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Actual problems of positioning of the robotic monitors to fire area in robotic fire suppression systems.
Part 1. Background to the development of RFSS and specific characteristics of the fire fighting by means of RFM

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ABSTRACT

The historical background of the creation of the predecessors of robotic fire suppression system (RFSS) — plants homing to the fire is described. The information on the successful use of mobile robots in the military, police, fire protection, unmanned aircraft, industry, transport, construction, agriculture, social sphere, for the investment of human life conditions, during scientific research is presented. There are shown fundamental differences between stationary RFSS firefighters from mobile robots. The practical reasons preventing the implementation of the widespread use of RFSS at the end of the last century are indicated. Brief information on the use of robotic fire monitor (RFM) for liquidation of the accident at the Chernobyl NPP is given. The analysis of the results of experimental and theoretical studies of the point of standing and scanning jets is carried out. There are described the main problems encountered in the design process of RFSS, which include RFM. It is shown the status of fire robots technology abroad. Russia's positions in the creation and production of RFM, in the development of the regulatory framework in relation to RFSS have been noted. The basic terms and definitions on navigation and parameters of fire extinguishing agent supply are formulated. The analysis of the main provisions of normative documents on the design and testing of RFSS is carried out. Comparative full-scale tests of domestic RFSS and foreign sprinkler automatic fire extinguishing system are presented, made by the Denmark company COWI A/S. Variants of the algorithm of functioning of the detection and navigation of the trunk of RFM to the fire with respect to the error of aiming and positioning are investigated. Different variants of implementation of the principle of operation of modern RFSS are considered.

Keywords: static (stationary) streams; vibrating streams; oscillating (scanning) streams; compact streams; spray stream; front streams; hinged streams; targeting detector; angular coordinates; irrigation area.

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Abbreviations

AFSS — automatic fire suppression system;
MFA — model fire area;
FEA — fire extinguishing agent;
RFM — robotic fire monitor;
WMS — water mist stream;
RFSS — robotic fire suppression system;
L_z — length of flame area taking into account positioning inaccuracy and dead zone of targeting detector at the time of extinguishing agent contact with the surface to be protected;
L_{flame} — flame length;
L_{spray} — spray area;
$L_{contact}$ — length of FEA contact area with surface to be protected;
$S_{coverage}$ — coverage area;
$S_{contact}$ — contact area of FEA and surface to be protected;
X — the coefficient taking into account the spreading over the horizontal protected surface (at the coverage intensity corresponding to the average coverage intensity of the ellipse); $X > 1$;
Y — the coefficient taking into account the spreading over the vertical protected surface (at the coverage intensity corresponding to the average coverage intensity of the ellipse); $Y > 1$;
α — angle of positioning inaccuracy;
β — angle of dead zone of targeting detector;
γ — additional coverage angle due to flowing down of FEA on the vertical surface to be protected (at coverage intensity equal to the coverage intensity at mid part of an ellipse);

δ — additional coverage angle due to spreading out of FEA on the horizontal surface to be protected (at coverage intensity equal to the coverage intensity at mid part of an ellipse);
θ — angle of attack of FEA straight stream and spray stream;
Δ — actual range of coverage angles;
λ — rated range of coverage angles;
ξ_v, ξ_h — the coefficient taking into account the increase in the area of FEA coverage, respectively, due to its flowing down on the vertical or spreading over the horizontal surface;
σ — range of coverage angles, taking into account the spreading out of FEA over horizontal protected surface;
η — angle of positioning inaccuracy;
ρ_{det} — angle of vision of targeting detector;
ρ_{RFM} — RFM monitor elevation angle;
φ — angle of RFM elevation correction with respect to the vision line of the targeting detector;
ψ — activation zone of targeting detector;
ω — range of scanning angles.

Terms and definitions

Vibrating compact stream or sprayed stream of FEA: compact stream or sprayed stream of FEA with small oscillations (less than 2°) around its axis in one or two planes;
range of fire extinguishing agent stream: the distance along the axis from the fire monitor to the epicentre of FEA contact spot with fire area;
high-angled stream: a stream falling from above to the sprinkler area;
oscillating (pendulous) straight stream or sprayed stream: uniform cycle oscillations of stream or sprayed stream controlled by rigid and non-reprogrammable program with stable parameters for supplying of FEA regardless of the size of the fire area and distance from fire area to robotic fire monitor;
positioning inaccuracy: deviation of the initial coordinates of the straight stream, the sprayed stream of FEA or scanning raster after a certain time or a certain number of cycles;
robotic fire monitor: a stationary automatic robotic fire extinguishing equipment with function of targeting to fire area, its fire monitor has several degrees of mobility that is movement-limited; robotic fire monitor operates according to an algorithm of the reprogrammable control device that provides monitor targeting to the fire area and supply of FEA for the elimination or containment of fire or cooling of process equipment and building structures;
robotic fire suppression system (RFSS): automatic fire suppression equipment consisting of a combination of several fire robot monitors connected by a common reprogrammable control system for fire detection and positioning to the fire area;
scanning: cyclic movement of robotic fire monitor controlled by a specific program;
scanning (line) straight stream or sprayed stream: straight or sprayed stream generated by the RFM and periodically moving in the horizontal and vertical planes;
sliding stream: stream with an angle of attack to the coverage area 90° > θ > 0;
static (quasi-static), or stationary, straight stream or sprayed stream: straight or sprayed stream of FEA, made by the stationary RFM, with permissible minor periodic deviations (less than 1°) from the centre line of FEA;
accuracy of RFM positioning when feeding a straight stream or a sprayed stream of extinguishing agent: the deviation between the programmable coordinates of the fire monitor position and its actual coordinates when feeding FEA;
angle of attack: angle at which a straight stream or sprayed stream of FEA is fed to the fire area;
angle of elevation: the angle between the horizontal plane and the axis fire monitor;
correction angle φ: deviation of the fire monitor angle of elevation with respect to the sighting angle of the targeting detector;
frontal stream: a stream quasi-perpendicular to the frontal coverage area, $\theta \approx 90°$;
efficient radius of extinguishing agent feed: the maximum range of FEA stream, in the final part of which the required hydraulic parameters (intensity and coverage area) are provided for the fire extinguishing or containment.

1. Historical background — predecessors of modern robotic fire suppression systems (RFSS)

It is hardly to imagine the rapid growth of labour productivity in industry without the intensive development and implementation of a variety of robotic technology complexes. The technical progress was the result of systematic international and national programs for creation of various-purpose robots for production and public tasks.

The gains in the field of mechatronics of robotic systems (mechanics, artificial intelligence, perception means, artificial vision, software, digital engineering) allowed to range new frontiers in the development of [1, 2]:

- adaptive (sensor-based) robots, the operating program of which purposefully changes the sequence or nature of actions depending on the controlled parameters of the working environment and/or the functioning of the robots themselves;

- intelligent robots, the operating program of which can be fully or partially generated automatically in accordance with the set task and depending on the state of the working environment.

These robots have been successfully applied in military science [3, 4], unmanned aviation [5], police [6], fire protection [7–9], industry [10, 11], transport [12], construction [13], agriculture [14, 15], the social sphere [16, 17], for improving the living conditions of a person [18, 19], scientific research [20].

In fact, all these robots including those designed for fire-fighting are mobile, made on the basis of wheeled or tracked chassis. And only industrial robots, designed for assembly, welding or painting works, are mostly stationary devices whose moving kinematic links have several degrees of freedom. Reasoning about the future of robotics, many experts still consider the development of mobile devices, especially anthropomorphic ones, minimization of intelligent robots' aggressiveness and elimination of errors in the interaction of humans and robots are to be priority areas [21, 22].

Unfortunately, modern advances in science and technology, implemented in the field of robotics, even in recent years, can hardly be implemented in relation to stationary RFSS for the following reasons:

- firstly, modern fire robots are not so much reprogrammable devices as remotely controlled machines;
- secondly, though seemingly straightforward of RFSS, they must perform various functions related to fire detection, determining the coordinates of RFSS positioning relative to the fire seat taking into account an angular misalignment, choose of the most optimal ballistic properties of static or scanning stream of FEA and hydraulic parameters of localization or fire suppression.

In this regard, the development of modern RFSS is based on the works made in the USSR in the second half of the 20th century.

The first attempts to create the predecessors of fire robots — self positioning devices — were undertaken at All-Russian Research Institute for Fire Protection of Ministry of Russian Federation for Civil Defense, Emergencies and Elimination of Consequences of Natural Disasters in the mid 60^{s}–early 70^{s} of the last century. Three designs were proposed, they completely differed by [23–25]:

- drive type (electric, water or oil hydraulic drives);
- sensor type of detectors (four dimensional diode IR matrix; two IR photoconductive resistors, the viewing angle of one of IR photoconductive resistors is limited by the horizontal gap, and the other one — by the vertical gap; and one UV photon counter, which viewing angle depends on the gap diaphragm limited from above);
- fundamentally different methods of positioning on the fire seat (to the energy centre of the fire, to the flame edge, under the flame edge).

A detailed description of these devices is given in [26, 27].

In those days, self-positioning devices did not gain widespread due to the imperfection of the drives, the low level of development of microprocessors and machine vision systems. In their principle of operation, they had the elements of adaptation and "hard" programming but did not have the ability to promptly change the control operating with respect to the fire area location and phases. A significant disadvantage of self-positioning systems was the supply of FEA with fixed fire monitor (stationary stream), i. e. no monitor scanning within the angular coordinates of the frontal flame zone, distance determination and automatic change of the fire monitor elevation angle to the object to be protected.

The result of the further development of automatic fire suppression systems was stationary RFM, experimental samples of which were first developed under the direction of N. L. Popov and Yu. I. Gorban for the protection of Kizhi wooden architecture monuments [28].

After the accident at the Chernobyl Nuclear Power Plant (Chernobyl NPP), one of the primary tasks was to clean the roof (about 110×30 m in size) of the 3rd power unit from radioactive contamination. By the telegram of Minister of Internal Affairs of the USSR A. Vlasov, three RFMs were sent to the Chernobyl NPP, they were installed with the help of helicopters at around 70 m of the roof of the 3rd unit and were successfully used to remove radioactive debris, pieces and dust from it. Thus, due to RFM, it was possible to save the health of many people, and first of all, soldiers of chemical troops, who would have to carry out this operation manually.

At the same time, analysis of the fire robotics as of the time of the Chernobyl accident [29, 30] showed that of the 54 types of robots known at that time, only six were stationary, and four RFMs were domestically produced (jointly developed by "Engineering centre "FR" LLC (Petrozavodsk Design and Technology Institute) and VNIIPO).

The main problem at the initial stage of RFM development was to determine the effect of the scanning speed on FEA effective range, in order to take this fact into account when calculating the distance between two adjacent RFM. For this purpose, experimental and theoretical studies of the ballistics of scanning streams were carried out (Fig. 1) [31].

Similar dependences of the effective range of scanning straight streams on the angle of inclination of the fire monitor PLS-20 were obtained for the feed pressure range of 0.6–1.0 MPa and with nozzle diameters of 25, 28, 32 and 38 mm.

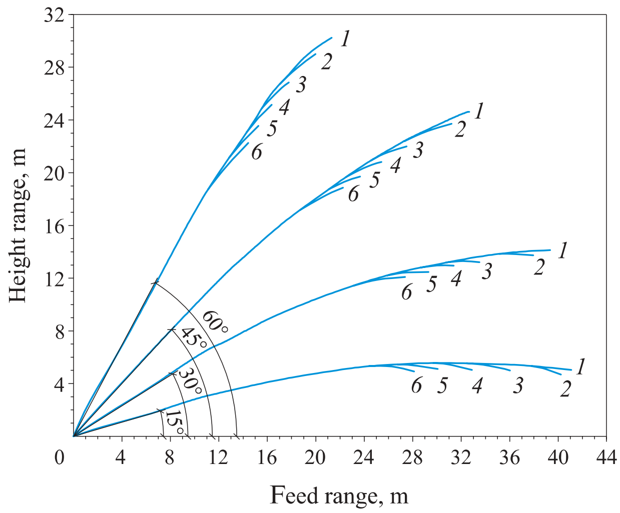

Fig. 1. Dependence of the range of scanning straight streams on the inclination angle of the fire monitor PLS-20 (at a pressure of 0.6 MPa, nozzle diameter 28 mm): *1* — static (quasi-static) straight stream part boundary; *2* — stream scanning speed 3 deg/sec; *3* — the same, 6 deg/sec; *4* — the same, 9 deg/sec; *5* — the same, 12 deg/sec; *6* — the same, 18 deg/sec

According to the results of studies of the scanning streams ballistics, it was determined that in the studied range of pressures and nozzle diameters:

- at a scanning speed of 3 deg/sec, the range of straight stream is reduced by 16 % compared to the quasi-static stream, 6 deg/sec — by 20 %, 9 deg/sec — by 30 %, 18 deg/sec — by 50 %;
- optimal scanning speed for a Class A fire should not exceed 6 deg/sec, and the scanning step on the horizontal plane at a distance of 20–40 m with nozzles of 28 or 32 mm should not exceed 0.5 m.

New automatic fire suppression technologies based on the state-of-the-art RFSS significantly expanded the technical capabilities of automatic fire supression systems. Nowadays, in our country RFSS find ever-widening applications for fire protection of extended various purpose premises, tank farms, wood storage places, and ground-based complexes in the petrochemical industry. The well-known Russian manufacturers of RFSS are: Limited liability company "Engineering centre of fire robots technology "FR" and International Association Systemservice, and Uralmekhanika LLC, Nizhnevolzhsky Industrial Holding Company, Scientific and Production Center Fire Fighting Systems LLC. Moreover, abroad the use of remote-controlled fire monitors are still limited.

Moreover, Russia leads the world in the development of the legal framework with respect to RPM and RFSS. Almost 20 years ago, the Fire Regulations NPB 84–2000 [32] were developed for the first time in world practice, these Regulations specified the general technical requirements and test methods of the RFSS. Currently GOST R 53326–2009 is valid. The requirements for the RFSS are also specified by Article 116 of the Federal Law No. 123-FZ "Technical Regulations on Fire Safety Requirements" (hereinafter — the Federal Law No. 123) [33].

Abroad requirements to Foam Monitors, Automatic Oscillating and Electrically Operated Monitors Systems are set in the FM 1421 standard [34], which will take effect only on May 1, 2019.

The Norwegian company COWI A/S has become interested in using low flow rate water mist RFM of type FR-LSD-S4Ub-IR-WM (manufactured by "Engineering centre of fire robots technology "FR" LLC) to protect wooden architecture monuments. At COWI A/S (Denmark), comparative field tests of these RFM with an Automatic sprinkler system with a sprinkler traditional automatic fire suppression system and water mist AFSS [35] were carried out.

The tests were carried out in high wooden panel rooms and on external walls with a height of 7 to 10 m. In conclusion, it was noted that in terms of water flow rate, extinguishing time, burning, wetting area and char depth of eight compared types of automatic fire suppression systems, the best results were demonstrated by ceiling-installed robotic nozzles (i. e. low flow rate RFM). They provide the registration of the fire area much faster than the sprinkler automatic fire supression systems, systematically and quickly extinguish it with a lumped water mist stream, and they are more efficient than three sprinklers by 1.6 times. In case of stronger fire, even K57 sprinkler (rated response temperature is 57 °C) is completely inefficient. The high speed and controlled-angle of FEA stream, directly into the fire area, allows reducing damage from charring, water, wetting and smoke formation. Low flow rate RFM provides bringing the 3–4 MW fire under control; if the fire power is above 4 MW, automatic fire suppression systems based on sprinklers and sprayers with a rated response temperature of 57 °C turned out to be absolutely inefficient. The mass of water used to extinguish fires by means of sprinkler automatic fire suppression systems within 10 min was 0.7–2.4 tons. Low flow rate RFMs compared to sprinkler automatic fire suppression systems allow to reduce the water flow rate by more than 70 %, and the charring area — by almost 15 times. Fire was extiguished by sprinkler automatic fire suppression systems in a few minutes in less than 1 of the 3 cases; in 1 of the 3 cases the fires were brought under control, and in 1 of the 3 cases the fires were not extinguished at all within 10 min (that means, before the arrival of the fire departments).

Tests to determine the fire extinguishing ability of the FR-LSD-S10Ub-IR type RFM and a low flow rate water mist FR-LSD-S4Ub-IR-WM [7] type RFM according to the program and test methods developed by

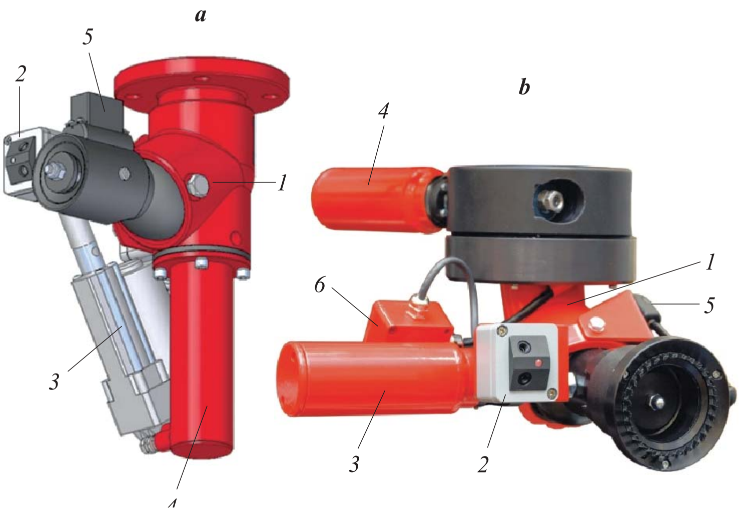

Fig. 2. Robotic fire monitors: *a* — ceiling-installed mini-monitor (firefighting mini robot) FR-LSD-S10Ub-IR; *b* — ceiling-installed mini-monitor (firefighting mini robot) FR-LSD-S4Ub-IR-WM; *1* — monitor with nozzle; *2* — fire detector and fire source targeting device; *3* — vertical rotation electric drive; *4* — horizontal rotation electric drive; *5* — electric drive for the formation of a straight stream or a sprayed stream; *6* — program control unit

the Engineering centre of fire robots technology “FR” were conducted in 2018 at the testing site of the centre.

A general view of the Engineering centre of fire robots technology “FR” facilities is shown in Fig. 2 [36].

The initial parameters and the results of the RFM test are given in Table 1.

When two FR-LSD-S10Ub-IR were tested, they were installed on one side of the model fire area. In both tests, model fire area was extinguished efficiently.

Photos of tests are shown in Fig. 3–5.

It should be noted that in the technically leading countries the actual printed works on the RFSS are almost absent, nevertheless three Russian materials [36–38] were published from 2016 to 2019 in the foreign periodicals on this topic!

New modern fire extinguishing technologies with the use of fire robots, made on the basis of fire monitors, are presented in the book [39]. It shows the origins of RFSS development in Russia, the successive improvement in their design, the use for eliminating the consequences of man-made catastrophes, as well as the possible aspects of their use for protecting unique objects of various purposes. The basic concepts of hydraulics in fire and stream ballistics, as well as flammable materials and fire extinguishing agents used in the fire monitors are considered.

The operation principle of modern RFSS can be implemented in the following versions:

- the general vision system of RFSS registers the fire, determines the size and coordinates of the fire area and transmits a command to target one or several RFMs; after targeting the corresponding RFMs to the fire area, they begin, in the mode specified by the program, to feed FEA to the fire area;
- the general vision system of RFSS registers the fire and transmits a command to its RFMs to detect the fire area; after targeting detector of one of the RFMs finds the fire area, it determines the size and coordinates and transmits a command to target RFM to the object to be protected.

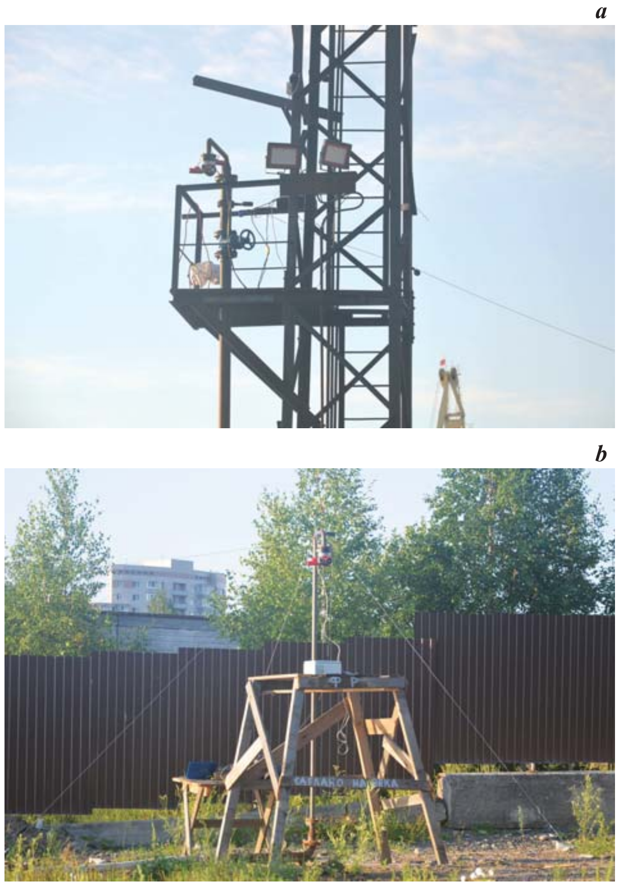

Fig. 3. Location of the RFM of type FR-LSD-S10Ub-IR at a height of 7.5 m (*a*) and 3.2 m (*b*) during testing

The RFSS control system allows to create several programmed modes for the supply of FEA in the form of both static and scanning straight streams or a sprayed stream. The other RFMs are either targeted by the RFSS control system, to the same fire area, or, if this is not required, do not take part in extinguishing the fire. The angle of the stream can vary up to 90°.

Table 1. The initial characteristics and the results of testing of the robotic fire monitors (RFM) of the type FR-LSD-S4Ub-IR-WM and FR-LSD-S10Ub-IR

Parameter	FR-LSD-S4Ub-IR-WM	FR-LSD-S10Ub-IR	
		FR 1	FR 2
Type of standardized fire (MFA) in accordance with GOST R 51057–2009	0.5A	4A	
Distance between RFM and MFA, m	12.0	26.5	25.0
Distance between RFM 1 and RFM 2, m	–	20	
RFM altitude above ground level, m	3.2	7.5	3.2
MFA base height above ground level, m	0.4	0,8	
RFM pressure of fire extinguishing agent (FEA), MPa	0.4	0.6	0.6
RFM flow rate, l/sec	4	10	10
RFM angular scanning speed at FEA supply, deg/sec	3		
Scanning angle with relative to the MFA center, deg:			
– horizontal	± 10	± 5	± 3
– vertical	–	5	10
FEA supply starting time from the moment of the MFA ignition, min:sec	08:49	11:26	
Duration of fire extinguishing until complete MFA burnout from the moment of the FEA supply, min:sec	6:40	7:58	

The significant advantage of the RFSS over sprinkler automatic fire suppression systems is the ability to detect and bring under control the fire area with the area of just 0.1 m^2 concentrating the supply of FEA with the same standard flow rate for both the automatic fire suppression system and the RFSS. For RFSS, the time to register and target RFM to the fire area is no more than 30 sec, and for sprinkler automatic fire suppression systems it exceeds 5 min. However, within these 5 min a fire can become uncontrolled, and may not be taken under control at all.

At the same time, it should be taken into account that any angular inaccuracy (positioning, angle of FEA attack, targeting, targeting detector or elevation of RFM) of 1° at a distance of 20 m leads to the displacement of a straight stream or a sprayed stream of FEA or the scan raster or path on 0.35 m, with an inaccuracy of 2°, the amount of displacement is almost doubled. Is 1° or 2° a lot or a little? Assume that the positioning inaccuracy with respect to the flame is two-sided. Then, it is necessary to enlarge the spot of FEA from a diameter of 0.5 to 0.7 and 1.4 m respectively at the time of contact with the object to be protected. The coverage area will also be increased from 0.2 to 1.13 and 2.84 m^2. However, if flow rate is the same, the coverage intensity will significantly decrease: by 5.65 and 14 times, respectively! If to sum inaccuracy for several positions, the coverage intensity will drop even more significantly. Nevertheless, even under these conditions and ensuring quasi-uniformity of coverage, e. g. due to the vibrating or oscillating feed of FEA, the coverage intensity will be about 0.5 l/(sec·m^2), i. e. for the group of premises 1 it will exceed the standard value for sprinkler by 6.25 times.

For ceiling-installed RFM, it is most expedient to ensure the supply of FEA to the fire center. However, for floor standing RFM, neither this method, nor even the method of positioning to any arbitrary point located on the flame edge, with small distances between the fire monitor and the fire area and significant flame sizes, do not give satisfactory results in extinguishing efficiency, since FEA do not affect directly into the fire area, but penetrates through the high-temperature area, covers the remote area not subject to fire.

The targeting angle at the same distance between the fire area and the sighting of the fire monitor depends on the fire size (Fig. 6) [26, 27].

For example, at the same distance from the fire monitor, but at different heights and fire areas, the energy centres of large flame A1 and smaller flame B1 have different polar coordinates relative to the axis of the monitor O. The targeting angle to the fire area also depends on its size: the bigger is the fire, the bigger is the range of targeting angle ($\alpha_1 > \beta_1$).

Targeting angular inaccuracy for any point on the fire edge, for example, C_1 or C_2, may be even bigger ($\gamma_1 \gg \beta_1$; $\gamma_2 \gg \beta_2$).

In this regard, when extinguishing class B fires, it is mostly preferred for floor standing RFSS to feed FEA under the flame edge, since regardless of fire size, FEA is fed directly to the fire area, as a result the fire extinguishing efficiency is significantly increased.

MFA

00:00 Ignition

05:00 Fire development

11:00 Fire development

11:26 Start of extinguishing

11:40 Extinguishing

13:55 Extinguishing

17:46 Extinguishing

19:24 End of extinguishing

Result of extinguishing

Fig. 4. Testing of the RFM of type FR-LSD-S10Ub-IR at extinguishing of the MFA class 4A

00:00 Ignition of MFA

03:30 Fire development

08:35 Fire development

08:49 Start of extinguishing

09:19 Extinguishing

13:00 Extinguishing

15:29 End of extinguishing

Result of extinguishing

Fig. 5. Testing of the water mist RFM of type FR-LSD-S4Ub-IR-WM at extinguishing of the MFA class 0.5A (the height of the water mist RFM is 3.2 m)

2. Particularities of fire suppression by stationary (static) and scanning streams RFM

In connection with significant achievements in the field of RFM design and RFSS software, widespread introduction of these technical means for fire protection of various-purpose objects, the emphasis in researches has been shifted to solving practical issues related to the development of regulatory requirements for the RFSS design.

The main problems in the RFSS design process including the RFM, arise when determining the distance between adjacent RFMs; choosing a fire detecting method; determining the angle of elevation of the RFM monitor, the allowable fire size (area of fire that needs to be covered); the choice of the type of FEA stream or stream (straight or sprayed, static, vibrating, pendulous or scanning), the method for determining the distance to the fire area, the nature of stream ballistics (high-

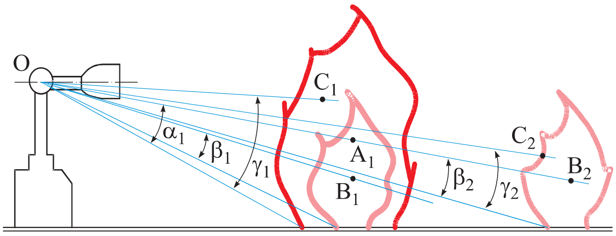

Fig. 6. The supply methods of the FEA to the fire from RFM: A_1, B_1 — energy centers of the larger and the smaller flames that are at equal distance from the RFM; B_2 — energy center of the remote flame; C_1, C_2 — points located on the contours of the flames; α_1, β_1, β_2, γ_1, γ_2 — the angular coordinates of the FEA supply relative to the flame edge

angled or frontal); when deciding what needs to be achieved when feeding FEA — spray the entire fire area at once or provide scanning within the fire area.

These positioning parameters determine the calculation of FEA flow rate and the intensity of coverage of the object surface to be protected when exposed to a water stream.

The projection of the coverage spot of high-angled or frontal static (standing) or horizontal scanning streams made by the RFM, depending on the angle at which the stream is spayed to the object to be protected, as a particular ideal case can take the form of a circle or more often an elongated ellipse.

The extinguishing of fires by static or small scanning streams (frontal, sliding or high-angle), formed by the RFM, has a number of significant features compared to extinguishing fires by spraying streams dispersed from sprinkler and drencher automatic fire suppression systems, which must be taken into account when designing an object's fire protection:

- before extinguishing fire in accordance with the algorithm of RFM operation, the automatic detecting fire coordinates, search for flame and targeting the fire monitor to fire should be provided (Fig. 7);
- fire extinguishing can be carried out with static (stationary), vibrating, oscillating (pendulous), and scanning (moving in angular coordinates) streams;
- in case of line scanning with the RFM, each point of the protected area is to be periodically exposed to FEA spot;
- the length and number of lines in the scanning raster depend on the type and overall dimensions of the fire area to be protected (location of combustible materials, process equipment, etc.), as well as on the diameter of FEA straight stream or sprayed stream;
- when protecting an object of certain linear dimensions, the range of scanning angles and consequently the duration of the scanning cycle depend on the distance between the RFM and the protected area;
- the range of scanning angles, besides the maximum permissible linear dimensions in width and depth of the fire load, is also determined by the accuracy of the RFM positioning to the fire area (by positioning and positioning inaccuracy, i. e., working out the cyclic program);
- algorithm for RFM targeting to the fire area, the type of fire detection equipment, and the coordinates of the fire monitor targeting to the fire area are selected depending on the tasks complexity (Fig. 8);
- the necessity to supply FEA stream under edge or to the flame epicentre is determined by the aggregate state of the fire load and the type of FEA;
- stream delivery range depends on the scanning speed, RFM pressure and the angle of elevation of the RFM monitor;
- feeding of FEA stream (compact or sprayed) should be carried out taking into account the angle of correction depending on the distance between the RFM and the object to be protected (fire area) (Fig. 9).

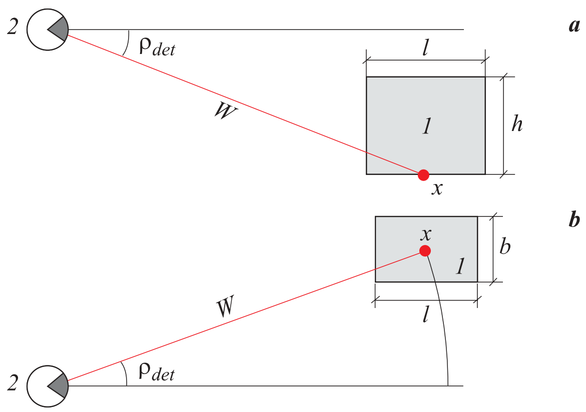

Fig. 7. Examples of sighting of the fire targeting detector: *a* — frontal, to the edge of the flame; *b* — to the centre of the horizontal surface of the fire load (or energy centre); *1* — protected object; *2* — fire targeting detector; *W* — detector sighting line; *l*, *b*, *h* — length, breadth and height of the protected object; *x* — detector sighting point; ρ_{det} — sighting angle of the fire targeting detector

The bigger are distances L and l between RFM and fire area, the bigger are angles φ, ρ_{RFM} and $\rho_{det.}$ At $L > l$ we have: $\varphi_L > \varphi_l$; $\rho_{RFM-L} > \rho_{RFM-l}$, $\rho_{det-L} > \rho_{det-l}$.

When designing the RFSS, one of the following options of the functioning algorithm for fire detection and RFM positioning to the fire area can be implemented:

1 — registration of the fire area by a general view fire detector or zone detector with the subsequent transmitting the appropriate command to one or more RFM for targeting to the fire area;

2 — registration of the fire area by machine vision system (MVS) with the subsequent transmitting the corresponding fire coordinates for automatic targeting one or several RFMs directly to the fire area.

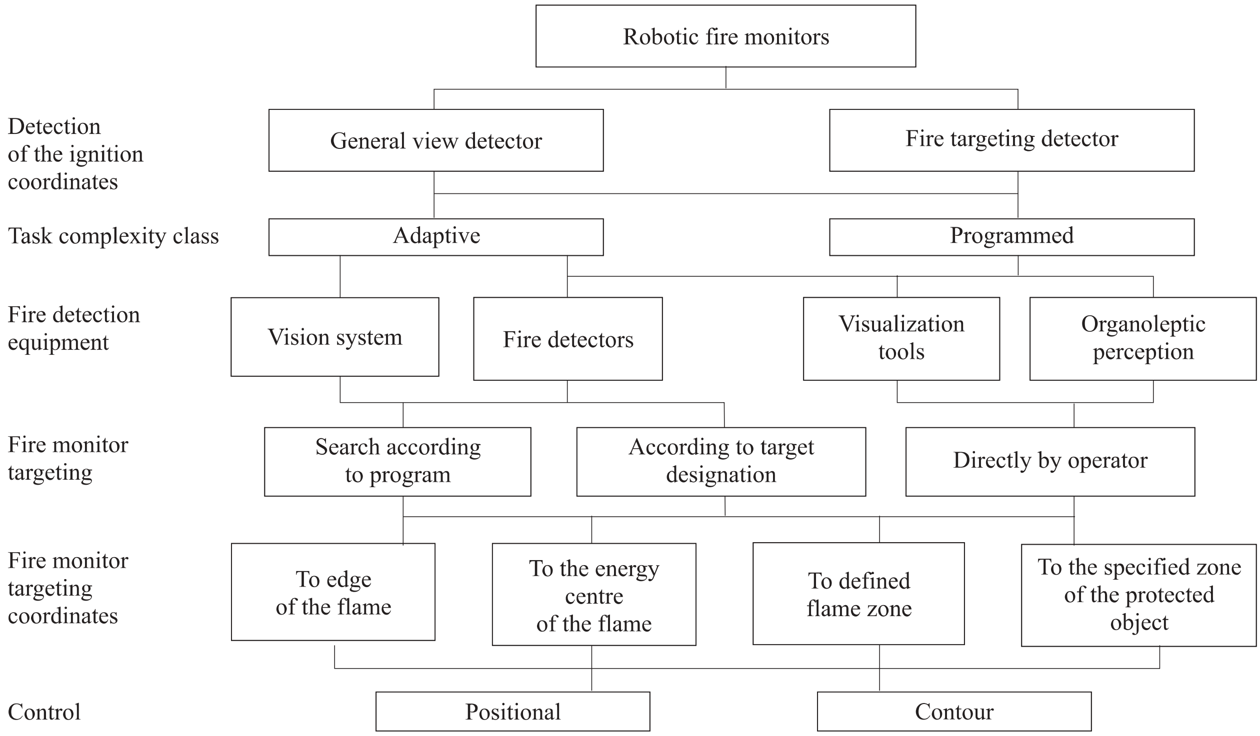

Fig. 8. Algorithm of the RFM targeting onto the fire source

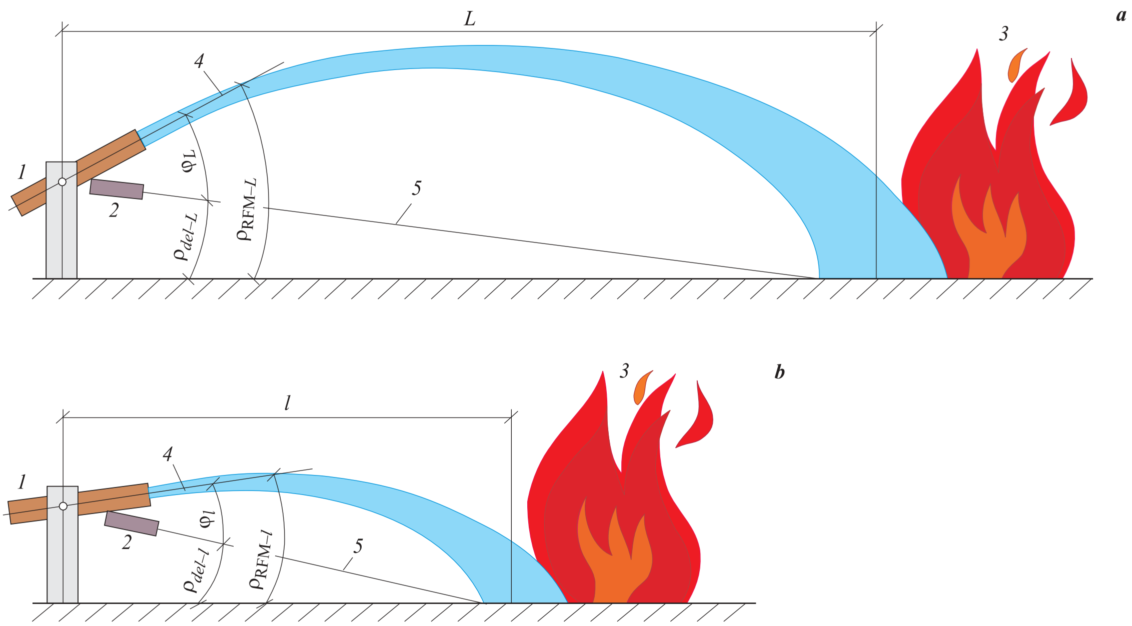

Fig. 9. The dependence of the correction angle on the distance between the RFM and the fire source: *a* — at $L \geq l$; *b* — at $l \leq L$; *1* — RFM; *2* — targeting detector; *3* — fire source; *4* — RFM elevation line; *5* — detector sighting line; L, l — the distance to the fire source; ρ_{RFM-L}, ρ_{RFM-l} — elevation angle of the RFM; ρ_{det-L}, ρ_{det-l} — sighting angle of the fire targeting detector; φ_L, φ_l — correction angle

In the process of positioning and extinguishing the fire, the RFSS control system should automatically make decisions on determining:

- method of FEA stream feeding to the fire area (high-angled sprayed stream, scanning streams or only one stream under flame edge);
- FEA stream discharge angle, depending on the stream range;
- the initial FEA feeding (to horizontal or vertical surface, above the edge of the protected area, at the fire epicenter, under the flame edge or to the side contour);
- correction angle (depending on the distance and pressure of FEA stream).

When extinguishing a fire load caused by straight combustible materials of low height, located on a hori-

Table 2. Detector response time to test fire source

Test fire source	Test fire source characteristic	Detector response time, sec, not more than
TP-2 Wood burning	70 beech bars of 10×20×250 mm each, laid in 7 layers	370
TP-4 Polymer materials burning	3 polyurethane foam mats of 500x500x20 mm each	180
TP-5 HFL burning with smoke	650 g of a heptane (97 % by vol.) and toluene (3 % by vol.) mixture in a pallet of 330×330×50 mm	240
TP-6 HFL burning without smoke	2000 g of mixture of an ethyl (90 % by vol.) and methyl (10 % by vol.) alcohol in a pallet of 435×435×50 mm	510

zontal surface, or spills of liquid, FEA shall be fed under flame edge. When protecting technological equipment of complex configuration, it is advisable to cover with several scanning streams. When protecting vertical surfaces from thermal effects, it may be enough to scan one stream into a given area (e. g. along the upper edge of this surface).

3. Basic provisions of regulatory documents on RFSS design and testing

The basic requirements and test methods of the RFSS and RFM are given in GOST R 53326–2009, and the general provisions on design are given in Set of rules 5.13130.2009 [40] (hereinafter SP 5) and in Administrative Regulations for Fire Safety — Industry Standard VNPB-STO [41]. However, when designing the RFSS with respect to a specific object of protection, uncertainty arises: which area-limiting fire areas can be brought under control or localized, at what FEA flow rate, at what distance to the RFM (since this information is not available in the regulatory documents).

Before designing the RFSS, it is necessary to determine the maximum permissible dimensions of the fire area (taking into account the inaccuracy of targeting to the fire area and positioning inaccuracy), for which it is still possible to ensure the localization or bringing the fire under control, since these parameters determine FEA pressure and flow rate, as well as the associated ballistics of straight stream or sprayed stream. However, the scanning range by with RFM monitor is determined not only by the allowable size of the fire area, but also by the inaccuracy of targeting and positioning.

In turn, the permissible dimensions of the fire area depend on the sensitivity and operation speed of the fire detection equipment and positioning duration of the RFM monitor to the fire area, inaccuracy of targeting and positioning. The fire detection speed is determined by the sensitivity of the MVS, a general view detector (or zone detectors), or targeting detector providing the RFM positioning with required accuracy to target FEA straight stream or spray stream to the fire area. The sensitivity of the MVS and detectors depends on the flame radiation intensity, its spectral characteristics and the distance to the fire area.

According to GOST R 53326–2009, the sensitivity of detectors is verified according to the method described in GOST R 50898–96 that applicable only to the tested TP-5 type fire area (Table 2). But even if we take into account other fire areas, e. g. TP-2, TP-4, TP-6, then they do not include the whole variety of combustible materials.

The speed of the detectors permissible according to GOST R 50898–96 (180–510 sec) is too high, but even if the running time is less for real fire area, we need to know how much. With an angular targeting speed of 9 deg/sec and the distance to the object to be protected of only about 20 m and a speed of about 1 sec, the movement on the front plane of the fire area will be about 3 m. To reduce this time to a minimum, it is necessary the fire to be registered by MVS with the subsequent transmitting the corresponding coordinates of the fire area for automatic targeting of the RFM directly to the fire area or by the RFM targeting detector, which moves together with RFM monitor in the vertical and horizontal planes and registeres the initial and final coordinates of the fire area in the process of positioning and searching for the fire area. It should be noted that the future is de-

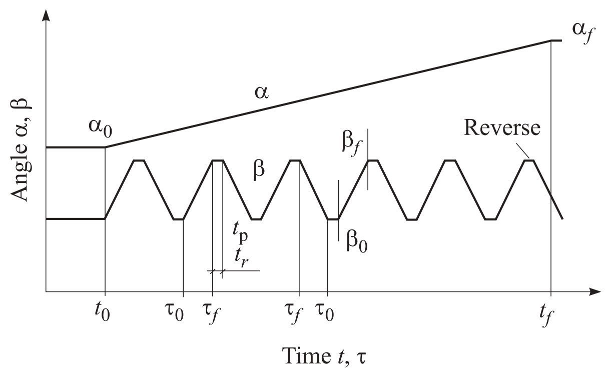

Fig. 10. Angular rotations of the RFM monitor during targeting at the fire source: α, β — angular rotations of the RFM monitor in the horizontal and vertical planes; α_0, α_f, β_0, β_f — the same, in the initial and final position of the search cycle; t, τ — duration of the rotation in the horizontal and vertical planes; t_0, t_f, τ_0, τ_f — the same, at the start and the end of the search cycle; t_r — reverse duration

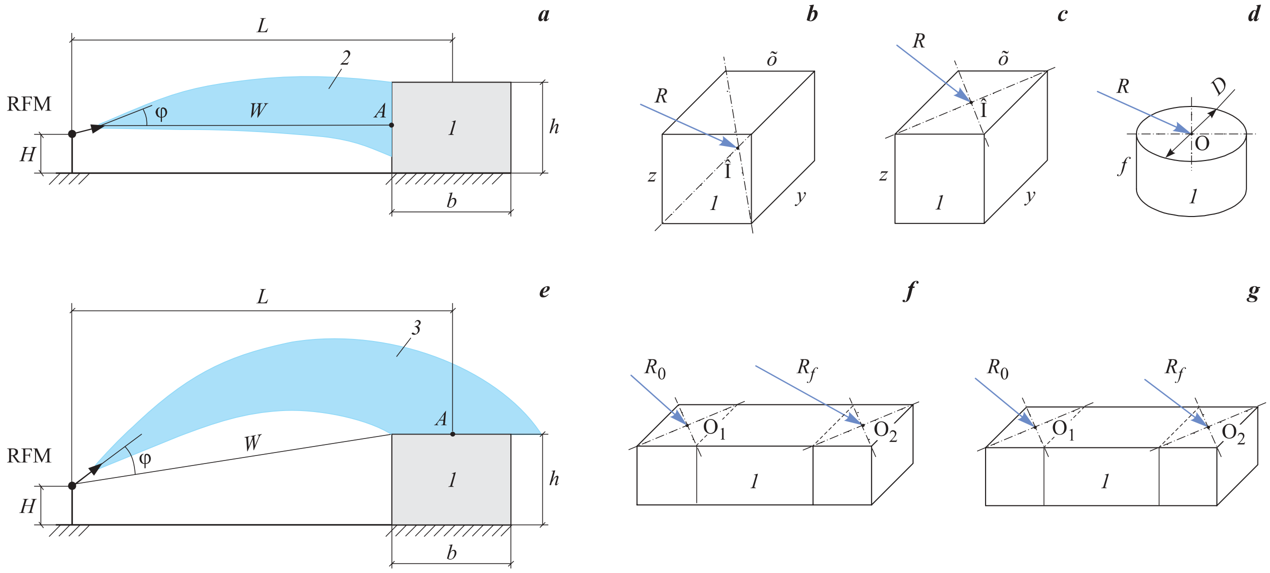

Fig. 11. Types of streams: *a*, *b* — frontal; *c*–*g* — high-angle; *a*–*c*, *e*, *f* — fire source of a class A; *d*, *g* — center of fire source of a class B; *a*–*e* — static (stationary) stream; *f*, *g* — scanning stream; *1* — protected object; *2* — frontal stream; *3* — high-angle stream; *L* — distance between the RFM and the protected object; φ — the correction angle (between the detector sighting axis and the RFM axis); *R* — the stream direction; *W* — detector sighting line; *l*, *b*, *h* — length, breadth (depth) and height of the protected object; *H* — the RFM rotation axis height

finitely in the machine vision system. Currently, intensive work is being carried out on the use of MVS as an independent fire alarm system and fire detection equipment as part of the automatic fire supression system.

Curves of angular movements of RFM monitor in the horizontal and vertical planes when positioning to the fire area are shown in Fig. 10.

In actual practice, the spectral characteristic of fire can significantly differ from a test fire. The high detector sensitivity according to GOST R 50898–96, e. g. to the TP-5 type fire area, does not mean that it has an acceptable sensitivity to the radiation spectrum of real fire.

The targeting detector that searches and records the angular fire coordinates, has a dead zone β on both sides of the flame, to which it does not respond. In practice, the stream is targeted to the fire area, firstly, with a certain positioning inaccuracy at an angle α and an angle positioning inaccuracy η due to specific features of the kinematics of the driving system and the RFM control system. According to GOST R 53326–2009, the maximum angle inaccuracy α should not exceed 2°.

In the method of determining the inaccuracy of RFM targeting and positioning, given in GOST R 53326–2009, it is not specified how this inaccuracy should be taken into account when designing an RFSS and how it will affect the given FEA flow rate. In this regard, the problems in justifying the FEA flow rate appear, since there are no recommendations on the maximum permissible inaccuracy for which the deviations in the Table 5.1–5.3 SP 5 [40] may be acceptable.

It should be noted that the advantage of RFSS in comparison with the sprinkler automatic fire suppression system is the ability to extinguish the initial fire area with a maximum flow rate (normatively equivalent for both types of system), which flow rate is much higher than for sprinkler automatic fire suppression system in terms of speed and efficiency in the early stages of fire. With increasing the fire area, the intensity decreases.

At the same time, it is necessary to take into account the differences in the structure and shape of the stream generated by sprinklers of automatic fire suppression system and RFM. For any type of sprinkler, the main parameter affecting on fire suppression efficiency is the coverage intensity within a certain area to be protected. The FEA stream from the standard sprinkler is usually targeted downward perpendicular to the horizontal surface so the projection of the covered spot is a circle. The RFM can generate both static and scanning streams (frontal, high-angled), and the stream velocity vector, depending on the RFM location relative to the protected object, can be positioned upward, horizontally or downward (Fig. 11).

According to clause 7.1.9 of SP 5 [40], each point of a room or equipment to be protected must be within the coverage area of at least two RFMs, and they can be located either on one side relative to the object to be protected, or on opposite sides.

To be continued

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The name of Leonid M. Meshman is associated with a new direction in fire fighting — fire robots and fire robotics industry. He headed this scientific direction at VNIIPO and introduced new terms, concepts and regulations in fire safety. He faciliateed this new technology in Kizhi and Chernobyl, at NPPs and CHPPs. The result of this long-term development was that Russia became the first country in the world where a new type of automatic fire suppression systems, robotic fire suppression systems, are introduced by statute and regulations. Now, the RFSSs protect hundreds of significant facilities throughout the country and abroad.

With respect, Yu. Gorban