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Investigation of the Conditions for the Use of Material with the Shape Memory Effect in the Sprinklers

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Abstract. The expediency of using nitinol, which is a material with the shape memory effect (SME), as a sensitive element (SE) of a sprinkler has been substantiated. The influence of various parameters on the SE dimensions is analyzed and it is shown that the response time of an element made of a material with the shape memory effect depends on the dimensions of the fixing device (FD) (the diameter of the glass bulb and its thickness). Calculations have shown that the use of the material minimizes the response time of the sprinkler. It is shown that the response time depends on the voltage (or current) in the electrical network, on the size of the fixing device, the cross-sectional radius of the actuator and the critical temperature at which the actuator is triggered.

1. Introduction and literature review

One of the achievements of materials science, which have found application in fire engineering, is the discovery of the shape memory effects. The interest of scientists in studying the nature and mechanisms of SMF is explained by the desire to deepen the fundamental understanding of the inelastic behavior of solids. [1]. The practical application of research is due to the possibility of creating devices and elements with new functionality. [2-4]. Among alloys with SMF, the most studied is nitinol. It is a compound of nickel (55%) and titanium (45%). The melting point of the alloy is 1240-1310 ^{0}C, the density is 6,45 g/sm^3. The positive qualities of nitinol include: resistance to corrosion; strength; the ability to memorize and restore the form; absorption of vibration energy; low level of deformation; high elasticity; the ability to adjust the temperature to change the form. These characteristics make the material almost ideal for use as a SE or an actuator for a sprinkler. The negative qualities that limit the introduction of the material into widespread use include the high cost and insufficient manufacturability of production. A promising area of application of new alloys in fire extinguishing systems is the creation of a hybrid fixing device, which will combine the functions of locking, sensitive and actuating elements. These are exactly the qualities that are necessary to minimize the response time of the sprinkler and the introduction of the extinguishing agent into the fire.

A sprinkler is a sophisticated device designed to detect and extinguish a fire. Obviously, the sooner a fire is detected, the less damage will be incurred. The principle of operation of sprinklers is based on the ability to respond to the thermal factor of a fire. Triggering occurs when the temperature-sensitive element heats up to a certain temperature. The lower this temperature, the faster the sprinkler will open. However, if the temperature is too low, there is a high probability of false opening. This can happen, for example, under the influence of energy-intensive equipment located in the room.

The choice of the optimal opening temperature of the sprinkler is an important task. It is known that an increase in the difference between the nominal response temperature and the maximum ambient temperature helps to reduce the likelihood of spontaneous opening of the device. This difference must be at least 20^0C. But the greater this difference, the longer the time of detection of ignition. Thus, minimizing the response time of a sprinkler under specific operating conditions remains an urgent problem. One solution is to use material with shape memory effect (nitinol) to create a sprinkler focused on fast response.

Analysis of literature sources [5-8] showed that among the priority areas for reducing the response time of sprinklers, two have gained the most popularity: the choice of material and the form of its components or the choice of the installation site and the number of sprinklers. The greatest effect can be provided by the implementation of the first approach or their combination. The way to select the material and form of the sprinkler components is ensured by minimizing the weight and size characteristics and using electrical or chemical action to open the sprinkler outlet. The paper proposes the use of nitinol (material with the shape memory effect) for a functional device that combines the functions of a sensitive and an actuator, which will reduce the functional redundancy of the structure, while leaving the minimum weight and size characteristics, which is important when using this material. The aim of the work is to analyze the feasibility of using nitinol as a sensitive element of a sprinkler, to determine the parameters that have the greatest influence on the size of such a sensitive element, to build a model of the response time of a sprinkler with elements made of material with the shape memory effect.

2. Construction of the model and its analysis

The subject of research is a sprinkler sensing element made of material with the shape memory effect. The research methodology is based on the formulas proposed in [9-10], methods and assumptions proposed in [11-12]. The preparation and conduct of the experiment was carried out in accordance with the theory of experiment planning [13]. The numerical implementation of the formulas is performed in the program Maple. The verification of the adequacy of the results obtained was carried out according to the Fisher criterion [13].

In accordance with the principle of construction of a sprinkler, its opening occurs when the sensitive element is destroyed. As a rule, SE is destroyed when the temperature reaches a threshold value. The distribution of temperatures in the SE of a sprinkler with a change in the ambient temperature is described by the equation of thermal conductivity:

$$\rho c \frac{\partial t}{\partial \tau} = \mathrm{div}(\lambda \, \mathrm{grad} t), \tag{1}$$

where ρ - is the density of the SE material, kg/m^3; c - specific heat of the material SE, J/(kg×K); t (x,y,z,τ) - temperature of points (x,y,z) SE, K; τ - moment of time, c; λ (x,y,z,τ) - coefficient of thermal conductivity of the SE material at the point (x,y,z), W/(m×K), with the initial condition (for τ=0):

$$t(x, y, z, \tau) = t_0, \tag{2}$$

where t_0 - initial value of SE temperature, K.

Boundary condition of the third kind (expresses the continuity of the heat flux at the boundary)

$$\lambda \frac{\partial t}{\partial n}\bigg|_b = \alpha (t_a - t)\big|_b, \tag{3}$$

where t_a (x,y,z,τ) - ambient temperature near the surface of the SE, K;

α - the heat transfer coefficient, which for forced convection depends on the similarity criteria of Reynolds (Re) and Prandtl (Pr) and lies within the limits 50 - 250 W/(m^2×K) [9]. Let us average expression (1) over the SE volume V. If ρ and c do not depend on coordinates, then the left-hand side of (1) takes the form

$$\rho c \frac{d\bar{t}}{d\tau}, \qquad (4)$$

where $\bar{t}$ - the average over the volume V SE value of temperature, K, which is determined by the ratio

$$\bar{t}(\tau) \equiv \frac{1}{V} \int_V dV\, t(x,y,z,\tau). \qquad (5)$$

The right-hand side of the averaged expression has the form of an integral over the SE volume

$$\frac{1}{V} \int_V dV\, \mathrm{div}(\lambda\, \mathrm{grad}\, t(x,y,z,\tau)) \cdot \qquad (6)$$

Transforming (6) according to the Ostrogradsky-Gauss theorem and using the boundary condition (3), we write (6) in the form of an integral over the surface of the SE

$$\frac{1}{V} \oint_S dS_n \alpha(t_{ВН} - t(x,y,z,\tau)) \cdot \qquad (7)$$

The temperature value on the SE surface can be associated with its average value

$$t(x,y,z,\tau) \approx \bar{t}(\tau) + (\vec{r} - \bar{\vec{r}}) \cdot \mathrm{grad}\, t, \qquad (8)$$

where $\vec{r}$ и $\bar{\vec{r}}$ - respectively, the radius vectors of the point (x, y, z) of the surface and the nearest point of the SE, in which the temperature is equal to its mean value $t(\bar{x}, \bar{y}, \bar{z}, \tau) = \bar{t}(\tau)$.

Let us estimate the second term on the right-hand side of (8). The value $|\vec{r} - \bar{\vec{r}}|$ is less than the cross-sectional diameter of the SE d. The grad t value is estimated using the boundary condition (3). Thus $\left|(\vec{r}-\bar{\vec{r}})\mathrm{grad}t\right| < \left|d\frac{\alpha}{\lambda}(t_a - \bar{t})\right| = Bi \cdot |t_a - \bar{t}|$, where Bi - Biot's dimensionless criterion, for this problem corresponds to the following value $Bi = \frac{\alpha}{\lambda} d << 1$.

The latter estimate shows that, with an accuracy of the order of Bi in expression (8) and integral (7), one can replace the temperature on the SE surface with its average volume value.

As a result, expression (1) takes the form

$$\rho c \frac{d\bar{t}(\tau)}{d\tau} = \frac{1}{V} \oint_S dS_n\, \alpha(x,y,z)\left[t_{ВН}(x,y,z,\tau) - \bar{t}(\tau)\right] \cdot \qquad (9)$$

Let us introduce the notation:

$$\overline{\alpha t_a}(\tau) = \frac{1}{S} \oint_S dS_n \alpha(x,y,z) t_a(x,y,z,\tau); \qquad (10)$$

$$\bar{\alpha} \equiv \frac{1}{S} \oint_S dS_n\, \alpha(x,y,z), \qquad (11)$$

where S - surface area of SE, m^2; $\overline{\alpha t_a}(\tau)$ and $\bar{\alpha}$ - mean the values αt and α averaged over the surface of SE, respectively.

Then expression (9) taking into account (10) and (11) takes the form

$$\rho \frac{d\bar{t}(\tau)}{d\tau} = \frac{S\bar{\alpha}}{V}\left[\frac{\overline{\alpha t_a}(\tau)}{\bar{\alpha}} - \bar{t}(\tau)\right]. \quad (12)$$

Introducing a value inverse to the time constant of the SE β, s^{-1}

$$\beta \equiv \frac{\bar{\alpha} S}{V \rho c}, \quad (13)$$

and effective ambient temperature t_a^{ef}

$$t_a^{ef} \equiv \frac{\overline{\alpha t_a}}{\bar{\alpha}} \equiv \frac{\oint_S dS_n \alpha t_a}{\oint_S dS_n \alpha}, \quad (14)$$

obtain (12) in the form

$$\frac{d\bar{t}}{d\tau} = \beta\left[t_a^{ef} - \bar{t}(\tau)\right]. \quad (15)$$

Neglecting the dependence of β and t_a^{ef} on $\bar{t}$, solve (15) and obtain

$$\bar{t}(\tau) = t_0 e^{-\beta\tau} + \int_0^{\tau} \beta t_a^{ef}(\tau') e^{-\beta(\tau-\tau')} d\tau'. \quad (16)$$

To simplify the notation, further accept $\bar{t}(\tau) \equiv t(\tau)$ and $t_a^{ef} \equiv t_a$.

Analyzing the change in the temperature of the SE in time (16), taking into account (13), we can conclude that the opening time of the sprinkler is in direct proportion to the size of the SE. The response time of a standard sprinkler is a function of the similarity criteria Nu and Re, when calculating which the value of the characteristic size of the SE δ is determined based on the fact that the width of the fusible lock is $b = 0{,}022\,m$, and its length $l = 0{,}036\,m$.

If a material with SME is used as a SE, and the SE form is taken in the form of a ring placed on a glass cylinder that plays the role of a FD, then the SE dimensions also depend on the wall thickness of the FD, the value of which, in turn, depends on the water pressure in front of the sprinkler.

The dimensions of FD depend on the water pressure in front of the spray arm, and the following condition must be met:

$$\sigma_c \geq \frac{PS_p}{S_{FD}}, \quad (17)$$

where σ_c - stress compressive of material FD, at which it deforms, which will entail partial or complete opening of the sprinkler outlet, MPa; P - water pressure in the pipeline before the sprinkler, Pa; S_p - cross-sectional area of the pipeline in front of the sprinkler, m^2; S_{FD} - contact area affected by water pressure, m^2, which for a fixing device in the form of a glass cylinder is determined:

$$S_{FD} = \pi R_o^2 - \pi r_i^2, \quad (18)$$

where R_o – outer radius FD, m; r_i – inner radius FD, m.

Solving together (17) and (18), determine the dependence of the dimensions of the FD on the water pressure in the pipeline

$$R_o^2 - r_i^2 \geq \frac{PS_p}{\sigma_c}. \tag{19}$$

Using the relationship between the radiuses of the FD and the thickness of its walls $h_{FD} = R_o - r_i$, where h_{FD} - wall thickness of FD; as well as the concept of the mean radius of the FD R_{FD} ($R_{FD} = R_o - 0{,}5h_{FD}$);a graphical representation of the dependency solution was obtained (17)–(19) (fig. 1). Analyzing the calculation results (fig. 1), we can conclude that for different values of the radius of the FD and the water pressure in front of the sprinkler, the required minimum dimensions of the wall thickness of the FD are much less than those made in the production. Consequently, the effect of water pressure in front of the sprinkler on the dimensions of the walls of FD can be neglected. The value of the minimum cross-sectional radius of the ring depends on how much force is required for the ring when changing its form in order for the glass cylinder to distroyed and the sprinkler to opened.
The condition for the contact of a ring made of material with SME and FD (glass cylinder) can be written in the following form [14]

$$R_o - \omega_c = R_{in}^r + \delta_r, \tag{20}$$

where ω_c - displacement FD, m; R_{in}^r - inner radius of a ring made of material with SME, m; δ_r - displacement of a ring made of material with SME, m.

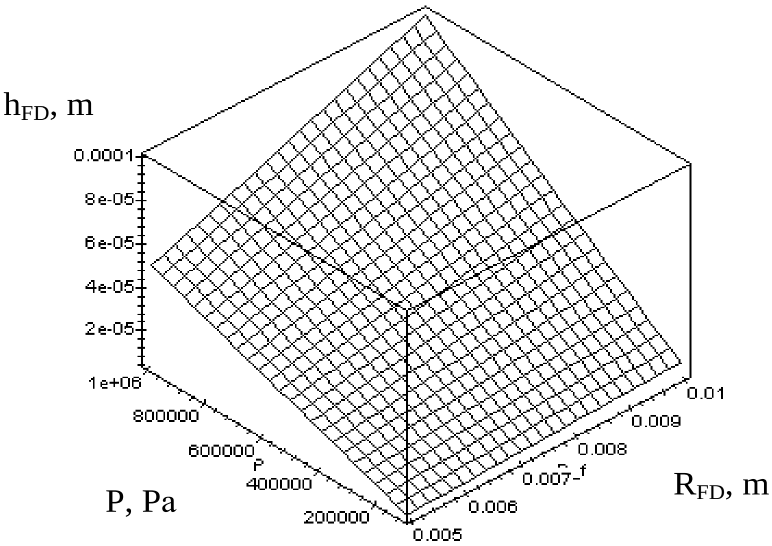


Figure 1. Determination of the minimum wall thickness (h_{FD}) depending on the pressure (P) in front of the sprinkler and the mean radius of the FD (R_{FD})

$$\omega_c = \frac{qR_{FD}^2\beta}{2Eh_{FD}}, \tag{21}$$

where q - strength of contact, N/m; R_{FD} – mean radius FD, m;
E - modulus of elasticity of the material of FD, N/m^2;
β - indicator related to size and material of FD

$$\beta = \sqrt[4]{\frac{3(1-\nu^2)}{R_{FD}^2 h_{FD}^2}}, \text{ m}^{-1},$$

where ν - Poisson's ratio of material of FD.

$$\delta_r = \frac{qR_{in}^r R_r}{S_r E_r}, \tag{22}$$

where R_{in}^r - inner radius of a ring made of material with SME, m; R_r - mean radius of a ring made of material with SME, m, $R_r = R_{in}^r + r$; r - cross-section radius of a ring made of material with SME, m; S_r - cross-sectional area of a ring made of material with SME, m^2; E_r - modulus of elasticity of a ring made of material with SME, N/m^2.
Knowing that the outer radius of the FD R_{FD} should be equal to the inner radius of the ring made of material with SME R_{in}^r, can write down the condition for the destruction of the FD

$$\frac{3q}{2\beta h_{FD}^2} = \sigma_c, \tag{23}$$

while maintaining the strength of the ring made of material with SME, which is determined

$$\frac{qR_r}{S_r} < \sigma_r, \tag{24}$$

where σ_r - permissible stress compressive of the ring made of material with SME, MPa.
It is known that the shape memory effect can be accompanied by a significant work of the sample, which determines the use of this material in sprinklers. For TiNi, work A can reach 208 kJ/m^3, while the deformation of the sample is 7%. Consequently, the correction factor must be taken within 20%. Then, we can assume that the ring is capable of creating a strength q, which depends on r as follows

$$q = \frac{F}{2\pi(R_{FD} + 0.5h_{FD})}, \tag{25}$$

where F – force that must be created of the ring made of material with SME to obtain strength of contact q, N:

$$F = \frac{AV}{l} = \frac{2A\pi^2(\frac{h_{FD}}{2} + R_{FD} + r)r^2}{l}, \tag{26}$$

where $l = 0{,}07\ (h_{FD}/2 + R_{FD} + r)$ - resizing the ring when it fires, m.
Solving expressions (23), (25) and (26) together, we can determine the value of the characteristic minimum size of a SE made of material with SME (radius of the cross-section of the ring). In fig. 2 shows a graphical representation of the dependence of the obtained value on the average radius of the FD R_{FD} and the wall thickness of the FD h_{FD}.
As seen from fig. 1 and fig. 2, even at high values of water pressure in front of the sprinkler, a small thickness wall of the FD is required. Based on the existing assortment of glass products used in sprinklers, as well as to ensure reliability requirements, when determining the minimum cross-sectional radius of the ring, it is advisable to take the wall thickness of the FD device within (0.0001÷0.005) m.
Thus, when constructing a sprinkler focused on quick response, the dimensions of the SE responsible for opening should be kept to a minimum. If the SE performs the functions of a fixing and locking device, then the possibility of reducing its size is limited, which follows from the performed analysis. This means that the functional tasks of the SE should only be the detection of ignition, and the functions of the actuating device should be performed by a separate element, which at the same time can create sufficient force to open the outlet in a minimum time.

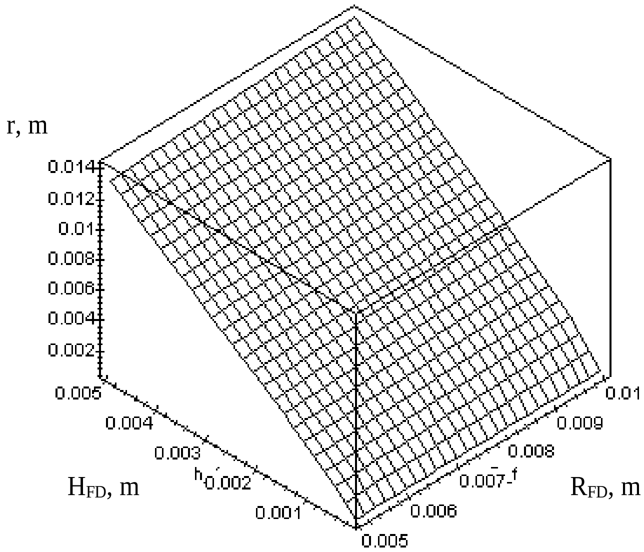


Figure 2. Determination of the minimum radius (r) of the cross-section of a ring with an SME (SE) depending on the wall thickness of the FD (h_{FD}) and the average radius of the FD (R_{FD})

To determine the response time of a sprinkler with a sensitive element made of a material with SME, an experimental study was carried out depending on three factors: the response temperature, the time constant, and the rate of temperature change. In this case, we take an additional value, which for a two-level experiment is equal to α=1.682, the total number of experiments is N=20, the number of observations in the center of the plan is n_0=6 [13]. Information on the levels of changes of the parameters is given in the table 1.

Table 1. Factor level changes

Variation interval and factor level	The rate of change in the temperature of the medium A_t (K/s)			Time constant SE T (s)	Response threshold SE tcr (K)
Zero level x_i=0	0.075	0.3	0.85	80	343
Variation interval δ_i	0.015	0.12	0.2	40	10
Lower level x_i=-1	0.06	0.18	0.65	40	333
Upper level x_i=+1	0.09	0.42	1.05	120	353
Additional points: x_i=-1,682	0.05	0.1	0.5	12.7	326
x_i=+1,682	0.1	0.5	1.2	147.3	360
Code designation	x_1			x_2	x_3

Processing the results of the experiment made it possible to obtain the regression equations:
- for the rate of change in the temperature of the medium A_t = (0.05÷0.1), K/s:

$$y_1 = 752.2 - 141.2x_1 + 39.9x_2 + 136.7x_3 + 27.1x_1^2 - 27.4x_1x_3; \qquad (27)$$

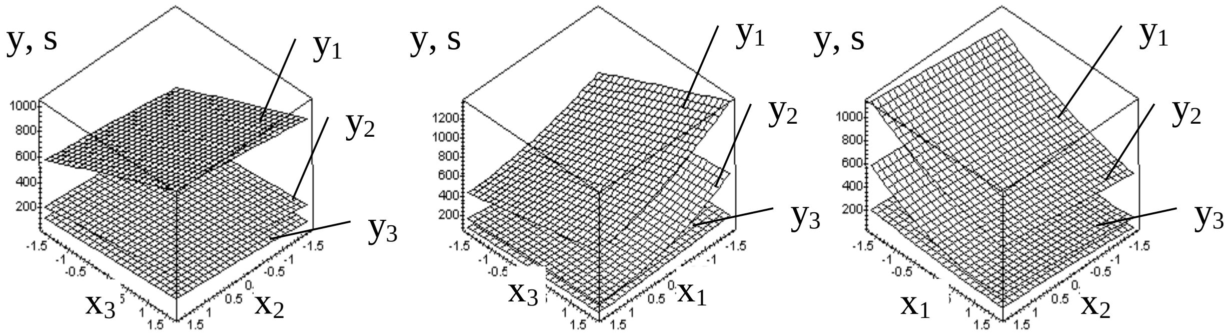
- for the rate of change in the temperature of the medium A_t = (0.1÷0.5), K/s:

$$y_2 = 242.1 - 98.6x_1 + 34x_2 + 38.8x_3 + 43.9x_1^2; \quad (28)$$

- for the rate of change in the temperature of the medium A_t = (0.5÷1.2), K/s:

$$y_3 = 122.2 - 20.3x_1 + 24.3x_2 + 15.7x_3. \quad (29)$$

The verification of the adequacy of the obtained models (27)-(29) was carried out according to the Fisher criterion [13]. The general view of dependences (39)-(41) for factors at different levels is shown in fig. 3.



a) b) c)

Figure 3. Dependence of the sprinkler response time with the maximum SE: a) on the threshold temperature of its operation and the SE time constant; b) on the rate of change of the ambient temperature and the threshold value of the response temperature; c) on the time constant of the SE and the rate of change in the ambient temperature.

As can be seen from Fig. 3, at the response threshold (326-360) K, the time constant (12-150) s and the rate of change in the temperature of the medium (0.05-1.2) K/s, the response time of the sprinkler having the maximum thermal SE, is in the range (60÷1200) s. For modern sprinklers, which have a glass flask as a shut-off device, the response time is in the range (200-270) s, while the sprinkler response time was determined under the condition that sprinkler was placed in a thermostat at an ambient temperature of 30±2 K is higher than the temperature of destruction of the thermal lock i.e., the time required to reach a certain temperature of the medium is not included in the given data. If we determine the response time of a modern sprinkler, which is under the same heat transfer conditions as the sprinkler under consideration, it turns out that the response time of a sprinkler with a thermal maximum SE, made from a material with SME, is less than the response time of a similar sprinkler by more than 3 times, or is in the same time interval.

3. Conclusions

The article examines the possibility of using a material with the shape memory effect to create sensitive elements of sprinklers, which will minimize their response time. The influence of various parameters on the SE dimensions is analyzed and it is shown that the response time of the SME element depends on the dimensions of the fixing device (the diameter of the glass bulb and the thickness of its walls). Based on the existing range of glass products used in sprinklers, as well as to ensure reliability requirements, when determining the minimum cross-sectional radius of the ring, it is advisable to take the FD wall thickness within (0.0001÷0.005) m. A model of the response time of an actuator made of a material with SME is obtained. It is shown that the response time depends on the voltage (or current) in the electrical network, on the dimensions of the control unit, the radius of the cross-section of the actuator and the critical temperature at which the actuator is actuated. Since an SME material is capable of «memory» at certain temperatures, its threshold should be set in the same way as for a sprinkler with thermal lock.

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