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REVEALING PATTERNS IN IMPROVING THE PERFORMANCE OF PORTABLE SMOKE AND HEAT REMOVAL DEVICES WHEN USING FINE SPRAYED WATER

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An issue related to the application of portable smoke and heat removal devices for buildings and structures is to provide for their effectiveness when removing smoke and reducing temperature. That us why the object of this study was a change in the performance of a portable smoke and heat removal device when using finely sprayed water. Improved efficiency of the use of portable smoke and heat removal devices was based on experimental studies. It was proved that the reduction of smoke concentration and temperature in the room to the initial conditions was achieved for independent smoke dispersion in 5340 s, and cooling occurred in 3120 s. With the use of a smoke and heat removal agent during air supply, the smoke dissipated in 720 s, and cooling took 1560 s. And with the simultaneous supply of air and a sprayed jet of water, smoke dispersal occurred in 360 s, and cooling in 1020 s, respectively. To determine the efficiency of the smoke and heat release device, a calculation-experimental method has been devised that makes it possible to estimate the coefficient of the smoke and heat release agent when supplying air and water. According to experimental data, it was calculated that the coefficient of effectiveness of the smoke and heat removal devices when supplying air and water compared to the means when supplying only air increases by 2.1 times. The practical significance is that the results were taken into account when devising methodical recommendations for extinguishing fires. Thus, there are reasons to assert the possibility of targeted regulation of the processes of smoke reduction and temperature reduction through the use of a smoke and heat release device that simultaneously supplies air and finely sprayed water

Keywords: smoke and heat removal device, air injection, temperature reduction coefficient, sprayed water jet

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1. Introduction

When eliminating a fire, dangerous factors for people's lives are the influence of high temperature of heated gases and combustion products not only in the burning room but also in the premises adjacent to it. Therefore, during firefighting, the use of heat and smoke ventilation systems to create smoke-free areas beneath the rising smoke layer has become ubiquitous. In this regard, their importance in evacuating people from buildings, reducing fire damage and financial losses due to smoke prevention, fire extinguishing, lowering ceiling temperature, and slowing down the lateral spread and expansion of fire has been determined.

To achieve this effect, it is important that smoke and heat exhaust ventilation systems operate at full capacity and without failure when required throughout the service life. The ventilation system of heat and smoke removal is a set of equipment for ensuring safety, which is designed to perform a certain role in a fire event.

Therefore, a significant tactical way to reduce such an impact on the personnel of fire and rescue units is to control the heat and smoke flows of a fire with the help of portable smoke and heat removal devices. These tools are intended for local increase of air pressure by injecting air to the personnel's work area or removing combustion products from the premises during a fire to normalize the temperature and air environment.

At the same time, portable smoke and heat removal devices, which are directly used on fires, are not very effective. This is confirmed by the fact that the technical characteristics of existing portable smoke removal devices do not meet the needs of fire departments in reducing dangerous fire factors, so there is a need to improve the main parameter of their performance. In addition, the mechanism of operation of smoke and heat removal devices under the influence of fire temperature and the reduction of their efficiency has not been sufficiently studied, which makes it impossible to obtain objective information about the nature of the processes that occur during fire extinguishing.

Therefore, it is a relevant task to carry out studies aimed at improving portable smoke and heat removal devices by revealing the regularity of changes in their performance.

2. Literature review and problem statement

Work [1] gives the results of a series of experiments in a bench pool with a fire to study the characteristics of combustion in a sealed environment. Although the fraction of oxygen in the space is gradually reduced by combustion compared to open conditions, the transient rate of heat release can still be calculated using the PER approach using the oxygen concentration measured in situ. The dimensionless flame height can be calculated using the McCaffrey model for open conditions, but a larger factor should be used because the flame burns under a "starved" mode when the oxygen fraction is low. The current leaky fire model with increased centerline temperature during pool fires is not suitable for a sealed environment. The centerline temperature rise decreases faster than predicted by the Nasra model, which is designed for cases with limited ventilation inside and late stages of a fire. In the study, a new engineering model was built by fitting a curve to the results of hermetic fire resistance tests. However, it is not known if Pagna's law could be suitable to describe the relationship between the frequency of flame oscillations and the fire diameter in a sealed environment; therefore, modified coefficients are needed.

The purpose of study [2] is to compare the output of carbon monoxide collected under an insufficiently ventilated atmospheric regime in order to determine the best method of reproducing the output of carbon monoxide. Thermal irradiations of 30, 50, and 65 kW/m^2 were applied to PMMA and plywood samples. Failure tests were performed using an air/gas-diluent mixture at a flow rate of 100, 150, or 180 L/min, which resulted in a drop in oxygen concentration to 17.5 vol. %. Tests with insufficient ventilation were performed using flow rates of 5, 10, and 20 l/min in an air atmosphere. Particle formation and emissions were also measured using a particle analyzer and are reported there. However, nothing is said about measures that should be taken to reduce smog.

Paper [3] notes that the removal of heat and smoke in the event of a fire or during certain industrial production processes strongly depends on the pressure field that is created in the wind flow around the building. Ventilation can be carried out either naturally with the help of pushing forces, or mechanically with the help of exhaust systems. The test procedure corresponds to an isolated vent on an infinite flat roof, and the ventilation performance calculated from these test results does not take into account all other important exposure parameters, especially such parameters as the geometry of the building, local ventilation of the wind flow, obstacles to other buildings, etc. In natural ventilation systems, the inflow is automatically combined with the outflow, which is directly related to the heat generation in the building. For mechanical exhaust systems, this relationship does not exist. In this way, the air in the space to be ventilated can mix with the fresh air through the jet released through the intake openings. However, the problems of ventilation, wind action and the design of ventilation holes have not been identified.

Study [4] investigates the smoke removal performance of a system with multiple side vents using large eddy simulation (LES) in a fire dynamics simulator (FDS). An analysis of the influence of the lateral vent width factor AR (n), the lateral exhaust velocity (v), and the distance between the vents (d) at different levels of heat release HRR (Q) on the smoke removal efficiency (E) was carried out. The results show that the distance between the vents (d) has little effect on the smoke extraction efficiency. The mass flow of smoke and the thickness of the smoke layer in the tunnel changed significantly through the side exhaust openings. The efficiency of smoke removal increases with the dimensionless HRR Q^* and the ratio of the width of the ventilation opening n at a constant lateral removal speed v. However, it decreases sharply with increasing dimensionless lateral exhaust velocity v^* due to the increase in fresh air drawn into the side vents. Smoke removal efficiency reached 100 % at a discharge velocity of 1 m/s for vents with an aspect ratio of 3.25. However, the correlation for smoke removal efficiency at the stage of one-dimensional smoke propagation was established based on dimensional analysis.

Studying the distribution of pollutants under different conditions in underground garages is of great importance for improving indoor air quality and reducing casualties during fires [5]. The cited paper presents a geometric model of an underground garage based on PHOENICS simulation. Corresponding results of CO concentration distribution and fire temperature distribution under ventilation and fire conditions were obtained. The results show that under ventilation conditions, adjusting the position of the supply ventilation fan can keep the CO concentration below 30 ppm in sections one through three and below 37 ppm in sections four through six. Flue gas temperatures remained below 50 °C during the evacuation and only a small area exceeded 2000 ppm CO. The existing ventilation and exhaust system provides effective fire protection but has a minimal impact on the evacuation of personnel due to the relatively lower temperature of the smoke.

In work [6], taking as an example a mine excavation with local ventilation under pressure, the distribution of the temperature field and the fire-fighting characteristics of water spraying from the excavation were studied with the help of numerical modeling and theoretical analysis. The paper explains a dynamics-based smoke control method for water spray in a semi-closed tunnel, and the equilibrium relationship between droplet drag and smoke buoyancy. A method of calculating the number of smoke blocks based on the thickness of the smoke stack was devised. Local ventilation and smoke movement created a circulation flow in the production, which was detected by examining the blowout velocity and temperature fields. Owing to this circulating flow, the size of the high-temperature region and the nature of the temperature stratification changed. The local ventilation and sprinkler systems were operated simultaneously, and the smoke volume was small and avoided much of the water splash effect with the circulating flow. However, when the smoke volume was high, the effect of the circulating flow was reduced, and the smoke collected close to the sprinkler head. However, the blocking effect of the water mist was significant.

The purpose of paper [7] was to review fire ventilation methods in fire safety and measurement methods used as characteristics of ventilation systems. Controlling smoke in the event of a fire can reduce carbon monoxide emissions, which pose the greatest danger to humans. In addition, this document provides a case study of the distribution and removal of smoke from the environment of the Velodrome where the fire occurred. For this case study, a Computational Fluid Dynamics (CFD) simulation of an exhaust ventilation system was developed to manage smoke in the environment of a building called the Velodrome. The results were examined and analyzed in a 3-dimensional plane. The results of these CFD simulations show that the source of the fire can be removed by activating the exhaust system, and thus the risk of fire victims' lives and property damage can be reduced. But the issues related to the presence of high temperature remain unresolved.

Study [8] highlights the efficiency of natural roof ventilation systems and its influence on the characteristics of fire flow in tunnels. Numerical analysis is performed using Large Eddy Simulation (LES) to predict fire growth rate and smoke movement in a tunnel with one or more roof openings. The smoke removal efficiency of ceiling vents is investigated by changing the size of the vent and the location of the fire source. Critical parameters such as mass flow rate through ceiling openings, smoke transit time, and fire growth patterns are presented. Openings in the ceiling are effective for the transfer of hot gases and reduce the longitudinal velocity of smoke. The location of the heat source and ceiling vents significantly affects the performance of the vents and the behavior of the smoke in the tunnel. However, it is still a challenge to model its life cycle assessment.

Paper [9] reports an experimental program to investigate the global structural behavior of a compartment in a three-story steel-framed building at the Mittal Steel Ostrava plant that was exposed to fire prior to demolition. The experiment made it possible to study the heating of external elements, the influence of the connection in the wall of sandwich panels, the development of temperature in light wooden panels and the degradation of a wood-concrete composite element. Before the compartment fire, a local fire was prepared to test the temperature development patterns in the unprotected column. Comparisons with simplified European standard calculations are included in the text to show strengths and weaknesses in predicting the temperature of structural elements during a fire. However, temperature is not the only property.

Smoke is a real threat during a fire in a closed underground garage and is a significant problem for firefighters dealing with the fire [10]. A model of smoke movement in the basement was created using Fire Dynamics Simulator (FDS) 6.0 software. The study used a basement model measuring 60 m (length)×30 m (width)×3 m (height) and having three typical floors. Smoke ventilation shafts were provided for the basements. A well-controlled liquid pool fire with a heat release intensity (HRR) of 2 MW was used as input. The ventilation strategy was enabled using mechanical exhaust fans and supply fans. The following parameters varied: the location of the fire, the presence or absence of sprinklers, the presence or absence of a smoke extraction system, the presence or absence of air inlets, the presence or absence of a jet fan and ducts. Modeling of smoke and heat control using forced, mechanical, and horizontal ventilation was carried out. When a jet fan and duct combination was used, the fastest smoke clearance time was achieved compared to the other scenarios.

Paper [11] reports the use of large eddy simulation (LES) to study fire-induced smoke dispersion generated by buoyancy in a subway station. The influence of natural and mechanical ventilation was studied at this station, which has an atrium height of 0 to 15 m, skylight sizes of 1×1 m^2 and 5×1 m^2, and an air exchange rate of 5 to 11 h. In addition, six different fire source locations with heat release ratios (HRR) of 4 and 7.5 MW are discussed. An exponential relationship was proposed to determine the correlation between smoke filling height and duration with a relative coefficient (R) of 0.9995. The results show that mechanical ventilation can significantly control the spread of smoke in the horizontal direction but has little effect on the dispersion of smoke in the vertical direction. If a fire starts directly below the atrium, most of the smoke generated will collect in the upper part of the atrium. In addition, the simulation helps predict the maximum density of soot in the smoke produced at different heat outputs (4 and 7.5 MW). However, the meaning of smoke is not the only property.

As stated in [12], numerical simulations and small-scale experiments are conducted to study the effect of baffles under the outlet on the flow structure and the effective efficiency of heat and pollutant removal. In addition, the authors introduce the performance evaluation indices PEIH and PEIM to comprehensively evaluate the performance of the vent, taking into account both the increase in the removal efficiency and the increase in the flow resistance. Analysis of the results reveals that when the concave partition is adopted at a height of 0.7 m from the tunnel ceiling, the maximum PEIH and PEIM (1.20 and 1.17, respectively) are achieved. Compared with a vent without a partition, the efficiency of heat and pollution removal is increased by 21.1 % and 18.1 %, respectively; however, the flow resistance increases by only 1.8 %. The proposed PEIH and PEIM can be used as a general index to evaluate the performance of other types of vents, as well as to optimize the location of the vents, which helps improve the performance of the transverse smoke extraction system in tunnel fires.

Study [13] presents a simplified model of tunnel smoke stratification, which can be used to study the effect of sprinkler water on stratified stability. The effect of sprays from sprinkler nozzles with different K-factors was numerically investigated using the FDS code (version 6.7.3). Experimental data reported in the literature have successfully confirmed the accuracy of the CFD method. The results show that the drag effect of water spray depends on the size of the drop. The smaller the droplets, the greater the thrust force for a given volumetric spray rate. By applying dimensional analysis and introducing the volume mean diameter to the control parameters, some correlation models have been proposed that consider droplet size to predict atomization-induced smoke movement and heat loss. The new correlation models help complete the authors' previous work but do not say whether they are practical for the fire safety design of tunnels with longitudinal ventilation systems when water sprinklers are included.

Numerical and experimental studies were conducted in [14] to evaluate the effectiveness of on-site emergency ventilation strategies to control the spread of smoke in the event of a fire in a traffic tunnel section. All fire tests used a fire heat output of 1 MW. This rate of heat release from the fire was chosen to minimize the risk of damage to the tunnel and associated systems while providing reliable data to visualize smoke movement in the tunnel. A numerical study used Computational Fluid Dynamics, Fire Dynamic Simulator version 4.0 to investigate smoke removal in a tunnel under a large 30 MW fire (bus or truck burning). In total, four field fire tests and seven numerical simulations were conducted. Based on the results of the study, recommendations were compiled for optimizing ventilation scenarios in the tunnel section. But the authors do not explain the way the reported research and developed recommendations could facilitate design.

Thus, it was established from the literature [2–4, 6, 7, 12–14] that in the event of a fire, strong smoke and an increase in room temperature are possible, which requires smoke and heat removal during its elimination. In addition, the parameters that provide effective smoke and heat removal have not been defined. The paucity of experimental studies to explain and describe the process of smoke and heat removal, neglecting the use of cooling substances leads to ineffective use of removal tools. Therefore, establishing the parameters of a rapid decrease in temperature and smoke in the premises and the influence of finely sprayed water on this process predetermined the need for research in this area.

3. The aim and objectives of the study

The purpose of our work is to establish the regularity of increasing the performance of portable smoke and heat removal devices when supplying a finely atomized jet of water. This will make it possible to obtain the optimal characteristics of portable smoke heat removal equipment for their effective use during the elimination of fires in premises and buildings of various purposes.

To achieve the goal, the following tasks were solved:

– to conduct experimental studies of a portable smoke and heat removal device to determine the parameters of smoke reduction and temperature reduction;

– to establish the features of evaluating the effectiveness of the use of a portable smoke and heat removal device when supplying air and water.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the change in the performance of a portable smoke and heat removal device when using finely sprayed water.

The subject of research is the dependence of the efficiency of removal of hazardous substances from premises and buildings when using finely sprayed water and changes in the technical characteristics of portable smoke and heat removal devices.

The hypothesis of the study assumed that improving the technical characteristics of portable smoke and heat removal equipment using finely sprayed water could contribute to the increase in efficiency when extinguishing fires in buildings.

4. 2. Researched materials used in the experiment

Studies on the determination of smoke and heat removal were carried out in a box measuring 11.64 5.44 4.45 m, in which the relevant equipment was placed. During experimental studies on smoke removal, the following equipment is used: a technical system for controlling the optical density of a polydisperse gaseous medium (Fig. 1). It includes a laser emitter, a radiation receiver (photoresistor), a power supply unit, and a digital milliammeter connected to the information and measurement system of IBS "Thermokont" through the ICP CON I-7016 analog input module.

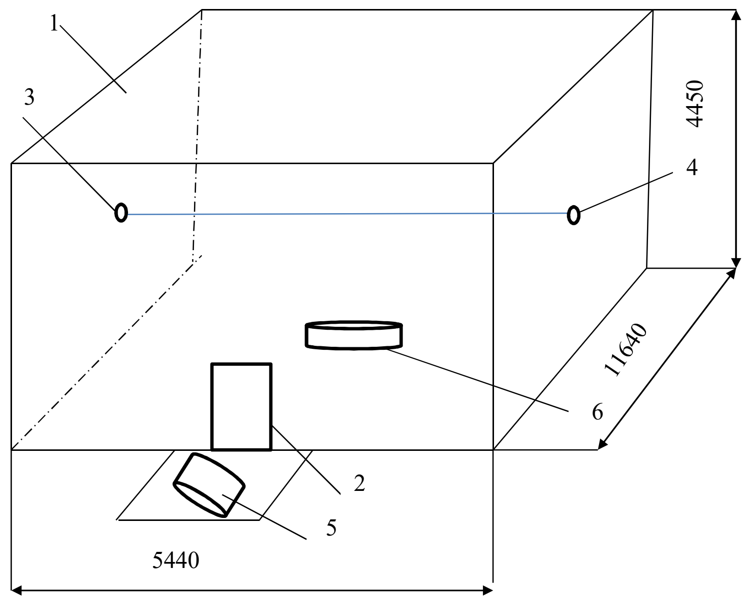

Fig. 1. Optical density measurement scheme: 1 — test box; 2 — doorway; 3 — receiver (photoresistor); 4 — laser; 5 — fan; 6 — smoke bomb

A Tohatsu VF 63AS-R fire engine pump (Japan) with a set of fire hoses was used to supply water to the advanced smoke and heat removal device. A smoke grenade (hand smoke grenade) was used to generate smoke in the test box.

Research on determining heat removal was conducted in a box, in which fire pits were placed at a distance of 2 m from each other (Fig. 2), made of a metal sheet 1.5 mm thick, 1.5×1.5 m in size and 150 mm high.

The diagram of the arrangement of thermocouples is shown in Fig. 3. Thermocouples 1–9 were located at a height of 0.5 m from the floor level of the test box, 10–18 – at a height of h_1=1.70 m from the floor level of the test box, 19–27 – at a distance of 0.1 m from the ceiling level test box)

The temperature was recorded in the test box with the help of installed thermocouples. The temperature in the box was also monitored using a thermal imager Testo 890 (made in Germany).

A portable smoke and heat removal device was used to remove smoke and heat. Fig. 4 shows a general view of the MCR MONSUN portable smoke and heat removal device manufactured by the MERCOR company, produced in Poland.

Fig. 2. Fire site during heat removal tests

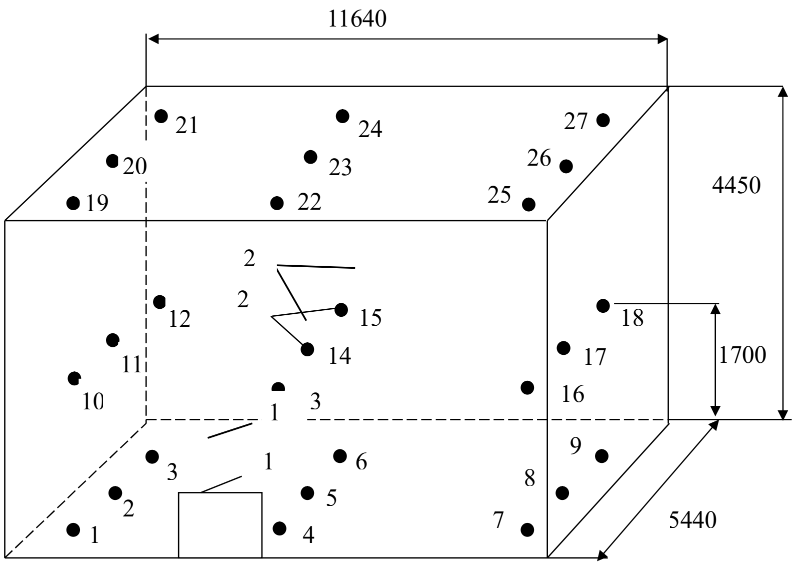

Fig. 3. Test box with thermocouple placement scheme: 1 – entry to the test box (located in the middle of the length of the test box); 2 – thermocouples

a

b

Fig. 4. General appearance of a portable smoke and heat removal device: *a* – general appearance; *b* – during compression

To create a sprayed jet of water in front of the smoke and heat removal device, a pipeline is used with spray nozzles installed on it with connecting fittings and a coarse water purification filter (Fig. 5).

Cylindrical nozzles made of aluminum were used as spray nozzles. Each spray nozzle consists of two half-cylinders. The first half-cylinder, 21 mm high, 25 mm outer diameter, and 19 mm inner diameter, contained twelve 0.8 mm diameter holes located on the horizontal surface of the nozzle. The second half-cylinder, 7 mm high, 5 mm inner diameter, and 12 mm outer diameter contained twelve 0.8 mm diameter holes located on the vertical surface of the nozzle. The corresponding openings of the two surfaces are located opposite each other at an angle of 90°.

At the same time, the jets of water passing through the indicated holes should intersect at an angle of 90°, which makes it possible to form a flow of sprayed water.

The combined supply of air to the room where the fire occurred and sprayed water makes it possible to more effectively reduce the temperature of the gas-air environment, as well as to dilute the combustible environment due to water mist.

a

b

c

Fig. 5. pipeline with equipment: *a* – spray nozzle; *b* – connecting head; *c* – coarse cleaning filter and ball valve

4. 3. Methodology for determining the performance of portable smoke and heat removal devices

All experiments on the determination of the effectiveness of smoke removal involved the creation of a smoky environment as a result of the operation of a smoke bomb in the test box and the measurement of the light transmission to the smoke and which passed through the smoke. This corresponded to the minimum value of the electrical voltage (mV) on the receiver and, accordingly, to the maximum density of the smoke and showed further smoke removal. Namely, in the first experiment, the time of self-dispersion of smoke was determined before the normalization of the gas-air environment in the test box.

In the second experiment, after smoking, the door of the test box was simultaneously opened and a portable smoke and heat removal device was activated, which pumped air into the test box. Its work continued until the normalization of the gas-air environment in the test box, which corresponded to the onset of the largest (maximum) reading value (mV) on the receiver.

In the third experiment, experimental studies similar to the second one were carried out, only with the use of a portable smoke and heat removal device with the simultaneous supply of air and a sprayed jet of water to the test box.

During the above-mentioned studies, for the control point of measurement, the dependences of the luminous flux in the presence of smoke in the room, which is proportional to the electrical voltage on the receiver, were obtained. The level of placing the laser emitter and receiver at a height of 1.7 m from the floor level of the test box, which corresponds to the average height of a person, was chosen as a control point for measuring the smokiness of the room.

Determination of temperature was carried out according to similar scenarios as during smoke removal. To this end, thermocouples were placed in the test box in accordance with the scheme and burners were installed on the supports, the bottom of the pan was covered with a layer of water approximately 20 mm thick, and 50 ml of fuel (gasoline) was poured per 1 dm^2 of the surface. The fuel was ignited, the room was kept in the fuel flame for 2 minutes, after which air was supplied to the test box, and a finely sprayed stream of water was added to it. The operation of the portable smoke and heat removal device continued during the time interval from the moment of reaching the maximum temperature of the gas-air environment in the test box according to the average readings of the thermocouples to the final temperature of 22 °C.

In the course of research, it was recorded how much and over what time the temperature drops at each point of installation of thermocouples in the test box during the operation of the portable smoke and heat removal device. According to the results of experimental studies, the dependence of the temperature on the time of operation of the portable smoke and heat removal device was obtained, and the effectiveness of the devices in reducing the temperature was evaluated.

5. Results of investigating the process of smoke removal and temperature reduction when using specialized tools

5. 1. Experimental studies of a portable smoke and heat removal device to determine the operating parameters of the room

Dependences on changes in smoke in the test box during experimental research are shown in Fig. 6.

According to the results of experimental studies, it was established that under the same conditions of conducting experimental studies, reducing the concentration of smoke in the room was achieved in 5340 s – for the independent dispersion of smoke. When using a smoke and heat removal device with air supply – 720 s, and with the use of a smoke and heat removal device with simultaneous air and sprayed water jet supply – 360 s.

In this way, it has been proven that water supplied together with air speeds up the process of smoke removal from the room by two times compared to when air is supplied alone, and by more than 14 times when dispersing smoke. According to the data shown in Fig. 6, the optical density of smoke was calculated according to the equation:

$$\mu = \frac{\lg\left(\frac{I_0}{I}\right)}{l}, \tag{1}$$

where I_0 is the initial light transmittance; I is the final light transmittance that passed through the smoke; l is the path of light.

The initial and final transmittance is determined by readings of the millivoltmeter connected to the photodetector. Therefore, the value of the optical density of smoke for this smoke-generating device is 0.28 $Np\cdot m^{-1}$.

Dependences of temperature change in the test box over time are shown in Fig. 7.

Fig. 8 shows the process of removing temperature and volatile products of combustion using a portable smoke and heat removal device with the simultaneous supply of air and a finely atomized jet of water to the test box.

The above results indicate that during full-scale fire tests under the same conditions of conducting experimental studies on lowering the temperature in the room, the following time cycle was achieved:

– with an independent decrease in temperature, it is 3120 s;

– with the use of a portable smoke and heat removal device during air supply – 1560 s;

– with the use of a portable smoke and heat removal device with the simultaneous supply of air and a finely sprayed jet of water – 1020 s.

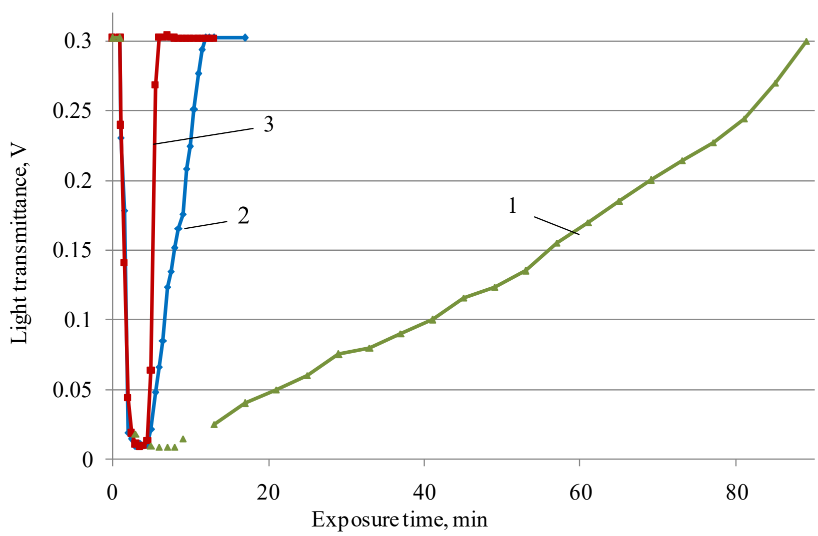

Fig. 6. Plot of the averaged values of the dependence of change in smokiness in the test box over time: 1 — independent suppression of smoke; 2 — smoke and heat removal device with air supply; 3 — smoke and heat removal device with simultaneous supply of air and a finely atomized stream of water

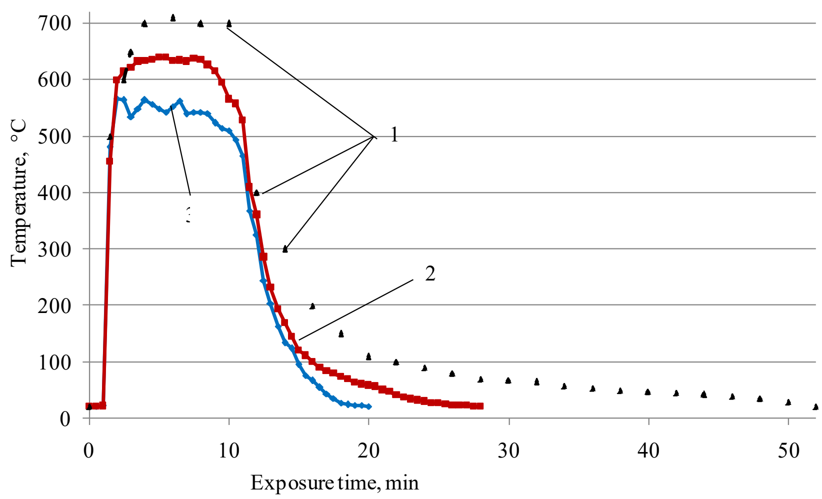

Fig. 7. Plot of the averaged values of the dependence of temperature change in the test box over time: 1 – independent decrease in temperature; 2 – for a smoke and heat removal device with air supply; 3 – smoke and heat removal device with the supply of air and a finely atomized jet of water

Fig. 8. The process of removing volatile combustion products from the box

Thus, it was established that water supplied together with air accelerates the cooling process in the room by one and a half times, compared to when only air is supplied.

5. 2. Evaluating the effectiveness of using a portable smoke and heat removal device when supplying air and a finely atomized stream of water

To evaluate the effectiveness of using a smoke and heat removal device, a method for determining efficiency has been devised, in which the efficiency is determined by the ratio of the time of smoke removal during forced removal to the time of independent deposition. Also, the time of temperature reduction was measured, and the characteristics of smoke and heat removal were evaluated after the test according to the efficiency coefficient E_m:

$$E_m = K \cdot \frac{\tau_c}{\tau_f}, \quad (2)$$

where τ_c – time of independent cooling of the room, minutes;

$\tau_{f.}$ – room cooling time by smoke and heat removal device, minutes;

K is the coefficient of smoke removal efficiency, which is determined by:

$$K = \frac{\tau_p}{\tau_m}, \quad (3)$$

where $\tau_{p.}$ – time of independent deposition of smoke, minutes;

$\tau_{m.}$ – time of forced deposition of smoke by a smoke and heat removal device, minutes.

The results of the smoke removal efficiency calculation are given in Table 1.

Thus, the coefficient of effectiveness of smoke removal when using the smoke and heat removal device while supplying air and water, compared to the tool when supplying only water, exceeds 1.5 times. Calculated based on (2), the efficiency coefficients of smoke and heat emission (E_m) when using the device while supplying air and water, are given in Table 2.

It was established that the coefficient of effectiveness of the smoke and heat removal device when supplying air and water compared to the device when supplying only air increases by 2.1 times.

Thus, the use of the proposed technique makes it possible to determine the effectiveness of using a smoke and heat removal device by experimental and calculation method and to increase the reliability of evaluation results.

Table 1

Smoke removal efficiency coefficient

Type of smoke removal	Deposition time τ, min	Smoke removal efficiency coefficient, K
Independent deposition	89	–
Reduction of smoke concentration by means of smoke and heat removal during air supply	12	7.4
Reduction of smoke concentration by means of smoke and heat removal during air and water supply	8	11.1

Table 2

Efficiency coefficients of smoke and heat removal devices with air and water supply (E_m)

Type of heat removal	Cooling time τ, min	Efficiency coefficient, E_m
Self-cooling	52	–
Temperature reduction by the device of smoke and heat removal with air supply	28	13.7
Temperature reduction by the device of smoke and heat removal with air and water supply	20	28.90

6. Discussion of results of investigating the process of smokiness and temperature reduction using a portable device

When studying the technology of removing combustion products and high temperature from the room by means of a smoke and heat emission device, as follows from our results (Fig. 6–8), the process of reducing smoke and temperature is natural. This is due to the absorption of volatile combustion products by water and, accordingly, the cooling of the surfaces after the fire.

It should be noted that the use of a smoke and heat removal device creates smokeless areas under the smoke layer with reduced temperature, which slows down the lateral spread and spread of the fire. Also, it serves in the evacuation of people. Obviously, this mechanism of influence of finely sprayed water is the factor regulating the process of smoke and heat removal, owing to which a safe atmosphere is formed. In this sense, the interpretation of the results of the determination of smoke and heat removal after exposure to flame, namely, a decrease in the value of the smoke-generating capacity, has to be interpreted. It was found that under the same conditions of conducting experimental studies on reducing the concentration of smoke in the room, it took 5340 s for the independent dispersion of smoke. When using a smoke and heat removal device with air supply – 720 s, and for a smoke and heat removal device with the simultaneous supply of air and a sprayed jet of water – 360 s. This indicates an intense change in the atmosphere of the room, which can be identified by the method of optical smokiness.

This means that taking this fact into account opens the possibility for effective regulation of the safe atmosphere in the premises directly during fire extinguishing.

A comparison of experimental studies on determining the temperature of the room when using smoke and heat removal devices shows that the processes of heat transfer during a fire are inhibited. Since the average temperature in the room under the action of the flame during a free burning fire reached 700 °C, the use of smoke and heat removal devices with air supply exceeded 620 °C. When using a smoke and heat removal device with the simultaneous supply of air and a finely atomized water jet, the temperature dropped to 520 °C (Fig. 7).

This does not differ from the practical data, well known from works [4, 6], whose authors, by the way, also associate the effectiveness of smoke and heat release with the use of water. But, in contrast to the results of research reported in [10, 11], our data on the influence of ventilation on the process of inhibiting smoke formation in adjacent rooms and temperature transfer allow us to state the following:

– the main regulator of the process is not so much air supply and smoke dilution but also the use of exhaust ventilation of various types;

– a significant impact on the process of reducing smoke and temperature when using portable smoke and heat removal devices is carried out in the direction of using water, which effectively absorbs combustion products and temperature.

Such conclusions can be considered appropriate from a practical point of view because they provide a reasonable approach to determining the required amount of water. From a theoretical point of view, this allows us to assert the determination of the mechanism of the processes of smoke elimination and temperature inhibition, which are certain advantages of this study.

However, it is impossible not to note that the results of the determination (Fig. 7) indicate an ambiguous influence of water on temperature changes. This manifests itself, first of all, in the temperature of the room during tests of the smoke and heat removal devices with the simultaneous supply of air and a finely atomized jet of water. Such uncertainty imposes certain restrictions on the use of our results, which can be interpreted as the shortcomings of this study. The disadvantage for the room is the high temperature, which must be reduced much lower than the average temperature of the room. The impossibility of removing the limitations within the framework of this study creates a potentially interesting area for further research. In particular, it may focus on detecting the moment of time when the temperature rises under the influence of fire. Such detection will allow us to investigate the smoke formation that begins to occur at this time and to determine the input variables of the process that significantly affect the onset of such a transformation.

7. Conclusions

1. It was established that under the same conditions of conducting experimental studies on reducing the concentration of smoke and temperature in the room to the initial conditions, independent dispersion of smoke was achieved in 5340 s, and cooling occurred in 3120 s. With the use of a smoke and heat removal device with air supply, smoke dispersion occurred in 720 s, cooling – in 1560 s. And for the smoke and heat removal device, with the simultaneous supply of air and a sprayed jet of water, smoke dispersion occurred in 360 s, and cooling in 1020 s, respectively.

2. The parameters characterizing the effectiveness of portable smoke and heat removal devices have been substantiated. Thus, the coefficient of effectiveness of the smoke and heat removal device when supplying air and water compared to the device when supplying only air increases by 2.1 times.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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