Современная наука и инновации. 2025. № 2. С. 84-93
ТЕХНИЧЕСКИЕ НАУКИ
ИНФОРМАТИКА, ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И УПРАВЛЕНИЕ

Modern Science and Innovations. 2025;(2):84-93
TECHNICAL SCIENCE
INFORMATICS, COMPUTER ENGINEERING AND MANAGEMENT

Research article
https://doi.org/10.37493/2307-910X.2025.2.8

Mathematical modeling of the automatic temperature control system of a conveyor-type tunnel furnace

Maxim Yu. Napalkin[1*], Ivan M. Pershin[2]

[1,2] North-Caucasus Federal University, Pyatigorsk Institute (branch) (56, 40 Let Oktyabrya Ave., Pyatigorsk, Stavropol Territory, 357500, Russia)
[1] maksnapalkin@mail.ru; https://orcid.org/0000-0001-8644-5470
[2] ivmp@yandex.ru; https://orcid.org/0000-0002-7618-1173
*Corresponding author

Abstract. *The article is devoted to the urgent problem of ensuring accurate and stable temperature conditions in conveyor-type tunnel furnaces, widely used in various industries for continuous heat treatment of materials. The efficiency and quality of processing directly depend on maintaining the temperature in each zone of the furnace within the specified limits. Deviations from the set parameters lead to a deterioration in the quality of the final product, an increase in the percentage of defects and inefficient consumption of energy resources. In this regard, the development and implementation of effective automatic temperature control systems is an important and urgent task to increase productivity and reduce production costs. Existing automatic temperature control systems are often based on classical proportional-integral-differential (PID) controllers with fixed parameters. However, such systems do not always provide optimal control in the dynamically changing conditions of the production process and under the influence of external disturbances, such as fluctuations in mains voltage, changes in conveyor speed or fluctuations in ambient temperature. This leads to a decrease in the efficiency of the furnace and instability of the temperature regime. The presented article proposes an approach to the development of an automatic temperature control system for a conveyor-type tunnel furnace based on the use of PID controllers with adaptive parameter setting. The adjustment of the controller parameters allows the system to automatically adjust to the changing operating conditions of the furnace and compensate for the influence of external disturbances, providing more stable and accurate temperature control. The proposed approach is designed to solve the problem of inefficiency of traditional PID controllers with fixed parameters.*

Keywords: automatic temperature control, tunnel furnaces, conveyor type, control system, adaptive algorithms, temperature sensors, thermal stabilization, intelligent controllers

For citation: *Napalkin MYu, Pershin IM. Mathematical modeling of the automatic temperature control system of a conveyor-type tunnel furnace. Modern Science and Innovations. 2025;(2):84-93. https://doi.org/10.37493/2307-910X.2025.2.8*

Научная статья
УДК 621.391

Математическое моделирование системы автоматического регулирования температуры туннельной печи конвейерного типа

Максим Юрьевич Напалкин[1*], Иван Митрофанович Першин[2]

[1,2] Северо-Кавказский федеральный университет, Пятигорский институт (филиал) (д. 56, пр. 40 лет Октября, Пятигорск, Ставропольский край, 357500, Россия)
[1] maksnapalkin@mail.ru; https://orcid.org/0000-0001-8644-5470
[2] ivmp@yandex.ru; https://orcid.org/0000-0002-7618-1173
*Автор, ответственный за переписку

Аннотация. *Статья посвящена актуальной проблеме обеспечения точного и стабильного температурного режима в туннельных печах конвейерного типа, широко используемых в различных отраслях промышленности для непрерывной термической обработки материалов. Эффективность и качество обработки напрямую зависят от поддержания температуры в каждой зоне печи в заданных пределах. Отклонения от заданных параметров приводят к ухудшению качества конечной продукции, увеличению процента брака и неэффективному расходованию энергоресурсов. В связи с этим, разработка и внедрение эффективных систем автоматического регулирования температуры является важной и актуальной задачей для повышения производительности и снижения издержек на производстве. Существующие системы автоматического регулирования температур зачастую основываются на классических пропорционально-интегрально-дифференциальных (ПИД) регуляторах с фиксированными параметрами. Однако, такие системы не всегда обеспечивают оптимальное управление в динамически изменяющихся условиях производственного процесса и под воздействием внешних возмущений, таких как колебания напряжения в сети, изменения скорости конвейера или колебания температуры окружающей среды. Это приводит к снижению эффективности работы печи и нестабильности температурного режима. В представленной статье предлагается подход к разработке системы автоматического регулирования температур для туннельной печи конвейерного типа, основанный на использовании ПИД-регуляторов с адаптивной настройкой параметров. Адаптация параметров регулятора позволяет системе автоматически подстраиваться под изменяющиеся условия работы печи и компенсировать влияние внешних возмущений, обеспечивая более стабильный и точный контроль температуры. Предлагаемый подход призван решить проблему неэффективности традиционных ПИД-регуляторов с фиксированными параметрами.*

Ключевые слова: автоматическое регулирование температуры, туннельные печи, конвейерный тип, система управления, адаптивные алгоритмы, датчики температуры, стабилизация тепловых режимов, интеллектуальные контроллеры

Для цитирования: *Напалкин М. Ю., Першин И. М. Математическое моделирование системы автоматического регулирования температуры туннельной печи конвейерного типа // Современная наука и инновации. 2025. № 2. С. 84–93.* https://doi.org/10.37493/2307-910X.2025.2.8

Introduction. Tunnel conveyor-type furnaces are widely used in various industries for continuous heat treatment of materials. The efficiency and quality of treatment directly depend on the accuracy and stability of maintaining the set temperature in each zone of the furnace. Deviations from the set parameters can lead to deterioration in product quality, increased defects and inefficient use of energy. Therefore, the development and implementation of effective automatic temperature control systems is an urgent task.

Existing systems are often based on classic PID controllers with fixed parameters, which does not always provide optimal control under changing process parameters and external disturbances. This paper proposes an approach to developing automatic temperature control systems for a conveyor-type tunnel furnace based on the use of PID controllers with adaptive parameter tuning, and also studies the effectiveness of the proposed system experimentally.

Materials and research methods. The difficulty of using automated systems also lies in the fact that for decades, enterprises have been accumulating production experience and empirical data. Successful use of information technology in crystal production requires the development of new approaches and improvement of existing methods.

The technical device designed to maintain a given temperature range in a conveyor-type tunnel furnace is an automatic regulator. To perform the assigned task, the regulator generates a control action designed to compensate for the impact of disturbances on the operating mode of the system [1].

Fig. 1 shows the diagram of the automatic temperature control system in a conveyor-type tunnel kiln for firing bricks.

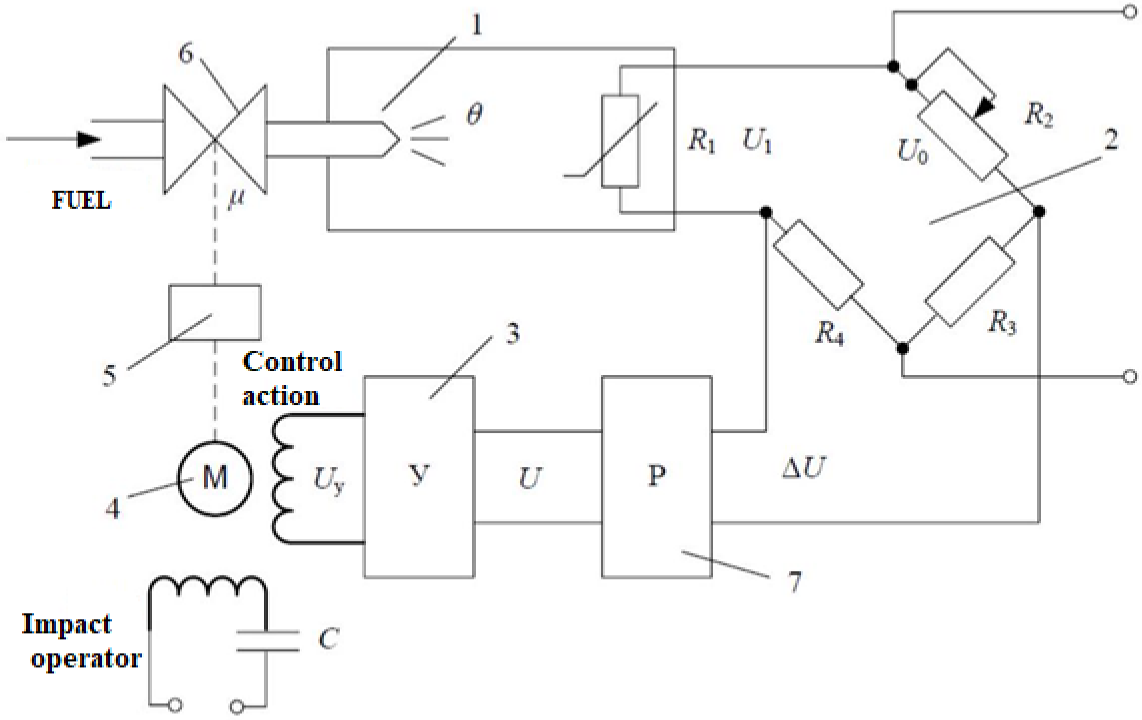

Fig. 1. Automatic control system diagram: 1 - furnace; 2 - measuring bridge circuit; 3 - differential magnetic amplifier; 4 - two-phase electric motor; 5 - gear reducer; 6 - valve; 7 - regulator.

In this system, the tunnel kiln is a control object whose controlled variable is temperature θ, and the regulating (control) action is the linear movement of the valve μ, on the value of which the amount of fuel supplied to the nozzle (the amount of heat) depends. The external disturbing action f is a combination of various factors: the initial humidity, the temperature of the fired brick, and changes in the temperature and humidity of the atmospheric air. When studying the system, we can limit ourselves to taking into account the influence of the initial humidity of the brick on the control object, considering it as the main disturbing action. The bridge circuit compares the voltage U_1, proportional to the temperature in the conveyor-type tunnel kiln θ, with the setting voltage U_0, i.e. in addition to the functions of the setting element (3O), it performs the functions of the comparing element (element). The unbalance voltage of the bridge circuit ΔU(mismatch signal) is fed to the controller (P), the synthesis of which must be performed in work [2]. The control action U is amplified by an amplifier (U), the output voltage of which controls the actuator (M). The latter, through the reducer, moves the valve, i.e. changes the control action μ, at the input of the control object.

The dynamic properties of the control object and the elements of the automatic control system are described by the following equations [10]:

$\mathrm{T}_0 \frac{d\theta}{dt} + \theta = k_0\mu - k_1 f$- object of regulation.

$\mathrm{U} = \mathrm{k}_2\theta$- temperature sensor.

$T_1 \frac{dU_y}{\mathrm{dt}} + U_y = k_3 U$- magnetic amplifier.

$\Delta U = U_0 - U_1$- comparing organ.

$T_2 \frac{d^2\mu}{dt^2} + \frac{d\mu}{dt} = k_4 U$- actuator with gearbox and valve.

Here $T_0, T_1, T_2$are the time constants, s; $\theta$is the temperature value in the furnace, $^{\circ}$C; $k_0, k_1, k_2, k_3, k_4$are the transmission coefficients; $\mu$is the linear displacement of the valve, cm; f is the disturbing effect on the control object; U_1 is the voltage drop across the thermistor, is the B; U_0 voltage drop across the setting resistor $R2$, B; ΔU is the bridge circuit imbalance signal (mismatch signal), B; U_y is the voltage at the amplifier output, V [3]. The values of the parameters of automatic temperature control system are given in Table 1. The output voltage of the magnetic amplifier is limited to 200 V [3]. The set value of the temperature in a conveyor-type tunnel furnace 950°Cis .

Table. Basic parameters of automatic temperature control system

T_0	k_0	k_1	k_2	k_3	T_2	k_4	f	T_1	v	σ
с	$\frac{°C}{cM}$	$\frac{°C}{\%}$	$\frac{B}{°C}$	-	с	$\frac{cM}{B \cdot c}$	%	с	%	%
4.5	10	15	1.4	2	0.026	0.01	45	0.06	0.5	30

According to the description of the system, the equation describing the control object has the form:

$$T_0 \frac{d\theta}{dt} + \theta = k_0\mu - k_1 f$$

Let's transform the equation by accepting $\frac{d}{dt} = p$:$(T_0 p + 1)\theta = k_0\mu - k_1 f$

Then the proper operator has the form: $Q(p) = T_0 p + 1$
Input action operator μ: $P_1(p) = k_0$
Input action operator t: $P_2(p) = -k_1$
Then the input transfer function μtakes the form:

$$W_{\sigma\sigma}(p) = \frac{P_1(p)}{Q(p)} = \frac{k_0}{T_0 p + 1}$$

and the transfer function for the disturbing effect:

$$W_{\text{воз}}(p) = \frac{P_2(p)}{Q(p)} = -\frac{k_1}{T_0 p + 1}$$

According to the description of the system, the equation describing the magnetic amplifier is: $T_1 \frac{dU_y}{\text{dt}} + U_y = k_3 U$

Let's transform the equation by accepting $\frac{d}{dt} = p$:$(T_1 p + 1)U_y = k_3 U$

Then the proper operator has the form: $Q(p) = T_1 p + 1$
Input action operator U: $P(p) = k_3$
Then the input transfer function Utakes the form:

$$W_{\mu y}(p) = \frac{P(p)}{Q(p)} = \frac{k_3}{T_1 p + 1}$$

According to the description of the system, the equation describing the actuator with a gearbox and valve is [4]:

$$T_2 \frac{d^2\mu}{dt^2} + \frac{d\mu}{dt} = k_4 U$$

Let's transform the equation by accepting $\frac{d}{dt} = p$:$(T_2 p^2 + p)\mu = k_4 U$

Then the proper operator has the form:$Q(p) = T_2p^2 + p$
Input action operator U: $P(p) = k_4$
Then the input transfer function Utakes the form:

$$W_{дви}(p) = \frac{P(p)}{Q(p)} = \frac{k_4}{T_2p^2 + p}$$

According to the description of the system, the equation describing the actuator with a gearbox and valve is [13]:$\mathrm{U} = \mathrm{k}_2\theta$
Let's transform the equation by accepting $\frac{d}{dt} = p$:$U = k_2\theta$

Then the proper operator has the form:$Q(p) = 1$
Input action operator θ:$P(p) = k_2$
Then the input transfer function Utakes the form:

$$W_{\partial}(p) = \frac{P(p)}{Q(p)} = \frac{k_2}{1} = k_2$$

Transfer function of the system for control action in open-loop form:

$$W_{u\theta p}(p) = W_{ли}\, W_{дви}\, W_{об} = \frac{k_0k_3k_4}{(T_1p+1)(T_2p^2+p)(T_0p+1)} = \frac{k_0k_3k_4}{T_1T_2T_0p^4 + (T_2T_0 + T_1T_2 + T_1T_0)p^3 + (T_2 + T_0 + T_1)p^2 + p}$$

In closed form:

$$W_{u\theta_3}(p) = \frac{W_{u\theta_p}}{1 - W_{конт}}$$

$$W_{конт}(p) = -W_{лу}\, W_{дви}\, W_{об}\, W_{\partial} = -W_{\partial}W_{u\theta p} = -\frac{k_0k_2k_3k_4}{T_1T_2T_0p^4 + (T_2T_0 + T_1T_2 + T_1T_0)p^3 + (T_2 + T_0 + T_1)p^2 + p}$$

$$W_{u\theta_3}(p) = \frac{k_0k_3k_4}{T_1T_2T_0p^4 + (T_2T_0 + T_1T_2 + T_1T_0)p^3 + (T_2 + T_0 + T_1)p^2 + p + k_0k_2k_3k_4}$$

Transfer function of the system for the disturbance in open form [6; 11]:

$$W_{f\theta p}(p) = W_{\sigma O3} = -\frac{k_1}{T_0p + 1}$$

In closed form:

$$W_{f\theta_3}(p) = \frac{W_{f\theta_p}(p)}{1 - W_{конт}(p)}$$

$$W_{конт}(p) = -W_{ми}\, W_{двие}\, W_{об}\, W_{\partial} = -W_{\partial}W_{и\,\theta p} = -\frac{k_0k_2k_3k_4}{T_1T_2T_0p^4 + (T_2T_0 + T_1T_2 + T_1T_0)p^3 + (T_2 + T_0 + T_1)p^2 + p}$$

$$W_{f\theta_3}(p) = -\frac{k_1(T_1T_2p^3 + (T_2 + T_1)p^2 + p)}{T_1T_2T_0p^4 + (T_2T_0 + T_1T_2 + T_1T_0)p^3 + (T_2 + T_0 + T_1)p^2 + p + k_0k_2k_3k_4}$$

Let us try to thin out the values of the amplifier coefficient. In the case where there are variable parameters, the roots of the characteristic equation of the system depend on these parameters, and the parameter space can be divided into regions that correspond to a fixed number of left roots.

Therefore, to determine the dependence of the system's stability on the values of this parameter, we will use the D-partition method [6; 11].

The equation of a closed system without a controller is:

$$W_{u\theta_3}(p) = \frac{k_0 k_3 k_4}{T_1 T_2 T_0 p^4 + (T_2 T_0 + T_1 T_2 + T_1 T_0)p^3 + (T_2 + T_0 + T_1)p^2 + p + k_0 k_2 k_3 k_4}$$

Let us designate the amplifier coefficient (k_3) as $\mu$and substitute the coefficients from Table 1 into the transfer function for the control action:

$$W_{u\theta_3}(p) = \frac{0{,}1\mu}{0{,}00702p^4 + 0{,}38856p^3 + 4{,}586p^2 + p + 0{,}14\mu}$$

Let us compose the characteristic polynomial of the closed system:

$$Q(\lambda) = 0{,}00702\lambda^4 + 0{,}38856\lambda^3 + 4{,}586\lambda^2 + \lambda + 0{,}24\mu$$

Due to the fact that the roots pass from one half-plane to another through the imaginary axis, the equation of the D-partition curve is obtained from the characteristic equation $Q(\lambda) =$ 0by substituting into it $\lambda = iw$:

$$Q(i\omega) = 0{,}00702(i\omega)^4 + 0{,}38856(i\omega)^3 + 4{,}586(i\omega)^2 + (i\omega) + 0{,}24\mu = 0$$

Resolving this equation with respect to the complex parameter:

$$\bar{\mu} = \mu + i\mu'$$

we get:

$$\mu = -0.3\omega^4 + 19{,}11041667\omega^2$$
$$\mu' = 1{,}679416667\omega^3 - 4{,}166666667\omega$$

the system is stable at $\mu(0; +\infty)$. Having adopted the gain coefficient $\mu = 5$, we will conduct a stability analysis using the Hurwitz criterion [5; 7]:

$$Q(\lambda) = 0{,}00702\lambda^4 + 0{,}38856\lambda^3 + 4{,}586\lambda^2 + \lambda + 1{,}2$$

Since all coefficients ($a_0 = 0{,}0702, a_1 = 0.38856, a_2 = 4{,}586, a_3 = 1, a_4 = 1{,}2$) are positive, the necessary stability condition is satisfied [14]. In accordance with condition [8], it is sufficient to calculate the determinant Δ_3:

$$\Delta_3 = \begin{vmatrix} a_1 & a_3 & 0 \\ a_0 & a_2 & a_4 \\ 0 & a_1 & a_3 \end{vmatrix} = \begin{vmatrix} 0{,}38856 & 1 & 0 \\ 0{,}0702 & 4{,}586 & 1{,}2 \\ 0 & 0{,}38856 & 1 \end{vmatrix} = 1{,}530561512 > 0$$

Therefore, the closed system is stable. Now we will perform a stability analysis with the coefficient $\mu = -1$:

$$Q(\lambda) = 0{,}00702\lambda^4 + 0{,}38856\lambda^3 + 4{,}586\lambda^2 + \lambda - 0{,}24$$

Since the coefficient is $a_4 < 0$, the necessary condition for stability is not met, therefore, with the coefficient $\mu = -1$the system is unstable. Thus, it is confirmed that the system is stable with the values of the coefficient $\mu(0; +\infty)$[9; 13] .

Research results and their discussion. Calculation of regulator parameters

Transfer function of the system in closed form:

$$W_{u\theta p} = \frac{0{,}2}{0{,}00702p^4 + 0{,}38856p^3 + 4{,}586p^2 + p}$$

In order to solve the synthesis problem, namely, so that the overshoot does not exceed 30%and the error for both the control and the disturbing effects is equal to zero, it is necessary to take as a normalized PF, a PF with third-order astaticism, since it must ensure our requirements. The order of astaticism is 3, i.e. $v = 3$and our object contains one integrating link, i.e. $v_0 = 1$, we obtain that the degree of astaticism will be equal to:

$$r = 3 - 1 = 2$$

Let's take a denominator polynomial of the sixth degree.

$$G_6(q) = q^6 + 36q^5 + 251q^4 + 485q^3 + 251q^2 + 26q + 1$$

The desired function takes the form:

$$W_H(q) = \frac{1}{q^6 + 36q^5 + 251q^4 + 485q^3 + 251q^2 + 26q + 1}$$

The numerator and denominator of the transfer function of the object are factorized:

$$W_{o\sigma}(s) = \frac{P(s)}{R(s)} = \frac{P^-(s)P^+(s)}{R^-(s)R^+(s)}$$

Polynomials with left zeros:

$$P^-(s) = 1, R^-(s) = 0{,}00702s^3 + 0{,}38856s^2 + 4{,}586s + 1$$

Polynomials with right and neutral zeros:

$$P^+(s) = 0{,}2, R^+(s) = s$$

The degrees of all polynomials are equal:

$$n_G = 6, n_{p^-} = 0, n_{p^+} = 0, n_{R^-} = 3, n_{R^+} = 1$$

The solvability conditions take the form:

$$\begin{cases} n_G \le n_M + n_N + 1 \\ n_G = n_{R^+} + n_N + r \\ n_{R^-} + n_M \le n_{p^-} + n_N + r \end{cases} \begin{cases} 6 \le n_M + 3 + 1 \\ 6 = 1 + n_M + 2 \\ 3 + n_M \le 0 + 3 + 2 \end{cases} \begin{cases} n_M \ge 2 \\ n_N = 3 \\ n_M \le 2 \end{cases}$$

These conditions are satisfied by $n_N = 3, n_M = 2$, respectively:

$$N(s) = a_0s^3 + a_1s^2 + a_2s + a_3, M(s) = b_0s^2 + b_1s + b_2$$

When these polynomials are substituted into the polynomial equation, it takes the form:

$$0{,}2(b_0s^2 + b_1s + b_2) + s^3(a_0s^3 + a_1s^2 + a_2s + a_3) = q^6 + 36q^5 + 251q^4 + 485q^3 + 251q^2 + 26q + 1$$

By equating the coefficients of the same powers, we obtain:

$$a_0 = 1, b_0 = 1255,$$
$$a_1 = 36, b_1 = 130,$$
$$a_2 = 251, b_2 = 5.$$
$$a_3 = 485,$$

From here:

$$N(s) = s^3 + 36s^2 + 251s + 485, M(s) = 1255s^2 + 130s + 5$$

Substituting these polynomials, as well as $P^-(s)$and $R^-(s)$into $W_p(s) = \frac{R^-(s)M(s)}{P^-(s)N(s)s^r}$, we obtain the transfer function of the controller:

$$W_p(s) = \frac{8{,}81010s^5 + 488{,}55540s^4 + 5805{,}97790s^3 + 1853{,}12280s^2 + 152{,}930s}{s^5 + 36s^4 + 251s^3 + 485s^2}$$

Transient process graph based on calculations:

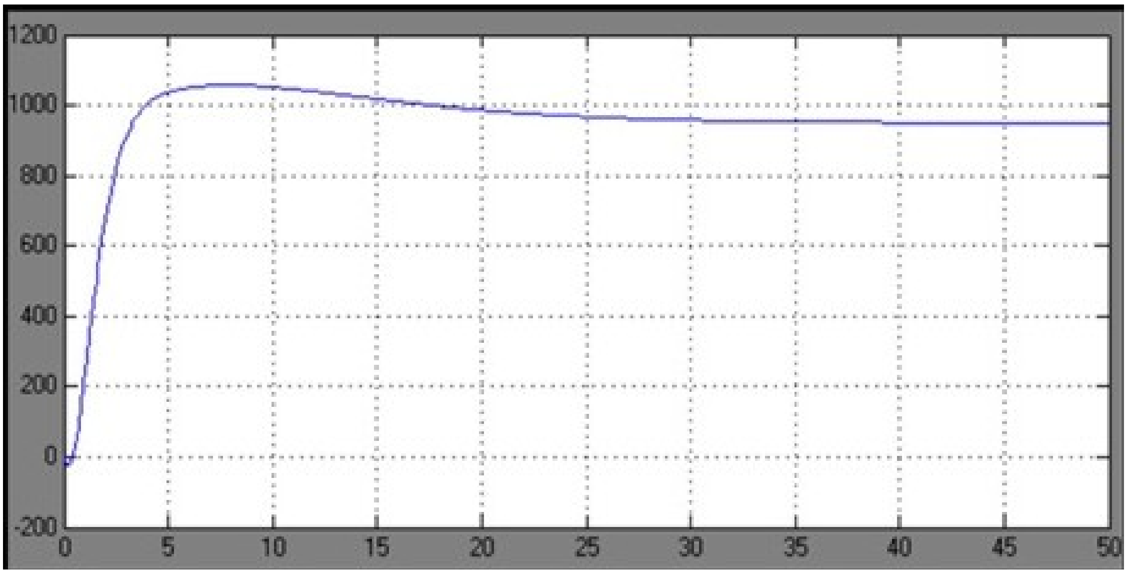

Fig. 3. Control action = 950, disturbance action 45

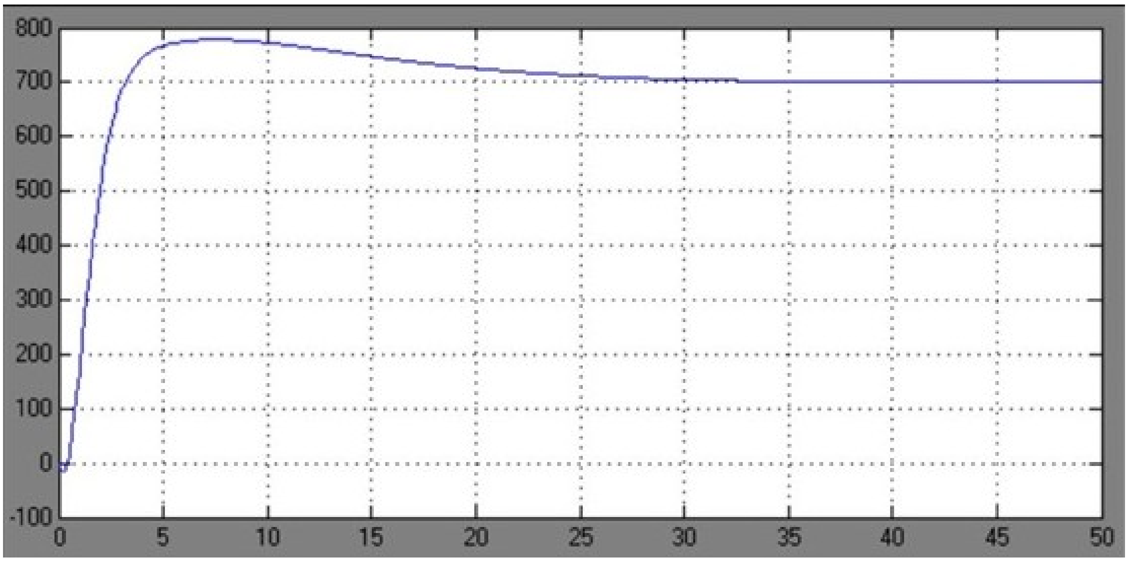

Fig. 4. Control action = 700, disturbance = 30

Conclusion. Analyzing the results of modeling a closed system in various modes, we can say that the speed and position errors are zero, the overshoot does not exceed 30%. The controller we synthesized meets the requirements imposed on it.

The proposed approach, based on PID controllers with adaptive parameter tuning, allows for changing process conditions and external disturbances to be taken into account, which can significantly improve temperature stability and reduce the percentage of defects. Further research and experimental testing of the proposed system on real production lines will confirm its effectiveness and determine the optimal parameters for various types of materials and technological processes. Successful integration of such systems requires taking into account accumulated production experience and developing new methods, which will allow for the full realization of the potential of information technology in production [12].

REFERENCES

1. Veselov GE. Komp'yuternoe upravlenie tekhnicheskimi ob'ektami. Taganrog, 2008. 182 p. (In Russ.).
2. Il'yushin YuV. Izluchenie. Aktual'nye voprosy sovremennoi nauki: collection of scientific papers. Chernov SS (ed.). Novosibirsk: NGTU, 2011. Issue 17. Part 1. P. 214-223. (In Russ.).

3. Il'yushin YuV. Parametricheskii sintez upravlyayushchikh vozdeistvii dlya stabilizatsii temperaturnogo polya izotropnogo sterzhnya. Sistemnyi sintez i prikladnaya sinergetika: collection of reports of the 4th international scientific conference. Taganrog: TTI YUFU, 2011. P. 205-212. (In Russ.).
4. Il'yushin YuV. Stabilizatsiya temperaturnogo polya v prostranstvenno dvukhmernom ob'ekte na osnove funktsii Grina. Perspektivy razvitiya informatsionnykh tekhnologii: collection of materials of the 2nd annual all-Russian scientific and practical conference. Novosibirsk: NGTU, 2011. P. 45-49. (In Russ.).
5. Chernyshev AB. Upravlenie temperaturnymi polyami ob'ektov s raspredelennymi parametrami. Bulletin of the Tomsk Polytechnic University. 2009;314(4):24-27. (In Russ.).
6. Pershin IM, Ilyushin YuV. Metod upravleniya temperaturnym polem na osnove funktsii Grina // Journal of Mining Institute. 2015;214:57-70. (In Russ.).
7. Malkov AV, Pershin IM. Sistemy s raspredelennymi parametrami. Analiz i sintez. M.: Nauchnyi mir, 2012. 476 p. (In Russ.).
8. Zaitsev SV. Realizatsiya regulyatora dvukh mernogo raspredelennogo ob'ekta // Sistemnyi sintez i prikladnaya sinergetika: collection of scientific papers of the All-Russian scientific conference. Rostov-on-Don: SFU, 2021. P. 348-350. (In Russ.).
9. Zaytsev SV. Realization of adaptive regulators in distribution control systems. Vestnik of Astrakhan State Technical University. 2020;3:99-104. (In Russ.). https://doi.org/10.24143/2072-9502-2020-3-99-104
10. Pershin IM, Nosova VA, Malkov AV. Proektirovanie raspredelennykh sistem upravleniya s ispol'zovaniem rezul'tatov eksperimental'nykh issledovanii // Sistemnyi sintez i prikladnaya sinergetika: collection of scientific papers of the All-Russian scientific conference. Rostov-on-Don: SFU, 2022. P. 218-223. (In Russ.).
11. Zaitsev SV. Metodika sinteza adaptivnykh raspredelennykh sistem upravleniya temperaturnymi polyami tunnel'nykh pechei: Avtoref. Diss… Cand. Tekhn. Sciences. Pyatigorsk: NCFU, 2012. 20 p. (In Russ.).
12. Voronin AYu, Zaitsev SV. The multidimensional control system of the thermal processes in the furnace of the tunnel type // Modern Science and Innovations. 2016;2:29-38. (In Russ.).
13. Konovalov BI, Lebedev YuM. Theory of Automatic Control. 3rd ed., suppl. and revised. St. Petersburg: Lan, 2010. 220 p. (In Russ.).
14. Petrova LS. Mathematical modeling of process of heating the multilayer bodies in the processing flows of high intensity energy on the basis of a system of nonlinear hyperbolic equations of heat conduction. Internet journal Naukovedenie. 2017;9(4):1-11. (In Russ.).

ЛИТЕРАТУРА

1. Веселов Г. Е. Компьютерное управление техническими объектами: учебное пособие. Таганрог, 2008. 182 с.
2. Ильюшин Ю. В. Излучение // Актуальные вопросы современной науки: сборник научных трудов / под общ. ред. С. С. Чернова. Новосибирск: НГТУ, 2011. Вып. 17. Ч. 1. С. 214–223.
3. Ильюшин Ю. В. Параметрический синтез управляющих воздействий для стабилизации температурного поля изотропного стержня // Системный синтез и прикладная синергетика: сб. докладов 4 международной научной конференции. Таганрог: ТТИ ЮФУ, 2011. С. 205–212.
4. Ильюшин Ю. В. Стабилизация температурного поля в пространственно двухмерном объекте на основе функции Грина // Перспективы развития информационных технологий: сборник материалов 2-й ежегодной всероссийской научно-практической конференции. Новосибирск: НГТУ, 2011. С. 45–49.
5. Чернышев А.Б. Управление температурными полями объектов с распределёнными параметрами // Известия Томского политехнического университета. 2009. Т. 314. № 4. С. 24–27.
6. Першин И. М., Илюшин Ю. В. Метод управления температурным полем на основе функции Грина // Записки Горного института. 2015. Т. 214. С. 57–70.
7. Малков А. В., Першин И. М. Системы с распределенными параметрами. Анализ и синтез. М.: Научный мир, 2012. 476 с.
8. Зайцев С. В. Реализация регулятора двух мерного распределенного объекта // Системный синтез и прикладная синергетика: сборник научных работ Всероссийской научной конференции. Ростов-на-Дону: ЮФУ, 2021. С. 348–350.

9. Зайцев С. В. Реализация адаптивных регуляторов в распределенных системах управления // Вестник Астраханского государственного технического университета. 2020. № 3. С. 99–104. https://doi.org/10.24143/2072-9502-2020-3-99-104
10. Першин И. М., Носова В. А., Малков А. В. Проектирование распределенных систем управления с использованием результатов экспериментальных исследований // Системный синтез и прикладная синергетика: сборник научных трудов Всероссийской научной конференции. Ростов-на-Дону: ЮФУ, 2022. С. 218–223.
11. Зайцев С. В. Методика синтеза адаптивных распределенных систем управления температурными полями туннельных печей: автореф. дис. ... канд. техн. наук. Пятигорск: СКФУ, 2012. 20 с.
12. Воронин А. Ю., Зайцев С. В. Многомерная система управления тепловыми процессами печи туннельного типа // Современная наука и инновации. 2016. № 2. С. 29–38.
13. Коновалов Б. И., Лебедев Ю. М. Теория автоматического управления. 3-е изд., доп. и перераб. Санкт-Петербург: Лань, 2010. 220 с.
14. Петрова Л. С. Математическое моделирование процессов нагрева многослойных тел при обработке потоками энергии высокой интенсивности на основе системы нелинейных гиперболических уравнений теплопроводности // Интернет-журнал «Науковедение». 2017. Том 9. № 4. С. 1–11.

INFORMATION ABOUT THE AUTHORS

Maxim Yu. Napalkin – specialist of the first category of the Editorial and Publishing Center, Pyatigorsk Institute (branch) North Caucasus Federal University, maksnapalkin@mail.ru

Ivan M. Pershin – Doctor of Technical Sciences, Professor, Pyatigorsk Institute (branch) North Caucasus Federal University, ivmp@yandex.ru

Contribution of the authors: the authors contributed equally to this article.
Conflict of interest: the authors declare no conflicts of interests.

The article was submitted: 01.104.2025;
approved after reviewing: 12.05.2025;
accepted for publication: 01.06.2025.

ИНФОРМАЦИЯ ОБ АВТОРАХ

Максим Юрьевич Напалкин – специалист I категории редакционно-издательского центра, Пятигорский институт (филиал) Северо-Кавказского федерального университета, maksnapalkin@mail.ru

Иван Митрофанович Першин – доктор технических наук, профессор, Пятигорский институт (филиал) Северо-Кавказского федерального университета, ivmp@yandex.ru

Вклад авторов: все авторы внесли равный вклад в подготовку публикации.
Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

Статья поступила в редакцию: 01.04.2025;
одобрена после рецензирования: 12.05.2025;
принята к публикации: 01.06.2025.