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REDUCING THE INTENSITY OF THERMAL RADIATION AT THE SUBLAYER EXTINGUISHING OF ALCOHOLS BY ECOLOGICALLY ACCEPTABLE AEROSOLS

V. Balanyuk
Doctor of Technical Sciences,
Associate Professor*
E-mail: bagr33@ukr.net
A. Kravchenko
Leading Inspector
State Emergency Service of Ukraine
in the Lviv Region
Pidvalna str., 6, Lviv, Ukraine, 79008
E-mail: anton.kravchenko101@gmail.com
O. Harasymyuk
PhD*
E-mail: Garas777@ukr.net
*Department of Environmental Safety
Lviv State University of Life Safety
Kleparivska str., 35, Lviv, Ukraine, 79007

This paper has theoretically substantiated and experimentally established the intensity of thermal radiation at burning and sublayer extinguishing of alcohols with environmentally acceptable aerosols.

An installation has been improved that determines the effectiveness of sublayer extinguishing with fire-extinguishing aerosols; a procedure that has been devised for determining the intensity of thermal radiation implies equipping it with an additional heat flow meter HFM–01 at a distance of 30 and 60 mm.

The task to establish the intensity of thermal radiation when burning alcohols and its impact on the process of sublayer extinguishing of alcohols with aerosols has been solved. The dependence of sublayer extinguishing efficiency on thermal radiation implies that the fire extinguishing aerosol completely shields the surface of the combustible liquid against its action.

The result of this study has established that the intensity of thermal radiation at a distance of 60 and 30 mm from the surface of an alcohol flame with an area of 234 cm^2 ranges from 0.8 to 4.7 kW/m^2; the intensity of burning and, accordingly, radiation, maximizes on seconds 30–40 of burning.

It has been found that the intensity of thermal radiation for ethanol decreases with the addition of an aerosol with an intensity of up to 0.2 g/s, and decreases even more at the intensity of supply from 1.2 g/s. With a further increase in the intensity of aerosol supply, the radiation intensity begins to decrease, probably due to a decrease in the rate of combustion. In this case, the flame first decreases in size up to 2 times, and then, after 2–3 seconds, it goes out. The use of fire-extinguishing aerosol for the sublayer extinguishing of alcohols ensures the effect of several factors that synergize and reduce the intensity of evaporation, burning, and, accordingly, thermal radiation

Keywords: fire-extinguishing aerosol, ethyl alcohol, ethanol, n-butanol, alcohol, isobutanol, sublayer fire extinguishing

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1. Introduction

Extinguishing liquids in tanks using foam extinguishing agents is currently the most common way to extinguish and prevent fires and explosions of alcohols and their vapor-air mixtures. The use of foaming solutions for sublayer extinguishing requires a complex infrastructural system for supplying a foaming agent, mixing it in the right proportion with water, and foam formation in a foam generator. A foaming agent in the mixture with water at appropriate proportions ensures the formation of foam that falls on the surface of the combustible liquid and ensures insulation of the surface of the liquid from the atmosphere preventing the contact of alcohol vapors with air. To extinguish alcohol, it is necessary to use a foaming agent for special purposes, since foam from a general-purpose foaming agent is actively destroyed at the surface of the polar combustible liquid due to its rapid dissolution in alcohol. In this case, the entire volume of foam enters the alcohol thereby polluting it.

Alcohol fires are characterized by significant scale, explosions before, during, or after a fire, significant damage, and subsequent environmental pollution both with alcohol burning products and foaming solution. In addition, to extinguish the fires of alcohols, one needs a significant amount of a foaming agent; sometimes its volume is several times larger than the volume of alcohol. Thus, on June 23, 2018, a fire occurred on the territory of the Zbarazh distillery in the Ternopil oblast (Ukraine) due to the explosion of ethanol-containing tanks [1]. The fire took more than 24 hours to eliminate and involved a significant volume of the foaming agent to extinguish it, as the stock of the foaming agent available at the plant was not enough. Extinguishing was complicated by a significant heat flow that formed as a result of ethanol burning. In the United States, in Baltimore [2], on May 14, an accident occurred on the bridge with a tanker truck carrying ethanol, which spilled and started burning. Four fire trucks were involved in the elimination of the accident, which supplied foam, however, the extinguishing was complicated by the fact that the alcohol leaked from the tank, and the foam did not effectively cover its surface in an upright position. In this case, the intensity of the heat flow from the fire was also significant and caused the ignition of combustible materials next to the fire. Thus, it is a relevant task to reduce the intensity of thermal radiation from this type of fire.

2. Literature review and problem statement

In order to reduce the cost, improve efficiency, speed of extinguishing, scientists are searching for new ones and improving existing means for extinguishing alcohols. Thus, the author of work [3] investigated the burning of eight combustible liquids and found that the intensity of thermal radiation of ethanol burning at significant volumes of burning is almost approaching the values for heptane, which, given the complexity of alcohol extinguishing, presents an additional problem. It should also be noted that it follows from the results reported in [3] that when extinguishing ethanol and other alcohols on a large scale, it is necessary to take into consideration the intensity of thermal radiation of their flame as one of the main factors that complicate the extinguishing and can cause ignition of the surrounding tanks and combustible materials. This issue is not studied in detail when extinguishing with fire extinguishing foams and is not investigated at all for the sublayer extinguishing with fire-extinguishing aerosols. Paper [4] describes the process of extinguishing 14 polar liquids with alcohol-resistant foaming agents. The authors indicate that not every polar liquid could be successfully extinguished by foam. In addition, the authors of [4] showed the factors that affect the effectiveness of extinguishing with foam and lead to its destruction. Such factors are the pressure of saturated vapors, the intensity of thermal radiation, and the chemical interactions between the foam and liquid, which leads to its destruction and flame propagation. The need to resolve this issue leads even to such atypical solutions as extinguishing alcohols in tanks by such means as foam-glass as reported in [5]. The authors experimentally determined the mass burnout rates, as well as the conditions for extinguishing a series of single-atom alcohols for a layer of foam glass of different thicknesses. The authors found that ethanol and isopropanol, despite low flash temperatures, are extinguished with a smaller layer of foam glass than n-butanol, n-pentanol, and n-heptanol. This is due to the lower caloric content of ethanol and isopropanol compared to other alcohols, as well as the presence of a noticeable amount of water in their composition. The authors of [5] found that the mass of granulated foam glass, required for extinguishing alcohols, is at least 15 times less than the mass of alcohol-resistant foam. The financial costs of extinguishing when using foam glass are 6.3 times less than when applying the foaming agent “SOFIR AFFF AR6%”.

For effective extinguishing and prevention of burning and explosions of alcohol-air mixtures, it is necessary to ensure, at the same time, the high efficiency of extinguishing and phlegmatization both within a closed volume and in the open space. Thus, paper [6] reports the results of a study that theoretically substantiated and experimentally confirmed that the effect of additives of phlegmatic gases to aerosols significantly improves the fire extinguishing efficiency of the resulting binary aerosol mixtures. The authors of [6] note that the result of adding nitrogen and carbon dioxide to the aerosol was a decrease in the fire-extinguishing concentration of components of the final binary mixture up to 30 %. The optimal ratios of components in the aerosol-gas mixture were: aerosol, 15 g/m^3; nitrogen, 12.5 %; or, aerosol, 15 g/m^3; carbon dioxide, 7 %. At the specified proportions, the mixture is fire extinguishing for the diffusion flame of heptane at low consumption of components.

The authors of [6] managed to prove that the action of fire-extinguishing aerosols is comprehensive due to the synergistic effect, which is manifested by the strengthening of the action of each component at the correct selection of the formulation composition.

In work [7], the effectiveness of the combined impact of the binary mixture of fire-extinguishing aerosol and CO_2 and N_2 gases to reduce the flame rate of the n-heptane-air mixture was substantiated and experimentally proven. Experimentally, it was found that the action of binary mixtures on the n-heptane-air mixture reduces the rate of flame propagation along it by up to 6.5 times compared to the rate of the flame propagation through the stoichiometric mixture. Taking into consideration the indicated effectiveness values at low concentrations, it could be predicted that the fire-extinguishing aerosols themselves would also demonstrate improved efficiency when extinguishing alcohols within confined volumes.

No less important is the ability of fire-extinguishing aerosol to effectively extinguish combustible liquids in open space. Thus, work [8] describes the process of the successful extinguishing of the 21B standard fire by a jet aerosol in the open space. Unlike foaming agents, the fire-extinguishing aerosol has low fire extinguishing concentrations, long shelf life, low cost, is environmentally acceptable, and, after extinguishing, it is neutralized naturally in the environment.

A very important point is that the burning behavior of a large-scale ethanol fire could differ significantly from the burning of petroleum products [9]. The study of small fires shows that ethanol fire radiation is much lower compared to gasoline and other petroleum products. In Sweden, the authors of [9] conducted a series of tests at 200 square meters of ethanol burning using a mixture of acetone and ethanol. The results showed that the heat flow from the burning of a mixture of acetone with ethanol was about twice as large as that of gasoline over the same area, although gasoline formed a much higher thermal radiation in small-scale tests. The reason for this, as the authors point out in [9], is that a large-scale fire of petroleum products generates a large amount of smoke, which, as a rule, blocks visible parts of the flame, thus reducing thermal radiation. The fire from the mixture of acetone with ethanol almost did not contain smoke, and, accordingly, the emitted heat was not dispersed by smoke. The results reported in [9] were obtained during an ethanol tank fire at the Kemble Port in Australia. One of the consequences of this phenomenon may be an increased risk of escalation and the complexity of fire extinguishing operations due to the greater heating of personnel and equipment. At the same time, as the authors point out, the fire was not extinguished while the alcohol simply completely burned out. As for the heat flow from fires with ethanol, there is an interesting dependence, which takes into consideration the blackness of the flame, the intensity of soot formation, and the rate of combustible burning.

Thus, the authors of paper [10] indicate that when burning alcohol in a deco with a diameter of 0.5 m, radiation occurs in the range of 11–14 kW/m^2, which is less than for a hydrocarbon flame of this size by 25–30 %. However, paper [10] indicates that ethanol fires with the addition of gasoline over an area of 254 m^2 are characterized by a significant heat flow, even larger than when burning gasoline, which correlates with the data reported in [8, 9].

One can see that the results of our analysis reveal that a significant stream of thermal energy is also emitted from fires with ethanol, which provides for additional foam destruction, which leads to a decrease in its fire extinguishing efficiency.

Concluding, we can argue that the main factor that would determine the process of burning alcohols is the heat flow from the burning zone to the surface of alcohol, as well as the impact of thermal radiation on the environment. In addition, the environment would receive a solution of a foaming agent, the products of the burning of alcohols, as well as a solution of alcohol itself with the foaming agent. These emissions enter the soils, the terrestrial and underground aquatic environments in which they spread rapidly as a result of their further dilution with water. Vapors of alcohols and products of their burning enter the atmosphere spreading over long distances, thereby polluting large areas. In addition, most foaming agents are biologically tough [11], however, even those that are promoted as environmentally acceptable do not actually fully meet environmental requirements.

Thus, works [12, 13] show that many manufacturers of foaming agents indicate that their products are environmentally friendly and quickly decompose in the environment. However, despite such claims, the authors of the cited work indicate that almost all products cause irreparable harm to the environment.

Thus, in the process of analyzing the literary sources, we have identified problematic areas related to the fact that fire extinguishing foam in contact with alcohol simply dissolves in it. At significant volumes of burning, taking into consideration the earlier conclusions that indicate a significant intensity of radiation, its effect is exerted on the surface of the combustible liquid with foam. This leads to that extinguishing a fire, in this case, requires significantly higher costs than those indicated in the reference literature and specifications. That likely explains the facts given in [8–10] on that large fires of alcohol are impossible, or almost impossible to extinguish.

So, given the above, there remain unresolved issues related to studying the impact of thermal radiation intensity and its effect on the process of sublayer extinguishing of alcohols by the environmentally-friendly aerosols.

Determining those factors that affect the intensity of thermal radiation during the sublayer aerosol extinguishing of alcohols would make it possible to understand the conditions for and mechanism of supplying fire-extinguishing aerosol in order to achieve its greatest extinguishing efficiency.

3. The aim and objectives of the study

The purpose of this study is to establish conditions for reducing the intensity of the thermal radiation of alcohol burning, as well as its impact on the process of the sublayer extinguishing of alcohols by environmentally acceptable aerosols, which would make it possible to devise and improve the technology of the sublayer extinguishing of alcohols as more efficient, low-cost one, as well as providing for the possibility of implementation at domestic enterprises.

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

– to experimentally determine the intensity of radiation from the burning of alcohols at a laboratory installation;

– to experimentally determine the parameters of change in the intensity of radiation from the fire of alcohols at the sublayer aerosol supply;

– to substantiate the factors that drive a decrease in the intensity of thermal radiation during the sublayer extinguishing of alcohols by fire-extinguishing aerosols, as well as their relationship.

4. Materials and methods to study thermal radiation intensity during burning and at the sublayer extinguishing of alcohols

In order to determine the intensity of thermal radiation and its effect on the process of the sublayer extinguishing of alcohols by aerosols, we used an installation for sublayer extinguishing described in work [14]. Ethanol, isopropanol, and n-butanol were chosen as alcohols, taking into consideration their characteristics and the nature of burning. Ethanol burns with an almost transparent blue flame; isopropanol and n-butanol – with red flames without soot secretion. The procedure for determining the intensity of a heat flow from a fire implied the following. The aerosol-forming compound used was a mixture of potassium nitrate and sucrose close to stochiometric.

The designed laboratory installation (Fig. 1) is a rectangular stainless-steel vessel of the following dimensions: width, 153 mm; length, 153 mm; and height, 185 mm. At the bottom of the tank with an area of 234 cm^{2,} there is a distributor, which is a volumetric plate with holes of 5 and 12 mm throughout its entire area for the uniform distribution of aerosol inside the vessel.

According to our procedure, the aerosol-forming compound (AFC) is placed in the receiving chamber and sealed, then we set fire to alcohol and allow 120 seconds for burning. We install and fix the heat flow meters HFM-01 in advance at a distance of 30 and 60 mm from the fire torch. From the moment of ignition to the end of the extinguishing process, we record the intensity indicators of the heat flow from the fire by two HFM-01s. After reaching a stable burning of alcohol (60 s), we set fire to the AFC with an electric lighter, which forms an aerosol that is fed to the distributor, which is located at the bottom of the vessel. Next, the aerosol passes through a layer of liquid and goes to its surface, from where it enters the burning zone. In order to ensure an appropriate burning rate of AFC, cylinders with a certain diameter were fabricated, which ensured their appropriate burning rate.

To determine the intensity of radiation from the ethanol fire site, an experiment was carried out with an aerosol distributor with holes' diameters of 5 mm, which, respectively, reproduce bubbles with an initial size of 5 mm. When the aerosol rises to the surface, its bubbles disperse (crush) and become smaller.

To determine the possibility of supplying the aerosol in a sublayer fashion, the intensity of thermal radiation from the flame of burning of various alcohols (ethanol, isopropanol, n-butanol) and a distance of 30 and 60 mm from the flame was experimentally determined. The dependence of the intensity of thermal radiation at a distance of 30 mm from the surface of the alcohol flame is shown on the charts in Fig. 2, 3.

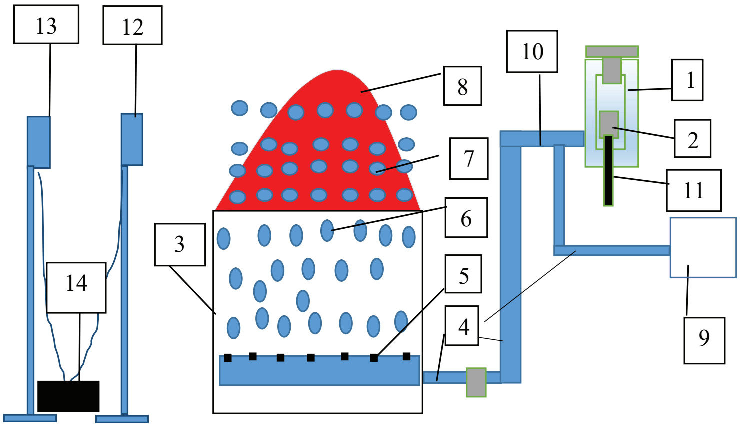

Fig. 1. Installation to determine the parameters of the sublayer extinguishing of alcohols: 1 – receiving chamber; 2 – a charge of AFC of a certain configuration; 3 – thermal insulator; 4 – pipeline; 5 – aerosol sprayer; 6 – aerosol bubbles; 7 – aerosol particles in the burning zone; 8 – diffusion flame of alcohol; 9 – tank with gas; 10 – valves; 11 – ignition source; 12 – the heat flow meter HFM–01 at a distance of 30 mm; 13 – the heat flow meter HFM–01 at a distance of 60 mm; 14 – HFM–01 signal receiver

For each experimental value of the point shown, 2 experiments were carried out, and the average arithmetic value of radiation intensity indicators was determined.

5. Results of studying thermal radiation intensity at burning and sublayer extinguishing of alcohols

5. 1. Experimental determining of radiation intensity caused by the burning of alcohols at laboratory installation

The results of determining the intensity of thermal radiation at a distance of 30 mm, and at a distance of 60 mm, are shown in Fig. 2, 3.

Taking into consideration that the experiment to determine the intensity of thermal radiation of alcohol burning at the sublayer aerosol supply was carried out under laboratory conditions, the data that are shown in Fig. 2–5 were analyzed and represented as regression equations.

The data on chart values given in Fig. 2 are shown as polynomial regression equations (1) to (3).

For ethanol

$$y=2e\text{-}08x^5-1e\text{-}06x^4-5e\text{-}05x^3+$$
$$+0.005x^2-0.015x+0.1164,$$

$$R^2=0.998. \qquad (1)$$

For isopropanol

$$y=1e\text{-}07x^5-2e\text{-}05x^4+0.0009x^3-$$
$$-0.0166x^2+0.152x+0.0869,$$

$$R^2=0.9989. \qquad (2)$$

For n-butanol

$$y=7e\text{-}08x^5-1e\text{-}05x^4+0.0006x-$$
$$-0.0089x^2+0.0696x+0.1693,$$

$$R^2=0{,}9968. \qquad (3)$$

The chart in Fig. 3 shows a change in the intensity of thermal radiation at a distance of 60 mm.

Next, we derived the polynomial regression equations (4) to (6) for the curves shown in the chart in Fig. 3.

For ethanol

$$y=1e\text{-}08x^5-1e\text{-}06x^4+4e\text{-}05x^3-$$
$$-9e\text{-}05x^2+0.0043x+0.0967,$$

$$R^2=0.9937. \qquad (4)$$

For isopropanol

$$y=-2e\text{-}08x^5+2e\text{-}06x^4-8e\text{-}06x^3-$$
$$-0.0017x^2+0.0486x+0.1127,$$

$$R^2=0.9956. \qquad (5)$$

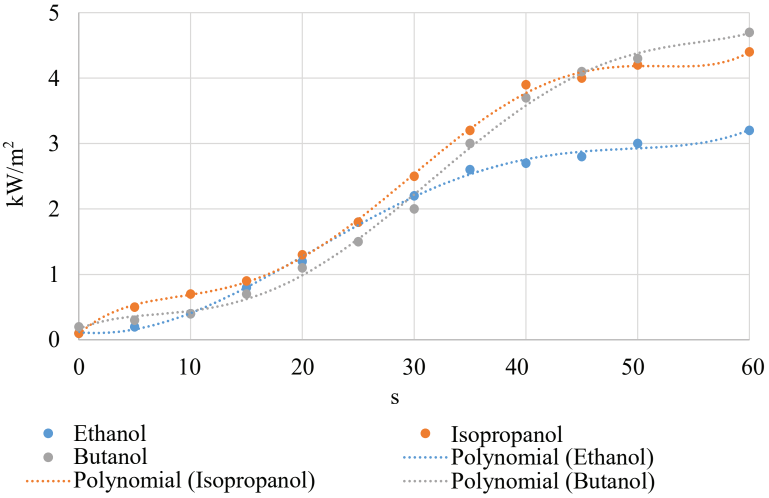

Fig. 2. Intensity of thermal radiation at a distance of 30 mm from the surface of the alcohol flame

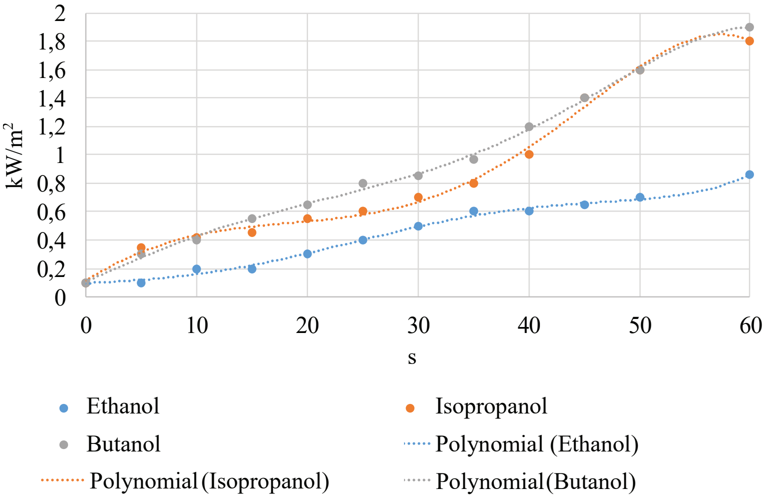

Fig. 3. Change in the intensity of thermal radiation at a distance of 60 mm from the surface of the alcohol flame when supplying the aerosol in a sublayer fashion

For n-butanol

$$y=-1e\text{-}08x^5+2e\text{-}06x^4-5e\text{-}05x^3+$$
$$+0.0002x^2+0.0339x+0.1067,$$

$$R^2=0.9983. \qquad (6)$$

Next, we experimentally determined parameters of the change in radiation intensity during the burning of alcohols at the sublayer aerosol supply.

5. 2. Experimental determination of parameters of the change in radiation intensity during the burning of alcohols at the sublayer aerosol supply

The dependence of the intensity of thermal radiation at a distance of 30 mm from the surface of the alcohol flame when supplying fire-extinguishing aerosol in a sublayer fashion is shown on the chart in Fig. 4.

The results of treating the values of the chart shown in Fig. 4 are given in the polynomial equations (7) to (9).

For ethanol

$$y=7e\text{-}09x^5-2e\text{-}06x^4+0.0001x^3-$$
$$-0.0014x^2+0.0595x-0.0476,$$

$$R^2=0.9153. \qquad (7)$$

For isopropanol

$$y=4e\text{-}08x^5-9e\text{-}06x^4+0.0006x^3-$$
$$-0.0138x^2+0.1657x-0.0344,$$

$$R^2=0.9317. \qquad (8)$$

For n-butanol

$$y=4e\text{-}08x^5-1e\text{-}05x^4+0.0007x^3-$$
$$-0.0151x^2+0.1569x-0.0862,$$

$$R^2=0.9351. \qquad (9)$$

Next, we established the dependence of radiation intensity during the burning of alcohols on the intensity of supply of fire-extinguishing aerosol. The dependence of the intensity of thermal radiation at a distance of 30 mm from the surface of the alcohol flame when supplying fire-extinguishing aerosol in a sublayer fashion is shown in Fig. 5.

The mathematical processing of the intensity values of thermal radiation at a distance of 30 mm from the surface of the alcohol flame when supplying fire-extinguishing aerosol in a sublayer fashion (Fig. 5) showed the results represented by polynomial equations (10) to (12).

For ethanol

$$y=-3.6401x^5+17.231x^4-26.951x^3+$$
$$+14.285x^2-2.4532x+3.2023,$$

$$R^2=0.9971. \qquad (10)$$

For isobutanol

$$y=-4.6172x^5+19.929x^4-28.084x^3+$$
$$+13.468x^2-3.455x+4.3862,$$

$$R^2=0.9979. \qquad (11)$$

For n-butanol

$$y=-5.2003x^5+24.197x^4-37.659x^3+$$
$$+21.057x^2-4.8597x+4.6988,$$

$$R^2=0.9969. \qquad (12)$$

The value of R^2 on the charts (Fig. 2–5) is quite close to unity, which explains the high reproducibility of data in the derived equations.

Obtaining these data would make it possible to predict the behavior and effectiveness of the sublayer extinguishing by a fire-extinguishing aerosol at different values of the intensity of its supply.

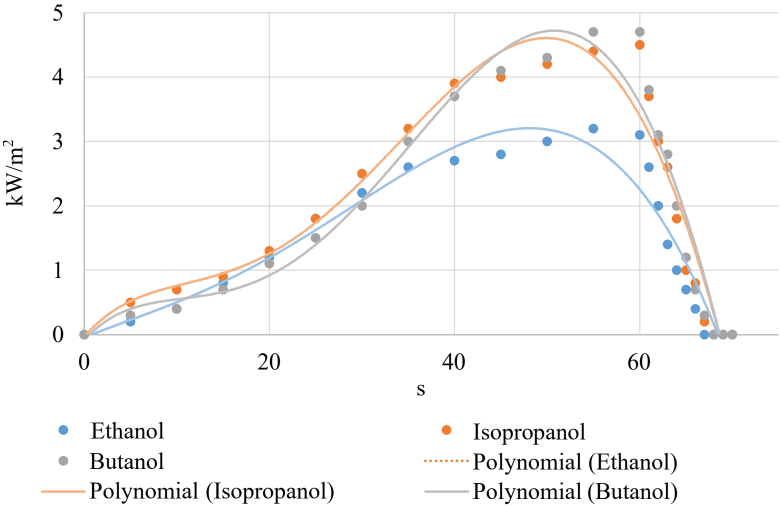

Fig. 4. The intensity of thermal radiation at a distance of 30 mm from the surface of the alcohol flame during sublayer extinguishing with fire-extinguishing aerosol

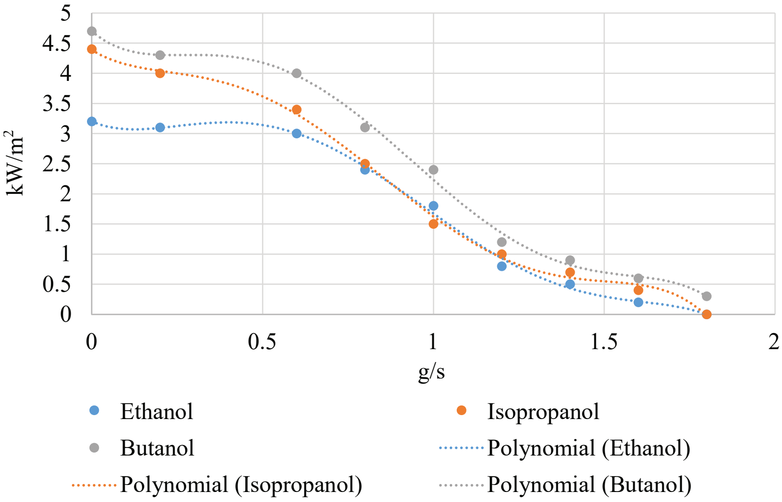

Fig. 5. Intensity of thermal radiation at a distance of 30 mm from the surface of the alcohol flame when supplying fire-extinguishing aerosol in a sublayer fashion

5. 3. Substantiation of factors that lead to a decrease in the intensity of thermal radiation during the sublayer extinguishing of alcohols by fire-extinguishing aerosols and their relationship

Based on the results of the derived equations (1) to (12), a logical scheme of the synergistic relations of the factors of aerosol sublayer extinguishing of alcohols was built, which ensure the blocking and reduction of the heat flow at all stages of alcohol extinguishing (Fig. 6).

From a practical point of view, the introduction of an aerosol into the diffusion burning zone ensures its effective suppression by reducing the intensity and shielding the thermal radiation as the main factor ensuring the course of the chemical reaction of burning. In addition, aerosol effectively reduces the intensity of a heat flow on the outside of the flame, which ensures cooling the surrounding combustible materials and preventing their ignition, which makes it possible to determine the conditions for effective use in the technology of sublayer fire extinguishing of alcohols.

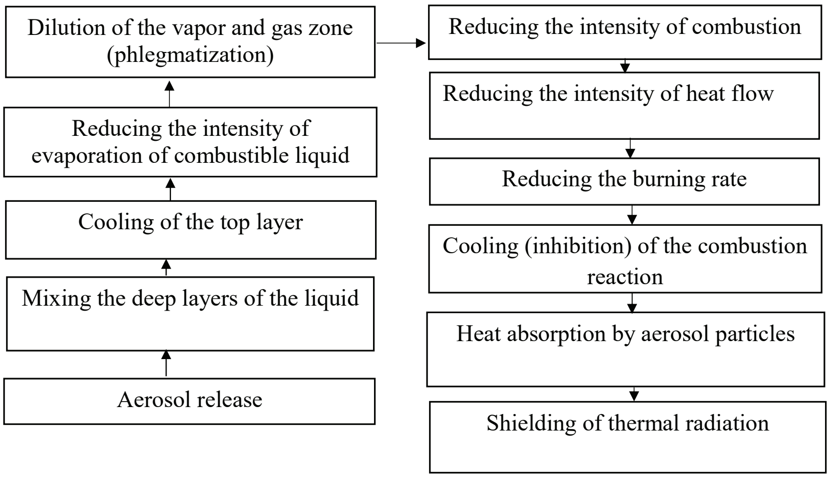

Fig. 6. Factors leading to a decrease in the intensity of thermal radiation during the sublayer extinguishing of alcohols with fire-extinguishing aerosols

Thus, the block diagram (Fig. 6) shows the relationship of factors leading to a decrease in the intensity of thermal radiation during the sublayer extinguishing of alcohols with fire-extinguishing aerosols. In general, the introduction of aerosol in the diffusion burning zone ensures its effective suppression by reducing the intensity and shielding the thermal radiation as the main factor ensuring the course of the chemical reaction of burning. In addition, aerosol effectively reduces the intensity of heat flow on the outside of the flame, which ensures cooling of the surrounding combustible materials and preventing their ignition.

6. Discussion of results of studying the intensity of thermal radiation at the sublayer extinguishing of alcohols

It is known that the brightness of the flame is determined by the amount of oxygen in the composition of the alcohol molecule. Thus, the molar masses of alcohols are $M(C_2H_5OH)$=46 g/mol, $M(C_3H_7OH)$=60 g/mol, $M(C_4H_9OH)$=74 g/mol. At the same time, the ethanol molecule contains approximately 35 % of O_2 atoms, 26 % in isopropanol, and 21 % in n-butanol. The high content of oxygen in ethanol ensures its burning with almost no light release and, accordingly, the heat flow would accept small values observed on the charts.

The charts in Fig. 2, 3 show that ethanol burning ensures the formation of a weaker heat flow, unlike isopropanol and n-butanol, which burn with flames with more intense radiation. The red coloration of the flame of alcohols is provided by an excess of carbon, the particles of which do not completely burn and emit thermal energy in the yellow range. This provides for the radiation of thermal energy somewhat more intensively than when burning some hydrocarbon fuels. This is explained by the fact that in this case soot and smoke are not formed, which also actively dissipate thermal radiation. This is due to the fact that on the charts (Fig. 2, 3) the thermal radiation curves for isopropanol and n-butanol lie above the ethanol radiation curve.

When extinguishing the fire sites of these alcohols with aerosol, there was a sharp decrease in the intensity of thermal radiation due to the absorption of heat by the particles of fire-extinguishing aerosol and, accordingly, their heating, inhibition, cooling, then decomposition and removal together with combustion products from the burning zone.

This process leads to a sharp decrease in the intensity of thermal radiation in a very short time throughout the entire volume and burning area. This is not observed when extinguishing with foam, where, to achieve the extinguishing effect, it is necessary to carry out a so-called “foam attack” whose purpose is to ensure the appropriate intensity of foam supply in order to prevent its destruction.

The charts in Fig. 2, 3 show that the significant intensity of thermal radiation, and, accordingly, burning, is achieved by alcohols on seconds 30–40, reach a maximum on second 60. This coincides with the conclusions drawn by the authors of work [15] who indicate that the burning of hydrocarbon fuels acquires a maximum scope in the first 60 seconds. At the same time, with the insufficient intensity of aerosol supply, extinguishing is not achieved while the intensity of radiation is significantly reduced.

To determine the parameters that substantiate the intensity of thermal radiation in the burning of alcohols, some aspects of radiation from fires in the spill, which are described in work [16], were analyzed. Given this, we can conclude that the effect of extinguishing a combustible liquid is achieved as a result of several stages and the synergic interaction between some factors. The first step is to cool the surface of the liquid when the aerosol is bubbled through a layer of liquid. Next comes the cooling and phlegmatization of the burning vapors and gases zone with inert aerosol components – (CO_2, N_2, aerosol particulate particles – KCO_3, $KHCO_3$, NH_4CO_3, etc.). The next step is to inhibit the burning reaction with these components, which leads to a decrease in the heat release and cooling of the burning zone. Dilution of the burning zone with alcohol vapors and gas dispersed products, which are formed during the thermal decomposition of aerosol particles, also leads to a decrease in the intensity of burning. This is confirmed by the results of the experiment, shown on the chart in Fig. 4, which shows that the intensity of the heat flow decreases sharply after supplying a fire-extinguishing aerosol in a sublayer fashion. The intensity of radiation from the burning zone is significantly reduced at a distance, and, already at 60 mm from the flame, these values are halved. However as can be seen from the charts, the intensity values of thermal radiation are much higher for alcohols that contain more carbon atoms in their molecule. Increasing the amount of carbon in the composition of the alcohol molecule ensures the conversion of chemical energy into heat and its radiation, due to the fact that it does not completely burn. Limiting the heat flow to the combustible liquid surface would lead to a decrease in temperatures in all areas of the diffusion flame and, accordingly, a sharp decrease in the rate of burning and thermal radiation reaction. Our results on the sublayer supply of fire-extinguishing aerosol indicate a synergistic effect among all factors that occur when an aerosol enters the zone of vapors and gases of diffusion flame. This leads to the shielding of the heat flow and a decrease in the temperature of the alcohol surface and, accordingly, a decrease in the intensity of alcohol evaporation and the amount of alcohol vapors that would enter the burning zone for burning.

Even with insignificant intensity of aerosol supply to the flame of alcohols, its thermal interaction with the release and absorption of thermal energy occurs. The chart in Fig. 5 shows that the intensity of radiation at a distance of 30 mm from the surface, the flame when supplying fire-extinguishing aerosol in a sublayer fashion with an intensity of about 0.2 g/s is already beginning to decrease, especially for ethanol. This could be explained by the fact that the aerosol as a polydisperse system most particles of which have dimensions of 0.05–1 μm [17–19] is able to effectively inhibit the flame already with minor additives. In a given case, this is due to the inhibition by aerosol solid particles – K_2O, KOH, K_2CO_3, $KHCO_3$ and other potassium compounds, which coincides with the conclusions drawn by the authors of work [18] who indicate that an additive with a volume of 0.1 % $KHCO_3$ leads to a decrease in the burning rate by 2 times. Taking into consideration the fact that these substances are the main components of the fire-extinguishing aerosol, which once again emphasizes their environmental acceptability. The same is argued by the authors of work [20, 21] who indicate a synergism between the chemical and physical components of aerosol. That provides for a significant decrease in the burning rate, which is confirmed by a further increase in the intensity of aerosol supply, which leads to a more significant decrease in the intensity of the heat flow. A more significant decrease in intensity occurs at the intensity values of the aerosol supply from 1.2 g/s. At the specified intensity of aerosol supply for ethanol, it is extinguished in the range of 30–50 seconds from the beginning of the aerosol effect.

It should be noted that the current study has limitations for large fire sites, where the values of radiation intensity could be more significant and demonstrate other intensity curves. However, based on the established dependences, it can be noted that in general, the number, the relationship of factors, and their effect would be the same for both small and large fire sites. Thus, it is possible to approximate the results based on the derived mathematical dependences and find the value of radiation intensity for large fire sites.

Thus, our results show a significant decrease in the intensity of thermal radiation at the sublayer aerosol supply. This is due to the resulting synergistic effect of the chain of interrelated factors that occur at the sublayer extinguishing with aerosol. An applied aspect of the use of the obtained scientific result is the possibility to devise technology of the sublayer extinguishing of alcohols as a more efficient, low-cost one, as well as providing for the possibility of its implementation at domestic enterprises.

In the process of advancing a given technology for using fire-extinguishing aerosol, one could face the task of its supply from deeper layers of a combustible liquid. This issue requires further research involving mathematical modeling and experimental confirmation of results.

In general, the development of the specified technology creates the prerequisites for the transfer of reported technological solutions to determine the new and effective conditions for the sublayer extinguishing of alcohols.

7. Conclusions

1. The intensity of thermal radiation at a distance of 30 and 60 mm from the surface of the alcohol flame with an area of 234 cm^2 was established. It was found that the intensity of thermal radiation for the specified alcohols ranges from 0.8 to 4.7 kW/m^2, and the intensity of radiation maximizes on second 30 to second 40 of burning, which is explained by heating the surface of alcohol and increasing the intensity of its evaporation.

2. It was experimentally established that the intensity of thermal radiation for ethanol initially decreases slightly when the aerosol is added with an intensity of up to 0.2 g/s and decreases even more at the intensity of aerosol supply from 1.2 g/s. With a further increase in the intensity of aerosol supply, the intensity of radiation begins to decrease, probably due to reducing the burning rate in the burning zone. In this case, the flame first decreases in size by 2 times and then goes out by second 3. The results of this work have allowed us to conclude that the main factor that affects the intensity of burning is the intensity of radiation, which ensures heating the surface of the liquid and the walls of the tank. The use of fire-extinguishing aerosol for the sublayer extinguishing of alcohols ensures the implementation of several factors that synergize and provide for the alternate reduction of evaporation intensity, further burning, and, accordingly, thermal radiation.

3. We have theoretically substantiated and demonstrated the relationship between factors leading to a decrease in the intensity of thermal radiation during the sublayer extinguishing of alcohols with fire-extinguishing aerosols. It was established that the sublayer supply of fire-extinguishing aerosol implements a series of factors that synergistically reduce the intensity of thermal radiation by cooling alcohol, phlegmatizing the vapor and gas zone, inhibiting the burning reaction zone and heat dissipation together with the heated aerosol. In addition, the release of the aerosol together with combustion products from the burning reaction zone ensures the shielding of the surrounding space from the flame.

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