Temperature regulator for containers with working substance in high-frequency metal vapor active media

E G Bukreev[1], O A Kozhemyak[1], I S Musorov[1], D N Ogorodnikov[1] and V V Drobchik[2]

[1] National Research Tomsk Polytechnic University, Tomsk, Russia
[2] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

evgenybukreev.rab@gmail.com

Abstract. This paper presents the study of the control functions for the temperature control of containers with the active substance in active media on metal vapors. Nonlinear control function was built and tested with a layout of container. Tests demonstrate discordant, but primary positive results of using nonlinear regulator instead of linear proportional-integral-differential (PID) regulator.

1. Introduction

Metal vapor active media, due to their unique properties, are widely used as brightness amplifiers for creating active optical systems [1-7]. Such systems allow visualization of processes under conditions of high-power background illumination, but it is not possible using standard techniques [8-12]. The task of visualizing the high-speed processes requires the development of high-frequency brightness amplifiers. To date, the record pulse repetition / amplification frequencies for active media on metal vapors are 700 kHz for copper bromide vapor media [12] and 830 kHz for strontium vapor media [13]. As a rule, an increase in the pulse repetition rate is possible with the use of gas-discharge tubes (GDT) of small diameter. The use of GDT of small diameter (up to 1 cm) requires more precise control of the parameters of the brightness amplifier, in particular, more precise regulation of the heating processes of containers with a working substance is necessary. Due to the small volume of the GDT, even a slight overheating of the containers leads to a sharp increase in the concentration of the working substance, as a result, to a breakdown of generation.

This paper presents the study of the control functions for the temperature control of containers with the active substance in active media on metal vapors. In particular, the control functions for the regulation and stabilization of the temperature of containers in an active medium on copper bromide vapor are investigated. The relevance of the work is due to the need to stabilize the temperature of copper bromide containers with high accuracy and prevent significant temperature deviations during the operation of the brightness amplifier in wide range of used characteristics – such as temperature, frequency, GDT's diameter and condition of isolation – which is most critical at high (over 100 kHz) pulse repetition / emission frequencies.

The paper considers linear and nonlinear controllers and their interaction with the heating system, the inertia of which is unknown. The use of mechanical or automatic relay systems, which currently in use, does not provide the accuracy needed to maintain constant emission / amplification parameters.

Hence, there is a need to use more accurate automatic controllers, the most common of which are proportional-integral-differential (PID) controllers.

The use of modern microcontrollers allows a more convenient way to put in the PID controllers functions of self-diagnosis, automatic tuning, etc., which led to the appearance of controllers with a built-in process model. The process of obtaining a model (identification) of the system is divided into two stages: obtaining the structural model of the system, defining the description of the object in a parametric form, and obtaining a parametric model in which the parameters of the system equation are determined for a known parametric description. In addition to directly studying the impact on the output parameters of the system, during identification, the device delay is studied, which in high inertial systems has a significant effect on the parameters of the PID controllers and forces slowing down the regulation process to simplify the mathematical model of the system and increase the predictability of the control response. The delay can be of two types: transport delay – due to the transient processes in electrical circuits, and natural delay – due to the inertia of the control system.

In addition, there are problems of integral saturation in circuits with hysteresis when designing and using PID controllers. These problems significantly affect the stability of output parameters in the systems with high inertia [14-16].

2. Problem statement

Using of classical non-adaptive linear PID regulator leads to necessity of studying the specific configuration of the active medium and the adjustment of the controller parameters to work with a particular device. Any deviations in the configuration, for example, the weaker thermal insulation of containers with the active substance, reduce the temperature stability of the system.

The purpose of study is developing of the control system with invariant parameters of control functions applied for the objects with high inertia.

3. Experimental setup

A coil of nichrome wire wound on a glass tube with a diameter of 39.2 mm and a length of 67.3 mm was used to heat the container. Thermal insulation was made with technical wool and fiberglass. The step-down DC-DC converter of 1.2 kW was used as a power supply.

The coil is heated by converting electrical energy into heat according to the Joule-Lenz law: $Q = P \cdot t$, where Q is the amount of heat released, P is the active power. The temperature change depends on the amount of heat released and the heat capacity of the object's material: $\Delta T = \Delta Q/C$, where C is the heat capacity of the material, T is the temperature.

Container with working substance is heated by heat transfer from the nichrome coil. During heating and maintaining the temperature, thermal energy is also dissipated by longwave radiation and heat transfer. The influence of the second factor significantly exceeds the influence of the first, due to which the heat dissipation of radiation can be neglected. Heating and scattering due to heat transfer is described by a differential equation:

$$\frac{\partial u}{\partial t} - \alpha^2 \cdot grad(u) = f(r,t) \qquad (1)$$

where a is a coefficient of thermal conductivity, r is a coordinate of a system point, t is a time.

Equation (1) shows that with increasing temperature of the container with the active substance, rate of heat propagation from heating element to external environment, the temperature of which remains approximately constant, increases, and decreases towards the container. The change in the rate of propagation of heat occurs nonlinearly, because of which control is complicated by the following factors:

- an increase in the input power by N times leads to an increase in the stabilized temperature by K times, and K is always less than N;

- when constant power is supplied to the heating element, the rate of change in the temperature of the container with the working substance non-linearly decreases as the temperature approaches the equilibrium state.

This creates a ascertain complexity in the control of the heater: the dynamics of heating change non-linearly, which, given the high inertia of the thermal system, leads to the non-obviousness of the container temperature over time. To accurately determine the temperature, it is necessary to solve a differential equation based on information about the current temperature of the container, the current temperature of the heater coil, and the thermal conductivity of the system.

If the control process is performed basing on the certain temperature of the container without taking into account its dynamics, the response of the control device will always be delayed. This is due to the natural delay in the transfer of heat from the heating coil to the container, and, insignificantly, due to the transport delay arising from the conversion of electrical energy into heat.

The presence of delays in control is a destabilizing factor and causes fluctuations. The elimination of delays is directly related to the decrease in the rate of change of the system state and leads to a decrease in the controller speed.

The study of the interaction of control functions with the heating system was carried out using a digital temperature sensor DS18B20, the measurement accuracy of which is ±0.5°C, at low temperatures (up to 100°C). In order to protect the sensor, the maximum operating temperature was limited to 110°C, after which the heater was forcibly turned off until the temperature returned to the operating range. The sampling frequency of the temperature values was 10 Hz (the sampling period was 100 ms), which turned out to be sufficient for the inertia of the layout under study. As a destabilizing factor, a change in the supply voltage from 230 V to 150 V and back was used.

4. Experimental results

4.1. Control system with PID controller
The control functions of PID controller are described by the following expressions:

$$P = \frac{(T_{st} - T)}{P_{coeff}} \tag{2}$$

$$I_k = I_{k-1} + \frac{(T_{st} - T)}{I_{coeff}} \tag{3}$$

$$D = \sum_{n=0}^{N-1} \frac{(T_{n+1} - T_n)}{D_{coeff}} \tag{4}$$

$$\gamma = \frac{P + I + D}{1000} \tag{5}$$

where T_{st} is a stabilization temperature; T is a current temperature; $N = 1000$ is number of samples; P, I, D are proportional, integral and differential terms, respectively; P_{coeff}, I_{coeff}, D_{coeff} are numerical coefficients of proportionality of the corresponding terms; γ is a fill factor. Thus, the memory of the differential term covers a period of 100 seconds.

The results of heating obtained up to 100°C, up to 70°C and the response to the destabilizing factor for the optimal, in terms of balance of the speed of the mode and response to changes in the supply voltage, the PID controllers coefficients are presented in Figure 1.

The optimal coefficients are obtained: $P_{coeff} = 5$, $I_{coeff} = 30000$, $D_{coeff} = 20$.
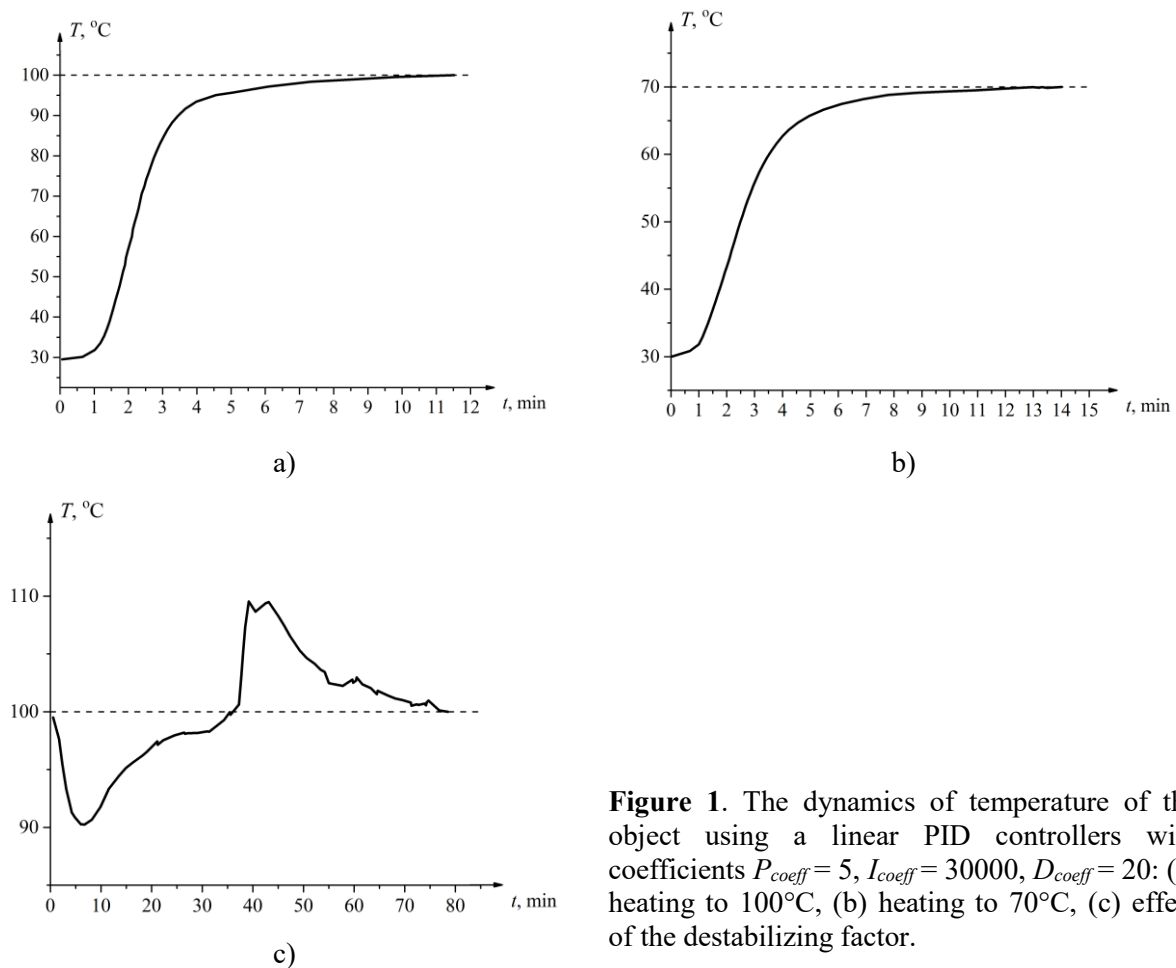
Figure 1. The dynamics of temperature of the object using a linear PID controllers with coefficients $P_{coeff} = 5$, $I_{coeff} = 30000$, $D_{coeff} = 20$: (a) heating to 100°C, (b) heating to 70°C, (c) effect of the destabilizing factor.

A significant (more than 10%) deviation of any of the coefficients leads to an increase in the stabilization time, or to the appearance of an overshoot when the system is heated, or to an increase in the amplitude of the deviations under the influence of destabilizing factors.

Time for reaching the operating temperature is: to the level of 100°C – 11 minutes; to the level of 70°C – 12.5 minutes, which is an acceptable preparation time for the equipment with no overshoot.

In the case of a sharp decrease in the supply voltage, a decrease in temperature by 10°C to 90°C is observed. Upon subsequent restoration of the voltage level, the temperature reaches a temperature limit of 110°C, after which a protective shutdown of the heater occurs. Thus, in both cases, the deviation is 10% and higher, which is unacceptable at high temperatures. At a stabilization level of 500°C, a temperature deviation of 10°C (2%) can lead to a breakdown in the generation of radiation. Also, in case of destabilization of temperature, its recovery occurs very slowly and takes about 40 minutes in both cases.

A decrease in amplitude of the deviations due to an increase in influence of the differential component leads to a significant increase in time for temperature stabilization due to a decrease in growth rate of integral component. In addition, this leads to an increase in heating time, since it requires a proportional reduction of the integral component, which leads to a deterioration in the operational properties of the object. Therefore, it is necessary to use different control functions for different stages of the heating process.

4.2. Control system with nonlinear controller
To describe nonlinear controller let us define the three stages of the heating process:

First stage – initial heating. The peculiarity of this stage is the lack of regulation necessity. Since the heat capacity of the heater is significantly less than the heat capacity of the heating object, a heating of spiral with constant high intensity limited by the following requirement to a certain temperature region: the heating rate should not be so large that, taking into account the natural delay of the heating system, the inertia of the temperature is sufficient to overcome most of the area of the second phase. The main term is a proportional term or some constant level. At the end of the initial heating stage, it is advisable to add a differential term, the purpose of which is to extinguish the inertia of the heater at the beginning of the stage of reaching the operating temperature. Thus, the differential term serves as a shock absorber for the transition from the first stage to the second.

Second stage – reaching the operating temperature. At this stage, the main term is integral, since, if the current temperature matches the required temperature, the proportional and differential terms are missed and the temperature is fully maintained by the integral term. The proportional and differential terms at this stage regulate the rate of increase of the integral term and perform a soft transition from the stage of initial heating to the operating mode.

Third stage – temperature stabilization. This stage is characterized by greater sensitivity to temperature deviations of all three terms. The task of maintaining the temperature at a given level is still carried out by the integral term and the temperature recovery rate depends on it. The differential term regulates the rate of deviation from a given temperature when exposed to destabilizing factors, and the proportional term, together with the integral, controls the amplitude of the deviations. The main limitation on the sensitivity of the term is imposed by the occurrence of temperature self-oscillations.

The control functions of nonlinear controller were described by the following expressions:

$$P = (0.1 < \frac{T_{st}}{(T_{st} - T) \cdot P_{coeff}} < 0.25) \cdot (T_{st} - T) \tag{6}$$

$$I_n = I_{n-1} + dI \tag{7}$$

$$dI = \frac{T_{st}^2 - T^2}{T_{st}^2 \cdot I_{coeff}} \text{ if } T > T_{st} \cdot 0.75, \text{ else } dI = 0 \tag{8}$$

$$D = \sum_{n=0}^{N-1} \frac{T_n - T_{n-1}}{D_{coeff}} \text{ if } T > T_{st} \cdot 0.65, \text{ else } D = 0 \tag{9}$$

$$\gamma = \frac{P + I + D}{1000} \tag{10}$$

where T_{st} is a stabilization temperature; T is a current temperature; $N = 20$ is a number of samples; P, I, D are proportional, integral and differential terms, respectively; P_{coeff}, I_{coeff}, D_{coeff} are numerical coefficients of the corresponding terms; γ is a fill factor.

The graphs of the P and the increment of the dI in relative units of the maximum fill factor for the case of $T_{st} = 100°C$, $P_{coeff} = 15$, and $I_{coeff} = 12$ are shown in Figure 2.

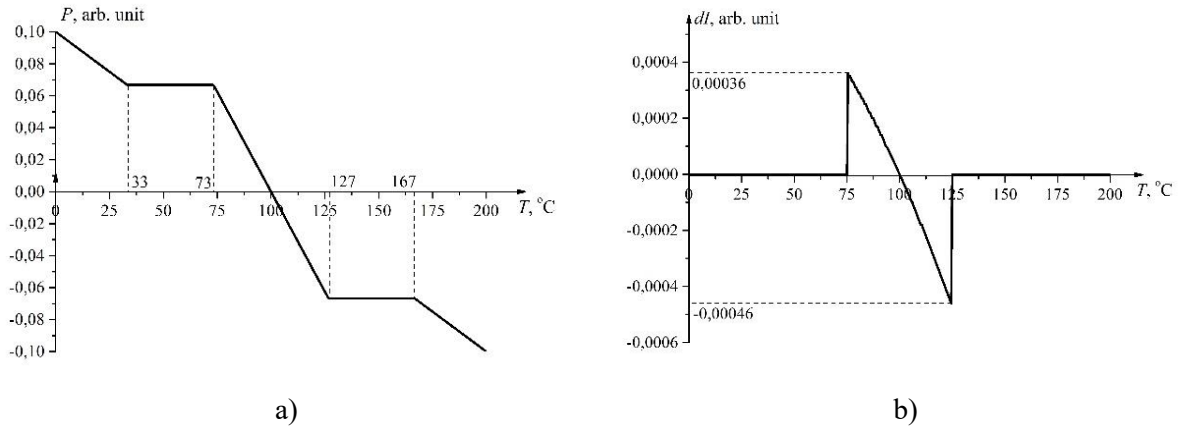a)   b)

Figure 2. Graphs of components of nonlinear controller: (a) proportional, (b) increment of integral component.

The results of heating obtained up to 100°C, up to 70°C and the response to the destabilizing factors for the obtained nonlinear controller coefficients are presented in Figure 3.
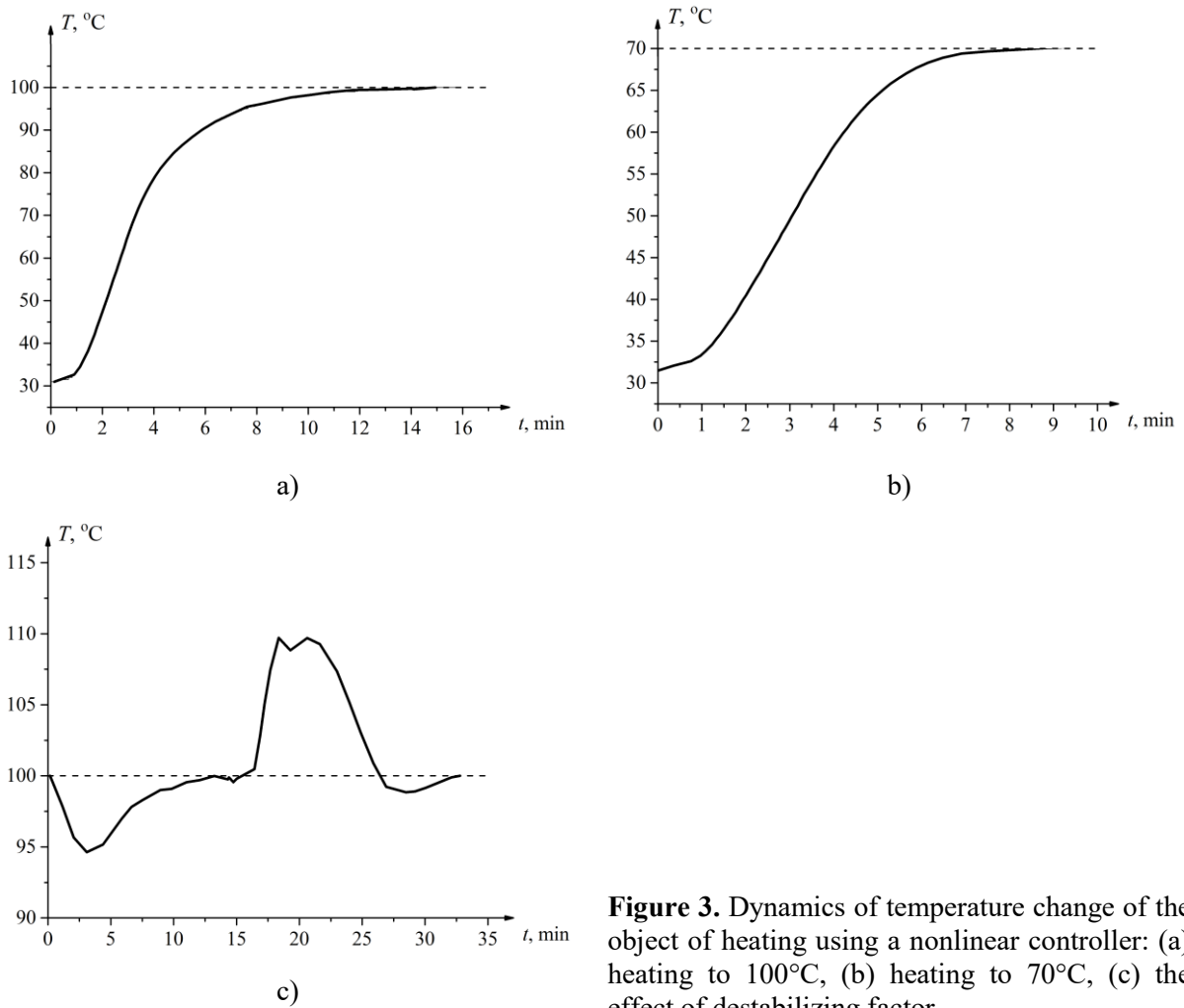

a)   b)

Figure 3. Dynamics of temperature change of the object of heating using a nonlinear controller: (a) heating to 100°C, (b) heating to 70°C, (c) the effect of destabilizing factor.

c)

The coefficients used at the initial heating stage and reaching the operating temperature stage: P_{coeff} = 15, I_{coeff} = 12, D_{coeff} = 12. Temperature sampling for the differential term is done every 4 seconds.

At the stage of temperature stabilization coefficients are: P_{coeff} = 15, D_{coeff} = 3. Temperature sampling for the differential component is done every 2 seconds. The coefficient I_{coeff} = 6 in the case when the deviation from the stabilization level increases, I_{coeff} = 12 in the case when the deviation decreases.

5. Discussion of results

As a result of replacing the linear controller with a nonlinear time for reaching the 100°C mode increased by 13% and amounted to 12.5 minutes. The time for reaching the 70°C mode decreased by 40% and amounted to 7.5 minutes. The difference in results between higher and lower levels of temperature stabilization can be explained by the lack of damping the inertia of the heated coil at high temperatures, which leads to an excessively high temperature rise at the second stage of the heater and delays the growth of the integral term.

A significant improvement in the dynamic parameters of the system was achieved at the stage of temperature stabilization. The time to return to the required level while reducing the supply voltage to 150 V was 14.5 minutes and decreased by 64%, with the restoration of the voltage to 230 V – 18 minutes and decreased by 55%. The amplitude of the deviation in the fall decreased by 45% and amounted to 5.5 V or 5.5%. When the voltage recovered, the amplitude of the deviation remained the same.

Results confirm that the goals and priorities of the heating system are different at each stage of heating. The experimental show the effectiveness of using the various control functions depending on the heating stage.

6. Conclusion

Research was carried out with layout of container that was identically similar to containers, which are used in metal vapor active media to keep active substance.

The time of the reaching the operating temperature stage at the lower boundaries of the temperature range was almost twice reduced. However, at the upper temperatures, the time of reaching the operating temperature stage has increased. As a result, the use of a nonlinear controller shows 1.3 times reducing in average time of this stage in comparison to PID controller usage.

In addition, it was possible to reduce the amplitude of the temperature deviation when the supply voltage drops and almost twice to reduce the stabilization time.

This results give an opportunity to improve a wide-range regulation qualities of commonly used PID regulator laws.

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