

Review

Research Status and Progress of Acoustic Fire Extinguishing Technology

Xinyue Shi, Zhaojun Tian *, Yi Lu and Qing Ye

School of Resource Environment and Safety Engineering, Hunan University of Science and Technology, Xiangtan 411201, China; sxy@mail.hnust.edu.cn (X.S.); luyijx@163.com (Y.L.); cumtyeqing@126.com (Q.Y.)

* Correspondence: tzhj@hnust.edu.cn

Abstract: Sound wave fire suppression, an emerging firefighting technology, demonstrates unique potential by regulating the physicochemical processes of flames. This paper systematically reviews the research progress in acoustic fire extinguishing technology. Through a literature review and systematic comparison of existing methodologies, it reveals the core mechanisms of flame suppression: low-frequency sound waves (40–80 Hz) disrupt combustion stability via airflow disturbance, while high-frequency waves (>1 kHz) may rely on thermal effects or resonance mechanisms, with sound pressure and waveform significantly affecting extinguishing efficiency. Experimental results demonstrate that acoustic cavity focusing technology extends the effective fire suppression distance to 1.8 m while improving cooling efficiency by 10–20%. Integration with drone platforms and adaptive feedback systems enhances fire extinguishing energy efficiency by over 30%. When combined with water mist, this approach reduces suppression time to 30 s while mitigating sound pressure hazards. However, the critical parameters distinguishing sound-induced “flame enhancement” from “suppression” remain undefined, with insufficient research on adaptability to solid fuels and complex environments (microgravity, confined spaces), and a lack of high-temperature-resistant acoustic materials and multi-physics coupling models. Current fire suppression technologies predominantly rely on airflow disturbance-driven indirect mechanisms, whose stability remains questionable under extreme scenarios. Future advancements require breakthroughs in acoustic metamaterials, the integration of intelligent algorithms, and the collaborative optimization of multi-technology systems to facilitate the transition of acoustic wave-based fire suppression from laboratory settings to real-world industrial firefighting applications. Additionally, this study proposes an optimized solution that integrates acoustic waves with complementary fire suppression approaches, aiming to enhance overall firefighting effectiveness. Concurrently, an interdisciplinary research framework must be established to address the dual challenges of mechanistic elucidation and practical implementation.



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1. Introduction

Among all kinds of disasters, fire is one of the most frequent and common disasters that threaten public safety and social development [1–3]. As an accident with serious consequences, fire not only endangers the safety of people’s lives and property, but also causes a series of serious environmental pollution problems [4–6]. Over time, the factors leading to fires have increased [7], and the incidence of various safety accidents caused

by fires has remained high for years. When there are fire sources, combustion aids and combustibles at the same time, fire will occur. The above three elements together constitute the generation of combustion phenomena [8]. Therefore, removing any one of the three elements will prevent the fire from occurring [9]. In addition, the combustion process is also influenced by a variety of external conditions, including environmental factors such as air pressure, temperature, and oxygen content, all of which affect the intensity and duration of combustion to varying degrees [10,11]. The initial combustion stage has the characteristics of low fire temperature, small fire, and slow fire spread, which is the best time to put out the fire [12]. Based on the above reasons, it is very important to adopt reasonable fire extinguishing means and fire extinguishing equipment in time to control the fire.

The development of fire extinguishing agents has evolved over an extensive period, with their variety expanding to encompass a diverse range of categories. These are primarily categorized into gaseous fire extinguishing agents, foam-based agents, dry powder agents, aerosol agents, and water-based systems, as well as specialized agents for unique applications [13]. Since the 1950s, Halon fire extinguishing agents have been used in critical settings due to their efficiency, stability, and low toxicity. However, their side effects and potential ozone layer damage have led to restrictions in their use [14,15]. Aqueous Film-Forming Foam (AFFF) is currently recognized as the most effective liquid fire extinguishing agent. This agent has been shown to rapidly form a film on the burning oil surface, thereby isolating oxygen and sealing the flammable liquid's vapor. This process results in the rapid suppression of the fire [16]. In recent years, as living standards have improved and environmental protection and health issues have become more prominent, researchers have discovered that long-chain fluorocarbon surfactants, such as perfluorooctane sulfonic acid (PFOS) in AFFF, exhibit high stability and are difficult to degrade. These substances have the potential to accumulate in the environment over an extended period, which could result in significant environmental contamination and health safety concerns [17]. Meanwhile, traditional fire extinguishers are often exposed to complex and ever-changing environmental conditions. During prolonged storage periods, factors such as intrinsic quality issues or external influences can lead to numerous instances where they fail to operate properly [18,19]. In contrast, acoustic fire extinguishing technology has garnered considerable attention from scholars due to its broad applicability, convenient storage characteristics, and environmental advantages [20], primarily due to its extensive range of applications, its convenient storage characteristics, and its environmental benefits. A substantial body of theoretical, simulation, and experimental research has been conducted on its practicality and feasibility, leading to significant advancements and providing substantial foundations and theoretical guidance for the future application of acoustic fire suppression technology in real-world scenarios.

This study systematically retrieved relevant literature from the Web of Science, Scopus, and Google Scholar databases using keywords such as “acoustic fire suppression”, “acoustic field and flame interaction”, and “acoustic fire extinguishing device”. The selection primarily focused on high-impact journal articles, conference papers, and significant patents, with an emphasis on experimental research and no geographical restrictions. Additionally, early influential studies (e.g., Tyndall, 2014 [21]) were included to provide a more comprehensive overview of the technological development.

This study aims to systematically review and summarize the current research status of acoustic fire extinguishing technology, exploring its underlying mechanisms, key influencing factors, and application prospects. The main contributions include a comprehensive analysis of various acoustic parameters (such as frequency, sound pressure, and waveform) affecting flame behavior, clarification of the differences between low-frequency and high-frequency sound waves in fire suppression mechanisms, and an evaluation of

the integration potential of acoustic fire extinguishing technology with other suppression methods (such as water mist, drones, and artificial intelligence). Optimization strategies are proposed to facilitate the practical application of this technology in real fire scenarios.

The unique contributions of this study are as follows: first, a systematic comparison of the bidirectional regulation effect of low-frequency (10–100 Hz) and high-frequency (>1 kHz) sound waves on both flame suppression and enhancement is conducted, highlighting their adaptability to different fuel types and extreme environments (e.g., microgravity). Second, artificial intelligence is introduced, and an intelligent control scheme based on deep learning is proposed, providing an innovative approach to optimizing acoustic fire extinguishing technology.

This study employs a systematic review methodology based on the PRISMA framework, integrating quantitative analysis (e.g., sound pressure–frequency correlation models) with qualitative synthesis (e.g., classification of extinguishing mechanisms). Experimental data and theoretical models are consolidated to comprehensively assess key technical parameters and optimization strategies for acoustic fire suppression. The study’s novelty lies in the multidimensional analysis of different acoustic parameters on fire suppression effectiveness and the proposal of an innovative direction for integrating acoustic technology with intelligent control systems, revealing both the potential and limitations of acoustic fire extinguishing technology and offering new perspectives for future research. The research framework of this study is shown in Figure 1.

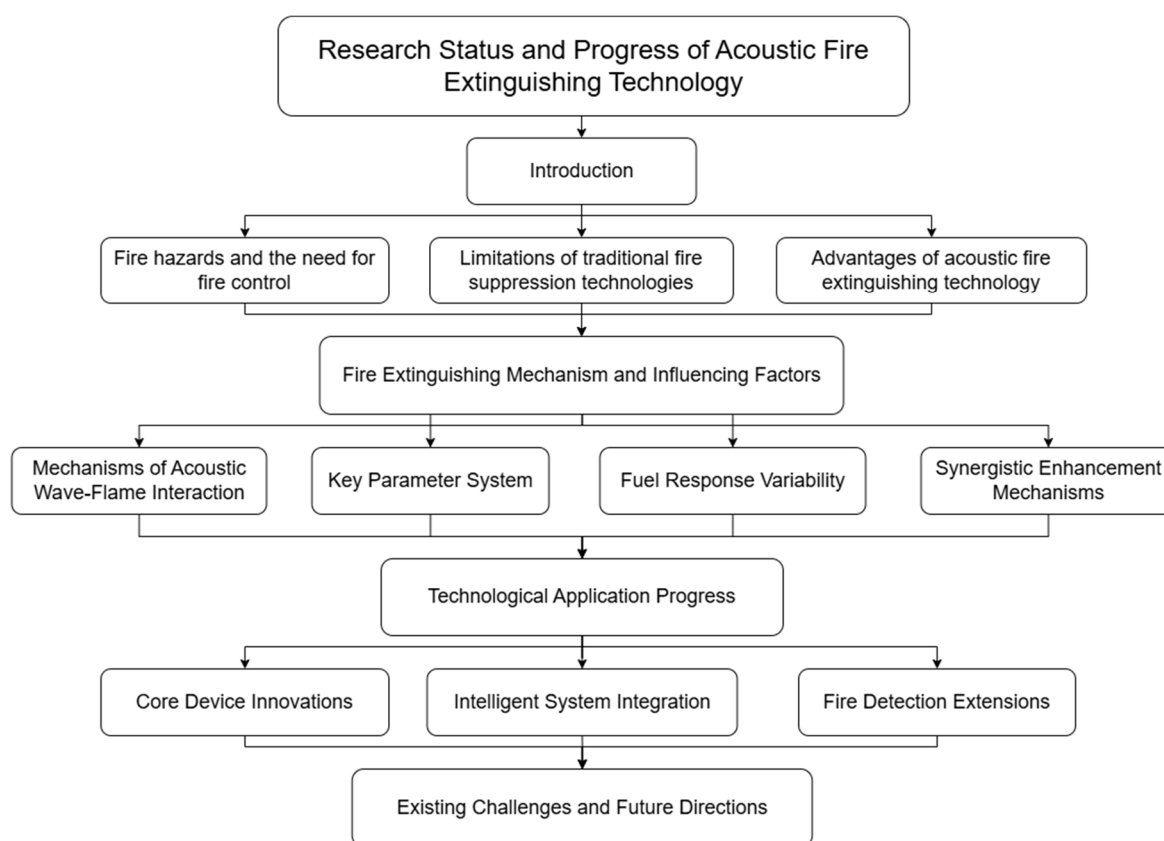


Figure 1. Framework of acoustic fire extinguishing technology research.

2. Fire Extinguishing Mechanism and Influencing Factors

2.1. Influence Mechanism of Acoustic Waves on Flame Behavior

In studying the mechanism of how sound waves influence flame behavior, scholars generally believe that flame extinction is primarily attributed to the airflow gener-

ated by acoustic vibrations, which leads to the suppression of combustion. As early as 1867, J. Tyndall discovered that sound produced by vocalization could affect flames [21]. Blaszczyk et al. [22] confirmed through single-droplet combustion experiments that low-frequency sound waves (<100 Hz) could inhibit combustion via the “wind effect”. The Friedman team [23] further quantified the effects of 30–50 Hz sound waves on laminar flames and proposed an extinction criterion based on the ratio of the Nusselt number (Nu) to the Spalding B number (B), revealing a nonlinear correlation between the flame extinction threshold and the velocity of the acoustically induced airflow. However, they did not conduct an in-depth analysis of chemical kinetics. Niegodajew et al. [24] found that obstacles significantly increased the sound pressure level threshold for extinction, confirming the crucial impact of disturbances in the sound wave propagation path on extinguishing efficiency. Xiong [25,26] tested candle flames in both a freely developing sound field and a cylindrical conduit-guided sound field, as shown in Figure 2. Through comparative experiments, it was pointed out that the primary cause of flame extinction was the airflow induced by speaker vibrations (rather than sound field pulsations), and that conduit constraints could enhance airflow intensity. This conclusion was further verified in Yang Yihan’s alcohol burner comparison experiment [27]. Cliftmann et al. [28] employed time-reversal focusing technology to achieve remote fire suppression and found that when sound waves in the range of 300–15,000 Hz generated a peak sound pressure of 191 dB at the focal point, the acoustic streaming effect could drive flame extinction, whereas conventional regional sound pressure (130 dB) was ineffective.

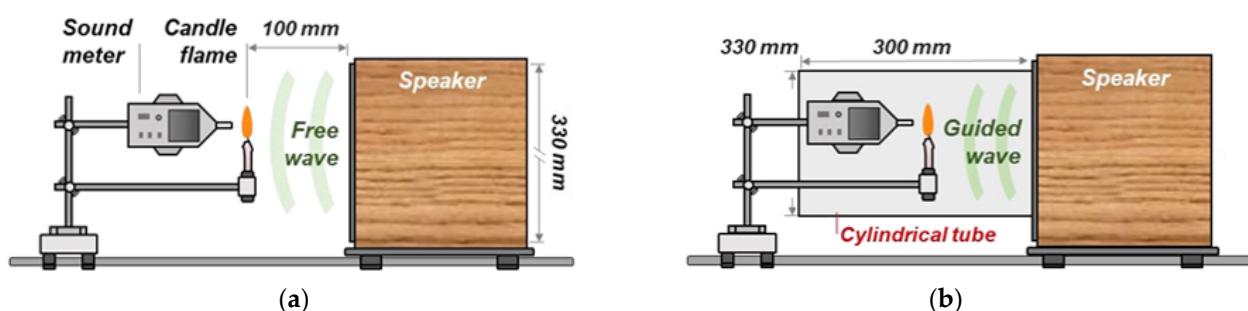


Figure 2. Experimental setup of sound field guided by free field and cylindrical duct [25]: (a) free acoustic field; (b) cylindrical acoustic field.

In fact, sound waves can not only extinguish flames but also promote combustion. Fa-chini et al. [29] confirmed through theoretical models that acoustic disturbances can enhance ambient temperature and chemical reaction rates, accelerating droplet evaporation and creating a combustion-promoting effect. Zheng’s team [30] found that acoustic excitation at 380–500 Hz induces periodic oscillations in laminar flames, where moderate excitation facilitates flame reignition via Kelvin–Helmholtz vortices, whereas excessive excitation leads to extinction due to turbulence-induced stretching. Shi et al. [31,32] developed a modified model that revealed a threshold effect of 20–100 Hz sound waves on fuel consumption rates: low frequencies (<80 Hz) tend to induce flame blow-off, while higher frequencies lead to complex reignition dynamics. Yang et al. [33] discovered that low-frequency, high-intensity sound waves (20–80 Hz) can suppress pulverized coal flames while enhancing particle combustion, whereas high-frequency sound waves stabilize combustion by modulating pulsations. Zhang [34] further verified through numerical simulations that increased sound pressure accelerates fuel mixing and intensifies combustion; however, exceeding a critical threshold leads to vortex breakdown and flame extinction. Research suggests that the effect of sound waves depends on the combination of frequency and sound pressure param-

ters, with the underlying regulation mechanism closely linked to vortex dynamics in the flow field.

Research on the coupling effect between acoustic and flow fields has revealed the dynamic regulation mechanism of sound waves in combustion processes. Hauser et al. [35] confirmed through transverse acoustic excitation experiments that sound wave modulation of swirl structures leads to asymmetric flame height and the formation of high-intensity OH* rotating zones. PIV data indicated a significant enhancement in the heterogeneity of the velocity field distribution at the nozzle. Wang's team [36] discovered that low-frequency acoustic excitation (6–100 Hz) can induce vortex merging in laminar flames, causing the oscillation frequency to decrease to half of the excitation frequency. Schlieren imaging revealed that the buoyancy-sound pressure coupling at the nozzle triggers four nonlinear response modes: frequency splitting, frequency doubling, difference frequency, and amplitude-frequency growth. Regarding the bidirectional coupling mechanism, studies have confirmed that sound waves regulate combustion dynamics through external disturbances, while pressure fluctuations generated by heat release in combustion, in turn, affect the propagation characteristics of the acoustic field [37]. Wang et al. [38] used dynamic mode decomposition (DMD) to quantify flame response characteristics, finding that when the excitation frequency (10–15 Hz) couples with the longitudinal mode of the flame, the oscillation amplitude increases, exacerbating instability. Such studies establish a quantitative correlation between acoustic parameters (frequency/amplitude) and flame instability thresholds, providing a theoretical foundation for combustion control.

2.2. Key Parameters of Acoustic Fire Extinction

The core effectiveness of acoustic fire extinction technology depends on the synergistic interaction of multiple parameters, including acoustic frequency, intensity (sound pressure level), waveform characteristics, and the relative position of the sound source to the flame. The optimal configuration of these parameters must consider the fuel type, combustion environment (e.g., atmospheric pressure, microgravity), and flame dynamics to achieve precise control over the combustion process.

Research on the acoustic regulation of combustion dynamics exhibits multi-scale parameter coupling characteristics. Fachini [39], through a droplet combustion model, revealed that combustion duration is synergistically controlled by the Damköhler number (Da), sound pressure amplitude (Δ), frequency (ω), and phase angle (δ). Specifically, when $Da < 1$ and $\cos(\omega\tau - \delta) < 0$, combustion terminates prematurely, whereas for $Da > 1$ with the opposite phase condition, combustion is sustained and intensified. Under high-frequency conditions ($\omega = 4\pi$), a discontinuous phase transition in extinction time was also observed. In the field of diffusion flames, Chen's team [40] discovered a strong correlation between acoustic frequency and flame response modes: 90 Hz excitation triggered intense oscillations, 150 Hz led to buoyancy-dominated flame dynamics, and 200 Hz resulted in a stable combustion state. Wang et al. [41] combined optical diagnostics to confirm that transverse acoustic excitation induces large-scale vortex structures (>50 mm), altering the flame pinch-off process and doubling the central oscillation frequency to 20.5 Hz. This study further elucidates the role of acoustic-vortex coupling mechanisms in flame instability regulation. Zhang et al. [42] pointed out that the primary mechanisms of flame extinction by acoustic waves (<100 Hz) include the impact of sound waves on the flame, the regulation of the equivalence ratio in the combustion zone, and temperature variations in the combustion region. The study revealed the physical principles of acoustic waves in both promoting and extinguishing combustion under different combinations of acoustic frequency and sound pressure. However, the explanation of the acoustic-physical mechanisms underlying the influence of sound waves on combustion remains insufficient.

McKinney et al. [43] found that a sound pressure level (SPL) of 90–130 dB could induce localized extinction in droplet stream flames, with the critical SPL positively correlated with frequency. Zong et al. [44] confirmed that 60 Hz sound waves had the most effective suppressive effect on methane flames, with an SPL of 108 dB causing a sharp decrease in flame height. Niegodajew [45] pointed out that 30 Hz low-frequency sound waves were more energy efficient than 50 Hz, with minimal influence from fuel load. Taspinar et al. [46] constructed a multi-parameter dataset (including fuel type, flame size, and distance) through 17,442 experiments and developed fire suppression prediction models using ANFIS and CN2Rule methods. Their study demonstrated that CN2Rule achieved 99.91% accuracy in determining critical parameters: frequency of 10–55 Hz, SPL of 85–110 dB, and airflow velocity of 2.5–17 m/s, providing an optimized framework for complex fuel scenarios. However, the model did not account for turbulence effects on generalization capability. Su et al. [47] revealed that in a 200–300 Hz acoustic field, inverse diffusion flame morphology exhibits a nonlinear evolution with SPL, with the KL factor positively correlated with the square root of SPL. Current research primarily focuses on steady-state parameter correlations, while transient flame extinction mechanisms and complex flow field coupling effects require further investigation. Wilk-Jakubowski's team [48] focused on the harmonic effects of low-frequency sound waves (13–20 Hz), discovering that as the harmonic order increased from the second to the tenth, the required extinction SPL rose from 120.7 to 129.4 dB, with power consumption increasing from 85 W to 900 W (at a 20 Hz fundamental frequency, the second-order harmonic required 580 W, while the tenth-order reached 1000 W). Their study confirmed that harmonic waves enhance turbulence-induced disturbances but are limited by energy efficiency and equipment size, suggesting the need to optimize modulation strategies and assess the applicability of high-order harmonics.

To further investigate the effect of acoustic amplitude on flames, Fujisawa et al. [49] conducted a visualized study on the flow characteristics of diffusion flames under acoustic stimulation. The study found that at an acoustic frequency of 150 Hz, as the acoustic amplitude increased from 0 V to 1.8 V, the flame height, oscillation amplitude, and light intensity were effectively reduced. Figure 3 illustrates the gradual decrease in flame brightness with increasing acoustic amplitude within the range of $E = 0$ –1.8 V. Notably, the waveform characteristics of the acoustic waves have a significant impact on the regulation effect.

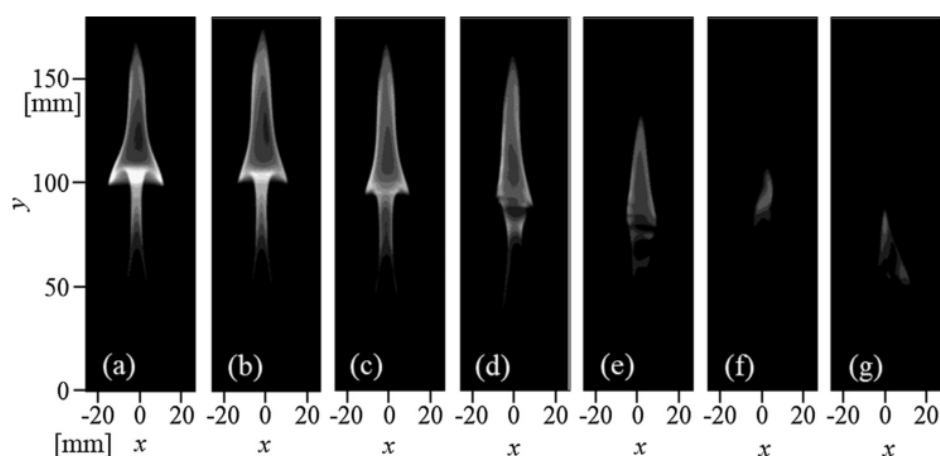


Figure 3. The relationship between flame brightness and input amplitude at 150 Hz [49]: (a) $E = 0$ V; (b) 0.3 V; (c) 0.6 V; (d) 0.9 V; (e) 1.2 V; (f) 1.5 V; (g) 1.8 V.

Ou [50] investigated the effects of acoustic waves on flames using a sound wave fire suppression device under three different waveforms: sine wave, square wave, and triangular wave. The experimental results showed that sine waves exhibited the best fire

suppression performance within the frequency range of 40–80 Hz, square waves were most effective at 30–70 Hz, and triangular waves performed optimally at 40–60 Hz. Additionally, she found that at the same frequency, acoustic waves had a weaker extinguishing effect at a lower sound pressure level (90 dB), while increasing the sound pressure level (102 dB) significantly reduced the extinction time. Therefore, waveform characteristics should also be considered when applying acoustic fire suppression.

Unlike traditional studies conducted in normal gravity, the regulation of combustion by sound waves in microgravity exhibits unique mechanisms. Tanabe et al. [51] proposed the acoustic Grashof number (Gr_a) through thermoacoustic flow experiments, revealing a power-law relationship between the combustion rate and Gr_a ($\propto Gr_a^{0.5}$ for $Gr_a < 1$ and $\propto Gr_a^{0.25}$ for $Gr_a > 1$). They also confirmed that an SPL of ≥ 135 dB could alter flame morphology. Dattarajan et al. [52] found that under microgravity, acoustic perturbations increased the methanol combustion rate by 200%, attributed to the synergistic enhancement of acoustic radiation force and flow effects. Regarding fire suppression efficiency, Suto [53] pointed out that low-frequency sound waves (20–40 Hz) performed better in normal gravity, whereas Beisner [54] discovered significant differences in extinction efficiency between 30.6 Hz low-frequency and 74 Hz high-frequency sound waves in microgravity, attributing the phenomenon to enhanced flame surface perturbations. Krikunova et al. [55] investigated the acoustic response of M-type premixed methane–air flames under different gravity conditions, using high-speed imaging and PIV technology to analyze flame dynamics. Their study found that low-frequency (< 160 Hz) acoustic excitation had little effect on flame structure, whereas at 160 Hz, the sound wave energy exceeded the primary airflow, inducing intense oscillations. As the frequency increased further, the primary airflow regained dominance, stabilizing the flame structure. Wen et al. [56] observed nonlinear edge flame oscillations induced by a 1150–1900 Hz acoustic field, though the critical extinction parameters remain unclear. Current research suggests that gravity plays a crucial role in the acoustic regulation of flames. However, further investigation is needed into the applicability of different fuels, interactions under complex flow conditions, and the precise critical conditions for flame extinction.

2.3. Response Characteristics of Flames from Different Fuels to Acoustic Waves

The influence of acoustic waves on flames varies significantly depending on the fuel type (solid, liquid, or gas). This section summarizes the response characteristics of different fuel flames to acoustic excitation and the underlying mechanisms based on experimental studies, categorized by combustion type.

The combustion of solid fuels is governed by both pyrolysis kinetics and thermoacoustic coupling effects. Zhang's study [57] revealed that an increase in acoustic frequency induces instability in the mass loss rate of wooden samples, which fundamentally arises from the competition between acoustic pressure gradients and thermal feedback mechanisms. Experiments confirmed that fuel geometric parameters (such as width and inclination) affect flame stability by altering local acoustic impedance distribution. When the acoustic pressure gradient reduces the pyrolysis rate by 50%, flame propagation ceases. Loboichenko et al. [58] verified the fire suppression effectiveness of low-frequency sound waves (14–21 Hz) on liquid fuels (Class B/C fires). Their study found that the enhancement of low-frequency turbulence effects could lower the extinction sound pressure threshold. However, due to thermal inertia effects, the applicability of this approach to solid fuels remains limited.

The combustion process of liquid fuels involves multiphase coupling of evaporation, mixing, and combustion, and their response characteristics to acoustic waves are closely related to the dynamic behavior of the fuel. McKinney [43] pointed out that when the

acoustically induced gas displacement approaches the droplet radius ($\Delta x \approx r$), the flame extinguishes due to the disruption of the mixing layer. The extinction sound pressure threshold was found to be positively correlated with frequency ($R^2 = 0.87$). This study provides new insights into the acoustic control of droplet combustion but does not address the effects of interactions between different droplets. The study by Xiong et al. [59] on the combustion of molten polyethylene droplets shows that the droplet falling rate significantly affects the fire-extinguishing efficiency of acoustic waves. At a low falling rate, the prolonged exposure of droplets to acoustic waves allows the pressure gradient formed by air vibrations to more easily disrupt the fuel–oxidizer mixing process, thereby enhancing extinguishing efficiency. Conversely, at a high falling rate, the increased fuel inertia weakens the disturbance effect of acoustic waves on the droplets, leading to a reduction in extinguishing efficiency. As shown in Figure 4, the variation in extinction probability of droplet flames under different sound pressure levels is presented for two different droplet heights and falling speeds.

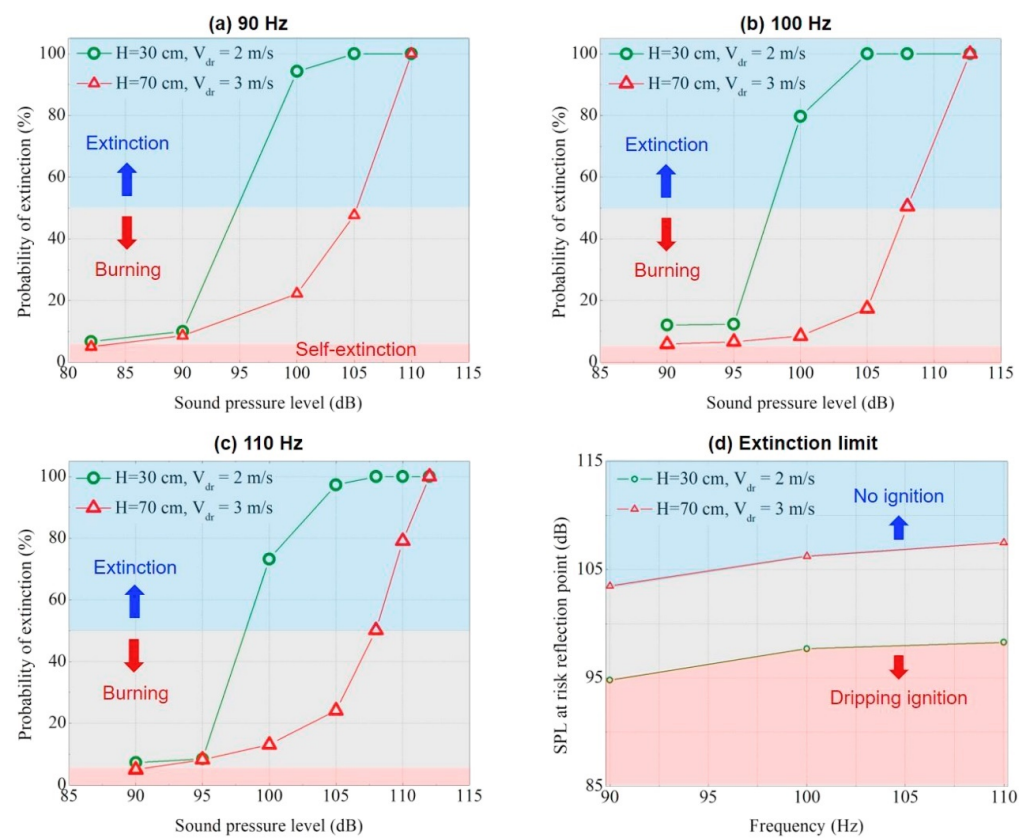


Figure 4. The extinction probability for dripping flames under two fall heights (velocities) varying with sound pressure at (a) 90 Hz, (b) 100 Hz, (c) 110 Hz, and (d) the mitigation of dripping-ignition risk by sound wave [59].

The study by Shi et al. [60] indicates a linear relationship between acoustic frequency, sound pressure, and diaphragm displacement (as shown in Figure 5). Further experiments on liquid pool fires reveal the quantitative relationship between acoustic parameters (frequency f , sound pressure peak P) and diaphragm displacement (δ):

$$\delta_{dv} \propto 15.22 - 0.31f + 2.57P_A \quad (1)$$

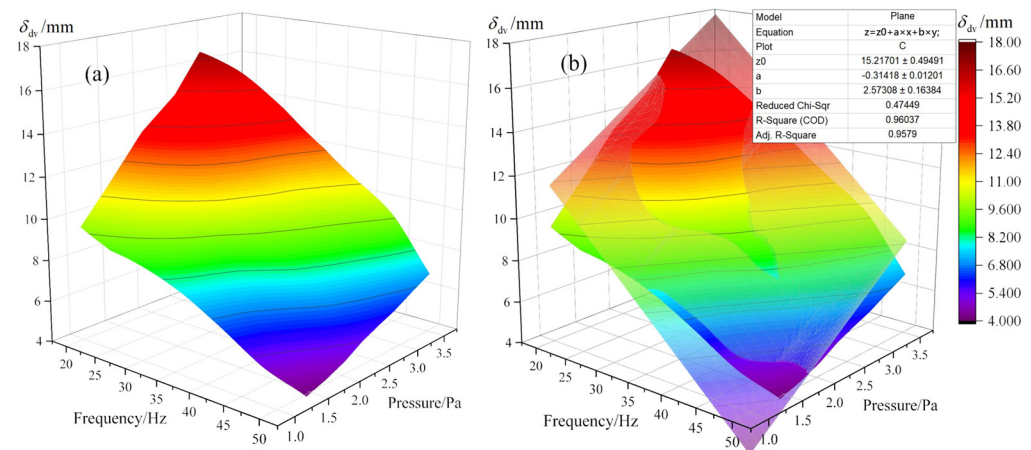


Figure 5. Relationship between acoustic source frequency, acoustic pressure, and diaphragm motion (a) Relationship between sound source frequency, sound pressure, and diaphragm displacement, (b) Linear relationship analysis of sound pressure, frequency, and diaphragm displacement ($R^2 = 0.96037$) [60].

Low-frequency acoustic waves (with lower f values) and high sound pressure (with higher p values) are more likely to induce significant diaphragm displacement, thereby enhancing flame disturbance. When the acoustic wave frequency resonates with the evaporation rate of the liquid pool, sound pressure fluctuations accelerate fuel vapor diffusion, disrupt flame continuity, and ultimately reach the extinction threshold. This indicates that the acoustic extinction mechanism of liquid flames depends on the synergistic interaction between acoustic parameters and fuel evaporation dynamics.

The acoustic response characteristics of premixed gas flames are highly correlated with flow field instability and chemical reaction rates. The study by Yu et al. [61] on methane/air flames shows that low-frequency acoustic fields (<50 Hz) easily induce flame oscillation or extinction. This occurs because low-frequency disturbances synchronize with the evolution of vortex structures at the flame front, leading to periodic fluctuations in heat release rates. In contrast, high-frequency acoustic fields (>210 Hz) have a minimal effect, as the disturbance frequency far exceeds the flame response time scale. Additionally, the study by Wu et al. [62] on the dynamic response of lean-burn dimethyl ether flames found that 100 Hz acoustic waves enhance vortex shedding effects in the flow field. The nonlinear growth of vortices in the outer recirculation zone leads to flame front instability. The experiments conducted by Wei et al. [63] on methane–ammonia–air swirling flames indicate that under low-frequency excitation (e.g., 50 Hz), the flame shape transitions to a V-type structure, increasing flame stretch strain and leading to local extinction. While high-frequency excitation does not alter the overall flame shape, it intensifies flame surface roughness, reflecting an enhancement of internal turbulence fluctuations. Notably, under low equivalence ratio conditions, the fuel oxidation reaction rate is lower, significantly reducing the flame’s resistance to disturbances and making it more susceptible to instability under acoustic field influence. As shown in Figure 6 (Prel means relative pressure), the variations in flame behavior under different frequencies are illustrated.

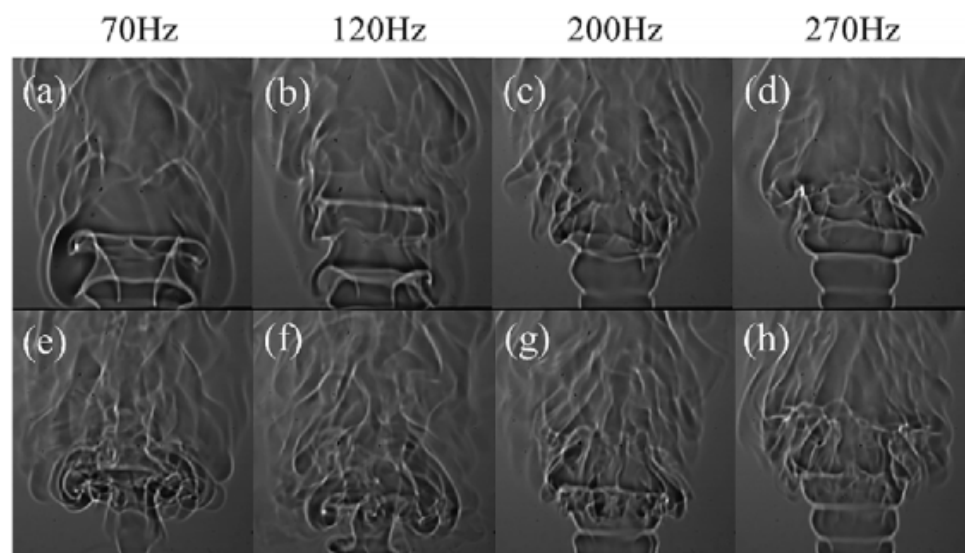


Figure 6. Flame schlieren images (a–d); $P_{rel} = 0.1$ with different excitation frequencies and intensities when the ammonia fraction is 10% and the equivalence ratio is 0.7; (e–h) $P_{rel} = 0.4$ [63].

2.4. Synergistic Enhancement Mechanism of Sound Waves and Water Mist

Friedman et al. [64] revealed through n-heptane flame experiments that low-frequency sound waves (62–80 Hz) can reduce the critical mass fraction of water mist by 53%. This enhancement mechanism originates from the regulation of the acoustic-induced flow field, which strengthens the fuel cooling rate. Huang's team [65,66] further quantified the ethanol flame extinction threshold and confirmed that 30 Hz sound waves enhance fire suppression efficiency through two pathways: increasing the flame oscillation angle to expand the water mist-flame contact area, and accelerating oxidizer transport to overcome the thermal equilibrium threshold.

In terms of engineering parameter optimization, Mao et al. [67] developed a synergistic scheme combining 1.5 kHz high-frequency sound waves with 40 g/m³ water mist, achieving both fire suppression and safe evacuation within 30 s. This approach reduces the required sound pressure level ($\Delta SPL = 14$ dB) through phase-change cooling, effectively mitigating secondary injury risks. The study found that the combination of sound waves and water mist yields optimal fire suppression effects at different frequencies: low frequencies (<100 Hz) primarily influence airflow direction, while high frequencies (>1 kHz) more effectively concentrate acoustic energy. Their interaction enhances water mist evaporation and flame oscillation, leading to more efficient fire suppression.

From the above studies, the key to acoustic fire suppression lies in the influence of sound waves on flame structure, the synergy of critical parameters, and the response differences among fuel types. First, sound waves alter the heat, mass, and momentum transfer of flames, affecting combustion stability through mechanisms such as vibration-induced flow, pressure gradients, and turbulence disturbances. Second, different frequencies, sound pressure levels, and modulation methods significantly impact fire suppression effectiveness, and optimal parameter matching can improve efficiency. Furthermore, flames from different fuels respond differently to sound waves, resulting in variations in extinction mechanisms. Additionally, the synergistic effect of sound waves and water mist enhances mist atomization and dispersion, increasing heat absorption and asphyxiation effects, thus improving fire suppression efficiency. Therefore, in-depth research on the interaction mechanisms between sound waves and flames, as well as the optimization of critical parameters, is crucial for advancing the practical application of acoustic fire suppression technology.

3. Application of Acoustic Fire Extinguishing Technology

Since its discovery, acoustic wave technology has expanded into diverse applications including acoustic ranging [68–70], non-destructive testing [71–73], structural detection [74,75], and particle agglomeration [76,77]. Current acoustic focusing methodologies primarily encompass geometric curved-surface focusing, ultrasonic demodulation-based directional control, multi-array coherent beamforming, electronic phased-array focusing, acoustic lens systems, and resonant cavity aggregation [78–80]. These techniques achieve directional wave propagation and energy concentration through distinct physical mechanisms, finding extensive applications in acoustic imaging, therapeutic ultrasound, particle manipulation, and flame suppression systems. Notably, acoustic lens focusing and resonant cavity aggregation have emerged as predominant technical approaches in developing acoustic fire extinguishers. Choudhary et al. [81] experimentally validated the energy transmission efficiency of acoustic beams through acoustic lenses and their fire prevention capabilities through enhanced thermal dissipation. Results demonstrated that acoustic fire extinguishers achieved 10–20% faster cooling of heated objects compared to conventional air-cooling methods, confirming the effectiveness of acoustic lens implementations in fire suppression. Beyond the conventional approach of integrating acoustic lenses with loudspeakers, their study proposed an alternative technique involving resonant cavity implementation at the sound source to concentrate acoustic energy. Dai et al. [82] analyzed the energy concentration theory of resonant cavities and mathematically derived their optimal energy concentration frequency. Building on this criterion, Yang [27] designed multiple cavity configurations, experimentally validating the frequency optimization principle. The incorporation of resonant cavities extended the effective fire suppression range of acoustic wave devices from initial operational failure to 1.8 m. Lin's [83] investigation of pool fires revealed that acoustic focusing cavities follow a duct-based acoustic transmission model with inherent filtering characteristics. Experimental results demonstrated that focusing cavities with 5 cm apertures significantly enhanced fundamental and harmonic sound pressure amplitudes at central positions when operating at 30–50 Hz input frequencies, thereby suppressing flame combustion. Ghosalkar et al. [84] studied a portable acoustic fire extinguishing system and tested the extinguishing effect of sound waves in the 20–40 Hz frequency range on different fuels (candle, wood, gasoline) flames. The experiments showed that the extinguishing time decreased as the frequency increased, and a converging collimator was more efficient than a non-converging one. The results indicated that the system is suitable for early-stage fires but cannot extinguish flames that have penetrated solid materials. Additionally, the wind-driven extinguishing mechanism may exacerbate certain types of fires. The study verified the feasibility of acoustic fire suppression, but its practical application remains limited by flame type and environmental conditions.

Recent advancements in acoustic fire suppression technology demonstrate effective integration with existing systems. Tang et al. [85] developed an acoustic wave-equipped drone specifically engineered for high-rise residential fire control, successfully expanding the technology's application scenarios. The Wilk–Jakobowski team [20,86–88] revealed the mechanism and intelligent application pathway of acoustic fire suppression technology through a series of studies. They developed a high-power acoustic fire suppression experimental platform and systematically investigated the suppression effects of low-frequency sound waves (15–20 Hz) and their amplitude modulation (AM) techniques on flames. The study found that optimizing sound wave frequency, sound pressure level, and employing frequency scanning technology can significantly enhance the hydrodynamic disturbance effect of sound waves on flames, with modulated sine waves demonstrating higher extinguishing efficiency than single sine waves. Experiments confirmed that this technology is highly effective in suppressing Class B (liquid) and Class C (gas) fires.

Innovatively, the research integrated deep neural networks (DNN) with the acoustic fire suppression system, enabling intelligent control through real-time flame image recognition. Additionally, an acoustic parameter database was established to match optimal sound wave modulation schemes to different fire source characteristics. However, the study did not cover solid fuel fire scenarios or verify system stability in complex airflow environments, pointing to directions for future research. This series of studies not only validated the feasibility of acoustic fire suppression but also provided theoretical support for developing novel, eco-friendly fire extinguishing equipment through intelligent control system integration. Yuan and Gan [89] designed another fire-suppression drone with acoustic capabilities, an innovative solution that not only enriches practical implementations but also pioneers new pathways for technological development, as illustrated in Figure 7. Furthermore, Zou [90] and colleagues invented a feedback-controlled low-frequency acoustic extinguisher. This system employs a frequency sensing module to detect flame oscillations, coupled with a controller-driven real-time frequency adjustment mechanism for acoustic transducers. Through precise frequency matching between emitter output and flame dynamics, it achieves rapid coupling oscillations that effectively suppress combustion while enhancing energy efficiency. De Luna et al. [91] constructed a dataset of 17,442 samples, incorporating features such as flame size, fuel type, and frequency, to compare the performance of eight machine learning models, including decision trees, random forests, and XGBoost. Their findings revealed that XGBoost achieved the highest classification accuracy (98.62%) after parameter optimization, confirming the strong correlation between acoustic parameters and fire suppression efficiency. By leveraging feature selection to enhance model generalization, this study provides valuable data support for real-time decision-making in intelligent fire suppression systems.

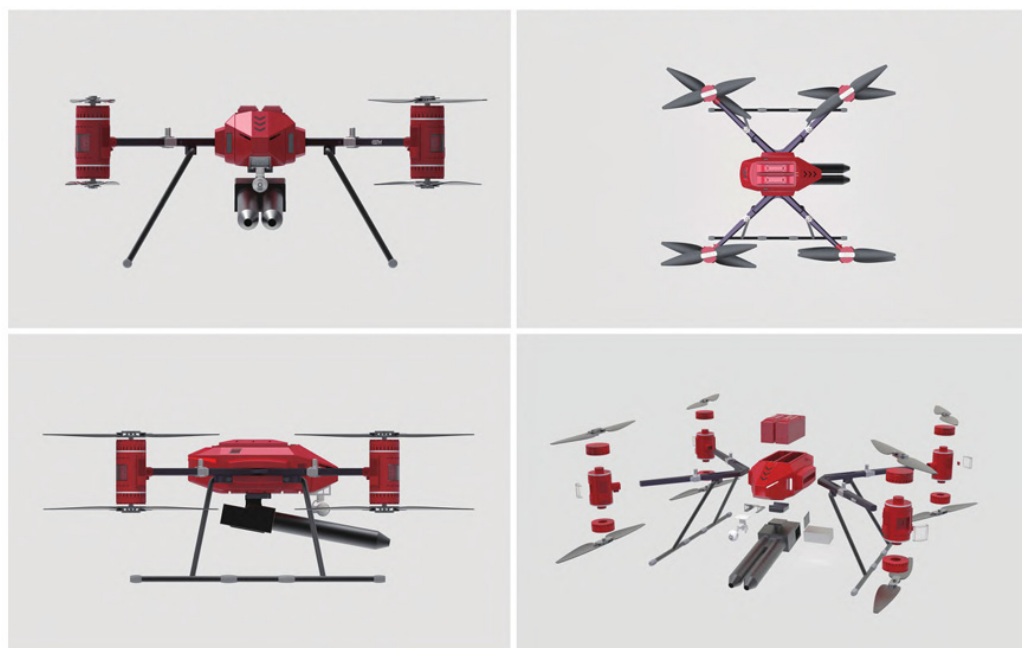


Figure 7. Concept map of acoustic fire extinguishing UAV [89].

Acoustic detection technology demonstrates significant advantages in fire rescue operations. Wang et al. [92] proposed HearFire, an indoor fire detection system based on silent acoustic sensing, utilizing commercial speakers and microphones to detect fire-induced sound absorption and speed variations. The system achieved a detection accuracy of up to 99.2% within a 7 m range and effectively distinguished flames from environmental noise. Compared to traditional smoke detectors, HearFire does not require direct contact with

the fire source and offers advantages such as low cost and remote sensing. However, its applicability in large spaces and multi-source fire detection requires further investigation. Tan [93] highlighted its capability to precisely locate trapped individuals, assess fire spread patterns, and evaluate structural stability through acoustic signature analysis in complex environments. Studies indicate this technology overcomes limitations of conventional search methods, achieving localization errors within 1 m. Its integration with artificial intelligence and big data analytics shows promising potential for broader disaster response applications. Yu et al. [94] developed an STM32 microcontroller-based detection system utilizing infrasound (<20 Hz) analysis, achieving sub-10 s alert response times with lower false alarm rates than traditional acoustic detection. The system leverages infrasound's superior penetration and long-range propagation characteristics, proving effective in complex architectural environments. While experimental validation confirmed its wall penetration capabilities, operational stability under extreme noise interference requires further optimization. This technological advancement establishes new directions for fire warning systems, with future industrial and high-rise building applications anticipated through integration with AI-driven algorithms.

This chapter reviews the application and development of acoustic technology in fire suppression and detection. From acoustic focusing methods to fire suppression system design, studies indicate that acoustic lenses and resonant chambers are the prevailing trends in acoustic fire suppression. Acoustic lenses enhance sound energy transmission efficiency, while resonant chamber focusing strengthens low-frequency sound wave disturbances on flames. Additionally, intelligent acoustic fire suppression technology has become a research hotspot, and novel devices such as acoustic fire suppression drones expand application scenarios, improving fire suppression capabilities in high-rise buildings and complex environments. In fire detection, the HearFire system utilizes silent acoustic sensing for high-precision flame detection, while infrasound detection technology demonstrates penetration advantages in complex architectural environments, offering a new direction for fire alarms. Looking ahead, integrating artificial intelligence, big data analysis, and advanced operational testing could further expand acoustic technology applications in fire suppression and detection, paving the way for greener and more efficient fire safety solutions.

4. Challenges and Future Research Directions

Despite significant progress in recent years, acoustic fire suppression technology still faces numerous unresolved issues and technical gaps that require further exploration and optimization.

4.1. In-Depth Study of Acoustic Fire Suppression Mechanisms

The core mechanisms of acoustic fire suppression are primarily attributed to flow disturbances, thermal-mass transfer regulation, and turbulence enhancement effects. However, the specific interaction mechanisms of sound waves with different fuel types and combustion modes remain unclear. For instance, low-frequency sound waves exhibit limited effectiveness on solid fuels (such as wood and coal powder), potentially due to thermal inertia effects that reduce suppression efficiency. Moreover, the nonlinear disturbances of sound waves on the flame front and their interaction with combustion chemical kinetics remain insufficiently studied, making it difficult to establish a comprehensive fire suppression prediction model.

4.2. Optimization of Acoustic Parameters and Control Strategies

Existing studies have explored the effects of sound wave frequency, sound pressure level, and waveform modulation (e.g., amplitude modulation and harmonic excitation)

on fire suppression efficiency, yet a unified optimization criterion is still lacking. A major challenge is determining the optimal acoustic parameters for various fuel types and fire scenarios. For example, although high-order harmonics (>10th order) can enhance turbulence disturbances, they suffer from high energy consumption. Additionally, the suppression mechanisms and ideal application scenarios of different waveforms (e.g., sine waves, square waves, and triangular waves) remain unclear. Furthermore, the propagation characteristics of sound waves in complex flow fields (e.g., turbulent and counterflow environments) need further investigation to improve their practical applicability in real fire incidents.

4.3. Applicability of Acoustic Fire Suppression in Microgravity and Extreme Environments

The study of acoustic fire suppression in microgravity environments is still in its early stages. While some research has demonstrated that sound waves can effectively enhance flame disturbances and improve suppression efficiency, key aspects such as fuel-specific applicability, optimal acoustic parameters, and suppression threshold conditions have yet to be established. Additionally, the stability and reliability of acoustic fire suppression in high-temperature, high-humidity, and strong-wind environments remain untested, necessitating extensive experimental validation and numerical simulations.

4.4. Engineering Applications of Acoustic Fire Suppression

Currently, acoustic fire suppression technology remains largely confined to laboratory research and has not yet been developed into widely applicable industrial products. Achieving miniaturization and portability of acoustic fire suppression devices to improve practical usability is a crucial research direction. Moreover, exploring how acoustic suppression can be integrated with existing fire suppression techniques (such as water mist, foam, and dry powder) to create more efficient and environmentally friendly fire suppression solutions remains an open challenge.

4.5. Intelligent Control of Acoustic Fire Suppression

In recent years, the integration of artificial intelligence (AI) with acoustic fire suppression has gained increasing attention. For instance, deep neural networks (DNNs) have shown potential in flame recognition and acoustic parameter regulation. However, existing intelligent systems primarily rely on fixed experimental datasets for training. Enhancing AI's adaptive capability in complex fire scenarios, improving model generalization, and enabling real-time decision-making remain key research priorities for the future.

5. Conclusions

This study reviews the fundamental principles, key influencing factors, and response characteristics of acoustic fire suppression across different fuel types. Additionally, it discusses recent advancements in intelligent fire suppression systems. The findings indicate that acoustic fire suppression primarily operates through flow disturbances, thermal-mass transfer regulation, and turbulence enhancement. Different acoustic parameters (such as frequency, sound pressure, and waveform) have significant effects on suppression efficiency. In particular, low-frequency sound waves (10–100 Hz) demonstrate better suppression for gas and liquid fuel flames, whereas the suppression mechanisms for solid fuel fires require further investigation.

Significant progress has been made in both theoretical and experimental research on acoustic fire suppression, particularly in the integration of AI and acoustic parameter optimization, which provides a technological foundation for intelligent and automated suppression systems. Additionally, the synergy between sound waves and traditional

suppression methods (such as water mist) has shown high fire suppression efficiency, offering a promising pathway for green and sustainable fire safety technologies.

However, several critical challenges remain, including the quantitative analysis of suppression mechanisms, optimal matching of acoustic parameters, applicability in extreme environments, and practical implementation of intelligent control systems. Furthermore, advancing the engineering development of acoustic fire suppression technology and bringing it into real-world applications is a key research direction. Future studies should leverage large-scale experiments, numerical simulations, and AI-driven optimization algorithms to further refine the theoretical framework of acoustic fire suppression and promote its application in aerospace, industrial fire safety, and smart building fire prevention.

Despite systematically reviewing the research progress on acoustic fire suppression technology, this study has the following limitations:

1. Variations in acoustic parameters (such as frequency and sound pressure level) and experimental conditions across different studies limit the cross-comparability and generalizability of the results.
2. Existing research primarily focuses on liquid and gaseous fuels, with relatively few studies on solid fuels and complex environments (such as microgravity and high-temperature turbulence), which may affect the comprehensiveness and applicability of the conclusions.
3. Since technological advancements in the industrial sector are not fully disclosed, the effectiveness of practical engineering applications requires further validation.

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