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Fire Suppression by Aerosols of Aqueous Solutions of Salts

O. P. Korobeinichev,[1] A. G. Shmakov,[1] A. A. Chernov,[1]
T. A. Bol'shova,[1] V. M. Shvartsberg,[1]
K. P. Kutsenogii,[1] and V. I. Makarov[1]

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Results of laboratory experiments were verified by full-scale tests in which two types of model fire sources were extinguished by salt-solution aerosols. The tests showed that short-term action of an aerosol cloud of an aqueous solution of potassium ferricyanide $K_3[Fe(CN)_6]$ on the flame front of a surface forest fire led to suppression of the gas-phase combustion, and in the case of a model fire source of class A (burning wood) to its complete extinction. The minimum extinguishing mass concentration of $K_3[Fe(CN)_6]$ in these experiments — 4.5 g/m^3 — is close to that measured earlier in laboratory experiments. It was found that, in fire suppression by an aerosol of the aqueous solution of $K_3[Fe(CN)_6]$, the volumetric flow rate of this fire suppressant was 30 times lower than the standard flow rate of pure water from a fire hose.

Key words: fire extinguishing, aerosols, fire suppressants, inhibitors, metal-containing compounds.

INTRODUCTION

Development and investigation of new effective and environmentally safe fire suppressants is a priority problem in fire extinguishing. At present, there are various methods of fire extinguishing by spraying water [1–15]. The main direct factor in this extinguishing method is a temperature decrease in the combustion zone due to evaporation of dispersed water. It is known that the effectiveness of using a water–gas cloud depends on the type of fire and dispersity of water droplets. In the methods described, the size range of water droplets is constant and wide and most of the water is in droplets larger than 100 μm. Therefore, a disadvantage of this method is a high water discharge per unit volume of the flame.

The effectiveness of extinguishing by water can be increased by both improving water dispersion and by adding various additives [16]. Recently, there have been a number of studies aimed at determining the effectiveness of extinguishing by aerosols of aqueous solutions [17–28]. Compounds such as NaCl, KCl, LiI, CH_3COOK, $CoCl_2$, $NiCl_2$, NaOH, $NaHCO_3$, $MgCl_2$, $CaCl_2$, $MnCl_2$, $FeCl_2$, etc., have been studied as additives. It has been found that some of the compounds are more effective combustion inhibitors than halons such as CF_3Br. Therefore, they are considered as promising additives to water for increasing the effectiveness of fire suppression. Results of laboratory experiments have shown that the most effective (per unit mass) fire suppressants are complex compounds of potassium and iron [29]. However, the effectiveness of fire suppressants determined in laboratory experiments is not always equivalent to the suppression effectiveness of large-scale fire sources. Therefore, only full-scale fire suppression tests with flames of various types allow correct (reliable) conclusions on the prospects of new fire suppressants and on the method of their delivery in the form of a fine aerosol to a fire source which is proposed in the present paper.

The purpose of the present work is to compare the effectiveness of traditional fire suppressant (water) and a new fire suppressant (an aqueous solution of potassium salt) by performing comparative full-scale field tests.

[1]Institute of Chemical Kinetics and Combustion, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; korobein@kinetics.nsc.ru.

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EXPERIMENTAL TECHNIQUE

The full-scale tests aimed at evaluating the suppression of various types of flame were performed using a transportable aerosol generator with adjustable size of particles (AGASP) of aerosols for two types of fire source: (a) a model source of a surface forest fire; (b) a model fire source of class 0.5A (burning wood). For each type of source, two series of experiments were performed: 1) using water without additives; 2) using aqueous inhibitor solutions.

In the field tests, an aerosol generator [30] mounted on a truck chassis was used. The aerosol generator comprises a compressed air source, tanks for gas-turbine engine fuel and aqueous inhibitor solutions, and a system for supplying fuel and working fluids. The aerosol generator is furnished with thermomechanical and technological air circuits, allowing the aerosol dispersity to be varied over a wide range. The circuit includes a source of compressed air, nebulizers with replaceable nozzles for air and liquid, and a system for measuring and controlling the flow rate of dispersed fluids. For weight saving, a TA-6A auxiliary aircraft power unit was used as a single source of compressed air.

The generator with the pneumatic circuit had the following parameters: an air mixture with water or a solution as the working body, nozzle jet velocity 330 m/sec, a jet velocity of up to 20 m/sec at a distance of 6 m from the nozzle, a jet diameter of about 1.2 m at a distance of 6 m from the nozzle, volumetric air flow rate 0.8 kg/sec, maximum flow rate of the solution or water 20 liters/min, median-mass particle diameter of the aerosol 20 μm [31].

The model source of a surface forest fire was a horizontal grassy area of size 3×4 m separated from the surrounding territory by a fire-prevention zone 1 m wide. The mass of combustible materials (dry grass, small branches of trees 2 cm in diameter) was 2 kg/m^2, and their moisture content corresponded to natural conditions. The wind speed did not exceed 2 m/sec, and the air temperature was +14°C. The horizontal velocity of flame propagation was about 25 cm/min.

The model fire source of class 0.5A corresponded to State Standard GOST 27586-88. It was a timber stack of cubic shape consisting of 45 timbers of 40×40 mm square section and 40 cm long. The timbers in the stack were arranged so that, in each layer, the distance between the timbers was 40 mm, and the timbers in the next layer were perpendicular to those in the previous one. The timber material was pinewood not worse than 3-rd grade with a moisture content of 12–14%. The outside timbers of the stack were fastened together by clamps and nails. For ignition of the source we used a $300 \times 300 \times 100$ mm metal pan which was placed under the stack at a distance of 0.5 m from the lower timbers. The pan was filled with 3 liters of water and 0.6 liters of A-76 (GOST 2084) gasoline. Extinguishing of the source began in 7 min after ignition of gasoline in the pan without removing the pan; the source was uniformly rotated around its vertical axis at a speed of 10 rpm. The tests were performed in open terrain at a wind speed of 0–3 m/sec and an air temperature of +18°C. The distance between the AGASP and the source was 6 m, and the aerosol jet diameter was not less than 1.2 m. According to the fire extinguishing test standards [32], a test is generally considered successful if extinction is achieved in not less than two of three attempts, the time of delivery of fire suppressant is not more than 180 sec, and repeated ignition does not occur within 10 min after the end of combustion.

The characteristics of the aerosol cloud produced by the thermomechanical circuit were determined from the following real-time measurements performed during suppression of the surface forest fire: measurements of the aerosol particle size and their mass concentration by a nephelometer [33]; flame temperature measurements by a digital thermal imager; digital video recording for obtaining three-dimensional computer models of time-space variation of the aerosol cloud shape and the flame of the ground forest fire by means of digital stereophotogrammetry and geoinformation system (GIS) technologies.

RESULTS AND DISCUSSION

Previously, some inorganic and organic potassium salts (K_3PO_4, $KOOCH_3$, KOOCCOOK, and $K_4[Fe(CN)_6]$) were studied [29] as fire suppressants using the cup-burner technique. Experiments using aqueous solutions of these salts to extinguish diffusion n-heptane flames showed $K_4[Fe(CN)_6]$ (potassium ferrocyanide) and $K_3[Fe(CN)_6]$ (potassium ferricyanide) to be the most effective fire suppressants. The minimum extinguishing mass concentration of $K_4[Fe(CN)_6]$ is 6.6 g/m^3 [29]. The salts have similar chemical properties, contain a large amount (3–4 atoms) of potassium in their molecules, and hence have similar fire suppression effectiveness. For our full-scale suppression tests using two types of model fire sources, we chose $K_3[Fe(CN)_6]$ since it is better soluble in water than $K_4[Fe(CN)_6]$.

(A) The flame of the model forest fire source was acted upon by an aerosol cloud produced by the AGASP. The fluid flow rate was 0.330 liter/sec, and the aerosol was supplied to the fire source for about 4 sec. In the first series of experiments (with pure water), the action of the aerosol cloud on the flame had no noticeable effects on the combustion. Thus, water aerosol without additives did not lead to flame quenching. In the second series of experiments, the flame was subjected to an aerosol of a 30% aqueous solution of $K_3[Fe(CN)_6]$. The dry-basis mass concentration of $K_3[Fe(CN)_6]$ in the flame zone was about 4.5 g/m^3, which is close to the minimum extinguishing concentration of $K_4[Fe(CN)_6]$ determined in laboratory experiments [29]. Thermal imaging measurements of the flame temperature showed that the action of the fire suppressant decreased the maximum flame temperature from 1000 to 500°C. Thus, it can be concluded that, when the aerosol cloud passes through the combustion zone, the flame quenches. However, some time after the termination of fire suppressant delivery, the burning resumed. This is due to the fact that the period of flame suppressant delivery (≈4 sec) is not sufficient for carbon residue (coke) to quench and cool. Hence, for complete extinction of the model source of surface forest fire, the time of flame suppressant delivery should be increased so as to reduce the combustion zone temperature below the self-ignition temperature of the combustible wood materials. A forest fire source containing combustible materials of different structure and composition (dry grass, small and large branches, coke, etc.) is a complex object of research from the point of view of obtaining reproducibility of results on the effectiveness of fire suppressants. Therefore, the minimum duration of fire suppressant delivery was evaluated for a more standardized flame source which is used in tests of fire extinguishers and provide well-reproducible and reliable results.

(B) The flame of a model fire source of class 0.5A was exposed to an air flow containing an aerosol of water or a 30% of aqueous solution of $K_3[Fe(CN)_6]$. According to specification requirements [16], for extinguishing timber stacks with a moisture content of 8–14% by the conventional method (using a fire hose), the flow rate of pure water should be 0.45 liter/(m$^2\cdot$sec) for an extinguishing time of 180 sec. Because, in the literature, there are no accurate quantitative data on the flame-suppression effectiveness of various fire extinguishing means for fire sources of class 0.5A, we assumed that the suppression effectiveness (total water flow rate) using a fire hose is equal to unity. This makes it possible to evaluate the suppression effectiveness of the methods studied relative to the fire suppression by water from a fire hose and thus to compare the effectiveness of the methods with each other.

The total combustion area of the model fire source with a well-developed surface is 2.37 m^2. The total volume of the source of class 0.5A is 0.058 m^3, and half of its is occupied by timber. Thus, according to the specifications, the suppression of this source requires 192 liters of water, which exceeds the volume of the free internal space of this source by almost a factor of seven. This is obviously due to the fact that the extinguishing of timber stacks involves considerable losses of water due to poor wetting and water running off from the burning surface. During fire suppression by water from a fire hose, large water droplets act only on the upper (and partly lateral) burning surface of the source. It is therefore reasonable to expect that the use of fine aerosol for fire extinguishing allow a considerable reduction in the water flow since the aerosol acts on burning surfaces regardless of their spatial orientation.

During fire suppression by the AGASP, only a small part of the fire suppressant is delivered to the combustion zone, and the rest is carried away by the gas flow. It can be assumed that the fire suppressant, together with the gas flow, is delivered into the model source through its frontal surface and is distributed in it over the free space between the wood timbers. From the ratio of the frontal surface area of the model source (0.144 m^2) and the cross sections of the aerosol jet from the AGASP (1.13 m^2), the portion of the fire suppressant delivered to the combustion zone is evaluated at 0.127. Thus, of a total fluid flow from the AGASP of 0.33 liter/sec, $0.33 \times 0.127 = 0.042$ liter/sec is delivered directly to the source.

Experiments with a pure water aerosol showed, that at this fluid flow rate, it was almost impossible to extinguish the model source by means of the AGASP within ≈170 sec. Extinction occurred when the time of delivery of the fluid is ≈280 sec. In this case, the degree of burnout of the combustible material is not less than 80%. Thus, to extinguish the model source by a water aerosol, it is necessary to consume not less than 11.8 liters of the fluid, which is ≈16 times smaller than the standard consumption of pure water in extinguishing by the standard method using a fire hose.

Experiments with a 30% aqueous solution of $K_3[Fe(CN)_6]$ in the form of an aerosol showed that its suppression effectiveness was higher than that of a pure water aerosol. Visible flame disappeared in 76 ± 6 sec after the beginning of suppression. The delivery of the fire suppressant for 154 ± 4 sec led to reliable extinction of the model source without its repeated ignition within 10 min after the termination of the suppression. This time interval is specified in the technique of testing fire extinguishers [32]. At smaller times of suppressant delivery, repeated self-ignition occurred as a rule. The flow rate of the $K_3[Fe(CN)_6]$ solution (delivered directly to the model fire source) was 0.042 liter/sec, which, for a fire suppressant delivery time of 154 sec, corresponds to a total discharge of the solution of 6.5 liters.

The dry-basis mass concentration of $K_3[Fe(CN)_6]$ in the flame zone was ≈4.5 g/m^3, which is close to the minimum extinguishing concentration of $K_4[Fe(CN)_6]$ — 6.6 g/m^3 [29]. Visual inspection of the combustible material after the extinguishing showed that all residues of the material were coated with $K_3[Fe (CN)_6]$. The burnout was higher in the middle of the model source than from the outside. The degree of burnout of the wooden timbers was ≈50%.

Thus, the results of the tests demonstrated the high effectiveness of the aerosol of a 30% aqueous solution of $K_3[Fe(CN)_6]$ for suppressing the model fire source of class 0.5A. At a dry-basis concentration of $K_3[Fe(CN)_6]$ of ≈4.5 g/m^3, the time of fire suppressant delivery should be not less than 154 sec. Furthermore, it was found that the flow rate of the aqueous solution $K_3[Fe(CN)_6]$ was ≈1.9 times lower than that of pure water for suppression by aerosol and ≈30 times lower than the standard flow rate of pure water for suppression using a fire hose.

CONCLUSIONS

Full-scale experiments were performed to study the suppression of model sources of a surface forest fire and a fire of class 0.5A (burning wood) by an aerosol of an aqueous solution of a potassium salt. The results of the experiments confirmed that the proposed fire suppressants are effective for suppressing both flame and smoldering combustion. The proposed extinguishing method using fine aerosols of solutions of potassium salts provides a factor of 30 reduction in the flow rate of the extinguishing fluid compared to fire suppression by pure water from a fire hose.

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REFERENCES

1. Yu. V. Alekhanov, A. E. Levushov, A. A. Logvinov, A. A. Loktev, and E. E. Meshkov, "One method for producing gas–liquid dispersions by means of a piston machine and its possible applications," in: *Proc. III Scientific and Technical Conference Scientifically-Innovative Cooperation*, Part 1 (2004), pp. 169–170.
2. A. Ya. Korol'chenko, "IFEX 3000 technology of pulsed water fire extinguishing," *Pozharovzryvobezopasnost'*, **2**, 3–5 (2000).
3. E. E. Meshkov and N. V. Nevmerzhitskii, "Method of producing gas–liquid dispersions," Russian Federation Patent No. 2220009, Appl. No. 2001123009. Publ. 06.27.03; *Byull. Izobr. Polezn. Modeli*, No. 18.4.1.
4. V. S. Terpigor'ev, Yu. I. Sokolov, and O. P. Shcherbakov, "Method of extinguishing fire by a gas–liquid mixture and a gas–liquid nebulizer for its implementation," Russian Federation Patent No. 2074544, Publ. 02.27.1997.
5. G. Sundholdm, "Fire extinguishing method and apparatus," Russian Federation Patent No. 2126282, Publ. 02.20.99.
6. V. S. Terpigor'ev, O. P. Shcherbakov, and V. M. Malinov, "Fire extinguishing apparatus," Russian Federation Patent No. 2193908, Publ. 03.20.01.
7. Yu. S. Alekseev, V. V. Donets, A. N. Zavoloka, V. F. Kravchukovskii, A. P. Kremena, A. A. Noda, N. F. Sviridenko, and V. V. Serbin, "Facility for producing a fluid jet with controlled droplet size," Russian Federation Patent No. 2209124, Publ. 07.27.01.
8. Yu. V. Zuev, A. V. Karpyshev, and I. A. Lepeshinskii, "Aircraft-based fire extinguishing method and equipment," Russian Federation Patent No. 2131379, Publ. 06.10.99.
9. Yu. V. Zuev, A. V. Karpyshev, and I. A. Lepeshinskii, "Method and nozzle for producing a gas–droplet jet," Russian Federation Patent No. 2107554, *Byul. Izobr.* (1998).
10. Yu. V. Alekhanov, M. V. Bliznetsov, Yu. A. Vlasov, V. I. Dudin, A. E. Levushov, A. I. Logvinov, S. A. Lomtev, and E. E. Meshkov, "Interaction of dispersed water with flame," *Pis'ma Zh. Tekh. Fiz.*, **29**, No. 6, 1–6 (2003).
11. *Fire Engineering*, Part 2: *Fire Vehicles* [in Russian] Stroiizdat, Moscow (1988), pp. 100–105.
12. N. P. Kurbatskii, *Issues of Forest Pyrology* [in Russian] Sukachev Institute of Forest, Krasnoyarsk (1970), pp. 340–353.
13. É. V. Konev, *Physical Principles of Combustion of Plant Materials* [in Russian], Nauka, Novosibirsk (1977), pp. 206–237.
14. S. S. Zhikharev, V. N. Piskunov, S. V. Tsykin, E. E. Meshkov, M. A. Zatevakhin, and S. G. Tsarichenko, "Modeling and optimization of fire extinguishing methods using dispersed water," in: *Aerosols and Safety*: Int. Scientific Practical Conf., Obninsk (2005), pp. 71–72.
15. S. V. Tsykin, "Method of fire extinguishing by capsules with water," *ibid*, pp. 194–196.
16. A. N. Baratov, *Combustion–Fire–Explosion–Safety* [in Russian], Research Inst. for Fire Protection, Russian Federation Ministry of Civil Defense and Emergency Response, Moscow (2003).
17. J. R. Mawhinney, "Design of water mist fire suppression systems for shipboard enclosures," in: *Proc. of the Int. Conf. on Water Mist Fire Suppression Systems* (November 4–5, 1993), Boras, Sweden (1993), pp. 16–44.
18. T. A. Moore, C. Weitz, S. McCormick, M. Clauson, "Laboratory optimization and medium scale screening

of iodide salts and water mixtures," in: *Proc. of Halon Option Technical Working Conf.*, Albuquerque (1996), pp. 477–498.
19. H. Shilling, B. Z. Dlugogorski, E. M. Kennedy, E. Leonardi, "Extinction of diffusion flames by ultra fine water mist doped with metal chlorides," in: *Proc. of the Sixth Australasian Heat and Mass Transfer Conf.*, Begell House, New York (1996), pp. 275–282.
20. R. Zheng, B. Rogg, and K. N. Bray, "Effect of sprays of water and NaCl-aqueous solutions on the extinction of laminar premixed methane-air counterflow flames," *Combust. Sci. Technol.*, **126**, 389–401 (1997).
21. A. K. Lazzarini, R. H. Krauss, H. K. Chelliah, and G. T. Linteris, "Extinction conditions of non-premixed flames with fine droplets of water and water/NaOH solutions," *Proc. Combust. Inst.*, **28**, 2939–2945 (2000).
22. B. Mesli and I. Gokalp, "Extinction limits of opposed jet turbulent premixed methane air flames with aerosols of water and NaCI-aqueous solution," *Combust. Sci. Technol.*, **153**, 193–211 (2000).
23. D. McDonnell, B. Z. Dlugogorski, and E. M. Kennedy, "Evaluation of transition metals for practical fire suppression systems, in: *Proc. of Halon Option Technical Working Conf.*, Albuquerque (2002), pp. 117–124.
24. R. Hirst and K. Booth, "Measurement of flame extinguishing concentrations," *Fire Technol.*, **13**, 296–315 (1977).
25. A. Hamins, G. Gmurczyk, W. Grosshandler, R. G. Rehwoldt, I. Vazquez, and T. Cleary, "Evaluation of alternative in-flight flame suppressants for full-scale testing in simulated aircraft engine nacelles and dry bays," in: *Proc. of Halon Option Technical Working Conf.*, Albuquerque (1994), pp. 345–465.
26. A. Hamins, "Flame extinction by sodium bicarbonate powder in a cup burner," *Proc. Combust. Inst.*, **27**, 2857–2864 (1998).
27. G. T. Linteris, V. R. Katta, and F. Takahashi, "Experimental and numerical evaluation of metallic compounds for suppressing cup-burner flames," *Combust. Flame*, **138**, Nos. 1/2, 78–96 (2004).
28. J. Liu, B. Cong, and G. Liao, "Experimental study on CH_4/air fire suppression effectiveness of water mist with metal chloride additives," in: *Book of Abstr. of 32th Int. Symp. on Combustion,* McGill University, Montreal, Canada (2008).
29. O. P. Korobeinichev, A. G. Shmakov, V. M. Shvartsberg, S. A. Yakimov, D. A. Knyazkov, V. F. Komarov, and G. V. Sakovich, "Testing organophosphorus, organofluorine, and metal-containing compounds and solid-propellant gas-generating composition doped with phosphorus-containing additives as effective flame suppressants," *Combust., Expl., Shock Waves*, **42**, No. 6, 678–687 (2006).
30. V. M. Sakharov, K. P. Kutsenogii, N. N. Verkhovskaya, A. N. Ankilov, V. I. Makarov, and E. I. Kirov, "Aerosol generator," Russian Federation Patent No. 950260 A01M7/00, Publ. 08.15.82, Byul. No. 30.
31. V. M. Sakharov, "Constructive and operational characteristics of an aerosol generator with controlled dispersity," in: *Optimization of the Insecticide Aerosol Technology* (collected scientific papers) [in Russian], Izd. SO VASKhNIL, Novosibirsk (1983), pp. 3–13.
32. State Standard GOST P 51057-2001: *Fire Engineering. Portable Fire Extinguishers. General Technical Requirements* [in Russian], Moscow (2001).
33. M. A. Bizin, P. K. Kutsenogii, K. P. Kutsenogii, and V. I. Makarov, "Automation of nephelometric measurements of mass concentrations of submicron atmospheric aerosols," *Opt. Atmos. Okeana*, **29**, No. 3, 291–296 (2007).