Application of Optimum Adaptive Generalized Predictive Control to Green Tea Drying

K. B. Fam[a],*, P. M. Murashev[a],, and V. N. Bogatikov [a],*****

[a] Tver State Technical University, Tver, 170026 Russian Federation
**e-mail: phambang79520897405@gmail.com*
***e-mail: myptver@gmail.com*
****e-mail: vnbgtk@mail.ru*

Abstract—One of the most frequently used operations in the processing industry is food drying. This is a complex, multiparameter, and nonlinear dynamic system, the degree of nonlinearity of which is determined by the operating range of the drying process. For a dryer to operate efficiently, it must not only be well designed, but the control strategies implemented must also be effective. And the drying process control system must maintain the necessary controlled variables in the face of many disorders that arise in production situations and the uncertainty of the conditions of the drying process. In the article, to improve the quality of process control under uncertainty in the conditions of the drying process, design methods are applied based on the use of a predictive controller for the state of system parameters using the Box–Wilson optimization method and the "experiment planning." In general, the results of the simulation of the green tea drying process control system show that the model predictive control (MPC) controller is stable and stable in terms of suppressing input disturbance. The control system of the MPC, when implementing the Box–Wilson method for the object model, provides relatively more efficient operation compared to traditional MPC.

Keywords*:* green tea drying, generalized predictive control, Box–Wilson method, "experiment design" techniques

DOI: 10.1134/S1054661823030112

INTRODUCTION

Tea is the second most consumed beverage (except water) in the world and is widely cultivated in China, India, and other regions. Green tea has been shown to reduce the incidence of chronic pathologies, such as [5] cardiovascular diseases. Moisture content is an important factor affecting the quality of tea. Excessive moisture content in tea accelerates mold growth [7]. Several studies were proposed on the relationship between the moisture content of tea and the quality of tea. In [8], it was shown that excessive aging of tea leads to a significant decrease in moisture content and inhibits the activity of polyphenoloxidase. And in [8], it was found that the decrease in moisture content led to significant changes in gene transcription and concentration of tea flavoring compounds, which enhanced the distinctive taste of various teas. Therefore, accurate control of the moisture content of tea is closely related to the quality of tea, which is of great importance in the production of tea. Currently, the control of moisture content in tea is based on the experience of workers, which is very subjective. In addition, it is difficult to guarantee the stability of the final moisture content in tea.

Received February 8, 2023; revised February 8, 2023; accepted February 8, 2023

1. HEAT TREATMENT PROCESS CONTROL STRATEGY

The main task of the drying process control is to maintain the set temperature of the drying material in conditions of uncertainty of internal and external disturbances, to control the movement of the conveyor belt to ensure the necessary moisture content in the tea leaves, preventing their overdrying (which increases energy consumption and can lead to thermal damage to thermosensitive solids), and to stabilize of the whole process.

The main parameters that determine the quality of the final product of the green tea drying process include the final humidity of green tea and the output temperature of tea. In convection drying, these parameters depend on the temperature of the drying chamber and the speed of the conveyor. Therefore, the task of the green tea drying controller is to control the heater, which ensures the rapid heating of the green tea layer to a set temperature and its further maintenance throughout the process, as well as the speed of movement of the green tea layer in the drying chamber.

A common method of process control is to use several supposedly independent control loops with feedback. Parameter control systems are implemented in the process control system to improve the performance of the process in a wide range of conditions.

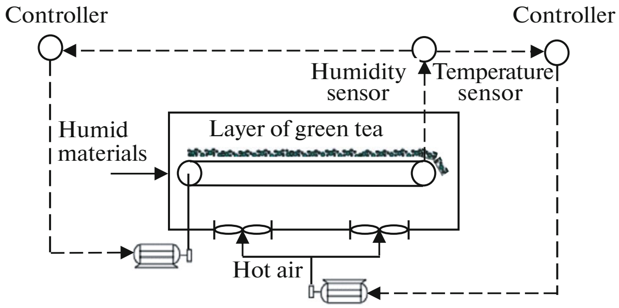

Fig. 1. Schematic of the conveyor dryer being evaluated.

Traditionally, the used regulators applied for the management of industrial technologies are proportional (P), proportional-integral-differentiating (PID), and proportional-integral (PI). This is mainly due to their ease of operation, reliability, and lack of specialized knowledge of the processes required for the initial design of the controller. The controller that provides the best performance can be selected by testing alternative combinations of P, PI, and PID controllers. There are currently three forms of self-configuring control. These are self-adjusting PID (SaPID), generalized minimum dispersion management (GMDM), and generalized predictive management (GPM). The application of SPID and GMDM control systems has been studied relatively recently and the result is presented in the works [1, 9]. The GPM provides a stable feedback response that minimizes some quadratic target function. This method of the receding horizon predicts the output of an object over several time intervals, using assumptions about future control effects [2]. With the help of the GPM, it is possible to obtain stable control of processes with variable parameters, with variable lag, provided that the input/output data are sufficient for a reasonable identification of the object.

The corresponding work is available in a previously published article on the same green tea drying system [4], which analyzed the dynamics of the green tea drying process. The reliability of the model of drying green tea leaves in a conveyor dryer has been investigated by comparing calculation and experimental data. It is shown that the program of dynamic modeling can be used in the design of the GPM system to control the temperature and final humidity of the green tea layer.

The purpose of this work is to study a new algorithm built on the joint application of the Box–Wilson method based on the planning of an experiment in the process of control of the technological process and the predictive control algorithm implemented on the MPC[1] regulator. The target function is presented in Eq. (3). And on its basis, an algorithm for controlling the drying process is built. The task is to achieve the desired moisture value of the green tea discharge layer (3–5%) and maintain the temperature to attain the heat load of the dryer, taking into account the correct flow rate of the heating layer of green tea, which is determined by the speed of the belt of the conveyor dryer. The dryer temperature is controlled by the supply of heated air.

[1] MPC—model predictive control.

It was assumed that the humidity and temperature of the green tea layer would be maintained at the desired level under optimal conditions using the GPM. The green tea dryer was given several perturbations, and the GPM system was monitored. Adding Box–Wilson process optimization at every step to predictive control makes management much more efficient.

2. CONTROL OF THE DRYING PROCESS USING THE BOX–WILSON METHOD

The conveyor dryer is designed for drying natural products (vegetables, fruits, medicinal herbs, etc.). This paper examines the drying process of green tea in such a dryer, the schematic drawing of which is shown in Fig. 1. It consists of a conveyor (1 × 10 m), which slowly moves a layer of wet material through the flow of the drying agent, and a set of temperature and humidity sensors. Preheated air with precisely defined characteristics is used as the drying agent.

The hot air is supplied at a speed of 0.08–0.13 m/s and is controlled by a calibrated temperature anemometer (405-B1) (Scantemp 410, TFA Dostmann, Wertheim-Reicholzheim, Germany) in the dryer chamber. The drying agent flows over the belt conveyor through the gaps from the bottom to the top, perpendicular to the direction of movement of the wet layer of green tea.

The loss in mass was determined in standalone mode by periodically weighing the tray on a digital balance with a resolution of $\pm 10^{-7}$ kg and located outside the chamber [9].

When designing the control system for the drying process of green tea, dynamic changes in tea humidity and drying temperature were taken into account.

The Box–Wilson method. In this work, predictive models of the drying process of green tea for control based on the Box–Wilson method were obtained [3]. The Box–Wilson method makes it possible to obtain a mathematical description of the process under study in some local region of factor space located in the vicinity of a selected point with coordinates. Let us move the origin of the factor space to the center point of the selected area as an example in Fig. 2.

Here u_i^0 is the normalized parameter that is written as [10]

$$u_i^0 = \frac{U_i - U_{i\,\mathrm{av}}}{\Delta U_i}, \quad U_{i\,\mathrm{av}} = \frac{U_i^+ + U_i^-}{2},$$
$$\Delta U_i = \frac{U_i^+ - U_i^-}{2},$$

where U_i is the actual parameter;

$U_{i\,\mathrm{av}}$ is the average value of the real parameter.

To apply this model, the output variable was expressed as a regression model with an interaction condition:

$$y = b_0 + \sum_{i=1}^{n} b_i \cdot u_i. \quad (1)$$

The matrix model:

$$Y = b_0 + B \cdot U,$$
$$B = [b_1, b_2, \ldots b_n], \quad (2)$$
$$U = [u_1, u_2, \ldots u_n]^T,$$

where b_0 is the value of the response function at the origin $b_0 = y(u_i^0)$;

y is the output of independent process variables value (temperature of the green tea discharge layer);

u_i are independent factors affecting the process flow (control effects, which are air temperature values, air movement speed and belt speed);

b_i are static linear model constants.

According to the method of planning the experiment, in order to find the constants of the linear model and apply optimization, it is necessary to conduct 2^n experiments. The "n" index shows the number of independent factors affecting the process. In this work, the matrix of the experimental plan is given in Table 1. The parameters of the first-order linear regression model are determined as follows:

$$b_i = \frac{\sum_{j=1}^{2^n} \varepsilon_{ij} y_j}{2^n},$$

where ε_{ij} are the parameter value codes in Table 1.

3. DEVELOPMENT OF CONTROL WITH PREDICTIVE MODELS USING THE BOX–WILSON METHOD

The basic idea of predictive control is to predict the future behavior of the system and obtain a locally optimal solution for the system [12]. A flowchart of the MPC system is shown in Fig. 3. The result of the solution is to determine a set of control signals corresponding to the predicted signal value in the future.

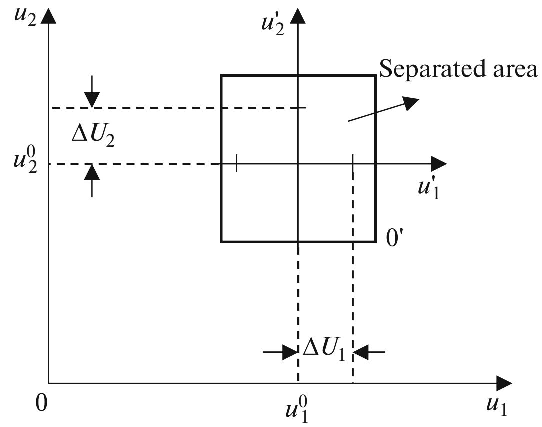

Fig. 2. Introduction of coded variables.

The work developed a regularized predictive control based on the use of the Box–Wilson method to predict the approximation of the direction of the system by the magnitude of the control signal in a small future period, finding the optimal control signal for the system at the present time. The problem of the regulator based on the use of the Box–Wilson method is solved using the convex quadratic programming (QP) problem by bringing the target function to the normal form. QP is solved using an algorithm based on the method of Lagrange multipliers.

$y(k+1|k)$ is the output forecast at the moment k; $u(k)$ is the control effect at the moment k; $y(r)$ are the set values.

3.1. The Regulator

Using the Box–Wilson method for an object model, the regular task of tracking the output with input constraints can be formulated as follows:

$$J(y, u) = \|Y_{k+1} - R_{k+1}\|_Q^2 + \|U_k - U_{k-1}\|_S^2, \quad (3)$$

Table 1. Matrix of the experimental plan

Experiment number	X_0	X_1	X_2	X_3	...	X_n
1	+	–	–	–	⋮	–
2	+	+	–	–	⋮	–
3	+	–	+	–	⋮	–
4	+	+	+	–	⋮	–
5	+	–	–	+	⋮	–
6	+	+	–	+	⋮	–
7	+	–	+	+	⋮	–
8	+	+	+	+	⋮	–
⋮	⋮	⋮	⋮	⋮	⋮	⋮

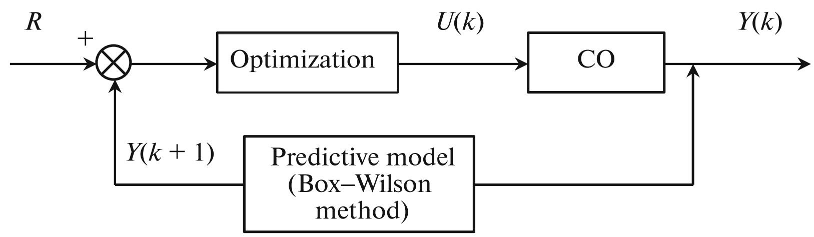

Fig. 3. Block diagram of the MPC system using the Box–Wilson method.

$$Y_{k+1} = b_0 + B \cdot U, \quad (4)$$

$$U_{\max} \geq U \geq U_{\min}, \quad (5)$$

where Q and S are the weights of regularization; Y_{k+1} is the vector of controlled variables, quality indicators (y_k^1 is the humidity of green tea, y_k^2 is the temperature of green tea); R_{k+1} is the vector of set values of quality indicators (r_k^1 is the set value of green tea humidity, r_k^2 is the set temperature of green tea); and U_k is the vector of control actions (u_k^1 is the temperature of the air, u_k^2 is the speed of movement of the belt).

This is understood as

$$\|Y_{k+1} - R_{k+1}\|_Q^2 = \|Y_{k+1} - R_{k+1}\| Q \|Y_{k+1} - R_{k+1}\|^T,$$

$$\|U_k - U_{k-1}\|_S^2 = \|U_k - U_{k-1}\| S \|U_k - U_{k-1}\|^T.$$

In this article, the solution is presented in the form of a problem of convex quadratic programming (QP), which is built in the standard form (3) [11]. There are various methods for optimizing quadratic programming problems. In this work, the finding of a solution uses an algorithm based on the method of Lagrange multipliers.

Solving the problem of optimizing quadratic programming. Target function:

$$J(y,u) = \|Y_{k+1} - R_{k+1}\|_Q^2 + \|U_k - U_{k-1}\|_S^2$$
$$= \|b_0 + B \cdot U - R_{k+1}\|_Q^2 + \|U - U_{k-1}\|_S^2$$
$$= U^T \left(B^T QB + S\right)U + 2\left(B^T Q(b_0 - R) - SU_{k-1}\right)^T U$$
$$+ \|b_0 - R_{k+1}\|_Q^2 + \|U_{k-1}\|_S^2 = U^T HU + 2g^T U + p,$$

where $H = B^T QB + S$;

$$g = B^T Q(b_0 - R) - SU_{k-1};$$

$$p = \|b_0 - R_{k+1}\|_Q^2 + \|U_{k-1}\|_S^2.$$

So $J(y,u) \to \min$ when $\frac{\partial J}{\partial U} = 0$.

From this, we get $2HU + 2g^T = 0$, whence

$$U = -H^{-1} g^T, \quad (6)$$

$$U_{\max} \geq U \geq U_{\min}. \quad (7)$$

The result of the optimization process is then applied to the object.

3.2. Development of an Automated Control System for the Drying Process of Green Tea

One of the main components of the system software is a program built on the basis of the Box–Wilson algorithm, which was proposed in the early 1950s by American scientists Box and Wilson. This approach develops a new direction of planning an experiment—orthogonal planning of an optimal experiment. The essence of the proposed method is as follows. At the first stage, for a certain local area of the existence of the object under study, the patterns of its behavior are determined by the method of planning the experiment and, as a result of their analysis, the direction to the optimum is determined, in which the parameters should be changed. Next, another experiment is carried out in a new area of the existence of the object, etc., until optimal conditions are achieved. The flow diagram of the algorithm is shown in Fig. 4.

The block diagram shows the interaction of the Box–Wilson method and the algorithm for solving the problem of quadratic programming.

Several input and output variables can be considered, but for this work, we will consider the temperature of the drying agent and the speed of the belt and the air in the chamber as input variables and the temperature and humidity of the green tea layer as output variables, since it is these two coefficients that have the greatest impact on the final quality of the tea product.

At time t, the current state of the process model is determined and control actions are calculated to minimize costs using a numerical minimization algorithm for a relatively short period of time in the future.

The predictive control algorithm shown in Fig. 4.

Step 1. Define the input parameters of the control object and limit the forecast area.

Step 2. Set the initial set of values.

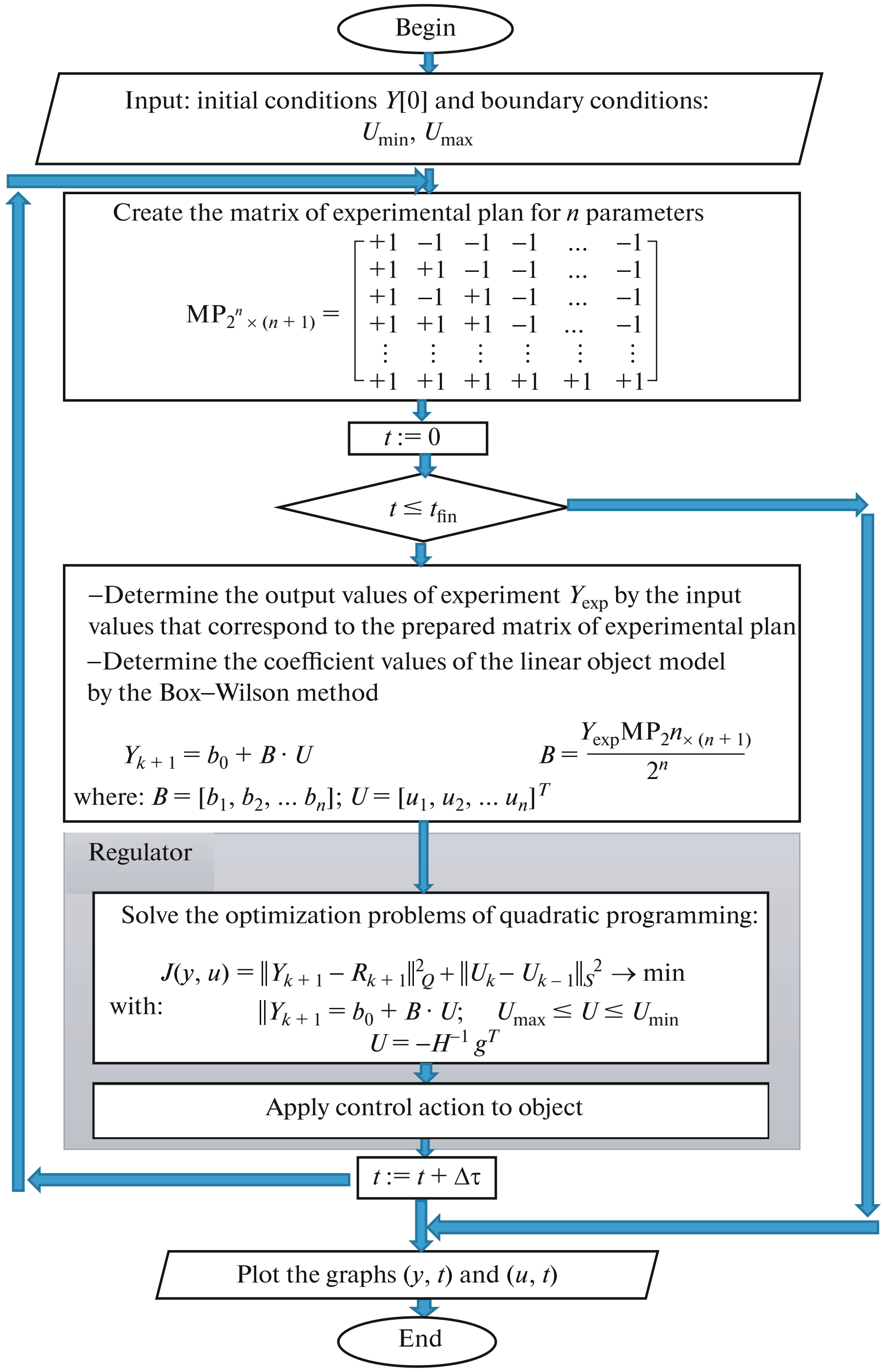

Fig. 4. Algorithm of the predictive control system based on the application of the Box–Wilson method.

Step 3. Construct and calculate the constants of the static linear predictive model of the object b_i using the Box–Wilson method based on the "experiment planning" method in the process of controlling the drying of green tea.

Step 4. Determine the output predicted value of the system $Y(k+1)$ at the moment k from the constructed model (step 3).

Step 5. Minimize the target function J.

Step 6. Identify the control signal $U(k)$.

The mathematical model for the controlled and regulated variables of the green tea dryer can be constructed as the following partial differential equations

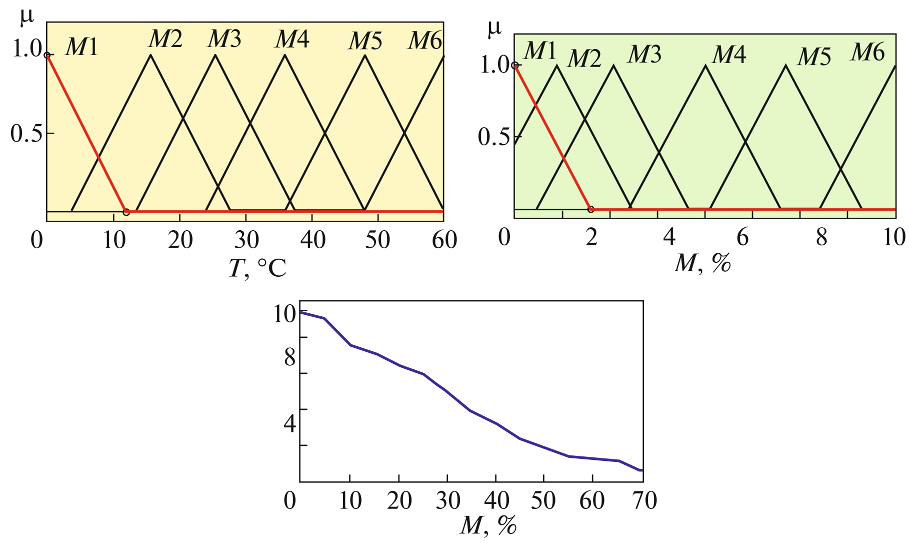

Fig. 5. Fuzzy approximation of the effect of the surface temperature of the green tea layer on humidity.

(PDEs) of the first order, which are defined as follows:

Energy transfer equation [3, 4]:

$$C_p \frac{\partial T(x,\tau)}{\partial \tau} = \lambda \frac{\partial^2 T(x,\tau)}{\partial x^2}. \quad (8)$$

Initial and boundary conditions:

$$T(x,0) = T_0, \quad (9)$$

$$\frac{\partial T(0,\tau)}{\partial x} = 0, \quad (10)$$

$$\lambda \frac{\partial T(r,\tau)}{\partial x} = k\left(T_c - T(r,\tau)\right), \quad (11)$$

where C_p is the specific heat capacity of dry leaves of green tea, $T(x, \tau)$ is the temperature of the layer of green tea, r is the thickness of the layer, λ is the coefficient of thermal conductivity, T_c is the temperature of the drying agent, k is the heat dissipation factors, and x is the axial position along the conveyor dryer.

Mass transfer equation:

$$\frac{\partial M}{\partial \tau} = -u_c \frac{\partial M}{\partial x} - K\left(M - M_e\right), \quad (12)$$

Table 2. Input and output variables

Input	Belt movement speed (u_1)
	Air speed (u_2)
	Air temperature (u_3)
Output	Humidity of tea (y_1)
	Temperature of tea (y_2)

where u_c is the speed of the conveyor belt, x is the axial position along the conveyor belt dryer, M_e is the equilibrium moisture content of tea leaves, and K is the mass transfer coefficient:

$$K = 10^{-6} T_c^{2.08} u_a^{1.11}.$$

Having solved such differential equations, we get the following mathematical model of the drying process of green tea:

$$T = \frac{\lambda^2}{kr}\frac{2}{\sqrt{\pi}}\int_{\frac{k}{2\sqrt{t}}}^{\infty} e^{y^2} d(y),$$

$$M = e^{\frac{-Kr}{u_c}} + KM_e e^{-Kt}.$$

The interaction between the surface temperature of the green tea layer and the moisture of tea leaves is a complex computational equation; therefore, to model this interaction in the proposed work, the construction of a fuzzy approximation system is used on the basis of the obtained values of experimental results and the conclusion of experts. An indistinct approximation of the effect of the surface temperature of the green tea layer on humidity is shown in Fig. 5. And a fuzzy approximation of the effect of green tea moisture on the surface temperature of the layer is shown in Fig. 6.

The result of the simulation of the control system for the drying of green tea in Fig. 6 showed that the MPC regulator is stable and stable in terms of input disturbance suppression and when implementing the Box–Wilson method for the object model in the MPC provides more efficient operation compared to traditional MPCs (Figs. 7 and 8).

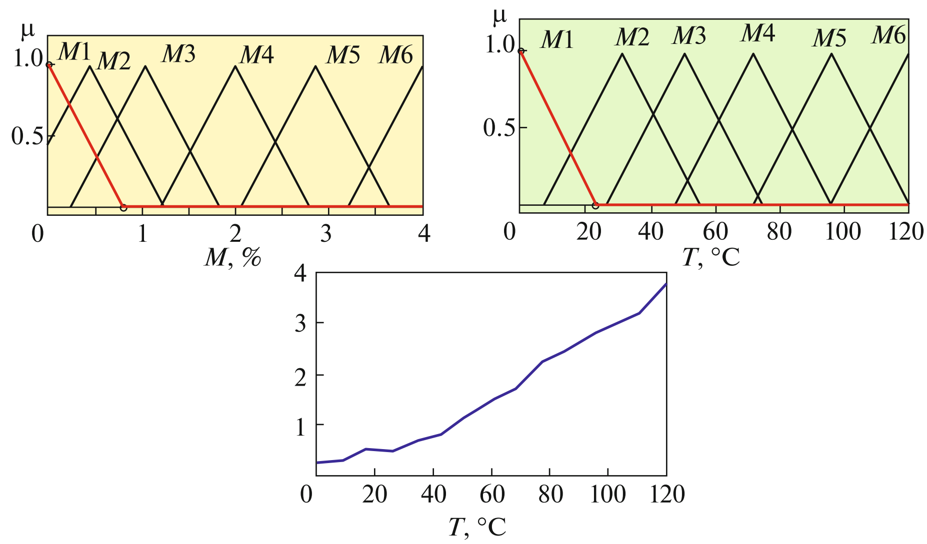

Fig. 6. Fuzzy approximation of the effect of green tea humidity on the surface temperature of the layer.

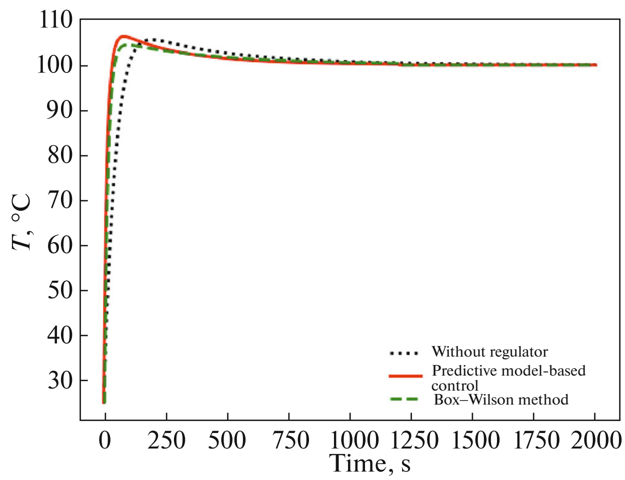

Fig. 7. The temperature of the green tea layer.

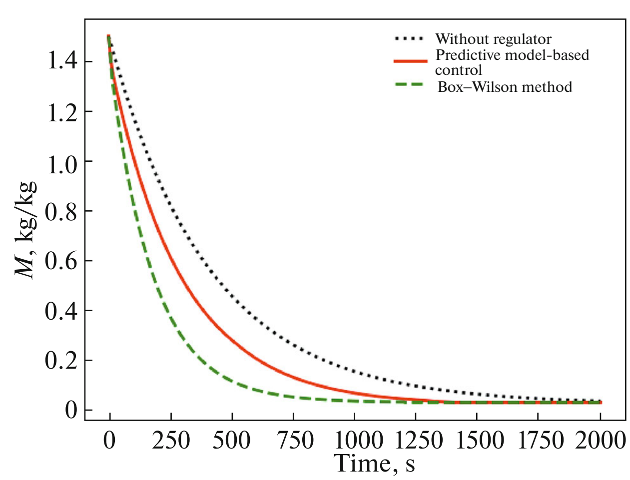

Fig. 8. The moisture content of the green tea layer.

CONCLUSIONS

Heat treatment processes such as roasting and drying are energy intensive. Given the ever-increasing cost of energy, it is necessary to improve the technology and process control system to reduce operating costs while maintaining or improving the quality of final tea products.

This work describes the design, modeling, and implementation of an automated control system for the drying process of green tea in a conveyor belt dryer based on the algorithm of the MPC regulator using the Box–Wilson method.

The drying process of green tea is modeled as a continuous system, where the control variable is the power supplied to the electric heater (temperature of the drying air), air speed, and belt speed, and the adjustable variable is the temperature and humidity of the layer of green tea in the drying chamber.

The results of the simulation of the green tea drying process control system show that the MPC regulator is stable and stable in terms of input disturbance suppression. The MPC control system when implementing the Box–Wilson method for the object model provides more efficient operation compared to traditional MPCs.

FUNDING

This work was carried out with the financial support of the Russian Foundation for Basic Research, project no. 20-07-00914.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. A. Alexandrov and M. Palenov, "Self-Tuning PID-I Controller," IFAC Proc. Volumes **44**, 3635–3640 (2011). https://doi.org/10.3182/20110828-6-it-1002.00439
2. M. P. Belov, T. H. Phuong, and D. V. Thuy, "Adaptive predictive control of servo drives of nonlinear systems with elastic links," Izv. S.-Peterb. Gos. Elektrotekh. Univ. LETI, No. **3**, 84–94 (2019).
3. G. E. P. Box and K. B. Wilson, "On the experimental attainment of optimum conditions," in *Breakthroughs in Statistics*, Ed. by S. Kotz and N. L. Johnson, Springer Series in Statistics (Springer, New York, 1992), pp. 270–310. https://doi.org/10.1007/978-1-4612-4380-9_23
4. K. B. Fam and V. N. Bogatikov, "Research of the dynamic properties of the control system with fuzzy controllers of the green tea drying process," in *Integrated Models and Soft Computing in Artificial Intelligence IMMV-2022, Kolomna, Moscow oblast, 2022* (Ross. Assots. Iskusstvennogo Intellekta, Pereslavl-Zalessky, Yaroslavl oblast, 2022), Vol. 1, pp. 145–155.
5. S. B. Khasanova, "Experimental and theoretical substantiation of the creation and standardization of medicinal herbal preparations with antioxidant activity," in *Doctoral Dissertation in Pharmacy* (Bashkir State Medical University, Ufa, 2016).
6. Yu. A. Komissarov, L. S. Gordeev, and D. P. Vent, *Processes and Apparatuses of Chemical Technology* (Khimiya, Moscow, 2011).
7. N. V. Lakiza and L. K. Neudachina, *Food Analysis* (Ural. Fed. Univ., Yekaterinburg, 2015).
8. K. M. Nikerova, "Activity of enzymes of the antioxidant system during changes in xylogenesis scenarios in *Betula pendula* Roth and *Pinus sylvestris* L," in *Candidate's Dissertation in Biology* (Karel'skii Nauchn. Tsentr Ross. Akad. Nauk, Petrozavodsk, 2020).
9. V. Pamuk, M. Alpbaz, and S. R. Asgharpour, "The dynamics of packed distillation column distillating the mixture of water-methyl-alcohol under the effect of several disturbances," Chemistry **14**, 226–253 (1990).
10. A. N. Pavlova and O. V. Kuznetsova, "Mathematical modeling and optimization of technological processes," Sovrem. Naukoemkie Tekhnol. Reg. Prilozhenie, No. 1, 78–87 (2021). https://doi.org/10.6060/snt.20216501.0010
11. The MathWorks, Inc., Model predictive control toolbox—Examples. http://www.mathworks.com/help/mpc/examples.html
12. R. N. Zhuchkov, "Application of predictive control approach in stabilizing control design of networked plants," Autom. Remote Control **76**, 1704–1712 (2015). https://doi.org/10.1134/s0005117915090167

Fam Kuang Bang is a graduate student of the Department of Information Systems of the Tver State Technical University.
He is a specialist in the field of automation of technological processes.

Pavel Mikhailovich Murashev is a graduate student of the Department of Information Systems of the Tver State Technical University.
He is a specialist in intelligent road safety systems.

Valerii Nikolaevich Bogatikov, Doctor of Engineering Sciences, Professor of the Department of Information Systems of the Tver State Technical University.
He is a specialist in the field of intelligent control systems of technological processes and production, as well as multiagent systems.