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ANALYSIS OF MODERN METHODS FOR PREVENTING THE SPREAD AND EXTINGUISHING FIRES

Olena Matskiv

Lviv Polytechnic National University,
12, S. Bandery Str., Lviv, 79013, Ukraine
olena.o.matskiv@lpnu.ua

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Abstract. Based on the literature review, the paper considers modern systems for preventing the spread of fires and the latest methods of fire extinguishing. The influence of the design parameters of facade fire eaves at the boundaries of fire compartments on the prevention of fire spread in high-rise buildings is shown using FDS modelling. To solve the problem of supplying extinguishing agents over a long distance, the use of a muzzle fire extinguishing unit for supplying containers filled with extinguishing agent is considered, a special fire muzzle for deep extinguishing of peat fires is proposed, the technology of fire extinguishing by a high-voltage electric field is determined, the functional capabilities of automatic fire extinguishing systems through the use of thermal imaging devices, as well as the method of vacuum fire extinguishing and flame extinguishing by low sound frequencies are shown.

Keywords: fire, prevention, fire extinguishing, means, methods, authors.

1. Introduction

Preventive fire safety measures are among the priorities of the state programme in the field of civil protection. Fire protection systems around the world, and in Ukraine in particular, are strictly regulated. Improvement of the fire safety situation in Ukraine is possible through the implementation of European safety management standards, including state regulation, supervision and control, as well as improvement of measures and means to prevent the spread and extinguish fires. To this end, the state is actively developing and improving the legislative norms and requirements for real estate objects of various functionnal purposes. The State Emergency Service of Ukraine continuously monitors compliance with fire safety standards, which includes regular inspections of real estate, control, training of personnel in fire prevention and firefighting, development, implementtation and control of technical methods of ensuring safety (Fire safety prevention, 2024). The Institute of Public Administration and Research in Civil Protection constantly analyses information on fires received from the territorial bodies of the SES of Ukraine and shows that the fire hazard situation and its consequences, in the form of material losses and serious injuries and deaths, are quite unsatisfactory in our country. In addition, fires release a large number of toxic products into the environment, including carbon monoxide, hydrochloric and hydrocyanic acid, nitrogen oxides, and acrolein, the ground concentration of which exceeds the maximum one-time maximum permissible concentrations. Thus, the study of modern fire prevention systems to reduce the time of free development of fires and effective fire extinguishing methods was the purpose of this paper.

2. Theoretical part

Statistics on the occurrence of fires in recent years in Ukraine show that the share of fires in the total number of fires is quite high in residential and administrative buildings and the complexity of extinguishing them is particularly high in high-rise

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buildings and over long distances. According to the analysis, Ukraine is among the top ten countries in terms of the number of high-rise buildings and structures, as the need for rational use of land allocated for construction due to its high cost and high level of urbanization is particularly relevant (Odynets et al., 2020). In particular, Kyiv took the first place among European cities in the ranking of the largest number of skyscrapers. As of 2023, there are more than 30 skyscrapers in the capital of Ukraine, ranging in height from 100 to 168 m (residential complex in 7 Klovskyi Descent) and more than 1,200 buildings over 35 m high. The number of high-rise buildings is also growing in other Ukrainian cities such as Lviv, Odesa, Dnipro and Kharkiv. In the global ranking of cities, New York ranks the first place with 6097 skyscrapers, Toronto is the second place with 2393 buildings and Dubai is the third place with 1574 skyscrapers constructed (Ukrreporter, 2024).

According to the analysis of fires that occurred in high-rise buildings over the past ten years, only 51 cases (7.2 % of the number of fires) had fire protection systems (93 systems in total), of which 8 were automatic fire extinguishing systems; 46 were fire alarm systems; 20 were smoke protection systems; and 19 were centralised fire surveillance systems (Odynets et al., 2020). In addition, the analysis of fires and their consequences in Ukraine and abroad showed that most fires in high-rise buildings were accompanied by fire spread through the facades, which made it impossible to extinguish them quickly and significantly complicated the work of fire and rescue units, and also necessitated the use of special firefighting equipment. The spread of fire through the external vertical building structures of high-rise buildings also made it impossible to extinguish the fire at the initial stage of its occurrence, including with the use of fire protection systems equipped in high-rise buildings (Yakovchuk et al., 2021). The results of the research also showed that the vast majority of firefighting equipment currently used in the territorial units of the SES of Ukraine does not allow the delivery of extinguishing agents at a distance of more than 100 m.

3. Results and Discussion

The analysis of scientific and technical publiccations and the regulatory framework in the field of fire safety shows that fire protection of high-rise buildings is based on a whole range of measures of fire protection systems and is regulated by regulations in the field of construction (DBN B.1.1-7: 2016, DBN B.2.2-9: 2018, DBN B.2.2-15:2019, DBN B.2.2-41: 2019, DBN B.1.2-7: 2008, DBN B.2.5-56: 2014), national standards (DSTU EN 12101-6: 2016, DSTU EN 12845: 2016) and other industry documents (According to Resolution of the Cabinet of Ministers of Ukraine 2010, No. 1746), the main requirements for structures in terms of fire safety are:

– maintaining the load-bearing capacity of structures for a specified period of time;

– limiting the spread of fire and smoke in buildings, to neighbouring buildings and adjacent territories;

– ensuring the evacuation of people from the building or their rescue in other ways;

– ensuring the safety of rescue teams.

Analysing the most high-profile fires that have occurred in buildings over the past few years, both in Ukraine and abroad, and were accompanied by the burning of facade systems, we can state that there is a problem in ensuring fire safety of the structures of the external walls of buildings and structures with facade insulation both at the construction stage and during their operation. Such fires in buildings with facade insulation are caused not only by gross violations of fire safety rules, but also by the use of construction and finishing materials with increased fire hazard (Yakovchuk et al., 2021).

In particular, the authors of studies (Odynets et al., 2020; Ballo et al., 2021) investigated the influence of the design parameters of facade fire eaves on the boundaries of fire compartments in preventing the spread of fire in high-rise buildings by using FDS modelling (fire dynamics simulator (FDS) of a computational fluid dynamic (CFD) model of the flow of fluid caused by a flame). The results of these studies have shown that the presence of a fire eave that meets the requirements (DBN B.1.1-7: 2016, DBN B.2.2-41: 2019) reduces the actual temperature at the level of the upper floor under which the fire occurred by 45–47 %. At the same time, during the research, the authors found an increase in the area of temperature distribution of the heating of the facade surface structure by 30–35 %, which is undoubtedly a negative phenomenon and can be explained by direct contact of the fire flame with a non-streamlined obstacle.

In the study (Nilsson et al., 2018), the authors investigated the impact of passive measures to prevent external vertical fire spread using the Fire Dynamics Simulator (FDS) tool. The results of the study show that equipping facade structures with a 0.6 m wide horizontal fire eave provides better fire protection than a structure without an eave, and, therefore, the use of horizontal eaves with a width of at least 0.6 m leads to less damage to the facade during a fire. The modelling of horizontal eaves with a width of 0.2 m and 0.3 m did not give satisfactory results. Thus, the use of horizontal eaves with a width of 0.6, 0.8, and 1 m allows to reduce the temperature of the facade surface 1.2 m above the window opening by 15–50 %. Also, in the study (Rukavina et al., 2017) it is found that the length of the protective structure should not be less than 1.2 m.

As shown in works (Mc. Grattan et al., 2013; Mc. Grattan et al., 2015), it is also important to study not only the most effective value of the length and width of the eave, but also its shape as an integral part of the impact on preventing the spread of fire and reducing the temperature distribution of the heating of the facade surface structure. The modelling results revealed a pattern of increasing the heating area of the facade for straight eaves of a non-streamlined shape, while the presence of a fire eave on the facade of a straight-shaped building does not completely prevent the spread of thermal effects during a fire, both vertically and horizontally, but significantly reduces its maximum value and increases the duration of heating of the facade surface. Also, the authors confirmed the assumption that direct contact of the turbulent heat flow from a fire with a non-streamlined obstacle increases the area of critical heating of the building facade under and above the fire eave by 30–35 % under the given conditions of the building model. The results of this modelling show a significant impact of the shape of fire facade eaves on the effectiveness of preventing the spread of fire through vertical building structures, namely, the use of streamlined eaves is the most effective design measure. Thus, it has been established that the presence of a fireproof facade eave with a projection of 0.75 m and 1.5 m is an effective means that can limit the temperature impact of a fire at the level of the upper floor under which it occurred from 870 °C to 450 °C and 270 °C, respectively. It has also been established that under these modelling conditions, the temperature of the facade surface for the upper floor located above the floor where the fire occurred, in the presence of a streamlined fire eave, decreases from 270 °C (±30 °C) to 180 °C (±10 °C), which can significantly affect the conditions for limiting further fire spread (Resolution of the Cabinet of Ministers of Ukraine 2010, No. 1746).

The material of facade insulation is also important for ensuring fire safety of buildings and structures. In particular, the study of the European experience in regulating external facade insulation has shown that the European Union has somewhat different approaches to building facade insulation (Tsyhankov et al., 2021). In contrast to the national regulatory framework, it is significant that in most countries it is allowed to combine facade insulation with fire reaction class NC with C1, provided that fire belts of appropriate sizes are installed. The height at which a material of a particular fire reaction class is allowed to be installed is clearly defined. As facade thermal insulation, materials of a low combustibility group (C1 according to the national classification) are allowed to be used up to a conditional building height not exceeding 26.5 m, provided that fire belts of the established geometric dimensions are installed. The most stringent requirements among European countries are set in Germany, where, starting from a nominal height of 7 m, it is mandatory to use materials with fire reaction class A, and up to 7 m, it is allowed to use class B, provided that fire belts are installed. In Slovakia, the Czech Republic and Croatia, the conditional line for the division of a building is a conditional height of 22.5 m. As a rule, up to 22.5 m, it is allowed to use class B facade material as thermal insulation, and over 22.5 m – class A. Based on the analysis of the national regulatory framework, the authors (Kovalov et al., 2019) determined that for buildings of the first degree of fire resistance, it is allowed to perform the outer surface of the cladding of the outer walls of the building using materials of the NC group, regardless of their conditional height. It is allowed to use external thermal insulation of materials with the combustibility group of heat-insulating material C1 and C2 for buildings with a nominal height of up to 26.5 m, except for buildings of the first degree of fire resistance, provided that fire belts are installed every three floors. At the same time, the national regulatory framework does not provide for the possibility of combining the facade of a building with the simultaneous use of thermal insulation made of materials of combustibility groups C1, C2 and NC. This does not fully comply with modern European approaches to the external thermal insulation of buildings.

Based on the analysis of foreign experience in regulating the external thermal insulation of buildings, the authors of this paper have developed the following proposals that would be appropriate to take into account when amending the national regulatory framework in the field of construction. In particular, in buildings with a nominal height of up to 47 m, the use of materials of combustibility groups C1, C2 should be allowed if the system of external cladding of the building walls with such materials is installed up to the level of 26.5 m. In buildings with a nominal height of up to 47 m, the use of materials of combustibility groups C1, C2 up to the level of 26.5 m is allowed in the internal layers of the external cladding system of the building walls. The following conditions must be observed:

– every 3 floors, a fire belt made of non-combustible materials with a width of at least two thicknesses of the insulation used must be installed;

– a fire belt made of non-combustible materials with a width of at least two thicknesses of the insulation used shall be installed around the perimeter of all light openings;

– the outer walls of stairwells shall be lined with non-combustible materials only;

– fire belts shall be installed at the boundaries of parts of buildings of different functional purposes;

– if one part of the exterior wall of the building is adjacent to another at an angle of less than 120° inclusive, fire belts made of non-combustible materials shall be installed at a distance of at least 4 m horizontally from the top of the inner corner of the exterior wall to the doorway of the entrance to the passage open to the outside, as well as to the doorway of the exit from this passage;

– a fire belt made of non-combustible materials shall be installed on the part of the wall adjacent to the external staircase or fire escape, which shall extend beyond the dimensions of such staircase by a distance of 1.5 m on both sides;

– if the facade of the building is combined with equipment made of transparent elements, fire belts with a width of at least 2 m shall be installed around the perimeter of such equipment;

– the outer cladding of the perimeter arches of buildings, as well as their interior, should be covered with a fire belt at least 1.5 m wide (Tsyhankov et al., 2021).

In addition to such constructive and technological methods of preventing the spread of fire, experts point to other technical and organisational reasons for the complexity of firefighting, such as lack of equipment and water, deterioration of equipment, and poor-quality extinguishing agents. However, the main reasons are the imperfections of the existing fire extinguishing technologies, and today, the scientific and technical challenge is to create fundamentally new technical means of fire extinguishing. Among such means, the development of new methods for delivering extinguishing agents over long distances to extinguish complex fires is relevant. The firefighting equipment currently used by the territorial units of the State Emergency Service of Ukraine does not allow extinguishing agents to be delivered over a distance of more than 100 m. There is fire extinguishing equipment designed to supply water, water solutions and foam at a distance of up to 100 m, as well as powder mixtures at a distance of up to 70 m (Kovalov et al., 2019). Therefore, to solve the problem of supplying extinguishing agents over a long distance, the authors of this paper propose to use a pneumatic muzzle fire extinguishing unit (MFU) – a pneumatic gun that provides a high-precision supply of containers filled with extinguishing agent directly to the burning zone by throwing a ballistic trajectory. In particular, high explosives (ammonal, ammonite, hexogen, etc.) allow for maximum efficiency due to the release of extinguishing agent energy released by the detonation of explosives. Upon entering the combustion zone, under the influence of internal forces, the container ruptures, releasing inert detonation products and powder composition. The analysis of various extinguishing agents and mixtures for use in containers has shown that in order to achieve the highest fire extinguishing efficiency in this case, it is advisable to use powder fire extinguishing mixtures. The authors also investigated the mechanism of fire extinguishing action of powder mixtures when they are released as a result of container destruction by excessive pressure created by explosive detonation products. In particular, the mechanism of fire extinguishing with the use of fire extinguishing powders (FEP) in containers is shown:

- dilution of the combustible medium with gaseous products of powder decomposition;
- cooling of the combustion zone as a result of heat consumption for heating the powder particles, their partial evaporation and decomposition in the flame;
- providing a fire barrier effect, which is achieved by passing the flame through narrow channels between the powder cloud particles;
- inhibition of chemical reactions responsible for the development of the combustion process by gaseous products of evaporation and decomposition of FEP;
- heterogeneous chain breakage on the surface of particles or solid decomposition products;

➢ homogeneous inhibition, which consists in interaction with active combustion centres of gaseous particles formed during the evaporation and decomposition of FEP;

➢ isolation of the burning surface from the combustion zone by a layer of solid waste particles that have not decomposed as a result of thermal impact.

The authors have also developed a methodlogy for determining the total mass of powder mixtures for extinguishing fires of classes A and B. The established analytical dependence allows calculating the number of containers filled with extinguishing powders of different formulations in case of an explosive release as a result of detonation of explosive compositions (Kovalov et al., 2019).

One of the existing types of pneumatic fire extinguishing units can be used as a muzzle fire extinguishing unit (Fig. 1).

Fig. 1. Impulse backpack pneumatic fire extinguishing units

The use of MFU makes it possible to effectively solve the problem of remote delivery of various extinguishing agents and mixtures by throwing containers than extinguishing complex fires in high-rise buildings and at particularly hazardous facilities (chemical contamination zones, minefields, fires at arsenals, etc.), while ensuring the safety of fire and rescue personnel.

Another radically new and effective method of extinguishing fires and preventing ignition is the non-contact method of extinguishing flames (Kozlenko et al., 2021). This method is particularly effective in extinguishing forest fires, as well as in preventing the ignition of particularly important industrial facilities. The purpose of the invention is to prevent fire by the method of electrical fire suppression, based on the physical effect of deflecting the flame to one of the different high-voltage potentials of the external electric field and carried out by exposing the flame to a strong pulsed electric field with a voltage of 5 kV/cm and above. The studies have shown that the higher the intensity of the external electric field, the higher the flame disruption speed. The larger the surface area of the electrodes, and the larger the area of the electrode that extinguishes the fire is equal to the area of the flame projection in the same plane, the more abruptly the flame can be extinguished. Moreover, the electrical power of the extinguishing voltage source practically does not depend on the flame power, but it is determined only by internal losses in the voltage source itself, i.e., it is negligible compared to the flame power in the centre of fire. For example, a 1 m high flame can be extinguished in 3 seconds with an electric power of 3–4 W and an electric field strength of 3–5 kV/cm. Structurally, such a device contains two electrodes connected to the poles of a high-voltage source of direct electric current in the form of two parallel mesh fences located at a certain distance from each other, and it is intended to fully or partially cover a fire-hazardous area of considerable length in a forest or field, to prevent the spread of a fire that may arise and try to spread rapidly. The developed device is easy to manufacture and operate and significantly increases the efficiency of firefighting over large areas and high wind speeds.

For deep extinguishing of peat fires, the authors (Sukach et al., 2021) developed a special fire extinguishing muzzle. Its conical shape, which is made of galvanized hardened steel with a tip and a soldered continuous spiral, allows extinguishing agents to be supplied to a depth of more than 2 metres. This increases the efficiency of supplying extinguishing agents to the centre of combustion by screwing the muzzle into the combustible layer, which allows extinguishing fires at a given depth, namely up to 7 metres, and the introduction of the muzzle using an electric screw pile driver (KR E 20 Z1) ensures safe working conditions for the firefighter when deepening the muzzle to a certain depth.

It is extended the functionality of automatic fire extinguishing systems by using thermal imaging devices and a method for determining the centre of the fire for guidance and application of automatic fire extinguishing equipment in another paper (Voznyuk, 2020). The author shows that incident energy is converted into voltage by combining a material that is sensitive to this type of radiation and electrical energy applied to it. In response to the energy of external radiation, such a sensing element generates an analogue voltage output signal, which will be amplified in the third block of the thermal imaging device and later converted into digital form. The output of the thermal imaging device is a two-dimensional digital image, i.e., as a result of sampling and quantization operations, a matrix of light intensity in the form of real numbers is formed. The last unit of the system is fire extinguishing equipment, which is automatically aimed at the centre of the fire in the space of the room, using the coordinates of the centre of the fire. To do this, two images of different projections from a thermal imaging device of the object under study are used to calculate its three coordinates in space. In the future, the author also plans to expand the development by modelling and using image processing and analysis methods (thermograms). For example, as a first extension, it is proposed to use filtering using two variants of the filter window dimension with the choice of a midpoint filter. And as the second, image segmentation by the method of spatial differentiation using a differential operator such as growing regions or splitting the image into homogeneous regions. Therefore, the development of a thermal imaging automatic fire extinguishing system that allows not to flood the entire room, but to timely affect the fire focus is a relevant task.

The latest fire extinguishing equipment is no less interesting. In particular, scientists have developed a new fire extinguisher for use in special enclosed spaces that sucks up flames and combustion products (A new fire extinguisher that can be used in space, 2019). The vacuum extinguishing method (VEM), proposed by researchers from Toyohashi University of Technology in Japan, is based on the completely ‘reverse’ action of a traditional fire extinguisher, namely the suction of flames, combustion products and even the fire source by vacuuming into a vacuum chamber. This reverse concept is suitable for specially enclosed spaces such as spacecraft and submarines, to prevent or stop the spread of harmful combustion products, to extinguish certain unusual fires that are serious and uncontrollable, such as metal powder fires. This method is also proposed for extinguishing fires in sterile rooms (e.g. operating theatres) where fire extinguishing agents can cause serious damage to the structure and equipment, resulting in a significant delay in reactivation.

In another paper (Systems and methods of fire extinguishers with sound waves, 2017), the authors developed an unusual fire extinguisher based on the idea of extinguishing fires with sound waves propagated through a mobile subwoofer gun (a low-frequency speaker for reproducing the lowest frequencies of the sound range). Proposed by two students from George Mason University in Virginia, the portable device focuses sound waves in a specific direction rather than spreading them out. Compared to the chemicals of classical fire extinguishers, their invention offers the cleanest way to extinguish flames with low sound frequencies. It has been established that a sound wave is a type of pressure wave that has the ability to remove oxygen from air molecules. By testing different frequencies, the authors found that high pitches are ineffective for flames, and the key lies in low-frequency bass sounds from 30 to 60 Hz. Given that oxygen is the main source of fire initiation and spread, this will allow its removal from the fire environment and stop the combustion process.

4. Conclusions

Thus, the analysis of scientific and technical publications on the latest fire extinguishing systems has shown that, in particular, based on the results of studies of the impact of the design parameters of facade fire eaves on preventing the spread of fire in high-rise buildings, the authors found that the presence of a fire eave reduces the actual temperature at the level of the upper floor under which the fire occurred by 45–47 %. The use of horizontal eaves with a width of 0.6, 0.8 and 1.0 m can reduce the temperature of the facade surface 1.2 m above the window opening by 15–50 %. The studies of not only the most effective eave length, but also its shape, have shown that the temperature of the facade surface for the upper floor above the floor where the fire occurred, in the presence of a streamlined fire eave, is reduced from 270 °C (±30 °C) to 180 °C (±10 °C), which can significantly affect the conditions for limiting the further spread of the fire. In addition, in buildings with a nominal height of up to 47 m, it is proposed to use materials of flammability groups G1, G2 for the construction of the external cladding system of the building walls and in the internal layers of the external cladding system of the building walls with these materials up to the mark of 26.5 m.

To solve the problem of supplying extinguishing agents over a long distance, the authors proposed to use a muzzle fire extinguishing unit that provides high-precision supply of containers filled with extinguishing agent by throwing them along ballistic trajectory directly to the combustion zone, and to use powder fire extinguishing mixtures to achieve the highest fire extinguishing efficiency.

To extinguish peat fires in peat-forest ecosystems, scientists have developed a special fire muzzle that is screwed into a layer of porous substances, earth, peat to a depth of 5 m, which increases the efficiency of extinguishing combustible substances, compounds and materials by supplying water (foaming agent solution) immediately from the moment the muzzle is inserted into the combustible layer.

The studies of the non-contact method of extinguishing flames have shown that the higher the strength of the external electric field, the higher the speed of flame disruption and the higher the speed of extinguishing flames. The development of a thermal imaging automatic fire extinguishing system allows us not to flood the entire room, but to timely affect the centre of ignition.

Modern fire extinguishing research has shown that the reverse concept of a vacuum extinguisher is suitable for preventing or stopping the spread of harmful combustion products, as well as for extinguishing uncontrollable fires. The authors of another fire extinguishing idea based on sound waves spread through a mobile subwoofer gun have shown that low-frequency bass sounds between 30 and 60 Hz are most effective for fire extinguishing, and a sound wave is a type of pressure wave that has the ability to remove oxygen from air molecules.

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