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Experimental Attempts of Using Modulated and Unmodulated Waves in Low-Frequency Acoustic Wave Flame Extinguishing Technology: A Review of Selected Cases

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In practice, some undesired signals perceived as noise (because of the sound sensation) can effectively extinguish flames. This article provides information on the applicability of acoustic waves (a case of using sine waves and sine waves amplitude modulated by a square waveform) in low-frequency acoustic wave flame extinguishing technology based on experimental results obtained from a laboratory stand, which is a scientific novelty. The benefits of using deep neural networks for flame detection based on dedicated solutions developed through international cooperation are also recognized. In addition, the potential advantages of combining both technologies (use in fully automatic systems), limitations, open problems, and plans for further research are identified. The paper concludes that it is possible to extinguish flames as soon as they appear (firebreaks) and prevent large fires from breaking out. This feature may effectively reduce material losses and increase widespread safety.
Keywords: acoustic flame extinguishing, firefighting systems, deep neural networks, electrical and mechanical engineering, fire extinguisher, flame suppression

Highlights
- *An analysis of the use of acoustic waves to extinguish flames shows that this technique is not fully explored.*
- *It is possible to control and extinguish flames using the acoustic method (especially firebreaks), which come from various materials (Class B and C fires).*
- *Both modulated and unmodulated acoustic waves can be applied to extinguish flames.*
- *The sound pressure at which the phenomenon of complete acoustic flame extinguishment was observed oscillates in the approximate range of 115 dB to 130 dB.*
- *Since it is possible to use artificial intelligence for flame detection, combining acoustic technology with artificial intelligence (a smart, environmentally friendly acoustic extinguisher) can bring many tangible benefits to society (including no need for human presence during an extinguishing action).*

0 INTRODUCTION

In practice, acoustic waves have many different applications, such as in industry, which can be exemplified by using low-frequency acoustic waves or infrasound to clean the heating surfaces of power boilers from sediments [1]. Such waves may also be applied in other industrial applications, such as electrostatic precipitators and bag filters, in cyclones, and in reactors of flue gas desulfurization systems [2]. In this regard, mathematical methods can be helpful, e.g., [3]. It should be noted that the cleaning properties of low-frequency acoustic waves were discovered by Matts Olsson, a Swedish engineer, who analysed the motion of dust particles exposed to the infrasound. He showed that the generation of acoustic waves (longitudinal waves) creates local pressures that cause the movement of pollutants at different speeds. The effectiveness of this technique depends on the frequency of the acoustic wave, which is generated in pneumatic generators currently manufactured by many plants around the world [4]. Another example of using acoustic waves can be flame control, which has many applications. Examples include using the acoustic field to reduce the emissions of combustion products such as soot. Moreover, there are numerous uses for controlling flames, such as applying the acoustic field to decrease the release of combustion by-products. However, due to the subject matter of this article, these issues have been omitted. Some items of literature are indicated in the bibliography as a reference to supplement the literature in this area.

Based on previous research, it has been observed that some signals treated in terms of noise can be useful in certain applications, e.g., to extinguish flames. Taking into account the use of acoustic waves to extinguish flames, the acoustic method is based on the use of movement (vibration) of air molecules

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resulting from acoustic waves, which are generated by a sound source. Especially low-frequency waves (bass) are considered as vibrations (oscillations) at sufficiently high sound levels that have extinguishing properties. Because of their length, such waves can reach difficult-to-access places, which is desirable. Since changes in air pressure affect flames with energy dependence on sound intensity, high-power sound sources are recommended [5] and [6]. While challenges such as extinguishing flames from a variety of sources using acoustic waves from high-power sound sources can be addressed by using waves with appropriately selected parameters, it was recognized that more research is needed, especially in the areas of using modulated and unmodulated waves, to discover as much as possible about the capabilities of this as yet unexplored flame extinguishing technique. This is important because waves of different frequencies and shapes, modulated and unmodulated, may be applied to extinguish (e.g., sine wave, sine wave modulated by a square waveform, sine wave modulated by a triangular waveform, etc.) as proven by recent research conducted in Poland. In practice, low-frequency modulated waves can be successfully used to extinguish flames, in addition to unmodulated waves [5] to [9]. The type and parameters of the generated acoustic waves translate into the extinguishing capabilities of the device. This is crucial because with the use of acoustic technology, flames of different materials, such as liquid and gaseous fuel, can be extinguished. From the point of view of extinguishing flames, the range and field of action of this technology are important. The extinguishing effects depend on the power delivered to the sound source and the components of the acoustic extinguisher (additional panels, screens, etc.) [9]. The level of sound pressure depends on the power delivered to the speaker. When modelling using regression functions, it is important to consider the linear increase in sound pressure recorded within a certain range. Thus, the expected values of the explanation variable can be determined in a limited range (modelling known from mathematical sciences may be applied for this purpose) [10] to [12]. The extinguishing effect depends on the frequency of the acoustic wave, which in turn affects the difference in power delivered to the sound source. For the above reasons, the influence of the frequency of the acoustic wave on the minimum electrical power delivered to the extinguisher, giving the extinguishing effect, was analysed.

Since research on this topic, particularly capabilities using sine waves and sine waves amplitude-modulated by rectangular waveforms remains limited, there was a need to fill the gap in this area. Given this knowledge gap, the objectives of the article are reflected and presented in its content. This article is divided into three main parts. The first describes the possibilities of using a smart sensor for flame detection, which can be successfully applied to acoustic technology. In turn, the second part includes and analyses the results of experimental attempts to extinguish flames with unmodulated and modulated waves (with amplitude modulation) using an acoustic extinguisher. In the last part, i.e., in the third part, future research of the smart environmentally friendly acoustic extinguisher, the many benefits of combining the two techniques, and some limitations of this technology (open problems) are pointed out.

1 METHODS

1.1 Theoretical Aspects

For the analysis of aspects of the use of artificial intelligence (AI) for flame detection, the literature review method, the comparative method, as well as some elements of the system analysis and individual cases were applied.

Similar to acoustic waves, artificial intelligence has many applications. It can be used to detect a variety of activities in large areas, such as airports, shopping malls, and other public places, as well as forests, industrial plants, etc. AI-based detection techniques may also be applied to detect a wide range of dangerous events (examples can be gas leaks and water leaks). AI-based systems can be used to detect and respond to potential threats in real time, allowing quick response and mitigation of any potential threats. These systems may monitor and analyse information from various outlets, such as cameras, to detect unusual occurrences, for example, based on pixel colour, and in the event of a positive fire or smoke detection, immediately notify the fire protection services. An advantage of AI-based detection systems is their ability to learn and adapt over time. In practice, protecting people and the targeted management for this purpose is a key issue [13] and [14]. By analysing data from past events, these systems can improve their accuracy and identify patterns that may not be immediately apparent to people. The use of artificial intelligence has allowed people to be removed from the equation of data processing, which can be demonstrated in many applications and also applied in acoustics [15] to [18]. This may lead to more effective prevention and better response times in emergency and crisis situations [13] and [19]. For example, artificial intelligence can be applied to detect and alert in the event of a fire, particularly in open outdoor spaces. AI-based flame detection systems offer a range of benefits beyond their ability to operate in open spaces. For example, they can provide more accurate and reliable detection than traditional sensors, reducing the risk of false alarms and ensuring that potential fires are identified as quickly as possible. Conventional smoke and temperature sensors are usually installed indoors and are vulnerable to external factors, resulting in a decrease in their effectiveness when used in a large area. This leads to the continued development of detection methods that use artificial intelligence. The smart module using deep neural networks can also be applied to monitor the environment and detect changes in temperature, smoke, or other indicators of potential fire. If any of these indicators are detected, the system may alert the relevant people or authorities, who can then take the necessary steps to prevent a fire from occurring and extinguish it. This module may identify the source of the flames and provide information to the authorities about the location of the fire and its size using, e.g., global navigation satellite systems (GNSS) coordinates. Thus, it becomes possible to capture information in an open landscape [20] to [23]. For the transmission of information, in addition to terrestrial technologies, satellite communications can be applied [24] to [29]. Furthermore, AI-based flame detection systems may also be integrated with other indoor systems, such as sprinklers or ventilation systems, to provide a complete fire safety solution.

In practice, a subset of artificial intelligence is machine learning. The use of a subdiscipline, in which the learning process is carried out unsupervised, provides a high-tech alternative to classical temperature or smoke sensors for flame detection. This is deep learning. It can be used to detect flames in a variety of ways, such as using recurrent neural networks (RNNs) to detect temporal patterns in video data and using convolutional neural networks (CNNs) to detect patterns in images. Deep learning may be applied to flame presence detection by analysing the colour and other characteristics of the flame (e.g., to identify the shape and size of the flame), as well as to smoke presence detection by analysing the colour, shape, and size of smoke particles in the environment [30] to [33]. The selected properties of the flame detection method are included in Table 1 for illustration purposes [34].

Modern flame detection systems based on computer vision and acoustic wave-based extinguishing techniques can work in tandem, automatically initiating extinguishing once a flame is detected, thus minimizing the risk to human life. However, in the event of a false alarm, no significant damage occurs, unlike traditional chemical extinguishing agents. Acoustic waves do not leave any tough stains or damage equipment, making them a non-invasive alternative. Additionally, acoustic technology can effectively extinguish fires in environments full of obstacles, which are characterized by their properties [35] to [37]. With the use of machine learning, it becomes possible to classify, inter alia, fuel type, flame size, frequency, and extinction or non-extinction status. Sample figures are provided in the article [36].

Table 1. *Properties applied to the flame detection method*

No.	Some examples of the considered properties
1	Color
2	Texture
3	Flicker
4	Shape
5	Dynamics

In practice, an acoustic extinguisher requires only a power source, such as a battery or mains, to effectively extinguish flames. It is particularly effective in extinguishing firebreaks and may be used to extinguish flames caused by substances that are difficult to extinguish using traditional fire protection methods [9], [38], and [39]. Information on the state of the art in acoustic flame extinguishing, including the frequency ranges, is presented, inter alia, in [39]. This is important because the goal is to find new composites that can be extinguished using acoustic technology. There is some research in nanotechnology, design, and environmentally friendly energy sources around the world [40] to [48].

The state of the art in the field of intelligent sensor flame detection capabilities includes information on modern camera-based fire detection techniques (as an aspect of fire management) and the effectiveness of such methods [7] to [9], and [49] to [53]. The smart module that is dedicated for flame detection in the acoustic extinguisher in the Polish-Bulgarian cooperation is included in Fig. 1 [7], [49], [51], and [53].

It uses deep neural networks. It becomes possible to equip an extinguisher with such a module so that an automatically activated extinguisher would reduce the risk of damage from the occurrence and spread of flames. Thus far, the work has considered two models dedicated to embedded systems: mask regions with convolutional neural networks (R-CNN) and single shot detector (SSD) MobileNet. Detection accuracy exceeds 96 % with the use of the region-based convolutional neural network mask [6] to [9], [51], and [53]. For the second model, i.e., SSD MobileNet, the detection accuracy is equal to 79 % [49] to [53]. In practice, the choice of the applied model is a compromise between the speed of recognition and its accuracy.

Fig. 1. *Flame detection module with the use of deep neural networks*

1.2 Experimental Aspects

In practice, acoustic waves are an effective way to extinguish flames of different sizes and intensities from liquids and gases. They can also be used to control flames originating from different materials. However, there are only a few papers closely related to the study of the possibility of extinguishing flames using acoustic waves, especially when gaseous fuel was used [7] and [54]. Acoustic waves may also be applied to extinguish flames, the source of which is liquid fuel. In this case, extinguishing is observed when the flame is moved away to a distance at which the fuel supply is cut off due to evaporation [9] and [55]. In addition to vaporizing the fuel, extinguishing is also influenced by spreading the flames over the largest possible area, resulting in a temperature change. Therefore, there was a need to fill the gap in this area.

An experimental method was applied to study the extinguishing capabilities in practice. The analysis of selected cases made it possible to evaluate the flame-extinguishing capabilities under specific conditions. The aim of the designers was to build an extinguisher that emits an acoustic beam in the direction of the flame source. The extinguisher has a closed one-sided waveguide of rectangular cross-section with a length of 4.28 m (its narrowing towards the outlet is noticeable). The principle of the waveguide is based on the amplification of the acoustic wave due to the occurrence of the resonance phenomenon. Standing waves appear at the resonant frequency. In practice, the minimum waveguide length at which the phenomenon of acoustic resonance is observed depends on the frequency and is twice as small for a closed, one-sided waveguide compared to an open waveguide [5]. Therefore, taking into account practical considerations (significant waveguide length for low-frequency acoustic waves), it was decided to build a fire extinguisher with a closed one-sided waveguide for acoustic waves with frequencies oscillating around 20 Hz. A test stand, presented in Fig. 2a, was built for this purpose. In addition to unmodulated waves, modulated waves may be applied for flame extinguishing.

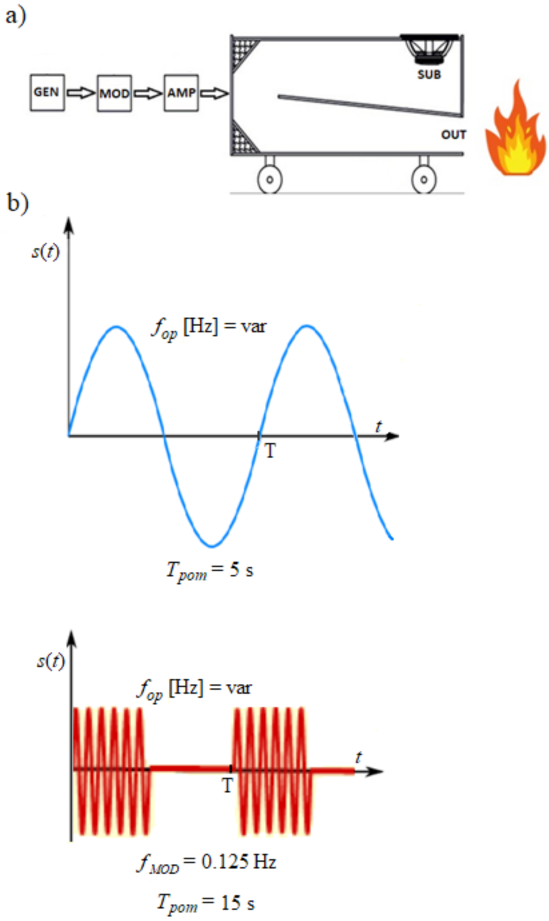

Fig. 2. *a) Components of the acoustic extinguisher: generator (GEN), modulator (MOD), amplifier (AMP), subwoofer, (SUB), outlet (OUT); b) Illustrative figures of the generated signals s(t) in the time domain t for unmodulated and modulated waveforms, respectively*

Analysing the principle of the loudspeaker, when the diaphragm swings out of its equilibrium position, there is a movement of air molecules that resist the moving diaphragm of the loudspeaker. As a result of the density of the particles, the pressure increases. At the same time, the accelerated particles transfer energy to neighbouring particles, which sets them in motion. Acoustic waves are emitted by both the front and back of the diaphragm of the sound source (the phases of the emitted waves are shifted 180 degrees). After the speaker's diaphragm reaches full tilt, it begins to vibrate in the opposite direction, creating an area of vacuum, which in turn results in the particles being turned back. To ensure that the waves emitted by the front and rear parts of the speaker diaphragm do not cancel each other, an acoustic baffle is applied. In this article, the sine wave and the sinusoidal wave amplitude modulated by a square waveform were used in these experimental attempts (see Fig. 2b). The photos of the experimental stand are presented in Fig. 3.

Fig. 3. *A test stand for the acoustic extinguisher (actual photos)*

In practice, it is easier to extinguish flames in a place with limited oxygen (indoor spaces) than in an outdoor area. However, for the purpose of this research, measurements were taken outdoors under similar conditions, using both modulated and unmodulated waves. This paper presents the results of experiments to extinguish flames coming from a candle (a point source of flames with a flame height of about 2 cm) placed at a distance of 0.5 m behind the extinguisher outlet. During the measurements, the background sound level was about 65 dB. The measurement time (T_{pom}) ranged from 5 seconds to 15 seconds (for unmodulated and modulated waveforms, respectively). A high-power acoustic extinguisher was applied for extinguishing, the sound source of which was a woofer with a nominal power of 1,700 Watts. Because of the properties of low-frequency waves, they reach hard-to-reach places, which is a definite advantage when using acoustic technology to extinguish flames from solids, liquids, and gases. For design reasons (the length of the waveguide), the extinguisher has a rectangular cross-section and a waveguide with a closed end. It is equipped with a Rigol DG4102 generator, a Proel HPX2800 power amplifier, and a B&C 21DS115 speaker. One component of the extinguisher is a modulator, and the other is analogue meters for electrical quantities (voltage, current, and power). All acoustic measurements were made using a dedicated SVAN meter (SVAN 979 model), which is a digital analyser and sound level meter at a distance of 0.5 m from the outlet of the acoustic extinguisher (where the point source of flames was located). To identify the operating frequency of the characteristics of the acoustic extinguisher, the sound pressure characteristics were determined as a function of frequency at a distance of 1 m from the device outlet. For frequencies between 17 Hz and 18 Hz, the minimum impedance level of the acoustic extinguisher of 11.4 Ω was recorded (a frequency of 17.25 Hz was called the operating frequency). A local maximum sound pressure is observed at this frequency. Therefore, for the purposes of the experimental attempts carried out, the working frequencies (f_{op} = var) were chosen to show the extinguishing capabilities of the device for four frequencies close to the working frequency (14 Hz, 16 Hz, 17 Hz, and 20 Hz). The lower frequency was set at 14 Hz (this is the minimum frequency at which it was possible to carry out successful flame extinguishing attempts, taking into account the technical capabilities of the extinguisher, especially the vibration of the speaker diaphragm). The highest frequency, i.e., 20 Hz, was chosen as the upper frequency of work, for which it was possible to acquire data for both unmodulated and modulated waves (a set of combined measurements). It should be noted that the choice of frequency was due to the design limitations of the sound source, including its mechanical load. The results of the experimental measurements are presented and discussed in the next section.

2 RESULTS AND DISCUSSION

2.1 A Case of an Unmodulated Wave

First, tests were conducted for an unmodulated (i.e., sinusoidal) wave and then for a sinusoidal wave amplitude modulated by a square waveform (for f_{MOD} = 0.125 Hz).

Table 2 provides information on the sound pressure level (SPL) required to extinguish flames depending on the operating frequency of the acoustic extinguisher for a sinusoidal wave. The acoustic measurements included in the article are for instantaneous root mean square (RMS) values of SPL according to the IEC 61672 standard (Class 1).

Table 2. *Overview table of the sound pressure values SPL [dB] necessary to extinguish flames as a function of frequency f [Hz] for a sinusoidal wave*

f [Hz]	SPL [dB]	f [Hz]	SPL [dB]
14	116.2	17	122.8
16	121.4	20	125.2

Analysing the data in Table 2, it can be seen that to extinguish flames, for the assumed conditions, the sound pressure level at the flame extinguishing site should be in the approximate range of 115 dB to 125 dB, depending on the given frequency. It should be mentioned that, with the use of all frequencies analysed, extinguishing flames with the acoustic technique proved to be effective. Fig. 4 provides a diagram of the influence of frequencies in the 14 Hz to 20 Hz range on the minimum sound pressure level at which complete flame extinguishment was observed. On the basis of the data obtained, it can be seen that the minimum sound pressure level at which complete flame extinguishment was noticed varies depending on the frequency of the acoustic wave. For a frequency of 14 Hz, it was equal to 116.2 dB. In turn, for the highest of the analysed frequency close to the operating frequency, i.e., 20 Hz, it was equal to 125.2 dB (the difference in sound pressure for the extreme values of the frequency was less than 10 dB, that is, 9 dB).

In Fig. 5, is a diagram showing the influence of frequency in the 14 Hz to 20 Hz range on the minimum electrical power that had to be delivered to the sound source of the extinguisher to completely extinguish flames for a sinusoidal wave.

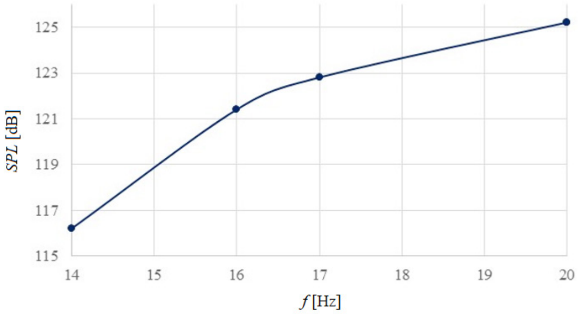

Fig. 4. *The minimum value of SPL [dB] required to extinguish flames depending on the frequency f [Hz] for a sinusoidal wave*

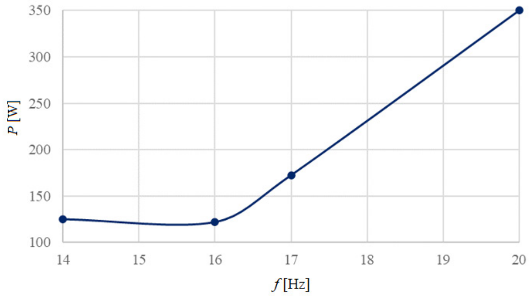

Fig. 5. *Minimum value of electrical power P [W] required to extinguish flames depending on the frequency f [Hz] for a sinusoidal wave*

As can be observed from the data obtained, in the frequency range analysed, there is a noticeable tendency for the power to increase with an increase in the frequency of the acoustic wave. The maximum value of power that had to be delivered to the sound source to extinguish flames was equal to 350 Watts for a sine wave with a frequency of 20 Hz. However, it should be taken into account that a short-term change in atmospheric conditions (in particular, wind speed and direction) can affect the results obtained. Therefore, it is sometimes recommended to repeat the measurements.

2.2 A case of Modulated Wave

The results achieved for a modulated waveform (a case of a sinusoidal wave amplitude modulated by a square waveform) appear to be interesting when compared to an unmodulated wave. Table 3 provides information on the SPL required to extinguish flames depending on the operating frequency of the acoustic extinguisher for a sinusoidal wave amplitude modulated by a square waveform (f_{MOD} = 0.125 Hz).

Analysing the results obtained in Table 3, it can be noted that to extinguish flames, the sound pressure level at the extinguishing site should be in the approximate range of 120 dB to 130 dB, depending on the adopted frequency (in the analysed cases, it turned out to be slightly higher with measured values for unmodulated waves). However, using all frequencies analysed, the extinguishing of flames with the acoustic technique with amplitude modulation (AM) technique was successful. This shows that the presented method can be applied successfully. It may have potential applications in the extinguishing of difficult-to-extinguish flames from burning materials with different properties. This is important because, as previously stated, low-frequency acoustic waves pass through both solids, liquids, and gases. Fig. 6 provides a diagram of the influence of frequencies in the 14 Hz to 20 Hz range on the minimum sound pressure level at which complete flame extinguishment was observed.

Table 3. *Overview table of the sound pressure values [dB] necessary to extinguish flames as a function of frequency [Hz] for a sinusoidal wave amplitude modulated by a square waveform*

f [Hz]	*SPL* [dB]	*f* [Hz]	*SPL* [dB]
14	122.6	17	124.4
16	124.2	20	126.5

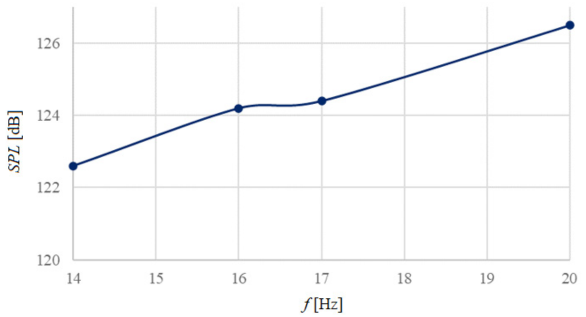

Fig. 6. *The minimum value of SPL [dB] required to extinguish flames depending on the frequency f [Hz] for a sinusoidal wave amplitude modulated by a square waveform*

On the basis of the data measured, it can be seen that the minimum sound pressure level at which complete flame extinguishment was noticed varies depending on the frequency of the acoustic wave. For a frequency of 14 Hz, it was equal to 122.6 dB. In turn, for the highest of the analysed frequency close to the operating frequency, i.e., 20 Hz, it was equal to 126.5 dB. This means that for the frequency range analysed, the difference in sound pressure for extreme frequency values was 3.9 dB. Below, in Fig. 7, is a diagram showing the influence of frequency in the 14 Hz to 20 Hz range on the minimum electrical power that had to be delivered to the extinguisher to completely extinguish flames for waves with the AM modulation technique.

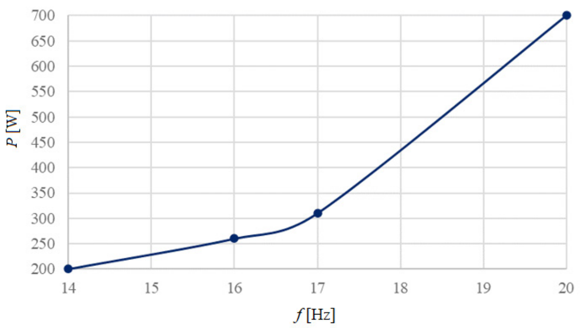

Fig. 7. *The minimum value of electrical power P [W] required to extinguish flames depending on the frequency f [Hz] for a sinusoidal wave amplitude modulated by a square waveform*

As can be seen from the data obtained, similar to Fig. 5, in the frequency range analysed, there is a noticeable tendency for the power to increase with an increase in the frequency of the acoustic wave. The maximum value of power that had to be delivered to the acoustic extinguisher sound source of the acoustic extinguisher to extinguish flames was equal to 700 Watts for a sinusoidal wave amplitude modulated by a square waveform (f_{MOD} = 0.125 Hz) for the highest of the analysed frequency, that is, 20 Hz. This means a twofold increase in the power required to extinguish flames in comparison with an unmodulated (sinusoidal) wave at the *SPL* of 126.5 dB because, for a sinusoidal wave, the effect of completely extinguishing flames was achieved for the electrical power of 350 Watts (the *SPL* was equal to 125.2 dB then). This means that moving away from the resonant optimum translates into an increase in the required power to extinguish flames (a rapid increase is noted, which affects the range of safe use of this technology).

Based on an analysis of the data in Figs. 4 to 7, it can be observed that the operating point at or close to the operating frequency of the acoustic extinguisher provides optimal conditions for extinguishing flames with the acoustic technique. Since the diagrams for unmodulated waves (Figs. 4 and 5) as well as for modulated waves (Figs. 6 and 7) come from the same extinguishing attempts (measurements of the acoustic pressure at which complete flame extinguishment was observed and measurements of the electrical power that had to be delivered to the extinguisher to completely extinguish flames), one can see some similarity in the shape of these two characteristics.

3 FUTURE RESEARCH

In the future, in addition to continuing research on the effect of acoustic wave parameters on flame extinguishing, further research is planned in the direction of flame detection. This is due to the fact that the advantages of using acoustic technology may be exploited in combination with artificial intelligence [56] to [59], which makes it possible to detect flames and then immediately extinguish them. Due to artificial intelligence, people can be excluded from the data processing chain, while detection and alarming in the case of flame detection can be realized with its help, for example, in an open space [58] and [59]. Any method that involves computer vision can replace traditional approaches relying on smoke or temperature detectors, which are installed mainly indoors. Additionally, they are susceptible to environmental factors and a significant decrease in their performance is observed when they are used in wide areas. This is reflected in the continuous development of detection techniques using artificial intelligence as an alternative to the classical approach. The benefit is that visible-light or infrared image sequences can be applied effectively to detect flames. The advantage is then a much higher level of intensity of fire pixels compared to other pixels [56], [57], and [60] to [62].

In the future, it is planned to analyse the possibilities of flame detection using smart sensors and information on contemporary camera-based fire detection techniques. This step is the first component of fire management before extinguishing the flames, which is the second component of fire management. The performance of these types of methods can be evaluated and compared to other methods. The issue of the use of acoustic waves to extinguish flames may be put together with the use of artificial intelligence for flame detection and the benefit of the solution proposed by combining both techniques. It is possible to use low-cost intelligent sensors to protect humans from exposure to sound waves while extinguishing flames. In practice, the system may be activated automatically without human presence (no need for human involvement when extinguishing flames) [7] to [9], [34], and [49] to [53]. The plan for future work is to improve a prototype of the autonomous acoustic fire extinguisher that will be controlled by software and will use the same electronics to control the motors as the robotic platform (control electronics for motors may be applied in the final version of the smart acoustic extinguisher). Furthermore, the plan is to test several types of neural networks for flame detection and add additional components to enhance the suppression of flames using acoustic waves. The development of AI-powered fire detection systems may represent a significant step forward in fire safety technology. As these systems become more advanced and widely adopted, we can expect to see a reduction in response times for emergency services, tangible and intangible damage, and loss of life.

In practice, the impact of acoustic waves on human health is controversial, as long-term exposure to these waves can cause various adverse effects. The severity of these effects is determined by the frequency of the wave and the sound pressure level. Common side effects include fatigue, headaches, reduced concentration, mood swings, sleepiness, and vibroacoustic disease. It is assumed that a person should not be subjected to infrasound and sound pressure levels that exceed the pain threshold of the human ear (if the sound pressure level exceeds 110 dB, it can cause many complaints [2], [49], and [63] to [65]). As long as the person is not present during the firefighting process, there is no risk to health. This is particularly important because, as indicated above, low-frequency acoustic waves, while effective in extinguishing fires, can cause some ailments. Although the use of acoustic waves for fire protection has its advantages, careful consideration must be taken to ensure the safety and well-being of people potentially exposed to these waves. On the other hand, the benefit of combining both techniques in an environmentally friendly acoustic extinguisher, including a smart sensor, is that there is no need to involve humans in the extinguishing of flames (no one has to participate in the firefighting action). The system uses acoustic waves that can be activated immediately when a fire is detected. In this way, it is possible to increase the chances that the flames will be detected and extinguished very quickly. It is well known that time is of the essence in fighting fires because the longer a fire lasts, the more it threatens the lives of people and animals and causes more damage, environmental degradation, and financial losses. In addition, this technology may find application when access to classical (i.e., chemical) fire protection measures is limited, or flames are difficult to extinguish using known methods. Furthermore, more research is needed to investigate the potential consequences of low-frequency acoustic waves and high sound pressure on building structures and room equipment (e.g., windows). This is especially relevant for waves of very low frequency and very high sound pressure levels.

4 CONCLUSIONS

As shown in the article, some undesired signals (due to sound sensation) treated in terms of noise can be useful in some applications. An example is the use of acoustic waves to extinguish flames (a scientific novelty). Acoustic extinguishers, in contrast to classic fire extinguishers, are not subject to periodic tank tests. Furthermore, fire extinguishing with their use is characterized by unlimited operation time (the extinguishing agents are sound waves, which do not exhaust). To work, acoustic extinguishers should be powered by a battery or mains. Therefore, this technique is characterized by lower extinguishing costs than traditional extinguishers, which is its undoubted advantage. Another advantage is the lack of environmental degradation and equipment destruction, as is often the case when using conventional fire protection (acoustic waves do not leave stains difficult to remove) [8]. Currently, this technology may be applied to extinguish Class B and C fires (the second aspect of fire management) when liquids or gases are burning. On the basis of the results obtained, it can be seen that the sound pressure at which the phenomenon of complete flame extinguishment was observed oscillates between 115 dB and 130 dB. Pressure depends on the electrical power that must be supplied to the extinguisher to extinguish flames (the power delivered to the sound source of the extinguisher ranged from 125 Watts to 700 Watts). As the results show, an acoustic extinguisher generating both unmodulated waves and modulated waves with an experimentally determined operating frequency or a frequency close to the operating frequency can be successfully used to extinguish flames, which can be applied, among other things, to extinguish flames originating from materials that are difficult to extinguish with currently known methods (research is being carried out around the world to find new fire-resistant composites). In addition, the possible change of parameters makes it versatile (it is possible to adapt its parameters to extinguish flames from a specific type of substance). However, it should be emphasized that this is a relatively new way of extinguishing flames (thus far, fully unexplored), so further research is needed to thoroughly understand the extinguishing capabilities of acoustic waves. On the other hand, its use in the presence of humans involves risks, as the influence of acoustic waves on human health is a controversial issue. This is because human beings in acoustic fields (especially long-term exposure) may cause some undesirable diseases. The dimension of the effects for people depends on the frequency of the wave and the sound pressure level. This is important because the pressure required to extinguish flames oscillates and even exceeds the pain threshold of the human ear. As is well known, time is of the essence when fighting fires because the longer a fire lasts, the more it threatens human and animal lives and causes more damage and financial losses. Fortunately, the acoustic system may be equipped with an intelligent module so that flame extinguishing can begin without unnecessary time delay when the flames are detected by a smart sensor and without the need for human presence, as is the case with the use of classic fire extinguishers. Taking into account future research on the smart, environmentally friendly acoustic extinguisher, this article also addresses fire detection (the other aspect of fire management), with a focus on the use of deep learning as a modern alternative to traditional temperature or smoke sensors. In practice, combining these techniques could offer significant benefits for environmental (fire) management and environmental technology (beneficial impact on the environment) [56], [57], [61] and [66]. Therefore, the advantages of employing acoustic technology can be maximized by integrating it with artificial intelligence, enabling the detection of flames and their prompt extinguishment. This allows us to extinguish flames as soon as they appear (firebreaks) and prevent large fires from spreading. This feature may effectively reduce material losses and increase safety, which is the antithesis of a threat to life. Ultimately, this technique is expected to be applied in industrial plants and production halls. Acoustic extinguishers can be installed in the walls and foundations of rooms, which reveals new possibilities for the application of this technique in the future. Engineering simulation may be used for measurements, including the use of the boundary element method [67] and [68], as well as image processing, motion detection and convolutional neural networks [69] to [72].

Fortunately, the benefit based on the solution presented by combining both techniques is then that there is no need for human intervention when extinguishing flames. No one has to participate in the firefighting action (the system that uses acoustic waves can be immediately activated when a firebreak is detected). Then, data about the fire detection may be rapidly transmitted to the relevant authorities in the form of a photo and comprehensive information primarily containing the location of the fire detection (including, e.g., the GNSS coordinates). Moreover, the transmitted information can include, among others, details such as the date when the photo was taken, the names of visible and infrared spectrum images (if necessary), and the corresponding ground truth image (if applicable). A factor in favour of this is that image sequences in the visible or infrared bands can be used successfully for flame detection, as stated in the article.

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