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ESTABLISHING PATTERNS OF NITROGEN APPLICATION FOR FIRE SAFETY OF SUNFLOWER GRAIN STORAGE FACILITIES

The issue of using nitrogen to eliminate fires in granaries is related to ventilating the grain mass with nitrogen while it is necessary to take into consideration the change in gas concentration. Therefore, the object of this research was the value of the minimum concentration of nitrogen to eliminate the combustion of sunflower grain. It has been proven that in the process of thermal destruction of sunflower grain, the composition of gaseous products of thermal destruction of sunflower grain contains more than 70 % of combustible gases. Namely: carbon monoxide, over 51 %; hydrogen, about 5.7 %; and hydrocarbons with a total concentration of 13.72 %, which provide fire hazardous properties of organic material. Therefore, it should be noted that the release of the amount of combustible gases during pyrolysis requires a reduction in the amount of oxygen in the gas-air environment to eliminate fire sites. Obviously, such a mechanism for the decomposition of sunflower grain during pyrolysis is a factor in regulating the extinguishing process, due to which the amount of nitrogen to eliminate combustion increases. Comparison of experimental studies on the composition of gaseous products of thermal destruction of sunflower grain and studies to determine the minimum fire extinguishing concentration of nitrogen, at which combustion was stopped, made it possible to justify the use of nitrogen. Based on the study's results on the elimination with nitrogen of fire sites of sunflower grain, the values of the minimum fire extinguishing concentration were revealed at extinguishing, about 33.7 % by volume. At the same time, terminating the combustion of sunflower grain occurs with a decrease in the concentration of oxygen in the gas-air environment of about 14 %. The practical significance is the fact that the results obtained for determining the minimum fire extinguishing concentration of nitrogen make it possible to establish operating conditions for granaries when eliminating fire sites

Keywords: sunflower grain, fire site, amount of nitrogen, fire extinguishing, oxygen concentration

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1. Introduction

According to the FAO (Food and Agricultural Organization) at the UN, it is noted that annual grain losses account for more than 10 % of total production and most of these losses depend on the moisture and high grain temperature. Given that in countries that are deficient in energy, a lot of grain is not brought to the required condition, there is heating and spontaneous combustion of the grain mound. In the world, there are a significant number of facilities, such as elevators, grain receiving enterprises, feed mills, where the technology provides for the preservation of products of plant origin in dispersed form, as well as its transportation.

Accidents that occur at such facilities cause not only material damage but also human casualties. Note that in terms of the spontaneous combustion of plant materials, its occurrence and development of a fire does not require an external impulse that initiates combustion, or high temperatures. Burning occurs due to heterogeneous oxidation in product volumes at low ambient temperatures and is accompanied by the formation of volatile combustible products. In addition, given the low thermal conductivity of the grain mass, there is an accumulation of heat in its volume, an increase in temperature and, accordingly, the rate of chemical reaction and ignition.

The most common way to eliminate fire sites in granaries is to unload and extinguish them during pouring. This technique of eliminating accidents is very energy-intensive, it leads to large losses of products, and is dangerous during the performance of relevant operations as it can lead to an explosion. One of the effective methods of eliminating fire sites is the possibility to ventilate the grain mass with nitrogen, maintaining the required level of concentration, that is, one needs to know the nitrogen consumption that is necessary to reduce the oxygen concentration to the required value of combustion inhibition.

Therefore, to eliminate fire sites using nitrogen, it becomes necessary to study in detail the fire extinguishing properties and the impact on changes in the concentration in the nitrogen-oxygen environment, which are necessary to establish the scope of application, which is addressed in this work.

2. Literature review and problem statement

Paper [1] considers the aspect of fire safety at premises protected by a stationary gas fire extinguishing system (FGE-system). Based on the analysis of design standards, it was argued that analytical models of gas leakage from the compartment ignore some parameters that may affect the change in gas concentration during the extinguishing process over time. Proper forecasting of the gas flow process can affect the value of the retention time, which is an important factor in the fire safety of premises protected by the FGE-system. The density of extinguishing gas is indicated as a parameter with great potential to extend the retention time. It has been observed that the density of a gas depends on atmospheric conditions, such as temperature, pressure, and humidity, which are not taken into consideration in standard models. In the research part, the analysis of the distribution of the concentration of nitrogen and nitrogen-argon mixtures by three methods was carried out. The experimental data were compared with analytical calculations using a standard model (model N) and a new proposed model extended by atmospheric conditions (model PK). The PK model showed greater accuracy in determining the process of changing the concentration of extinguishing gas. The new proposed model can be a valuable tool for further analysis of gas flow through the premises. Nothing was said about fire extinguishing concentrations.

Liquid nitrogen works as an important medium for extinguishing and preventing fire due to its effectiveness in eliminating oxygen and removing heat [2]. For this purpose, a tunnel model with a temperature monitoring system and experimental study of heat and mass transfer of liquid nitrogen to a carbon-porous medium (CPM) was built to optimize the parameters of liquid nitrogen injection. The results show that the injection site and the amount of liquid nitrogen together with air leakage significantly affect the temperature distribution in the CPM and the nonequilibrium heat inside and outside the coal particles. The liquid nitrogen injection position determines the location of the lowest CPM temperature and residual liquid nitrogen. In a deeper layer of coal, coal particles take longer to achieve thermal equilibrium between the surface and inside. Air leakage accelerates the increase in temperature at the bottom of the coal seam, which is the main cause of the inefficiency of fire prevention. Measured CPM temperature fluctuations can be caused by incomplete contact of coal particles with liquid nitrogen occurring in the coal layer. Moreover, secondary temperature drop (STD) occurs and increases with increasing liquid nitrogen injection, and the STD phenomenon is explained by the distribution of temperature at different locations. However, issues that are associated with the extinguishing mechanism remain unresolved. The reason for this may be the principles of operation of the extinguishing agent, which, accordingly, makes such studies difficult.

Paper [3] notes that the use of liquid nitrogen to extinguish fire sites on liquid fuel remains a new and relevant topic. The behavior of liquid nitrogen to extinguish a fire has not yet been fully studied, and relevant research is still in its infancy. In that article, a flexible system of liquid nitrogen jets was created to study the process of interaction of liquid nitrogen with pool fire in open space. The main purpose of that work was to compare the characteristics of quenching vertical/horizontal jet of liquid nitrogen to extinguish fire sites of petroleum products using measurements of weight, temperature, and infrared thermal image. As a result, the experiment found that liquid nitrogen has satisfactory efficiency for fire extinguishing the pool. It was also found that the horizontal jet of liquid nitrogen is more efficient than the vertical one in terms of fire extinguishing time and the required amount of liquid nitrogen. The shape of the flame of fire during the period of the horizontal jet of liquid nitrogen was completely different than during the period of the vertical jet of liquid nitrogen. The mechanism of fire extinguishing is revealed, respectively, by a vertical/horizontal jet of liquid nitrogen. Therefore, it becomes necessary to study the conditions for the formation of a barrier to the spread of the flame and establish the effective action of nitrogen with the formation of a certain concentration.

In the studies reported in [4], it is substantiated and experimentally confirmed that the addition of nitrogen to the aerosol of inorganic potassium salts significantly increases the efficiency of fire extinguishing of the obtained binary mixture. As a result of the research, it was found that the addition of nitrogen to the aerosol reduces the fire extinguishing concentration of the components of the final binary mixture by 30 %. It has been experimentally confirmed that the optimal ratio of components in a mixture of binary mixture, which consists of aerosol, is 10 g/m^3 and nitrogen 12.1 %. It is fire extinguishing for the diffusion flame of heptane and at the same time provides a life-safe concentration of oxygen. It has been established that the high efficiency of the binary aerosol nitrogen mixture is achieved due to the synergism of the components of the mixture. The value of intensity and decrease in temperature of diffusion and kinetic flame in its presence in the aerosol-nitrogen mixture was determined. The study of the fire extinguishing efficiency of aerosol-nitrogen mixtures is necessary to determine the conditions and methods of extinguishing a fire with a mixture in enclosed spaces. The obtained dependences and characteristics of aerosol nitrogen mixtures can be the basis for the creation of environmentally friendly, cheap, and easy-to-manufacture fire extinguishing agents. Especially with high efficiency of fire extinguishing, which can be used to extinguish fire sites in the zones of temporary stay of people and living organisms without visible damage to them as a result of volumetric extinguishing of fire sites with the described mixtures. However, they cannot ventilate the grain mound.

Fire extinguishing tests using double water fog under low pressure in low-pressure environments were carried out to test the effectiveness of water fog systems in low-pressure environments [5]. The results of the experiment show that the suppression time becomes shorter for the lower pressure in the chamber, and the corresponding total weight of the water and nitrogen used decreases as the pressure in the chamber becomes lower. For the event of a 30 cm diameter pool fire, the extinguishing time is 20.19; 7.5; and 2.24 at a chamber pressure of 60, 38, and 24 kPa, respectively. In the event of a fire in the cargo hold, it is proposed to open the cargo compartment ventilation valve at a high cruising height in order to relieve pressure and achieve rapid extinguishing of the fire. When a fire occurs in a place located outside the center under a nozzle of water fog, the effect of suppressing water fog will be relaxed. The size of the fire has little effect on the extinguishing process under a pressure of 24 kPa. Under critical spraying conditions with a pressure difference between the inlet and outlet of the water nozzle of 0.05 MPa (5.04 dm/min) and a pressure difference for nitrogen of 0.10 MPa (10.97 dm/min), the suppression time is 18.66 seconds. However, it is not specified how these compositions can be used for dispersed organic materials.

In study [6], a liquid nitrogen supply system was created to extinguish fire sites of petroleum products in an open tank. The effect of liquid nitrogen flow rate, pipe diameter, and liquid nitrogen release distance on the suppression process was analyzed according to mass loss, combustion rate, and temperature changes. With a liquid nitrogen ejection distance of 0.50 m and a pipe diameter of 0.04 m, the fire extinguishing time was the smallest, at 1.6 s, and the rate of decrease in temperature above the surface of the liquid fuel reached 275 °C/s. Cooling of the fuel surface and the purge process were found in the experiments as two types of fire extinguishing mechanisms. Based on flame images taken by a high-speed camera, the phenomenon of flame expansion may occur at the beginning of liquid nitrogen injection, especially in a situation with a higher flow rate of liquid nitrogen. Three approaches are provided for extinguishing large-scale fire sites (ground stationary system, mobile transport, and directional transportation of liquid nitrogen). The results are an important reference for firefighting activities. However, the relevant physicochemical data on changes in nitrogen concentration in the process of quenching are not given.

In [7], the results of the use of a nitrogen protection system for 15 years in a crude oil storage park equipped with vertical hazard class tanks II and III with a stationary roof without pontoons were analyzed. Under nitrogen protection conditions, the rate of localized corrosion of the inner surface of the roof of crude and industrial crude oil storage tanks is 0.013–0.015 mm/year, which is about 100 times lower than the rate of corrosion in the natural gas phase inside the tank. Continuous operation of the nitrogen protection system ensures fire and explosion safety of tanks. Interruptions in nitrogen protection practically do not affect the efficiency of through perforation of the roof until the end of the regulated service life of the tanks but increase the fire and explosion hazard due to the formation of pyrophoric corrosion deposits.

Earlier studies reported in [8] have shown that liquid nitrogen can effectively extinguish fire sites in long and narrow spaces, and internal blocking can speed up the process of suffocation of fire. To study the effect of blocking on the efficiency of fire extinguishing liquid nitrogen in a long and narrow space, an example of a tunnel is taken in that paper to conduct an experimental study of the effect of the blocking state on the efficiency of fire extinguishing of the liquid. nitrogen. The study shows that the process of firefighting the economic tunnel is the result of the joint action of liquid nitrogen and blocking, in which oxygen insulation and suffocation of liquid nitrogen play a dominant role, and the presence of blocking accelerates the process of asphyxia. The closer the lock to the source of fire and the greater the blocking rate, the more significant the blocking contributes to the suffocating effect of liquid nitrogen to the insulating oxygen effect. However, it should be noted that the upper lock can lead to an increase in the temperature of the local space. If one does not take timely measures, excessively high temperatures can lead to damage to the structure. Thus, the choice of reasonable blocking measures and optimization of sealing methods can maximize the effect of extinguishing a fire with liquid nitrogen. Relevant research is an important reference to guide the development and application of liquid nitrogen extinguishing technology.

In study [9], it was noted that the efficiency of extinguishing a pure hybrid fire extinguishing agent consisting of nitrogen and water fog was experimentally studied by the method of a cup burner with methane/air flame. A series of hybrid agents with different weight ratios of nitrogen and water fog (average diameter according to Sauter: 12.6 microns) was tested and compared to nitrogen and water fog, which were used separately. The minimum mass concentration of extinction (MEC) of pure nitrogen and water fog were 32.1 % and 15.2 %, respectively. In the MEC combination, hybrid agents were between the limit values of nitrogen and water fog used separately. Approximately linear dependence has been demonstrated for nitrogen suppression and water fog suppression behavior in combination. The field of flow of suppressors during the flame suppression process was investigated using the particle image velocity measurement method (PIV). A small part of the water droplets near the flame front evaporated, which contributed to the extinguishing of the flame due to the absorption of heat and the dilution of oxygen. The remaining fog was captured vertically by the flow of air, having little effect on the base of the flame.

Work [10] discussed a stationary hybrid fire extinguishing system, which in recent years has been used in fire protection around the world. A system with two pipes with four heads supplied by water fog and inert gas (air or nitrogen) was used. A stack of 50 pine boards (fire class A) was used as a combustible material. It was located in the corner of the compartment, and the nozzles were located symmetrically in the center (volumetric suppression). The extinguishing processes differing in the ratio of water fog to gas are analyzed. The quenching time was taken as the most important parameter indicating the effectiveness of quenching. The effect of water flow on the extinguishing process was discussed. A clear dependence of the quenching time on the water/gas ratio has been proved. The best performance of the hybrid system was observed at a water consumption of 3 dm^3/min and nitrogen as an inert gas, but no change in oxygen concentration was said. The results obtained during the experiments can be useful in the development of new international standards.

Liquid nitrogen (LN 2), as a highly effective and environmentally friendly extinguishing agent, is widely used to extinguish fire sites in enclosed spaces by cooling and inerting [11]. It is very important to understand the cooling and inert effects of LN 2 introduced into a confined space. An experimental closed-space platform was developed to investigate the injection of LN 2 into a platform with various injection parameters such as mass flow, pipe diameter, and tilt angle. In addition, a mathematical model for quantifying cooling and inertness effects using heat exchangeability, inertness coefficient and cooling rate is proposed. The results showed that the inertness effect gradually increased with increasing mass flow from 0.014 to 0.026 kg/s, and then tended to equalize; the corresponding pipe diameter of 12 mm was optimal for the cooling and inertia effects in this experiment. In addition, a positively increasing angle of inclination can contribute to cooling and inertia effects. However, there was little impact on cooling and inerting with an angle of inclination of less than 0°. That study could provide technical guidance for environmentally safe firefighting with LN 2 in a confined space.

In study [12], a new type of N2-inhibitor-water fog (NIWM) technology was proposed to solve the problem of preventing and extinguishing a fire in the production part of a coal mine. Appropriate equipment has been developed and manufactured. Provided that the gas pressure and liquid pressure were 0.5–2 MPa, NIWM equipment produced water mist with an average Sauter diameter (SMD) in the range of 166–265 microns. Experimental results of operating parameters of NIWM equipment were consistent with theoretical conclusions. The two-phase flow spray theory can be used as a theoretical guide for this technology. After that, on the basis of NIWM equipment, experiments were carried out to inhibit low-temperature (30–100 °C) oxidation and quenching of high-temperature combustion of a large dose of a coal sample. The water mist from SMD 188 μm had good diffusion in the container. The inhibitory effect of N_2-inhibitor-water fog on the low-temperature oxidation of coal was obviously greater than that of the individual material. Water fog N_2 completely extinguished the burning coal in 20 minutes. The addition of water fog solved the lack of a weak cooling effect of N_2. At different stages of the coal-oxygen reaction of N_2, the inhibitor and water fog play a very different role in controlling the coal-oxygen reaction process, which is not a simple accumulation of these three substances. The combination of N_2, inhibitor, and water fog should be determined according to the state of fire of the mine produced. Based on the conclusions of the research, a scheme for placing NIPM fire extinguishing agents in the product has been developed. The results of research have proven the feasibility and effectiveness of this technology, and it is of great importance for preventing and combating the spontaneous combustion of coal in craters. However, to achieve prediction accuracy, a more acceptable and reasonable flame inhibition model should be created.

As an effective and environmentally friendly cryogenic fire extinguishing agent, liquid nitrogen (LN2) is very promising for extinguishing fire sites in narrow and long underground confined spaces [13]. It is difficult to extinguish the fire of the city communal tunnel due to its complex and narrow design characteristics. Thus, the work is aimed at studying the feasibility and effectiveness of extinguishing the LN2 fire in the city communal tunnel. Experimental study of LN2 fire extinguishing characteristics in urban the underground utility tunnel was carried out in a reduced 1/3.6 tunnel model with different injection parameters such as the direction of the LN2 nozzle and the distance between the LN2 nozzle and the fire source. The results show that LN2 can quickly put out a fire in a utility tunnel. The LN2 rapid quenching mechanism involves a combined cooling and inert effect. When the LN2 emission distance is 2 m and 4 m, the fire extinguishing time increases by 8.7 % and 27.5 %, respectively, for horizontal input. On the contrary, vertical injection is more efficient when the LN2 nozzle is far from the fire source. When LN2 is injected into the sewer tunnel, a sharp evaporation occurs, followed by thermal expansion. The evaporating cryogen forms a low-temperature nitrogen cloud that quickly cools the gas. As the cloud spreads, the pyrolysis gas becomes inert and the fire is isolated from oxygen and finally extinguished. However, it is not specified to what concentration oxygen decreases.

In [14], a study was conducted to analyze the fire extinguishing characteristics of a double liquid system using a large amount of nitrogen to spray water. The extinguishing properties of the resulting comosium were preliminarily evaluated according to four fire spray scenarios in a 260 m^3 engine case, as described in the FMAPPROVAL 5560 resolution. Diesel fuel or heptane was used in fire tests. Subsequently, the mixing reactor model was used to analyze test results and make a fire extinguishing assessment for hypothetical protection using only water fog or nitrogen component dual system. Analysis of the studies showed that either the nitrogen component or the water fog component can extinguish the fire for all the fire scenarios studied. As a result, it is more appropriate to call a dual liquid system a hybrid fire extinguishing system instead of a traditional water fog system or gas system. Based on the analysis of studies, it is proposed that a double liquid system can be designated as a gas system, water fog system, or hybrid system if the concentration of dry oxygen in the chamber during fire extinguishing is below 12.5 % above 16 %, or between 12.5 % and 16 %, respectively. System safety factors and discharge duration for hybrid systems, the efficiency of fire extinguishing of which is improved by combining water fog with a large amount of inert gases, are also proposed. However, the effect of a double liquid system on reducing oxygen concentration and extinguishing the flame has not been studied.

Thus, it was established from literary sources [5–7, 9–14] that the supply of nitrogen to a fire site is capable of eliminating combustion but the parameters that ensure this process are not defined. Therefore, the establishment of the parameters of nitrogen application to inhibit combustion and the effect of oxygen concentration on this process necessitated research in this area.

3. The aim and objectives of the study

The aim of this work is to identify patterns of elimination of fire sites of sunflower grain during the supply of nitrogen and changes in the concentration of oxygen in the environment. This makes it possible to justify the possibility of expanding the scope of nitrogen application for the fire safety of granaries.

To accomplish the aim, the following tasks have been set:

– to conduct a study of the fire hazardous properties of volatile pyrolysis products of sunflower grain;

– to investigate the minimum concentration of nitrogen to reduce oxygen and eliminate the combustion of sunflower grain.

4. The study materials and methods

4. 1. The object and hypothesis of research

The object of this study is the concentration of nitrogen to eliminate the combustion sites of sunflower grain.

The hypothesis of our research assumes that according to the results of establishing a change in oxygen concentration and determining the minimum extinguishing concentration of nitrogen, it becomes possible to eliminate the fire sites of sunflower grain.

4. 2. The materials used in the experiment

For the study of a fire site, samples of sunflower seeds of oblong-ovate shape, slightly hedral, 8÷15 mm long and 4÷8 mm wide, black, were used (Fig. 1).

Fig. 1. Sunflower grain samples

The samples were dried to a moisture content of 5 %. The bulk density of sunflower grain samples at a moisture content of 5 % was about 300 kg/m^3.

To determine the possibility of using nitrogen to eliminate model fire sites, gaseous balloon nitrogen was used.

4. 3. Methods of research of fire hazardous properties of sunflower grain pyrolysis products and minimum fire extinguishing concentration of nitrogen

One of the methods that makes it possible to investigate the formation of volatile pyrolysis products of sunflower grain is gas chromatographic analysis. Given that the highest content of combustible components is found in gaseous products formed as a result of pyrolysis, the thermal decomposition of sunflower grain was carried out without air access.

To obtain gaseous products of thermal destruction of sunflower grain, special equipment was used on the basis of a tubular electric furnace with a thermostat [15]. The qualitative and quantitative composition of these mixtures was determined by the gas chromatographic method using the LHM-7A gas chromatograph.

To determine the patterns of nitrogen use to eliminate the ignition sites of sunflower grain, the minimum fire extinguishing concentration was determined. For research, an installation was used to determine the minimum fire extinguishing concentration of gas extinguishing substances, which was modified [16]. The required concentration of nitrogen was produced in the gas-air mixture block and fed to the test chamber where the hearth was located (Fig. 2).

The essence of the method implied that a gas-air flow of a certain concentration of nitrogen was created around the fire site, at which the site was extinguished for 10 s.

For research, a fire site was made (Fig. 3).

The tests are carried out in the following sequence. The model hearth was filled with sunflower grain weighing 20±0.5 g, provided that the material covers the solder of the thermocouple. Air (oxidizer) was supplied with a flow rate of 20 dm^3/min. The heater was turned on and the sample under study was heated before the start of intense gas emission (~250÷260 °C); the set temperature was maintained. After that, it was set on fire, the heater was turned off and kept for 60 s. Nitrogen was supplied through the dispenser, increasing and recording the nitrogen consumption at which the flame was extinguished.

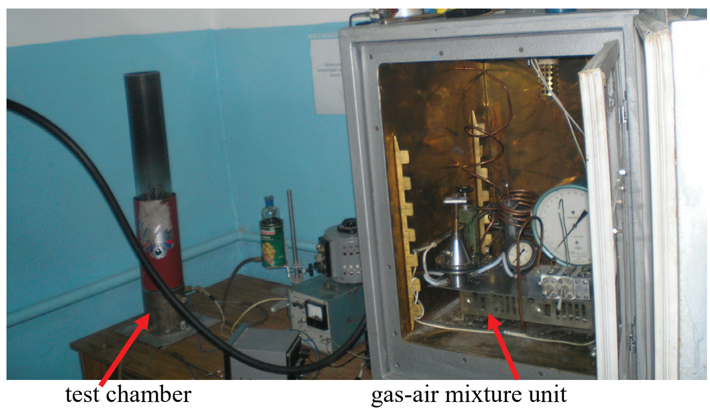

Fig. 2. Installation for determining the minimum fire extinguishing concentration

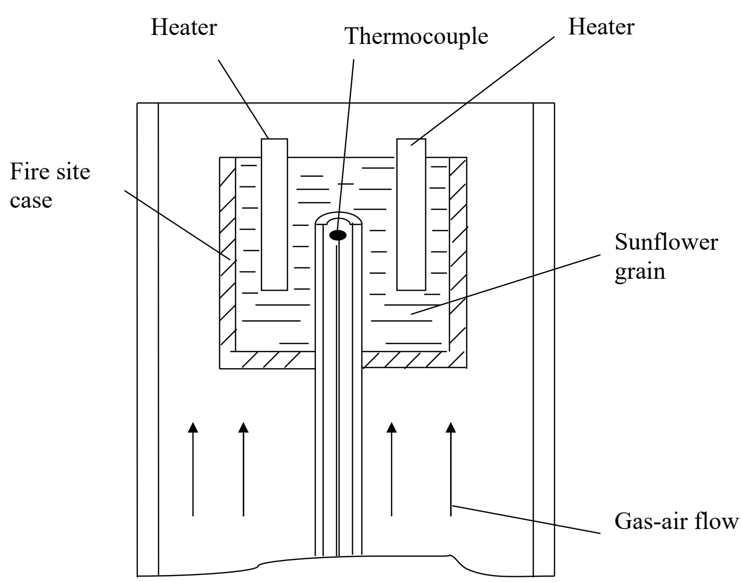

Fig. 3. Sunflower grain fire site

The value of the minimum extinguishing concentration of nitrogen C_{me} (% by volume) was determined by the formula:

$$C_{me} = \frac{V_n}{V_n + V_o}, \qquad (1)$$

where V_r is the nitrogen consumption (dm^3/min) at which the extinguishing of the flame in the model fire is achieved;

V_o – oxidizer flow rate (dm^3/min).

The concentration of oxygen in the gas-air environment was also recorded at which the model fire was extinguished using the INDUSTRIAL SCIENTIFIC M40 GAS analyzer (made in USA).

5. Studies of the conditions for the use of nitrogen to eliminate fire sites of sunflower grain

5. 1. Results of studies of gaseous products of thermal destruction of sunflower grain

The results of determining the volatile pyrolysis products of sunflower grain, which were obtained during the tests and determined on the chromatograph, are given in Table 1.

Table 1

The composition of gaseous products of thermal destruction of sunflower grain

Component	The content of components in volatile products of sunflower grain destruction, % by volume
Carbon dioxin	28.32
Carbon monoxide	51.96
Hydrogen	6.68
Methane	10.41
Ethan	1.02
Propane	0.81
Butane	0.44
Pentane	1.04

As the results of gas chromatographic analysis of the obtained combustible gas mixtures of sunflower grain show (Table 1), they make up a significant amount of combustible gases, in particular, carbon monoxide, over 51 %, hydrogen, about 5.7 %, and hydrocarbons, with a total concentration of 13.72 %. Therefore, it should be expected that to eliminate the combustion sites of such ffires, a certain amount of fire extinguishing agent will be needed.

5. 2. Results of determining the minimum extinguishing concentration of nitrogen when extinguishing a model fire of sunflower grain

The process of extinguishing the model site of sunflower grain is shown in Fig. 4–6.

Table 2 gives the results of determining the minimum extinguishing concentration of nitrogen.

As can be seen from the research results given in Table 2, the termination of combustion of the sunflower grain fire site occurs at a minimum fire extinguishing concentration of about 33.7 % by volume.

To assess the effectiveness of fire protection, we calculated the oxygen concentration that can be achieved by supplying nitrogen, according to the equation given in [16]:

$$C_{O2} = 20.95 - \frac{21.95}{100} \cdot C_{me}. \qquad (2)$$

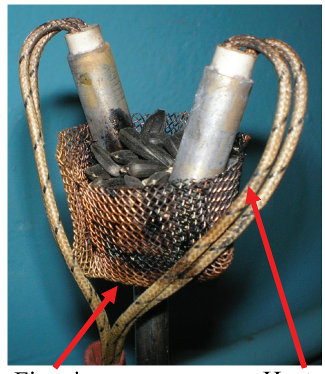

Fig. 4. Model fire of sunflower grain fire

a *b*

Fig. 5. Igniting the model fire of sunflower grain: *a* – heating; *b* – ignition of the fire site

a *b*

Fig. 6. Extinguishing the model fire site of sunflower grain: *a* – suppression of combustion; *b* – the fire site after extinguishing

Table 2

Results of determining the minimum extinguishing concentration of nitrogen at which the combustion of sunflower grain terminated

Experiment No.	Nitrogen volume, dm^3/min	Nitrogen C_{MB} value (% by volume)
1	10.1	33.62
2	9.8	32.82
3	9.9	33.12
4	9.8	32.88
5	10.2	33.78

The results of studying the concentration of oxygen in the gas-air environment are given in Table 3.

Table 3

Results of determining the concentration of oxygen at which the combustion of sunflower grain terminated

Experiment No.	Measured oxygen concentration in the gas-air environment, %	The concentration of oxygen in the gas-air mixture, calculated from (2), %
1	14.4	13.90
2	14.2	14.07
3	14.3	14.01
4	14.3	14.06
5	14.1	13.87

The termination of combustion of sunflower grain occurs at a concentration of oxygen in the gas-air environment of about 14 %.

Taking into consideration the results given in Tables 2, 3, using a three-factor simplex-central method of experiment planning in the mathematical environment Statistica 12, statistical processing of results was carried out.

As factors of variation, we chose the amount of nitrogen, dm^3/min (factor X_1); oxygen concentration in the gas-air environment, % (Table 4).

Table 4

Variation factors

Factor	Code	Variation level			Variation interval
		–1	0	+1	
Amount of nitrogen, dm^3/min	X_1	9.8	10	10.2	0.2
Oxygen concentration in the gas-air environment, %	X_2	13.8	14.1	14.4	0.3

As the initial parameter (response function), the minimum fire extinguishing concentration of nitrogen was selected, the value of which was recorded during sample tests. The experiment planning matrix and its mathematical implementation are given in Table 5.

As a result of modeling, regression equations were obtained and ternary surfaces of changes in the initial parameter were constructed depending on changes in variation factors (Fig. 7).

Regression equation:

$$Y_{p.} = 33.124 - 0.502 \cdot X_1 + \\ +1.008 \cdot X_2 + 0.213 \cdot X_1 \cdot X_1 - \\ -0.617 \cdot X_2 \cdot X_2 + 0.395 \cdot X_1 \cdot X_2. \quad (3)$$

The F-criterion was calculated, which is F_c=13.24, and a tabular F-criterion is defined, the value of which is $F_{t.}$=19.3. Given that $F_c<F_t$, it is concluded that the regression equation is adequate.

The results of calculating the optimal ratio of the amount of nitrogen and oxygen concentration according to the regression equation (3) are given in Table 6.

Thus, on the basis of computer simulation, the best value of the amount of nitrogen, which is 10.2 dm^3/min, and the amount of oxygen in the mixture, which is about 13.8 %, was determined.

Table 5

The matrix of the experiment and its implementation

No. of entry	Factor, form		Planning matrix		Response function	
	X_1	X_2	Amount of nitrogen, dm^3/min	Oxygen concentration in gas-air environment, %	Y actual	Y calculated
1	1	1	10.2	14.4	31.78	33.62
2	1	–1	10.2	13.8	32.66	30.81
3	–1	1	9.8	14.4	33.97	33.83
4	–1	–1	9.8	13.8	32.82	32.61
5	1	0	10.2	14.1	33.43	32.83
6	–1	0	9.8	14.1	31.48	33.84
7	0	1	10	14.4	33.22	33.51
8	0	–1	10	13.8	34.83	31.50
9	0	0	10	14.1	34.12	33.12
10	0	0	10	14.1	33.68	33.12
11	0	0	10	14.1	33.16	33.12

Table 6

Calculation of the optimal ratio of the amount of nitrogen and oxygen concentration

X1 ↓	X2 →	–1	–0.75	–0.5	–0.25	0	+0.25	+0.5	+0.75	+1
		13.80	13.88	13.95	14.03	14.10	14.18	14.25	14.33	14.40
–1	9.80	32.61	33.03	33.38	33.65	33.84	33.95	33.99	33.95	33.83
–0.75	9.85	32.29	32.74	33.11	33.40	33.62	33.76	33.82	33.81	33.71
–0.5	9.90	32.00	32.47	32.87	33.19	33.43	33.59	33.68	33.69	33.62
–0.25	9.95	31.74	32.23	32.65	33.00	33.26	33.45	33.56	33.60	33.55
0	10.00	31.50	32.02	32.47	32.83	33.12	33.34	33.47	33.53	33.51
+0.25	10.05	31.29	31.83	32.30	32.70	33.01	33.25	33.41	33.49	33.50
+0.5	10.10	31.10	31.67	32.17	32.59	32.93	33.19	33.37	33.48	33.51
+0.75	10.15	30.95	31.54	32.06	32.50	32.87	33.15	33.37	33.50	33.55
+1	10.20	30.81	31.44	31.98	32.45	32.83	33.15	33.38	33.54	33.62

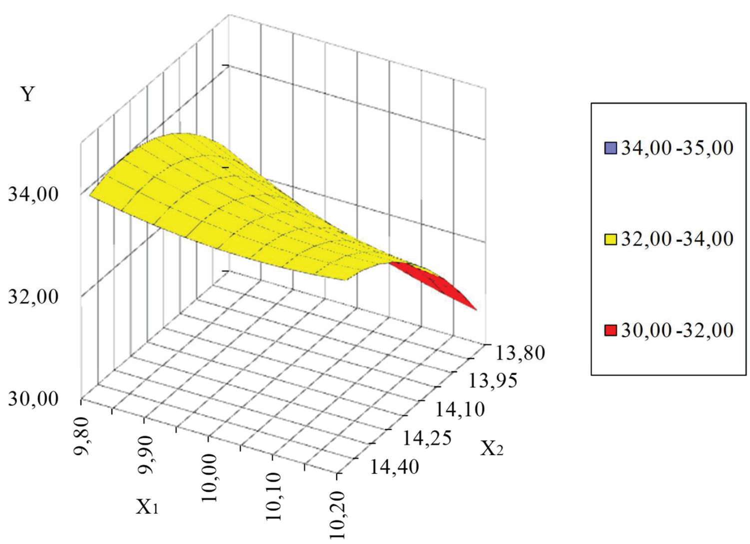

Fig. 7. Ternary surfaces of changes in the initial parameter depending on changes in the factors of variation in the amount of nitrogen and oxygen concentration

6. Discussion of results of the study on the elimination of sunflower grain ignition sites

In the study of volatile pyrolysis products of sunflower grain (Table 1), the process of emitting combustible gases is natural: carbon monoxide, over 51 %; hydrogen, about 5.7 %; and hydrocarbons with a total concentration of 13.72 %. This is due to the fact that to eliminate the fire sites of such fires, one will need a certain amount of fire extinguishing agent.

The data obtained during the elimination of the fire with nitrogen indicate the use of a significant concentration associated with a decrease in the concentration of oxygen in the gas-air environment.

It should be noted that the release of the amount of combustible gases during pyrolysis requires a reduction in the amount of oxygen in the gas-air environment to eliminate fire sites. Obviously, such a mechanism for the decomposition of sunflower grain during pyrolysis is a factor in regulating the process by which the amount of nitrogen to eliminate combustion increases.

This means that taking into consideration this fact opens up the possibility for the effective use of nitrogen directly under the conditions of serial use in the elimination of fire sites in granaries.

Comparison of experimental studies on the composition of gaseous products of thermal destruction of sunflower grain and studies to determine the minimum fire extinguishing concentration of nitrogen at which combustion stopped makes it possible to justify the use of nitrogen. The value of the minimum extinguishing concentration of nitrogen approached 33.7 % by volume.

This does coincide with the practical data well known from works [17, 18], the authors of which, by the way, also associate the elimination of fire with the inhibition of oxidation in the system "combustible substance-oxidizer", or neutralization of high temperature [19]. However, unlike the results of studies published in [4, 9], the data obtained on the effect of the amount of nitrogen on the inhibition of combustion, in particular, on quenching, suggest the following:

– the main regulator of suppression of combustion of the fire of sunflower grain is a change in the concentration of oxygen in the gas-air environment;

– the processes of ventilation of the grain mass with nitrogen have a significant impact on the process of eliminating the fire, maintaining the required level of concentration.

Consequently, the elimination of fire sites is closely related to a decrease in the concentration of oxygen in the gas-air environment, which is confirmed in [11]. At the same time, it is possible to ventilate the grain mass with inert gas in order to concentrate oxygen and stop the development of fire sites.

Such conclusions may be considered appropriate from a practical point of view since they allow a reasonable approach to determining the minimum concentration of nitrogen to eliminate fire sites of sunflower grain. That allows us to assert having determined the mechanism of extinguishing processes of dispersed materials, which are certain advantages of this study.

However, it is impossible not to note that the results of our determining (Tables 2, 3) indicate the ambiguous effect of the change in nitrogen concentration on the process of extinguishing a fire site. This is manifested, first of all, in the concentration of oxygen at which the combustion of sunflower grain was stopped. Such uncertainty imposes certain restrictions on the use of the results obtained, which can be interpreted as the shortcomings of this study. The inability to remove restrictions within the study gives rise to a potentially interesting direction for further research. In particular, it can be focused on identifying the moment of time when nitrogen is supplied from which the intense inhibition of flame combustion begins. Such a detection will make it possible to investigate the structural transformations in the fire sites of sunflower grain, which begin to occur at this time, and to determine the input variables of the process that significantly affect the beginning of such a transformation.

7. Conclusions

1. The results of our gas chromatographic analysis of the obtained combustible gas mixtures of sunflower grain showed that they constitute a significant amount of combustible gases, in particular, carbon monoxide, over 51 %; hydrogen, about 5.7 %; and hydrocarbons, with a total concentration of 13.72 %.

2. Based on our results of experimental studies on the elimination of the fire site of sunflower grain, it was established that the termination of the fire occurs at a minimum fire extinguishing concentration of about 33.7 % by volume. The concentration of oxygen in the gas-air environment decreases to the level of 14 %. Based on the computer simulation, the best value of the amount of nitrogen of 10.2 dm^3/min was determined, which ensures the fulfillment of the task, and the amount of oxygen in the mixture of about 13.8 %.

Conflict of interests

The authors declare that they have no conflict of interests 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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