THE EFFECTIVENESS OF CONDENSED AEROSOLS FOR FIRE SUPPRESSION IN ELECTRICAL EQUIPMENT

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INTRODUCTION

The list of enclosures equipped with electrical and electronic units includes very wide range of various objects. Usually these objects have elevated level of fire danger due to presence of constantly energized equipment and high concentration of fire loading. In addition to this, the following circumstances can influence fire scenario in such enclosures:

- presence of cables, which can be heated up to 200-300 ^oC and more due to short circuit conditions or another accident;

- wide range of operational temperatures (±40 ^oC);

- free volume of enclosure can be rather small in comparison with total volume of the enclosure;

- the level of integrity of the enclosures varies in wide limits;

- the electrical and electronic equipment can be installed into special structures which can require separate fire suppression inside of the structure;

- air venting conditions, etc.

As a result, very different fire scenarios can be realized in enclosures with installed electrical and electronic units. This circumstance requires application of various fire extinguishing agents: carbon dioxide, nitrogen, argon, HFC's. To establish effective ways of using of the another agent - condensed aerosol - for fire suppression in the objects described above the presented work was done.

The following features of application of condensed aerosols which influence their effectiveness were investigated in our work:

- temperature of fire extinguishing aerosol (modern condensed aerosol generators produce aerosol with temperature range from 100-200 ^oC to 500-600 ^oC [1,2]);

- difficulties in achieving of fire extinguishing density in whole volume of protected enclosure due to that the density of heated aerosol is less than the density of air in the enclosure;

- sedimentation of solid particulates from the aerosol can cause corrosion of some materials.

The presented paper summarizes the results obtained to clarify the influence of above mentioned factors on effectiveness of fire suppression by condensed aerosols in enclosures equipped with electrical and electronic units. The experimental program consists of 4 parts including investigation of effectiveness of fire suppression by condensed aerosols in the enclosures with electrical and electronic equipment; fire suppression of cable traces; fire suppression in cabinets with electrical equipment; influence of the aerosols on various electrical and electronic devices and their elements.

FIRE SUPPRESSION IN MODEL ENCLOSURES AND CABINETS

An influence of initial temperature and fire loading. The experiments were conducted in sealed cabinets (with a volume ranging from 0.11 to 0.24 m^3) and enclosures with a volume ~44 and ~400 m^3 at atmospheric initial pressure and initial temperatures from –35 to + 170 °C. Ethanol, gasoline A-76, rubber, PMMA and PVC were used as combustibles. Condensed aerosols were formed by combustion of several aerosol forming compositions (STK-2MD, STK-6-1, SBK-2; the details for these pyrotechnical compositions are indicated in [3]) in special generator.

It was obtained that mean temperature in protected enclosure become higher due to application of condensed aerosol for extinguishing of alcohol combustion (Fig. 1). Preburning time in these tests was 90-120 s. As it follows from the experimental results, the elevation of temperature directly corresponds to elevation of density of the aerosol.

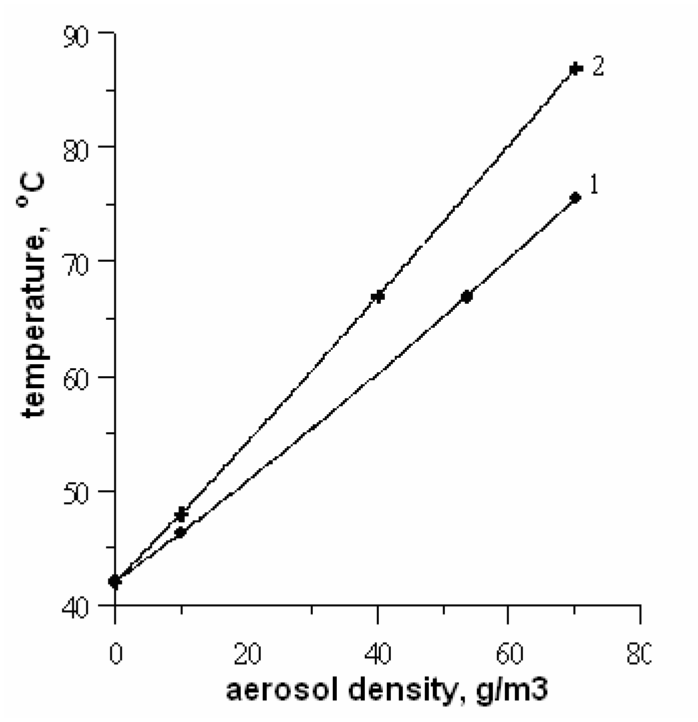

Figure 1. The dependence of mean temperature in enclosure (V=0.11 m^3) at application of aerosols for extinguishing of ethanol pool fire.

Aerosol forming compositions: 1 – STK-2MD; 2 – SBK-2.

To extinguish model fires at elevated air temperatures it is necessary to achieve increased aerosol density in comparison with normal conditions. This fact follows from experimental results presented at Fig.2. In particular, it was obtained that extinguishing density of aerosol at elevated air temperatures can be obtained by multiplying of extinguishing density of aerosol at normal conditions by safety factor of 1.5-2.0. The lowest value of safety factor should be used for aerosols with low temperature (formed by generator with inner cooling system). These data were also used in our full-scale experiments (see Tables 1-3).

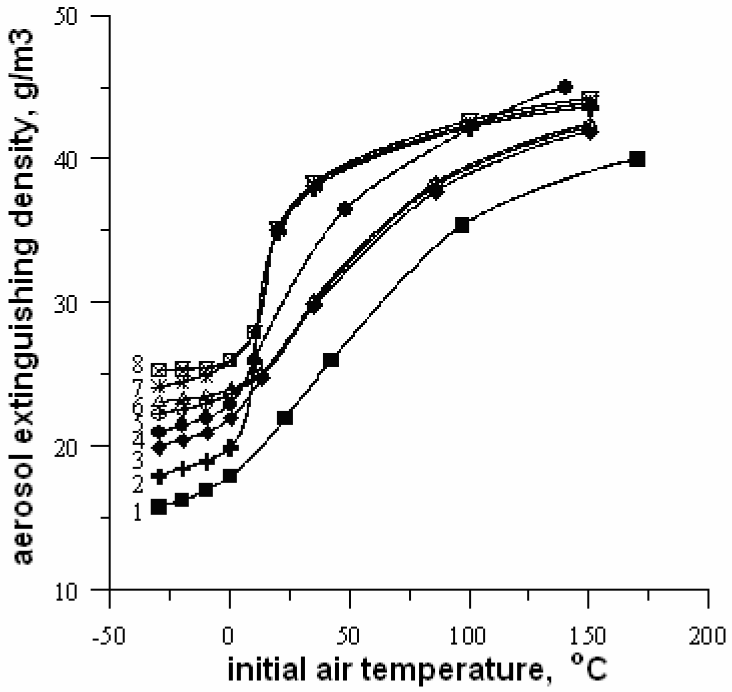

Figure 2. The dependence of aerosol extinguishing density for various combustibles (1-PVC; 2,7,8- gasoline A-76; 3,5,6-rubber; 4-PMMA) on initial air temperature in the enclosure and preburning time (1-4 - 10 s; 5,7 - 30 s; 6,8 s - 60 s).

When initial air temperature decreases in comparison with normal air temperature the extinguishing density of the aerosol also decreases. But it was found that for initial air temperatures below (-10) ^{o}C this effect in some cases doesn't take place. In particular, the influence of low temperature in protected volume on effectiveness of fire extinguishing disappears with the increasing of preburning time, temperature of the aerosol, sizes of model fire source etc. It means that real temperature during fire suppression in distinct cases become substantially higher than initial one due to heat release from fire and elevated temperature of condensed aerosol.

An influence of the generators arrangement on extinguishing efficiency. It was established that condensed aerosol is the most effective if it is supplied into the bottom part of protected enclosure. In this case the aerosol effectively extinguishes all model fire sources arranged in upper part of the enclosure due to lift of heated aerosol. A dependence of extinguishing density of the aerosol on intensity of its supply into protected volume presented at Fig.3. If the aerosol has increased initial temperature in comparison with another one, it should be supplied into protected enclosure more intensively (Fig. 4).

<u>Peculiarities of fire suppression in the enclosures with electrical equipment installed into cabinets</u>. Three possible ways of fire suppression for such enclosures were investigated in our work: 1) total flooding by condensed aerosol for the enclosure; 2) simultaneous supply of the aerosol into the enclosure and into cabinet with electrical equipment inside; 3) supply of the aerosol into the cabinet only.

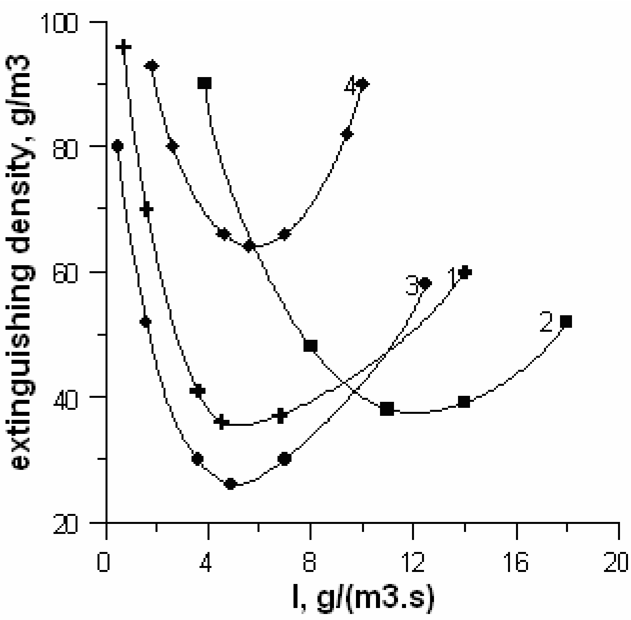

Figure 3. Dependence of extinguishing density of the aerosol on intensity of its supply into protected volume. Aerosol forming compound – SBK-2. Combustible – PMMA.

1,2 – fire suppression in upper part of the enclosure (1 – aerosol supply into upper part of the enclosure; 2 - aerosol supply into bottom part of the enclosure); 3,4 – fire suppression in bottom part of the enclosure (3 – aerosol supply into bottom part of the enclosure; 2 - aerosol supply into upper part of the enclosure).

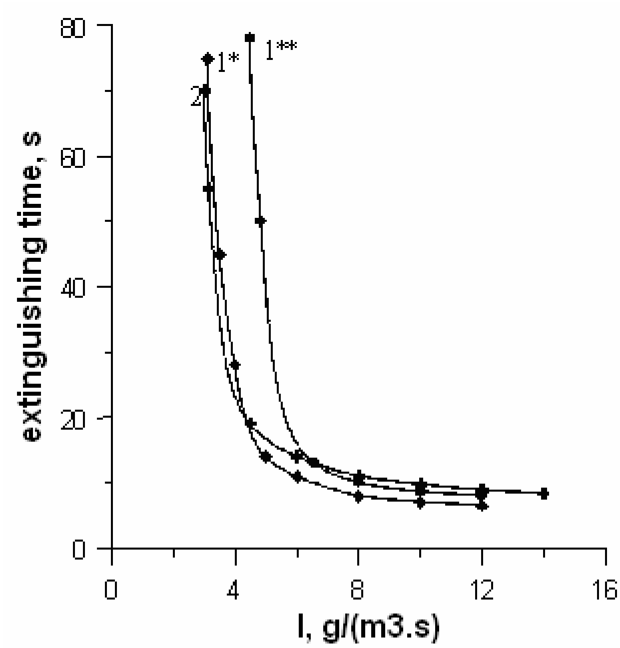

Figure 4. Dependence of extinguishing time for PMMA on intensity of aerosol supply into protected volume. Aerosol forming compounds: 1* - STK-2MD (T_c ~ 950 ^oC; T_c – temperature of combustion), 2 – STK-5-1 (T_c ~ 1100 ^oC), 1 - SBK-2 (T_c ~ 1250 ^oC)**

The experiments were made in model enclosure with a volume of 1.5 m^3 (0.6x2.5x1.0 m) with a factor of non-hermeticity of 0.5 %. A cabinet with a volume of 0.11 m^3 (0.4x0.4x07 m) with changeable factor of non-hermeticity (from 0 to 6 %) was arranged in the enclosure. Samples of PMMA with various sizes and cans with gasoline were used as model fire sources. Preburning time in the experiments was 120 s. Aerosol was formed by combustion of aerosol forming compound SBK in generator without coolant. Typical experimental results presented at Fig. 5.

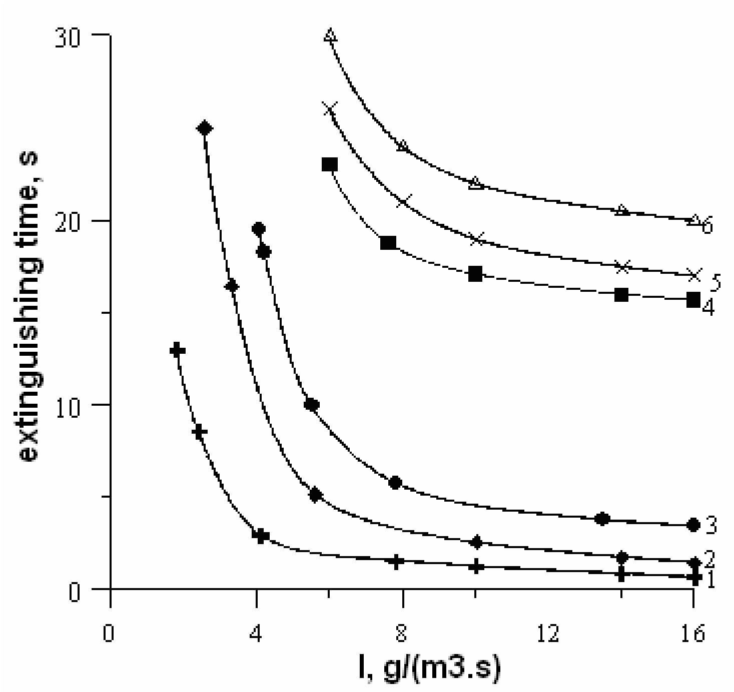

Figure 5. Dependence of extinguishing time for gasoline on intensity of aerosol supply into protected volume: 1 – simultaneous supply of the aerosol into the enclosure and into the cabinet; 2,3 – direct supply of the aerosol into the cabinet; 4-6 – total flooding by condensed aerosol in the enclosure for various square of model fire S (1,2,6 - S = 0.006 dm^2; 5 - S = 0.03 dm^2; 3,4 - S = 0.49 dm^2)

It follows from obtained data that the best results in fire suppression can be achieved with direct supply of the aerosol into the cabinet (curves 2,3 Fig.5). When the aerosol supplies simultaneously into the enclosure and into the cabinet (curve 1 Fig.5), extinguishing time decreases, but the amount of aerosol forming compound should be substantially increased to achieve fire suppression. When condensed aerosol is supplied into the enclosure only, serious problems in fire suppression in the cabinet arises (curve 6 Fig.5); in particular, for small model fires fire suppression in some cases can not be achieved.

An influence of "free volume" factor and air venting conditions. The experiments were conducted in typical electrical cabinets having a volume ranging from 0.9 to 4.0 m^3 with a factor of non-hermeticity of 1.1 – 1.3 %. During the experiments the volume of the cabinet was loaded by electrical equipment (up to 70 % of total volume). Electrical equipment were arranged in the cabinets in accordance with two main schemes: 1) separate elements or group(s) of units which not allow existence of flows in channels; 2) structures with channels. Ratio of square of surface of electrical units to total volume of the cabinet *F* were used as the main parameter characterizing an influence of loading on effectiveness of fire suppression.

It was found that electrical units with smooth surface arranged into a structure without channels, occupying not more than 50 % of total volume of the cabinet, doesn't influence effectiveness of fire suppression, but cause elevation of extinguishing time (up to 2-3 times and more) (Fig. 6). Electrical units with rough surface or arranged into a structure with channels inside cause substantial decrease of the effectiveness of fire suppression by condensed aerosol.

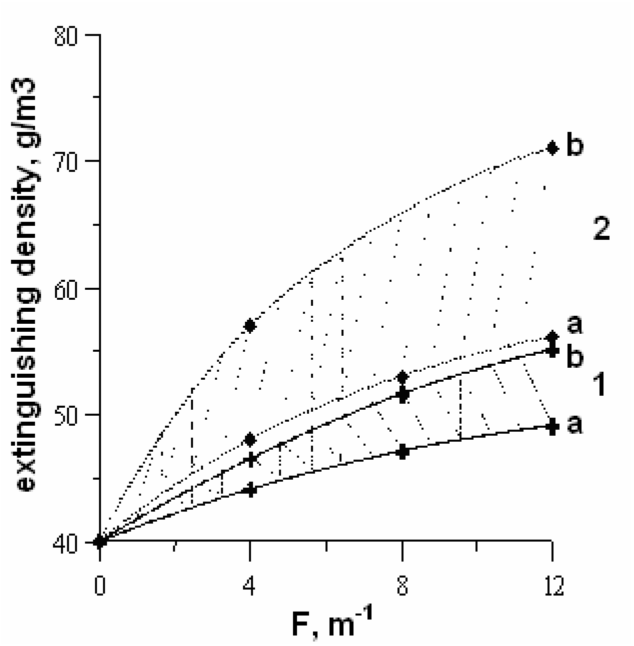

Figure 6. An influence of surface of electrical units and their arrangement on efficiency of fire extinguishing in cabinets with electrical equipment. Surface: a – smooth, b – rough. Arrangement: 1 - separate elements or group(s) of units which not allow existence of flows in channels; 2 - structures with channels. Aerosol forming compound: STK-2MD

An influence of air venting on effectiveness of fire suppression was also studied for the case of cabinet equipped with various electrical and electronic units. The experiments were conducted with velocity of air venting from 0 to 0.1 m^3/s and F=10-12. 5 model fire sources were arranged in the cabinet; preburning time was 120 s. The results presented at Fig. 7. It was established that increase of venting velocity causes progressive elevation of intensity of aerosol supply into the cabinet.

An influence of non-hermeticity of protected volume. It was obtained experimentally that losses of condensed aerosols with low initial temperature (less than 500 ^oC) through openings of protected enclosure are substantially less in comparison with rather "hot" aerosols (initial temperature more than 500 ^oC). Due to this extinguishing time for "cooled" aerosols is less than for "hot" aerosols. Fig. 8 summarizes the results obtained for application of "cooled" aerosols for extinguishing of combustion of gasoline, PMMA and electrical cables in enclosures having a volume up to 400 m^3 and height up to 6 m with various non-hermeticity.

An empirical dependence of on intensity of aerosol supply into bottom part of protected volume on initial temperature of aerosol (T_i), initial temperature in protected enclosure (T_o), parameters of non-hermeticity for bottom part and upper part of protected enclosure (N_b and N_u correspondingly) can be expressed as

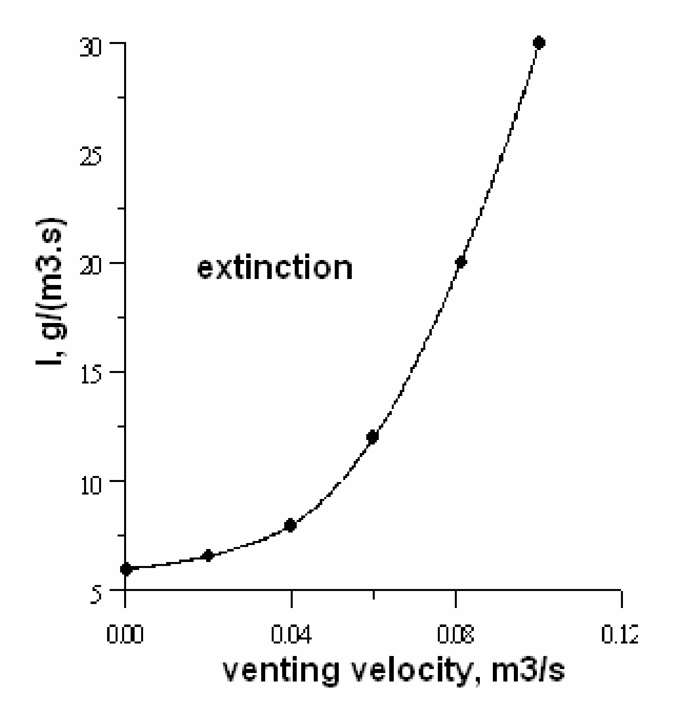

Figure 7. Dependence of intensity of aerosol supply directly into the cabinet on venting velocity

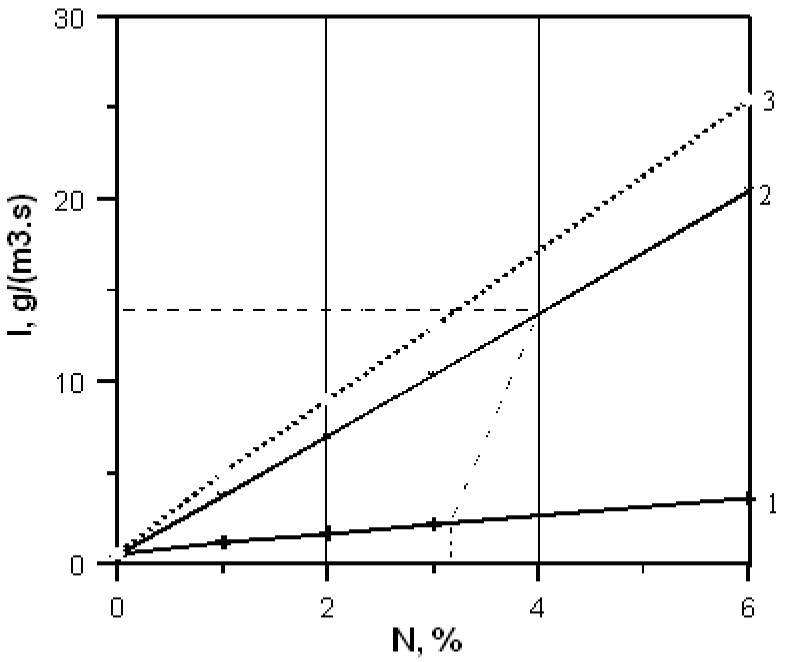

Figure 8. Dependence of on intensity of aerosol supply into bottom part of protected volume on parameter of non-hermeticity of protected volume (N).

Locations of openings in protected enclosure: 1 – bottom part of the enclosure; 2 – in upper part or in upper and in bottom part of the enclosure ($N_u/N_b<1$); 3 – in upper and in bottom part of the enclosure ($N_u/N_b>1$)

$I = 0.45 \cdot I_{T_o} (1 + T_i / T_o)(0.34 N_b + 2.7 N_u + 2)$ for the aerosols with initial temperature less than 500 ^oC;

$I = 0.45 \cdot I_{T_o} (1 + T_i / T_o)(0.34 N_b + 2.7 N_u + 2)$ for the aerosols with initial temperature more than 500 ^oC,

where I_o - intensity of aerosol supply into bottom part of sealed protected volume (N=0).

THE RESULTS OF FULL-SCALE EXPERIMENTS

Fire suppression in cable traces. The experiments were conducted at real objects like vertical channels or tunnels with the volume ranging from 10 to 400 m3 and fire loading up to 60 kg/m3. The temperatures before the beginning of fire suppression were in the range from -30 ^oC to 200 ^oC. Generators of condensed aerosol on a base of STK-2MD or SBK-2 with/without coolant were used in the experiments.

Model fire source contains at least two assemblies of cables oriented vertically or horizontally. The assemblies were arranged above a pan filled with gasoline or diesel fuel. The number of cables in the arrangement varies from 3 to 5. Cables having a diameter from 30 to 80 mm with PVC, rubber or paper insulation, protected by cotton or metal net were used in the experiments. Cable assembly was ignited by combustion of fuel in the pan or by electrical overloading of cables in the assembly (applied voltage was 35 kV or less). Temperature and oxygen concentration in protected volume were controlled during the experiments. Temperature measurements were made by thermocouples with a diameter 150 μm in proximity of model fire source and in various parts of protected volume). The main results of the experiments presented in Tables 1 and 2.

Table 1. An influence of initial temperature of the aerosol on effectiveness of fire suppression in cable traces

Protected volume, m^3	Fire loading	Initial conditions of fire suppression	T_i, ^oC	T_e, s	ΔT_v, ^oC	M_{afc}, kg/m^3
~400	Gasoline, PMMA, cables with rubber insulation	Cables in working regime ($T_c \le 80°C$)	~950 - 1250	35	70-100	0.07-0.08
		Cables in working regime ($T_c \le 80°C$)	~200	15	50	0.12-0.13
44	cables with rubber insulation	Electrically overloaded cables ($T_c \ge 200°C$)	~950 - 1250	120-180	90-140	0.095-0.100
		Electrically overloaded cables ($T_c \ge 200°C$)	~200	15	60	0.150

T_c – temperature of cable; T_i – initial temperature of condensed aerosol; t_e – extinguishing time; ΔT_v – elevation of temperature in protected volume; M_{afc} – mass of aerosol forming compound required for fire suppression.

Table 2. Fire suppression in cable traces.

Enclosure	V, m^3 (a x b x h)	Fire loading	Preburning time, s	T_i, °C	t_e, s	ΔT_v, °C	M_{afc}, kg/m^3	Conclusion+
Part of horizontal channel	10.0 (1x10x1)	**cables with rubber or PVC insulation protected by cotton net; gasoline	60	1250	17	81	0.065	Extinction
			120 150	950	21 22	60 65	0.070 0.075	Extinction
			150	1250	60	110	0.120	Continuing smouldering
			180 240	950	85 90	94 100	0.120 0.140	
Part of tunnel	13.2 (2x3.3x2)	***cables with rubber or PVC insulation	60	1250	21	78	0.065	Extinction
Part of vertical channel	10.0 (1x1x10)	*cables with rubber or PVC insulation; gasoline	60 120	1250	17 18	78 82	0.066 0.070	Extinction
			120	950	22	60	0.074	
			150		50	65	0.080	
			180		85	92	0.085	
Vertical channel	59.5 (3.7x2.7x 6.0)	*cables with rubber insulation protected by metal net; diesel fuel	360	1250	40	95	0.108	Extinction
Part of tunnel	68 (2x17x2)	**cables with rubber insulation; gasoline	60	950	30	78	0.140	Extinction
Basement	~420 (9x17.3x 2.7)	**cables with rubber insulation; gasoline	40	1250	38	76	0.110	Extinction

V –protected volume; *- ignition of unloaded cables by combustion of igniter (gasoline or diesel fuel); **- ignition of cables under loading (380 V) by combustion of igniter; ***- ignition of overloaded cables (applied voltage 15 kV);+ - oxygen concentration in protected volume 18.5-19.8 % vol.

As it follows from Tables 1 and 2, the effectiveness of fire suppression by the aerosols decreases for cables with smouldering insulation. Prolongation of preburning period also decreases the effectiveness of fire suppression; if the preburning period exceeds 120-150 s, the condensed aerosols became ineffective.

Successive extinguishing of cable fires in vertical channels requires 20 % elevation of design application density in comparison with extinguishing of cables arranged horizontally. In the case of vertical channels the generators of condensed aerosol should be arranged at several levels above the bottom part of the channel depending on characteristics of the generators.

Fire suppression of electrical and electronic equipment. The experiments with generators of condensed aerosol with/without coolant were conducted in typical cabinets with electrical equipment. The cabinets have a volume in a range from 0.9 to 4.0 m3. The cabinets were loaded by electrical equipment up to 70 % of the volume of the cabinet. Preburning period was 120s in all of the experiments. Experimental results presented in Table 3.

Table 3. Fire suppression in electrical cabinets and enclosures with electrical equipment

Cabinet/enclosure description	V, m^3	K, %	Fire loading	T_i, ^oC	M_{afc}, kg/m^3	ΔT_v, ^oC
Cabinet with control units	4.7	30	Gasoline, rubber, PMMA	900-1250	0.07	60-100
Cabinet with control units	4.7	30	Gasoline, rubber, PMMA	<200	0.12-0.14	40-60
Cabinet with electronic devices	1.9	45	Gasoline, PVC, PMMA, polyethylene	900-1250	0.08	50-100
Cabinet with electronic devices	1.9	45	Gasoline, PVC, PMMA, polyethylene	<200	0.12-0.14	30-50
Enclosure with cabinets equipped with electronic devices	64.0	30	Gasoline, PVC, PMMA, polyethylene	900-1250	0.10-0.12	90-160

K – part of volume of cabinet/enclosure loaded by electrical/electronic devices.

The obtained results confirm preliminary conclusions made on the basis of laboratory-scale experiments. Also it is necessary to mention that all tested electrical and electronic equipment was able to perform its functions during at least 1 month after the experiments.

It was obtained that presence of several electrical units, occupying no more than 50 % of the volume of the cabinet, doesn't influence effectiveness of fire suppression by condensed aerosols, but causes substantial increase (up to 2-3 times) in a time of fire extinguishing. If the arrangement of electrical equipment allows existence of vertical flows in "channels", the effectiveness of fire suppression falls down drastically.

Special series of the experiments were made to investigate an influence of ventilation of the cabinets on effectiveness of fire extinguishing. Ventilating flow rate was in the range from 0 to 0.08 m3/s. It was revealed by the experiments that design application density increases exponentially with an increase of the flow rate. The effectiveness of the aerosols became higher if the aerosol has low initial temperature.

Also it is necessary to mention that all tested electrical and electronic equipment was able to perform its functions during at least 1 month after the experiments.

CONCLUSIONS

1. The effectiveness of condensed aerosols for fire protection of cable traces, electrical and electronic equipment was investigated experimentally.

2. It was obtained that condensed aerosols are effective for suppression of cable fires. The effectiveness of the aerosols became higher if the aerosol has low initial temperature and design application density is maintained by extended discharge of fire suppression system during 5 min. and more.

3. To extinguish cable fires at elevated (up to 200 ^{o}C) temperatures, the design application density obtained at normal conditions (20-25 ^{o}C) should be multiplied by a factor 1.5 – 2.0.
4. The effectiveness of fire suppression by the aerosols decreases for cables with smouldering insulation. Prolongation of preburning period also decreases the effectiveness of fire suppression; if the preburning period exceeds 120-150 s, the condensed aerosols became ineffective.
5. Successive extinguishing of cable fires in vertical channels requires 20 % elevation of design application density in comparison with extinguishing of cables arranged horizontally. In the case of vertical channels the generators of condensed aerosol should be arranged at several levels above the bottom part of the channel depending on characteristics of the generators.

6.It was obtained that presence of several electrical units, occupying no more than 50 % of the volume of the cabinet, doesn't influence effectiveness of fire suppression by condensed aerosols, but causes substantial increase (up to 2-3 times) in a time of fire extinguishing. If the arrangement of electrical equipment allows existence of vertical flows in "channels", the effectiveness of fire suppression falls down drastically.

7. Extinguishing density of the aerosol increases exponentially with an increase of venting velocity.

8. All tested electrical and electronic equipment was able to perform its functions during at least 1 month after the experiments.

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