soot suppression at the fuel flow rate of 70 mL/min

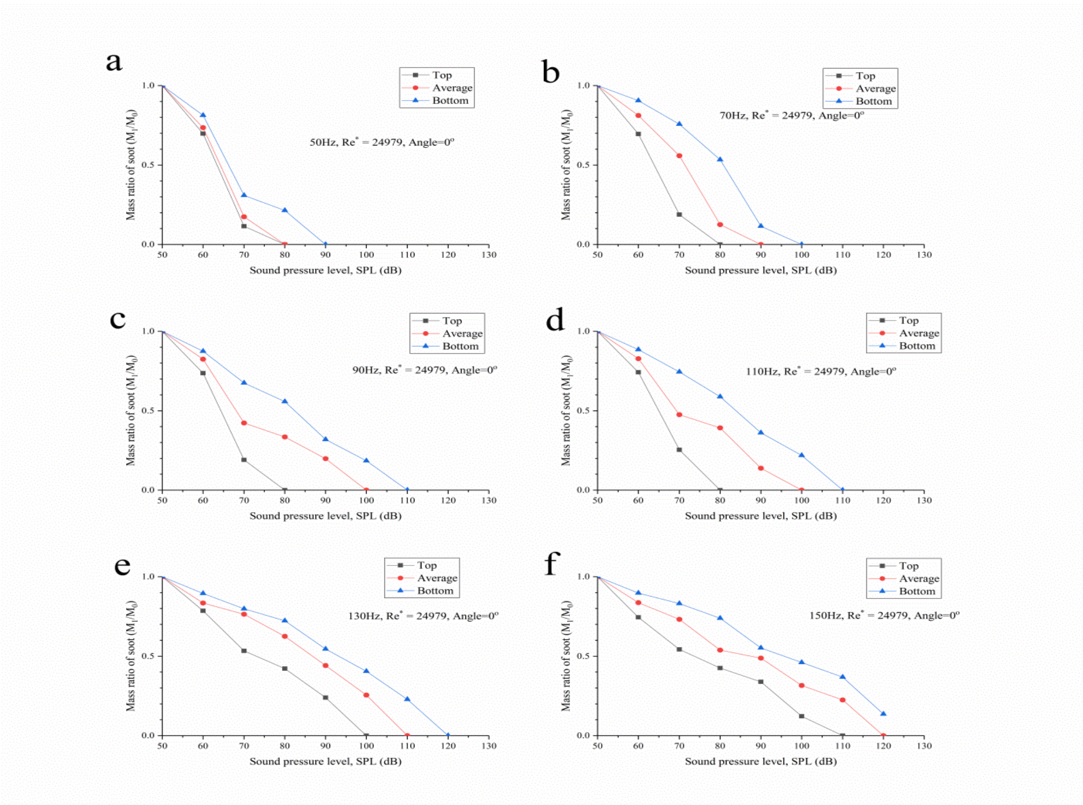

Fig. 10. Effects of the acoustic oscillation position on soot suppression at the fuel flow rate of 90 mL/min

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Figure 11 shows flame temperature measured using the two colour thermometer under the acoustic oscillation. The diameter of the spot is 1.6 mm. The spot is applied on the flame 5 mm below the top boundary. The acoustic oscillation is separately applied on the top, average, and bottom regions of the flame. The flow rate is 90 mL/min. The acoustic oscillation angle is 30°. SPL and frequency remain constant. Flame temperature is maintained at approximately 1570 ℃ without any acoustic oscillation. Flame temperature rapidly increases after the acoustic oscillation application. Flame temperature is higher when the acoustic oscillation is applied to the top region of the flame than that when it is applied to the average and bottom regions of the flame. The highest temperature when the acoustic oscillation is applied to the top area of the flame is >1850 ℃. The highest temperature when the acoustic oscillation applied to the average and bottom regions of the flame is <1800 ℃. Figure 12 shows flame temperature for different acoustic oscillation angles. The spot is applied on the flame 5 mm below the top boundary. When the acoustic oscillation angle is 30°, the acoustic oscillation is aimed at the top region of the flame (soot oxidation zone). The flame temperature is high when the acoustic oscillation angle is 30°, which is >1850 ℃. The reoxidation of soot particles can lead to an increase in flame temperature [19].

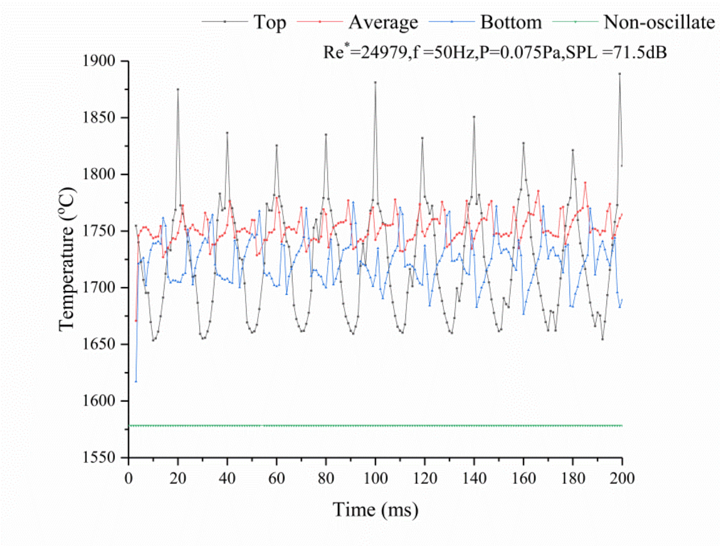

Fig. 11. Flame temperature at different acoustic oscillation positions

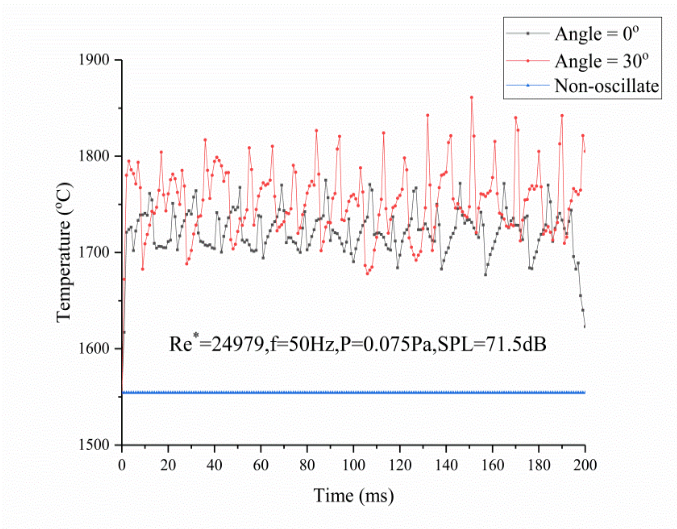

Fig. 12. Flame temperature at different acoustic oscillation angles

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IV. Conclusions

This study applied acoustic oscillations to acetylene diffusion flames for soot suppression. The soot suppression efficiency highly depends on the angles and positions of the applied acoustic oscillations. The optimum angle for soot suppression increases with the fuel flow rate, and the optimal position of applying the acoustic oscillation is the top region of the flame, that is, the soot oxidation zone. The acoustic oscillations applied on the top region of the flame leads to a drastic increase in flame temperature, which is considerably higher than that obtained by applying acoustic oscillations to the average and bottom regions of the flame. Because the mixing of the fuel gas and excessive air is intensified due to the acoustic oscillation application on the soot oxidation zone, soot particle oxidation is considerably accelerated, which effectively improves the soot suppression efficiency.

Acknowledgements

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complementary

Nomenclature

f = frequency (Hz)
A = amplitude (V)
Q = the flow rate of acetylene (mL $\cdot$min^{-1})
T = flame temperature (K)
a = the angle of loudspeakers (°)
M = mass of soot (mg)
H = the length of flame (mm)
SPL = sound pressure level (dB)
P = sound pressure (Pa)

Subscripts

0 = non-oscillate
1 = acoustically oscillated
T = the top area of the flame
B = the bottom area of the flame
A = the average area of the flame