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LABORATORY STUDIES OF MATHEMATICAL MODELS THERMAL OBJECTS

Is devoted to the development and analysis of mathematical models of thermal objects. The extruder adopted as a thermal object is a vivid example of multi-zone pass-through technological units, the value of which is enormous for the domestic economy. In the article, the replacement of a real industrial object with a laboratory sample is carried out to work out the methodology of practical identification when obtaining a mathematical model with its subsequent analysis. A positive result is able to transfer the obtained results to a real technological unit. In the article, the object of research was selected, possible representations of mathematical models of industrial objects were analyzed, methods of practical identification were reviewed, the method of practical identification of thermal objects was selected, a series of natural experiments was prepared in laboratory conditions and numerical results were obtained, numerical parameters of coefficients were determined transmission and transport delay of mathematical models, time constants of mathematical models were found, analysis of mathematical models of a laboratory installation from the angle of optimization was carried out. The obtained results made it possible to correctly approach the identification of the working zone of a multi-zone pass-through technological unit using the example of an extruder, which carries out the technological process of processing agricultural raw materials by separating product fractions. Namely, decide on the type of primary converter (temperature sensor), the location of the sensors on the object, evaluate the cross effects of the heating zones in statics, choose the structure and parameters of PI (proportional, integrating components) and PID (proportional, integrating, differential components) regulators to maintain the temperature specified by the technical task in the working area of the extruder.

Keywords: practical identification, thermal object, temperature, sensor, mathematical model, Laplace transform.

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ЛАБОРАТОРНІ ДОСЛІДЖЕННЯ МАТЕМАТИЧНИХ МОДЕЛЕЙ ТЕПЛОВИХ ОБ'ЄКТІВ

Присвячена розробці та аналізу математичних моделей теплових об'єктів. В якості теплового об'єкту прийнятий екструдер з розділенням фракцій продукту – яскравий приклад багатозонних прохідних технологічних агрегатів, цінність якого для вітчизняного господарства величезна. В статті здійснене заміщення реального промислового об'єкту лабораторним зразком для відпрацювання методики практичної ідентифікації при отриманні математичної моделі з її наступним аналізом. Позитивний результат спроможний перенести отримані результати на реальний технологічний агрегат. В статті здійснений вибір об'єкта дослідження, проаналізовані можливі представлення математичних моделей промислових об'єктів, оглянуті методи практичної ідентифікації, здійснений вибір методу практичної ідентифікації теплових об'єктів, підготовлена серія натурного експерименту в лабораторних умовах та отримані чисельні результати, визначені чисельні параметри коефіцієнтів передачі та транспортного запізнення математичних моделей, знайдені сталі часу математичних моделей, здійснений аналіз математичних моделей лабораторної установки під кутом оптимізації. Отримані результати дозволили грамотно підійти до ідентифікації робочої зони багатозонного прохідного технологічного агрегату на прикладі екструдера, який здійснює технологічний процес переробки сільськогосподарської сировини шляхом розділення фракцій продукту. А саме визначитись з типом первинного перетворювача (датчика температури), місця розташування датчиків на об'єкті, оцінити перехресні впливи зон нагрівання в статиці, підібрати структуру і параметри ПІ (пропорційна, інтегруюча складові) та ПІД (пропорційна, інтегруюча, диференційна складові) регуляторів для підтримки заданої технічним завданням температури в робочій зоні екструдера.

Ключові слова: практична ідентифікація, тепловий об'єкт, температура, датчик, математична модель, перетворення Лапласа.

Selecting the research object. Modern objects belonging to the class of multi-zone passing technological units have been widely applied in various fields of industry. Much attention has been paid to the study of these objects. Currently, multi-zone units represent a fairly wide class of objects; however, the emergence of new technologies is constantly expanding this class. In particular, one of such new, most complex and insufficiently studied objects from the considered class is extruders that implement the technology of pressing vegetable oils [1].

In principle, the extruder consists of heating zones, pressing zones through which the useful product is removed, a receiving hopper, feed screws, and a matrix for forming a by-product. The prepared raw material (oilseeds) is introduced into the receiving hopper and, thanks to the feed augers, moves along the unit. Along the way, it goes through a series of stages of processing, the end result of which is a useful product (vegetable oil) and a by-product (cake).

In the first and second heating zones, the raw material is subjected to crushing, the resulting mint passes through the stage of moisture-thermal treatment, and the formed pulp enters the first zone for pre-pressing. During the first pressing, the liberated useful product is removed from the extruder, and the complex mixture, consisting of mint and pulp, undergoes the moisture-thermal treatment again and enters the second pressing zone, where the final pressing takes place. The liberated useful product is removed from the object and enters the sludge tank, where the gravity sedimentation stage takes place. A by-product in the form of a cake shell formed by the matrix is also removed from the object and enters the storage tank.

The main advantages of the considered technology and implementing equipment are:

- productivity close to optimal for a small producer (for sunflower seeds – 1200–1500 kg per 8-hour shift),
- the possibility of aggregating several extruders with a common raw material loading system and a single by-product conveyor, which allows you to focus on an average manufacturer,
- extremely low costs for maintenance personnel – one operator per unit of equipment or per aggregated group of three to five units,
- low level of energy consumption (installed power – 13 kWh, consumed – 10 kWh),
- no need for preliminary processing of raw materials (washing, frying, etc.) and additional processing of a

useful product (the processed product is separated into oil and fuz by a three-day settling at room temperature),

- a wide range of processed crops (sunflower, soybeans, rapeseed, mustard, corn, cotton, etc.), quick and easy changeover to another oilseed crop (replacement of pressing sleeves),
- small dimensions and weight,
- the possibility of the extruder operating in a mobile version for processing customer-supplied raw materials at the place of its deployment.

The only fundamental drawback is the low (compared with the complete process) yield of a useful product – 33–42 % with an oil content of the feedstock of at least 50 % [2]. This disadvantage is largely compensated by the fact that the resulting by-product with an oil content of up to 18 % is an excellent high-protein supplement for poultry, fish, and cattle, which can be effectively used.

Ukraine is a country with great agricultural potential. However, the production of a large range of food products requires the creation of a powerful production base for processing, storage, etc. these goods. At the same time, in the light of new economic relations, the processing industry is of particular importance.

Insufficient production volumes of domestic food products are immediately compensated by an increase in their import purchases, although such a solution is not always acceptable. In Ukraine, production capacities in the processing of oil-seeds are used on average by 35 %. The main reasons for poor performance:

- lack of working capital,
- lack of supply high-quality raw materials for enterprises,
- high cost of raw materials,
- constant increase in prices for energy carriers and transport services,
- unsettled issues of payments and mutual debt between suppliers of raw materials, processors and trade organizations, the budget and off-budget state funds.

All this leads to high costs per unit of output, reduces the competitiveness of domestic food products over imported ones.

Given the above, the widespread introduction of the considered equipment in the domestic economy is of particular importance. The listed advantages of the selected object are consistent with modern trends in production. Therefore, a detailed study of multi-zone passing technological units with separable product fractions is a very urgent task.

Problem statement. According to the experts in this work, who are called on to focus on the control of the working thermal zone of the extruder. The main parameter of the thermal zone is the temperature in the range 0–300. From one side, the temperature is one of the widest parameters, from the other side, the most important and last parameter. In any case, the development of temperature processes in the working thermal zone of the extruder is the necessary intellectual motivation and information and control systems and automatic control systems, including computerized ones, which are necessary for optimizing the functioning of the selected industrial object.

The construction of systems for control, diagnosis or management of industrial equipment, to intensify its work, or to optimize according to the selected quality indicator, is impossible without a detailed study of the object. With a scientific approach, such a study is implemented by building a mathematical model of the object or mathematical models of the processes that take place in this object. The presence of a mathematical model allows, on the one hand, to carry out analytical or simulation modeling procedures, with further verification of the results obtained during modeling by field tests. On the other hand, the mathematical model allows you to make optimal technical decisions, for example, choosing the type of sensors depending on the selected criteria, determining the places of installation of sensors, identifying the number of sensors for successful monitoring of thermal processes, etc.

The most popular mathematical models of the studied objects are differential equations in partial derivatives (for the analogue case) or difference equations (for the digital representation). The disadvantage of these equations is their almost complete inapplicability in engineering calculations. Therefore, in practice, they use the transformation of differential equations into algebraic ones using the Laplace transformation with further use in engineering analyses.

The synthesis (building) of mathematical models is fundamentally possible in two ways:

- analytical,
- practical identification.

In this article, the way of building a mathematical model by methods of practical identification is chosen.

The main task set by the authors is to replace a real industrial object with a laboratory sample, to obtain experimental data for such a sample and to work out the methodology of practical identification. A positive result is able to transfer the obtained results to a real technological unit.

Thus, the goal of the research is the synthesis (building) of a mathematical model of the thermal working zone of multi-zone passing technological units on the example of an extruder.

The object of research is mathematical models of industrial equipment in the form of algebraic equations.

The subject of research is methods of practical identification.

The main tasks set by the authors:

- analyse the representation of mathematical models of industrial objects,
- carry out an overview of practical identification methods,
- choose a method of practical identification of thermal objects,
- to form a laboratory sample of a thermal object, which would have technical indicators adequate to a real industrial object,
- prepare a set of primary transducers (sensors) and organize measuring channels with automatic indication of the result,
- prepare and implement a series of field

experiments,

- to determine the numerical parameters of the transmission coefficient and transport delay of the mathematical model,
- determine the time constants of the mathematical model,
- optimize the order of the mathematical model by changing the location of the sensor or selecting the type of sensor.

These tasks are basic. In the course of research, additional problems of a conceptual and technical nature were certainly considered.

Determining the mathematical model of the object or the processes occurring in it is an extremely important task in researching industrial and agricultural equipment [3]. The availability of mathematical models of objects and processes allows you to obtain the characteristics of the equipment, determine its main parameters, conduct theoretical and simulation modeling, etc. Without existing mathematical models of objects and processes, it is impossible to competently synthesize control or management systems of the researched equipment [4].

Building mathematical models of objects and processes is fundamentally possible in two ways:

- theoretical synthesis [5],
- obtaining models experimentally [6].

Experimental and theoretical ways have their advantages and disadvantages. Therefore, most studies try to combine, to a reasonable extent, the advantages of these approaches. In this article, it was decided to focus on obtaining models of objects and processes of industrial and agricultural equipment experimentally. The choice of the experimental method in the development of mathematical models, chosen for the study of the unit, is determined by the presence of sensors of identified parameters, the presence of standard recorders, the presence of proven and well-recommended methods of information processing, a priori information about the structure of the research object.

The method of practical identification was chosen as the basic method of obtaining models of objects and processes. This makes it possible to obtain dynamic models with the detection of transport delays, inertias, oscillations and to move from models with distributed parameters to models with concentrated parameters [7].

Analysis of the representation of mathematical models of industrial objects. Based on the accepted class of models, as well as on the analysis of the physical nature of the object, it is appropriate to use the method of practical identification by transient characteristics [8]. The chosen method involves applying unitary functions of the "rectangular wave" type or close to it to the object and measuring the output coordinate with the measuring channel. In practice, the identification algorithm must be implemented on the basis of an experimental setup. The installation should be abstracted from the influence of destabilizing factors and the possibility of measuring the transient characteristics of the research object should be made possible through multiple observations.

The obtained mathematical model can be presented in the form [8]:

- differential equation:

$$(T_1^2 p^2 + T_2 p + 1) y = kx,$$

where k – link transmission ratio,
T_i – time-constant,
p – the Laplace operator,
moreover T_1 and T_2 are linked by a condition:

$$\varsigma = \frac{T_2}{2T_1} < 1,$$

- in the form of a transfer function:

$$W(p) = \frac{k}{T_1^2 p^2 + T_2 p + 1},$$

- in the form of a transient characteristic:

$$h(t) = k\left[1 - \frac{\sqrt{\alpha^2 + \beta^2}}{\beta} e^{\alpha t} \sin(\beta t + \operatorname{arctg}\frac{\beta}{\alpha})\right],$$

where $\alpha = -\dfrac{T_2}{2T_1^2}$, $\beta = \dfrac{\sqrt{4T_1^2 - T_2^2}}{2T_1^2}$.

- in the form of an amplitude-phase function:

$$W(j\omega) = \frac{k(1 - T_1^2\omega^2) - jkT_2\omega}{(1 - T_1^2\omega^2)^2 + T_2^2\omega^2},$$

- in the form of amplitude and phase-frequency functions:

$$\begin{cases} A(\omega) = \dfrac{k}{\sqrt{(1 - T_1^2\omega^2)^2 + T_2^2\omega^2}}, \\ \varphi(\omega) = -\operatorname{arctg}\dfrac{T_2\omega}{1 - T_1^2\omega^2}. \end{cases}$$

All methods of representing the mathematical model of the object, and in this case the oscillating link, are identical. In these studies, the representation method based on the transfer function is adopted:

$$W(p) = \frac{k}{T_1^2 p^2 + T_{2i} p + 1}.$$

Review of methods of practical identification. One of the main tasks of identification of industrial objects is the determination of dynamic characteristics by transient functions. There are seven main methods, each of which has its own advantages and disadvantages. In this review, the indicated methods are classified and the one that is optimal based on the criteria of simplicity and convenience for further calculations is selected.

Classification of methods [9]:

1. Approximation of the transient characteristic by the solution of a differential equation with simple real roots.
2. Approximation of the transient characteristic by the solution of a differential equation with simple roots.
3. Determination of transfer function coefficients by

the "area" method.

4. Approximation of the transient characteristic by the solution of the second-order differential equation.

5. Approximation of the transient characteristic by the solution of the first-order differential equation with a delay.

6. Approximation of the transient characteristic by the solution of a differential equation with multiple real roots.

7. Approximation of transient characteristics of objects containing integrating links.

Each of the mentioned methods is a method of practical identification, each has its own advantages for certain conditions, known types of objects, peculiarities of operating conditions.

For this case, considering that the investigated equipment is a thermal inertial object, which is described by an inertial link with a delay, which means that it is represented by aperiodic processes, the most successful choice for identification is the first method - the method of successive logarithms.

This method is grapho-analytical and allows for both structural and parametric identification.

Choosing a method for practical identification of thermal objects. The method of successive logarithms is used to identify smooth non-oscillatory transition functions represented by the expression [10]:

$$h(t) \approx c_0 - \sum_{i=1}^{n} c_i e^{-\alpha_i t} ,$$

where $c_0 = h \approx h(T_y)$, c_i and α_i – real numbers, and the roots of the characteristic equation α_i must satisfy the empirical inequality

$$\frac{\alpha_i}{\alpha_{i+1}} \le 0{,}5 \div 0{,}7 ;\ i = 1, 2, ..., n-1 .$$

These conditions mean that the transfer function $W(p)$ has only simple poles located at a sufficiently large distance from each other along the real axis.

The idea of the method consists in successive approximation $h(t)$ first by solving the equation of the first order, the function $c_1 e^{-\alpha_1 t}$, and if this approximation is unsatisfactory, then the second component is taken into consideration $c_2 e^{-\alpha_2 t}$, that is, the order of the approximating equation is taken equal to 2, etc. The unknown c_i and α_i are determined at each stage of approximation using the logarithm operation, as a result of which this method received the name of the method of successive logarithms. The sequence of actions when using it is as follows:

1. An experiment is conducted to obtain the transient characteristics of a thermal object.
2. The sampling time is determined Δt.
3. A tabular dependency is built $T_i^{\text{o}} = f(t_i)$.
4. A graphical dependency is built $T^{\text{o}} = f(t)$.
5. The net lateness time is cut off τ.
6. The transmission coefficient is determined k. $k = T^{\text{o}}_{\text{уст}} / A_{\text{вх}}$.
7. A tabular dependency is built $\left|h_1\right|_i = f(t_i)$. $\left|h_1\right|_i = T^{\text{o}}_{\text{уст}} - T^{\text{o}}_i$.
8. A tabular dependency is built $\lg\left|h_1\right|_i = f(t_i)$.
9. A graphical dependency is built $\lg\left|h_1\right| = f(t)$.
10. An asymptote to the dependence is drawn $\lg\left|h_1\right| = f(t)$ at $t \to \infty$.
11. Parameters are defined $\lg c_1$ and t_1.
12. Parameter is defined α_1. $\alpha_1 = \dfrac{\lg c_1}{t_1}$.
13. Time-constant is determined T_1. $T_1 = \dfrac{1}{\alpha_1}$.
14. A tabular dependency is built $c_i = c_1 e^{-\alpha_1 t_i}$.
15. A tabular dependency is built $\left|h_2\right|_i = \left|h_1\right|_i - c_1 e^{-\alpha_1 t_i}$.
16. The numerical values of the non-relational functions are evaluated $\left|h_2\right|_i$, after that the order of the transfer function is determined $W(p)$.
17. Paragraphs 8–16 are repeated of this algorithm.
18. The iterative method proves the position when the values of the non-relational functions are unrelated $\left|h_j\right|_i \approx 0$ in the entire time range.
19. The transfer function (mathematical model) has the form [8]:

$$W(p) = \frac{k}{(1+pT_1)(1+pT_2)...(1+pT_n)} e^{-p\tau} .$$

The algorithm is presented graphically in the Fig. 1.

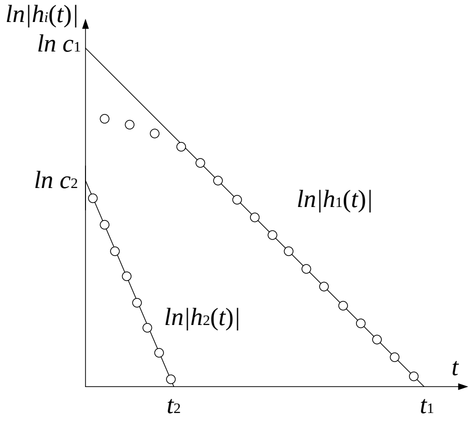

Fig. 1. The method of successive logarithms

The practice of applying the method of successive logarithms to determine the dynamic characteristics of the transient characteristics of industrial objects shows that in the vast majority of cases $h(t)$ it is possible to approximate the sum of two to four exponents.

It is possible to approximate the sum of two to four exponents. c_i and roots α_i is carried out according to the transient characteristic, from which the net delay time and the transmission coefficient have already been determined k.

Preparation and results of a natural experiment. In order to obtain a mathematical model of the thermal object, a number of natural experiments were performed (Novovolyn Scientific Lyceum of the Volyn Regional Council, physics department) and the results were processed.

Two types of primary Einstein transducers (sensors) were chosen for the experiments, which are assembled in a measuring channel with a digital output and a USB output port. The software (interface), which polls the port according to the corresponding exchange protocol, is supplied by the manufacturer.

The first sensor. Copper sensor, the sensitive element is made in the form of a probe. The external view is shown in Fig. 2.

The main characteristics of the sensor:
- range of measured temperatures: –40–140 °C,
- measurement error: ± 2 %,
- resolution: 0,03 °C,
- sampling frequency: 10 samples per second,
- response time: 40–60 sec.

Fig. 2. Temperature sensor with a copper sensitive element

The second sensor. Thermocouple, the sensitive element is made in the form of a "drop". The external view is shown in Fig. 3.

Fig. 3. Temperature sensor with a sensitive element in the form of a thermocouple

The main characteristics of the sensor:
- range of measured temperatures: 0–1200 °C,
- measurement error: ± 2 %,
- resolution: 0,03 °C,
- sampling frequency: 10 samples per second.

Both selected sensors are supported by MiLAB software (see Fig. 4).

Experiment 1. Prepared installation (see Fig. 5) involves the following chain:

heater → water → water → sensor.

Such transitions equate to transitions between nodes of the studied industrial object.

A copper sensor was used for the experiment.

The input of the step function ("rectangular wave" function) was implemented by supplying power to the heating element. The output transient characteristic $h(t)$ was recorded by the measuring channel (see Fig. 6).

Fig. 4. Using the interface

Fig. 5. Layout of the experimental setup

As a result of the experiment, data was obtained that indicate the presence of a transport delay (see Fig. 6), which will clearly affect the dynamic indicators of the object when conducting simulation modeling or a full-scale experiment.

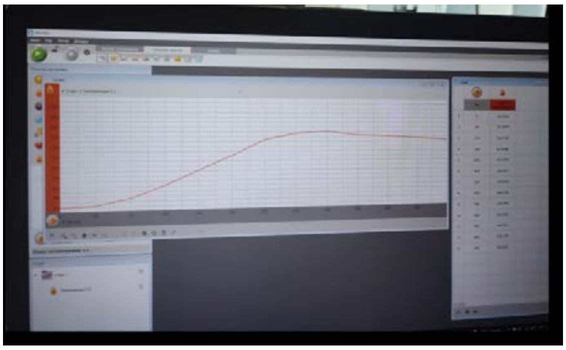

Fig. 6. Transient characteristic fixation

Experiment 2. To reduce the impact of traffic delays, a setup was prepared (Fig. 7), the purpose of which was to eliminate this harmful parameter.

The experimental data demonstrate the absence of transport delay τ (see Fig. 8).

Experiment 3. The layout of the experimental setup is presented in Fig. 9. During the experiment, a sensor based on a thermocouple was used.

In the third experiment, the chain is used:

heater → metal → sensor.

The transient characteristic $h(t)$, in this case, received the minimum value of the transport delay τ and a high indicator of the transmission coefficient k.

Fig. 7. Layout of an experimental installation with a reduced rate of transport delay

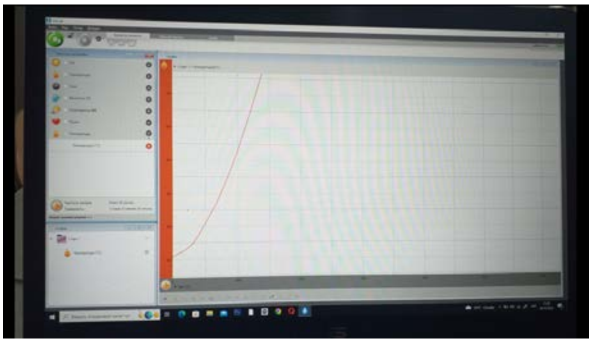

Fig. 8. Acceleration part of the transient characteristic of the experimental setup with a reduced transport delay indicator

Fig. 9. Layout of the experimental setup using a thermocouple

Determination of the numerical parameters of the transmission coefficient and transport delay of the mathematical model. The method of successive logarithms involves determining the order of the mathematical model and the time constants T_i of this model. The determination of the transport delay τ and the transmission ratio k is determined directly from the transient characteristic $h(t)$.

The transmission coefficient is determined by the ratio:

$$k = \frac{T^{\text{o}}_{\text{уст}}}{A_{\text{вх}}},$$

and the transport delay is determined from the condition:

$$0 \le h(t) < \Delta,$$

where Δ – error of measuring equipment.

Taking into account the conditions for finding the two specified parameters of the mathematical model, it is obtained:

- Experiment 1. $k = 0{,}43\frac{^{\text{o}}\text{C}}{\text{B}}$, $\tau = 300$ с,
- Experiment 2. $\tau = 0$ с,
- Experiment 3. $k = 0{,}78\frac{^{\text{o}}\text{C}}{\text{B}}$, $\tau = 0$ с.

Determination of time constants of the mathematical model. The determination of the time constants of the mathematical model is carried out on the basis of the algorithm presented in this article above.

According to the data of the first experiment, a transient characteristic was formed, which is presented in Fig. 10.

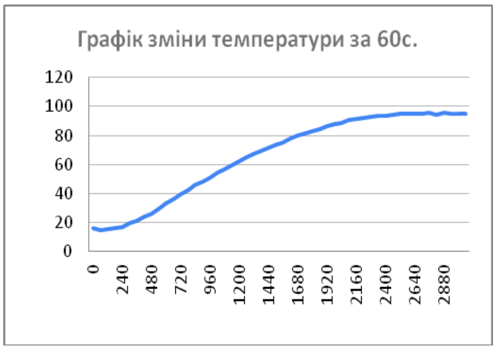

Fig. 10. Transient characteristic (experiment 1)

The experimental data were processed by the method of successive logarithms according to the given algorithm. According to the results of experimental data processing by the method of sequential logarithm, the resulting table was formed (Table 1).

Table 1 – Identification results by experiment 1

Constant values	
Voltage, V	220
Time delay, min	5
Maximum temperature, °C	95,04757
t_1, min	35
lnc1	8,5
α_1	0,242857143
Time constant 1	4,117647059
t_2, min	25
lnc2	17
α_2	0,68
Time constant 2	1,470588235
t_3, min	22
lnc3	16,7
α_3	0,759090909
Time constant 3	1,317365269

The data in Table 1 indicate the 3rd order of the transfer function and determine the time constant T_i.

The data of experiment 3 were processed in a similar way. The resulting table was formed based on the results of the experiment 2.

The order of the mathematical model (experiment 3) equals to 2.

Table 2 – Identification results by experiment 3

Constant values	
Voltage, V	220
Time delay, min	0
Maximum temperature, °C	170,79296
t_1, min	32
lnc1	12,6
α_1	0,39375
Time constant 1	2,53968254
t_2, min	30
lnc2	12,4
α_2	0,413333333
Time constant 2	2,419354839

Analysis of mathematical models of the laboratory installation. Based on the results of the research, mathematical models of the thermal object were found. Laboratory samples were used as a thermal object.

The general appearance of the mathematical model of the thermal object is as follows:

$$W(p)=\frac{k}{\prod\limits_i \left(1+pT_i\right)}e^{-p\tau}.$$

For the chain

heater → water → water → sensor

the mathematical model took shape:

$$W(p)=\frac{0{,}43}{\left(1+4{,}12p\right)\left(1+1{,}47p\right)\left(1+1{,}32p\right)}e^{-5p}.$$

For the chain

heater → metal → sensor

the mathematical model:

$$W(p)=\frac{0{,}78}{\left(1+2{,}54p\right)\left(1+2{,}42p\right)}.$$

The comparison of models indicates a significant simplification of the structure when shortening the transmission chain of the thermal process and the correct choice of the primary transducer (sensor).

Research conducted in laboratory conditions can be extrapolated to real industrial objects and showed how important the choice of the sensor and its location on the object is for simplifying control, diagnostic or management systems. In this case, it concerns the object of the class of multi-zone passing technological units – an extruder for the production of vegetable oils.

Conclusion. As a result of the conducted scientific research, a mechanism for obtaining a mathematical model of a thermal object by means of practical identification by the method of successive logarithms was developed. A mathematical model is an algebraic equation and can easily be used for analytical and simulation modeling.

During the implementation of the experimental part, the tasks of minimizing the impact of transport delay τ, acquiring the nominal value of the transmission coefficient k, and eliminating time constants of high orders T_i were performed. This made it possible to lower the order of the transfer function, $W(p)$, which is the mathematical model of the thermal object.

The obtained results made it possible to correctly approach the identification of the working zone of a multi-zone passing technological unit using the example of an extruder, which carries out the technological process of processing agricultural raw materials by separating product fractions. Namely, determine the type of primary transducer (temperature sensor), the location of the sensors on the object [11], evaluate the cross effects of heating zones in statics using the Bristol matrix [12], choose the structure and parameters of PI (proportional, integrating components) and PID (proportional, integrating, differential components) of regulators to maintain the temperature specified by the technical task in the working zone of the extruder.

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