Environmental and Climate Technologies
2022, vol. 26, no. 1, pp. 319–330
https://doi.org/10.2478/rtuect-2022-0024
https://content.sciendo.com

The Use of Acoustic Effects for the Prevention and Elimination of Fires as an Element of Modern Environmental Technologies

Valentyna LOBOICHENKO[1], Jacek WILK-JAKUBOWSKI[2*], Grzegorz WILK-JAKUBOWSKI[3], Radosław HARABIN[4], Roman SHEVCHENKO[5], Victor STRELETS[6], Alexander LEVTEROV[7], Alexander SOSHINSKIY[8], Nataliia TREGUB[9], Oleksii ANTOSHKIN[10]

[1,5–8,10]*National University of Civil Defence of Ukraine, 94 Chernyshevska Str., 61023, Kharkiv, Ukraine*

[2]*Kielce University of Technology, 7 Tysiąclecia Państwa Polskiego Ave., 25-314, Kielce, Poland*

[3,4]*Old Polish University of Applied Sciences, 49 Ponurego Piwnika Str., 25-666, Kielce, Poland*

[3,4]*Institute of Crisis Management and Computer Modelling, 28-100, Busko Zdroj, Poland*

[9]*Kharkiv State Academy of Design and Arts, 8, Mystetstv Str., 61002, Kharkiv, Ukraine*

Abstract **– The paper studies the current state of the art in the use of acoustic effects in the prevention and elimination of fires. For this purpose, the literature review method was applied. The well-known approaches to fire extinguishing and their impact on the environment are considered. Multifaceted studies by a wide range of scientists on the possibilities of the acoustic effect in fire extinguishing are noted. The analysis of literary sources showed the negative impact of both the fires themselves and the majority of fire extinguishing agents on the environment. Variants of the use of the acoustic effect for the prevention and elimination of fires of various combustible substances are considered. The influence of the frequency of acoustic waves, scanning speed, power, and other acoustic parameters on flame extinguishing is noted. The possibilities of using a deep neural network for flame detection have been studied. The limitations and advantages of acoustic technology and further prospects for its development as an element of environmental technologies are shown.**

Keywords **– Acoustics; deep neural network; environmental technology; fire; pollution**

Nomenclature		
AM	Amplitude Modulation	–
SoM	System on Module	–
R-CNN	Region-based Convolutional Neural Networks	–
VSAT	Very Small Aperture Terminal	–

1. INTRODUCTION

Computer modeling and modern technologies play a key role in understanding phenomena in many fields of science [1]–[4]. In practice, acoustic waves have many applications [5], [6],

* Corresponding author.
E-mail address: j.wilk@tu.kielce.pl

one of which is the use of acoustic waves to extinguish flames. However, this is a novel solution that is in the testing phase [7]–[9]. Currently, appropriately selected chemicals are still applied to extinguish flames [10]–[12]. Therefore, researchers have been working on the comparative evaluation of the firefighting properties of fire protection agents and their composition [13]–[16], biodegradation of petroleum hydrocarbons or technological risk [17], [18].

A novel acoustic technology is of great interest to people involved in fire protection. In this field, the works of researchers from Europe, Asia and America, but in this article, due to the limited volume, it is focused on the works of European researchers. Through the analysis of the literature review, it becomes possible to review the knowledge in this field, including solutions for extinguishing flames with the usage of acoustic waves, which appeared in scientific works. They can constitute the state of the current knowledge of the analysed subject. In addition, the literature review method allows one to show the trends and prospects for the potential application of acoustic technology in the future for extinguishing flames in open and closed spaces (e.g., preliminary research for extinguishing fires of oil and oil products), considering the limitations of this technology. The projected aim is primarily to extinguish flames in a closed space where the amount of oxygen is limited compared to an open space.

2. Methods and Methodology

Due to the review nature of the paper, several research methods were used in this paper. The application of each of them was analysed by evaluating its usefulness in achieving specific research objectives. Elements of system analysis were used to develop a conceptual approach (including determining the structure of the issue under study). To present the possibility of using acoustic effects for the prevention and elimination of fires as an element of modern environmental technologies, in addition to the literature review method, the method of individual cases and the comparative method were used, which proved to be useful in the analysis of innovative solutions.

3. Results

3.1. Research on the Use of Acoustic Waves to Extinguish Flames

Since many academic and research institutions around the world are conducting research into the use of acoustic waves for flame suppression, this indicates the hopes placed in this technology. The results of the conducted research are included in some articles and patent applications on the possibility of using acoustic waves for flame extinguishing. In 2020, multiple media took interest in this topic [19]–[24]. This method appears to be safer (due to its non-invasive nature) and less expensive than currently known flame suppression techniques. One prototype of the acoustic extinguisher is shown in Fig. 1. Its technical properties are described in [25].

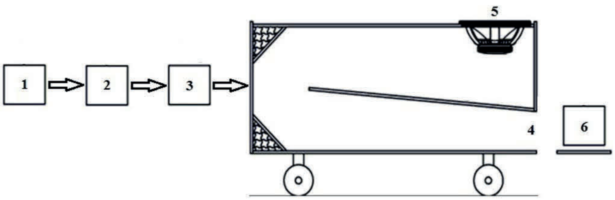

Fig. 1. Elements of the high-power acoustic extinguisher: 1 – generator; 2 – modulator; 3 – power amplifier; 4 – output; 5 – sound source; 6 – flame source.

Information on the identification of a technogenic emergency in the acoustic radiation of a hazard zone [26] and the development of a model of the burning substance in the burning seat [27], as well as acoustic methods was presented in the works of Ukrainian scientists [28]–[30]. The effectiveness of acoustic waves depends on the level of pressure turbulence to disrupt the flame front, extend it, and extinguish it [25], [31]–[33]. This is the result of the cumulative acoustic effect of mean flow and oscillatory perturbations [32]. In practice, flame extension affects its aerodynamic distortion [34]. The deviation of one of the ambient parameters acts to change the direction of propagation of the flame front. Consequently, this affects the increase of heat emission up to the flammability limit [31], [35]–[37]. The sound pressure, depending on the power delivered to the sound source, increases linearly up to a certain point, which allows the regression function model to be used within a certain range, as shown, inter alia, in [38]–[40]. In fact, the lower the frequency, the easier it is to extinguish flames [32]. As the frequency decreases, a decrease in the power that must be delivered to the sound source to extinguish the flames is observed. Similarly, decreasing the distance between the device output and the flame source results in a decrease in the power that must be delivered to the speaker to extinguish the flames [37], [41]. The value of the average flow effect varies with the level of sound pressure (it does not depend on the excitation frequency) [42]. The flame breaks into pieces when the level of the critical sound pressure value is exceeded. When using a screen, for short distances between the screen and the probe, a pressure increase can be observed throughout the entire measurement range [43].

Since 2008, the acoustic flame extinguishing technique has been of interest to the DARPA Agency (Defense Advanced Research Projects Agency) [44]. This research used liquid fuel and loudspeakers located on both sides of the tank. The generation of acoustic waves allowed the flames to be suppressed and completely extinguished.

Information on extinguishing the combustion process using acoustic waves is given in [6]. Radomiak *et al.* determined the limiting value of the acoustic pressure, below which no flame extinction was observed [35]. In practice, when using low-power waves (20–30 W), the operating range of this technology is very limited – a few cm [35]. Only the use of acoustic waves with high and very high acoustic power allows significantly increase the operating range of the technology [45]. The paper [45] describes an acoustic extinguisher that is capable of extinguishing flames at a distance of less than 2 meters from the sound wave output. The authors analyzed the effects of acoustic wave parameters, distance from device output, and frequency on flame extinguishment.

Moreover, experimental results on the possibility of extinguishing flames using low-frequency sinusoidal acoustic waves (below 21 Hz) are given in the paper [9]. In this paper, in addition to the characteristics of sound pressure as a function of the power delivered to the extinguisher, the characteristics of sound pressure as a function of distance from the extinguisher output and the characteristics of sound pressure and electrical power delivered to the extinguisher as a function of frequency were included. This article also contains results showing the possibilities of extinguishing flames with the use of the frequency sweep technique. The novelty is the extinguishing tests using the frequency sweep technique – analysis of selected cases (the frequency was changed in a certain time interval from a fixed initial value to the final one). These experiments determined, among other things, the power required to be delivered to the loudspeaker to extinguish the flames, depending on the parameters set (frequency range and tuning time). Wilk-Jakubowski showed that flames can be extinguished using variable frequency acoustic waves, which may have practical applications in extinguishing flames originating from different materials [9].

It should be noted that acoustic fire extinguishers were also the subject of some inventions, several of which appeared after 2010. Their advantage is that they extinguish flames in both closed and open spaces. Some of them allow for improved flame extinguishing performance when the phases of the acoustic waves emitted at the output by the front and back surfaces of the sound source membrane are different [46]. The solution [47] uses flame extinguishing in addition to the acoustic power of the waves emitted by the surfaces of the sound source membranes for extinguishing. In turn, a chamber in the form of a tube is attached to the device housing [48], which serves as a waveguide and collimator of acoustic waves. In practice, low-frequency, modulated and focused acoustic waves with high acoustic power can be successfully used to extinguish small fires [9].

As indicated in [49], the inconvenience of currently known solutions is the need to use acoustic panels connected together with an acoustic baffle attached to them. In turn, the use of materials that strongly absorb acoustic waves allows us to eliminate the negative impact of destructive interference on the fire extinguishing process and has a positive effect on the operation of the device by reducing unwanted vibrations. The proposed solution, through the proper placement of acoustic wave-absorbing materials, makes it possible to suppress only the unfavorable part of the energy emitted by the back surface of the loudspeaker diaphragm, which was not used to extinguish the flames.

Alternatively, for the purpose of extinguishing the flame, the solutions described in [50]–[52] seem to be useful. The first invention relates to the generation of vortex rings, whose visualization is achieved by means of smoke, condensed steam, gases, macroscopic particles, and special light sources. The remotely ignited wick extinguisher described in [51] uses air movement to extinguish the flame of a lit wick. A receiver acts on the circuit. Due to the generation of a pulse of appropriate amplitude and duration, the transmitter diaphragm is displaced, so that a volume of air is displaced, which translates into extinguishing the flame of the lit wick. In this way, the user can extinguish the flame of a lit wick lamp at a distance.

As in the patent application for methods and systems to perturb phenomena with waves presented in [53], the solution [52] concerns the process of extinguishing, expanding, and controlling flames using an acoustic apparatus. The amplitude, frequency, and standing wave mode are indicated as factors that determine the intensity of the flames. The creation of an acoustic current is the result of the application of an appropriately selected amplitude and frequency. This current contributes to the intensity of the flame through turbulent combustion. The interference phenomenon is the result of the association of sources, which, along with the acoustic current, increases the efficiency of reagent mixing, resulting in an acoustic barrier against the flame.

Moreover, the results presented in several publications show that modulated waveforms can be used to extinguish flames. In the paper [54], Wilk-Jakubowski *et al.* reported the necessary power delivered to the sound source and the influence of sound pressure on the extinguishing flames, depending on the distance from the extinguisher output, in the range of 50 cm to 130 cm (the step was equal to 10 cm). Sinusoidal waves modulated by a triangular waveform and triangular waves were used for this purpose [54]. In turn, in the paper [55] they present results on flame extinguishing capabilities using sinusoidal waves and *AM*-modulated waves (sinusoidal waves modulated by a rectangular waveform) for several selected frequencies. An inversely proportional relationship has been experimentally shown between the decrease in sound pressure with increasing distance from the device output. These articles emphasize that it is possible to build a system consisting of multiple acoustic extinguishers and to use mechanisms that are indispensable for the propagation of acoustic waves. The solutions used may include properly placed interference screens, baffles, and acoustic panels that can improve the performance of the acoustic extinguisher due to constructive interference [54]. It is crucial that the sound waves are directed toward the flame source.

Numerous articles can be found in the literature on the response of a mixed laminar flame to low-amplitude acoustic forcing [56], harmonic disturbances in laminar immiscible flames [57], thermoacoustic oscillations in a ducted flame [58], hydrogen combustion in a transverse acoustic field [59], application of acoustic waves to combustion inhibition and turbulent combustion analysis [60], [61], effect of curvature on diffusion flame extinction [62] and acoustic wave interaction with flames considering physical properties [63], [64]. Based on the research on combustion presented above, it is possible to conclude that acoustic waves can be used to extinguish flames, while combustion can occur in a discontinuous way [34], [45], [62]–[65].

The combustion rate depends on the frequency of the acoustic waves [66]. Furthermore, using an intelligent module, the fire extinguisher may be automatically activated when flames are detected [25], [55]. Information on this topic will be presented in the next section of this paper.

3.2. The Use of a Deep Neural Network for Flame Detection

An innovative approach to extinguishing flames is, in addition to the use of acoustic waves, to apply a deep neural network to determine if a fire has occurred. Such an intelligent module can be part of the acoustic extinguisher equipment. If flames are detected, the extinguisher may automatically be activated to extinguish them (at the current stage of acoustic technology development, research in this field is ongoing). Wireless links can be applied for communication [67], [68], including, e.g., inexpensive VSATs that provide communication from remote and hard-to-reach locations. This is important because increased emergency management expenditures are recorded year after year [69]. Robots find applications in crisis management [70], [71]. Such terminals have proven their worth during natural disasters, as exemplified by the case of Japan [72], [73]. When other systems fail and ground infrastructure is destroyed, satellite systems can be applied to communicate with evacuees, as well as to recover communications, and is then often the only way to provide communications, as evidenced in Japan [74]–[76]. When using satellite links, it is crucial to take into account the natural factors affecting the propagation of the radio signal [77]–[80].

It should be noted that the advantage of using artificial intelligence is the possibility of activating the system without human involvement, which is particularly important for the protection of human life and health. The benefits of applying neural networks include the relatively low cost of purchasing components and the high efficiency of flame detection [25]. In practice, several different properties are taken for flame detection. They are listed in Table 1.

TABLE 1. PROPERTIES FOR FIRE DETECTION TECHNIQUES

Properties
colour
dynamics
flickering properties
shape
texture
combined features, processing techniques

Artificial intelligence can be particularly helpful for flame detection wherever environmental factors, such as temperature or dust presence, would prevent the use of commonly known sensors [54], [55]. The deep neural networks section of the paper [55] describes a system that may operate as a standalone platform as well as interface with other modules (e.g., Arduino). It is equipped with a 16-bit processor and two 64-bit RISC-V processors. The fire extinguisher may be controlled discretely. The advantage is the speed of operation (the computation time is about 10 ms). The algorithm consists of the following several steps [55]: (1) System initialization and preparation of the peripherals of the AI HAT (Artificial Intelligence HAT) module for data exchange; (2) Reading images from cameras and feeding them to the inputs of the deep neural network; (3) Processing and classification of data for flame detection by the deep neural network; and (4) Signalling flame detection (if applicable), notifying relevant services of the location of the fire (including sending an image), and activating the acoustic system to extinguish the flames. In practice, when the deep neural network detects flames, the pixel coordinates will be returned. The program contours a rectangular frame around the flames, mapping the pixels on which the flames are detected.

In the paper [25], Wilk-Jakubowski *et al.* presented an example of a kit consisting of the SoM and a reference backplane, in which the experimental results of flame extinguishing using sinusoidal waves modulated by rectangular waveforms (AM modulation) are provided in the first part. In practice, a deep neural network can be integrated into a fire suppression system without the use of temperature and smoke sensors, although these sensors can also be connected to the system [25].

Similarly, Ivanov *et al.* provided an example of the use of deep neural networks for flame detection [81]. The *MobileNet* architecture was used for this purpose. Such networks can be learned from both static images and video streams [82]–[85]. Static images may be applied to learn neural networks, and then the networks can be tested based on the video stream captured from the cameras, which is particularly applicable when real fires occur [82], [85]. One can use, among other things, the Mask R-CNN [86]. The system consists of multiple components (including a computer module, a USB camera, and an image processing unit). Since the hardware is based on a Raspberry Pi board to which the camera is connected, there is support for multiple operating systems. Two relay modules (24 V control signals) may be used to control the fire extinguisher.

Examples of solutions are also given, among others, in [87], [88]. The flame detection robot is presented in Fig. 2. This picture shows, inter alia, the result of detection in an image with good contrast between the fire and the surrounding background. In practice, the detection accuracy is very good (exceeds 96 % when using the Mask R-CNN).

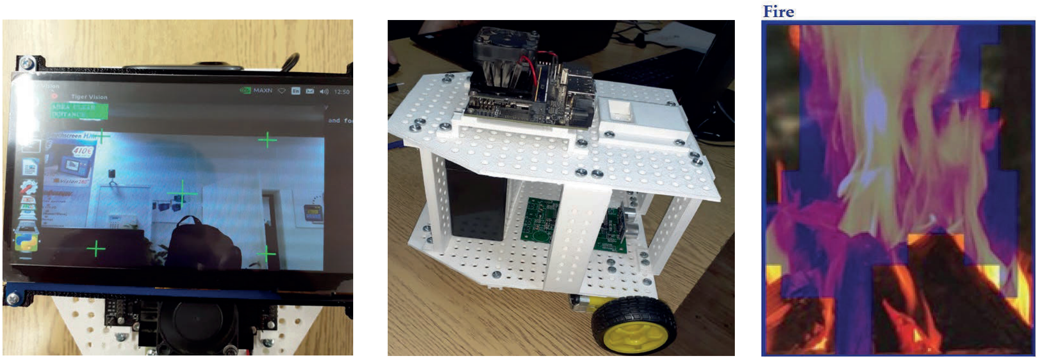

Fig. 2. A robot that detects flames using deep neural networks and an example of detection with good fire contrast to the surrounding background.

We can apply many libraries in the software. Exemplification may be as follows: OpenCV (for computer vision and machine learning), Matplotlib (separation library), TensorFlow (for machine learning), and NumPy (to provide support for multidimensional arrays). One example of the technology described here is also presented in the papers [54], [55].

4. Discussion on Advantages and Limitations of Using Acoustic Technology

Currently, acoustic technology is in the testing and development phase. Ultimately, it may become a permanent part of equipment, industrial halls and facilities, tanks for flammable liquids and burning gases, as well as equipment exposed to flames. In practice, acoustic waves pass through solids, liquids, and gases. The advantage of using acoustic waves is their non-invasive nature. The application of such systems allows one to partially replace the currently used means of fire protection. Additionally, acoustic extinguishers can be a complementary means of fire protection, for example, by permanently installing the system in places exposed to the outbreak of flames. Acoustic waves, unlike typical means of fire protection, do not remain dirt and do not emit gases harmful to human health. It is possible to use acoustic technology together with a low-cost intelligent sensor, so that the acoustic system can automatically activate when flames are detected. The disadvantage is that the size of the acoustic system capable of operating at low frequencies can be eliminated by building a stationary system (permanently placed in the industrial hall, building foundations, or structure of the facility). The use of acoustic screens and panels increases the possibilities of the technology. At this time, this technique could be a potential alternative to B- and C-class fire extinguishers (for extinguishing liquid and gas flames). In the case of solids, the use of this technology is limited by the fact that heat cannot be removed from inside the material, resulting in the reignition of the material.

It is worth mentioning that acoustic fire extinguishers are not subject to periodic tank testing, as is the case with classical fire extinguishers. Compared to traditional means of fire protection, this technology is characterized by an unlimited operating time (the extinguisher only needs to be powered by the mains or the battery). Ultimately, acoustic systems, although they cannot always be used, are therefore characterized by lower flame extinguishing and operating costs than in the case of typical fire protection means [9], [25], [45], [54], [55], [81], [89], [90]. In the case of using the technology, it is crucial to determine the limits of its range of action, the possible impact on human health (assuming the presence of people during the firefighting action), and the influence of very low-frequency acoustic waves on building structures [54], [55], [68]. The impact of acoustic waves on human health is undesirable, especially in the situation where one is in the acoustic beam (especially long-term exposure). Low-frequency acoustic waves adversely affect the human body, with their impact depending on the sound intensity level and frequency (symptoms include headaches, fatigue, indigestion, decreased concentration, mood swings, drowsiness, and even vibration of internal organs) [91]. In practice, low-frequency sound waves can cause vibroacoustic disease (VD) if the sound pressure level is greater than 110 dB [92]. Prolonged exposure to a sound field may lead to neurological and even psychiatric disorders.

5. CONCLUSION

Scientists from European countries present many research works that confirm the effectiveness of using acoustic waves to extinguish flames. In order for this technology to be effective, the acoustic beam should be focused in the smallest possible area, as well as the operating frequency of the acoustic wave should be well adapted to the specific application. The geometry of the beam ought to be directed and modelled in such a way as to hit a flame source as accurately as possible. Wireless technologies may be applied for data transmission. Fire detection information could be sent from remote areas that are inaccessible using, among others, satellite networks. This is important in the case of installing a fire extinguishing system and sensors in difficult-to-reach locations, without adequate technical infrastructure, or in areas where cable investment would be economically unjustified.

Since flames are difficult to extinguish using low-power sound sources, by using high and very high acoustic power delivered to the sound source, it becomes possible to increase the distance between the output of the flame source and the extinguisher [9], [25], [35], [45], [54], [55], [81]. Due to the use of low-frequency acoustic waves, a high-power fire extinguisher has a sizable size. Therefore, to realize the potential of this technology, it is ultimately necessary to miniaturize the system components and use high-power sound sources while maintaining health-safe sound pressure levels. In addition, the use of low-frequency acoustic waves requires prior testing for material strength and the impact of acoustic waves on people's health in the facility.

It is expected that in the future the flame extinguishing acoustic technology can be applicable wherever the access to classical (chemical) means of fire protection is limited or the flames are difficult to extinguish with the use of currently known methods.

ACKNOWLEDGEMENT

Authors would like to thank the company ‘Ekohigiena Aparatura Ryszard Putyra Sp.J.’, 19 Strzelecka St., 55-300 Środa Śląska, Poland and ‘Przedsiębiorstwo Handlowo-Techniczne SUPON Sp. z o.o.’, 105 Sandomierska St., 25-324 Kielce, Poland for their support in the realization of the research.

It is the intention of authors to include this work in the support provided by National Science Center (Narodowe Centrum Nauki), under the Miniatura grant entitled “Environmentally friendly methods for extinguishing flames on the basis of the acoustic method” (“Przyjazne dla środowiska metody gaszenia płomieni na przykładzie metody akustycznej”), in the framework of the conducted research.

References

[1] Fagioli F. F., Paolotti L., Boggia A. Trends in Environmental Management Systems Research. A Content Analysis. *Environmental and Climate Technologies* 2022:26(1):46–63. https://doi.org/10.2478/rtuect-2022-0005
[2] Pięta P., *et al.* Multi-domain model for simulating smart IoT-based theme parks. *Proc. SPIE (Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments)* 2018:10808. https://doi.org/10.1117/12.2501659
[3] Chomać-Pierzecka E., *et al.* Analysis and Evaluation of the Photovoltaic Market in Poland and the Baltic States. *Energies* 2022:15(2):669. https://doi.org/10.3390/en15020669
[4] Wilk-Jakubowski G. Wpływ technologii informatyczno-komunikacyjnych na funkcjonowanie współczesnych społeczeństw. Rola informatyki w naukach ekonomicznych i społecznych. Innowacje i implikacje interdyscyplinarne (The influence of information and communication technologies on the functioning of modern societies. The role of computer science in economic and social sciences. Innovations and interdisciplinary implications.). Kielce: Publishing House of the University of Economics Bolesław Markowski in Kielce, 2011. (in Polish)
[5] Felis J., Kasprzyk S. Akustyczna metoda usuwania osadów pyłowych w kotłach energetycznych (Acoustic method of removing dust deposits in power boilers). Presented at XV National Scientific-Didactic Conference of Theory of Machines and Mechanisms, Białystok-Białowieża, Poland, 1996. (in Polish)
[6] Węsierski T., Wilczkowski S., Radomiak H. Wygaszanie procesu spalania przy pomocy fal akustycznych (Extinguishing the combustion process with acoustic waves.). *Bezpieczeństwo i Technika Pożarnicza* 2013:30(2):59–64. (in Polish)
[7] Wilczkowski S. Poszukiwanie nowych sposobów gaszenia pożarów (Searching for new ways to extinguish fires.). BiT Nauka i Technika Pożarnicza. Józefów: Wydawnictwo CNBOP-PIB, 1988. (in Polish)
[8] Shevchenko R. I., *et al.* Review of up-to-date approaches for extinguishing oil and petroleum products. *SOCAR Proceedings* 2021:SI1:169–174. https://doi.org/10.5510/OGP2021SI100519
[9] Wilk-Jakubowski J. Analysis of Flame Suppression Capabilities Using Low-Frequency Acoustic Waves and Frequency Sweeping Techniques. *Symmetry* 2021:13(7):1299. https://doi.org/10.3390/sym13071299
[10] Wilczkowski S. Środki gaśnicze (Extinguishing media.). Kraków: Szkoła Aspirantów Państwowej Straży Pożarnej, 1995. (in Polish)
[11] Loboichenko V., *et al.* Comparative Analysis of the Influence of Various Dry Powder Fire Extinguishing Compositions on the Aquatic Environment. *Water and Energy International* 2019:62(7):63–68.
[12] Gurbanova M., *et al.* Effect of inorganic components of fire foaming agents on the aquatic environment. *Journal of the Turkish Chemical Society, Section A: Chemistry* 2020:7(3):833–844. https://doi.org/10.18596/jotcsa.785723
[13] Dadashov I., Loboichenko V., Kireev A. Analysis of the ecological characteristics of environment friendly fire fighting chemicals used in extinguishing oil products. *Pollution Research* 2018:37(1):63–77.
[14] Loboichenko V., *et al.* Review of the Environmental Characteristics of Fire Extinguishing Substances of Different Composition used for Fires Extinguishing of Various Classes. *Journal of Engineering and Applied Sciences* 2019:14(16):5925–5941. https://doi.org/10.36478/jeasci.2019.5925.5941
[15] Gurbanova M., *et al.* Comparative assessment of the ecological characteristics of auxiliary organic compounds in the composition of foaming agents used for firefighting. *Bulletin of the Georgian National Academy of Sciences* 2020:14(4):58–66.
[16] Dadashov I. F., *et al.* About the environmental characteristics of fire extinguishing substances used in extinguishing oil and petroleum products. *SOCAR Proceedings* 2020:1:79–84. https://doi.org/10.5510/OGP20200100426
[17] Lazaruk Y., Karabyn V. Shale gas in Western Ukraine: Perspectives, resources, environmental and technogenic risk of production. *Pet Coal* 2020:62(3):836–844.
[18] Rusyn I. B., *et al.* Biodegradation of oil hydrocarbons by Candida yeast. *Mikrobiolohichnyi Zhurnal* 2003:65(6):36–42.
[19] Siwik K. Dźwiękiem gaszą ogień. Niezwykły wynalazek Polaków (They put out the fire with a sound. An unusual invention of Poles) [Online]. [Accessed 02.06.2020]. Available: https://www.ckm.pl/m/lifestyle/dzwiekiem-gasza-ogien-niezwykly-wynalazek-polakow,23571,a.html (in Polish)
[20] Orkisz-Gola J. To może być przełom w pożarnictwie. Kielecki naukowiec zastąpił gaśnice... głośnikiem (This could be a breakthrough in firefighting. A scientist from Kielce replaced the fire extinguishers with ... a loudspeaker) [Online]. [Accessed 03.06.2020]. Available: https://kielce.tvp.pl/48364339/to-moze-byc-przelom-w-pozarnictwie-kielecki-naukowiec-zastapil-gasnice-glosnikiem (in Polish)
[21] Angora. Dźwiękowa gaśnica (Sound extinguisher) [Online]. [Accessed 21.06.2020]. Available: https://www.pressreader.com/poland/angora/20200621/ 282230897934076 (in Polish)
[22] Eska Rock. Polacy zgasili ogień dźwiękiem! Oto nowy wynalazek z Politechniki Świętokrzyskiej (Poles put out the fire with a sound! Here is a new invention from the Kielce University of Technology) [Online]. [Accessed 04.06.2020]. Available: https://www.eskarock.pl/rozrywka/polacy-zgasili-ogien-dzwiekiem-oto-nowy-wynalazek-z-politechniki-swietokrzyskiej-aa-gTin-qmqs-w2KD.html (in Polish)

[23] Poljskaja Nauka. Uchenij Keltskogo tehnologicheskogo universiteta razrabotal innovacionnij akusticheskih ognetushitelj (A scientist from the Kielce University of Technology has developed an innovative acoustic fire extinguisher) [Online]. [Accessed 08.06.2020]. Available: http://polishscience.pl/ru/ученый-кельцкого-технологического-у (in Russian)

[24] Krumov K. Ucheni ot Blgarija I Polsha sjzdadoha umen pozharogasitelj (Scientists from Bulgaria and Poland have created a smart fire extinguisher) [Online]. [Accessed 05.06.2020]. https://www.monitor.bg/bg/a/view/ucheni-ot-bylgarija-i-polsha-syzdadoha-umen-pojarogasitel-206283 (in Bulgarian)

[25] Wilk-Jakubowski J., Stawczyk P., Ivanov S., Stankov S. Control of acoustic extinguisher with Deep Neural Networks for fire detection. *Elektronika ir Elektrotechnika* 2022:28(1):52–59. https://doi.org/10.5755/j02.eie.24744

[26] Levterov A. Identification of a technogenic emergency on the acoustic radiation of a hazard zone. *Municipal economy of cities* 2019:5(151):100–106.

[27] Levterov A. Identification model development of the burning substance in the zone of the burning seat. *Problems of Fire Safety* 2019:45:92–97.

[28] Levterov A. A. Acoustic Research Method for Burning Flammable Substances. *Acoustical Physics* 2019:65(4):444–449. https://doi.org/10.1134/S1063771019040109

[29] Kalugin V. D., Levterov O. A., Tutiunik V. V. The method of early detection of the source of ignition. UA Patent 127254, 2018.

[30] Kalugin V. D., Levterov O. A., Tutiunik V. V. Method of extinguishing a fire. UA Patent 137790, 2019.

[31] Kordylewski W. Spalanie i paliwa (Burning and fuel). Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej, 2008. (in Polish)

[32] Niegodajew P., *et al.* Application of acoustic oscillations in quenching of gas burner flame. *Combustion and Flame* 2018:194:245–249. https://doi.org/10.1016/j.combustflame.2018.05.007

[33] Kowalewicz A. Podstawy procesów spalania (Basics of combustion processes.). Warsaw: Wydawnictwo Naukowo-Techniczne, 2000. (in Polish)

[34] Im H. G., Law C. K., Axelbaum R. L. Opening of the Burke-Schumann Flame Tip and the Effects of Curvature on Diffusion Flame Extinction. *Proceedings of the Combustion Institute* 1990:23(1):551–558. https://doi.org/10.1016/S0082-0784(06)80302-4

[35] Radomiak H., *et al.* Gaszenie płomienia dyfuzyjnego przy pomocy fal akustycznych (Diffusion flame extinguishing with acoustic waves.). *Bezpieczeństwo i Technika Pożarnicza* 2015:40(4):29–38. (in Polish) https://doi.org/10.12845/bitp.40.4.2015.2

[36] Roczniak M. Fizyka hałasu. Część I. Podstawy akustyki ośrodków gazowych (Noise physics. Part I. Fundamentals of acoustics of gas centers.). Gliwice: Wydawnictwo Politechniki Śląskiej, 1996. (in Polish)

[37] Vovchuk T. S., *et al.* Investigation of the use of the acoustic effect in extinguishing fires of oil and petroleum products. *SOCAR Proceedings* 2021:2:24–31. https://doi.org/10.5510/OGP2021SI200602

[38] Marek M. Wykorzystanie ekonometrycznego modelu klasycznej funkcji regresji liniowej do przeprowadzenia analiz ilościowych w naukach ekonomicznych. Rola informatyki w naukach ekonomicznych i społecznych. Innowacje i implikacje interdyscyplinarne (The use of an econometric model of the classical linear regression function to carry out quantitative analyzes in economic sciences. The role of computer science in economic and social sciences. Innovations and interdisciplinary implications.). Kielce: Wydawnictwo Wyższej Szkoły Handlowej im. Bolesława Markowskiego w Kielcach, 2013. (in Polish)

[39] Marek M. Aspects of Road Safety: A Case of Education by Research –Analysis of Parameters Affecting Accident. Presented at The Education and Research in the Information Society Conference (ERIS), CEUR Workshop Proceedings 2021:3061:64–75. [Online]. [Accessed 12.02.2022] http://ceur-ws.org/Vol-3061/ERIS_2021-art07(reg).pdf

[40] Marek M. Bayesian regression model estimation: a road safety. Presented at The Sixth Smart City Applications International Conference (SCA 2021). *Lecture Notes in Networks and Systems* 2021:393. https://doi.org/10.1007/978-3-030-94191-8_13

[41] Yılmaz-Atay H., Wilk-Jakubowski J. A Review of Novel Approach for the Fire Resistance of Chemical Materials: from Basic Science to Innovations. *Polymers* 2022:14(6):1224. https://doi.org/10.3390/polym14061224

[42] Chen L. W., Zhang Y. Experimental observation of the nonlinear coupling of flame flow and acoustic wave. *Flow Measurement and Instrumentation* 2015:46:12–17. https://doi.org/10.1016/j.flowmeasinst.2015.09.001

[43] Niegodajew P., *et al.* Application of acoustic oscillations in flame extinction in a presence of obstacle. Presented at XXIII Fluid Mechanics Conference (KKMP 2018). *IOP Conf. Series Journal of Physics (Conf. Series 1101)*, 2018. https://doi.org/10.1088/1742-6596/1101/1/012023

[44] Defense Advanced Research Projects Agency. DARPA sound based fire extinguisher [Online]. [Accessed 16.07.2012]. Available: https://www.extremetech.com/extreme/132859-darpa-creates-sound-based-fire-extinguisher

[45] Stawczyk P., Wilk-Jakubowski J. Non-invasive attempts to extinguish flames with the use of high-power acoustic extinguisher. *Open Engineering* 2021:11(1):349–355. https://doi.org/10.1515/eng-2021-0037

[46] Wilk-Jakubowski J. Urządzenie do gaszenia płomieni falami akustycznymi (Device for flames suppression with acoustic waves). PL Patent 427999, 2019. (in Polish)

[47] Wilk-Jakubowski J. Urządzenie do gaszenia płomieni falami akustycznymi (Device for flames suppression with acoustic waves). PL Patent 428002, 2019. (in Polish)
[48] Wilk-Jakubowski J. Urządzenie do gaszenia płomieni falami akustycznymi (System for suppressing flames by acoustic waves). PL Small Patent (utility model) 70441, 2018. (in Polish)
[49] Wilk-Jakubowski J. Urządzenie do gaszenia płomieni falami akustycznymi (Device for flames suppression with acoustic waves). PL Patent 234266, 2019. (in Polish)
[50] Lippold A. Device and circuit for the generation of vortex rings. U. S. Patent 4735282, 1988.
[51] Thigpen H. D. Remote lighted wick extinguisher. U. S. Patent 5899685, 1999.
[52] Formigoni P. O. Process of extinction, expansion and controlling of fire flames thru acoustic. U. S. Patent 20100203460, 2010.
[53] Tran V., Robertson S. Methods and systems for disrupting phenomena with waves. U. S. Patent 10569115, 2020.
[54] Wilk-Jakubowski J., *et al.* The using of Deep Neural Networks and natural mechanisms of acoustic waves propagation for extinguishing flames. *International Journal of Computational Vision and Robotics* 2022:12(2):101–119. https://doi.org/10.1504/IJCVR.2021.10037050
[55] Wilk-Jakubowski J., Stawczyk P., Ivanov S., Stankov S. High-power acoustic fire extinguisher with artificial intelligence platform. *International Journal of Computational Vision and Robotics* 2022:12(3):236–249. https://doi.org/10.1504/IJCVR.2022.122580
[56] Karimi N. Response of a conical, laminar premixed flame to low amplitude acoustic forcing – a comparison between experiment and kinematic theories. *Energy* 2014:78:490–500. https://doi.org/10.1016/j.energy.2014.10.036
[57] Magina N., *et al.* Spatio-temporal evolution of harmonic disturbances on laminar, non-premixed flames: Measurements and analysis. *Combustion and Flame* 2017:180:262–275. https://doi.org/10.1016/j.combustflame.2016.09.001
[58] Kashinath K., Waugh I. C., Juniper M. P. Nonlinear self-excited thermoacoustic oscillations of a ducted premixed flame: bifurcations and routes to chaos. *Journal of Fluid Mechanics* 2014:761:399–430. https://doi.org/10.1017/jfm.2014.601
[59] Kozlov V. V., *et al.* Combustion of hydrogen in round and plane microjets in transverse acoustic field at small Reynolds numbers as compared to propane combustion in the same conditions. *International Journal of Hydrogen Energy* 2016:41(44):20231–20239. https://doi.org/10.1016/j.ijhydene.2016.07.276
[60] Leśniak B., Wilczkowski S. Próby zastosowania fal akustycznych do hamowania procesów spalania (Attempts to use acoustic waves to inhibit combustion processes.). Józefów: Wydawnictwo CNBOP-PIB, 1988. (in Polish)
[61] Simon D. M., Wagner P. Characteristics of turbulent combustion by flame space and space heating. *Journal of Industrial and Engineering Chemistry* 1956:48(1):129–133. https://doi.org/10.1021/ie50553a038
[62] Im H. G., Law C. K., Axelbaum R. L. Opening of the burke-schumann flame tip and the effects of curvature on diffusion flame extinction. *Symposium on Combustion* 1991:23(1):551–558. https://doi.org/10.1016/S0082-0784(06)80302-4
[63] Kornilov V. N., Schreel K., De Goey L. P. H. Experimental assessment of the acoustic response of laminar premixed Bunsen flames. *Proceedings of the Combustion Institute* 2007:31(1):1239–1246. https://doi.org/10.1016/j.proci.2006.07.079
[64] Zambon A. C., Chelliah H. K. Acoustic-wave interactions with counterflow single- and twin-premixed flames: finite-rate kinetics, heat release and phase effects. *Proceedings of the Combustion Institute* 2007:31(1):1247–1255. https://doi.org/10.1016/j.proci.2006.07.156
[65] Lentati A. M., Chelliah H. K. Physical, thermal and chemical effects of fine-water droplets in extinguishing counterflow diffusion flames. *Symposium on Combustion* 1998:27(2):2839–2846. https://doi.org/10.1016/S0082-0784(98)80142-2
[66] Blaszczyk J. Acoustically disturbed fuel droplet combustion. *Fuel* 1991:70(9):1023–1025. https://doi.org/10.1016/0016-2361(91)90254-8
[67] Šerić L., Stipanicev D., Krstinić D. ML/AI in Intelligent Forest Fire Observer Network. Presented at International Conference on Management of Manufacturing Systems (Conference 3rd EAI 2018), Dubrovnik, Croatia, 2018. https://doi.org/10.4108/eai.6-11-2018.2279681
[68] Šerić L., Stipaničev D., Štula M. Observer network and forest fire detection. *Information Fusion* 2011:12(3):160–175. https://doi.org/10.1016/j.inffus.2009.12.003
[69] Wilk-Jakubowski G. Normative Dimension of Crisis Management System in the Third Republic of Poland in an International Context. Organizational and Economic Aspects. Łódź-Warszawa: Wydawnictwo Społecznej Akademii Nauk, 2019.
[70] Wilk-Jakubowski G., Harabin R., Ivanov S. Robotics in crisis management: a review. *Technology in Society* 2022:68:101935. https://doi.org/10.1016/j.techsoc.2022.101935
[71] Wilk-Jakubowski G., Harabin R., Wilk-Jakubowski J. Non-governmental organizations in crisis management: a review of the literature. Busko-Zdroj–Kielce, Poland, 2022 (unpublished).
[72] Eguchi S., *et al.* Multi-mode portable VSAT for disaster-resilient wireless networks. Presented at Asia Pacific Microwave Conference (APMC 2014), Sendai, Japan, 2014.
[73] Kameda S., *et al.* Development of satellite-terrestrial multi-mode VSAT using software defined radio technology. Presented at Asia Pacific Microwave Conference (APMC 2014), Sendai, Japan, 2014.

[74] Wilk-Jakubowski J. Information systems engineering using VSAT networks. *Yugoslav Journal of Operations Research* 2021:31(3):409–428. https://doi.org/10.2298/YJOR2002

[75] Wilk-Jakubowski J. Overview of broadband information systems architecture for crisis management. *Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska – IAPGOS (Informatics, Control, Measurement in Economy and Environmental Protection)* 2020:10(2):20–23. https://doi.org/10.35784/iapgos.1608

[76] Sasanuma M., *et al.* Research and development of very small aperture terminals (VSAT) that can be installed by easy operation during disasters – Issues and the solutions for implementing simple and easy installation of VSAT earth station. Japan: The Institute of Electronics, Information and Communication Engineers (IEICE), 2013.

[77] Wilk-Jakubowski J. Measuring Rain Rates Exceeding the Polish Average by 0.01%. *Pol. J. Environ. Stud.* 2018:27(1):383–390. https://doi.org/10.15244/pjoes/73907

[78] Wilk-Jakubowski J. Predicting Satellite System Signal Degradation due to Rain in the Frequency Range of 1 to 25 GHz. *Pol. J. Environ. Stud.* 2018:27(1):391–396. https://doi.org/10.15244/pjoes/73906

[79] Wilk-Jakubowski J. Total Signal Degradation of Polish 26-50 GHz Satellite Systems Due to Rain. *Pol. J. Environ. Stud.* 2018:27(1):397–402. https://doi.org/10.15244/pjoes/75179

[80] Loboichenko V., *et al.* Assessment of the Impact of Natural and Anthropogenic Factors on the State of Water Objects in Urbanized and Non-Urbanized Areas in Lozova District (Ukraine). *Ecological Engineering & Environmental Technology* 2021:22(2):59–66. https://doi.org/10.12912/27197050/133333

[81] Ivanov S., *et al.* The using of Deep Neural Networks and acoustic waves modulated by triangular waveform for extinguishing fires. Presented at International Workshop on New Approaches for Multidimensional Signal Processing (NAMSP 2020), Technical University of Sofia, Sofia, Bulgaria, 2020. *New Approaches for Multidimensional Signal Processing ('Smart Innovation, Systems and Technologies' series)* 2021:216:207–218. https://doi.org/10.1007/978-981-33-4676-5_16

[82] Janků P., Komínková–Oplatková Z., Dulík T. Fire detection in video stream by using simple artificial neural network. *Mendel* 2018:24(2):55–60. https://doi.org/10.13164/mendel.2018.2.055

[83] Szegedy Ch., Toshev A., Erhan D. Deep Neural Networks for Object Detection. *Proceedings of the 26th International Conference on Neural Information Processing Systems (NIPS'13)* [Online]. [Accessed 10.03.2022]. Available: https://papers.nips.cc/paper/2013/hash/ f7cade80b7cc92b991cf4d2806d6bd78-Abstract.html

[84] Foley D., O'Reilly R. An Evaluation of Convolutional Neural Network Models for Object Detection in Images on Low-End Devices. *Proceedings for the 26th AIAI Irish Conference on Artificial Intelligence and Cognitive Science* [Online]. [Accessed 10.03.2022]. Available: http://ceur-ws.org/Vol-2259/aics_32.pdf

[85] Kurup R. Vision Based Fire Flame Detection System Using Optical flow Features and Artificial Neural Network. *International Journal of Science and Research* 2014:3(10):2161–2168.

[86] Zhang, X. Simple understanding of Mask RCNN [Online]. [Accessed 22.04.2018]. Available: https://medium.com/@alittlepain833/simple-understanding-of-mask-rcnn-134b5b330e95

[87] Ivanov S., Stankov S. Acoustic Extinguishing of Flames Detected by Deep Neural Networks in Embedded Systems. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 2021:XLVI-4/W5-2021:307–312. https://doi.org/10.5194/isprs-archives-XLVI-4-W5-2021-307-2021

[88] Ivanov S., Stankov S. The Artificial Intelligence Platform with the Use of DNN to Detect Flames: A Case of Acoustic Extinguisher. *Lecture Notes in Networks and Systems* 2022:371:24–34. https://doi.org/10.1007/978-3-030-93247-3_3

[89] Wilk-Jakubowski J., *et al.* Analysis of Environmentally Friendly Acoustic Firefighting and Fire Detection Systems on the Basis of Central and Eastern Europe Research Considering COVID-19 Times. Kielce-Gabrovo-Busko-Zdroj, Poland-Bulgaria, 2022 (unpublished).

[90] Sai R. T., Sharma G. Sonic Fire Extinguisher. *Pramana Research Journal* 2017:8:337–346.

[91] Tempest W. Infrasound and Low Frequency Vibration. London: Academic Press Inc., 1976.

[92] Noga A. Przegląd obecnego stanu wiedzy z zakresu techniki infradźwiękowej i możliwości wykorzystania fal akustycznych do oczyszczania urządzeń energetycznych (Review of the current state of knowledge in the field of infrasound technology and the possibility of using acoustic waves for cleaning energy devices.). *Zeszyty Energetyczne* 2014:1:225–234. (in Polish)