Acoustic Extinguishing

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Contributor: Jacek Wilk-Jakubowski

In the fire-extinguishing process, in principle, one of the components in the fire tetrahedron must be removed. For example, a natural gas fire occurring on a stovetop burner can be extinguished in various ways: Eliminating the fuel source by shutting off the gas supply may be the first option. Another option is to completely cover the flame to block any oxidizer that is present, such as oxygen in the air, during combustion.

electrical engineering | firefighting | flame extinction | flame-extinguishing methods | acoustic oscillations | acoustic pressure | flame-retardant materials | acoustic extinguishing

1. Introduction

Fire can be defined as a chemical combustion process involving the high temperature oxidation of a flammable material (or a fuel). As a result of this reaction, energy is released and heat is produced. Oxygen, temperature, fuel, and chemical reactions are required for the fire to start. These four elements are called a fire tetrahedron. For the fire to continue, the oxidizer and fuel supply must continue. Consequently, the heat given to the environment in the combustion reaction allows the fire to preserve its heat and ensures that the chain reactions required for the spread of the fire take place [1][2][3]. **Figure 1** shows the traditional fire-development stages. Accordingly, no flame is visible in the first stage, and the smoldering phase occurs. In the second stage, ignition occurs. With well-ventilated flaming, fire growth occurs at this stage. New fuel or the right fuel and oxygen mixture is required for the fire to develop. At the flashover point, the fire spreads by reaching sufficient oxygen, fuel, and heat. After the fully developed phase is reached, the available fuel is exhausted and combustion ends. Those who try to extinguish the fire after the flash exceeds the level experience greater difficulty [4].

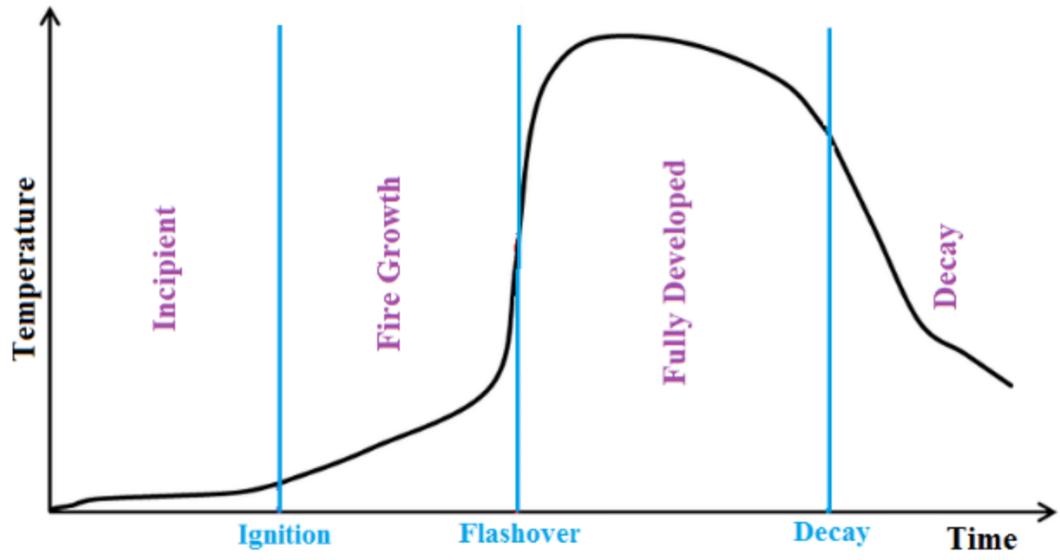

Figure 1. Traditional fire development.

In the fire-extinguishing process, in principle, one of the components in the fire tetrahedron must be removed. For example, a natural gas fire occurring on a stovetop burner can be extinguished in various ways: Eliminating the fuel source by shutting off the gas supply may be the first option. Another option is to completely cover the flame to block any oxidizer that is present, such as oxygen in the air, during combustion. Another alternative is the application of water that quickly removes heat from the fire. Blowing hard on a flame can be considered a similar practice in principle, as it will shift the heat of the already burning gas away from the fuel source. Another option is to apply various chemicals that delay the chemical reaction in fire until they slow the rate of combustion [1][2][3][4].

2. Fire Extinguishing

Currently, flames are extinguished with the use of fire extinguishers that contain appropriately selected chemicals. The cost of their purchase is significant, and it has been noticed that they have a negative impact on the environment and human health. The best example seems to be the halon extinguishers, which are withdrawn from production because of their harmful nature. Halon extinguishers are now being replaced by so-called pure extinguishing agents, which are appropriately selected extinguishing gases. According to the NFPA 2001 (National Fire Protection Association) standard, these agents include selected halogenated hydrocarbons and inert gases [5][6]. Although chemical technologies are well developed and widely used, their use is fraught with inaccessibility in areas of difficult access. In addition, they are invasive and their chemical composition is mostly toxic. Another drawback of using traditional fire extinguishers is the short operating time and the fact that when the extinguishing agent is exhausted, refilling of the tank can only be performed by professional services (this operation is time-consuming and transporting the extinguishing agent to the place of the fire is quite problematic). For these reasons, it is not standard practice to fill tanks with the extinguishing agent after it is exhausted, at the site where the flames are extinguished. Any delay in extinguishing the flames is of great importance, as spreading flames pose a threat to human life and health, as well as financial losses. It seems safer for the environment (usually when extinguishing a flash fire) to use fire blankets. However, when the flames spread, this method is dangerous, especially for people who are close to the source of the flames, because of the risk of burns and uncontrolled air blast. For these reasons, the use of this method is severely limited [7].

Recently, the search for new, environmentally safe, and inexpensive methods of fighting fires has become a particularly important topic. Controlling and steering the flame has many different applications, despite the complicated nature of this process. In this area, there have been numerous studies carried out in recent years in Europe and around the world, which can be exemplified by the growing number of publications related to this topic. Some authors proposed the use of the acoustic field to reduce the emission of undesirable combustion products, such as soot, or presented the application of acoustic waves in industry [8][9]. The rapid development of technology in the 11th century also allowed the use of physical phenomena accompanying the propagation of acoustic waves for flame extinguishing. This approach could provide an alternative or complement to available flame control and suppression methods in the future and could revolutionize the currently available firefighting measures. Research in this area was carried out by the U.S. Defense Advanced Research Projects Agency (DARPA), starting in 2008 under the Instant Fire Suppression Program (IFS) [10]. The reason for initiating this program was the fire on the aircraft carrier USS “George Washington”, which within 12 h caused material losses estimated at $70 million. The escalation of this event led to strategic action. Taking into account the shortcomings of traditional means of fire protection, the need to look for new ways to combat uncontrolled phenomena, which are fires, was noticed. In addition, the solutions found in the following are relevant in this regard: (A) No. 4,735,282—“Device and circuit for the generation of vortex rings” (5 April 1988); (B) No. 5,899,685—“Remote lighted wick extinguisher” (4 March 1999); (C) No. 2010/0203460—“Process of extinction, expansion and controlling of fire flames thru acoustic” (12 August 2010) [11][12][13][14]. Furthermore, the “Mythbusters” in 2007 proved that flames can be extinguished using an appropriately amplified and modulated human voice (they achieved a sound pressure level that exceeds the pain level of the human ear) [15]. Acoustic waves were also used to extinguish flames a few years ago by two American students, Seth Robertson and Viet Tran. After a year of experimentation, they built a device that is capable of extinguishing flames [16].

Based on the literature review, the first attempts to extinguish flames using acoustic waves in Europe took place in the 1990s. This topic was again discussed in 2017 in Poland after obtaining a grant co-financed by the Ministry of Science and Higher Education from the “Innovation Incubator +” program (project no. 3 entitled “Non-invasive project of acoustic extinguisher using natural mechanisms of sound waves propagation to extinguish liquid fires in closed spaces”) [17][18]. Three patents and one small patent (utility model) can be identified as the results of this research [19][20][21][22]. In the conducted experiments, scientists showed that acoustic waves may be used to extinguish, inter alia, burning gases. In practice, the range and effectiveness of the acoustic flame-extinguishing technique depends on the acoustic flux density. An example of a high-power acoustic extinguisher is shown in **Figure 2**.

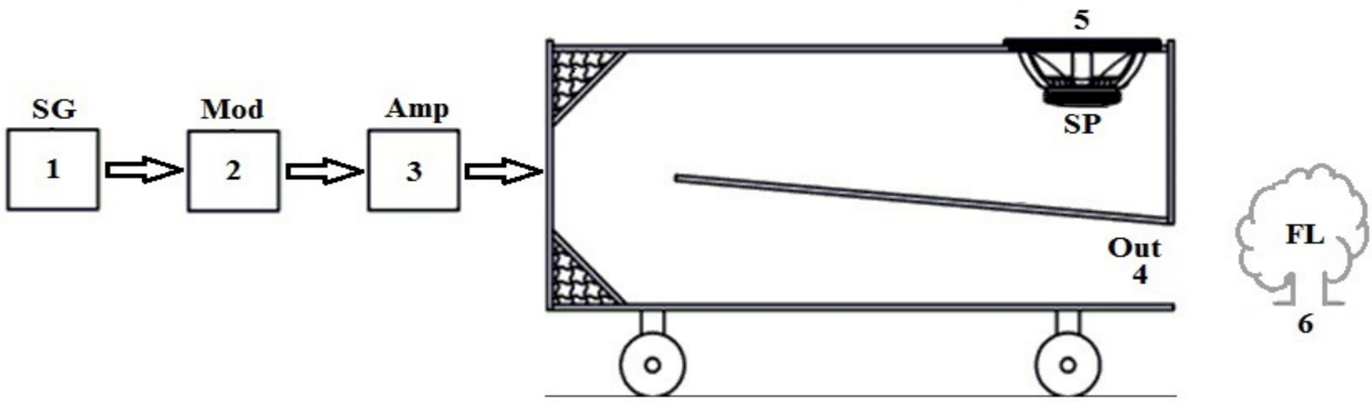

Figure 2. Components of an example acoustic extinguisher: (**1**) signal generator, (**2**) amplitude modulator, (**3**) amplifier, (**4**) device output, (**5**) acoustic wave source (speaker), (**6**) flame source.

In 2020, the Polish and Bulgarian media published many articles discussing the possibility of acoustic flame extinguishing [23][24][25][26].

Since the technique of extinguishing flames using acoustic waves is a novel technique, few studies can be found in the literature that present the state-of-the-art in this field. In this entry, due to the limitations relating to the areas indicated (Central and Eastern Europe), the following sections focus primarily on the work of researchers from this area. As a complement to the state-of-the-art, the works of other researchers from outside the old continent (especially from America and Asia) who have taken up this topic are also discussed.

2.1. State of the Art in the Use of Acoustic Flame-Extinguishing Technology

There are known studies in Central and Eastern Europe concerning the possibility of using very low-power acoustic waves to extinguish flames a short distance from the device output, e.g., [27][28]. In the available literature, researchers find several articles related to experimental research of flame behavior as a result of the acoustic field (articles [29][30][31][32][33] may serve as examples). There are few articles and scientific papers devoted to the potential use of high-power acoustic waves for flame extinguishing (this technology is relatively new and is still in the testing phase). This technique is particularly suitable for extinguishing firebreaks (in the first phase of the origin of the fire) [7]. In practice, the effectiveness of firefighting action using the acoustic method depends on the amplitude of air vibrations, which differs according to the sound source applied. The causal factor is the movement of particles forced by sound with the power necessary for this phenomenon to occur. Due to their physical properties, low-frequency sounds propagate uniformly in all directions and enter into hard-to-reach places, which is an unquestionable advantage. It seems desirable to explain this phenomenon. Propagated acoustic waves, through the transmission of medium disturbances (changes in air pressure), affect the flames with energy proportional to the value of the sound intensity, which defines the average value of the acoustic energy stream that flows through a unit of surface perpendicular to the direction of wave propagation [34]. For practical reasons, the notion of the sound intensity level expressed in dB may be used. Waves with low frequencies and high sound intensity are perceived as vibrations. The action of acoustic waves on flames results in the following: tearing them apart when the critical frequency is reached, dispersion (weakening), and extinguishment. This is possible when the temperature of the torn-off portion of the flame is lower than the ignition temperature of the flame portion. The mechanism of flame stream rupture due to acoustic wave interaction is discussed in detail in the entry [35].

By analyzing the literature review, it was found that different types of flames have been extinguished in an open environment or inside a resonant tube. The simplest waveguide can be a closed and not very practical to use (due to its dimensions) tube with a circular cross-section. In addition to cylindrical tubes, other waveguides may also be useful, such as exponential or conical tubes. A characteristic of tube resonators is that their transverse dimensions are much smaller than the wavelengths at which they amplify. The acoustic wave is amplified as a result of the resonance phenomenon occurring in the resonator due to the reflection of the acoustic wave inside the waveguide and the overlapping of waves. A standing wave, whose position does not change in space, is created as a result of the overlapping of waves that move in the same direction but have opposite returns. Then, the amplitude of waves of a certain frequency is amplified. The distribution of standing waves (**Figure 3**) is given and discussed in [36].

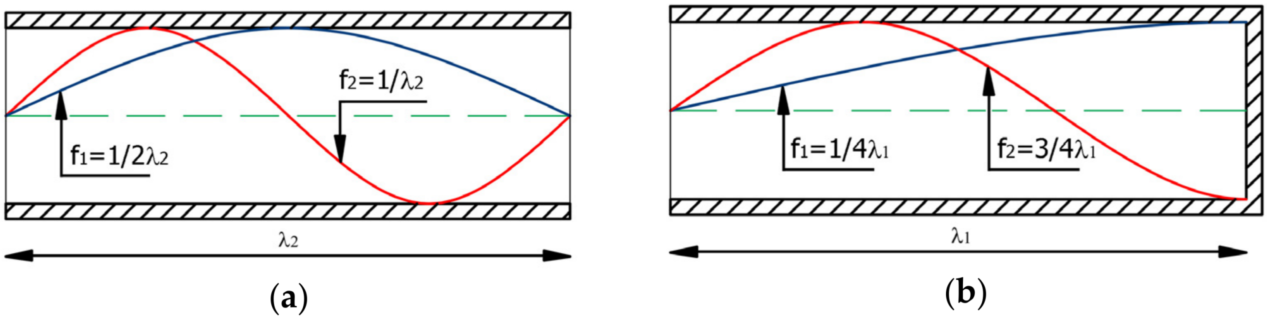

Figure 3. Standing wave distribution for the first and second resonant frequencies in an open tube (**a**) and a closed-end tube (**b**).

The point where the vibration amplitude is equal to 0 (node) at the open end of the tube, which is the output of the device (at this point, the sound pressure reaches a minimum value), is marked in red (these considerations apply to **Figure 3** on the left side). On the other hand, the point where the vibration amplitude is maximum (arrow) at the closed end of the tube is marked in blue (at this point, the sound pressure reaches a maximum value). As can be seen in **Figure 3**, the sound pressure decreases with the increase in the distance from the closed end of the tube (the minimum pressure level is noted at the open end of the tube). In **Figure 3** (right side), the nodes at the open ends of the tube are marked in red. The end of the waveguide can be considered as a point source from which a wave of frequency equal to the frequency of the standing wave generated in the waveguide is propagated [8]. In addition, the use of a diaphragm allows one to increase the sound pressure value pointwise (the increase in sound pressure is noted when the diameter of the device output is reduced). Because the required waveguide length is twice as small in a closed-end tube than in an open tube, the closed-end tube is typically used for practical applications.

In the literature, experimental results may be found to illustrate the flame behavior due to the interaction of acoustic waves. Depending on the frequency, it can be observed that the acoustic field may be both linear and nonlinear. In practice, the sound pressure increases linearly only in a certain range, depending on the electrical power applied to the sound source, and the combustion may have a discontinuous pattern [34][35][36]. Some works have described unpredictable wrinkling [37][38] or bifurcation [39][40] of the flame.

Im, Law, and Axelbaum proved that flame extension due to turbulent vortices results in an aerodynamic distortion of the flame, which consequently leads to flame extinction [35]. The turbulence values of one of the ambient parameters interact with the propagation velocity of the flame front, affecting the change in its direction. Then, the flame extends, which results in increased heat emission until the flammability limit is exceeded [28][41][42].

Taking into account non-European studies, McKinney and Dunn-Rankin used methanol located in front of the output of the resonating tube as a fuel [43]. They recognized that the acoustic pressure required to note the extinguishing effect is dependent on the frequency and diameter of the methanol droplet. Therefore, they analyzed the extinguishing capability for different droplet diameters, frequencies, and sound pressures. The researchers showed that increasing frequency results in better mixing between the fuel and the oxidizer, and consequently, a higher sound pressure is required to extinguish the flames [43]. In other words, when the flame is moved far enough away from the methanol droplets, the fuel supply resulting from the evaporation process is cut off. As the droplet size increases, the sound pressure needed to burn the flame increases. By comparing the operating frequency and flame power, it is expected that a thin (high) flame is easier to extinguish than a wider flame. From this, it can be concluded that flame inertia is also an important factor in determining the level of minimum sound pressure at which the extinguishing effect may be observed.

Beisner et al. used a lit Zippo lighter in microgravity as the flame source for their experiments [44]. They applied a one-ton acoustic wave for extinguishing. These researchers concluded that it is easier to extinguish the flame using low-frequency acoustic waves, especially in microgravity, than in an ordinary gravitational field.

In turn, Bennewitz et al. [45] included extinction criteria for single drops of three different fuels.

On the other hand, Friedman and Stoliarov, in their research, attempted to explain how acoustic perturbations affect flames with a laminar diffusion line [46]. Another research objective was to determine the necessary conditions to extinguish the flames. Similarly to the other researchers, it was found that it is easier to extinguish the flame using low-frequency acoustic waves (as the frequency increases, an increase in the minimum sound pressure necessary to extinguish the flames is noted). In addition, it has been observed that as the acoustic pressure increases, the average mass loss rate of the fuels increases. In practice, the extinction process is associated with a temporary increase in the local flame deformation rate as the flame moves toward the droplet surface [46].

In the vast majority of studies, liquid fuels were used for the generation of flames. It is noticeable that, apart from the studies conducted in Poland, there is practically no research on the possibility of extinguishing flames using gaseous fuel, e.g., [17][47][48][49][50]. There is a lack of experimental studies that contain information on the influence of the distance of the device output from the flame source, produced with gaseous fuel, on the extinguishing process. It is worth noting that when gaseous fuel is used, unlike liquid fuel, the evaporation process does not occur. Research conducted in Poland has focused primarily on determining the minimum level of sound pressure and power delivered to the sound source at which the extinguishing effect is observed, depending on the frequency of the acoustic waves and the distance between the source of the flame and the device output.

The possibilities of extinguishing a diffusion flame using the acoustic technique, taking into account the critical frequency value and the limit of acoustic power, are presented in [28]. The extinguishing phenomenon was visualized by means of a streak apparatus (a shadow method was applied using variations in the refractive index with a change in the density of the medium). In that research, it was shown that for a given value of the heat power of the flame, it is possible to extinguish it with acoustic waves of different frequencies (35 ÷ 155 Hz) for a power of less than 30 W. The highest extinguishing capacity was recorded for low frequencies. This entry also provides information on the flame extinction efficiency coefficient derived from the ratio of the limiting power and the thermal power of the flame with an appropriate multiplier (10^{-4} m^3). As shown, this coefficient is functionally related to the critical frequency of the acoustic wave [28].

Niegodajew et al. [47] used acoustic waves in the frequency range (30–50 Hz) for extinction, for different burner powers and at different flame-source distances from the device output. The operating frequency range was chosen in a noncoincidental way. It was stated in [48] that for acoustic waves with frequencies below 100 Hz, the combustion rate decreases. Confirmation of this fact can also be found in some other publications, such as [43], where it was shown that the easiest way to extinguish the flame is to apply the lowest of the frequencies analyzed within the range of 75–135 Hz. On the other hand, it was suggested in [46] that a further reduction in frequency has a beneficial influence on the extinguishing effect.

To the researchers' knowledge, there is a paucity of work in the literature that investigates the effect of various obstacles on flame extinguishment using acoustic waves. Niegodajew et al., in their paper [5], presented experiments showing how an acoustic screen affects the process of extinguishing flames with the use of acoustic waves (a single-obstacle model was applied). The experiment consisted of two phases, which were repeated three times to increase the accuracy of the measurements. In the first phase, the acoustic pressure required to extinguish the flames was determined. Two independent variables were analyzed, i.e., the fuel load and the distance between the acoustic screen and the device output. In the second phase, the acoustic field between the device output and the acoustic screen was studied. From the data presented, it can be concluded that the largest range of sound pressure variation was observed for a short distance from the acoustic screen (in this case 15 cm). Above this distance, a slight change in sound pressure values was observed (the use of a screen had little effect on the sound pressure level). This was evident regardless of the power delivered to the sound source. In the case of a close location of the screen and a probe, a systematic increase in the sound pressure was observed throughout the measurement range, regardless of the distance between the device output and the screen. The researchers concluded that the direct environment affects the ability to extinguish flames using acoustic waves [5]. In a situation where there was an object directly behind the flame, the process of extinguishing the flames despite the increase in acoustic pressure was hindered. The closer the object was to the flame, the greater the sound pressure that was required to extinguish the flames; thus, it can be noted that increasing the sound pressure alone is not crucial to extinguishing the flames [5]. The mean flow effect is also a causal factor that impacts the flame-extinguishing process. To visualize the flame behavior under the influence of acoustic waves, the Schlieren method was applied. According to Chen and Zhang and Niegodajew et al. [30][47], the mean flow effect is independent of the excitation frequency and increases due to an increase in acoustic pressure. Based on the camera images, researchers infer that the flame itself follows the fuel flow until it is detached from the burner output. This means that the mean flow causes a deflection of the fuel jet and affects the separation of the flame from the burner output by moving it from its original position. When the critical sound pressure is reached, the flame is interrupted. On the basis of this, it may be concluded that flow and oscillatory disturbances affect flame extinguishing [47].

The researchers of [27] provided information on extinguishing the combustion process with the use of acoustic waves, which have a nondestructive effect on protective objects. As highlighted by the researchers, the ideal solution seems to be the usage of acoustic waves for firefighting, especially as elements of fixed firefighting systems. This long-term approach can be an alternative or complement to the classical methods of fire protection. As stated by the researchers, in the case of generating acoustic waves with frequencies from 20 Hz to 5000 Hz, when the power applied to the loudspeaker was less than 30 W, the largest amplitude of change in sound pressure for the tested system was achieved for the frequency of 40 Hz [27]. For these experiments, depending on the frequency, the power difference at which the extinguishing effect was observed varied by 17 times at three-and-a-half times the acoustic pressure difference [27].

In the case of many experiments conducted in Poland using high-power acoustic extinguishers, the flame sources were candles placed in the axis of the waveguide behind the device output, as well as a professional gas-fueled mock-up that was used in practice to evaluate the effectiveness of firefighting actions carried out with traditional fire extinguishers (they were placed in both longitudinal and transverse positions in the axis of the waveguide). The operating frequency of the experiments oscillated around 17.25 Hz and was chosen in a noncoincidental way because the minimum acoustic impedance of 11.4 Ω was recorded for this frequency [36][49]. This was achieved by analyzing measurements of the experimentally derived impedance curve of the extinguisher, in the range from 10 Hz to 90 Hz. For the determined frequency, the vibrations of the speaker’s cone were smallest, which allowed the effective use of the power of the sound source. It was shown that it is possible to extinguish flames using multiple frequencies, both lower and higher than the operating frequency, while the distance of the extinguisher from the flame source is also important. At low frequencies, the more turbulent effects of acoustic waves on the flames were noted (the vibration amplitude increased significantly). However, frequency mismatch may be associated with substantial vibrations of the loudspeaker diaphragm (design limitations of the sound source). On the other hand, the emission of acoustic waves at a frequency higher than the operating frequency affected the increase in electrical power delivered to the loudspeaker to extinguish the flames (subacoustic power energy increases) [49]. From the point of view of an extinguishing action carried out with the use of an acoustic system, it is desirable to produce a sound pressure at a level sufficient to quickly extinguish the flames while maintaining a minimum sound pressure reserve (the term sound pressure reserve is understood as the excess sound pressure added to the minimum pressure at which flame extinguishment was observed). Therefore, the reserve is a correction for flame-extinguishing conditions that are different from laboratory conditions [49]. The researcher showed that variable-frequency acoustic waves can be used to extinguish flames, which may have a potential significance in suppressing flames originating from different materials.

It is worth emphasizing that fire locations usually have different concentrations of volatile substances such as CO_2, smoke particles, O_2, CO, NO_x, etc. Since acoustic waves pass through solids, liquids and gases, according to the theory, acoustic extinguishers can be effectively used to extinguish fires of different classes [49]. This is because the acoustic field has a point effect on the flame source. In practice, it is possible to adjust the frequency and amplitude of vibration of acoustic waves to the flame source, which makes it possible to note that acoustic extinguishers are universal in contrast to classical fire-protection measures. It is also possible to use acoustic waveforms with different modulation and varying frequency; for example, when the composition of the substance is not exactly known [49]. According to the combustion triangle, which denotes the condition of fire formation, the composition of a fire includes the following: oxidant, heat and combustible material. From the point of view of flame extinguishing, it is important to generate waves with a frequency chosen to locally repel oxygen molecules from the air. Besides the frequency, the acoustic power is an important parameter, which influences the effectiveness of the acoustic-wave extinguishing process. It has been proven that the effectiveness of the extinguishing process depends on the amplitude of vibration of acoustic waves. The sound wave increases the speed of air movement at the periphery of the flames, thus reducing the area in which the combustion process occurs. This can be seen perfectly in the video presented by DARPA [10][36][50]. Thus, researchers have two dynamics (the acoustic field increases the air velocity, which disturbs the flame boundary layer; in turn, the disturbance of the flame surface leads to more vaporization of the fuel, which affects the expansion of the flame, thus lowering its overall temperature). The acoustic method thus appears promising for flame extinguishing when access to conventional extinguishing agents is limited or when the composition of the substance is unknown. It is also worth noting that while harmful gases are emitted into the air during a fire when effective-though-harmful fire-protection agents (e.g., halon fire extinguishers) are used, acoustic waves are not a chemical product and do not pollute the air, which is a great advantage [7][49].

2.2. Possibilities of Using Deep Neural Networks Together with Acoustic Technology to Fight Fire

In the literature on the subject, there are works in which Deep Neural Networks (DNN) are used to determine whether a fire has occurred and, if so, the extinguishing system can be activated automatically. This is feasible if the acoustic extinguisher is equipped with an intelligent module. Communication is not a problem, especially when using wireless data transmission techniques (it becomes possible to remotely activate the acoustic system depending on the detection of flames by sensors and Deep Neural Networks without human intervention, which is important to protect against the effects of low-frequency waves on human health) [18][51]. This may find applications in robotics and emergency management [52][53]. Works carried out in Central and Eastern Europe, supported by institutions dealing, inter alia, with fire protection, resulted in the development of an acoustic system concept that is capable of extinguishing flames with the use of sound waves. Such a non-invasive acoustic extinguisher equipped with a flame-detection module with Deep Neural Networks may constitute an autonomous device capable of activating when flames occur. Research in this area is especially carried out as part of the cooperation between Polish and Bulgarian scientists.

Stawczyk et al. demonstrated the influence of air turbulence resulting from varying sound pressure on flame continuity for different distances from the flame source and multiple frequencies [36]. In practice, the effectiveness of the extinguishing process depends on the amplitude of the air vibration. Acoustic power and acoustic wave frequencies are important factors [7]. The acoustic extinguisher presented by the researchers generates a directional acoustic flux to effectively extinguish flames.

For the frequency of 14 Hz, very good extinguishing efficiency was found with the lowest electrical power delivered to the extinguisher. The use of low frequencies forces a much longer waveguide. This is due to the fact that the lower the frequency, the longer the wavelength. As the frequency increases, the power required to extinguish the flames increases (the extinguishing range is affected by the concentration of the acoustic beam) [17]. On the other hand, the use of higher frequency acoustic waves allows for a reduction in the size of the acoustic extinguisher. The application range is determined by the frequency of acoustic waves, which is very important, especially in the case of acoustic waves with high acoustic pressure below the range of human hearing (infrasound). Due to their harmfulness, no human presence during extinguishing should take place. To perform quantitative analyzes, the classical regression function model can be used in the linear range [54].

The subject of recent research, however, is the possibility of connecting an acoustic fire extinguisher to smart sensors and using Deep Neural Networks to determine whether the flames have been detected, that is, whether a fire has occurred. Ivanov et al. presented the beginnings of the use of acoustic techniques to extinguish flames [50]. The researchers pointed out that current methods of extinguishing flames involve the use of solid, liquid, or gaseous extinguishing agents. The acoustic method works by increasing fuel evaporation and dispersing the flames over a large area and results in the reduction in flame temperature and the area over which the flames occur. The velocity of air movement at the edge of the flames increases, while the density of the acoustic jet affects the operating range of the acoustic extinguisher. This entry demonstrated the feasibility of using Deep Neural Networks for flame detection based on learning from images or video streams [55][56][57][58][59][60]. Such a system, consisting of a computer module, a USB camera, and a Movidius stick vision processing unit, may be connected to an acoustic fire extinguisher and can allow it to be activated when the flames are detected. The hardware is based on a Raspberry Pi board, which allows support for multiple operating systems. The controller is capable of generating complex video signals, including 576 i and 480 i for PAL, NTSC. A USB camera is connected to the Raspberry Pi (the resolution is 1280 × 720 pixels). Two relay modules (24 V control signals) can be applied to control the fire extinguisher depending on the detection of flames in the captured video stream. Many technologies and libraries are implemented in the control software, the most important of which are: OpenCV (computer vision and machine learning library), Matplotlib (separating library), TensorFlow (for machine learning), and NumPy (for handling multidimensional arrays). The neural network is based on the MobileNet architecture, designed for mobile and embedded applications. The described technology was also presented in [17]. Many other libraries, such as Imutil [7], may be useful as an auxiliary tool for the implementation of neural networks for flame suppression. These networks can be implemented in various processing systems (CPU, VPU, and GPU).

Publication [7] describes a development kit consisting of a System on Module (SoM) and a reference backplane (the purpose was to develop computationally powerful embedded systems). The board has GPIO pins to control the acoustic flame-extinguishing system. An example of flame detection is illustrated in **Figure 4**.

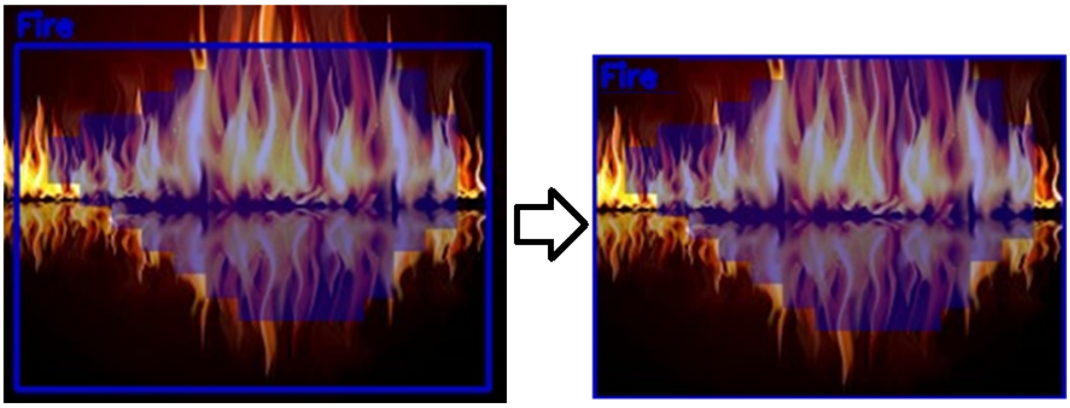

Figure 4. Dominant fire source image and flame detection.

The neural network presented is reliable in flame detection, so it can be integrated into modern fire-protection systems (without the use of additional sensors) [7]. The acoustic system can also be connected to smoke and temperature sensors, so human presence is not required during extinguishing (the extinguishing system is able to be activated automatically).

The researchers of [17] presented a method for extinguishing flames with a high-power acoustic extinguisher using modulated and unmodulated acoustic waves (the sound does not have to be loud; the important thing is that it is appropriately modulated). The extinguisher is equipped with a flame-detection module using artificial neural networks. These networks were learned using still images and video streams. Such an intelligent module applied in an acoustic fire extinguisher can support fire protection implemented using acoustic flame-suppression technology [49]. This is a new method, as the acoustic extinguisher equipped with a fire detection module using Deep Neural Networks is an innovative approach in fire protection as a result of Polish–Bulgarian cooperation (between the Kielce University of Technology and the Technical University of Gabrovo). The effect of this research is a fire-extinguishing system with high and very high acoustic power, and the artificial intelligence platform. Sinusoidal waves modulated with a triangular waveform (AM modulation was applied in this case), and unmodulated triangular waves were used to extinguish the flames [17]. For the sinusoidal waveform modulated by a rectangular waveform (AM modulation, MFreq = 0.125 Hz = const.), the results for the electrical power delivered to the sound source (required to extinguish the level of flames) and the sound pressure level as a function of distance from the output of the extinguisher were provided in [7]. Ivanov et al. showed that AM-modulated waveforms are effective for flame extinguishing [50]. Sinusoidal waves modulated by triangular waveforms may also be applied for this purpose. The results presented in this entry showed the sound pressure level at which the flames were effectively extinguished as the function of a distance from the extinguisher output, ranging from 50 cm to 130 cm. An inversely proportional relationship was experimentally demonstrated between a decrease in sound pressure level and an increase in the distance from the extinguisher output. This means that the greater the distance from the flame source, the higher the electrical power that has to be delivered to the sound source to extinguish the flames.

The researchers of [18] provided results for a system that can operate as a standalone platform and work with other hardware modules, such as Arduino. This platform is equipped with a 16-bit processor for Deep Neural Network processing as well as two 64-bit RISC-V processors. A Kendryte K210 processor was applied for flame detection. If they are identified, the control of the acoustic extinguisher is applied discretely. The advantage of the system is its high processing speed (the computation time is about 10 ms) [18]. This entry reports results on the flame-extinguishing capabilities of a high-power acoustic extinguisher for a sine wave and a sine wave modulated by a rectangular waveform for several analyzed frequencies (15, 17, and 20 Hz). These networks are useful for flame detection in various equipment, buildings, or transport (land, water, and air), especially where, for example, ambient temperature and the presence of dust prevent or significantly influence the efficiency of using other types of flame-detection techniques [18]. In this respect, foundries, sand dryers, and heat treatment plants, inter alia, can be pointed out. Moreover, acoustic flame-extinguishing technology may find application for extinguishing flames of substances whose properties make it impossible to extinguish them by conventional means or wherever access to conventional fire-protection agents is severely limited (e.g., in aircraft, trains, ships, etc.). In addition to the availability of many technologies, the low cost of the components used and the high efficiency of flame detection should be mentioned as the advantages of flame detection using neural networks instead of traditional sensors [7].

The researchers showed that it is possible to construct an acoustic system consisting of multiple extinguishers and take advantage of the natural mechanisms that accompany the propagation of sound waves (constructive interference) [17]. Furthermore, interference screens, acoustic baffles, and panels, as well as many materials that absorb the harmful part of the acoustic wave energy in order to obtain additional gain, may be applied. This is important because low-frequency acoustic waves are poorly attenuated by the medium in which they propagate. Remote surveillance systems can be implemented using satellite communications. For this purpose, it is important to know the propagation phenomena that affect the attenuation of radio waves in the atmosphere of the Earth [61][62][63]. Other technologies described in articles by Croatian researchers [64][65] can also be useful for the transmission of data, from locations where a fire has occurred.

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