RESEARCH AND DEVELOPMENT OF THE DRYING TECHNOLOGY

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Abstract. Static and dynamic characteristics of the drying process as an object of automation are experimentally determined in the work. It was established that the drying object can be represented as two linked "air" – "drying object" and has interconnected input and output parameters. A mathematical description of the static and dynamic characteristics of the drying process as an object of automatic regulation has been researched and carried out. With the help of mathematical processing of experimental data, mathematical dependences on the studied regulation channels were obtained as the transfer functions, differential equations, and acceleration curve equations. The obtained experimental time characteristics of the drying object on different control channels are approximated with an error of less than 3% by differential equations of the 1st order with a delay. The object is characterized by variable constant time and delay time values for different drying phases.

Key words: Automatic regulation, temperature, humidity, drying, regulation channel, differential equation.

1. Introduction

Drying is a complex technological heat and mass exchange process that must ensure the preservation of all the properties of substances in the drying product, which is possible if the optimal parameters of this process are observed. Thus, during drying, the thermodynamic and thermophysical properties of the drying product, in particular, heat capacity and thermal conductivity, constantly change. It is necessary to strictly follow the recommended drying modes depending on the humidity and the intended purpose of the drying product. One of the ways to solve this problem, according to the authors, is research and mathematical description of static and dynamic characteristics of drying objects, as well as mathematical processing of experimental data. The mathematical interpretation of the studied phenomena should be the basis for the development, modeling, and substantiation of the parameters of the automation systems of specific drying facilities under the technological maps of the drying processes of these facilities.

2. Drawbacks

Each object of drying has its specificity, which determines the need to apply and strictly observe variable drying modes, which are characterized by a certain ratio at individual stages of the technological process of the temperature and humidity of the drying agent. Research into the automation of the drying process is being conducted in the direction of increasing the number of analyzed parameters of drying chambers [1-2], developing and improving the element base, in particular sensors, which are used to form primary information about the state of the microclimate in the drying chamber [6, 8, 9], executive mechanisms, microcontrollers [5, 7], simplifying the process of developing software for microcontrollers, which control executive mechanisms. The main defects of technological solutions are the inaccuracy of individual elements of automation, unsatisfactory consideration of the specifics of the drying process, and agrotechnical requirements for the finished product at a minimum of proper communication between regulatory parameters. The shortcomings of drying equipment and the lack of reliable process automation systems significantly reduce the effectiveness of artificial drying.

3. Goal

Study the characteristics of drying objects to improve the technological process by a control system.

4. The drying process as an object of automatic regulation

Knowledge of the static and dynamic qualities of the drying process as an object of automation is necessary for substantiating the rational scheme of automatic regulation, choosing the type of regulator, and setting it correctly.

The study of these patterns is possible both theoretically and experimentally. In the first case, the equations of dynamics and statics are made based on the analysis of physical processes in the object, and the application of the laws of conservation of energy and matter. Experimental methods require minimal data on the essence of the processes. They consider several factors of the differential equations of dynamics or transfer functions of automation objects. These methods are easy in a mathematical description. Considering the complexity of the drying process due to the simultaneous flow of heat and mass exchange phenomena, the dynamic and static properties of the automation study objects were determined experimentally.

The temperature during the drying process can worsen the quality and speed of drying. Optimum moisture level is an important factor in achieving a quality product. Automatic regulation can maintain the desired level of humidity during the drying. Setting up automatic regulation can help reduce energy consumption in the drying process, optimize the use of heat and other resources, and reduce heat and energy losses. By the technological requirements, the input and output parameters of the object are selected and the internal connections between them are a priori planned (Fig. 1).

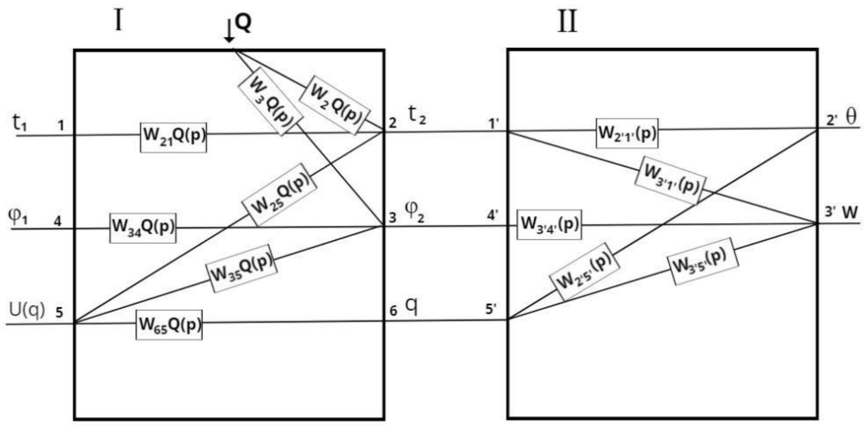

Figure 1. Structural diagram of the "air-drying object" system: 1 – air, 2 – drying object, W(p) – transfer functions.

Therefore, the drying process is characterized by a set of interconnected parameters shown on the structural diagram of the regulatory object. Here, the structural diagram of the "air-drying object" system is conventionally depicted as two sequentially connected links (I-II). In drying units, these links are combined. The input parameters of the first link are temperature t_1, humidity φ_1, air flow rate q, which is supplied to the heater, and the amount of heat Q, which was released by the heater or its power P. The output parameters of the first link and, accordingly, the input parameters of the second link are temperature t_2, relative humidity φ_2, and airflow rate q at the outlet of the heater. Neglecting the expansion of air during heating, its consumption before and after the heater is assumed to be the same. The initial parameters of the second link and the entire facility are the following parameters, temperature Θ and humidity W of the drying facility. It is necessary to mathematically describe the set of specified parameters and connect the group of initial parameters with the group of input values by a system of equations.

On the structural diagram, the connection of input and output parameters is shown in the form of transfer functions W(p) by channels: W_2 Q(p) is air temperature in the drying chamber t_2; is heater capacity P(Q); W_1 (Q)(p) – air humidity in the chamber φ_2; is heater capacity P(Q); W_{21} (P) is temperature in the drying chamber t_2; is outdoor air temperature t_1; W_{34} (P) is relative air humidity in the drying chamber φ_2; is relative humidity of the outside air φ_1. W_{25} (P) is air temperature t_2; air consumption q; W_{35} (P) is relative humidity $\varphi_{2;}$ is air consumption q; $W_{2`1`}$ (P) is the temperature of the drying object Θ; is air temperature t_2; $W_{3`1`}$ (P) is the humidity of the drying object W; is air temperature t_2; $W_{3`4`}$(P) is humidity of the drying object W; is relative humidity φ_2; $W_{4`3`}$ (P) is relative humidity φ_2; is humidity of the drying object W; $W_{2`5`}$ (P) is temperature of the drying object Θ; is air consumption q; $W_{3`5`}$(P) is humidity of the drying object W; is air consumption q.

The dynamic properties of the dryer under study were determined by removing the transient characteristics during the jump-like impact of each of the parameters of the input group separately during a pre-stabilized process. The size of the drying chamber is 13,25 x 5,75 x 2,9 m. Static characteristics were determined by the channel "heater power (P) – air temperature in the chamber (t_2)" at a constant air flow rate (q):

$$t_2 = f[P(t)]_{q=const} \qquad (1)$$

Knowledge of such a static characteristic is necessary to be convinced of the correctness of assumptions about the linearity of dynamic characteristics.

The static characteristics of the object under study (Fig. 2) were measured over the entire temperature range when the drying chamber was empty (curve 1), when the drying chamber was fully loaded (curves 2, 3, 4), and in the phases of drying (curves 3' and 4').

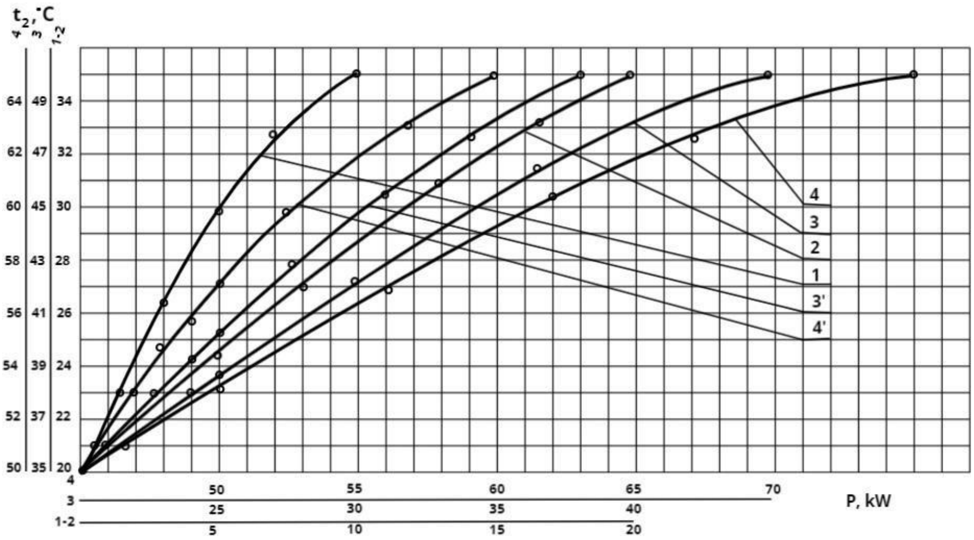

Figure 2 Static characteristics of the object according to the channel "air temperature t_2 – power of the heater P" at q=const: 1- with an empty drying chamber; with a loaded drying chamber: 2 – temperature up 35^{0}C, 3 – temperature 35-50^{0}C, 4 – temperature 50-65^{0}C, 3` – the 1st day of drying, humidity 50%, 4` – the 2nd day of drying, humidity 20%.

For the mathematical description of the static characteristics of the control channel "Air temperature t_2 – power of the heater P"- a graphical method was used [3, 5]. The obtained experimental data were approximated by equations:

$$t_2 = AP^B, \quad (2)$$

where B and A are constant parameters of the equation. Taking logarithm from the equation (2), we obtain:

$$lg\, t_2 = lg\, A + B\, lg\, P \quad (3)$$

According to (3), graphs were built, with the help of which the values of parameters A and B were determined (Table 1).

Equation (3) is non-linear. Nevertheless, considering temperature changes occur within limits during the operation of the automatic regulation systems, it was assumed that the static characteristics can be linearized:

$$f(p) = f(a) + \frac{p-a}{1!}f'(a) + \frac{(p-a)^2}{2!}f'(a) + \cdots + \frac{(p-a)^n}{n!}f^n(a) + R_n(p), \quad (4)$$

where a is the specified power coordinate, which value was selected from Fig. 2:

$$t_2 = 15 + (p - 10)\,1.05 \quad (5)$$

Analysis of other curves in Fig. 2 has underlined that the static characteristics of the object are linear.

Table 1. Values of parameters A and B

Number of the curve in Fig. 2 / parameters	1	2	3	4	3’	4’
A	3	1.5	1.2	0.95	1.8	2.1
B	0.7	0.79	0.8	0.81	0.74	0.72

5. Study of the dynamic characteristics of the drying process

The dynamic properties of the object were determined by the transient process that appeared while introducing regulatory influence into the technological mode of operation. In addition, the object under study, as shown by previous studies, is characterized by the relative inertia of transient processes along regulation channels. To obtain a simplified methodology for the synthesis of regulating scheme, the time characteristics were determined.

The study of the dryer according to the channel "air temperature t_2 – power of the electric heater P” was carried out with a jump-like change in the air heating power and with a pre-stabilized drying process, which is characterized by a constant value of the relative humidity of the air entering the chamber. The dynamic characteristics of the drying chamber were determined at partial and full loading of material at different process phases. For each phase of the drying process, the difference between the initial and established temperature values was equal to 15^{0}C, which provides for the specified limits of temperature changes during the transition from one drying phase to another. Analysis of the transient characteristics of air heating in the dryer for different modes of the drying process (Fig. 3) shows that with different values of input disturbances, to obtain the same constant value of air heating, different air heating time was required drying chamber is 60 minutes. The duration of heating period in the loaded drying chamber was 87 minutes for phase I at 35^0C, and 94 and 102 minutes for the II ($35\text{-}50^0$C) and III ($50\text{-}65^0$C) phases, respectively.

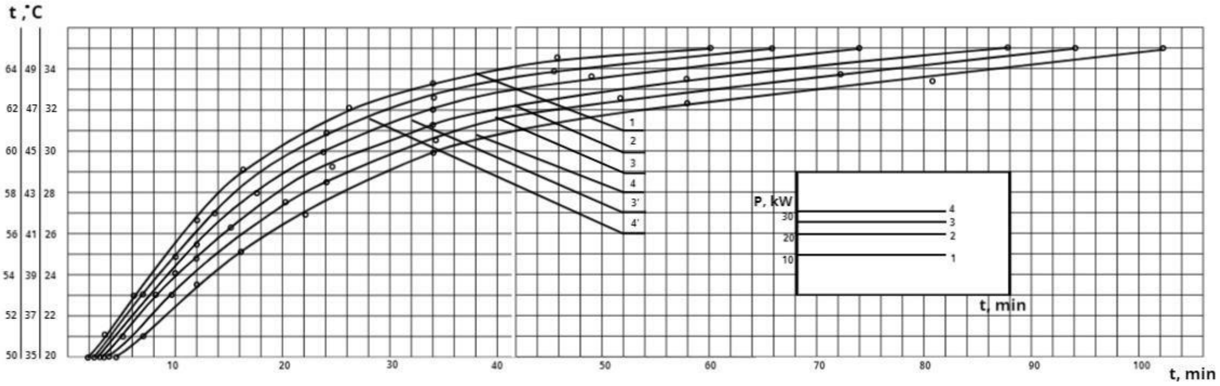

Figure 3 Time characteristics of the object according to the channel "air temperature in the chamber t_2 – power of the heater P": 1- when the drying chamber is empty; with a loaded drying chamber: 2 is temperature up 35^0C, 3 is temperature $35\text{-}50^0C$, 4 is temperature $50\text{-}65^0C$, 3`concerns the 1st day of drying, temperature $35\text{-}50^0C$, humidity 50%, 4` concerns the 2nd day of drying, temperature $50\text{-}65^0C$, humidity 20%.

The study of the drying process on the channel "Relative air humidity φ_2 – air consumption q" was carried out with a sudden change in the amount of fresh air supplied to the chamber and a stabilized relative air humidity φ_2. The ventilation system of the chamber works in the air recirculation mode. When the $t_2 = 35^0$ C and relative air humidity φ_2=80% are set in the chamber, the ventilation system switches from the "recirculation" mode to the moisture emission mode. At the same time, fresh air is supplied to the chamber, which is preheated, and moist air is released into the atmosphere. Transient characteristics were recorded on the control channel under consideration. The humidity of the drying object in the first phase was 75%, in the second phase – 47%, in the third – 22%.

Transient characteristics along the control channel "Temperature of the drying object Θ – air temperature t_2" were recorded when the temperature t_2 in the dryer changed and the relative air humidity φ_2 was stable. Since the object is quite inertial and it is impossible to achieve a jump-like change in the air temperature, then studies were carried out in the following way.

In the drying chamber, the appropriate values of temperature and relative air humidity were set ($t_2 = 35^0$C, φ_2 =80%), due to technological requirements. Then the temperature of the control batch of the drying object was measured. In this case, it was 20^0C. With the stabilized values of the parameters t_2 and φ_2, the control batch of the drying object was introduced into the drying chamber and the time taken as the beginning of the transition process was recorded. According to the described method, transient characteristics were recorded along the considered channel for the second and third phases of drying, with the only difference being that the control batch was transferred from one chamber of the dryer to the second, while simultaneously fixing its initial parameters. Transient characteristics are graphically shown in Fig. 4.

Transient characteristics on the control channel "Humidity of the drying object W – air temperature t_2", were recorded. The initial humidity was W_p=85%. The final humidity of the drying object W = 30% was taken for the first phase. The final value of the humidity of the drying object for the second drying phase is W = 10%, the final humidity of the drying object for the third phase is W = 5%.

The following parameters were set in the drying chamber: a) for the I phase, $t_2 = 35^0$C, φ_2 = 80%; b) for the II phase, t_2 = 50°C and φ_2 = 50%; c) for the third phase of drying t_2 = 65°C and φ_2 =30%. Initial values of relative humidity were: a) for the I phase φ_2 =95%; b) for the II phase φ_2 =80%; c) for the III phase of drying φ_2 =50%.

The dynamic properties of the object on the cross channels "Temperature of the drying object Θ – air consumption q and "Humidity of the drying object W – air consumption q," were recorded for the 1st phase. Transient characteristics were determined in the following way. Control batches of the object drying was placed in three chambers. The temperature and relative humidity of the air were stabilized in the first chamber q =10000 m^3/h in the second and – q = I5000 m^3/h in the third chamber =20000 m^3/h.

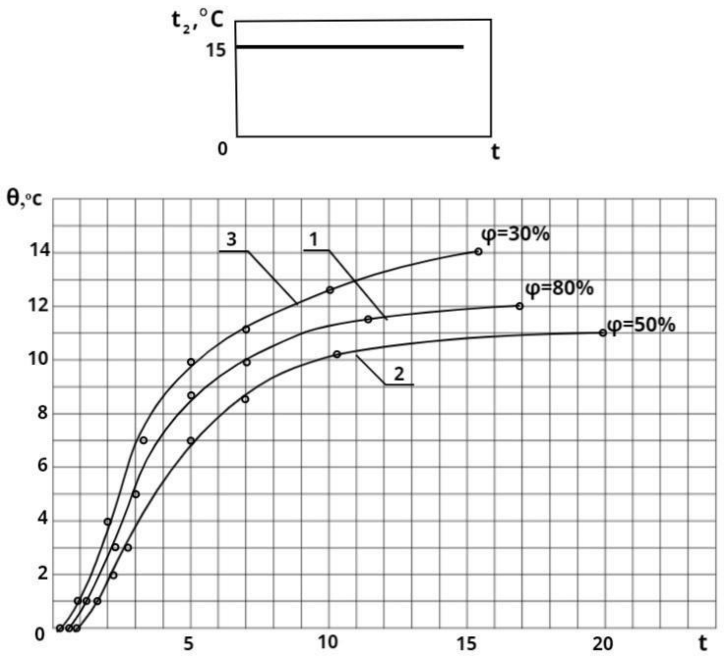

Figure 4 Time characteristics on the channel "temperature of the drying object Θ – air temperature t_2": 1 is the first phase of drying, 2 is the second phase of drying, 3 is the third phase of drying,

During the operation of the drying unit, moist air is periodically removed, and fresh air accumulated, the temperature of which is lower than in the chamber. Therefore, the time characteristics were determined by the control channel "Air temperature t_2 – air consumption q". The following operating parameters were set in the chamber: $t_2 = 35^0$ C and φ_2=80% for the I phase; $t_2 = 50^0$C φ_2 =50% for the II phase and t_2 = 65°C, φ_2 =30% for the III phase. Air consumption q changed in leaps and bounds. During the drying process, as a result of the dehydration of the wet drying object, the relative air humidity φ_2 increases. In this regard, time characteristics were determined on the channel "Relative air humidity – humidity of the drying object". The following values of air temperature t_2 were set in the drying chamber: for the I phase $t_2 = 35^0$C, for the II phase of drying $t_2 = 50^0$C, and for the III phase of drying t_2 = 65°C. After reaching the above temperature values, the relative air humidity φ_2 was measured. The humidity of the drying object in the I phase was W = 80%, in the II drying phase W = 50%, and in the III drying phase W = 20%.

Dynamic characteristics of control objects are the transfer functions Wp of differential equations (De) and amplitude-phase characteristics (APH). For the mathematical description of time characteristics, we chose the method of taking sequential logarithms [7-9]. Since the time characteristics of each control channel have a net delay, the approximation becomes much more difficult, since the order of the differential equation of the object being described increases. It is appropriate to consider the object of regulation by isolating the link of pure delay and presenting it as two sequentially connected links. In this case, the general transfer function is defined by the following expression:

$$W(p) = W_1(p) \cdot W_2(p), \qquad (6)$$

where $W_1(p) = e^{-p\tau}$ is pure delay transfer function; $W_2 \, p)$ is the transfer function of the link with a transient process without net delay. The equation of the part of the curve without net delay can be represented as a sum of exponents:

$$Y(t) = K - \sum_{m=1}^{n} C_m e^{Pmt} \qquad (7)$$

at $t = \infty$ $\quad t \approx \sum_{m=1}^{n} C_m e^{Pmt}$, (8)

where K is amplification factor; C_m is a constant; P_m are the real roots of the characteristic equation. As time increases, the terms $C_m \cdot e^{P_m t}$ of the equation decrease. As time increases, the equality hold:

$$Y(t) = K - C_1 \cdot e^{p_1 t} \qquad (9)$$

Taking logarithms from this expression, we get the equation of a straight line:

$$\lg(K - Y(t)) \approx lgC_1 + 0.434P_1 t \qquad (10)$$

Starting from a certain point, the curve $\lg(K - Y(t))$ differs a little from its asymptote – the straight line $lgC_1 + 0{,}434P_1t$. The segment cut off by the asymptote on the ordinate axis is equal to lgC_1 i.e.:

$$lgC_1 = \lg(K - Y(t)) = 0$$

At the moment of time corresponding to the point of intersection with the abscissa axis, the equality holds:

$$\lg(K - Y(t)) = 0 = lgC_1 + 0.434P_1 t \qquad (11)$$

We determine the value of the root from equation (11):

$$P_1 = -\frac{lg\,C_1}{0.434t} \quad (12)$$

determine the second root of P_2, we perform similar calculations. The equation obtained from the experimental overclocking curve without the net lag section can be written in the following form:

for I order $Y\ t\ = K - \ C_1 \cdot e^{p_1 t}$

for II order $Y\ t\ = K - \ C_1 \cdot e^{p_1 t} - C_2 \cdot e^{p_2 t}$

The initial conditions are zero and, accordingly:

$Y(t)_{t=0} = 0$ and $Y(0) = K - C_1 - C_2 = 0$

$Y`(t)_{t=0} = 0$ and $Y`(0) = C_1P_1 + C_2P_2 = 0$

If equation (13) corresponds to the experimental acceleration curve, let's transform it according to Laplace kind:

$$X_{output}\ P\ = \frac{K}{P} - \frac{C_1}{P+P_1} - \frac{C_2}{P+P_2}, \quad (14)$$

Dividing the latter by the Laplace transform of the input signal, $X_{вх.} = \frac{A}{P}$ we obtain the transfer function of the object $W_2(p)$.

$$W_2\ p\ = \frac{X_{output}\ p}{X_{input}\ p} =$$

$$= \frac{P^2(K-C_1-C_2)+P(KP_1+KP_2-C_1P_2-C_2P_1)+KP_1P_2}{A(P+P_1)(P+P_2)} \quad (15)$$

But since K- C_1 – C_2 = O, then

$$W_2(p) = \frac{P(KP_1+KP_2-C_1P_2-C_2P_1)+KP_2P_1}{A(P+P_1)(P+P_2)} \quad (16)$$

By replacing the value of K in the terms in parentheses with $C_1 + C_2 = K$, we obtain

$$W_2(p) = \frac{P(C_1P+C_2P_2)+KP_2P_1}{A(P+P_1)(P+P_2)} \quad (17)$$

Given that $C_1P_1+C_2P_2=0$, then

$$W_2(P) = \frac{K}{A(\frac{1}{P_1}P+1)(\frac{1}{P_2}P+1)} \quad (18)$$

Marking $\frac{K}{A} = K_{уст.}$; $\frac{1}{P_1} = T_1$ and $\frac{1}{P_2} = T_2$, get:

$$W_2(P) = \frac{K_{уст.}}{(T_1P+1)(T_2P+1)} \quad (19)$$

Considering the net lateness, we obtain

$$W(P) = \frac{K_{уст.} \cdot e^{-p\tau}}{(T_1P+1)(T_2P+1)} \quad (20)$$

6. Results of data processing

Mathematical dependences on the studied regulation channels were obtained as transfer functions W(P), differential equations, and equations of acceleration curves. For the regulation channel "Air temperature – power of the heater P" equations of the II and I orders are used. The curves constructed by differential equations of the 1st and 2nd orders almost coincide, so we describe the experimental curves for all control channels by differential equations of the first order and transfer functions of the first order with a delay. The transfer functions are given only for the regulation channel "t_2- P" since they are generally the same for all regulation channels. Tables 2 and 3 have summarized the time constants, amplification factors, and delay times for the studied channels.

For the regulation channel "Air temperature t_2 – heater power P" we give the corresponding mathematical dependencies and summarize the coefficients in Table 2.

Differential equation of the second order:

$$T_1{}^2 \frac{d^2t_2(t)}{dt^2} + (T_1 + T_2)\frac{dt_2(t)}{dt} + t_2(t) = K_{est}P(t-\tau) \quad (21)$$

The equation of the acceleration curve

$$t_2 = K - C_1 e^{-\frac{t-\tau}{T_2}} + C_2 e^{-\frac{t-\tau}{T_2}} \quad (22)$$

Differential equation of the first order:

$$T_1\frac{dt_2(t)}{dt} + t_2(t) = K_{est}P(e-\tau) \quad (23)$$

The equation of the acceleration curve

$$t_2 = K(1 - e^{-\frac{t-\tau}{T_1}}) \quad (24)$$

Transfer function $W_1(p)$:

$$W_1(P) = \frac{K_{est}e^{-p\tau}}{T_1P+1} \quad (25)$$

For the rest of the control channels, we present the corresponding mathematical dependencies for the I, II and III drying phases and summarize the dependencies and coefficients in Table 3.

Table 2. Parameter values for the control channel "Air temperature t_2 – heater power P"

The name of the parameter and its value	Curve numbers in Fig. 3					
	1	2	3	4	3’	4’
τ, min	2.5	3.0	4.0	5.0	2.7	2.6
T_1, min	15.2	22.6	24.4	27.2	18.4	16.4
$K_{est,}\ \frac{^0C}{kW}$	1.5	0.75	0.6	0.5	0.83	1.5
K, ^{0}C	15.0	15.0	15.0	15.0	15.0	15.0
C_1, ^{0}C	15.8	15.85	15.86	15.9	15.7	15.8
C_2,^{0}C	0.8	0.85	0.87	0.9	0.7	0.8
T_2, min..	7.2	7.2	7.15	7.0	7.0	7.2

Table 3. Differential equations, acceleration curve equations and parameter values for control channels

The name of the parameter and its value	Differential equation	The equation of the acceleration curve	Drying phases		
			I	II	III
Control channel "Drying object temperature -- air temperature t_2"					
τ, h.	$T\frac{dQ\;t}{dt}+Q\;t\;= K_{est}t_2(t-\tau)$	$Q=K(1-e^{-\frac{t-\tau}{T}})$	0.5	0.8	0.4
T, h.			6.2	8.2	5.5
$K_{est}, \frac{^0C}{^0C}$			0.8	0.73	0.93
K, ^{0}C			12.0	9.0	14.0
Control channel "Humidity of the drying object W -- air temperature t_2"					
τ, h	$T\frac{dW\;t}{dt}+W\;t\;= K_{est}t_2(t-\tau)$	$W=C_1e^{-\frac{t-\tau}{T}}+C_2$	1	1	1
T, h			12	10	8
W_{p}, %			85	50	25
$C_1=W_p-C_2$, %			55	40	20
C_2, %			30	10	5
$K_{est}, \frac{\%}{^0C}$			3.7	2.7	1.3
Control channel "Temperature of the drying object Q -- air consumption q"					
τ, h.	$T\frac{dQ\;t}{dt}+Q\;t\;= K_{est}q(t-\tau)$	$Q=K(1-e^{-\frac{t-\tau}{T}})$	0.4	0.5	0.6
T, h.			5.4	6.2	6.8
$K_{est}, \frac{^0C}{m^3/h}$			0.0012	0.0008	0.006
K, ^{0}C			12	12	12
Control channel " Humidity of the drying object W -- air consumption q"					
τ, min	$T\frac{dw(t)}{dt}+W(t)=K_{est}q(t-\tau)$	$W=C_1e^{-\frac{t-\tau}{T}}+C_2$	1	1	1
T, min			13	12	11
C_2, ^{0}C			85	85	85
$C_1=t_{2p}-C_2$, ^{0}C			55	55	55
t_{2p}, ^{0}C			30	30	30
$K_{est}, \frac{^0C}{m^3/h}$			0.0055	0.0036	0.0027
Control channel "Air temperature t_2 – air consumption q"					
τ, min	$T\frac{dt_2\;t}{dt}+t_2\;t\;= K_{est}q(t-\tau)$	$t_2=C_1e^{-\frac{t-\tau}{T}}+C_2$	1	1	1
T, min			10	9	8
C_2, ^{0}C			30	42	55
$C_1=t_{2p}-C_2$, ^{0}C			5	8	10
t_{2p}, ^{0}C			35	50	65
$K_{est}, \frac{^0C}{m^3/h}$			0.0005	0.0008	0.001
Control channel "Relative humidity φ_2 – humidity of the drying object W"					
τ, min	$T\frac{d\varphi_2\;t}{dt}+\varphi_2\;t\;= K_{est}W(t-\tau)$	$\varphi_2=K(1-e^{-\frac{t-\tau}{T}})$	2	2	3
T, min			9,8	11	13
$K_{est}, \frac{\%}{\%}$			0,43	0,8	2
K, %			95	80	70
Control channel "Relative humidity φ_2 – air consumption q"					
τ, min	$T\frac{d\varphi_2(t)}{dt}+\varphi_2=K_{est}q(t-\tau)$	$\varphi_2=C_1e^{-\frac{t-\tau}{T}}+C_2$	2,5	2,5	2,5
T, min			9,8	8	6
C_2, %			40	30	20
$C_1=\varphi_p-C_2$, %			40	20	10
φ_p, %			80	50	30
$K_{est}, \frac{\%}{м^3/h}$			0.004	0.002	0.001

Based on the conducted research, it can be stated that the object can be represented in the form of two links "air" and "drying object" and has interconnected input (t_1та W_0) and output (t_2 , φ_2 , q, W, Q) parameters. The maximum spread of air temperature in the drying chamber does not exceed ± 2.5^0, relative air humidity ± 9%. The set values do not go beyond the permissible deviations of the mode parameters provided by the technological requirements. The statistical characteristics of the object are linearized within 15 ± 3°C with an error of 3%, which indicates the linearity of the object. The obtained experimental time characteristics of the object on different control channels are approximated with an error of less than 3% by differential equations of the 1st order with a delay. The object is characterized by variable constant time (T) and delay time (τ) values for different drying phases. For the "air" link, τ is 1-5 min., T = (8-27.2) min., for the "drying object" link, τ varies within 0.4-1 h., T – within (5.5-13) h. In this way, regulation laws and optimal regulator setting parameters are defined.

7. Conclusions

1. Automatic regulation of the drying process is important to ensure high quality. First, it was accepted that the process of artificial drying should be carried out in three phases with the provision of the following temperature and humidity regime: I phase: t = 35°C; φ = 80%; II phase: t = 45°C; φ = 50%; III phase: t = 65°C; φ = 30%. The following automation requirements are formulated: the statistical error of temperature adjustment Δt_c and relative air humidity $\Delta\varphi_c$ would not exceed ± 1°C and, accordingly, ±7,5%; maximum regulation of temperature t_g and relative air humidity φ_g can be 4°C and 10%.

2. The study of the properties and features of the production plant for drying as an object of automation made it possible to establish that: the object can be represented in the form of two "air" links – "drying object" and has interconnected inputs t_1 , φ_1 , g and initial parameters t_2 , φ_2 , g, W, Ɵ; the statistical characteristics of the object are linearized within 15 ±3°C with an error of 3%, which indicates the linearity of the object; obtained transmission functions of the object on the experimental regulation channel; the approximation error does not exceed 3%. The object is characterized by different values of constant time (T) and delay time (τ) for different phases of drying; for the "air" link, τ is 1-5 min., T = 18-27.2 min., for the "drying object" link, τ varies within 0,4-1 h, T – within (5.5 – 13) h.

3. Modeling of the drying process, the developed mathematical description of the static and dynamic characteristics of the technological drying process gives the possibility to conclude how the system reacts to external influences and what changes may occur over time and also to predict how the system functions in different conditions and what corrective actions may be necessary. Then you can determine the optimal para- meters of regulators or control algorithms to achieve the desired dynamics of the system, such as reaction speed, stability, accuracy, etc.

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9. Mutual claims of authors

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Reference

1. Automation of production processes: a study guide/ V.O.Fedynets, I.S.Vasylkivskyi, G.A. Nikolin. – Lviv: SPOLOM, 2022.- 192 p. URL:http://www.lvivpolitechnic.com.ua/
2. Executive devices of automation systems: educa- tional. guide/I.S. Vasylkivskyi, V.O. Fedynets, J.P. Yusyk.-Lviv: Publishing House of Lviv Poly- technic, 2020. – 220 p. URL: http://www. lvivpolitechnic.com.ua/, https://vlp.com.ua/node/ 20204.
3. Katsuhiko Ogata, *Modern Control Engineering*,Pearson Education, Inc., Prentice Hall, 2010, 905p.URL: http://surl.li/sxpsm
4. Vasyl Fedynets, Ihor Vasylkivskyi. Theory and practice of temperature measurement by thermoelectric transducers // Energy and control systems. – 2023. – Vol. 9, № 2. – P. 82–92. URL:https://science.lpnu.ua/sites/default/files/journal-paper/2023/dec/32755/jeecs-09-02-2023-paper-04-pdf DOI: 10.23939/jeecs ISSN: 2415-7287(Online) 2411-8028 (Print)
5. T. A. Kinney, Proximity sensors compared: Inductive, capacitive, photoelectric and ultrasonic, Online: http://machinedesign.com/sensors/proximity-sensors-compared-inductive-capacitive-photoelectric-and-ultrasonic (accessed on 2024-03-31)
6. T. Agarwal, Temperature sensors – Types, Working & Operation, white paper, Online: http://www.elprocus.com/temperature-sensors-types-working-operation/ (accessed on 2024-03-31)
7. Common Actuator Types, Online: http://www. vma.org/?ActuatorTypes (accessed on 2024-03-31)
8. 50 Sensors Applications for Smarter World, Libelium, Online: http://www.libelium.com/ top_50_iot_sensor_applications_ranking/ (accessed on 2024-03-31)
9. Rayes, A., Salam, S. (2022). The Things in IoT: Sensors and Actuators. In: Internet of Things from Hype to Reality. Springer, Cham. https://doi.org/ 10.1007/978-3-030-90158-5_3