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Actual problems of positioning of the robotic monitors to fire area in robotic fire suppression systems.

Part 2. RFM operating programs for fire extinguishing with static streams considering RFMs positioning to fire area*

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ABSTRACT

The efficiency of robotic fire monitors depends on the fire extinguishing method chosen for these programmable devices to the large extent. This efficiency depends on the correct target, it means on the correct positioning. This issue contains final materials based on fire tests conducted according to the program and methods of VNIIPO in 2014–2018 years. Options for RFM positioning with respect to fire area are described. Curves of coverage by static high-angled or frontal streams are given. It is shown that curves depend on the angle of stream attack to the protected surface. The features of fire extinguishing with static streams at angles of attack of 90° and less than 90° are given. The parameters at which fire is to be extinguished by static stream are given for stream contact spot with surface and covered area.

Keywords: scanning streams; static streams; angle of attack; effective range; targeting detectors; angular coordinates; coverage area.

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1. RFMs positioning with respect to fire area

Options of RFM positioning with respect to fire area are shown in Fig. 12–15.

If each place of room or point of equipment to be protected must be located in operation area of at least two RFMs it does not mean that two RFMs should simultaneously operate and extinguish the fire area. Efficient fire extinguishing can be provided by only one RFM. At the same time, according to the results of experiments, the most efficient operation of RFSS is observed when FEA is supplied simultaneously from two oppositely installed RFMs.

The total flow rate of fire extinguishing agent and the duration of RFSS continuous operation shall be at least as those specified in Table 5.1 of Set of rules 5.13130.2009 (SP 5) [40]. The total flow rate of RFSS is to be specified taking into account the number of RFMs simultaneously operated, the hydraulic losses in supply pipeline, type and size of fire load, technological features of the object, type of rooms (1, 2 or 4) according to Appendix B of SP 5 [40].

It is indicated in Table 5.1 of SP 5 [40] that for general-purpose sprinklers, according to GOST R 51043–2002 (Automatic water and foam fire fighting systems. Sprinklers, spray nozzles and water mist nozzles. General technical requirements. Test methods), the minimum coverage area with the required coverage intensity is 12 m^2, and for conventional AFSS (depending on room class according to Construction Rules SP 5 [40]) — from 60 to 180 m^2.

The projection of covered spot of high-angled streams, or frontal streams, or scanning straight streams, or sprayed FEA streams generated by one RFM, depending on angle of stream supplying to object to be protected, may be in the form of a circle or an ellipse.

For the stream to cover minimum protected circular area of 12 m^2, its diameter shall be at least 4 m, and the diameter of the circle circumscribed about a four-square of 60 m^2 — at least 11 m. However, the wider is the stream, the smaller is its effective maximum range, therefore in case of FEA wide streams their range will

* It is continuation. See the beginning of this article in *Pozharovzryvobezopasnost/Fire and Explosion Safety*, 2019, no. 3.

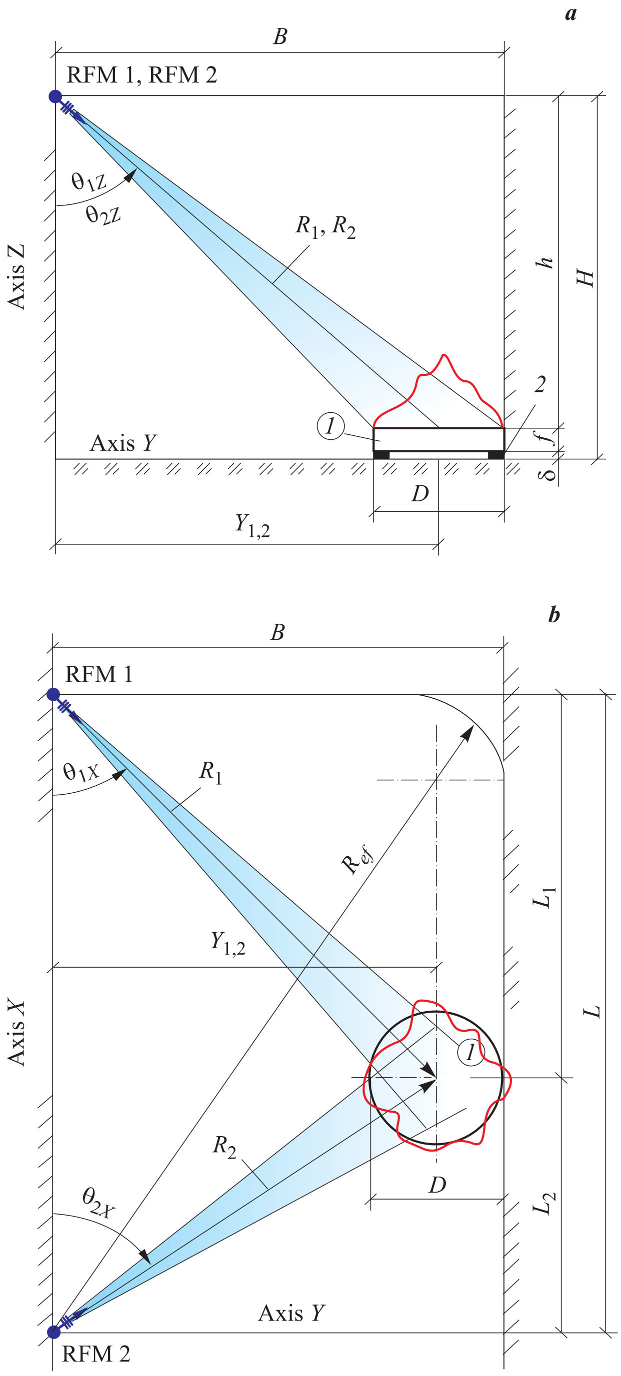

Fig. 12. RFMs positioning with respect to class B fire area if they are located at one side and in case of use of static (stationary) streams: *a* — side view; *b* — top view; *1* — fire load (tray with liquid fuel); *2* — support; *B* — room width; *D* — diameter of the tray with liquid fuel; *H* — height of RFM installation; *h* — perpendicular distance between liquid fuel surface and RFM rotation axis; *L* — distance between RFMs along axis *X*; L_1, L_2 — perpendicular distance between the center of the tray with liquid fuel and RFM 1 and RFM 2 respectively; R_1, R_2 — conventional axes of straight stream or FEA sprayed stream; R_{ef} — efficient range of FEA stream; *f* — height of tray sides; θ_{1Z}, θ_{2Z} — angle of attack of straight stream or FEA sprayed stream along the axis *Z* of RFM 1 and RFM 2 respectively; θ_{1X}, θ_{2X} — angle of attack of straight stream or FEA sprayed stream along the axis *X* of RFM 1 or RFM 2 respectively; $Y_{1,2}$ — *Y* axial distance between center of fire load and RFM 1, RFM 2

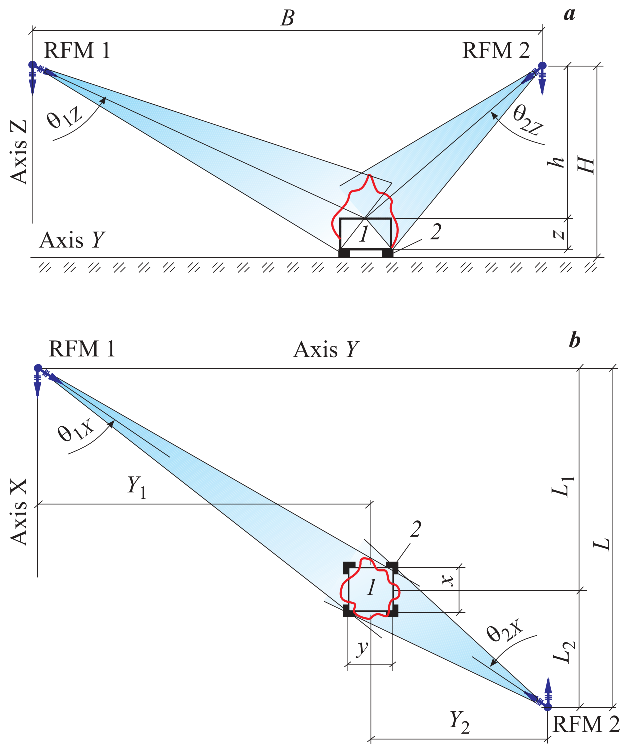

Fig. 13. RFMs positioning with respect to class A fire area if RFMs are located opposite to static (stationary) stream supply: *a* — side view; *b* — top view; *1* — wooden stack-pile; *2* — support; *H* — height of RFM installation; *h* — perpendicular distance between top surface of fire load and RFM rotation axis; *L* — distance between RFMs along axis *X*; L_1, L_2 — perpendicular distance between the center of fire load and RFM 1 and RFM 2 respectively; *x*, *y*, *z* — length, width and height of fire load; Y_1, Y_2 — distance along the axis *Y* between center of fire load and RFM 1 and RFM 2 respectively

not exceed several meters, which is absolutely unacceptable for the specific conditions of RFSS use.

The RFM control system shall provide hydraulic and traveltime parameters, including the stream spray angle and correction angle between the vision line of targeting detector and the elevation line of RFM, so that notwithstanding of the distance to fire area the diameter of FEA stream spot that contacts with the object to be protected shall be kept unchanged.

Coverage curves for high-angled or frontal streams depend on stream angle of attack θ to the protected surface.

In actual practice, RFM provides space protection in the horizontal plane within about 360°. Curve of coverage of the protected surface by RFM stream at the angle of attack $\theta = 90°$ is a circle, and in other cases — an ellipse, and the smaller is the angle of attack θ, the more elongated will be the ellipse.

The number of scanning lines is determined depending on the size of FEA spot that contacts with the surface to be protected and the height of area to be protected.

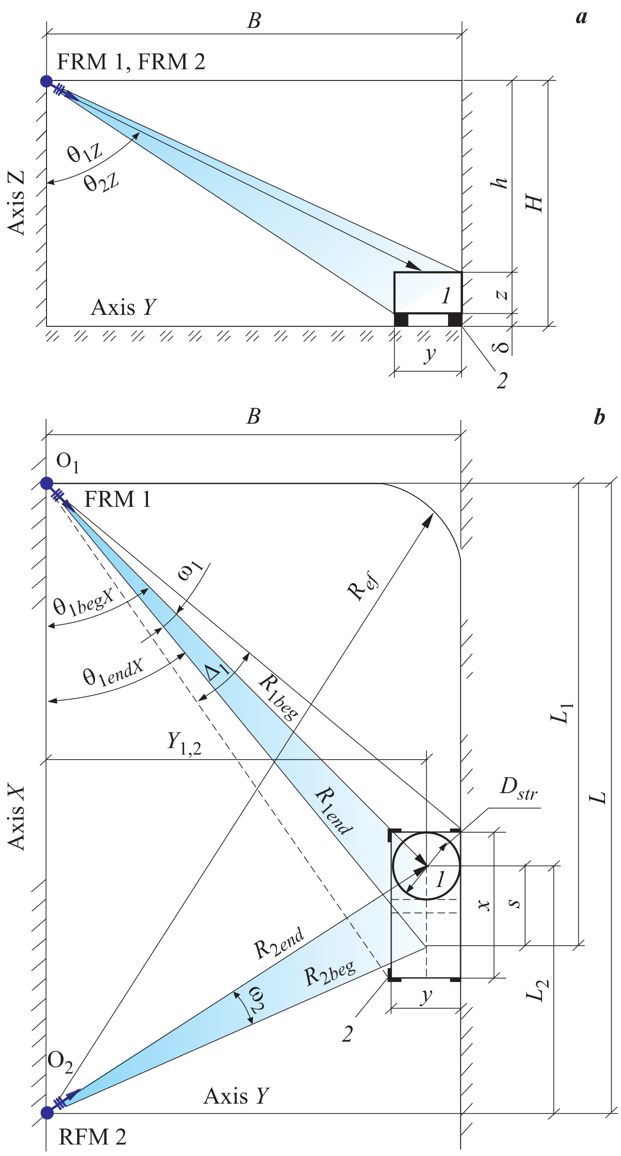

Fig. 14. RFMs positioning with respect to class A fire area if they are located at one side and in case of scanning streams: *a* — side view; *b* — top view; *1* — fire load; *2* — support; *B* — room width; *H* — height of RFM installation; *h* — distance between top surface of fire load along axis *Z* and RFM rotation axis; *L* — distance between RFMs along axis *X*; L_1, L_2 — distance between the center of top surface of fire load along *X* axis and RFM 1 and RFM 2 respectively; R_{1beg}, R_{1end}, R_{2beg}, R_{2end} — conventional axes of straight stream or FEA sprayed stream at the beginning and end of scanning cycle of RFM 1 and RFM 2 respectively; R_{ef} — efficient range of FEA stream; *x*, *y*, *z* — length, width and height of fire load; θ_{1Z}, θ_{2Z} — angle of attack of straight stream or FEA sprayed stream along the axis *Z* of RFM 1 and RFM 2 respectively; θ_{1X}, θ_{2X} — angle of attack of straight stream or FEA sprayed stream along the axis *X* of RFM 1 or RFM 2 respectively; ω_1, ω_2 — scanning angle range of RFM 1 and RFM 2 respectively; Δ_1 — actual coverage angle range for RFM 1; $Y_{1,2}$ — *Y* axial distance between center of fire load and RFM 1, RFM 2

Based on different RFM positioning schemes at Fig. 8–11*, the sighting of targeting detector to fire area and the elevation of RFM have different angular three-dimensional positioning. To simplify and reduce wordage

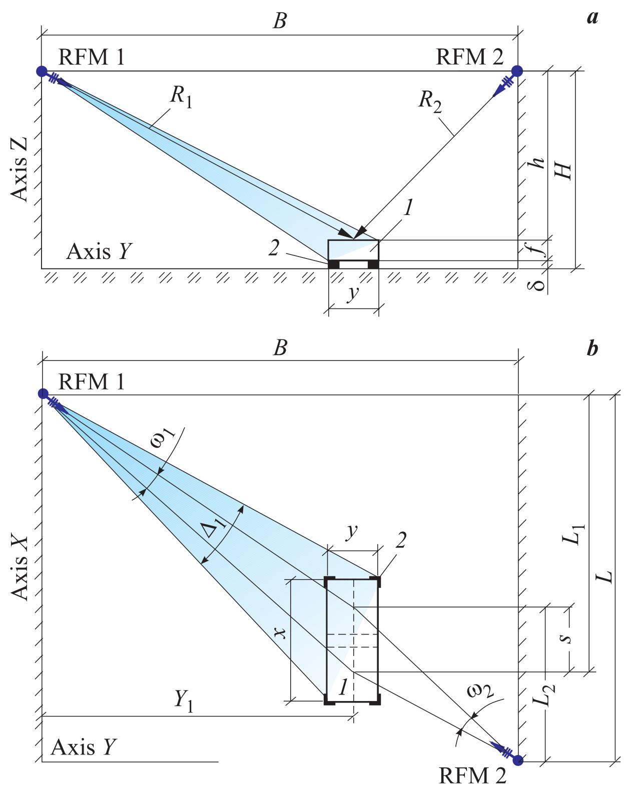

Fig. 15. RFMs positioning with respect to class B fire area (extended rectangular tray) if they are located at opposite sides and in case of scanning streams: *a* — side view; *b* — top view; *1* — fire load (extended rectangular tray); *2* — support; *B* — room width; *H* — height of RFM installation; *h* — distance between face of liquid fuel along axis *Z* and RFM rotation axis; L_1, L_2 — distance between the center of tray with liquid fuel and RFM 1 and RFM 2 respectively; R_{1beg}, R_{1end}, R_{2beg}, R_{2end} — conventional axes of straight stream or FEA sprayed stream at the beginning and end of scanning cycle of RFM 1 and RFM 2 respectively; Y_1 — distance between RFM 1 and center of fire load along axis *Y*; *f* — height of tray side walls; *x*, *y* — length and width of tray; ω_1, ω_2 — scanning angle range of RFM 1 and RFM 2 respectively; Δ_1 — actual coverage angle range for RFM 1

Based on the results of measurements of stream spot, the coverage both inside the circle and inside the ellipse is uneven. The enough concentrated area with satisfactory coverage intensity is located at a distance of about 90 % of the maximum range (the far drops). The distance to this area is considered to be effective range. Stream spot area where 70 % of the supplied water falls dawn is the efficient coverage area. When stream vibrating, oscillating, or scanning, the coverage becomes more uniform. The effective area of coverage spot shall be taken into account when programming coverage mode subject to stream range.

* See the beginning of this article: L. M. Meshman, V. A. Bylinkin, Yu. I. Gorban, M. Yu. Gorban, K. Yu. Fokicheva. Actual problems of navigation to the fire robotic trunks in robotic fire extinguishing system. Part 1. Background to the establishment of RFS and specific characteristics of the fire fighting RFM. *Pozharovzryvobezopasnost/Fire and Explosion Safety*, 2019, vol. 28, no. 3, pp. 70–88 (in Russian). DOI: 10.18322/PVB.2019.28.03.70-88.

of material, streams contact with surface of fire load is any further considered in one plane.

2. Operating programs for RFMs used for fire suppression with static streams

2.1. Static streams positioned to the front surface ($\theta \approx 90°$)

Maximum allowable fire area for static streams ($\theta \approx 90°$) is calculated based on circle area S_c, that is resulted from stream or sprayed FEA contact with object to be protected.

In this case, the RFM program targets monitor by one of the following ways, based on positioning inaccuracy angle α and the dead zone angle of targeting detector β:

- under flame edge so that the lower flame edge is entirely within the contact spot of stream and surface to be protected (Fig. 16,*a*);
- to flame center so that the area to be protected being in fire, is entirely within the contact spot of stream and surface to be protected (Fig. 16,*b*).

At the same time, in all cases, the RFM operating program provides the FEA stream targeting to the fire area by:

- analyzing FEA pressure and if it changes the program changes the ballistics with respect to the vertical targeting angle (elevation angle) of monitor outlet nozzle depending on the distance to fire area and FEA pressure;
- selecting the FEA spray angle depending on the distance from RFM to fire area.

In Fig. 16,*a* and 16,*b*, the range of coverage angles, with regard to FEA spreading in horizontal direction over the protected surface, is equal to actual range of coverage angles $\sigma = \Delta$. Let us assume that in this case the RFM program, taking into account the angle of positioning inaccuracy α and dead zone angle of targeting detector β, positions RFM to the axis of BB_1 flame and determines, depending on the distance to fire area, the required FEA stream diameter D_{str} at the moment of its contact with fire surface, wherein stream diameter is bigger than flame length, i. e. $D_{str} > L_{fl}$. When RFM targeting to fire area, its monitor can move not only in

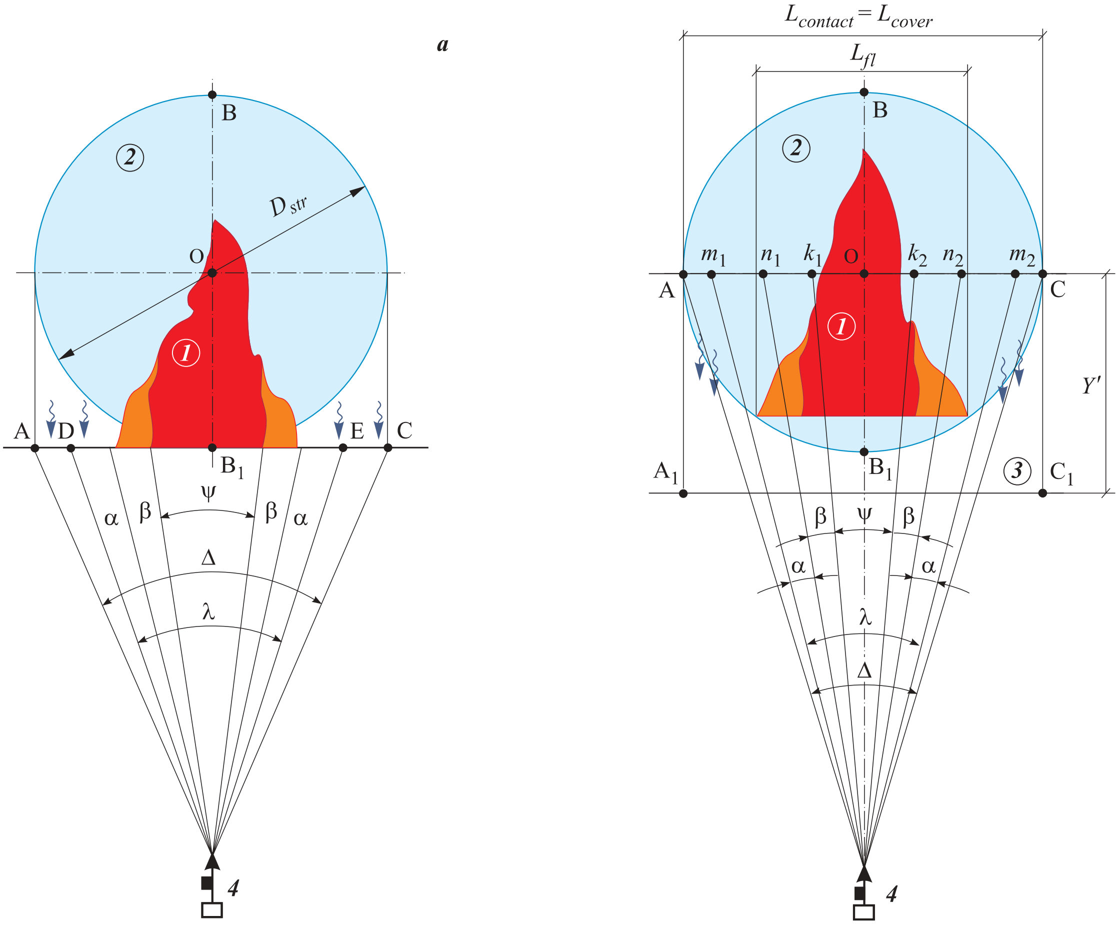

Fig. 16. Curve of frontal surface coverage with static stream with an angle of attack of $\theta \approx 90°$ during its targeting: *a* — under flame edge; *b* — to flame center; *1* — flame; *2* — coverage area at the moment of stream contact with surface to be protected; *3* — additional area covered due to FEA flowing down in vertical direction; *4* — RFM; D_{str} — stream diameter at the moment of its contact with the protected surface; $L_{contact} = L_{cover} = AC$ — the length of contact and coverage area when FEA contacts with protected surface; L_{fl} — flame length; Y' — is the distance along the Y axis to the center of the flame

horizontal direction — from left to right or right to left, but also simultaneously in vertical direction — from up to down or from down to up.

If stream is supposed to be sighted along the axis of registered BB_1 fire area and it is not beyond the area of stream contact with the ABC surface, and the angle λ is not bigger than angle Δ, then static frontal stream provides the fire extinguishing. In this case, the contact spot of stream and covered surface have the following parameters:

- contact spot:
  a) in angular coordinates (hereinafter: for simplicity of description angular coordinates was taken only along axis X):

$$\Delta \geq \lambda = \psi + 2\alpha + 2\beta; \qquad (1)$$

  b) in linear dimensions (hereinafter: if $R >> D_{str}$ (where R — stream operating range) we take curve area L to be straight):

$$L_{contact} = D_{str} = AC = 2R\,\mathrm{tg}\,(\Delta/2) \geq 2R\,\mathrm{tg}\,(\psi/2 + \alpha + \beta) \qquad (2a)$$

or $$L_{contact} \approx \pi\,\Delta R/180 \approx \Delta R/57.3; \qquad (2b)$$

  c) area

$$S_{contact} = \pi D_{str}^2/4 = 0.785 D_{str}^2; \qquad (3)$$

- coverage area:
  a) in angular coordinates:

$$\Delta \geq \lambda = \psi + 2\alpha + 2\beta; \qquad (4)$$

  b) in linear dimensions:

$$L_{cover} = D_{str} = AC = 2R\,\mathrm{tg}\,(\Delta/2) \geq 2R\,\mathrm{tg}\,(\psi/2 + \alpha + \beta) \qquad (5a)$$

or $$L_{cover} \approx \Delta R/57.3; \qquad (5b)$$

  c) coverage square area:

$$S_{cover} = S_{contact} \geq \frac{\pi D_{str}^2}{8} + Y' D_{str}^2 = \left(\frac{\pi}{8} + Y'\right) D_{str}^2. \qquad (6)$$

It is assumed that, firstly, coverage intensity in S_{cover} area is not lower than in $S_{contact}$ circle, since FEA after contact with the vertical surface flows down along the Y axis; secondly, intensity and uniformity of coverage are within $Y' \approx (1.0 \div 2.0)\, D_{str}$. When $Y' = 0.5 D_{str}$, i. e. with coverage area limited by height $BB_1 = D \sim D_{str}$, we have:

$$S_{cover} = S_{contact} \geq \frac{\pi D_{str}^2}{8} + 0.5 D_{str}^2 = \left(\frac{\pi}{8} + 0.5\right) D_{str}^2 \approx 0.89 D_{str}^2.$$

Whereby coverage intensity is within the limits of circle area of diameter D_{str} (see Fig. 16,*a*) and shall correspond to GOST R 51043–2002 and SP 5.13130.2009 [40]).

If fire area is beyond the contact spot of stream and surface S_{ABCB_1}, i. e. the angle λ is bigger than angle Δ, then conditions (4)–(6) are not fulfilled and the fire cannot be extinguished by static stream, so to extinguish fire it is necessary to increase stream diameter D_{str}, or use line scanning.

2.2. Static streams targeted at an angle to frontal surface (0 < θ < 90°)

For static streams targeted at an angle to frontal surface ($0 < \theta < 90°$), the maximum permissible fire area is initially estimated based on ellipse area S_e generated when stream or FEA sprayed stream contact with the object to be protected.

As in the previous case, the RFM program positions monitor by one of the following ways, based on positioning inaccuracy angle α and the dead zone angle of targeting detector β:

- under flame edge so that the lower flame edge is entirely within the contact spot of stream and surface to be protected (Fig. 17,*a*);
- to flame center so that the area to be protected being in fire, is in coverage area along FEA contact ellipse axis (alignment of vertical flame axis with contact ellipse small axis) (Fig. 17,*b*).

At the moment of contact between straight stream or FEA sprayed stream with a diameter D_{str} and burning area, there appear a contact area in the form of ellipse $S_{contact\,(ABCB_1A)}$, which provides the overlapping of fire area.

The smaller is the angle of attack θ, the larger is the area of ellipse $S_{contact\,(ABCB_1A)}$ and at a constant flow rate the less is coverage intensity. Since FEA stream will slide by inertia along coverage surface in the direction of its supply (along the X axis), the coverage intensity in the middle of ellipse will not change in a certain area of semi-ellipse BDB_1.

It is assumed that, in comparison with coverage intensity in the area of stream direct contact with surface, the coverage intensity in area located along the direction of FEA stream at a certain distance from the boundary of stream contact with covered surface at angle of attack θ from 0 to 90° varies from maximum to minimum, and vice versa, in a certain area located below the coverage line — from minimum to maximum (i. e., coverage intensity corresponding to intensity in contact area of stream and surface).

At a certain angle of attack θ, the length of additional coverage area CD may be in excess of positioning inaccuracy α_2 and the dead zone β_2 of targeting detector. In this case, the stream diameter D_{str} may even be taken somewhat less than flame width, therefore at a small angle of attack only the angle of targeting inaccuracy α_1 and dead zone angle β_1 of targeting detector can be considered.

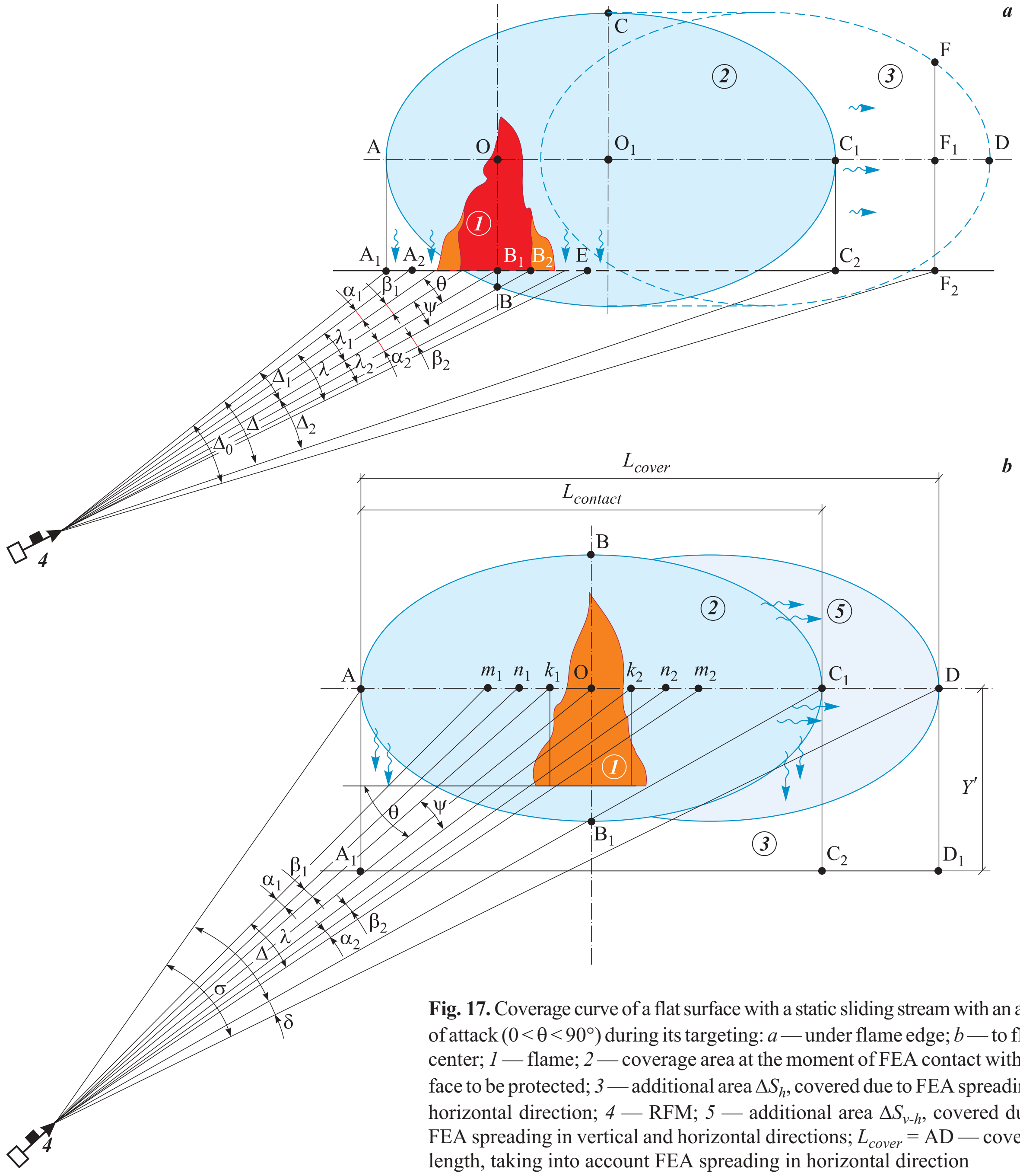

Fig. 17. Coverage curve of a flat surface with a static sliding stream with an angle of attack ($0 < \theta < 90°$) during its targeting: *a* — under flame edge; *b* — to flame center; *1* — flame; *2* — coverage area at the moment of FEA contact with surface to be protected; *3* — additional area ΔS_h, covered due to FEA spreading in horizontal direction; *4* — RFM; *5* — additional area $\Delta S_{v\text{-}h}$, covered due to FEA spreading in vertical and horizontal directions; L_{cover} = AD — coverage length, taking into account FEA spreading in horizontal direction

However, at higher angle of attack θ the area of stream contact spot with surface $ABCB_1A$ is smaller, the additional coverage area of $ABDB_1A$ is also reduced and more of FEA flows down in vertical plane. Therefore, at a high angle of attack angle of positioning inaccuracy shall be considered and dead zone angle of targeting detector on both sides of flame, i. e., both $(\alpha_1 + \beta_1)$ and $(\alpha_2 + \beta_2)$.

If stream is supposed to be sighted along the axis of registered flame and fire area is within area of stream contact with the $S_{contact} = ABCB_1A$ surface, and the angle λ is not bigger than angle Δ, then static stream with θ angle of attack to frontal surface provides the fire extinguishing. In this case (at $R >> D_{str}$), and let's say at a small angle of attack the contact spot of stream and surface at quasi-constant rate of coverage and coverage area have the following parameters:

- contact spot:
  a) in angular coordinates:
  at $\theta < 45°$:

$$\Delta \geq \lambda = (\psi + \alpha_1 + \beta_1); \quad (7a)$$

  at $\theta \geq 45°$:

$$\Delta \geq \lambda = (\psi + \alpha_1 + \beta_1 + \alpha_2 + \beta_2); \quad (7b)$$

  b) in linear dimensions:

$$L_{contact} = AC = D_{str} / \sin\theta; \quad (8)$$

c) coverage square area:

$$S_{contact} = \pi \cdot AC \cdot BB1/4 = \pi D_{str}^2 / 4 \cdot \sin\theta; \quad (9)$$

- coverage area:

a) in angular coordinates:

$$\sigma = \Delta + \delta; \quad (10)$$

b) in linear dimensions:

$$L_{cover} = AD = (AC + CD) D_{str} / \sin\theta; \quad (11a)$$

at $\theta < 45°$:

$$L_{cover} \approx (\Delta + \delta) R / 57.3 \geq \geq (\delta + \psi + \alpha_1 + \beta_1) R / 57.3; \quad (11b)$$

at $\theta \geq 45°$:

$$L_{cover} \approx (\Delta + \delta) R / 57.3 \geq \geq (\delta + \psi + \alpha_1 + \beta_1 + \alpha_2 + \beta_2) R / 57.3; \quad (11c)$$

c) coverage square area:

$$S_{cover} \approx S_{contact} + \Delta S_h + \Delta S_v = = 0.5 (S_{contact} + \Delta S_{hBDD_1}) + \Delta S_{vADD_1A_1}. \quad (12)$$

If fire area is beyond area $ABDB_1A$ and angle λ — bigger than angle σ, i. e. conditions (10)–(12) are not fulfilled, the fire cannot be extinguished by static stream. So to extinguish fire it is necessary to increase stream diameter D_{str} (as well as to increase flow rate to provide coverage intensity) or use line scanning (by increasing flow rate).

Similar rules are reasonable for static high-angled stream.

If the protected area is covered with static high-angled or frontal stream (without RFM scanning), calculation of RFM flow rate required to extinguish fire is simplified: coverage intensity and flow rate are taken according to GOST R 51043–2002 and SP 5 [40]. While also, the operating program shall provide quasi-constant area of FEA contact spot with the protected surface (regardless distance from RFM to the protected surface) by adjusting the stream opening angle.

RFM flow rate Q (l/m^2) for static frontal stream that is supplied at angle to frontal surface or high-angled stream shall be calculated as follows:

$$Q = KiS_{contact} / \sin\theta = KiS_{cover}, \quad (13)$$

where K — flow rate ratio; $K = 1{,}2 \div 1{,}3$;

i — rated coverage intensity according to SP 5 [40], l/(sec·m^2).

Contact spot area of stream with surface in a form of full-circle at $\theta = 90°$ shall be calculated as $S_{contact.c} = \pi D_{str}^2 / 4$, in a form of ellipse at $\theta \neq 90°$ — as $S_{contact.e} = \pi D_{str}^2 / (4 \sin\theta)$.

As much as S_{cover} increases when compared to $S_{contact}$, as much FEA flow rate shall be increased. It is necessary to take this factor into account when designing the RFSS and when determining the distance between RFM that are part of RFSS, and try to adjust the angle of attack θ of each RFM as high as possible.

Conclusions

In practice, static streams are not often used in RFSS. However, the concepts introduced and the calculations given are essential for scanning streams that are widely used in RFSS directly for fire extinguishing, and they will be mentioned in the next final chapter.

To be continued

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