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INVESTIGATION OF NOZZLES FOR WATER MIST SYSTEMS IN FIRE SUPPRESSION IN ENGINEERING FACILITIES

A B S T R A C T

of a dissertation for the award of the educational and scientific degree "Doctor" in professional field 5.8 Exploration, Extraction and Processing of Mineral Resources, scientific specialty: "Occupational Safety Engineering and Fire-Fighting Equipment"

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The research presented in the dissertation was carried out by the author.

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Title: “Investigation of Nozzles for Water Mist Systems in Fire Suppression in Engineering Facilities”

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I. GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

Fires in engineering facilities such as road tunnels, transformer substations, industrial buildings, production halls and underground garages pose a considerable danger to human life and can cause serious damage to individual elements or to the entire structure. In recent decades a number of tunnel fires have resulted in loss of life and disruption of road infrastructure, which also affects the economy. Among the factors that increase the risk are growing road traffic, the transport of dangerous goods, and the mismatch between the capacity of the facilities and the traffic load.

Technical and organizational measures are required to improve safety in tunnels, to prevent incidents and to limit their consequences. Fires can cause damage to the structure and the infrastructure, as well as injuries and loss of life as a result of high temperatures and the release of toxic gases. Primary attention should be paid to limiting combustion in the initial stage, protecting the structural elements and providing conditions for evacuation. The consequences of a fire depend to a large extent on the simultaneous development of the fire and the progress of the evacuation.

The essence of a water mist fire protection system, used for control and/or suppression of fires, is the introduction of fine droplets, in the form of mist, into the combustion zone. The aim is to achieve a lower fire power and temperature, to dilute oxygen with water vapour and to reduce infrared radiation. In addition, the fire is extinguished or maintained at a low energy level, which considerably facilitates extinguishing. The systems of this type that are currently applied require a high pressure of 36 to 160 bar, as well as a separate piping system and armature suspension. These requirements make the construction and maintenance of the systems concerned more expensive to a certain extent, which is why they are rarely applied.

The main object of research in the dissertation is nozzles for generating water mist and the possibilities for their application in fire suppression systems for engineering facilities.

By means of a purpose-built experimental stand, scientific and applied research was carried out on two types of fine nozzles. Their specific parameters and characteristics were determined, and the results can be used in the design and testing of water mist fire protection systems in operating facilities, specifically under road tunnel conditions. At the same time, the results achieved will broaden the field of application of this type of fire suppression system.

Aim of the dissertation

The main aim of the dissertation is to investigate water mist nozzles and to develop a model of a fire suppression system for road tunnels. The system is intended to limit the heat release rate and the temperature of the fire and to support safe evacuation and the protection of the infrastructure in tunnels.

To achieve the stated aim, the following main tasks were solved:

1. Study of the possibilities for applying low-pressure water mist in road tunnels
2. Investigation of the dynamics of fires in road tunnels on the basis of mathematical and physical modelling
3. Analysis of the various types of spray nozzles and their influence on the distribution of the water mist.
4. Development and construction of a stand for testing nozzles for water mist fire suppression systems
    4.1. With vertical spraying
    4.2. With horizontal spraying
5. Modelling and extinguishing of a design fire with a fixed low-pressure water mist fire suppression system.
6. Investigation of a physical model of water mist fire suppression systems

The following methods are used to solve the set tasks:

1. Literature review and analysis of regulatory and technical documents.
2. Analysis of mathematical models and of the results of full-scale fire tests.
3. Comparative analysis of the technical characteristics and experimental data for different types of nozzles.
4. Experimental design, construction and measurement.
5. Controlled tests in an experimental tunnel.
6. Physical and mathematical modelling, parametric analysis and generalization of the experimental relationships.

II. CONTENT OF THE DISSERTATION

CHAPTER I. REVIEW OF THE CURRENT STATE OF INDUSTRIAL FIRE SUPPRESSION SYSTEMS

I.1. Types of industrial fire suppression systems. Operating principle. Significance. Application

The most common water-based extinguishing installations are the so-called sprinkler or deluge systems. Sprinkler fire suppression installations are a system of pipes through which pressurized water flows (Fig. 1). Supply is provided from an independent water source, which must have sufficient capacity to ensure the delivery of water at maximum load for a specified period of time. The pressure in the piping system is provided by pumps, and the entire system is under constant monitoring. When one or more of the automatic sprinklers is subjected to a thermal effect, they are activated, allowing water to flow out through them. The water stream strikes a deflector, which disperses the water in directions with a specified size and extinguishing properties. Only the sprinkler heads located above or close to the seat of the fire are opened, i.e. those whose action is necessary for extinguishing. This is the most commonly encountered system, with a proven wide field of application, for example for the protection of warehouses, offices, and industrial and commercial facilities.

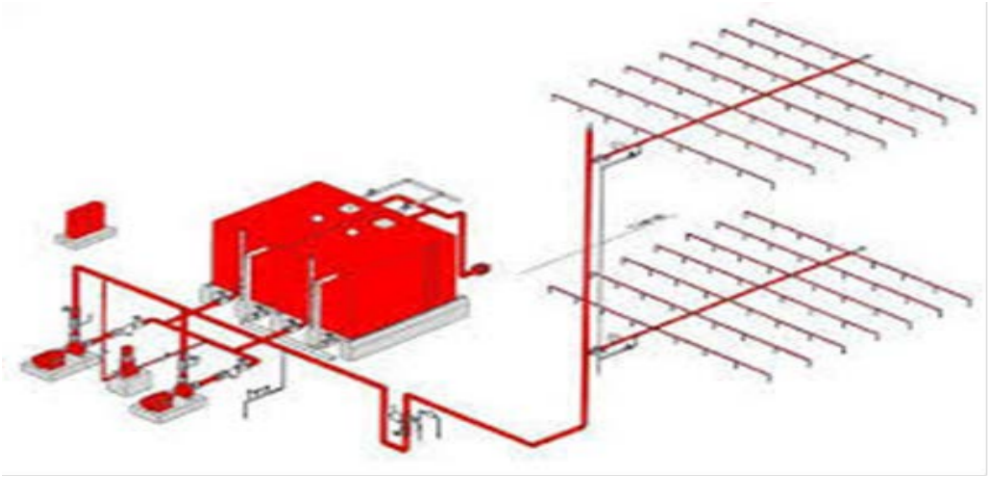


Figure 1. Schematic diagram of a fire suppression system

https://megaelectronics.bg/izgrazhdane-na-sprinklerni-sistemi/

In practice, twin-fluid nozzles are also used to generate water mist, in which the water is atomized through interaction with a compressed gas, for example air or nitrogen. In water-air nozzles the energy of the air stream assists the breaking up of the water into fine droplets. This mechanism allows water mist to be generated at a relatively low water pressure, with the spray characteristics depending on the nozzle design, the pressures and the ratio of the flow rates of the two fluids (Gupta et al., 2012; Jeong and Lee, 2021).

I.2. Analysis and evaluation of fire suppression systems

When selecting the type of fire suppression system in road tunnels, it is necessary to analyse and evaluate both the possibilities for applying protective devices and the specific characteristics of fires, by applying a systems approach to ensuring traffic safety.

Water mist extinguishing in road tunnels is based on creating a maximum cooling effect in the fire zones, with a view to reducing the consequences for the occupants, the tunnel structure and the equipment in it. Water mist has the universal property of extinguishing or suppressing fires of ordinary combustible materials.

I.2.1. Types of fires

Standard NF EN 2 distinguishes fire classes according to the type of combustible substance:

- class A – fires of solid materials, usually producing glowing embers when burning;
- class B – fires of flammable liquids and of solid materials that melt and burn as liquids when ignited;
- class C – fires of flammable gases;
- class D – fires of metallic materials;
- class F – fires of oils and fats used in cooking appliances.

The last class takes into account the specific characteristics of the products used in cooking (oils and fats), although at first sight they are similar to those of class B.

The applicability of water mist for extinguishing live electrical equipment, oils and fats is determined for the specific system by testing and by the manufacturer’s instructions. It should not be assumed to be universally applicable to fires of metals or of substances that react dangerously with water.

Depending on the heat release rate (HRR) of the fire in the growth period when the water mist system is activated, it can achieve:

- extinguishing of the fire;
- prevention of the spread of the fire beyond the zone of origin;
- suppression of fire development at a low energy level, by reducing the heat release rate.

I.2.2 Elements and operating principle of water mist fire suppression systems

With modern technologies, different droplet sizes can be generated by varying the pressure of the water passing through and the geometric parameters and dimensions of the spray nozzle (Table 7). An analysis of the existing methods for spraying water shows that there are two types of systems, which differ according to the droplet size distribution. The first type are the water mist systems and the second type are systems with large droplets, also called “sprinklers”.

Table 7. Characteristics of water mist

Droplet diameter	Reaction surface per litre of water	Fire protection system
1 mm	2 m^2	Irrigation system
0.1 mm	20 m^2	Fine water spray
0.01 mm	200 m^2	Water mist

Table 8 classifies water mist systems according to the minimum working pressure, in accordance with NFPA 750.

Table 8. Types of water mist systems

Minimum working pressure	System type
> 35 bar	High-pressure system
12 – 35 bar	Medium-pressure system
< 12 bar	Low-pressure system

Table 10 presents the classification of water mist in accordance with NFPA 750. Practical experience shows that Class III water mists are suitable for class “A” fires, since their droplet size allows them to reach the surface of the solid combustible substance, provided that it is not covered, and consequently cooling of the combustible substance can be achieved. Nevertheless, this type of water mist is less effective than Class I mist for cooling the gas phase (air and smoke). In fact, with larger droplets the surface-to-volume ratio is smaller, which reduces the heat transfer between the gas and the liquid. For this reason, the heat absorption during droplet evaporation and the absorption of radiation is lower for larger droplets.

Table 10. Classification of water mist according to NFPA 750

Class I	Class II	Class III
$D_{v0.9} \leq 200$ µm	200 µm $\leq D_{v0.9} \leq$ 400 µm	400 µm $\leq D_{v0.9} \leq$ 1000 µm

I.3. Main conclusions. Aims and tasks of the research

The water mist system has both advantages and disadvantages. It has a significant influence on the aero- and thermodynamics in road tunnels, including the resistance to the air flow, the velocity, the temperature distribution and the spread of smoke.

Precise coordination of the operation of the water mist with the emergency ventilation system is necessary. Theoretical analyses and experimental verification of the results of numerical modelling are needed to optimize it.

CHAPTER II. INVESTIGATION OF FIRE DYNAMICS IN ROAD TUNNELS BASED ON PHYSICAL AND MATHEMATICAL MODELLING

II.1. Essence and types of road tunnels

A road tunnel is defined as an enclosed road alignment intended for the movement of motor vehicles, with access restricted solely through portals, regardless of the type of construction or the construction method. Owing to its specific nature, a road tunnel requires – at the discretion of the owner or the responsible designer – specialized design considerations related to lighting, ventilation, fire protection and the provision of emergency evacuation facilities.

The shape of the tunnel is determined by its external contour (exterior), which in most cases is a result of the chosen construction method. Despite the structural diversity, the internal geometry of the tunnel is usually rectangular, in order to ensure efficient and safe movement of motor vehicles. The geometry along the length of the tunnel may vary, especially where there are different structural sections built using different tunnelling technologies. Changes in the cross-sections are usually due to the transition from one construction method to another – for example from drill-and-blast to the “cut-and-cover” method.

II.2. Analysis of the physical modelling of fire development

Fire tests conducted in the Runehamar tunnel in 2003 investigate the ignition and growth phases. During the growth phase the longitudinal ventilation velocity in the tunnel was approximately 2.5 m/s in each of the tests, while the heat release rate (HRR) increased gradually.

The graph in Figure 36 presents data for a heavy goods vehicle (HGV) with a tarpaulin covering the cargo and in the absence of significant longitudinal air flow, where the HRR does not show a substantial increase until about 10 minutes after ignition.

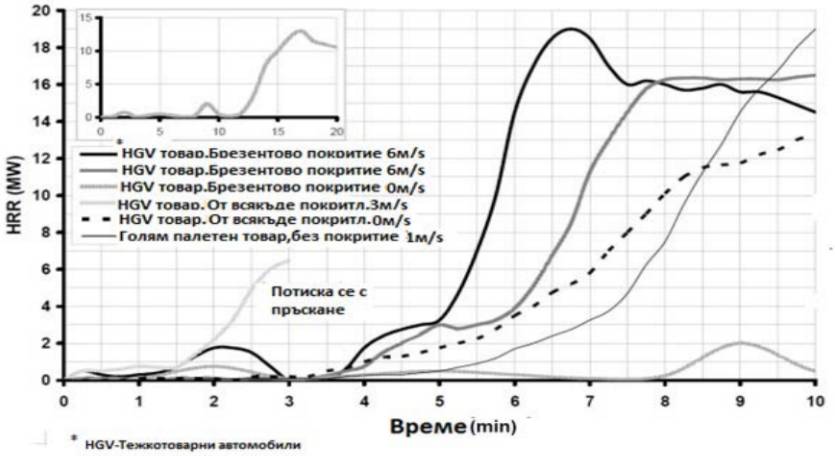


Figure 36. Fire type – time to suppression by spraying

Compartment fires are often modelled using a “t^2-fire” (Directorate-General for Public Works and Water Management, 2002), in which the heat release rate is assumed to grow in proportion to the square of the time after ignition. According to this classification, fires are divided into

“slow”, “medium”, “fast” and “ultrafast”, with corresponding proportionality coefficients of approximately 3, 11, 44 and 178 [W/s²].

None of the experiments considered can be adequately modelled with a “t²-fire”. In most cases the initial growth rate is similar to that of a “medium” fire, but later a transition to growth exceeding that of an “ultrafast” fire is observed. Instead of a parabolic relationship between heat release and time, these experiments are better described by a two-stage linear approximation:

- First stage – slow growth from ignition up to a power of 1–2 MW.
- Second stage – rapid growth from several MW to tens of MW.

The analysis of the data shows two main relationships:

- The ventilation velocity affects the time required for the transition from the ignition phase to the phase of rapid fire growth.
- The rate of fire growth in the second phase depends on the ventilation velocity, with a higher velocity probably also leading to faster development of combustion.

II.3. Analysis of the results of mathematical modelling of fires

When defining the simulated fire, the detection time, the fire growth and the activation of the fire suppression system must be carefully assessed. It is of particular importance to define clearly the capabilities of the detection system and the activation time of the emergency ventilation and suppression systems. In a large number of cases the delay between fire detection and system activation can reach several minutes. If such a delay exists, an important characteristic of the system is its ability to detect and localize a small fire (of approximately 1 MW power) during the “delay phase”. Otherwise, if the fire is not detected in time, before it enters the intensive growth phase, then after the fire suppression system is activated the fire will have developed beyond the reach of the water mist.

This underlines the need for the assessment of the operational characteristics of the water mist system to be in direct relation to the characteristics of the detection system. On this basis, the details of the assessment of the effectiveness of the detection system must be comparable to those of the water mist.

On the basis of the above observations, when defining the design fire it is important to take into account also the ventilation conditions that will occur in a real fire in the tunnel.

The calculations are carried out on the basis of modelling of so-called design fires. The aim of such modelling is to determine the expected dynamics of fire development in the absence of fire-fighting intervention. The results obtained serve as input data for the design of water mist fire suppression systems.

The design fire is defined on the basis of the following main parameters:

- Geometric characteristics of the compartment (dimensions, shape, volume);
- Type and spatial distribution of the combustible materials;
- Ventilation characteristics – presence and type (natural or mechanical).

The size of the water droplets is of essential importance for the mechanism of their interaction with the flame and the burning surface. Finely dispersed

droplets of small diameter usually evaporate in the gas zone above the seat of the fire, contributing mainly to the cooling of the smoke gases and to inertization through the release of water vapour. Larger droplets manage to enter the flame zone, absorbing larger quantities of heat before they evaporate. Only the largest droplets reach the burning surface, where they can have a direct cooling effect on the material.

As the temperature of the gas environment rises, the distance travelled by the droplets until they evaporate completely decreases. As their diameter increases, this distance grows. The relationships are presented in Table 21 and are essential for the selection of nozzles for a specific fire scenario.

Table 21. Gas phase through which the droplets pass

Temperature [°C]	**Typical fall distance of a droplet with a diameter of [µm]**				
	10	**50**	**100**	**500**	**1,000**
400	15 nm	9.1 µm	146 µm	2.5 m	9.9 m
600	9 nm	5.5 µm	87 µm	1.5 m	6.0 m
800	6 nm	3.9 µm	63 µm	1.1 m	4.3 m
1,000	5 nm	3.0 µm	49 µm	0.5 m	3.3 m

II.4. Fire safety management in road tunnels

Safety in tunnels should be assessed for all persons who use them for passage, servicing, or for actions during incidents and crisis situations. The following groups are considered:

- tunnel users;
- tunnel maintenance and operating personnel;
- emergency service personnel; and
- people outside the tunnel (for example people in buildings above the tunnel or near the entrances).

A fixed fire suppression system can improve conditions in a fire by limiting the spread of the fire, lowering the temperature of the gases and reducing the radiant heat fluxes. Its early activation is essential to support evacuation. However, the influence on the concentrations of toxic gases and smoke must be assessed together with the ventilation regime, since suppression of combustion does not in itself guarantee a reduction of all hazardous products (Bergeson et al., 2020).

The advantage of fixed fire suppression systems is that they slow down the rate of fire spread and therefore the survival of every casualty is increased, as is the potential for responders to rescue anyone who is injured and unable to evacuate unaided. Tests and computational analyses show that the vertical momentum of an activated fixed fire suppression system can carry the higher concentrations of toxic gases in the upper levels of the tunnel cross-section down to the lower parts; this effect was observed in measurements from full-scale tests (“Fire tests for water mist fire suppression systems in road tunnels, underground”) (Leucker and Leismann, 2013). Although no adverse effect of this phenomenon has been observed in real events involving activation of a fixed fire suppression system, this again underlines the importance of the activation strategy and of the protective ventilation system. Visibility is a critical factor for effective self-rescue in fire conditions.

The use of fixed fire suppression systems affects visibility because of the aerosol effects caused by the water mist or the dispersed droplets, which further limit visual clarity in the affected area. This deterioration of visibility should be taken into account when developing evacuation and risk management strategies in road tunnels.

When a fixed fire suppression system is activated, the cooling and the momentum of the water jet can disturb the stratification of the smoke and carry smoke gases to the evacuation zone. This effect should be taken into account when coordinating the fire suppression and the ventilation systems (Bergeson et al., 2020).

Conclusions to Chapter II:

The rate of fire development and the size of the fire are of essential importance for tunnel safety. Both are influenced by the nature of the fire load, the technical condition of the vehicles involved, the air flow conditions in the tunnel during fire development, and the engineering fire safety design of the specific tunnel.

The maximum heat release rate of a fire depends on the quantity and type of the combustible materials forming the fire load, the oxygen supply conditions, the characteristics of the tunnel and the action of the fire protection systems. In fires of passenger cars the heat release rate is usually relatively low. By contrast, in fully developed fires of cargo in heavy goods vehicles and in fires of spilled liquid fuel, very high values of this parameter can be reached.

CHAPTER III. INVESTIGATION OF NOZZLES FOR WATER MIST FIRE SUPPRESSION SYSTEMS

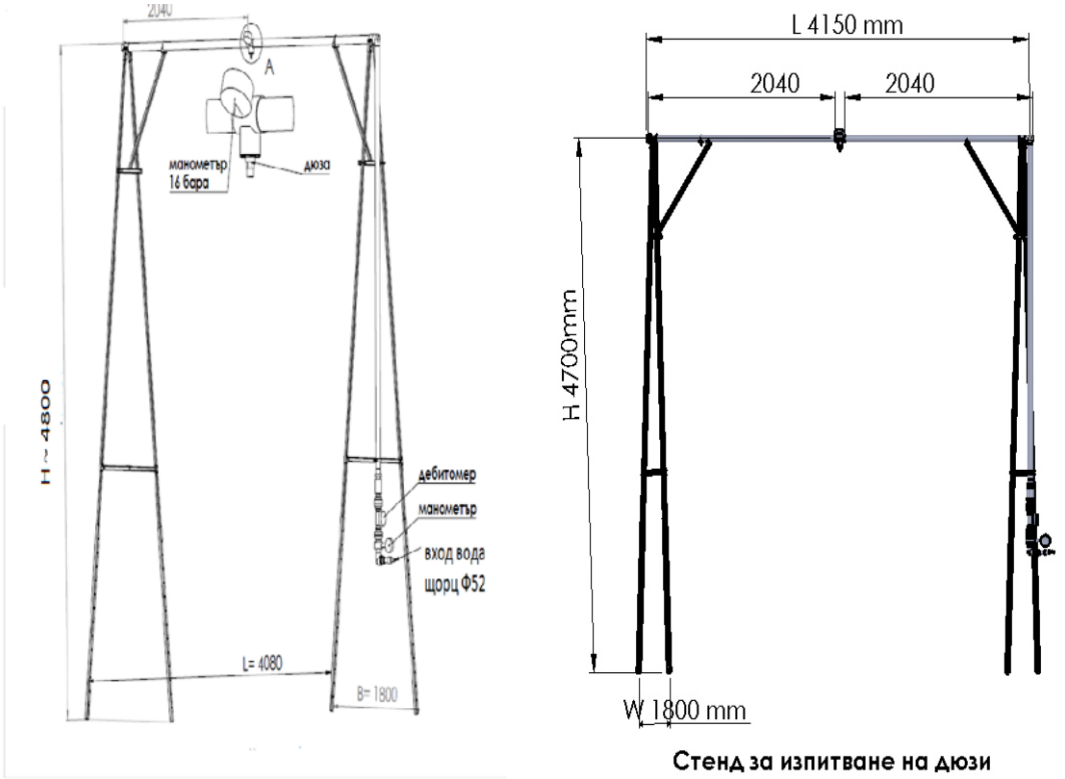
III.1. Development and construction of a stand for nozzle testing

III.1.1. With vertical spraying

In connection with what has been presented so far, experimental investigations were carried out aimed at studying and modelling a fixed low-pressure water-based fire suppression system for fire protection (FP) in road tunnels using water mist. The main aim of the tests carried out is to evaluate the effectiveness and to confirm the validity of the claims regarding the performance and effectiveness of the systems and nozzles that generate fine water mist from small water droplets at a low working pressure in the range of 3.5–16 bar.

A series of experimental tests was carried out during the study. In the first stage, tests were performed on the formation of fine water droplets with a diameter of up to 1000 μm through a nozzle mounted on a specialized test stand, which provides vertical spraying of the water mist towards the asphalt surface of the experimental ground. In the second stage, fire extinguishing tests were carried out, in which the water mist is sprayed horizontally by means of a fan system relative to the floor surface of the experimental installation, simulating the conditions in a road tunnel.

Figure 43 shows the general view of the designed stand, intended for testing nozzles that generate fine water mist at a low working pressure. The stand allows the nozzle to be positioned at a working height (H) in the range from 4.7 m to 5.8 m, with the possibility of vertical adjustment in steps of 1 m. The stand provides a clearance of 2.04 m in both directions from the nozzle to the vertical supply pipe and to the other free-standing end of the armature.



Стенд за изпитване на дюзи

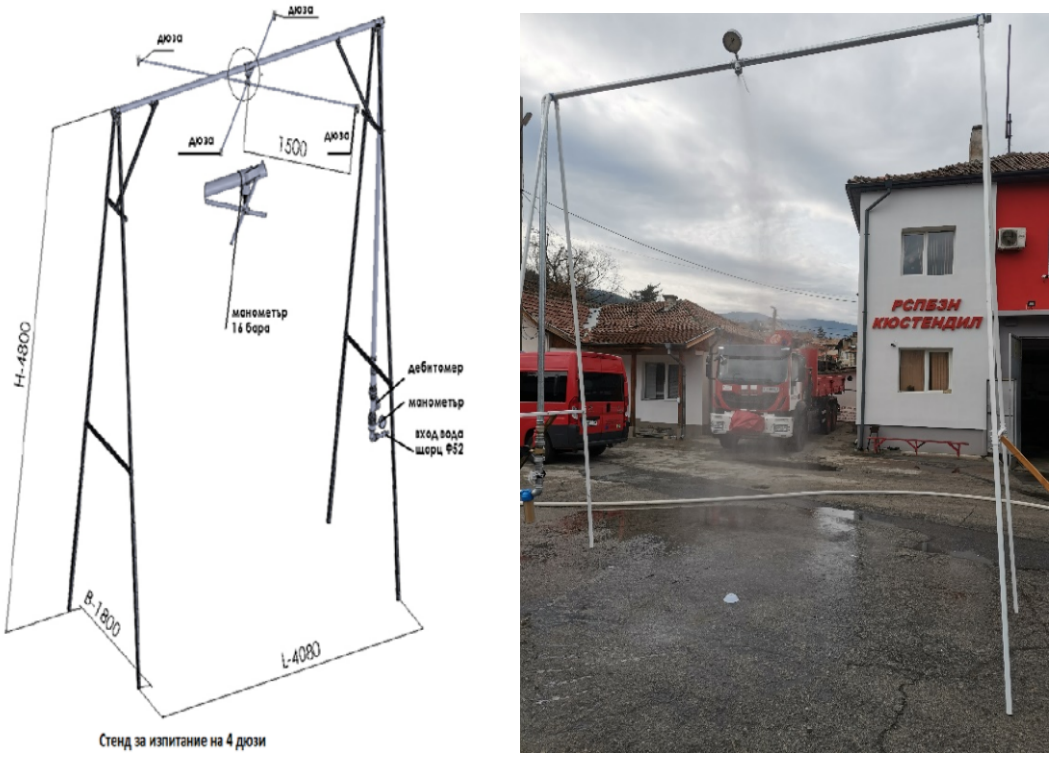


Figure 43. Nozzle test stand

The stand used in the experimental investigations was independently designed and constructed by the doctoral candidate in order to provide a suitable experimental environment for studying the characteristics of low-pressure water mist fire suppression systems. In developing the design, specialized engineering solutions were applied that take into account the technological characteristics of water-based fire suppression systems as well as the specific conditions of their direct application in tunnels.

The first tests were carried out with a stand for spraying low-pressure water mist, with the jet directed vertically towards the asphalt surface. The experiments used the tested GW M5 nozzle from GW Sprinkler A/S (2018) (Fig. 46). This is a compact nozzle that generates fine water mist at low pressure. It was specially developed for total-flooding and local water mist protection systems, and is suitable for both marine and land-based applications, including road tunnels.



Figure 46. GW M5 nozzle

The tests assess conformity with the parameters specified by the manufacturer. Table 27 presents the values of the flow rate of the GW M5 nozzle as a function of pressure, obtained during the tests.

Table 27. Flow characteristics of GW model M5, water flow rate as a function of pressure

Water flow/pressure relationship, Q (P)				
Pressure – P, bar	**√P**	**K-factor**	**Water flow – Q, L/min**	**K-factor – average**
3	1.73	5.00	8.65	**5.003**
4	2	5.00	10	
5	2.24	4.98	11.16	
6	2.45	4.99	12.23	
7	2.65	5.01	13.28	
8	2.83	5.01	14.18	
9	3	5.03	15.09	
10	3.16	5.01	15.83	
11	3.32	5.01	16.63	
12	3.46	4.99	17.27	

The main aim of the tests is to determine the size and number of the droplets produced, as well as the coverage area and density.

The coverage zone when operating with the GW model M5 nozzle reaches a diameter of up to 3.2 m at the corresponding working pressure, shown in Fig. 51. In order to determine experimentally the actual coverage under vertical spraying of water mist, glass tiles measuring 0.2 × 0.2 m (Fig. 53) were used, placed horizontally at ground level at radial distances of 500 mm, 1000 mm and 1500 mm from the centre of the nozzle. The tiles were pre-treated with silicone oil in order to preserve the shape of the droplets that landed on them and to make it possible to determine their number and size as a function of distance.

Figure 52 shows the layout of the experimental tiles at the three radial distances. The applied silicone layer helps to record accurately the characteristics of the water droplets during the spraying of the water mist.

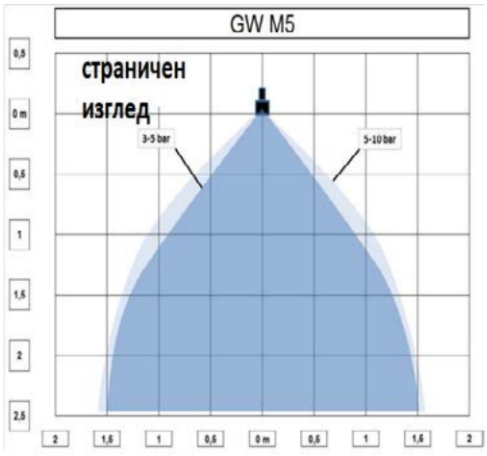


Figure 51. Side view – vertical spraying of water mist, coverage diameter

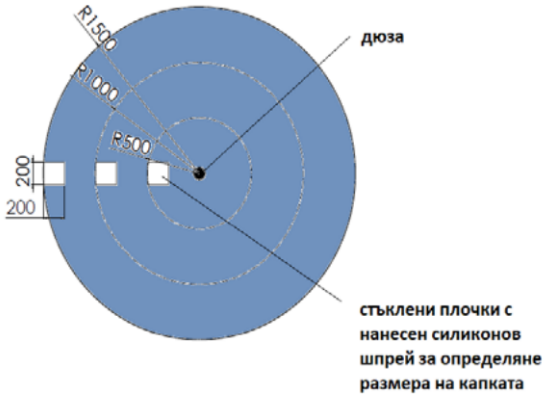


Figure 52. Diagram – Radius (R) of water mist spraying from the GW M5 nozzle

The general set-up of the experimental method includes the use of a glass tile with millimetre paper for calibrating the scale, whereby at 150 % magnification a scale of 39 × 39 µm was determined (Fig. 53). With an actual size of the millimetre scale of 10 mm, a ratio of 10:39 = 2564 µm was established, and for the purposes of the analysis a simplified scale of 1:250 µm was adopted.

The size of the droplets is determined from the black imprint formed by the silicone oil, which envelops the water droplet and subsequently spreads over the surface of the glass. It is assumed that the resulting imprint corresponds to the approximate diameter of the droplet. The measurements were made using the graphic editor “Photoscape”.



Figure 53. Experimental tile

The results and measurements obtained from the experiments are shown in Table 28 and presented graphically in Fig. 57. The distribution of the droplets is by size (Dp) and by radius (R) from the nozzle. In the experiment carried out it was established that there are no droplets with a diameter larger than 1 mm or 1000 µm.

Table 28. Distribution of droplets by size Dp at radius R from the nozzle

Class	Droplet diameter, Dp	Radius on the sprayed surface, R			Droplet diameter at distance from the nozzle, µm			Droplet diameter – min-max, µm	Number of droplets, %	Number of droplets – averaged, %	Number of droplets – rounded, %	Water mist classes by droplet size Dp
		500 mm	1000 mm	1500 mm	500 mm	1000 mm	1500 mm					
1	0≤200	240	180	156	0-200	0-200	0-200	0-200	from 50.8 to 54.1	52.45	52	1
2	200≤400	180	156	126	225-398	225-388	250-393	225-398	from 40.5 to 44.1	42.3	42	2
3	400<1000	24	18	24	500-750	750-950	625-967	500-967	from 5.1 to 7.8	6.45	6	3
4	1000>	0	0	0	0	0	0	0	0	0	0	4
Droplets by R		444	354	306								
Total droplets by R		1104								101.2	100	

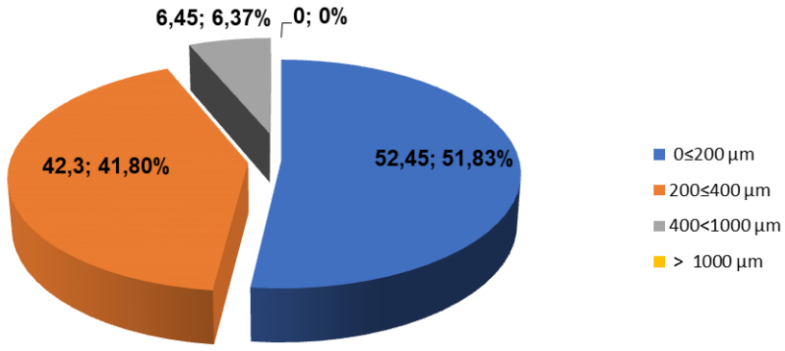


Figure 57. Water mist classes by droplet size Dp

On the basis of the experimental results obtained and the calculations performed, the minimum coverage density of the water flow over the area under consideration was determined. The calculation algorithm is carried out as follows:

- For a spray diameter D – 3 m; pressure P – 6 bara; water flow – 12.23 L/min:

$$S = \frac{\pi D^2}{4} = \frac{3{,}14.3^2}{4} = 7{,}065\,m^2 \qquad \text{(III. 1)}$$

where S is the coverage area [m²]; D is the coverage diameter, m;

$$Q_{exp.} = \frac{Q_{flow}}{S} = \frac{12.23}{7.065} = 1.73\,mm/\min \qquad \text{(III.2)}$$

$Q_{exp.}$ – the average spray intensity (density of the water coverage), mm/min;
Q_{flow} – the volumetric flow rate of the nozzle, L/min;
S – the coverage area, m². The equality 1 L/(m²·min) = 1 mm/min is used; in the example Q_{flow} = 12.23 L/min.

III.1.2. With horizontal spraying

The development of the stand and the investigations with horizontal spraying are based on preliminary studies and simulation tests with fixed fire suppression systems that spray a water agent by means of a jet fan. In the specific case, a test installation of a fixed low-pressure water fire suppression system was designed and modelled, providing horizontal spraying of water mist by means of an industrial fan, whose operating principle resembles the effect of a jet fan.

The investigated system, shown in Figure 58 and Figure 59, consists of components and elements, modelled in a specific order, which are optimally adapted to the conditions of the experimental tests. Under real operating conditions, the installation of water mist systems with horizontal spraying must be carried out only by qualified specialists who have the necessary skills and knowledge for installing sprinkler systems. This is necessary in order to minimize the risks of incorrect functioning of the system caused by failure to observe the instructions and the precautions.

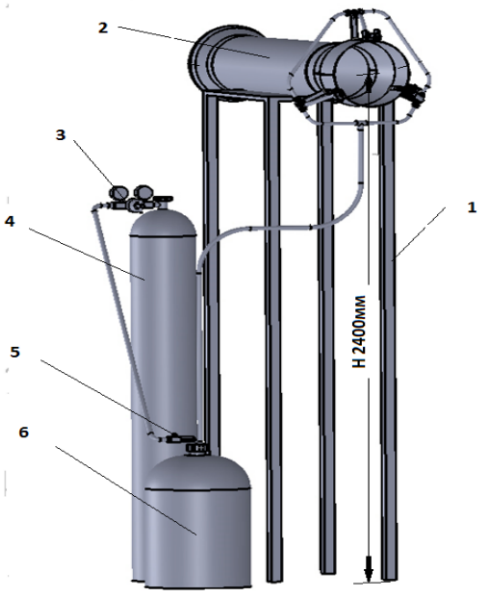


Figure 58. Diagram of the investigated system
1 – stand; 2 – main test structure; 3 – pressure regulator;
4 – nitrogen cylinder; 5 – ball valve; 6 – water vessel, 11 litres, for supplying the liquid under pressure



Figure 59. Model of the installation of a fixed fire suppression system

Before the start of the modelled experiments with the fixed fire suppression system with horizontal spraying of water mist, the air flow velocity during operation of the CK 250 A fan at maximum speed was measured. The measurements were made using a TESTO 435 anemometer (Germany, reg. No. DM/034 112, Fig. 71), recording the values of the air velocity [m/s] and the temperature [°C] of the air flow at the cone and at distances from 1.0 m to 6.0 m beyond it. The results obtained show a velocity range from 0.42 m/s to 3.06 m/s (Fig. 71 – Fig. 77), while the temperature of the air flow varies between 28 °C and 29 °C.

The measurements up to 6.0 m from the cone are justified by the fact that under the experimental conditions the spraying of water mist from the CK 250 A fan reaches precisely this distance, which makes it critical for determining the effectiveness of the system in the experimental tunnel. The graphical representation of the change in the air flow velocity in the modelled tunnel is shown in Fig. 70.

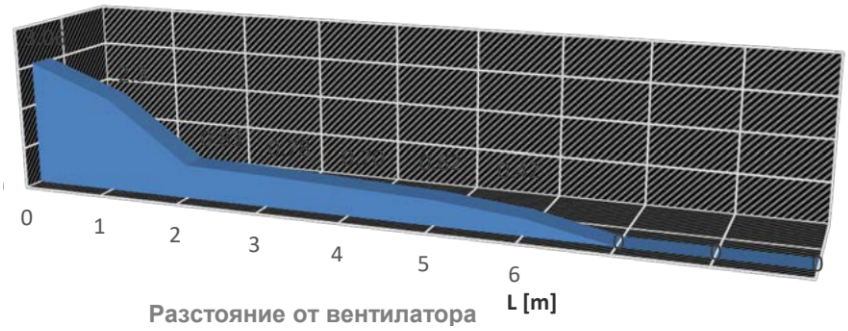


Figure 70. Air flow velocity from the CK 250 A fan in the modelled tunnel

The tunnel for carrying out the present tests was modelled in a workshop hall measuring 30 m in length, 7.5 m in width and 6 m in height (Fig. 78 and Fig. 79).



Figure 78. Modelled experimental tunnel

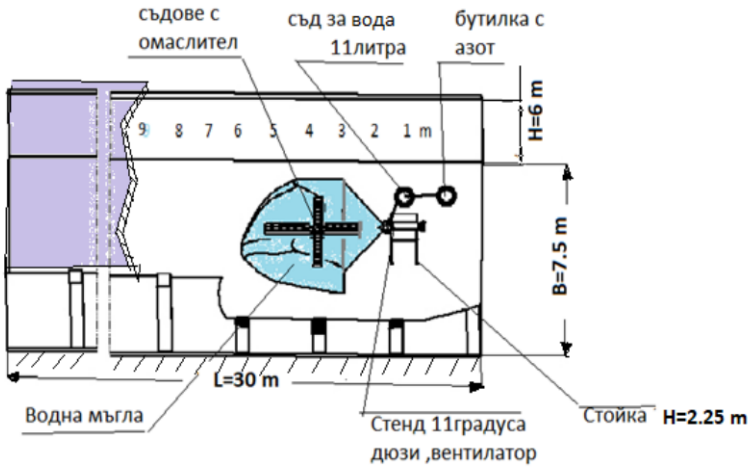


Figure 79. Diagram of the modelled tunnel and the fixed fire suppression system

In the experiments carried out with the fixed fire suppression system for horizontal spraying, the operation of the nozzles corresponds to the specified manufacturer's characteristics and models. As shown in Fig. 83, the most intensive wetting of the floor surface is observed at a distance of 1.0 to 4.0 m, with a coverage of approximately 3.0 m in diameter.



Figure 83. Spraying and wetting capability of the GW M5 nozzle

Figure 85 shows graphically the arrangement of the vessels with liquid and the coverage of the water mist sprayed by the system.

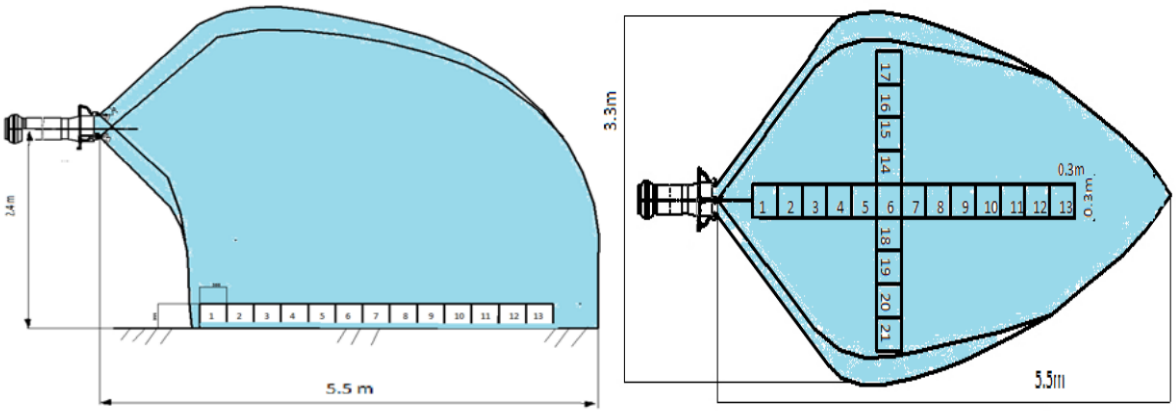


Figure 85. Diagram – sections of the water flow and the vessels for suspending liquid – vertical and horizontal

Investigations and results with horizontal spraying

After the operation of the fire suppression system had stopped, the vessels with suspending liquid (oil-based medium) were examined. It was established that the droplets that landed have clearly defined contours and well preserved sizes (Fig. 87). Using millimetre paper, the approximate sizes and number of the droplets were determined.



Figure 87. Vessels with suspending liquid, millimetre paper and recorded droplets

A selected sample of vessels with suspending liquid from the configuration shown in Fig. 85, positioned along the direction of spraying, was taken. In them the sizes of the droplets that landed are preserved, which makes it possible to determine their number and size at different distances along the direction of action of the nozzles. The arrangement of the vessels was chosen so as to give a realistic picture of the distribution of the droplets both along the length and along the width of the spraying of the water mist.

In vessel No. 1, located at a distance of 1.0 m, it was established that droplets with a diameter of up to 500 µm make up about 58–60 %, those with a diameter of up to 1000 µm about 30–35 %, and droplets with a diameter over 1000 µm about 5–7 % of the total number (Fig. 87).

Table 31. Parameters of DCU nozzles, model 1940 PNR

Angle	DAU	DBU	DCU	DDU	Code	D mm	D1 mm	Capacity – lpm						
								Pressure – bar						
								0.7	1.0	2.0	3.0	5.0	7.0	10
90°	•				1118 xx	1.2	0.8	0.57	0.68	0.96	1.18	1.52	1.80	2.15
	•				1147 xx	1.3	1.0	0.71	0.85	1.20	1.47	1.90	2.25	2.68
	•	•			1188 xx	1.4	1.2	0.91	1.09	1.54	1.88	2.43	2.87	3.43
	•	•			1212 xx	1.5	1.2	1.02	1.22	1.73	2.12	2.74	3.24	3.87
	•	•	•		1235 xx	1.6	1.3	1.14	1.36	1.92	2.35	3.03	3.59	4.29
	•	•	•		1294 xx	1.8	1.3	1.42	1.70	2.40	2.94	3.80	4.49	5.37
	•	•	•		1370 xx	2.0	1.4	1.79	2.14	3.02	3.70	4.78	5.65	6.76
		•	•		1470 xx	2.3	1.8	2.27	2.71	3.84	4.70	6.07	7.18	8.58
		•	•		1588 xx	2.6	1.8	2.84	3.39	4.80	5.88	7.59	8.98	10.7
		•	•		1659 xx	2.7	2.0	3.18	3.80	5.38	6.59	8.51	10.1	12.0
		•	•		1740 xx	90°	2.9	2.0	3.57	4.27	6.04	7.40	9.55	11.3
		•	•		1835 xx	3.3	2.0	4.03	4.82	6.82	8.35	10.8	12.8	15.2
		•	•		1940 xx	3.3	2.4	4.54	5.43	7.68	9.40	12.1	14.4	17.2
		•	•		2105 xx	3.5	2.6	5.07	6.06	8.57	10.5	13.6	16.0	19.2
			•		2117 xx	3.7	2.7	5.65	6.75	9.55	11.7	15.1	17.9	21.4
			•	•	2147 xx	4.0	3.2	7.10	8.49	12.0	14.7	19.0	22.5	26.8
			•	•	2164 xx	4.1	3.2	7.92	9.5	13.4	16.4	21.2	25.1	29.9
			•	•	2188 xx	4.7	3.2	9.08	10.9	15.4	18.8	24.3	28.7	34.3
			•	•	2235 xx	5.2	3.8	11.4	13.6	19.2	23.5	30.3	35.9	42.9
				•	2294 xx	5.8	3.8	14.2	17.0	24.0	29.4	38.0	44.9	53.7
				•	2370 xx	Три	дюзи	DCU.	модел	1940	PNR.	6.4	са	монтирани

Three DCU nozzles, model 1940 PNR, are mounted along the contour of the cone of the experimental installation at an angle of 120° and at a height of 2.4 m from the floor (Fig. 91). The installation was carried out in accordance with the requirements for mounting height, spacing between the nozzles and water pressure given in Table 31 (marked in yellow).

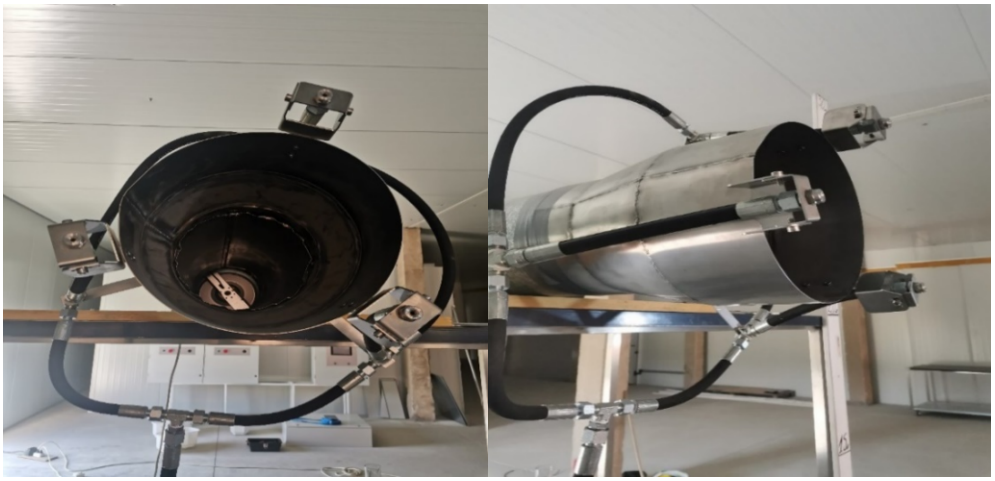


Figure 91. Cone with mounted DCU nozzles, model 1940 PNR

In the investigations carried out, the operation of the DCU nozzles, model 1940 PNR, in horizontal spraying with a fixed fire suppression system corresponds to the specified manufacturer's characteristics and models (Fig. 92). The most intensive wetting of the floor surface is observed at a distance of 1.5 m to 4.5 m, with a diameter of about 3.0 m. In comparison with the GW model M5 nozzle (Fig. 83), the experimental results show that the wetting and coverage of the DCU 1940 PNR are more uniform and denser, which guarantees a higher effectiveness of the nozzle.



Figure 92. Spraying and wetting capability of the DCU 1940 PNR nozzle

The system is hydraulically sized to ensure that the water pressure corresponds to the recommended pressure for all nozzles in the activated zone. The investigations continue with the placement of vessels measuring 300×300 mm, containing suspending liquid, in the active zone of horizontal spraying of the water mist. Their purpose is to capture and preserve the size of the water mist droplets that landed (Fig. 93).



Figure 93. Arrangement of vessels for suspending liquid in the active zone of the fire suppression system

When testing the DCU nozzles, model 1940 PNR, the water flow of the sprayed water mist in horizontal spraying forms a clearly defined elliptical coverage shape (Fig. 93 and 85). The increased reach relative to the specified technical characteristics is due to the effective action of the CK 250 A fan, with wetting reaching up to 6.0 m, unlike the GW model M5 nozzle, for which the coverage is up to 5.0 m.

In the test environment the system is activated to spray water mist at low pressure. The duration of spraying with DCU 1940 PNR nozzles is about 38–42 s, which corresponds to the time for consuming 11 litres of water from the reservoir. This corresponds to the technical characteristics of the nozzle manufacturer, with a production flow rate of 17.2 L/min at a pressure of 10 bar (Table 31).

In vessel No. 1 at a distance of 1.5 m along the length of spraying of the water mist from the spraying nozzles, it was established that droplets that landed in the suspending liquid (oil-based medium) with a diameter (D) of up to 500 μm are in the order of about 58-60 %. Droplets with a diameter (D) of up to 1000 μm are in the order of about 30-35 %, and those with a diameter (D) over

1000 μm are in the order of about 3-5 % of the total number of droplets that landed and were recorded.

III.2. Modelling and extinguishing of a design fire with a fixed low-pressure water mist fire suppression system

Tests on a spilled liquid fuel fire were carried out in the experimental tunnel in order to evaluate the effectiveness of a fixed low-pressure water mist fire suppression system. A system with GW nozzles, model M5, was tested, with the arrangement of the system unchanged. An aluminium pan with a diameter of 600 mm and a height of 130 mm was used to create the seat of the fire (Fig. 96).



Figure 96. Pan for flammable liquid

During the preparation of the design fire, the pan was filled with 5 litres of water and 1 litre of petrol, forming an ignition source with a power of about 200 kW. About 20 s after ignition, needed for the fire to develop (Fig. 97), the fire suppression system is activated. The water mist begins to suppress the fire effectively (Fig. 98), limiting its power and not allowing it to reach maximum values. In addition, the mist captures the soot released and carries it down to the floor, while the smoke level remains low.



Figure 97. Fire development

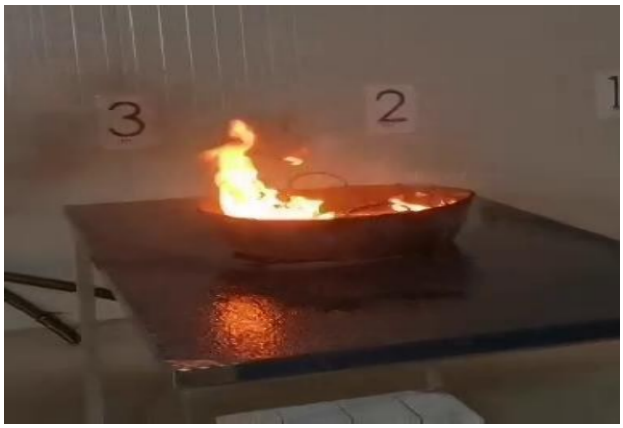


Figure 98. Fire suppression

In the test installation with a 11-litre fluid vessel the water is used up in about 42–45 s. In this time it is not possible to extinguish a fire of such power, since the aim of the test is to evaluate the effectiveness of the system in holding back the development of the fire at low levels.

For prolonged operation in real conditions it is necessary to size the water supply according to the design fire, the required flow rate and the required duration of operation. In the project under consideration a duration of about 60 minutes is assumed; its sufficiency must be assessed against the specific scenario and the response time of the emergency services.

In addition, tests were carried out with mounted DCU nozzles, model 1940 PNR. The location of the system is unchanged, as in the preceding tests. For the fire an aluminium pan with a diameter of 600 mm and a height of 130 mm was used, filled with 5 litres of water and 0.5 litres of petrol, forming an ignition source with a power of about 100 kW. After ignition, 20 s are allowed for the fire to develop (Fig. 99), after which the low-pressure water mist system is activated.

The water mist effectively suppresses the development of the fire (Fig. 100 and 101), holding it at low levels and not allowing it to reach maximum power. In addition, the mist captures the soot released and carries it down to the floor, keeping the smoke level low. Fig. 102 shows the complete extinguishing of the fire by the fixed low-pressure water mist system.



Figure 99. Fire development



Figure 100. Fire suppression



Figure 101. Bringing the fire under control



Figure 102. Extinguishing of the fire

III.3. Main conclusions and recommended parameters

With the use of the developed experimental installation, which includes a reservoir with a volume of 11 l of working fluid (water) that is used up in approximately 38–42 s, it was established that the water mist generated through nozzles of type GW model M5 and DCU model 1940 PNR, thanks to the sufficient coverage area, not only suppresses the fire but also effectively brings it under control by limiting its development. In

some cases complete extinguishing of the fire that had arisen was also achieved (Fig. 102), which proves the effectiveness of the system both in holding back fire development at low levels and, depending on the fire power, in achieving final extinguishing.

The results of the experimental investigations carried out show that the droplet size distribution (Dp) generated by the GW model M5 and DCU model 1940 PNR nozzles meets the requirements of standard EN 14972. For the investigated models of fixed low-pressure water mist fire suppression systems, it is established that the use of a fan of type CK 250 A leads to an increase in the coverage perimeter. This is due to the increased velocity of the droplets, which allows a longer travel path before settling and accordingly provides higher protection effectiveness in the event of fires in enclosed spaces, such as workrooms, road tunnels and cable tunnels.

The comparative analysis of the two types of nozzles shows that the DCU model 1940 PNR nozzle generates water mist with smaller droplet diameters and provides denser coverage of the protected zone at the design working pressure of 10 bar. The droplets with a diameter of up to 500 μm generated by this type of nozzle are significantly more numerous than those produced by the GW model M5 nozzle, which contributes to the higher effectiveness of the extinguishing process.

It has been established experimentally that in fires of higher power the system limits their development and does not allow maximum intensity to be reached during operation. In fires of lower power, not only limitation but also complete extinguishing of the seat of the fire is observed.

CHAPTER IV. INVESTIGATION OF A PHYSICAL MODEL OF WATER MIST FIRE SUPPRESSION SYSTEMS

IV.1. Development of a physical model of water mist fire suppression systems

There is no universal optimal droplet size for water mist. The effectiveness of fire extinguishing depends on a complex of parameters, including the droplet size distribution, the water flow rate, the arrangement and number of nozzles, as well as the conformity of the system with the specific conditions of the protected facility.

The classification of water mist is necessary and useful when selecting fire suppression systems in rooms where the objects of protection are stationary, adequately constructed and can be closed off when a fire occurs. In road tunnels, however, none of these conditions is met. A fire can occur in any tube and along its entire length, involving different types of vehicles and combustible loads.

When a fire occurs, it can be assumed that its initial area corresponds to the overall dimensions of the vehicle, which vary within wide limits: length – from 6 to 16.5 m, width – from 1.80 to 2.60 m and height – from 2 to 4 m.

The supply of air in the tunnel is carried out in two main modes:

- normal ventilation, depending on the traffic intensity before a fire occurs;
- emergency ventilation — after detection of the fire, in order to provide conditions for the evacuation of people and to support fire-fighting actions.

It is obvious that the ventilation conditions are an additional uncertain, but essential, factor in fire development. In view of these uncertainties and of the classification of water mist, it can be assumed that fire suppression systems in road tunnels should provide a predominant quantity of droplets of class 1 and class 2, as well as a limited quantity of droplets of class 3.

The influence of ventilation on the spread (transport distance) of the water mist droplets is a major aspect in the investigation of these systems. This is especially important given the linear nature of tunnels, the location of the jet fans and the distances between the cross-passage evacuation galleries. The greatest effect of water mist is achieved when the droplets enter zones in which they can evaporate effectively. In the event of late activation of the system, a larger zone of spread is necessary in order to provide cooling of surfaces that have already been heated.

The design of fire protection systems in road tunnels is a dynamically developing field, in which numerical models are increasingly used as an advanced tool for investigating variants and optimizing solutions.

The analysis of the spread of low-pressure water mist droplets gives grounds for proposing a modern approach to the investigation and design of fire protection systems in road tunnels.

IV.2. Experimental investigations and processing of the results

The distance along the tunnel reached by the sprayed water is the main indicator of its interaction with the main air-gas flow.

The developed physical-mathematical two-fluid water–air (gas) model, in which each of the phases is considered with its own characteristics such as velocity, density and temperature, represents an approximate solution. The results obtained were analysed by comparison with experimental data, which makes it possible to assess the adequacy of the model.

Notation used:

m_p – *mass of the liquid phase,* kg*;*

$\overrightarrow{V_p}(x,y$ – *velocity of the liquid phase,* m/s*;*

C_R – *aerodynamic drag coefficient;*

$\overrightarrow{V_g}(x,y)$ – *velocity of the air-gas flow,* m/s*;*

$Re_p = \frac{D_p V_r}{\nu}$ *Reynolds number criterion;*

$\overrightarrow{V_r} = \overrightarrow{V_g} - \overrightarrow{V_p}$ – *relative velocity,* m/s*;*

The main idea in considering the flows of one medium in another is the use of the so-called two-fluid model “Applied Fluid Mechanics” (Antonov, 2009, 2016). In it, each of the phases is considered with its own velocity, density and temperature. It is solved using the methods known from fluid mechanics – the Lagrangian (substantial method) or the Eulerian (local method). The two phases represent separate fluid media, described by one and the same systems of differential equations, with the link between them being the forces of interphase interaction. The parameters of the two phases are written in the equations with subscripts: “g” for the air (gas) medium, taken as the carrier, and “p” for the admixtures, in this case the droplets.

Interphase interaction is effected by the following forces:

• mass force – $m_p \vec{g} = \vec{f}_m$;

• aerodynamic drag force – $\vec{f}_A = 0{,}5 C_R s \rho_g (\vec{v}_r) \vec{v}_v$,

$C_R = f(\mathrm{Re}_p)$, $\mathrm{Re}_p = \frac{D_p v_r}{\nu}$;

where: C_R is the drag coefficient;

s – the midsection of the droplet, m²;

ρ_g – the gas density, kg/m³;

v_r – the relative velocity of the droplet with respect to the gas, m/s; v_r – its modulus, m/s;

Re_p is the Reynolds number of the droplet;

D_p – the droplet diameter, m;

ν – the kinematic viscosity of the gas, m²/s. The sign of the projections of the force is determined relative to the relative velocity.

• midsection (the largest cross-section of the droplet in the direction of motion) – s, for an assumed approximately spherical shape

$s = \frac{\pi D_p^2}{4}$;

• Saffman force – $f_s = C_s \sqrt{\frac{\rho_g}{\mu}} \left(\frac{D_p}{2} \right)^2 \sqrt{\frac{\partial u_g}{\partial y}}$.

μ – the dynamic viscosity of the gas, Pa·s;

u_g – the longitudinal velocity of the gas, m/s;
y – the transverse coordinate, m; $\partial u_g/\partial y$ is the transverse velocity gradient, s^{-1}.

The Saffman force is described by the expression:

$$f_s = C_s\sqrt{\frac{\rho_g}{\mu}}.\left(\frac{D_p}{2}\right)^2\sqrt{\frac{\partial u_g}{\partial y}}, \qquad \text{in which } C_s = 6.46 .$$

(IV.1)

The model is two-dimensional. The velocity components are only along x and y. In the transverse direction it is assumed to be constant.

For the motion of a droplet in a two-phase flow, the Lagrange equation for the translational motion of a single particle is used. It has the form:

$$m_p\frac{d\vec{V_p}}{dt} = \sum_{i=1}^{n}\vec{f_i} \qquad \text{(IV.4)}$$

where f_i are the interphase interaction forces, chosen at discretion for the particular case being solved.

In scalar form (IV.4) is written as follows:

$$m_p\frac{du_p}{dt} = -0{,}5C_R.s.\rho_g\left(u_p-u_g\right)\sqrt{\left(u_p-u_g\right)^2+\left(V_p-V_g\right)^2} \qquad \text{(IV.5)}$$

$$m_p\frac{dV_p}{dt} = \pm m_p g - 0{,}5C_R.s.\rho_g\left(V_p-V_g\right)\sqrt{\left(u_p-u_g\right)^2+\left(V_p-V_g\right)^2} \pm f_s \qquad \text{(IV.6)}$$

Equations (IV.5) and (IV.6) are integrated under the following boundary conditions:

$$t = 0,\ x = y = 0,\ u_g = u_{g_0},\ V_p = V_{p_0},\ u_{y_0} = \text{const},\ V_g = 0 . \qquad \text{(IV.7)}$$

With the condition adopted according to (IV.7), $V_g = 0$ and u_g = const, equations (IV.5) and (IV.6) can be written in the form:

$$m_p\frac{du_p}{dt} = -0{,}5C_R.s.\rho_g\left(u_p-u_g\right)\sqrt{\left(u_p-u_g\right)^2+V_p^2} \qquad \text{(IV.10)}$$

$$m_p\frac{dV_p}{dt} = \pm m_p g - 0{,}5C_R.s.\rho_g V_p\sqrt{\left(u_p-u_g\right)^2+V_p{}^2} \qquad \text{(IV.11)}$$

($u_n - u_g$) is replaced by u_n^*

$$m_p\frac{du_p}{dt} = -0{,}5C_R.s.\rho_g u_p^*\sqrt{u_p^{*2}+V_p^2} \qquad \text{(IV.12)}$$

$$m_p\frac{dV_p}{dt} = \pm m_p g - 0{,}5C_R.s.\rho_g V_p\sqrt{u_p^{*2}+V_p{}^2} \qquad \text{(IV.13)}$$

The boundary conditions of (IV.12) and (IV.13) are analogous to (IV.7).

$$t = 0,\ x = y = 0,\ u_g = u_{g_0} = \text{const},\ V_p = V_{p_0} = 0,\ V_g = 0,\ u_p^* = u_p - u_{g_0} \qquad \text{(IV.14)}$$

The sign in front of the mass force on the left-hand side of (IV.13) is determined by the orientation of the coordinate system, and it is always directed vertically downward.

Numerical solution

The system of equations (IV.12–IV.13) is solved numerically using the finite difference method. The boundary and initial conditions (IV.7) form the initial values of the sought quantities:

$$u_p^{(0)} = 0;\ v_p^{(0)} = v_{nozzle},$$

With the presented numerical model for determining the trajectory of a sprayed droplet from a water mist installation, different variants can be modelled for the droplet sizes (from 100 to 1000 μm) and for different velocities of the main (air) flow. The accuracy of the results obtained, presented in Fig. 109 and Fig. 110, was compared with experimental data published in (Rein et al., 2009; Crosfield et al., 2009; Hua et al., 2002). At an air flow velocity of 2 m/s (Fig. 109), the maximum relative error is 11 %.

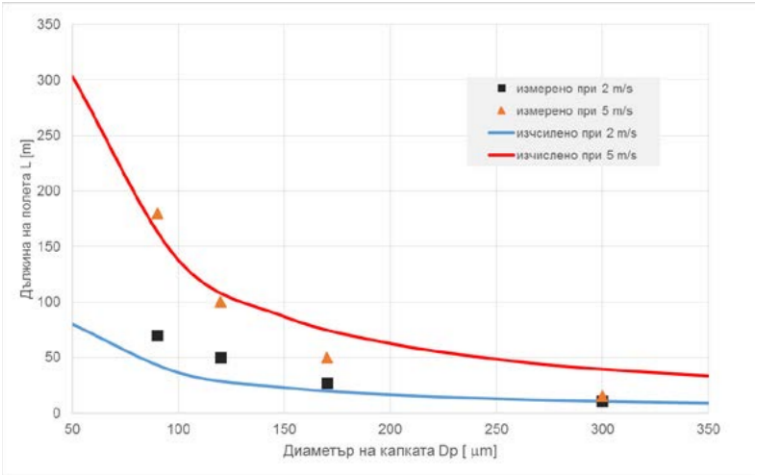


Figure 109. Comparison of experimental data from (Rein et al., 2009) with results from the numerical model

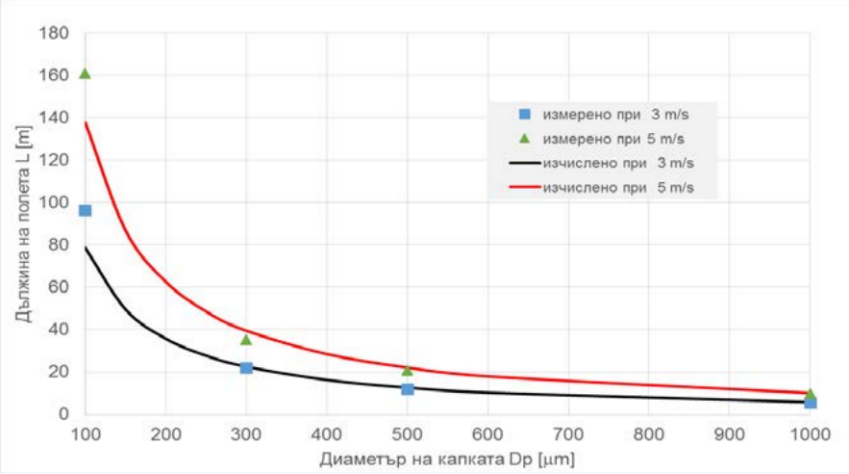


Figure 110. Comparison of experimental data from (Crosfield et al., 2009) with results from the numerical model

Figures 111 and 112 show the modelling results obtained for a horizontal section of a tunnel with a velocity of water outflow from the nozzle V_p=10 m/s and an outflow height y=6 m above the roadway. The modelling results show satisfactory agreement with the experimental data. This provides grounds for constructing the graphical relationships, constructed within the limits of the required velocity until the evacuation of the passengers, Fig. 111, and during the subsequent direct extinguishing, Fig. 112.

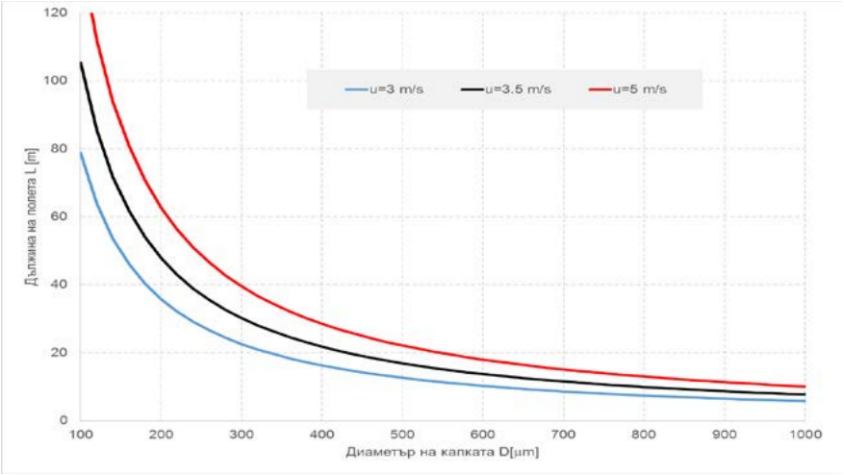


Figure 111. Required velocity of water outflow from the nozzle above the roadway until the evacuation of the passengers

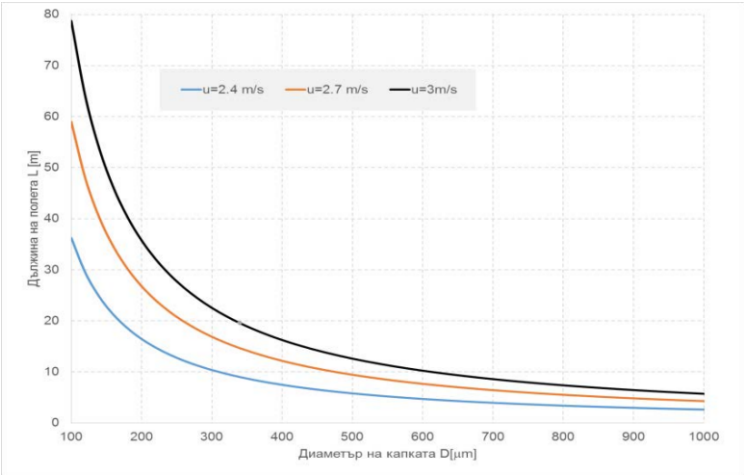


Figure 112. Required velocity of water outflow from the nozzle above the roadway during the subsequent direct extinguishing

IV.3. Parametric analysis of the model of interaction between water mist and ventilation in a road tunnel fire

On the basis of the experimental investigations carried out, a model of the spread of water mist droplets in a ventilated road tunnel was developed. The comparative analysis of experimental investigations carried out by other authors shows that the model gives reliable results and, for numerical modelling, a sufficient accuracy of the flight distance of the droplets until they fall on the roadway. The developed model makes it possible to design water mist systems that function together with ventilation systems, thereby creating conditions for optimizing their interaction. The results obtained can be used as a basis for applying an integrated approach in the design of specific systems.

The present research should be developed further through an analysis of the interaction of the water mist when a fire occurs in a road tunnel. Early detection of the fire is of essential importance, since it must ensure timely activation of the water mist in order to limit the spread of the fire and reduce its heat release rate.

The dimensions and area of the vehicles that may be the object of fire suppression and extinguishing with water mist in a road tunnel are presented in Table 34. In

depending on the position of the vehicle that is the source of the fire, at the moment of its detection at least two adjacent installations must be activated.

Table 34. Vehicles subject to water mist action

Vehicle	Overall dimensions, [m]			Horizontal area, S [m²]
	Length, (L)	Width, (W)	Height, (H)	
Passenger car	6.0	1.80	2.0	10.8
Van	6.0	2.35	2.45	14.1
Truck (up to 20 t)	13.6	2.45	2.45	33.3
Bus	13.7	2.55	3.3	34.9
Truck (up to 40 t)	16.5	2.60	4.0	42.9
Fire tanker 12 m³	9.76	2.50	3.41	24.4

IV.4. Methodology for creating a model of a fixed fire suppression system in a tunnel

An example model of a fixed fire suppression system intended for application in road tunnels was developed on the basis of the experimental tests carried out on the GW model M5 nozzle. The model clarifies the main principles and requirements that should be taken into account in the design, construction and operation of fixed fire suppression systems with water mist nozzles in road transport tunnels.

IV.4.1. General provisions

The system under consideration belongs to the so-called zone protection systems. The fire suppression nozzles are usually mounted under the ceiling of the tunnel. When activated in the relevant protected zone, they spray water in the form of fine water mist.

The whole tunnel or individual sections of it are covered by nozzles distributed in separate sections. Each section covers a protected zone with a length of approximately 25–30 m of the tunnel. The sections are connected via section valves to the main fire water main and the pump station. The main fire water main is permanently under pressure and filled with water.

In the event of activation of an installation, automatically from fire detection or manually, one section valve opens and the pump is automatically started by the signals received from the control system. The fire water supply must provide a water flow at minimum pressure for at least two sections simultaneously. The water supply must be sufficient for normal operation of the installation:

- minimum 30 minutes for tunnels with an underground length of up to 600 m;
- 40–60 minutes for tunnels with a length of over 600 m.

IV.4.2. Interaction with other systems

Ventilation systems are designed in accordance with the conditions of normal operation as well as the emergency modes associated with a fire. Failure to observe the design emergency ventilation modes can lead to a significant reduction in the effectiveness of the fire safety systems.

IV.4.3. Hydraulic sizing

With regard to the hydraulic sizing of the system, the manufacturer's production characteristics of the GW M5 water mist nozzle (Fig. 113) were compared with the measured flow indicators achieved in the tests carried out (Fig. 114), characterizing the reliability and effectiveness of the designed system.

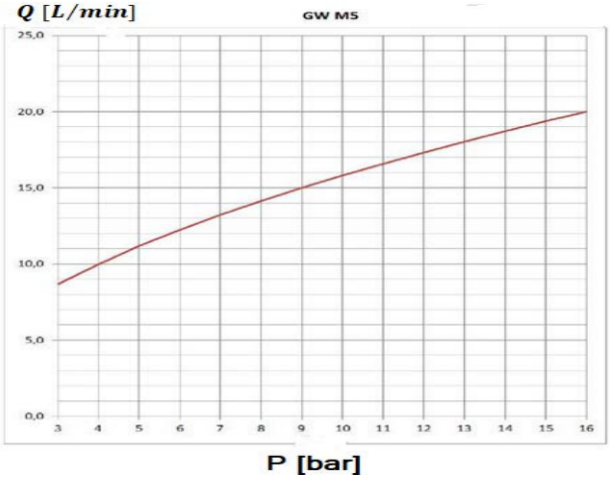


Figure 113. Flow characteristics of the nozzle according to the manufacturer

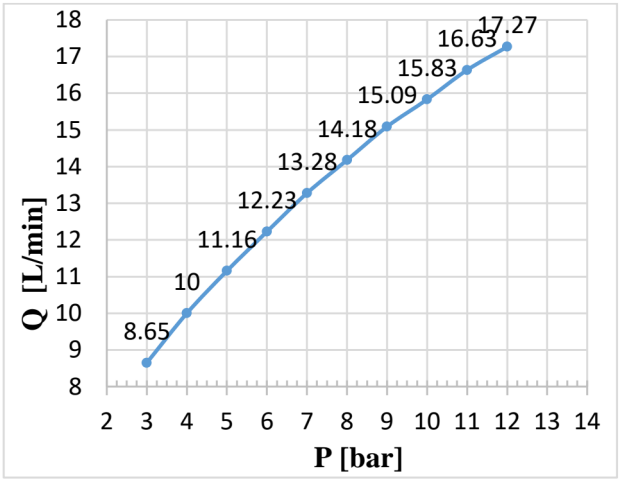


Figure 114. Measured flow characteristics of the GW model M5 nozzle

IV.4.4. Design solution of a fixed fire suppression system

The design implementation of the fire suppression system determines the distribution of the nozzles in the tunnel and the sequence of installation. The design implementation is based on engineering methods, tests carried out and real conditions in the tunnel. For the design two-way tunnel with emergency lay-bys, a length of 800 m is chosen.

Figure 115 shows a cross-section of the modelled design implementation of the fixed fire suppression system for area water coverage of the roadway with a width of 7500 mm and an installation height of 4800 mm from the roadway of the tunnel, i.e. from the area of water coverage.

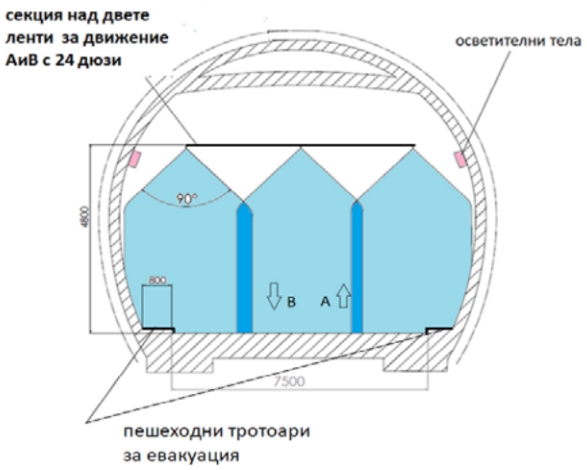


Figure 115. Cross-section of the tunnel and section of the spraying water covering the roadway for two-way traffic

It is designed that for each section three parallel rows of piping are installed, with a single length of each row of 24,000 mm, installation of 8 nozzles per row at 3,000 mm, and a row-to-row nozzle spacing of 2,800 mm. The distance between the three rows of a section is 5,600 mm; the width of the tunnel, with the carriageway and the walkways for evacuation, is 9,100 mm (Fig. 116). The figure shows two adjacent sections with a total length of 48,500 mm. The design solution provides that, when the system needs to be activated, at least two adjacent sections are activated simultaneously.

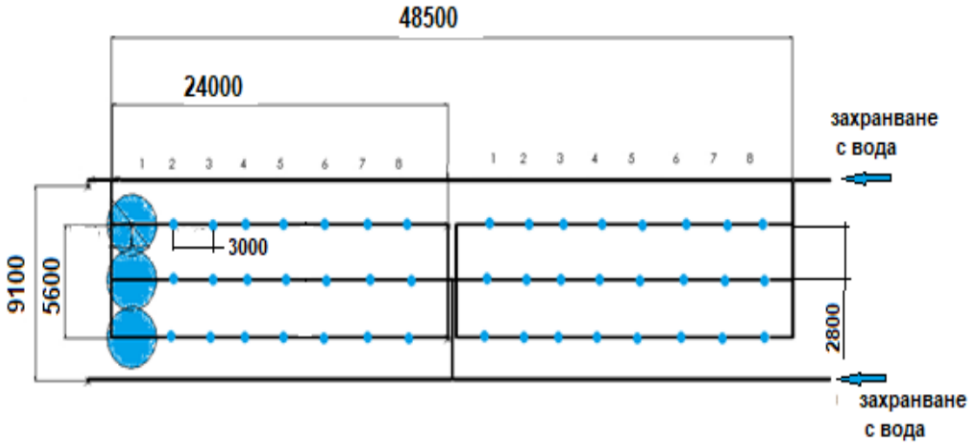


Figure 116. Diagram of the modelled sectioned fire suppression system

The fixed fire suppression system consists mainly of a pump station for water supply, a piping system, nozzles and section valves. Consequently, this is a comparatively uncomplicated device. Figure 117 shows the design configuration and the arrangement of the elements of the structure of the fixed low-pressure water mist fire suppression system in a tunnel with two-way traffic, including also the design sizing for protection of the roadway.

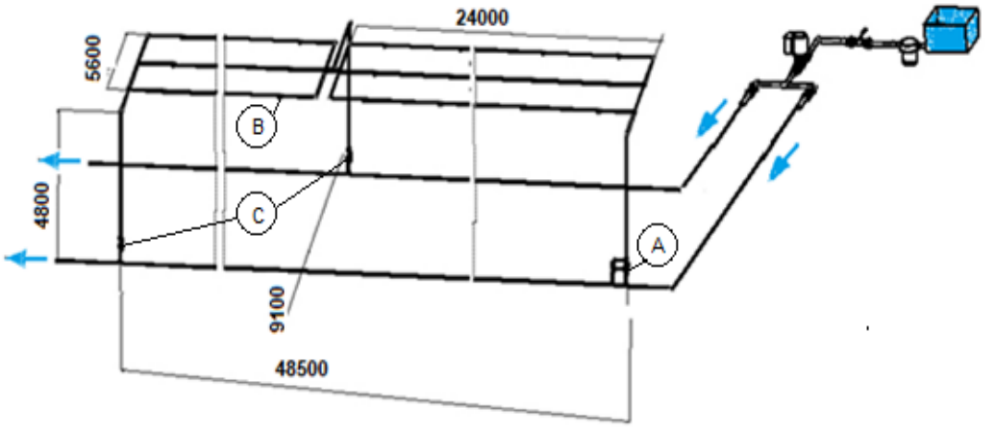


Figure 117. Diagram of the structure of the fixed fire suppression system

Figure 119 shows a top view of a two-way road tunnel with an installed fixed fire suppression system. A section is illustrated that includes two adjacent sections, showing the connection diagram, the way in which the system is supplied, and the zones of area coverage on the roadway.

The coverage length of each section is of the order of 25 m. With the design solution implemented in this way, full coverage of the roadway within the protected section is ensured.

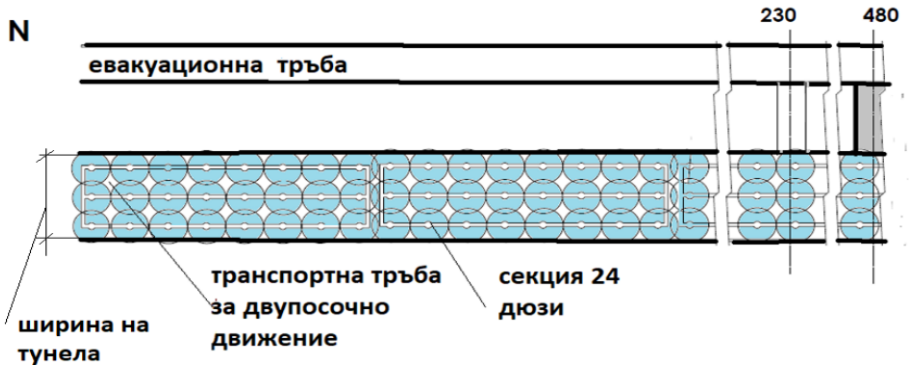


Figure 119. Coverage diagram of two sections at roadway level for two-way traffic in a road tunnel – top view

IV.4.5. Types and sizes of vehicles passing through tunnels

The vehicles that can cause a fire or be affected by one are an essential factor in determining the design characteristics of the fire suppression system. It is sized in order to provide dense coverage of the roadway in the tunnel and safe operation when it is activated.

IV.4.6. Installation and commissioning of a fixed fire suppression system

Installation is carried out in accordance with the requirements of the manufacturer GW Sprinkler and the design documentation. As with most manufacturers, the use of stainless steel for the pipes of the system is recommended, which was also done in the tests. The support of the nozzle pipe is designed to withstand vibrations and movement that may occur during operation of the facility. The piping systems with nozzles are designed so that the installation of the nozzles does not create a risk of damage either to the piping system or to the nozzles themselves.

The nozzles are installed after the final construction and secure fixing of the piping system, flushing of its internal channels to remove contamination and subsequent blowing through with compressed air to remove residual water. Compressed air is used only in preparing the pipeline, and not for atomizing the water during operation of the nozzles. After installation, the protective caps are left in place to protect the nozzles from mechanical damage and contamination, in accordance with the manufacturer's instructions.

The tightening of the nozzles to the internal thread of the piping system is carried out with a controlled torque of 4 Nm ± 1 Nm. Deviation of the deflector pin from the central axis of the opening, or its incorrect positioning, leads to uneven distribution of the water jet and deterioration of the performance characteristics.

IV.4.7. Activation and operation of the system

Throughout the entire period of fire development in a road tunnel, the operator and the rescue services should ensure simultaneous automatic and manual control, by sections, of the fire suppression system, in order to determine and apply the most effective strategies for evacuation and protection of human life.

Depending on the availability of trained personnel, the expected risks, the type of system, the control means used and the regulations in force, these requirements imply that the water mist system should be controlled by remotely actuated control elements, and not by heat-sensitive (self-activating) devices, which do not provide the possibility of visual control and operational intervention.

The water mist system should be controlled on a sectional principle. In order to optimize effectiveness, the length of the individual protected sections should be limited to zones with sufficiently high temperatures, at which effective evaporation of the water droplets is ensured, taking into account the possible uncertainty in the location of the fire.

Outside these zones the effectiveness of the water mist decreases significantly, since the droplets do not reach conditions for complete evaporation and accordingly do not achieve the required cooling and inhibiting effect.

IV.4.8. Maintenance of the components of a fixed fire suppression system

On the basis of empirical data, practice and the standards referred to above, the maintenance (inspection) intervals for fixed fire suppression systems in tunnels can be summarized (Table 41).

Table 41. Maintenance (inspection) intervals of the main components of the pump station

Component / interval	Monthly	Quarterly	Annual
Pump station	X		
Pipelines			X
Nozzles			X
Electric valves		X	

Monthly maintenance activities are, as a rule, carried out by the operating personnel. The systems should be designed so that these activities can also be performed by trained, but not necessarily highly qualified, personnel. On the other hand, annual maintenance activities must be assigned to authorized specialized companies or to the contractor who installed the system.

CHAPTER V. MAIN CONCLUSIONS, SCIENTIFIC AND APPLIED CONTRIBUTIONS

V.1. Main conclusions

The research carried out shows that it is possible to generate fine water droplets at low pressure and to suppress model fires in the experimental configuration investigated. The cooling effect is associated with the heating and evaporation of the water. The degree of reduction of water consumption relative to other systems should be determined for comparable fire scenarios and test conditions.

Water mist acts through cooling, local reduction of the oxygen concentration as a result of vapour formation, and limitation of radiative heat exchange. The relative contribution of these mechanisms depends on the size and velocity of the droplets, the type of fuel and the ventilation conditions.

Depending on the design objectives, the action of water mist systems can be considered in the following directions:

1) Extinguishing the fire – termination of combustion under the conditions for which the system has been designed and tested.
2) Suppression of the fire – reduction of the heat release rate and of the intensity of combustion.
3) Control of the fire – limiting its growth and the thermal impact on adjacent materials and structural elements.

The effectiveness of a water mist system depends on the nozzle design, the working pressure, the water consumption and the conditions of application. The low-pressure systems investigated represent a possible solution for the types of tunnels considered. Their selection should be based on test results, fire risk analysis and a technical and economic assessment.

The design of low-pressure water mist systems must be based on tests under representative fire scenarios and on the applicable standards. Compliance and approvals relate to the specific system, its configuration and the conditions of application; they should not be taken as a general confirmation for all possible fire risks.

V.2. Scientific and applied contributions

The following scientific contributions are presented in the dissertation:

1. Low-pressure nozzles were investigated with the aim of achieving a suitable droplet distribution by area and size in extinguishing fires in road tunnels. The spray intensity over the experimental area was investigated at different radii of placement of the measuring vessels.
2. The distribution of water and the droplet sizes in the investigated configuration were established. The observed deposition of smoke particles is grounds for additional investigation of the influence of the system on visibility.
3. The comparison of the GW M5 and DCU 1940 PNR nozzles shows that, under the investigated conditions, DCU 1940 PNR provides a more favourable distribution of the spray intensity and of the droplet size. The conclusion relates to the specific experimental configuration.

Applied scientific contributions consist of:

1. A stand for testing nozzles with vertical and horizontal spraying was designed and built, which makes it possible to investigate the distribution of droplets over differently oriented surfaces.
2. A stainless-steel cone with an angle of 11° was designed and built. Nozzle holders are arranged along its contour at 120°, with the possibility of adjusting the direction from 0° to 90° relative to the direction of the air flow.

Contributions of an economic and practical orientation are:

1. Automatic activation of the system compensates for the longer arrival time of the fire brigade and allows firefighters to approach the combustion zone for effective extinguishing, which leads to significant cost savings.
2. The installation of low-pressure water mist systems can be carried out during periods of lowest traffic and does not require closure of the tunnel tube during the day.
3. The installation costs are recovered over the operating life of the systems if, during that time, at least one large or very large fire occurs. The moment of such an event cannot be predicted, but the ASFINAG statistics (ILF, 2013) show that it is very likely. The benefit of loss reduction is greatest for severe fires: 42% of it relates to catastrophic fires, 29% to very large fires and 27% to large fires, or a total of 98% to these three categories. Small fires give only 2% of the benefit. The economic viability must be verified for each tunnel individually, taking into account its location and length, the share of heavy goods vehicles, the gradients before and in the tunnel, and the frequency of traffic.
4. Data from other countries were used as a guide to the benefit/cost ratio. According to Fathi Tarada (2009), the average value for the conditions in the United Kingdom is 1.27, which is adopted as the minimum for Bulgarian conditions.

V.3. Additional conclusions on the application of low-pressure water mist systems:

1. Various fixed fire suppression systems for safety in engineering facilities, energy and mining sites and tunnels were investigated. The expediency and effectiveness of fixed water mist systems has been proven.
2. Fixed systems improve the conditions for self-rescue. The suppression of heat release allows rescue teams to approach the seat of the fire. The flow of mist from the nozzles protects firefighters from the infrared heat of the flame, a protection that most extinguishing technologies do not provide.
3. Limiting the heat release rate of the fire reduces the thermal impact on the tunnel structure. With the activation of two adjacent installations in the fire zone, the spread of combustion to adjacent vehicles is prevented.
4. The cooling effect depends on the initial temperature of the water, the degree of evaporation and the final temperature of the steam. Heating about 1 kg of water from 20 °C to 100 °C and evaporating it completely absorbs about 2.6 MJ of heat.
5. The main elements – the nozzles for low-pressure installations – were investigated, and the extinguishing of a simulated fire and the operation of the system were modelled. A model and diagrams of a fixed low-pressure water mist system are proposed. A database with the main parameters for design purposes has been formed. The main activities for the use and maintenance of this type of system are given.

LIST OF PUBLICATIONS ON THE DISSERTATION

1. Mihaylov M., Stoykov Vl. Propagation of water mist in a ventilated road tunnel, ISSN 0861-5713, journal “Mining and Geology” [Минно дело и геология], Year LXXVII, Issue 1-2/2023, pp. 48-56
2. Mihaylov M., Stoykov Vl. Modelling of fixed fire suppression installations with low-pressure water mist nozzles, ISSN 0861-5713, journal “Mining and Geology” [Минно дело и геология], Year LXXVII, Issue 3-4/2023, pp. 50-62
3. Mihaylov M., Stoykov Vl. Modelling of fixed fire suppression installations for low-pressure water mist with horizontal spraying, ISSN 0861-5713, journal “Mining and Geology” [Минно дело и геология], Year LXXVII, Issue 9/2023, pp. 54-63
4. Mihaylov M., Stoykov Vl. Modelling of fixed fire suppression installations for low-pressure water mist with horizontal spraying, ISSN 0861-5713, journal “Mining and Geology” [Минно дело и геология], Year LXXVII, Issue 10/2023, pp. 56-63.

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