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IMPROVING THE THERMOSTATIC STEAM TRAP CHARACTERISTICS USING SPRING ELEMENTS WITH THE SHAPE MEMORY EFFECT

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The object of research is the deformation-force characteristics of spring elements of thermostatic steam traps with the shape memory effect.

The research solves the problem related to the imperfection of the design of steam traps controlling elements and their high inertia.

Experimental studies on the impact of the spring force elements cooling rate on the deformation-force characteristics were conducted. Experimental studies showed that the significant impact of the spring force elements cooling rate on the deformation-force characteristics is observed exceptionally under the deformation mode at a temperature $t \leq M_f$. Based on the results of the experiments, it was found that decreasing the cooling rate from 66.7 to 0.013 °C/s has a positive effect on the spring element deformation-force characteristics.

Distinctive feature of the work is the study of winding pitch and thermal force cycling impact on the deformation-force characteristics of spring elements. It was found that using thermal force cycling makes it possible to reduce the force required for complete compression of the spring element by 60 %. Intensive decrease in the force required for the complete compression of the spring elements occurs during the first 100 thermal force cycles.

The rational method for spring elements heat treatment has been given. It is based on the next steps: heating to a temperature of 400–500 °C for 1 hour; exposure at this temperature for an hour; cooling with rate 0.013 °C/s, the number of thermal force cycles is at least 100 with a winding pitch of $8 \cdot 10^{-3}$ m. Based on research results, an improved design of thermostatic steam trap with controlling element in the form of cylindrical compression spring made of the VSP-1 alloy based on nitinol has been presented

Keywords: steam trap, spring element, shape memory effect, inertia, thermal force cycling

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1. Introduction

The purpose of the steam trap is to remove condensate, air, and other non-condensable gases from the steam system, while preventing steam from escaping. A steam trap is an important part of any steam system. It is an important link between the fresh steam and the condensate system, keeping the steam in the process for maximum heat utilization, but releasing the condensate and non-condensable gases at appropriate time.

The size of the steam trap is determined by the conditions of the system and such process parameters as maximum pressure of steam and condensate, temperature, flow rate, condition of process control by temperature. All steam traps are categorized according to the international standard ISO 6704:1982.

The use of steam traps in heating installations makes it possible to significantly save money; however, every year the amount of savings decreases due to the need for repair or replacement, as well as calibration. In [1], it is noted that after a year of operation, the decrease in the efficiency of the installation can reach 3.2 %.

Steam traps are subject to a number of requirements, the main of which are efficiency (minimum steam loss), high durability, reliability and simplicity of design, resistance to corrosion, erosion, and cavitation. None of the currently used types of steam traps, which differ in the principle of operation and design, fully satisfy the basic requirements for them.

The most common causes of steam trap failure are outlined in [2]. A common type of failure of steam traps is a violation of hermeticity, which leads to steam loss. This can increase operating costs up to USD 50,000 per year and even lead to degradation of the technological system [3]. In particular, in work [4] it is noted that due to steam losses in steam traps and their maintenance, the annual costs were approximately USD 3580 per steam trap. Thus, durability and reliability of operation are the most important characteristics of the steam trap. Since the durability and reliability of steam traps are predetermined by the deformation and strength characteristics of spring elements, our study is relevant.

2. Literature review and problem statement

Papers [5, 6] report the results of studying the effect of thermal-force cycling (TFC) on the thermoelastic properties of springs with a shape memory effect (SME). The method of differential scanning calorimetry was used to study the structure of the spring material. Studies have shown that a change in critical transformation temperatures was observed in the springs, but they stabilized after the 25 °C cycle. It was also found that spring samples processed at 500 °C were more ductile compared to samples processed at 600 °C. It is important to note that all calorimetric studies were performed at a cooling rate of 10 °C/min. However, there is no data in the cited works regarding the possibility of using the results for other cooling rates and in general the influence of the cooling rate on the deformation and strength characteristics of spring elements.

In study [7], a differential actuator with one degree of freedom was developed using springs with a shape memory effect as internal actuators. The peculiarity of this drive is the simultaneous adjustment of stiffness and position. The research was conducted on an SME spring made of wire with a diameter of 0.75 mm. The dependence of the drive stiffness change on the force generated in the spring due to the shape memory effect was obtained experimentally. However, there is no information in the work about the possibility of using the results for spring elements of a larger diameter, which are used in steam traps.

Works [8, 9] report the results of research and development of a low-temperature thermostat, which contains a spring element with SME based on NiTiFe alloy. This regulator is able to provide heat exchange between two tanks at different temperatures. The spring element in the regulator is subject to R-phase conversion, which is associated with a small hysteresis (typically 1–2 °C) and gives the advantage of precise control over a given temperature range. The samples were studied at a temperature from 25 °C to –100 °C with a cooling rate of 0.33 °C/s in a nitrogen atmosphere. However, the limited low-temperature range in which the research was carried out excludes the possibility of using the obtained data in other designs of regulators with SME springs.

In paper [10], tension and compression springs with SME were investigated to test the proposed hysteresis model. Both types of springs were made using nitinol. The springs had the following parameters: diameter 0.5 and 1 mm, average diameter of the coil 5 mm and 10 mm, number of turns 28 and 11. The springs were heated by a slowly increasing constant electric current from 25 °C to 100 °C and cooled again to 25 °C. As a result of experimental studies, electro-thermomechanical characteristics of springs were established. Special software for designing SME springs has also been developed. However, the results need to be verified for springs with other geometric characteristics and processing modes.

In [11], the fatigue of Ni-Ti springs with SME, which are used to activate flow valves, was investigated. The diameter of the studied spring was 0.89 mm. Heat treatment of the studied springs from SME consisted of homogenization for 24 hours at a temperature of 500 °C, followed by quenching in water at 25 °C. According to the research results, it was established that at a load of 270 MPa, after $1.2 \cdot 10^6$ cycles, changes in the structure of the material are observed, which bear signs of functional fatigue. However, there are no data in the work regarding the influence of the technique of thermal treatment of springs on the deformation and strength characteristics.

Work [12] reports the results of research on ensuring the stabilization of the characteristics of spring elements and the formation of optimized parameters of the shape memory effect due to preliminary heat treatment and subsequent thermal-force cycling. On the basis of experimental data, approximating dependences were obtained, which make it possible to evaluate the changes in the deformation-force characteristics of spring elements in the process of thermo-force cycling, depending on the number of cycles and the deformation of the guidance. However, the cited work lacks data on the geometric dimensions of the investigated spring elements and temperature regimes of processing.

Our review of the literature showed that the existing technological solutions mainly focus on the production of spring force elements from SME thermostats, which work under different operating conditions compared to the operating conditions of steam traps. Therefore, it is necessary to conduct studies on the influence of the technique of heat treatment of springs and their geometric characteristics on the deformation and strength characteristics of spring force elements in the designs of steam traps.

3. The aim and objectives of the study

The purpose of our work is to devise rational technological solutions for the manufacture of a steam trap using materials with a shape memory effect.

To achieve the goal, the following tasks must be completed:

– to conduct experimental studies on the influence of the cooling rate of the force elements of the spring on the deformation and force characteristics;

– to conduct experimental studies on the influence of the winding step and thermal-force cycling on the deformation-strength characteristics of spring elements with the shape memory effect;

– to improve the design of the steam trap.

4. The study materials and methods

The object of the study is the deformation and strength characteristics of the spring elements of thermostatic steam traps with the shape memory effect. The subject of research is the technology of making steam traps.

Heat treatment of spring elements includes the following components: heating to a certain temperature, holding at this temperature, and subsequent cooling at a certain speed, as well as thermal-force cycling.

In the course of the study, a hypothesis was put forward that the implementation of a thermopower drive in the form of springs based on materials with a shape memory effect would reduce steam losses and increase the service life of steam traps.

As part of the study, the following assumptions and simplifications were accepted:

– it was believed that the impurities contained in the VSP-1 alloy based on nitinol do not have a significant effect on the deformation and strength characteristics;

– the research was carried out for the lifting angles of the spring coils from 14° to 22°;

– the maximum force applied to the elastic elements did not exceed 100 N.

Our review of the literature [5, 6] showed that the rational temperature range for the endurance of spring elements with SME ranges from 400–500 °C. In the studies, heating was carried out to a temperature of 420 °C. The duration of the periods of heating the samples to this temperature and holding them at this temperature in the furnace was 1 hour. This time is taken on the basis of studies for springs of similar size given in [13].

In our studies, the cooling rate of samples after heat treatment varied from 0.013 to 66.7 °C/s. The number of thermal-force cycling cycles ranged from 0 to 1000 cycles.

Experimental studies on the influence of the speed of cooling of spring force elements and the number of TFC cycles on the deformation and strength characteristics were carried out under laboratory conditions.

The VSP-1 structural alloy based on nitinol was used as the spring material. The temperature intervals of phase transformations of this alloy are quite acceptable for thermostatic steam traps. Direct martensitic transformation begins at M_s=60–80 °C and ends at M_f=30–50 °C. The reverse martensitic transformation begins at A_s=80–90 °C and ends at A_f=85–115 °C.

The research was carried out on spring force elements made of wire of one fuse with a diameter of $d=2\cdot10^{-3}$ m. The wire was wound on mandrels with a step from $5\cdot10^{-3}$ to $8\cdot10^{-3}$ m, with a winding diameter of 2*d*. Then it was rigidly fixed in all degrees of freedom.

Heat treatment of springs was carried out in a muffle furnace equipped with a thermostat. The air temperature inside the furnace was determined by a TL-4 type thermometer with a division value of 1 °C.

The duration of periods of heating, holding at a constant temperature in the furnace, and the duration of cooling of the samples were recorded using a stopwatch with an absolute error of ±0.2 s. The air temperature was controlled by a TL-4 type laboratory thermometer with a division value of 0.1 °C.

The deformation-force characteristics of the spring elements were determined on an experimental setup consisting of a measuring section and a thermostat. The measuring section contains a dynamometer and a device for installing a spring between the movable and stationary supports. The thermostat contains an electric heater with a temperature regulator and a contact thermometer. The temperature of the liquid in the thermostat was controlled by a TL-4 type laboratory thermometer with a division value of 0.1 °C.

The inertia of the spring elements is determined by their heating time, which leads to the recovery of the shape memory ($t\geq A_f$). Experiments were performed with spring elements made of VSP-1 alloy with a wire diameter of $2\cdot10^{-3}$ m, the number of turns from 4 to 12, and a winding diameter of 2*d*. The elemental composition of the VSP-1 alloy is given in Table 1.

The springs were immersed in a thermostat with liquid. With the help of a stopwatch, the time during which the spring restored its original shape was measured.

Table 1

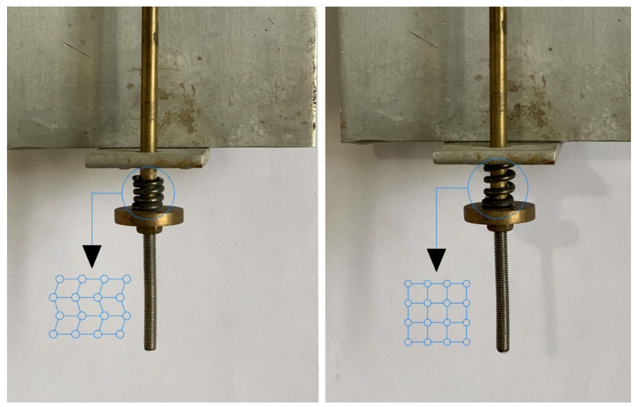
Elemental composition of VSP-1 alloy

Element	Ni	Ti	Fe	Si	C	Mn	Se
Content, %	53.6	45.6	0.3	0.2	0.12	0.1	0.08

The force required to compress the spring force elements in the cold state ($t\leq M_f$) and which developed during the reverse martensitic transformation ($t\geq A_f$) was measured with a dynamometer with an absolute error of ±0.1 N. The length of the spring was measured with a caliper with an absolute error of $\pm0.1\cdot10^{-3}$ m.

Thermal-force cycling of spring elements provided for their maximum possible deformation at temperature $t\leq M_f$ with rigid fixation in this position and temperature changes in the temperature ranges of direct and reverse martensitic transformation.

A photograph of the studied spring with the shape memory effect during direct and reverse martensitic transformation is shown in Fig. 1.



a *b*

Fig. 1. The studied spring with the shape memory effect: *a* — direct martensitic transformation upon cooling $t\leq M_f$ (low-temperature martensitic lattice structure); *b* — reverse martensitic transformation upon heating $t\geq A_f$ (high-temperature austenitic cubic structure)

Based on the results of experimental studies, the relative force P/P_τ^{max} and deformation ε_n of the spring force elements were determined. Here *P* is the force applied to the spring element at the temperature $t\leq M_f$. The value P_τ^{max} is the maximum force applied to the spring element produced with the maximum cooling rate after heat treatment, at the temperature $t\leq M_f$.

The relative deformation of the spring force element was determined by the formula:

$$\varepsilon_n=\Delta l_n/\Delta l_{max}=(l_h-l_c)/(l_i-nd), \quad (1)$$

where l_h and l_c are the length of the spring in hot (at temperature $t\geq A_f$) and cold (at temperature $t\leq M_f$) states; l_i – the initial length of the spring after heat treatment; Δl_{max} – the maximum possible deformation of the spring (before the contact of the turns); *n* is the number of turns of the spring; *d* is the diameter of the spring wire.

The relative useful power was determined by the formula:

$$P^u/P_\tau^u=\left(P_h^{max}-P_c^{max}\right)/P_\tau^u, \quad (2)$$

where P^u is the maximum usable force developed by the spring element at temperature $t\geq A_f$; P_h^{max} – the maximum force developed by the spring element at temperature $t\geq A_f$, P_c^{max} – the maximum force required to compress the spring element at temperature $t\leq M_f$; P_τ^u – the maximum useful force developed by a spring element manufactured at the maximum cooling rate and at a temperature of $t\geq A_f$.

5. Research results on the development of technological solutions for the manufacture of steam trap

5. 1. Studying the influence of the cooling rate on the deformation and strength characteristics of spring elements

First, studies into the influence of the cooling rate on the deformation-strength characteristics of spring force elements at a temperature of $t \geq A_f$ (form recovery mode) were carried out. The results of the study are represented in the form of the dependence of the relative force on the relative deformation of force spring elements at a temperature of 100 °C (Fig. 2).

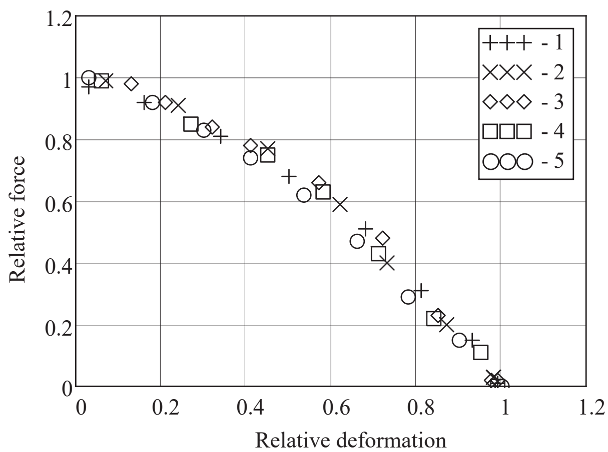


Fig. 2. Dependence of relative force on the relative deformation of spring force elements at a temperature of 100 °C, produced with cooling rates: 1 – slowed down in the furnace at 0.013 °C/s; 2 – in the furnace; 3 – accelerated in the furnace; 4 – in the air; 5 – in water at 66.7 °C/s

Further studies were aimed at evaluating the influence of the relative force required for maximum compression of the spring element on the cooling rate after heat treatment (Fig. 3).

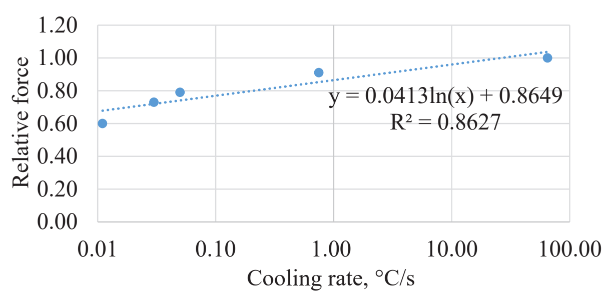


Fig. 3. Influence of the relative force required for the maximum compression of a spring element at a temperature of 25 °C on the rate of its cooling after heat treatment

The influence of the cooling rate on the relative maximum useful force developed by the spring element was also established (Fig. 4).

The studies illustrated in Fig. 2–4 are carried out for a winding pitch of $6 \cdot 10^{-3}$ m and the number of thermal-force cycling cycles of 150.

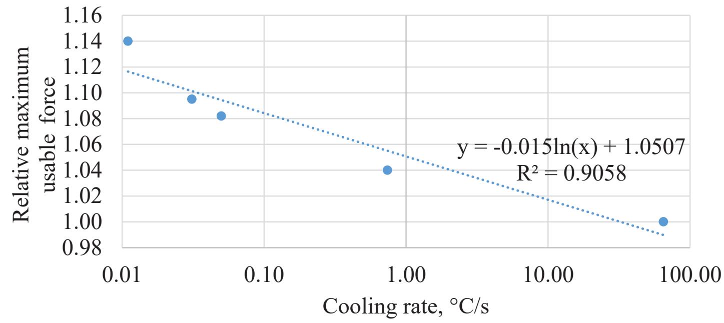


Fig. 4. Effect of cooling rate on the relative maximum usable force developed by the spring element

5. 2. Studying the influence of the winding step and thermal-force cycling on the deformation-strength characteristics of spring elements

The results of studies on the influence of winding step on the force required for full compression of the spring element at a temperature of 25 °C are shown in Fig. 5. The number of TFC cycles in the studies ranged from 0 to 1000.

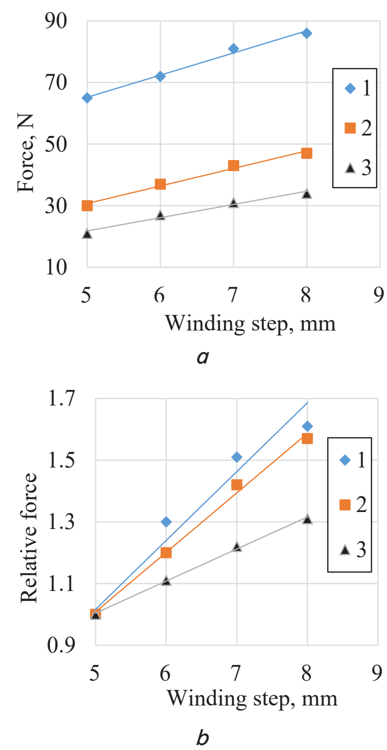


Fig. 5. Influence of the winding step on the force required for full compression of the spring element at a temperature of 25 °C: *a* – absolute values; *b* – relative values; 1 – spring elements without thermal-force cycling; 2 – after 50 cycles of thermal-force cycling; 3 – after 1000 cycles of thermal-force cycling

An intense decrease in the force required for full compression of the spring elements with a winding pitch from $5 \cdot 10^{-3}$ to $8 \cdot 10^{-3}$ m occurs during the first 100 cycles of TFC. Further cycling leads to stabilization of force values.

Fig. 6 shows the effect of thermal-force cycling on the maximum usable force developed by spring samples with a winding pitch from $5 \cdot 10^{-3}$ to $8 \cdot 10^{-3}$ m at $t \geq A_f$.

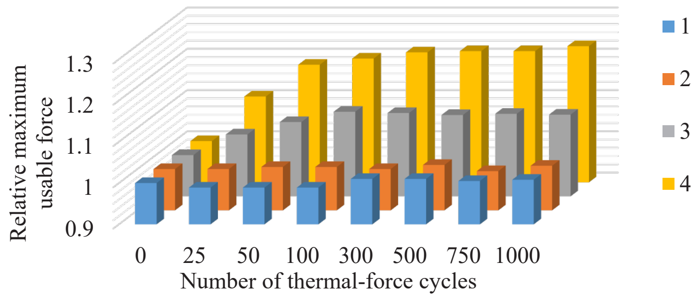


Fig. 6. Influence of thermal-force cycling on the relative maximum usable force of spring elements: 1 – winding step $s=5\cdot10^{-3}$ m; 2 – $s=6\cdot10^{-3}$ m; 3 – $s=7\cdot10^{-3}$ m; 4 – $s=8\cdot10^{-3}$ m

It is worth noting that for spring elements with a winding pitch of $5\cdot10^{-3}$ and $6\cdot10^{-3}$ m, thermal-force cycling practically does not affect the value of the maximum usable force.

The results of the study of the influence of the winding step on the maximum usable force of the spring elements are shown in Fig. 7.

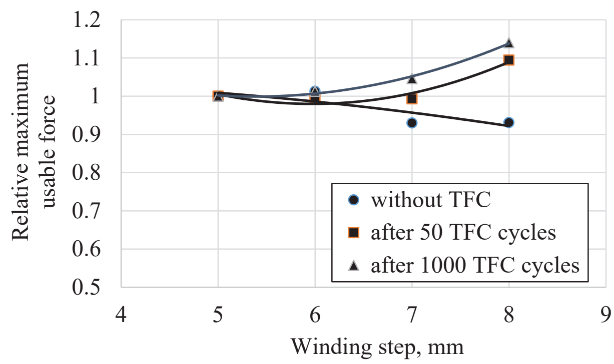


Fig. 7. Influence of the winding step on the relative maximum usable force of the spring elements

It should be noted that the use of TFC makes it possible to increase the maximum usable force of spring elements.

5. 3. Improvement of the steam trap design

Taking into account the results of research (Fig. 4, 6) and data from the literature [5, 6, 13], a rational technological process of heat treatment of spring elements includes the following components:

– heating to a temperature of 400–500 °C for 1 hour [5, 6];

– exposure at this temperature for 1 hour [13];

– cooling at a rate of 0.013 °C/s (Fig. 4);

– thermal-force cycling of spring elements with the number of cycles at least 100 and a winding pitch of $8\cdot10^{-3}$ m (Fig. 6).

Spring elements manufactured using the above technology have a direct (at temperature $t\geq A_f$) and reverse (at $t<A_s$) effect of thermomechanical shape memory. Such a thermopower drive (TPD) of the controlling element has low inertia (time constant 2–3 s) and low spring weight.

The design of the improved thermostatic steam trap with the TPD controlling element in the form of a cylindrical compression spring made of the structural alloy VSP-1 based on nitinol is shown in Fig. 8.

The steam trap consists of housing 1 with valve seat 2 located between inlet 3 and outlet 4 channels and cover 5 with union nut 6. Inside the housing is a TPD in the form of a cylindrical compression spring 7, which has a forward and reverse SME. Spring 7 is installed on movable spindle 8 of the locking element (plates 10) and is located between it and adjusting rod 11.

Adjustment rod 11 is marked with divisions for the convenience of setting the steam trap to a certain working pressure of the environment. Each of them corresponds to a certain force developed by the spring at temperature $t\geq A_f$, and the distance between the disk and the valve seat h at $t\leq M_f$. The indicator is the upper end of the union nut.

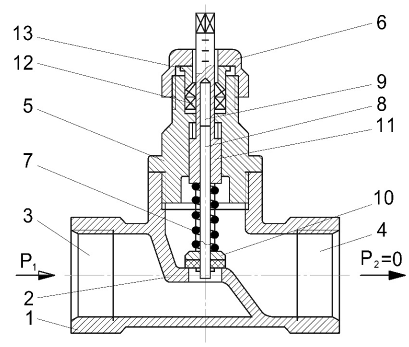


Fig. 8. Steam trap with a controlling element drive in the form of a cylindrical spring made of VSP-1 alloy with a shape memory effect [14]: 1 – body; 2 – saddle; 3, 4 – input and output channels; 5 – head; 6 – union nut; 7 – spring from EPF; 8 – rod; 9 – blind hole; 10 – plate; 11 – adjusting rod; 12 – gland packing; 13 – Grundbux

The steam trap works as follows. In the initial position, the steam trap is disconnected from the heat sink. Using the adjusting rod, a certain distance h_p is set between the base of rod 3 and valve seat 1 (Fig. 9). In this case, the temperature of spring 4 is lower than the temperature of the end of the direct martensitic transformation ($t<M_f$) and is equal to the ambient temperature. The spring has a maximum involuntary compression, which is determined by the inverse SME. Under the influence of gravity, plate 2 rests on seat 1 of the valve.

When condensate with temperature $t<M_f$ is fed into the inlet channel, the plate rises above the valve seat to a height h under the influence of the pressure of the environment (Fig. 9). This gap determines the free movement of the spring when restoring its shape memory.

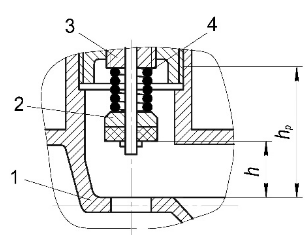


Fig. 9. Valve plate position at condensate temperature $t\leq M_f$ [14]

When condensate with temperature $t>A_s$ enters the inlet pipe, the spring starts to move the plate in the direction of the seat and at the temperature of the environment $t\geq A_f$ presses it to the seat. Energy losses with flying steam are practically absent.

The flow capacity and allowable working pressure are adjusted using a flywheel that is attached to the adjusting rod.

Thus, on the basis of our research, the design of the thermostatic steam trap with the TPD controlling element made of the VSP-1 alloy with SME has been improved. The general appearance of the steam trap is shown in Fig. 10. The improved structure of the steam trap is protected by patent [14].

Fig. 10. General view of the steam trap with the controlling element of the drive in the form of a spring made of the VSP-1 alloy with the shape memory effect

6. Discussion of results of the development of technological solutions for the manufacture of a steam trap

Imperfect design of controlling elements of steam traps and their high inertia leads to steam losses. The use of spring elements with SME in steam traps made it possible to minimize losses and improve their operational characteristics. The deformation and strength characteristics of spring elements with SME depend on the heat treatment technology. According to the experimental data illustrated in Fig. 2, the cooling rate does not affect the deformation and strength characteristics of the spring elements in the form recovery mode at temperatures $t \geq A_f$. A significant influence of the cooling rate on the deformation-strength characteristics is observed under the deformation mode at the temperature $t \leq M_f$. At the same time, in contrast to [5, 6], it was established that an increase in the cooling rate from 0.013 to 66.7 °C/s leads to an increase in the force required to induce deformation in the martensitic state by 40 % (Fig. 3). In addition, there is a 14 % decrease in usable power (Fig. 4). According to these results, it is advisable to reduce the cooling rate of spring elements to 0.013 °C/s, which has a positive effect on the deformation-strength characteristics of spring elements with SME.

According to the research results shown in Fig. 5, it was established that thermal-force cycling makes it possible to reduce the force required for full compression of the spring element by 60 %. This leads to the formation of a reverse SME, which consists in a spontaneous change in the dimensions of the spring elements in the direction of deformation. Residual deformation accumulates. The sum of the residual deformation and the deformation due to the reverse SME after 100 TFC cycles reaches 40 % of the maximum possible deformation.

Thermal-force cycling helps reduce the force required to deform the springs in a cold state. As a result, the usable force of spring elements with a winding pitch of $7 \cdot 10^{-3}$ and $8 \cdot 10^{-3}$ m increases by 10 and 20 % after 100 cycles of TFC (Fig. 6). However, in contrast to work [15], the intensive growth of the usable strength occurs during the first 100 cycles, not 25. This can be explained by a different composition of the alloy with SME, namely, the presence in the alloy, in addition to 50 % Ti and 49 % Ni, also 1 % W [15]. Thus, it is important to note that our research results are limited by the elemental composition of the VSP-1 alloy (Table 1). Therefore, the use of alloys with SME of a different composition as a material for spring elements requires experimental verification and validation of the results reported in this work.

Analysis of data in Fig. 7 reveals that for typical spring elements (number of turns $n=5$) without TFC, an increase in the winding step leads to a decrease in the maximum usable force by 7 % (Fig. 7). The TFC of typical spring elements leads to an increase in the maximum usable force when the winding step is increased from $5 \cdot 10^{-3}$ to $8 \cdot 10^{-3}$ m. After 1000 cycles, the increase is 14 %, and after 50 cycles – 10 %. This is due to both a decrease in the force required for full compression of the spring and a change in the force when restoring the shape.

According to the results of research, it was established that the restoration of the shape of the springs at 100 °C occurs in a very short time and does not exceed 1 second. The degree of recovery of the form is 100 %. So, this means that thermal-force cycling does not affect the inertial properties of spring force elements.

The results of our research made it possible to determine the rational component technologies for the heat treatment of springs. This includes the following processes: cooling at a rate of 0.013 °C/s; thermal-force cycling of at least 100 cycles with a spring winding step of $8 \cdot 10^{-3}$ m.

Our review of the literature [1–4] did not reveal the use of alloys with a shape memory effect as a material for a thermal-force drive in pipeline fittings. In contrast to the classic designs of steam traps [2, 4], the improved structure involves the use of a controlling element in the form of a spring element made on the basis of a material with a shape memory effect. A feature of the improved design is the use of TFC in the manufacture of springs in the temperature range of direct and reverse martensitic transformation. This makes it possible to obtain a thermoelectric drive with direct and reverse SME and eliminate the need to install a return spring. In addition, the TFC makes it possible to increase the usable force during the restoration of the shape and reduce the necessary force during the reverse deformation.

The improved thermostatic steam trap has a number of advantages over existing designs:

– structural and technological simplicity;
– low inertia (time constant no more than 2–3 s);
– low mass (2.5–3.8 times less than known designs);
– a longer service life due to the high cyclic stability of the TPD material (10^5–10^7);
– maintainability and low cost;
– reduction of steam losses;
– ease of maintenance.

It is important to note that our experimental studies on the deformation-force characteristics of spring elements are limited by the following geometric dimensions of the spring: wire diameter ($d=2 \cdot 10^{-3}$ m) and winding diameter $2d$.

The disadvantage of the research is that the results can be used only for a new type of steam traps with SME and working pressure within 1 MPa. Therefore, it is advisable to carry out further research for larger geometric dimensions of the spring, which will make it possible to design steam traps with SME and working pressure exceeding 1 MPa.

7. Conclusions

1. Experimental studies have shown that only under the deformation mode at the temperature $t \leq M_f$ there is a significant

effect of the cooling rate of the spring elements on the deformation-strength characteristics. It was also found that increasing the cooling rate from 0.013 to 66.7 °C/s leads to a 40 % increase in the force required to cause deformation in the martensitic state.

2. Experimental studies on the influence of thermal-force cycling and the winding step on the deformation-strength characteristics of spring elements were carried out. As a result, it was found that the use of thermal-force cycling makes it possible to reduce the force required for full compression of the spring element by 60 %. An intense decrease in the force required for full compression of the spring elements with a winding step from $7\cdot10^{-3}$ to $8\cdot10^{-3}$ m occurs during the first 100 cycles of TFC. Thus, the rational number of TFC spring cycles is at least 100.

3. The design of the thermostatic steam trap has been improved by manufacturing the controlling element in the form of a spring based on a material with a shape memory effect. Our structure of the steam trap has a number of advantages, the main of which are the following: structural and technological simplicity, low inertia and mass, longer service life and low steam losses.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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