Для ліквідації пожеж в будівлях запропоновано використовувати установку періодично-імпульсної дії газоводяного гасіння. Обґрунтувані технічні вимоги щодо її розробки. Проведені експериментальні дослідження фізичного принципу установки, який забезпечує створення дрібнорозпиленого водяного струменя з оптимальними значеннями дисперсності крапель води. За результатами проведених досліджень виявлено значення тиску, швидкості ударної хвилі та дисперсності крапель води

Ключові слова: технічні засоби, дрібнорозпилена вода, газоводяний струмінь, гасіння пожеж, пожежне навантаження, площа гасіння

Для ликвидации пожаров в зданиях предложено использовать установку периодически-импульсного действия газоводяного тушения. Обоснованы технические требования по ее разработке. Проведены экспериментальные исследования физического принципа установки, который обеспечивает создание мелкораспыленной водяной струи с оптимальными значениями дисперсности капель воды. По результатам проведенных исследований выявлено значения давлений, скорости ударной волны и дисперсности капель воды

Ключевые слова: технические средства, мелкораспыленная вода, газоводяная струя, тушение пожаров, пожарная нагрузка, площадь тушения

IMPROVING THE INSTALLATION FOR FIRE EXTINGUISHING WITH FINELY-DISPERSED WATER

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1. Introduction

At present, personnel of the fire-rescue units (FRU) use water when extinguishing 90 % of fires. It is predetermined by the fact that water is the most common fire-extinguishing substance. Water is characterized by high specific heat capacity and heat of vapor formation, it is chemically inert to most chemicals and materials, cheap, environmentally safe, and readily available. When FRU put out the fires at residential buildings [1, 2], water is fed to the center of a fire using the B firehoses by sprayed jets. The result of extinguishing a fire is that the amount of water consumed by firehoses reaches 2.7 to 3.7 l/s; in this case, about 4–6 % is delivered to the center of the fire. The remaining amount of water is useless, leading to a collapse of the structures of buildings, damage to property and equipment [3, 4]. The use of water firehoses without fire-rescue vehicles is also impossible.

Currently, the most promising direction for extinguishing fires in residential buildings is the use of technical means, which enable the formation of finely dispersed water jets. These tools enhance the efficiency of water use with a corresponding decrease in water consumption [5]. This is

achieved because when employing finely-dispersed water, a cooling surface grows, depending on the dispersity, from $0.18 \ \text{l/m}^2$ to $0.017 \ \text{l/m}^2$. This enables the accelerated decrease in temperature in the confined spaces, from critical $1,000 \, °C$ to $40 \, °C$ [6].

The relevance of our work is explained by the need for the further development of technical means capable of receiving and delivering finely-dispersed water to the center of a fire, in order to improve efficiency of fire extinguishing at buildings and facilities.

2. Literature review and problem statement

The use of finely-dispersed water makes it possible to extinguish fires mainly by diluting a gas combustible medium with steam formed during evaporation of droplets. Paper [7] determined that the effectiveness of extinguishing fires with finely-dispersed water, which is defined by the duration and consumption of water for extinguishing the fire, is affected by the diameter of droplets or dispersion. That is why a lot of attention when creating new promising pilot equipment for extinguishing fires has been paid recently to installations

capable of delivering the finely-dispersed water of appropriate dispersion with the required performance.

However, the scope of application of firefighting means is limited by their weight and standard dimensions. Thus, papers [8, 9] proposed using a powder/water gun for extinguishing gas fountains applying the pulse high-speed water jets. To this end, it is necessary to have a powder charge and a fire-extinguishing substance (water). Using this installation requires a recharge after each shot; speed of the fire-extinguishing substance is about 800 m/s, which is not applicable when putting out fires in buildings. Such a water gun meets the requirements in terms of the dispersity of spraying water, but it fails to satisfy requirements for performance efficiency.

Authors of paper [10] propose, in order to obtain a water jet, using vehicles for gas-water suppression of fire. The operation of a vehicle implies that a water flow is fed to the cut-off of an aircraft engine nozzle and is sprayed by a jet stream of exhaust gases. Dimensions, weight, engagement of a large number of rescuers (over 16 people) and auxiliary machinery for carrying out the fire-extinguishing are the main shortcomings of these technical means.

Paper [11] proposed the use of pulse fire extinguishing installations manufactured by firm IFEX of Germany. The principle of operation is based on applying the pressure pulsations or consumption (more often, both) on the flow of fluid sprayed. However, this equipment has significant drawbacks, namely, the structural complexity, pulsing supply, and a limited amount of compressed air and a fire-extinguishing substance.

In [12, 13], it is proposed to apply the knapsack devices for extinguishing fires with finely-dispersed water. The principle of operation is based on that obtaining finely-dispersed water for extinguishing fires is achieved through the impact on a water jet of the gas flow that comes out of the channel at great speed from the firehose. The drawback is low productivity and the need to use air cylinders of high pressure.

Papers [14, 15] proposed using mobile extinguishing installations for the suppression of fire. Finely dispersed water jet is obtained at the expense of the energy supplied to the fluid as a result of the dynamic interaction between the fluid and the flow of gas (air). The use of plants requires a compressor for feeding a fire-extinguishing substance, which limits the scope of application.

Existing techniques of fire extinguishing using finely-dispersed water jet make it possible to extinguish mostly local centers of fires or large fires [16, 17]. There are no proper technical means in order to extinguish developed fires at facilities, which makes the use of existing tools insufficiently effective. Therefore, there is a scientific and technical task to substantiate and develop compact technical means of fire fighting using finely-dispersed water jet in order to extinguish developed fires at facilities. This task can be solved by the development of fire-fighting installations with a periodic-pulse action.

3. The aim and objectives of the study

The aim of present work is to study an installation for fire-extinguishing with finely-dispersed water of the pulse-periodic action, which employs a gas-detonating principle of throwing, applied instead of conventional pneumatic and mechanical principles.

To accomplish the aim, the following tasks have been set:
– to substantiate the physical principle of a fire-extinguishing installation, which would enable obtaining a finely-dispersed water jet with optimal values of dispersion of water droplets;
– to investigate parameters of the installation for fire-extinguishing with finely-dispersed water of the pulse-periodic action.

4. Operation principle of the installation for fire-extinguishing with finely-dispersed water of the pulse-periodic action using a gas-detonating throwing charge

To implement the periodic-pulse technique for obtaining finely-dispersed water, we designed a fire-extinguishing installation whose structure is shown in Fig. 1. The device is composed of piston compressor 1 with cylinder 2 and piston 3, placed inside cylinder 2. Reciprocating motion of piston 3 is enabled by crank mechanism 4, coupled with an external drive. The top of cylinder 2 has the attached cylinder head 5 with intake branch tube 6 and valve 7. Fuel feed system 8 is connected to intake branch tube 6. Fuel supply can be executed both directly into cylinder 2 of the compressor and into intake branch tube 6 of the compressor. Detonation tube-barrel 9 is connected to cylinder 2 of piston compressor 1 through branch tube 10 in head 5. Forced ignition of the mixture is enabled by using spark plug 11. Supply of water into the barrel is carried out through low-pressure hose 13 via valve 12.

To ensure effective acceleration and dispersion of water by the products of detonation, the ratio of areas of the elements of the installation is set so that during installation's work the following condition is met:

$$\frac{S_{piston}}{S_{DT}} > \frac{c}{4 \cdot U_{piston}}, \qquad (1)$$

where S_{DT} is the cross-sectional area of the inner channel of detonation tube barrel, S_{piston} is the area of piston of the piston compressor, U_{piston} is the mean piston speed, c is the speed of sound, m/s [18].
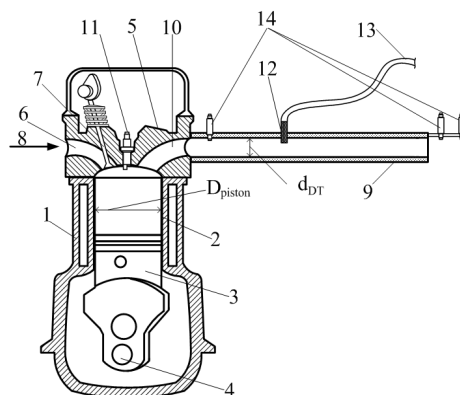

Fig. 1. Diagram of a fire-extinguishing installation of the pulse-periodic action: 1 — piston-type compressor; 2 — cylinder; 3 — piston; 4 — crank mechanism; 5 — head of the compressor; 6 — intake branch tube; 7 — valve; 8 — fuel feed system; 9 — barrel; 10 — branch tube; 11 — spark ignition system with a spark plug; 12 — valve for water supply; 13 — hose for water supply; 14 — pressure sensors

The principle of operation of a fire-extinguishing installation of the pulse-periodic action is as follows.

By using the external drive, piston 3 is set into reciprocating motion in cylinder 2 of compressor 1. The external drive is connected to crank mechanism 4, which ensures a reciprocating motion. In the process of motion of piston 3 from the top dead centre (TDC) to the bottom dead centre (BDC), intake valve 7 opens, and fuel gas mixture is pressured into cylinder 2 of compressor 1 through intake branch tube 6 in head 5 using fuel feed system 8. Upon reaching BDC, intake valve 7 closes. Due to the set ratio of the specified areas, during further movement of piston 3 from BDC to TDC at the set speed, there occurs the compression of gas mixture in cylinder 2 of compressor 1 and in detonation tube-barrel 9, whose element is branch tube 10. This leads to an increase in density, temperature, and pressure in the combustible mixture near the closed end of detonation tube-barrel 9 and in the tube-barrel itself. When the piston approaches TDC, there occurs the ignition of combustible mixture by spark plugs 11. Next, there is a rapid transition of combustion to detonation in detonation tube-barrel 9. Valve 12 is used to feed water through hose 13 from the source of water. As a result, a supersonic jet of detonation products ensures the acceleration and dispersion of water that comes out of barrel 9 over a short time when the piston is close to TDC. Then the process is repeated. Water was fed to barrel 9 continuously, at a flow rate of 0.5 l/s. General layout of the installation and its operation is shown in Fig. 2.

Fig. 2. Fire-extinguishing installation of the pulse-periodic action: *a* — general layout of the installation; *b* — installation at work

The application of a fire-extinguishing installation of the pulse-periodic action will make it possible to improve the efficiency of fire suppression at facilities by using finely-dispersed water. Thus, when employing the installation during fire extinguishing, water consumption will equal 1,800 l/h, which will enable the removal of heat from a fire site at about 4 GJ/h.

5. Procedure for conducting the study

Calculation of parameters for a detonation gas charge, which is achieved over compression time, was performed in the programming environment ANSYS. Geometrical dimen-

sions of the studied object were set in accordance with the parameters of the experimental installation. Specifically, a diameter of the detonation tube was equal to 20 mm. Length of the tube with a section for the acceleration of water aerosol was 1 m. Diameter of the piston compressor was 95 mm. The piston's stroke was 105 mm. Mean speed of the piston motion was 10 m/s. The motion of the piston from BDC to TDC was set by the equation of the sinusoid. Temperature of the walls of the cylinder and the detonation tube was 363 K. Initial temperature of the charge was 293 K. Based on the results of numerical study, we established distributions of pressure, temperature, and density of the charge in the fire-extinguishing installation of the pulse-periodic action during compression of the gas detonation charge.

Experimental study was conducted using a mixture of technical propane-butane (LPG) with air. Cycle feed equaled 30 mg/cycle, which formed a fuel-air mixture in the piston compressor, close to stoichiometric composition.

We measured pressure in the detonation tube-barrel at point *a* (Fig. 3) using the pressure sensor ADZ-SML 10.0÷100 bar made by the German firm ADZ NAGANO. The relative error of measurement of pressure is equal to 0.5 %. We calibrated the sensors ADZ-SML 10.0. in advance in a high-pressure chamber at a metrological base. The sensor was connected to a series circuit with a resistance of 49.9 Ohm and 1.01 kOhm. The measurement was performed by picking the voltage at resistor of 1.01 kOhm at a power voltage of 33 V. We obtained the following values for voltage at relative pressure: 0 bar – 3.92 V; 10 bars – 5.48 V; 20 bars – 7.04 V; 30 bars – 8.61 V; 60 bars –13.36 V. Resistance of the load was equal to 1,001 Ohm. Using the method of least squares, we obtained a sensitivity of the sensor of $0.156 \pm 0.001_{0.9}$ V/bar. Given that the sensor produces a signal for current, the sensitivity of the sensor is not dependent on power voltage.

We measured the velocity of the shock wave based on a method of time markers. Two pressure piezo sensors were installed at a distance of 1 cm from the end of the tube-barrel with a length of 0.6 m. Distance between sensors *b* and *c* was equal to 5 cm (Fig. 3). Piezoceramic CTS-19 was used as piezo sensitive elements of the sensors. Response time of the sensor did not exceed 1 µs. Measurement of signals from sensors was performed at the digital oscilloscope RIGOL DS1102E under the mode of registration of a single pulse triggered by the input signal.
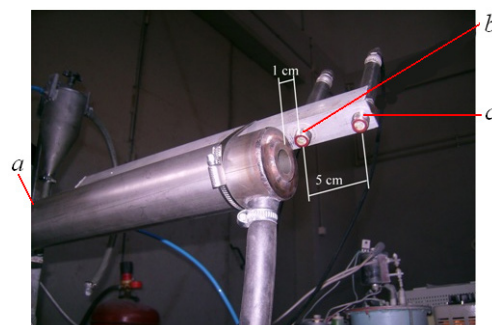

Fig. 3. Arrangement of pressure sensors at points *a, b,* and *c*

The study into determining a diameter of the water droplets (dispersion) was carried out using the method of trapping the droplets of water. We poured motor oil in a metal pan the size of 2,000×100×50 mm. When feeding a finely-dispersed gas-water jet from the installation's barrel, droplets of the sprayed liquid settled on the oil. Drops of water in contact with the surface of the oil did not dissolve for a long time, they did not drown, did not stick to each other, and maintained their spherical shape. This allowed us to measure the size of water droplets using a scale ruler and to determine their mean diameter.

6. Results of studying the parameters of an installation for fire-extinguishing with finely-dispersed water of the pulse-periodic action

A special feature of the designed installation relates to the ultra-fast filling of the barrel with a combustible mixture under high pressure. During such filling, prior to initiating the detonation, combustible mixture in branch tube 10, and part of tube-barrel 9, is under pressure exceeding the atmospheric pressure. Based on the results of numericalsimulation, we derived a distribution of excess pressure at the time of initiation of detonation, which is shown in Fig. 4.
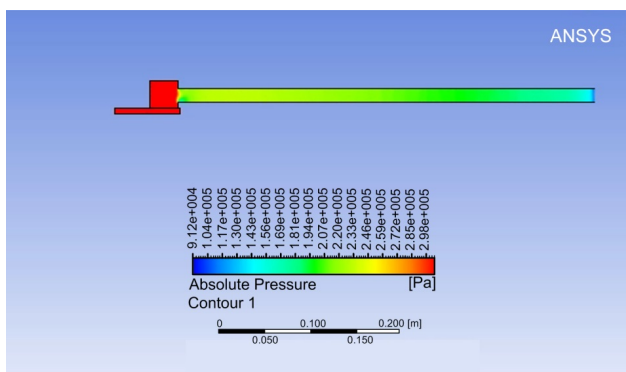

Fig. 4. Distribution of excess pressure at the moment of initiation of detonation

The time of feeding the mixture and a barrel length were selected in such a way that the fuel mixture cannot come out of the barrel until the moment the detonation is initiated. Therefore, as a result of detonation combustion, there is a complete combustion of the combustible mixture in the installation. The use of compressor and a spark ignition at the elevated energy of discharge make it possible to consistently obtain detonation on combustible mixtures with a significant deviation from stoichiometric composition. This ensures efficient dispersion of water jets in the installation's barrel by the flow of detonation products. As a result, the obtained finely-sprayed gas-water jet is fed to extinguish fires.
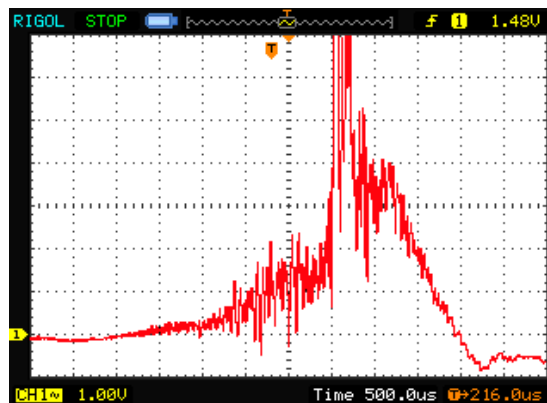
The results of pressure measurement at point a using the sensor ADZ-10.0 are shown in Fig. 5.

As the installation operates based on the detonation mixture, the cycle of detonation alternates with the cycle of blowing. By amplitude, the excess pressure of gases at point a without combustion exceeded 0.3 MPa, as a result of combustion the pressure increased by more than 3–4 times. The pressure oscillogram demonstrates a respective sequence of pressure waves that reflect these cycles. A more detailed investigation of change in pressure

at point a, using a piezo sensor, revealed the existence of explosive combustion. In this case, the duration of such a combustion is a few hundreds of microseconds. Before each cycle of the explosive combustion there is a jump caused by a stray pick-up from the spark plug unit. An analysis of oscillogram showed that the time delay between a spark and the explosion is about 2 ms.

a

b

Fig. 5. Results of pressure measurement: a — pressure at point a; b — change in pressure over the period of explosive combustion at point a

The results of signal measurements at points b and c, based on which we determined a velocity of the shock wave, are shown in Fig. 6.
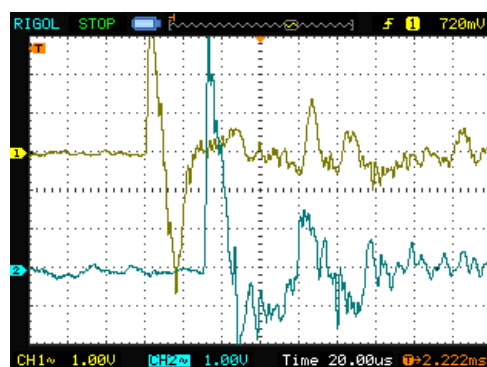

Fig. 6. Results of signal measurements at points b and c

Results of the measurements allowed us to obtain a jump-like change in pressure at sensors. At the same time, the time

over which a wave traveled between the sensors, based on the results of multiple measurements, amounted to 29–30 μs. This corresponds to the velocity of the shock wave of 1,667–1,724 m/s. According to experimental data, the rate of detonation in a propane-air mixture is 1,800 m/s [18, 19].

The total estimation of consumption for the heating and feeding of compressed gas mixture per one detonation cycle is 500 J at the performance efficiency of the preparation systems not exceeding 60 %. One detonation cycle consumes about 30 mg/cycle of combustible mixture. Detonation cycle frequency is greater than 20 Hz.

The estimated total power of the installation is 50 kW. It is known that the critical diameter of a tube-barrel, at which a transition of combustion into detonation is possible, is equal to size λ of the detonation cell. For the propane-air mixture λ≈50 mm. As the inner diameter of the tube-barrel is 20 mm, the transition of combustion into detonation occurred at the expense of compression and heating of the combustible mixture.

Based on the results of this study, it was found that the size of water droplets was in the range of 60–100 μm. Thus, by using the designed installation for fire-extinguishing with finely-dispersed water, we achieved forming the droplets with an optimal diameter.

7. Discussion of results of operation of the installation for fire-extinguishing with finely-dispersed water of the pulse-periodic action

Water is the most common fire-extinguishing substance for suppressing fires [21]. During evaporation, water accepts heat from the fire site and reduces the oxygen concentration in the air. When converting to vapor, water increases its volume by 1,700 times. The application of a compact jet of water, in which the dispersion of water droplets is about 1,000 μm, leads to a significant consumption of water and reduces the efficiency of fire suppression. This is explained by the fact that water has a low coefficient of thermal conductivity. Therefore, when passing through the flame of a fire, large droplets almost do not heat and do not absorb heat. As a result, there is excessive water consumption. The largest fire-extinguishing capacity is demonstrated by a jet of water sprayed to tiny droplets smaller than 100 μm [22, 23]. Thus, the formation of droplets in the proposed installation of up to 100 μm makes such an installation effective.

Existing technical means for fire-extinguishing with finely-dispersed water jet mostly enable the suppression of local fire sites, or fires at an early stage of development at facilities. There are no proper technical means in order to extinguish developed fires at facilities, which makes the use of existing tools ineffective.

Resolving these issues is possible by using a fire-extinguishing installation of the pulse-periodic action. Based on the experimental results, we shall calculate parameters for the fire-extinguishing installation. The main fire "driver" at residential buildings is wood (pine) that the furniture, doors, etc. are made of. That is why we take wood as a base for establishing the effectiveness of the fire-extinguishing installation. We assume that the energy of vaporization is fully spent to reduce the temperature of wood (pine) from a temperature of combustion of 1,000 °C to a temperature below the temperature of self-combustion of wood at 300 °C. The result implies that the wood with a weight of 2,500 kg will be saved from fire over 1 hour. Given that the average fire load at residential buildings is 20 kg/m², the area protected against a fire in this case will be equal to 125 m² [3]. The feed of water to the installation can be increased or decreased depending on the area of a fire, but the optimum supply is in the range of 0.5–1 l/s. The results of our study allow us to argue about promising prospects for the further work in this direction.

There may emerge difficulties during practical application in case the mass and weight parameters of the installation should be decreased. These problems, however, could be resolved by the application of modern materials.

8. Conclusions

1. We have proposed an installation for fire-extinguishing with finely-dispersed water of the pulse-periodic action to suppress developed fires at facilities. We considered and presented the principle of operation of the installation for fire-extinguishing with finely-dispersed water with an optimal value for the dispersion of water droplets. The installation was designed in such a way that it ensures acceleration and effective dispersion of water by the products of detonation. We established the optimum feed of water to the installation, 0.5–1 l/s, which depends on the area of a fire. This means that during operation water consumption to suppress the fire would equal 4 GJ/h. Thus, given the average fire load at buildings, the area of fire extinguishing in this case would make up 125 m².

2. We have conducted experimental study in order to establish operational parameters of the installation for fire-extinguishing with finely-dispersed water. Basic settings are determined that make it possible to effectively disperse water jets in the barrel of the installation by a flow of detonation products, in particular, the velocity of the shock wave, which amounted to 1,667–1,724 m/s. It was found that one detonation cycle uses about 30 mg/cycle of combustible mixture. Detonation cycle frequency is greater than 20 Hz. The estimated total power of the installation is 50 kW. It was established that the resulting dispersion of a finely-dispersed water jet by the method of trapping the droplets of water was within 60–100 μm.

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