New ways and means of localization and extinguishing surface forest fires

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Abstract. In the present article, we discuss fire extinguishing agents used for complex inhibition of surface fires. We demonstrate the reduction in organic combustible volatile products by 2.5-3 times with a simultaneous increase in the yield of the reaction water. To determine the composition of volatile fractions responsible for combustion we used chromatography. The results of field tests are presented.

1. Introduction

Forest fires is a natural disaster; they are characterized by uncontrolled burning of large forest areas. According to the type of spread, forest fires can be divided into three main groups: surface, crown and ground fires. Crown fires, accompanied by loss of wood, environmental disturbances, and sometimes by death of humans and forest animals, pose the greatest danger; however, the overwhelming majority of forest fires are surface fires that can also cause significant damage to a forest area millions of hectares in size and harm human life and health.

Sustainable burning occurs only in the presence of a combustible substance and oxygen or other oxidizing agent, and only when a constant transfer of heat from the flame to the combustible substance is possible. The basic principle of fire suppression is elimination of one or several components of burning; that is, reduction of the amount of combustible material, concentration of the oxidizing element, temperature or activation energy of the reaction. All these factors are taken into account when developing methods for extinguishing forest fires. The main methods of fire fighting include:

- cooling of a burning object or organic substrate to a temperature below the burning temperature;
- slowing down the rate of the oxidation process using combustion inhibitors;
- reducing the air access to a burning object;
- reducing the oxygen concentration in the combustion zone by diluting it with inert non-flammable gases.

In fighting forest fires, water, foams and powders, inert gases (nitrogen, carbon dioxide), refrigerants, and mixed compounds are often used. Water is the most affordable product with high heat absorption of about 3880 kJ/kg. Due to the high coefficient of surface tension, water is usually mixed with surface-active substances (surfactants).

Suppression of surface forest fires with water is rather challenging due to a difficult terrain and large losses, and it is almost impossible to suppress crown and ground (in particular, occurring in peat) fires using water.
Therefore, the task is to find effective methods for localisation and suppression of forest fires using new extinguishing agents that have a different fire extinguishing effect. The approach to creation of a barrier to a surface fire can be based on a chemical or physical concept.

2. Materials and Methods
To localize and suppress surface forest and steppe fires, a fireproof mobile screen made of basalt-fiber cloth was used. The screen was installed vertically to isolate the ground cover unaffected by fire from all types of heat transfer (conduction, thermal radiation and convection) from the edge of the fire. The proposed screen is light-weight, it has a simple design and can be easily installed; it also has a high fire resistance (up to 1100 °C) and can be reused. The main elements of the fireproof screen are basalt fabric, made of filaments 11-12 microns in diameter, and installation stands. The nominal width of the fabric, which determines the height of the fireproof screen, varies in the range of 95-120 cm. The mounting stands are made of rigid, hollow, pointed at one end rods up to 1 cm in diameter made of tightly glued twisted basalt threads.

To suppress surface forest and steppe fires, OTS-KM fire extinguishing agent was used consisting of amidophosphate KM, carbamide solution and water in the ratio of 25:15:60. The fire extinguishing agent was applied to the burning area by spraying until fine particles were formed using portable backpack sprayers.

The composition of combustible volatile products accompanying flame combustion was determined by the method of pyrolytic gas-liquid chromatography using a flame ionization detector.

3. Results and Discussion
Fireproof screens have high efficiency when used against a steady surface fire characterized by burning of ground cover and forest floor, with a burning temperature of about 900 °C.

The design features and a small mass (about 12 kg) of a mobile kit allow the use of fireproof screens in difficult landscape conditions, including during landing. Installation of the screen takes a few minutes. The screen material retains its properties after operation, that is, it can be reused.

Technical characteristics of basalt fiber materials used for fireproof screens are presented in Table 1.

| Characteristic                          | Unit of measurement | Value           |
|----------------------------------------|---------------------|-----------------|
| Fabric thickness                       | mm                  | 0,11± 0,02 ÷ 0,34 ± 0,03 |
| Fabric nominal width                   | cm                  | 95 ÷ 120        |
| Surface density                        | g/m²                | 100 ± 15 ÷ 345 ± 25 |
| Flammability class                     | -                   | Not flammable  |
| The limiting temperature of application, not higher than | °C                 | +1100           |
| Water resistance                       | -                   | Yes             |

The screen is designed so that it forms a fire break (an equivalent of a mineralized strip); the protective screen covers the ground from the side of the incoming fire. The width of the fire break is about 30 cm and depends on the width of the screen. For example, when a fabric has the width of 100 cm, the vertical part of the fire-proof screen will be 70 cm, and the ground (horizontal) part will be 30 cm in width. Thus, the design combines two different methods of localization of surface fires: mineralization and shielding.

Note that the creation of mineralized strips, as a rule, requires the use of heavy machinery and mechanisms, which is not always possible in the forest; therefore it is necessary to apply other methods of soil and ground cover treatment.
The chemical concept of surface fire suppression is based on the inhibition of combustion by a reaction [1] somewhat opposite to photosynthesis, which forms the basis of the so-called theory of catalytic dehydration. Carbohydrates, the main component of plants, under the influence of catalysts and thermal energy of an approaching fire decompose according to an idealized scheme [2] (1):

\[(C_6H_{10}O_5)_n \rightarrow 6nC + 5n(H_2O)\]  

(1)

Flame retardants used as fire extinguishing agents function as catalysts, changing the mechanism of thermal decomposition of carbohydrates and generating a high amount of reaction water [3]. An acidic environment is needed for dehydration, which is created by flame retardant transformations upon thermal exposure to the approaching fire. Changes in the mechanism of decomposition of plant material (substrate) are accompanied by a reduction in the yield of combustible volatile products (CVP) and a significant decrease in the overall thermal effect. This effect is not as strong as the thermal effect of the ignition impulse necessary for its occurrence; if the ratio of these effects is less than 1, the development of combustion is impossible. In addition to a thermodynamic view of fire extinguishing, aspects of the so-called gas theory should be taken into account. The products of decomposition of a flame retardant, in particular NH₃ and CO₂; when mixed with the reaction water, create a "blowing out effect" [4]. They dilute the gas-vapor mixture and thereby reduce both the concentration of combustible substances and the concentration of oxygen which is required for oxidative processes (burning) [5]. The density of these gases is higher than the density of air. They, as it were, wrap up the K-phase, in which the combustion process is substantially impeded, and the released products are carried outside the burning zone to the environment where the temperature is below the one required for burning [6]. Burning consists of two phases, a fiery burning and burning of the coal residue. The phase of fiery burning is of great importance. It accounts for the bulk of the heat released by different groups of forest combustible substrates. Fallen needles, dead grass and mosses quickly dry out and act as conductors of combustion in case of fire and thus ensure its continuous spread. The fiery burning of wood accounts for about 80% of the total heat released by fire. The proportion of CVP formed during gasification of needles varies widely, from 65 to 90%.

Using chromatography, we studied the composition of CVP. Their amount is sharply reduced due to flame retardant treatment of the substrate. The yield of such flammable substances as formaldehyde, methanol, and acetic acid decreases, but as a result of this redistribution of the products of thermal decomposition, the yield of reaction water increases by 1.8 times. The main exothermic reaction, carbon oxidation, is incomplete. CO output decreases.

The composition of organic compounds formed from wood fiber in the pyrolytic cell at a temperature of 750 °C in 20 s in a nitrogen carrier gas was determined by the method of pyrolytic gas-liquid chromatography using a flame ionization detector. The resulting chromatograms are shown in Figure 1.
Here we omit identification of the compounds formed (which is a separate topic); we point out that the total number of identified compounds determined by the peak area of chromatograms and their quantity decrease as a result of fire protection approximately 3 times, which indicates a significant change in the mechanism of generation of CVP. The reduction in their output also reduces the reaction exotherm. This confirms the essence of fire protection consisting of a significant reduction and change of CVP, as well as in a large amount of energy required for their formation. The calorific value of the substances (\(g_{TEO}\)) and the thermal ignition impulse required for this (\(g_u\)) were determined by a calorimetric method. The smallest ratio as the most dangerous in assessing the flammability of substrate was determined as an indicator of flammability (2):

\[
k_f = \frac{g_{TEO}}{g_u}\tag{2}
\]

This indicator depends on the type and content of a flame retardant in the substrate. When the mass fraction of amidophosphate KM [7] per phosphorus is 3% (of the main “working” element) \(g_{TEO} = 2.8\) MJ/kg; \(g_u = 6.5\) MJ/kg; \(k_f = 0.43\).

The burning of the coal residue is accompanied by accumulation of carbon. The carbonization process leads to the carbon-like dense residue acting as an additional barrier to the heating of the fresh mass of the substrate, since the thermal conductivity of coal is 2-3 times lower than the original substrate. This is important for bush wood and similar thermally thick materials. For dry grass as a thermally thin material, it is insignificant [8].

In real surface forest (or steppe) fires, a significant part of the heat from the combustion of the substrate is dissipated. Therefore, on the one hand, the fire extinguishing agent consumption required to suppress the edge of fire will be lower than the theoretical; on the other hand, due to uneven application or draining of the solution into the soil, the fire extinguishing agent consumption might be higher. Real statistics that take into account the specifics of the ground cover are required.

The ability of a fire extinguishing agent to inhibit the burning of the edge of fire and thereby localize a surface fire was tested.

In the course of fire prevention and fighting exercises conducted on the territory of the Lisinsky experimental forest management unit, fire-retardant treatment of soil and ground cover with
amidophosphate KM when creating fire breaks demonstrated high efficiency. Treatment of the soil covered by dry grassy vegetation 1 m wide with 25% amidophosphate KM at a flow rate of about 1000 cm$^3$/m$^2$ allowed a surface fire to be stopped along the whole front (the wind speed was 6 m/s). A combined method of using a fireproof screen and fireproof treatment of soil and ground cover under the screen makes it possible to more effectively limit the spread of surface fires, even with significant gusts of wind (up to 25 m/s).

For extinguishing forest fires, OTS-KM fire extinguishing agent turned out to be the most effective. Studies demonstrated that the use of this substance can reduce the consumption of a fire extinguishing agent by about 6 times compared with water. Moreover, the use of this substance allows us to suppress re-ignition of combustible base. The fire extinguishing effect of OTS-KM is based on the reduction of the concentration of volatile combustible substances and on their chemical transformations resulting in gaseous non-combustible substances.

To assess the effectiveness of OTS-KM, a 25% KM amidophosphate solution with the addition of 1% surfactant, and a 50% KM amidophosphate solution to which 15% carbamide solution was added to a concentration of 25% were compared between themselves and with water using the amount required to extinguish a source of ignition until complete suppression of combustion as the basis of comparison.

The model burning area was an object weighing 10 kg with an area of 0.5 m, consisting of a mixture of plant materials: willow branches (70%), birch logs (10%), softwood bark (10%) and dry grass (sedge, 10%). The moisture content of the mixture was in the range of 10-25. Ignition of the samples was performed using an incendiary apparatus.

After ignition, the mixture burned freely in calm weather conditions for 5 minutes. Then an extinguishing agent was applied with the help of a portable backpack sprayer.

Data on the consumption of fire extinguishing agents are provided in Table 2. Note that the water cools the zone of fiery combustion, but the upper charred layer dries quickly, and the heated layer underneath continues to heat up. The CVPs are released, ignited and the burning cycle resumes. Water consumption is given for complete fire suppression.

**Table 2. Suppression of a model fire.**

| Extinguishing agent composition, % | Extinguishing agent consumption, cm$^3$ |
|-----------------------------------|-----------------------------------------|
| Water (100)                       | 3300                                    |
| Water + surfactant (99 +1)        | 2950                                    |
| Water + KM + surfactant (74 +25 +1) | 490                                    |
| Water + KM + carbamide (60 +25 +15) | 310                                    |

Note: when exposed to water without KM, repeated ignition of the burning center was observed. Therefore, we report the amount of water required to fully extinguish the fire.

The above studies support the results of previous studies on the effectiveness of KM amidophosphate (OTS-KM) in suppression of forest fires [9].

Adding a solution of carbamide to OTS-KM allows us to reduce the consumption of fire extinguishing agent by almost 2 times.

In general, we demonstrate that the chemical concept of suppression of surface forest and steppe fires provides an opportunity to effectively fight fire with the same volume of extinguishing agent with chemical additives to cover an area nearly 6 times larger than that when water alone is used.

This is primarily due to the fact that ammonia is released from carbamide when heated, which reduces the oxygen concentration in the combustion zone. Reducing the temperature of the combustion process improves the conditions of fire suppression, allows us to get closer to the combustible base and conduct its high-quality flame retardant treatment.

Fire extinguishing agent (OTS-KM) with the addition of a solution of carbamide with good spraying when fine particles are formed opens up a possibility to reduce substantially the consumption of a fire extinguishing agent, and is an effective method for suppression of ground (peat) fires. OTS-
KM can also be used for preventive treatment of forests in crowded places, in recreation areas, along public roads, to create fire breaks, and arrange temporary quasi-mineralized bands and fire barriers.

Attention should be paid to the environmental aspect of using amidophosphate KM and carbamide solution which include phosphorus and nitrogen elements used for fertilizing soil and feeding plants in a form similar to that of standard fertilizers.

4. Conclusions

1. For localizing and stopping surface forest and steppe fires, an effective method is to install a fireproof screen made of a basalt fiber fabric along the edge of a surface fire and simultaneously treat the ground cover under the screen with the fire extinguishing agent OTS-KM.

2. The use of OTS-KM for fighting forest fires can reduce the consumption of an extinguishing agent (as compared with water) by 10 times and eliminate re-ignition.

3. OTS-KM is an effective substance for preventive treatment of forests in crowded places, recreation areas, of temporary mineralized strips, fire barriers and breaks.

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