

Modeling of Concentration Parameters and Geometry of Aerosol Cloud During Extinguishing Combustion Centres in Open Space

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Abstract. The article considers a simplified approach to assessing the shape and concentration characteristics of an aerosol cloud formed during the extinguishing of liquid fires in open space. The model includes the effect of natural convection and a thermal flare, which allows determining the working volume of the cloud and the limits of concentration sufficient to stop the burning. It is analyzed how the critical concentration changes with an increase in the volume of the cloud, and it is shown that this does not lead to a decrease in the aerosol consumption. The results can serve as a basis for designing autonomous aerosol systems at critical infrastructure facilities.

Fires of flammable liquids in open areas develop very quickly and are accompanied by significant thermal effects. Under such conditions, the fire easily spreads to adjacent energy and industrial facilities or equipment, which is especially noticeable now, when the number of affected energy nodes is constantly growing [1; 2]. This increases the need for local response means that can operate autonomously in open space conditions and provide extinguishing even at the initial stages.

Conventional foam and water systems have certain shortcomings in efficiency: a rather long system operation time, unreliability in adverse conditions, and instability in combat conditions [3; 4]. Gas compositions also work worse, since their concentration near the flame decreases almost immediately due to intensive dispersion [5; 6]. Against this background, more and more attention is being paid to fire-extinguishing aerosol generators that form a dispersed cloud with high reactivity and do not require the supply of water or powder components [7; 8].

Although the mechanisms of action of fire-extinguishing aerosols in closed volumes have been studied in considerable detail [9–10], the situation in an open environment looks different. The issue of the spread of an aerosol cloud in the air, maintaining its concentration and the influence of external flows has been studied only partially. For such conditions, there is actually a lack of engineering approaches that would allow describing the shape of the cloud, its concentration characteristics and the time during which it retains its extinguishing effect, taking into account the interaction with the ascending flame of combustion products [11–12]. Because of this, it is difficult to determine the required charge mass, the optimal installation height of generators and other parameters of their operation in open space.

Introduction

The problem addressed in this paper is related to the lack of a convenient engineering approach for assessing the shape of the aerosol cloud and changes in its concentration during extinguishing liquid fires in an open environment. Such an approach is needed primarily for local fire protection systems at critical facilities, primarily energy and industrial, where the speed of response directly affects the scale of possible man-made losses [13–14].

The problem of extinguishing fires of combustible liquids remains an important area of modern fire safety research, particularly in the context of improving the efficiency of local fire protection systems. In the work of C. L. Beyler, the characteristics of large hydrocarbon pool fires and the factors influencing heat release and flame stability in open conditions are analyzed, which are important for assessing the development of liquid fuel fires and selecting appropriate suppression strategies [15]. Experimental studies by I. Marková and co-authors are devoted to determining the

fire size and burning characteristics of gasoline pool fires, providing important data for evaluating the effectiveness of various fire-extinguishing approaches in open environments [16]. In addition, L. Zheng and co-authors investigate the mechanisms of combustion inhibition by dispersed particles and show how the size distribution and chemical composition of particles influence flame suppression processes [17]. These studies form an important scientific basis for understanding the mechanisms of fire suppression and for further development of aerosol-based fire-extinguishing technologies. At the same time, a separate group of studies focuses directly on the application of aerosol fire-extinguishing agents and the peculiarities of their operation under real conditions.

Experimental studies devoted to the operation of aerosol compositions in an open environment also occupy a prominent place in the scientific literature. In particular, the works of Balanyuk present the results of measurements of the concentration effect of aerosol in the open air and show the effectiveness of the pulse method of extinguishing liquid cells [3, 13]. However, these works focus mainly on assessing the concentration of the reagent and almost do not touch on the issue of the formation of the cloud itself, its geometry and changes over time under conditions of natural convection - a factor that is of significant importance for engineering calculations in open space [5]. In applied research on fire protection, considerable attention is paid to highly dispersed aerosol reagents and water-based media. In the work of Z. Sun and co-authors, the influence of heat flows on the formation of a flame of explosive liquids is considered and the limitations of traditional extinguishing agents under conditions of unstable air movement are shown [13]. The research of J. Lu and I. Liu is devoted to assessing the effectiveness of local extinguishing systems at critical energy facilities; the authors draw attention to the importance of pulsed introduction of the reagent and control of the dispersion of the cloud in the early stages of its formation [11, 6].

Despite the significant amount of work in this area, most studies are mainly concerned with extinguishing in closed volumes or analyze individual diffusion mechanisms without taking into account how the aerosol cloud behaves in open space. Often overlooked are the issues of its shape, changes in concentration and the time during which the cloud retains extinguishing properties - namely, this interval in real conditions is quite short. Without understanding these features, it is difficult to reasonably design local fire protection systems for energy and industrial facilities.

Objectives

The main purpose of the work is to create a simplified engineering approach that can be used to describe the shape of an aerosol cloud and the change in its concentration during the extinguishing of liquid fires in open conditions. The model takes into account the influence of natural convection and the thermal flame torch, which allows assessing the possibilities of practical application of local aerosol systems at energy and industrial facilities.

To achieve this goal, the following tasks are solved in the work:

- to consider existing approaches to the use of aerosol compositions for extinguishing liquids and determine what limitations the current models have when it comes to working in open space;
- to find out how an aerosol cloud is formed under the influence of an upward thermal flow, and to describe the features of its movement in conditions of natural convection;
- to present a simplified mathematical scheme that allows assessing the geometry of the cloud and the effective volume within which liquid cells can be extinguished;
- show an approach to determining the average extinguishing concentration of an aerosol and outline the duration of the interval during which this concentration remains effective;
- formulate practical recommendations for the use of fire-extinguishing aerosol generators for local protection of critical infrastructure facilities in an open environment.

Main part

The operation of fire-extinguishing aerosol generators in an open environment has a number of features: the movement and behavior of the cloud are affected by the size and dispersion of particles, the thermal effect of the flame and natural convection. Because of this, the extinguishing

mechanism under such conditions is significantly different from the processes observed in closed volumes.

Aerosol particles carry active components directly to the combustion zone and can suppress radical chain reactions. This effect is described in works devoted to the combined use of aerosols, gas and powder compositions [8, 15, 16].

After leaving the generator, the aerosol cloud moves downward in a pulsed flow, counteracting the rising combustion products. This behavior is explained by the high velocity of the particles at the outlet and their subsequent turbulent mixing with the flame torch [14; 15]. Initially, the cloud has a shape close to a truncated cone, but over time the motion stabilizes, and a zone of relatively constant concentration is formed. Its volume for engineering assessments is conveniently described by a simplified cylindrical model. If the generator is located at a height H above the liquid surface, the effective radius of the cloud can be determined by the approximation: $R_{ef} \approx 0,7H$, and the height of the most concentrated part - as: $h_{ef} \approx H$.

Then the effective volume of the cloud, within which a concentration sufficient to inhibit the combustion reaction is achieved, is:

$$V_{eff} = \pi R_{ef}^2 h_{ef}. \quad (1)$$

To systematize the modeling results, it is advisable to generalize the geometric characteristics of the aerosol cloud depending on the height of the generator installation. This allows us to more clearly trace the patterns of changes in the effective radius and volume of the cloud under natural convection conditions.

Table 1. Geometric parameters of the aerosol cloud depending on the height of the generator installation [8, 12]

Generator height H , [m]	Effective radius R_{ef} , [m]	Effective volume V_{eff} , [m ³]
0.5	0.35	0.19
1.0	0.70	1.54
1.5	1.05	5.18
2.0	1.40	12.3

Analysis of the data in Table 1 shows a nonlinear increase in the effective volume of the cloud with increasing generator installation height. If the radius increases almost proportionally to the height, then the volume increases according to the cubic law. This confirms the significant influence of the geometric factor on the formation of the inhibition zone.

Research by Balanyuk shows that for successful local extinguishing, it is precisely the achievement of a critical concentration in the active combustion zone that is decisive, and not the complete filling of the space with aerosol [11–12]. To assess this effect, engineering calculations use the aerosol utilization factor, which reflects the fraction of the solid charge mass that actually participates in creating the working concentration, taking into account losses in the open environment. In practice, its value is usually taken within 0.3–0.5. Then the mass of aerosol that actually acts in the combustion zone can be calculated as:

$$m_{ef} = \eta m_a, \quad (2)$$

and the average concentration in the effective volume:

$$C_{average} = \frac{m_{ef}}{V_{ef}}. \quad (3)$$

According to the results of video recording, it is clear that the aerosol maintains a sufficient concentration only for a short time - up to approximately 10 seconds. This duration correlates well with the ideas about the relaxation nature of turbulent disperse flows [4; 13]. If C_{ser} exceeds the critical value determined for a specific flammable liquids C_{cr} , the aerosol provides local extinguishing. In the presence of wind transport, it is advisable to introduce a correction factor k_w (1.0–1.5), which affects the required mass of aerosol:

$$m_a^{needs} = \frac{c_{cr} V_{ef}}{\eta} k_w. \quad (4)$$

The proposed model allows you to assess where exactly it is advisable to place generators, what mass of aerosol charge they should deliver and how long the effective operation of the system can be expected at open energy facilities. The use of such a model helps to justify the parameters of real aerosol installations and develop solutions that ensure a quick response and reduce possible losses when extinguishing liquid fires in an open environment.

To generalize the influence of external factors on the extinguishing efficiency, a systematization of the main physical factors was performed (Table 2).

Table 2. Factor influence on the formation and efficiency of an aerosol cloud [5, 9]

Factor	Impact on Geometry	Impact on Concentration	Engineering Implications
Natural convection	Cloud expansion	Decrease in local concentration	Increase in required mass
Thermal plume	Symmetry deformation	Dilution in the fuel jet center	Optimization of injection point
Particle dispersion	Structure stabilization	Increase in inhibitory capacity	Optimization of particle size distribution
Wind load	Asymmetry and cloud displacement	Mass loss of reagent	Introduction of co

For an integral generalization of the influence of physical and constructive factors on the efficiency of aerosol extinguishing, it is advisable to use a radar (multi-axis) diagram (Fig. 1). This approach allows for a comprehensive assessment of the relative weight of each factor and to identify the dominant parameters that determine the stability of the working concentration in the combustion zone.

The radar diagram (Fig. 1) demonstrates that the most critical influence is exerted by natural convection and wind loading, which significantly reduce the time of existence of the working concentration of the aerosol. At the same time, the dispersion of particles and the charge utilization factor determine the inhibition efficiency at the micro level. Therefore, the maximum efficiency of the system is achieved only under the condition of simultaneous optimization of the geometry of the generator placement and the granulometric characteristics of the aerosol.

The results obtained indicate that the most significant influence on the efficiency is exerted by the combination of convection and wind transport, which limits the time of existence of the working concentration to approximately 8–10 seconds.

The proposed model is especially useful for critical infrastructure facilities, where fires often occur in the open air, and the possibilities of supplying water or other traditional means are limited. In such situations, it is important not only to choose the appropriate reagent, but also to ensure a sufficient concentration of aerosol precisely in the active zone of the flame - and to do this in that short period of time when the system is able to act most effectively.

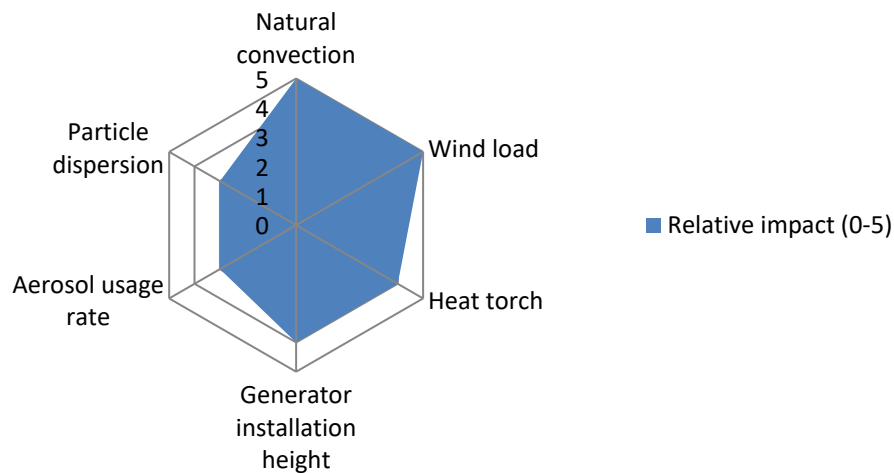


Fig. 1. Integral radar assessment of the influence of physical and structural factors on the efficiency of aerosol extinguishing in an open environment [3, 16]

Therefore, it is important to determine in advance what type of combustible medium the system will operate with, because it is on this that further experimental verification and calculation models of local fire extinguishing depend.

Fires at transformer substations are complicated by the fact that transformer oil burns with intense heat release, forms a powerful torch and maintains a high temperature of combustion products for a long time. Under such conditions, only highly dispersed inhibitors work effectively, capable of partially shielding the heat flow and suppressing radical chain reactions.

In further calculations, T-1500 transformer oil was used as the basic combustible medium - one of the most common types used at energy facilities in Ukraine and meets the conditions for studying autonomous aerosol systems.

Table 3. Physico-chemical parameters of transformer oil T-1500, adopted for research [17, 12]

Parameter	Designation	Value	Units	Note
Flash point	F p	145–160	°C	In an open crucible
Autoignition temperature	A t	310–330	°C	With open air access
Density at 20 °C	ρ	0.88–0.92	g/cm ³	Determines the mass of the combustible layer
Dynamic viscosity at 40 °C	η	11–14	mm ² /s	Affects spreading
Calorific value	Q	41–43	MJ/kg	High heat transfer
Flammability group (fire class)	—	B	—	Liquid combustibles

The key indicator of the effectiveness of aerosol systems is the critical extinguishing concentration C_{cr} , at which the radical chain reaction of transformer oil combustion stops. It determines the minimum mass of the active aerosol phase that must be delivered to the effective volume V_{ef} . Based on preliminary modeling, taking into account the geometric parameters of the cloud and the aerosol utilization factor η , values were obtained C_{cr} for different generator heights.

Further analysis is advisable to carry out through the integration of geometric parameters with concentration characteristics (Table 5).

Table 4. Calculated values of the critical extinguishing concentration C_{cr} for stopping the combustion of transformer oil T-1500 (note: for the aerosol utilization factor $\eta = 0.4$)

Generator location height H , [m]	Effective radius R_{ef} , [m]	Effective volume V_{ef} , [m ³]	C_{cr} , [kg/m ³]	Minimum mass of aerosol required for extinguishing, [g]
0.5	0.35	0.19	0.045–0.060	9–12
1	0.7	1.54	0.030–0.045	46–69
1.5	1.05	5.18	0.025–0.040	130–207
2	1.4	12.3	0.022–0.036	270–442

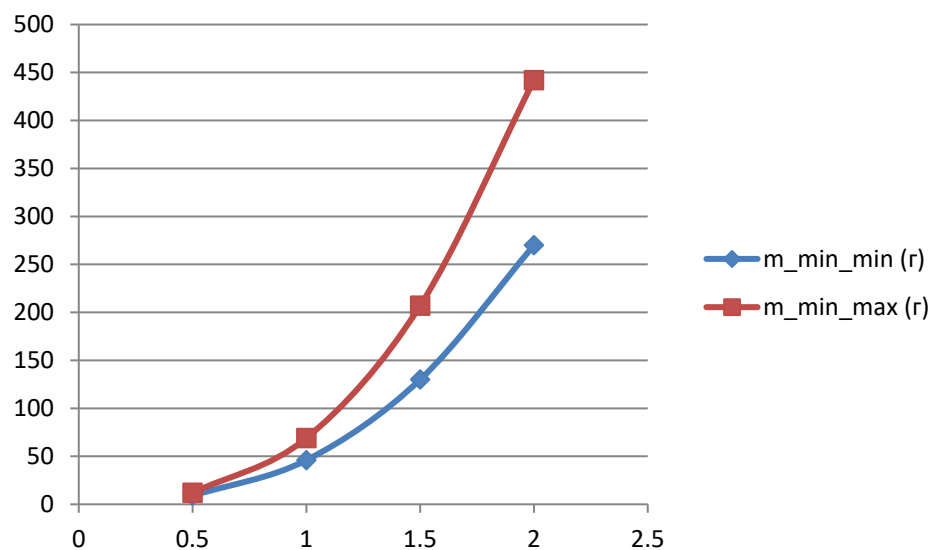
Note: The practical range of C_{cr} is given for aerosols based on potassium-containing salts, which is confirmed in studies of the mechanisms of radical flame inhibition [18-20].

Table 5. Integral concentration parameters of aerosol extinguishing of transformer oil T-1500 ($\eta = 0.4$) [7, 15]

H , [m]	V_{ef} , [m ³]	C_{cr} , [kg/m ³]	Minimum aerosol mass, [g]
0.5	0.19	0.045–0.060	9–12
1.0	1.54	0.030–0.045	46–69
1.5	5.18	0.025–0.040	130–207
2.0	12.3	0.022–0.036	270–442

Table 5 shows that with an increase in the effective volume, the critical extinguishing concentration decreases, but the minimum mass of the aerosol increases. This is explained by the fact that although the required inhibitor density per unit volume decreases, the total coverage volume increases much faster.

To clearly confirm the identified trend, it is advisable to present the dependence of the minimum mass of aerosol required for extinguishing T-1500 transformer oil on the height of the generator installation. Such visualization allows us to assess the practical scale of the increase in reagent consumption with an increase in the geometric parameters of the aerosol cloud (Fig. 2).

**Fig. 2.** Dependence of the minimum aerosol mass m_{min} on the generator installation height H when extinguishing transformer oil T-1500 ($\eta = 0.4$) [6]

The graph (Fig. 2) shows that the minimum aerosol mass increases sharply nonlinearly with increasing generator installation height. Although the critical concentration decreases, the increase in the effective volume occurs faster, which causes a significant increase in the total reagent consumption. This confirms that optimizing the installation height is a key engineering parameter when designing autonomous aerosol systems in an open environment.

As calculations show (Table 2-4), an increase in the generator installation height leads to an increase in the volume of the aerosol cloud, and at the same time the value of the critical extinguishing concentration C_{cr} changes.

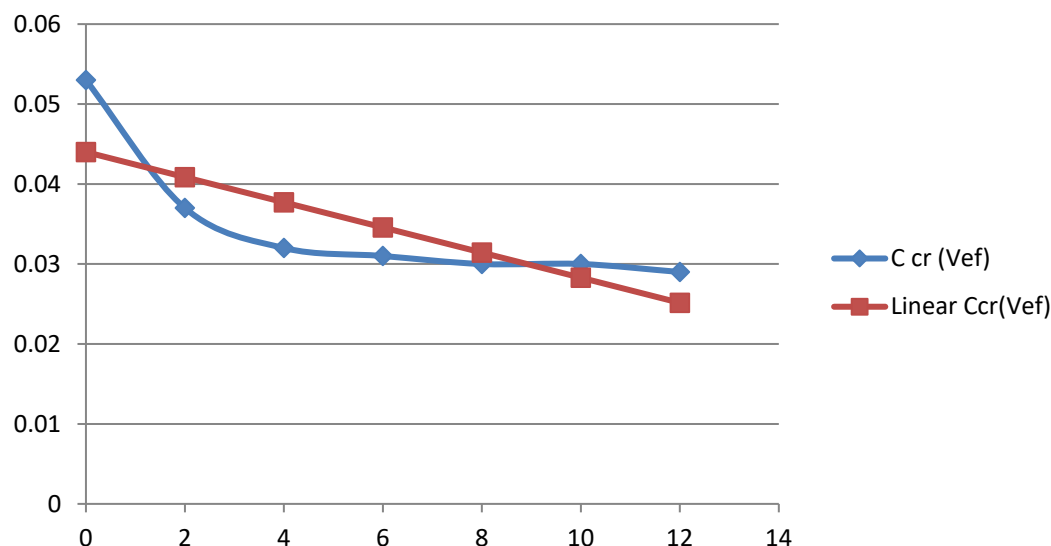


Fig. 3. Dependence of the critical extinguishing concentration C_{cr} on the effective volume of the aerosol cloud V_{eff} when extinguishing transformer oil T-1500

The graph (Fig. 3) shows that with an increase in the effective volume of the aerosol cloud, the critical extinguishing concentration C_{cr} decreases. At the same time, the total reagent consumption does not decrease, because a larger mass of aerosol is required to fill a larger volume. This behavior of the curve indicates that when designing local systems in an open environment, it is important to take into account not only the minimum required inhibitor concentration, but also the location of the generators and the actual geometry of the cloud. This allows you to more accurately determine the mass of the charge and the operating parameters of aerosol systems for extinguishing liquid cells at critical infrastructure facilities.

Conclusions

The analysis shows that a simplified engineering scheme for describing the formation of an aerosol cloud in an open environment can be effectively used to assess the processes of extinguishing liquid cells. The model takes into account the effect of natural convection, upward heat flow and mechanisms of radical chain inhibition, which allows us to quantitatively describe the geometry of the cloud and determine the mass of aerosol sufficient to create a working extinguishing concentration. Calculations have shown that with an increase in the effective volume of the cloud, the critical concentration decreases, but the total reagent consumption does not decrease. This is explained by the need to supply a larger mass of aerosol to cover a wider inhibition zone. This result emphasizes the importance of the correct choice of the generator installation height and the rational use of the dispersed charge in open conditions.

The results obtained indicate that local aerosol systems work well when extinguishing transformer oil at energy facilities, especially when water supply or the use of foam compositions are difficult or require more time for deployment. Such systems have the advantage of efficiency and can provide a quick response to the burning centers of high-temperature liquids in the autonomous mode.

Further development of the work may involve refining the model taking into account wind transport and uneven turbulent scattering of aerosol particles. It is also important to test the model in real conditions of an open environment - this will allow determining the correction factors necessary for engineering calculations. A separate direction may be the development of practical recommendations for the selection of parameters of aerosol generators - charge mass, dispersion and feed rate - in order to ensure rational design of autonomous fire extinguishing systems at energy facilities.

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