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IDENTIFYING THE REGULARITIES OF N-HEPTANE FLAME INHIBITION BY INORGANIC COMPOUNDS

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The task related to using inorganic compounds for extinguishing flames is to enable their inhibitory capacity during operation within wide limits. Therefore, the object of the current research was aqueous solutions of inorganic salts, on which the effectiveness of inhibitory properties during interaction with n-heptane flame was established. It has been proven that increasing the mass flow rate of water by 1.5 mg/s reduces the intensity of OH-radicals radiation from 70 % to 30 % and lowers the flame temperature by 90 °C. However, it was found that when potassium salts are given, the intensity of OH-radicals radiation decreases by more than 6 times, potassium chloride and sulfate reduce the intensity of OH-radicals radiation by more than 2.8 times. Among ammonium salts, salts of dihydrogen phosphate and ammonium hydrogen phosphate reduce the relative intensity of radiation of OH radicals by more than 1.3 times. Sodium salts include nitrates and sodium chloride, which reduce the relative radiation intensity of OH radicals by more than 1.6 times. This is manifested, first of all, in the enrichment of the combustible environment with fuel. When determining the flame temperature of flammable liquids, it was established that n-heptane has the most stable and highest flame temperature, which is 1768 °C. When adding inorganic compounds to the flame of n-heptane, nitrate salt, and potassium chloride, the flame temperature increased by less than 20 °C. However, ammonium salts increased the flame temperature to over 140 °C, despite the presence of water. The practical significance is that the results were taken into account during the design and development of extinguishing agents for extinguishing fires. Therefore, there are reasons to assert the possibility of regulating flame extinguishing processes by using inorganic compounds capable of inhibiting active flame radicals

Keywords: fire extinguishing agents, n-heptane flame, flame inhibition, flame active radicals, flame temperature

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1. Introduction

Despite the wide use of various substances for extinguishing fires, trends are observed to expand the scope of application of water-based fire extinguishing mixtures. The mechanism for stopping the burning of such a substance implies cooling the zone of chemical reaction, and, as a result, reducing the reaction rate and reducing heat generation. In addition, due to the decrease in the temperature in the combustion zone, the thermal destruction of the combustible substance is slowed down and, therefore, the release of volatile combustible substances into the combustion zone is prevented.

Thus, according to the data from the fire statistics center at the International Association of Fire and Rescue Services, it was established that fires most often occur in residential buildings, hotels, and other places of mass occupancy (CFS CTIF 2023, No. 28). However, the use of water for extinguishing fires has certain disadvantages, in particular, resistance to sub-zero temperatures, it does not have an inhibitory effect. In view of this, there is a need to increase the efficiency of water by using inorganic salts.

Today, various liquid fire-extinguishing mixtures based on water are being developed in the world. Given that the fire-extinguishing ability of water is determined mainly by its cooling effect, as well as the fact that water vapor dilutes the combustible medium. However, it can be increased by giving the solution the properties of a chemical flame retardant, i.e., increasing the inhibitory capacity. To this end, a large set of inorganic salts are used as additives; however, some salts are environmentally hazardous and increase the corrosive effect of water, while others do not provide the necessary level of inhibition. In this regard, the use of aqueous solutions for fire extinguishing requires conducting fundamental studies into the effect of high flame temperature on them.

Therefore, research aimed at determining the flame-inhibiting properties of inorganic compounds and establishing the amount of their components in an aqueous solution to inhibit the combustion process is relevant.

2. Literature review and problem statement

In work [1], using theoretical, experimental, and numerical modeling approaches, the complex mechanism of flame inhibition of a preliminary mixture of hydrocarbons/air with monoammonium phosphate ($NH_4H_2PO_4$) powder is studied. Experimental results demonstrate that the laminar burning rate of a premixed CH_4/air/$NH_4H_2PO_4$ flame decreased non-linearly with increasing $NH_4H_2PO_4$ powder concentration. A comparison of the simulated laminar burning rate from the kinetic model with the measurements revealed a fairly good agreement, which proves the dominant chemical inhibition characteristics of $NH_4H_2PO_4$ powder in the CH_4/air premixture flame. Gas-phase chemical kinetic analysis shows that H_3PO_4 plays an important role in reducing the laminar burning rate of a premixed CH_4/air flame with $NH_4H_2PO_4$ powder; however, the effect of NH_3 was negligible. In addition, the catalytic cycles of small phosphorus species absorbed H and OH radicals in the flame, which led to the disappearance of excess free radicals, creating a saturation effect, and reducing the rate of laminar burning. However, no optimal solutions regarding its concentration have been established.

In [2], the effectiveness of inhibition of oxalate and bicarbonate on flame propagation from polyethylene dust explosion was analyzed from two aspects of flame structure and flame propagation speed. The results show that all types of explosion suppression powder can inhibit flame propagation and the inhibition effect increases with increasing powder concentration. At the same inhibitor concentration, $KHCO_3$ had the best explosion suppression performance, followed by $NaHCO_3$, followed by $K_2C_2O_4$ and $Na_2C_2O_4$. That is, the suppression efficiency of the potassium salt powder explosion was better than the suppression efficiency of the sodium salt explosion with the same acid radical ion. And the explosion suppression efficiency of bicarbonate powder was better than that of oxalate with the same metal ion. From a chemical point of view, powders can be subjected to pyrolysis with the formation of active free radicals Na·and K and react with highly active radicals H·and OH. They are formed as a result of the interaction, with the formation of Na⇔NaOH and K⇔KOH cyclic reaction, and then plays the role of suppressing the explosion, interrupting the chain reaction. However, bicarbonate powder mainly performs the functions of thermal desorption, oxygen dilution, and thermal protection, while oxalate only has the functions of oxygen dilution and thermal shielding.

In order to determine the best explosion suppressant for Al-Mg alloy dust explosion, the inhibitory effects of $Al(OH)_3$ and $Mg(OH)_2$ powders on Al-Mg alloy explosion were investigated [3]. The flame suppression experiment was conducted using a modified Hartmann tube experimental system. The experiment was conducted using an experimental spherical explosion system with a volume of 20 L, as well as suppression mechanisms for two types of powders on Al-Mg alloy dust. The results demonstrate that by increasing the mass fractions of $Al(OH)_3$ and $Mg(OH)_2$, the flame height, flame propagation speed, and deflagration explosion pressure can be effectively reduced. When 80 % $Mg(OH)_2$ powder was added, the explosion pressure was reduced to less than 0.1 MPa, and the explosion was contained. Due to the strong polarity of the $Mg(OH)_2$ surface, agglomeration occurs easily; therefore, when the added amount is small, the inhibition effect is weaker than that of $Al(OH)_3$. Since the decomposition temperature of $Mg(OH)_2$ is higher, the same amount absorbs more heat and exhibits stronger adsorption of free radicals. However, it is not said how these materials coalesce during storage.

In work [4], the effect of turbulent fluctuations on combustion inhibition by trimethyl phosphate (TMP) is studied in turbulent flames of premixed methane and air. Instantaneous flame patterns are detected using the OH-PLIF (planar laser-induced fluorescence) system. The results show that the turbulent combustion regime of a methane/air flame can be changed from a thin reaction zone (TRZ) to a distributed reaction zone (DRZ) regime due to high inhibitor loading. The addition of an agent can obviously reduce the turbulent consumption rate. From the reaction point of view, the difference in turbulent transport between active radicals (H and OH) and phosphorus-containing species (PO_2, HOPO, $HOPO_2$, etc.) can lead to radical reduction. However, nothing is said about the impact on the application technology.

In study [5], experiments were conducted to evaluate the inhibition efficiency of dimethyl methyl phosphonate (DMMP) on a methane/air diffusion flame. An optical diagnostic system (hydroxyl planar laser-induced fluorescence) was used to measure the distribution of OH radicals in flames. The results show that when the concentration of DMMP exceeds 0.6 %, the marginal inhibition efficiency of DMMP decreases to almost zero. The normalized peak OH concentrations are found to remain constant with a value of 0.9 for flames near the extinction limit. Furthermore, the use of DMMP alone could not extinguish the flame even with the addition of 4.59 % DMMP. When the inhibition efficiency of DMMP becomes saturated, a large number of phosphorus-containing molecules agglomerate around the flame. However, particle generation is the cause of the DMMP saturation phenomenon when extinguishing a continuous flow diffusion flame.

In [6], in order to isolate oxygen, reduce temperature, and stop the free radical chain reaction, an inorganic salt inhibitor and a radical scavenger were combined to form a complex inhibitor to prevent coal autoignition. Experimental results show that the complex inhibitor has a coordinated inhibitory effect throughout the entire process of self-ignition of coal with a double physicochemical inhibition effect. Compared with the untreated coal, the amount of CO released from the coal sample treated with the complex inhibitor decreased by 88.7 % at 128 °C, and the degree of inhibition reached 82.5 % at 100 °C. The combined inhibitor plays an inhibitory role by reducing the content of hydroxyl, methyl, methylene groups, and active components containing carbonyl groups in coal, while the relative content of carbonyl compounds is significantly reduced. During the oxygen adsorption and bulking step, free radicals were released from the inhibitor compounds and captured oxygen and carbon free radicals. N,N-Dibenzyl hydroxylamine (DBHA) contains multiple scavenging sites that can simultaneously trap multiple free radicals in the coal. Butylhydroxytoluene (BHT) reacts with free oxygen-containing functional groups to form stable compounds, which interrupts the formation of ketones and aldehydes. However, it would be expedient to investigate the mechanism of inhibition by a complex coal autoignition inhibitor.

Paper [7] discusses the final limits of the influence of chemicals on flame inhibition. Special attention is paid to inhibition cycles that regenerate the inhibitor. It has been demonstrated that for such an inhibitor in a stoichiometric methane/air flame, additive levels in the range of 0.001–0.01 mole percent will reduce the flame speed by approximately 30 %. This efficacy roughly corresponds to the observed behavior of metal inhibitors such as iron pentacarbonyl, which is 2 orders of magnitude more effective than currently used suppressants. However, this correspondence between the behavior of the “ideal inhibitor” and iron carbonyl leads to the fact that only gas-phase processes can explain its inhibitory ability.

Alkali metal compounds such as ($NaHCO_3$)s and (Na_2CO_3)s are widely used fire extinguishing agents that can be distributed as powders or aqueous solutions [8]. To this end, analytical expressions for the decomposition position of these inhibitory particles are searched to reveal the influence of flame and powder properties on the problem of thermal decomposition. The latter is first solved analytically using a simple thermal decomposition model of alkali metals coupled with a two-step chain-branching mechanism for flame chemistry. Numerical simulations using detailed chemistry for CH_4/air and H_2/air flames are then compared. Based on these analytical findings, a model is proposed for a critical particle size above which weak inhibition can be observed. This shows the ability of alkali metal powders to effectively moderate highly reactive mixtures such as C_2H_2/air and H_2/air flames, but there is a need to consider the predicted particle sizes required for rapid decomposition in such cases.

Paper [9] outlines preliminary studies of flame inhibition by metal-containing compounds, and for later work focuses on experimental and modeling studies of inhibited premixes, countercurrent diffusion, and forward diffusion flames by the authors. Strong flame suppression by metal compounds when added at a low volume fraction occurs through catalytic cycles in the gas phase, which leads to highly efficient recombination of radicals into the reaction zone, while the reactions of these cycles occur in some cases at rates close to collision. The effectiveness of the agent requires that the inhibiting species and radicals in the flame overlap, and this can sometimes be limited by the rate of transport in the gas phase. However, the effect of particle formation on the effectiveness of the inhibitor depends on the metal concentration, particle size, time for their formation, flame temperature, and thermophoretic force in the flame.

A comparative study of the suppression efficiency of various water mist additives was conducted in a countercurrent flame apparatus [10]. Introduction of ultrapure water mist 1 ml/min. reduced the critical strain rate by 14 %. Chemical additives can improve the suppression of water mist, except for $FeSO_4$ and H_3PO_4. Their suppression efficiency can be sorted in descending order: organic alkali metal salts ($K_2C_2O_4$, $C_2H_3KO_2$), inorganic alkali metal salts (KCl, $KHCO_3$, K_3PO_4), phosphorus-containing compounds (K_3PO_4, $NH_4H_2PO_4$, H_3PO_4), and inorganic iron compounds ($FeCl_2$, $FeSO_4$). It is assumed that the effectiveness of chemical additives in suppressing highly stretched diffusion may depend on the following factors: chemical nature, residence time controlled by conditions, and residual particles containing the additives. However, the values of these factors do not cover the full range of applications.

Work [11] shows that the process of decomposition of inhibitors can be adequately represented by one irreversible step for trimethyl phosphate (TMP). Subsequently, graph-based mechanism reduction methods and sensitivity analysis are used to highlight key catalytic inhibition reactions. The resulting skeletal kinetic mechanism consists of 4 types and 7 reactions. This work also proposes a global mechanism containing 3 species and 3 reactions. In the global model, flame inhibition is described by a 2-stage model. These models are validated in premixed and diffuse flame environments. The development of skeleton/global models reduces the computation time by about 82 % compared to the detailed model. However, no mention is made of the effect on quenching.

Thus, it was established from the literature [1–4, 6, 8, 10] that inorganic compounds are capable of inhibiting hydrocarbon flames during fire extinguishing during operation. However, the parameters that ensure high efficiency in reducing the active radicals of the flame, the values of which are necessary for the design and manufacture of fire extinguishing agents, have not been determined. A small number of experimental studies to explain and describe the inhibition process leads to a decrease in their effective use. Therefore, establishing the parameters of flame inhibition and the influence of inorganic compounds on the process of extinguishing the flame predetermined the need for research into this area.

3. The aim and objectives of the study

The aim of our work is to identify the regularities of n-heptane flame inhibition by aqueous solutions of inorganic salts. This makes it possible to substantiate the mechanism of action of ammonium salts, urea, and alkali metal salts for extinguishing hydrocarbon flames.

To achieve the goal, the following tasks were solved:

– conducting the modeling of a hydrocarbon flame inhibition process when interacting with aqueous solutions of inorganic salts;

– establishing characteristics of the change in flame temperature during interaction with a combustion inhibitor.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of research is the inhibitory properties of aqueous solutions of inorganic salts based on ammonium salts, urea, and alkali metal salts during interaction with n-heptane flame.

The scientific hypothesis assumes that n-heptane flame flammability decreases when it interacts with aqueous solutions of inorganic salts.

In the course of the research, the following assumptions and simplifications were adopted, which relate to the peculiarities of the combustion process of n-heptane and other processes at the modeling object:

– which determine the impact of changes in external conditions on the object of research and the lack of interrelationships between process implementations, namely: the course of the process of supplying inorganic compounds to the flame is the same, temperature, humidity, and pressure are not variable;

– a sample of the vapor-air mixture during combustion is homogeneous.

4. 2. Researched materials used in the experiment

Heptane vapor obtained by the carburation method was used as a fuel. The studied solution was sprayed using a pneumatic nozzle and fed into the flame coaxially with it. Solutions of halides, carbonates, sulfates, nitrates, sodium, and potassium phosphates, and ammonium phosphates of various concentrations (2.5; 5.0; 10.0; and 20.0 % wt) were used to conduct research on the determination of the inhibitory capacity of inorganic compounds. The studied inorganic salt solution was sprayed using a pneumatic nozzle and fed into the flame coaxially with it.

4. 3. Methodology for determining n-heptane flame inhibition indicators

Determination of n-heptane flame inhibition indicators by inorganic compounds was carried out by evaluating radiation. Flame radiation was recorded using the SDL-1 spectrometer. The scheme of tests to determine the inhibitory ability of inorganic compounds on n-heptane flame is shown in Fig. 1.

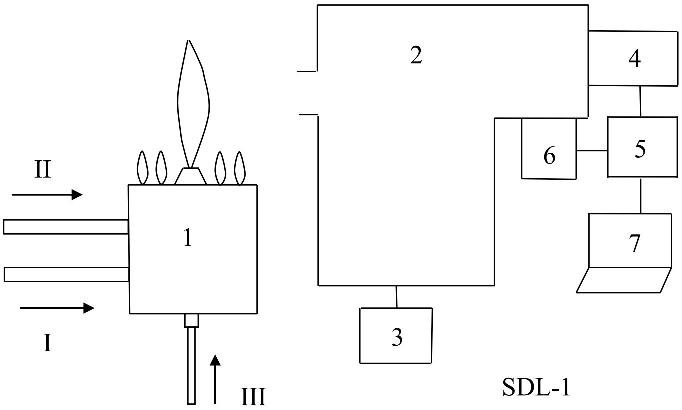

Fig. 1. Schematic of n-heptane flame inhibition research: 1 – burner; 2 – monochromator of the SDL-1 spectrometer; 3 – engine control unit; 4 – photoelectronic multiplier; 5 – amplifier; 6 – photo receiver; 7 – personal computer

The measure of the inhibitory action was taken to be a decrease in the emission intensity of the 3064 Å band belonging to the OH radical, which is responsible for the propagation of the combustion chain reaction. Also, to confirm the mechanism of n-heptane flame inhibition, CH-radicals (4315 Å band emission) were measured, which confirms the enrichment of the flame with fuel, and C_2-radicals (5636 Å band emission), which characterizes carbon cracking in the flame The essence of the method for determining the flame inhibition of n-heptane is the decomposition of the radiation spectrum during the interaction of the substance with the flame and the registration of radiation bands on the spectrometer.

The effect of sprayed water and salt solutions on the flame temperature was also studied. The research was carried out using the SDL-1 spectrometer. The flame temperature determination scheme is shown in Fig. 2.

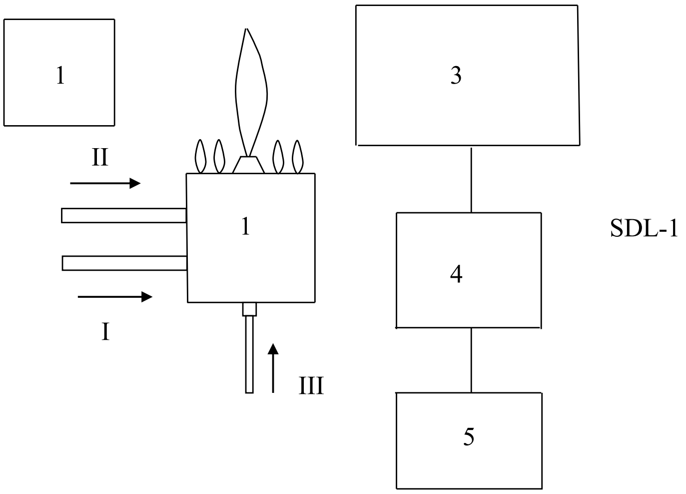

Fig. 2. Schematic of determining the flame temperature of a combustible substance: 1 – radiation source (lamp TRSH 2850-3000); 2 – burner; 3 – monochromator of the SDL-1 spectrometer; 4 – photo detector; 5 – microscope

The flame temperature was measured by the inversion of the spectral lines along the resonance lines of sodium. As a source of comparison, the reference tape lamp TRSH 2850-3000 was used. The absorption spectrum was observed using an optical microscope.

The essence of the method for determining the flame temperature of a combustible substance by the optical method is based on the change in the spectral intensity of flame radiation depending on the temperature when sodium is added, which gives the flame a yellow color, and is recorded by a microscope.

5. Results of determining the inhibitory characteristics of inorganic compounds when interacting with an n-heptane flame

5. 1. Results of research on changes in active flame radicals upon introduction of aqueous solutions of inorganic salts

The flame temperature of a number of flammable liquids, in particular, n-heptane, nefras, acetone, gasoline (A-80), and ethanol, was investigated. The results are given in Table 1.

Table 1

Results of studies on determining the flame temperature of n-heptane, nephras, acetone, gasoline (A-80), and ethanol

Substance	Average flame temperature, °C
n-heptane	1768
nefras	1750
acetone	1707
gasoline (A-80)	1660
ethanol	1692

As can be seen from Table 1, the highest flame temperature was determined in n-heptane; therefore, the influence of inorganic compounds on the flame temperature was determined with this hydrocarbon.

Fig. 3 shows the results of studies on determining the effect of water on the intensity of radiation of active flame radicals.

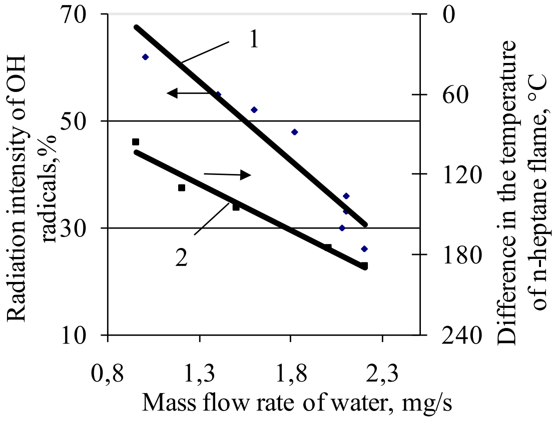

Fig. 3. Dependence of the relative radiation intensity of OH radicals (1) and the n-heptane flame temperature (2) on the mass flow rate of water supplied to the burner

From Fig. 3, it was established that with an increase in the mass flow rate of water supplied to the burner, the flame temperature decreases (Fig. 1).

Thus, an increase in the mass flow rate of water by 1.5 mg/s reduces the flame temperature by 90 °C. Similar to this dependence, the intensity of OH-radical radiation decreases.

Fig. 4–6 show the results of studies on determining the effect of aqueous solutions of inorganic salts on the intensity of radiation of active flame radicals.

From Fig. 4, it was established that potassium nitrate has the greatest inhibitory effect on the flame of n-heptane from potassium salts since its concentration at 20 % wt reduces the radiation intensity of OH radicals by more than 6 times. However, other compounds also inhibit the flame to a sufficient extent, in particular, potassium chloride and sulfate, which reduce the intensity of OH-radicals radiation by more than 2.8 times.

As can be seen from Fig. 5, dihydrogen phosphate and ammonium hydrogen phosphate have the greatest inhibitory effect among ammonium salts, which reduce the relative intensity of OH-radicals radiation by more than 1.3 times. Among sodium salts (Fig. 6), nitrates and sodium chloride have the greatest inhibitory effect on the flame of n-heptane, which reduce the relative intensity of radiation of OH radicals by more than 1.6 times.

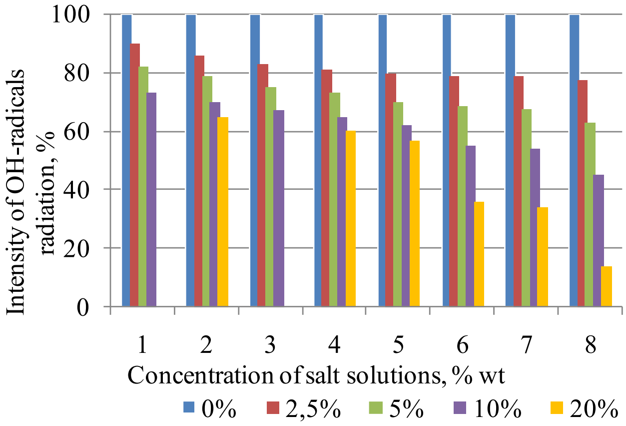

Fig. 4. Dependence of the relative intensity of OH-radicals radiation on the concentration of salt solutions supplied to the burner: 1 — potassium dihydrogen phosphate (KH_2PO_4); 2 — potassium bromide (KBr); 3 — potassium sulfate (K_2SO_4); 4 — potassium bicarbonate ($KHCO_3$); 5 — potassium carbonate (K_2CO_3); 6 — potassium fluoride (KF); 7 — potassium chloride (KCl); 8 — potassium nitrate (K_2NO_3)

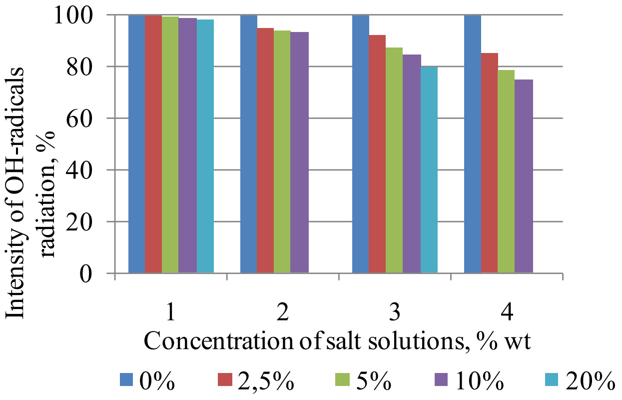

Fig. 5. Dependence of the relative intensity of OH-radicals radiation on the concentration of salt solutions supplied to the burner: 1 — urea ($CO(NH_2)_2$); 2 — ammonium nitrate (NH_4NO_3); 3 — ammonium hydrogen phosphate ($(NH_4)_2HPO_4$); 4 — ammonium dihydrogen phosphate ($NH_4H_2PO_4$)

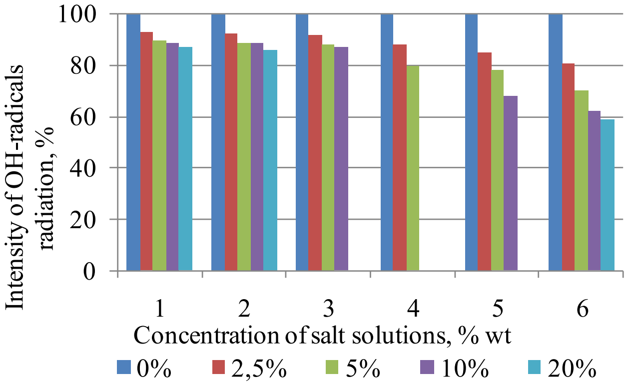

Fig. 6. Dependence of the relative intensity of OH-radicals radiation on the concentration of salt solutions supplied to the burner: 1 — sodium acetate ($NaCH_3COO$); 2 — sodium sulfate (Na_2SO_4); 3 — sodium bicarbonate ($NaHCO_3$); 4 — sodium fluoride (NaF); 5 — sodium chloride (NaCl); 6 — sodium nitrate ($NaNO_3$)

Thus, from Fig. 4–6 it follows that when salt solutions are fed into the flame, the intensity of OH-radicals radiation decreases. The obtained data indicate that solutions of potassium salts in general have a greater inhibitory effect on the flame than ammonium and sodium salts. Of the potassium and sodium salts, nitrates and halides are the most effective in their inhibitory effect, and of the ammonium salts, monoammonium phosphate.

The main inhibitory effect of inorganic compounds is the reduced concentration of active free radicals in the flame. However, effective schemes of inhibition are represented by two important types of elementary reactions: those as a result of which active centers are captured (Fig. 7, 1a–1d), thus stopping the further development of chains, and those in which inhibitory particles are regenerated (Fig. 7, 2a–2d). In this regard, a study was conducted to determine the emission of CH-radicals and C_2-radicals during flame inhibition, which is illustrated in Fig. 8, 9.

Fig. 8, 9 show the resulting regression dependences of the radiation intensity of radicals on the concentration of salt solutions, which are described by equations of the type:

$$v(t)=a_0+a_1 \cdot t+a_2 \cdot t^2, \tag{1}$$

where t is the concentration of aqueous inorganic salt solutions, % wt;

a_0, a_1, a_2 are regression coefficients.

Experimental data were processed by the method of least squares. Variance was minimized:

$$D=[v(t_i)-I_i]^2, \tag{2}$$

where $v(\tau_i)$ are the theoretical values of radiation intensity determined by formula (1);

I_i – experimental values of radiation intensity.

After minimizing D, the mean square deviation σ was calculated using the formula:

$$\sigma=\sqrt{D/(n-n_0)}, \tag{3}$$

where n is the number of measurements; n_0 is the number of unknown parameters.

The results of experimental data processing on n-heptane flame inhibition by salt solutions are given in Table 2.

The difference between experimental and calculated values does not exceed 5 %, which is considered reliable in engineering calculations.

$$KNO_3+Fuel \rightarrow K_2O+M, \qquad 1a$$
$$K_2O+H^{\bullet} \rightarrow 2KOH, \qquad 1b$$
$$KOH+OH+OH^{\bullet} \rightarrow H_2O+KO^{\bullet}, \qquad 1c$$
$$KO^{\bullet}+H^{\bullet} \rightarrow KOH. \qquad 1d$$
$$K+O_2+M \rightarrow KO_2+M \qquad 2a$$
$$KO_2+H_2 \rightarrow KOH+OH \qquad 2b$$
$$KO_2+OH \rightarrow KOH+O_2 \qquad 2c$$
$$K+HO_2 \rightarrow KO_2+H \qquad 2d$$

Fig. 7. Scheme of inhibition of flame reactive radicals

Table 2

Deviation of the radiation intensity of n-heptane flame radicals under the action of salt solutions supplied to the burner

Inorganic salt sample	Parameter value			
	CH-radicals		C_2-radicals	
	D	σ	D	σ
Potassium nitrate (K_2NO_3)	0.0961	0.219203	0.000529	0.016263
Potassium chloride (KCl)	0.099225	0.222739	0.0025	0.035355
Potassium carbonate (K_2CO_3)	0.100489	0.224153	0.054289	0.164756
Potassium bromide (KBr);	0.097344	0.220617	0.038025	0.137886
Potassium dihydrogen phosphate (KH_2PO_4)	0.043681	0.147785	0.088804	0.210718
Ammonium hydrogen phosphate ($(NH_4)_2HPO_4$)	0.088209	0.210011	0.000361	0.013435

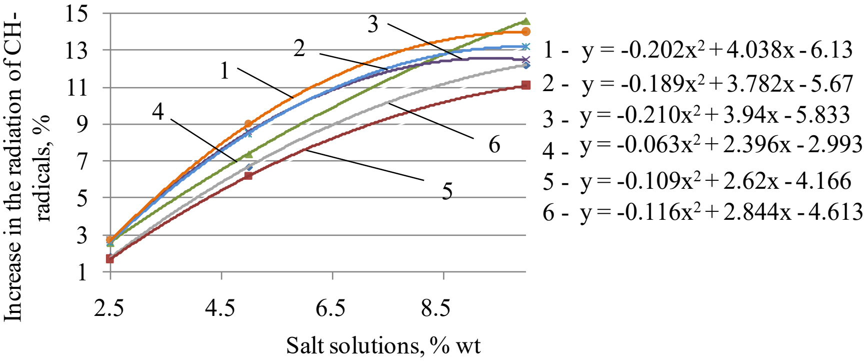

Fig. 8. Dependence of the intensity of CH-radicals radiation on the concentration of salt solutions fed to the burner: 1 — potassium nitrate (K_2NO_3); 2 — potassium chloride (KCl); 3 — potassium carbonate (K_2CO_3); 4 — potassium bromide (KBr); 5 — potassium dihydrogen phosphate (KH_2PO_4); 6 — ammonium hydrogen phosphate ($(NH_4)_2HPO_4$)

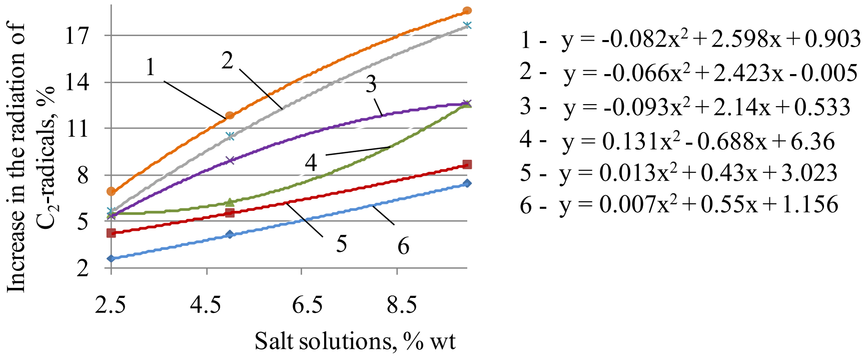

Fig. 9. Dependence of the intensity of radiation of C_2 radicals on the concentration of salt solutions fed to the burner: 1 — potassium nitrate (K_2NO_3); 2 — potassium chloride (KCl); 3 — potassium carbonate (K_2CO_3); 4 — potassium bromide (KBr); 5 — potassium dihydrogen phosphate (KH_2PO_4); 6 — ammonium hydrogen phosphate ($(NH_4)_2HPO_4$)

As can be seen from Fig. 8, 9 when inhibiting the n-heptane flame simultaneously with a decrease in OH radicals, an increase in CH radicals and C_2 radicals was established, which, accordingly, characterizes the enrichment of the flame with fuel.

5. 2. Results of studies on the effect of inorganic compounds on the temperature of n-heptane flame

The results of determining the flame temperature of n-heptane when adding aqueous solutions of inorganic salts are shown in Fig. 10.

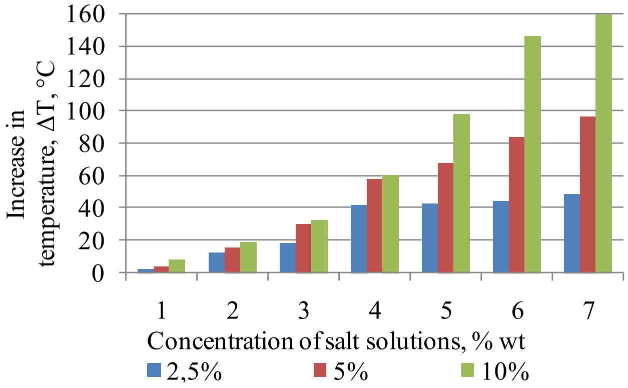

Fig. 10. Dependence of the n-heptane flame temperature increase on the concentration of salt solutions fed to the burner: 1 – potassium nitrate (K_2NO_3); 2 – potassium chloride (KCl); 3 – potassium hydrogen carbonate ($KHCO_3$); 4 – potassium bromide (KBr); 5 – potassium dihydrogen phosphate (KH_2PO_4); 6 – ammonium dihydrogen phosphate ($NH_4H_2PO_4$); 7 – ammonium hydrogen phosphate ($(NH_4)_2HPO_4$)

From Fig. 9, it was established that the greater the inhibitory efficiency of the salt, the smaller the temperature increase caused by the introduction of the solution into the flame. When adding inorganic compounds to the flame of n-heptane, nitrate salt, and potassium chloride, the flame temperature increased by less than 20 °C. However, ammonium salts increased the flame temperature to more than 140 °C, despite the presence of water.

This indicates that under the action of the investigated inhibitors, the decrease in the speed of flame propagation is not related to a decrease in its temperature.

6. Discussion of results of investigating the process of flame inhibition by inorganic compounds

When studying the process of flame inhibition by inorganic compounds, the process of reducing the relative intensity of OH-radicals radiation, which follows from the obtained results, is natural (Fig. 4, 5; Table 3). This is due to the effect of atoms of alkali metals and ammonium salts on the recombination of oxygen atoms during the decomposition of inorganic compounds under the action of flame, which slows down the combustion processes.

It should be noted that the presence of inorganic compounds in the flame leads to the decomposition and formation of alkali metals and phosphorous compounds, followed by interaction with the active radicals of the flame, which leads to inhibition of the speed of flame propagation. Obviously, this mechanism of operation of these inorganic compounds is the factor regulating the process, due to which the reaction mixture is enriched with fuel, as the number of oxygen atoms decreases. In this sense, there is an interpretation of the results of determination of the radiation intensity of CH-radicals and C_2-radicals, namely, an increase in their number when chemical compounds are added to the flame. It was found that the greater the inhibitory efficiency of the salt, the smaller the temperature increase caused by the introduction of the solution into the flame. This indicates that under the action of the investigated inhibitors, the decrease in the speed of flame propagation is not related to a decrease in its temperature.

This means that there is an opportunity for effective fire extinguishing and the use of fire extinguishing devices with the direct application of aqueous solutions of inorganic salts at objects of various purposes.

A comparison of experimental studies on flame inhibition by inorganic compounds and studies on the magnitude of the increase in flame temperature indicates inhibition of flame combustion processes. At the same time, it was established that the lower the flame temperature, the higher the inhibitory efficiency of the aqueous salt solution (Fig. 9). This does not differ from the practical data, well known from works [1, 6], the authors of which also relate the effectiveness of extinguishing the flame during the decomposition of an inorganic compound under the influence of a flame. But, in contrast to the results of studies reported in [12, 13], the data on the effect of combustion inhibitors on the process of slowing down the burning rate allow us to state the following:

– the main regulator of the process is not so much the formation of a significant number of atoms of alkali metals or phosphorus compounds, which are released during the decomposition of inorganic salts and inhibit the flame, but also suppression of combustion since certain fire extinguishing substances neutralize the combustible environment from oxygen;

– a significant influence on the process of extinguishing a hydrocarbon flame when using surface-active substances is carried out in the direction of the formation of a heat-insulating layer on the surface of the combustible liquid.

Such conclusions can be considered appropriate from a practical point of view because they allow for a reasonable approach to the inhibition of the hydrocarbon flame by inorganic compounds when the isolation of oxygen of the hydrocarbon flame begins [14, 15]. From a theoretical point of view, they allow us to assert the determination of the mechanism of the processes of both a decrease in the relative intensity of OH-radicals radiation and a change in the flame temperature, which are certain advantages of this study. However, it is impossible not to note that the results of the determination (Tables 7, 8) indicate an ambiguous influence of inorganic compounds on the change in the intensity of radiation of CH-radicals and C_2-radicals. This manifests itself, first of all, in the enrichment of the combustible environment with fuel, which is formed during the recombination of oxygen atoms.

Such uncertainty imposes certain restrictions on the use of our results, which can be interpreted as the shortcomings of this study. The impossibility of removing the mentioned limitations within the framework of this study gives rise to potentially interesting areas of further research. In particular, they can be aimed at detecting the moment of time when the fire-extinguishing properties of inorganic compounds begin to decline under the influence of high temperature. This will make it possible to investigate the structural transformations of inorganic compounds that begin to occur at this time, and to determine the input variable parameters of the process that significantly affect the onset of such a transformation.

7. Conclusions

1. It was experimentally established that increasing the mass flow rate of water by 1.5 mg/s reduces the flame temperature by 90 °C. Similar to this dependence, the radiation intensity of OH radicals decreases from 70 % to 30 %.

When adding inorganic compounds to the flame of n-heptane, it was established that potassium nitrate possesses potassium salts since its concentration at 20 % by weight reduces the radiation intensity of OH radicals by more than 6 times. However, other compounds also inhibit the flame to a sufficient extent, in particular, potassium chloride and sulfate, which reduce the intensity of OH-radicals radiation by more than 2.8 times. Among ammonium salts, dihydrogen phosphate and ammonium hydrogen phosphate have the greatest inhibitory effect, reducing the relative intensity of OH-radicals radiation by more than 1.3 times. Sodium salts include nitrates and sodium chloride, which reduce the relative radiation intensity of OH radicals by more than 1.6 times.

2. When determining the flame temperature of combustible liquids, it was established that n-heptane has the most stable and highest flame temperature, which is 1768 °C. When inorganic compounds were added to the flame of n-heptane, nitrate salts, and potassium chloride, the flame temperature was increased by less than 20 °C, but ammonium salts increased the flame temperature by more than 140 °C, despite the presence of water.

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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