Information control system for dynamic modes of tumble dryer

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Abstract. The development of information and control systems that provide solutions to the tasks of energy-saving management of complex technological objects is an urgent problem, since the introduction of such systems in various industries allows not only to reduce energy costs significantly, but also to improve the quality of products. One of the most labor-intensive stages in the development of an information control system is the creation of its algorithmic support, since the models, methods and algorithms being developed must take into account all the specific features of the control object. Modern industrial production, as a rule, includes many energy-intensive technological processes and facilities, among which it is possible to distinguish drying processes, which are widespread. The article deals with the development of algorithmic and software of information and control system by dynamic modes of tumble dryer unit used for distillery dreg drying. While the algorithmic support developing, methods of analysis and synthesis of systems at a set of operating states, the Pontryagin maximum principle, the method of synthesizing variables and graph theory were used. The software modules of the information control system that implement the developed algorithmic software are integrated into the existing production management system. The developed control system allows reducing energy costs in dynamic modes of drying processes by 3-10%.

1. Introduction

Currently, more and more attention is paid to energy conservation. One of the ways to reduce the cost of products and improve the competitiveness of production is the introduction of information management systems (IMS) by energy-intensive objects. The most frequently used energy-intensive technological objects in the industry are drying installations. This paper discusses the features of the development of IMS by dynamic modes of the tumble dryer operation (IMS TD).

The theoretical basis of the study was scientific works on the theory of optimal control of M. Atans, P.L. Falb [1]; A.E. Bryson, Yu Shi Ho [2]; E.B. Lee, L. Marcus [3]; R. Bellman [4]; L.S. Pontryagin [5]; Yu.L. Muromtsev et al. According to the results of the analysis of the current state of research on the issues of IMS building with complex technological objects, the following problem areas can be identified:

1) in a number of currently used production management systems, there are no algorithms that allow energy-efficient management by the dynamic modes of drying installations, which makes the work practically relevant;

2) existing methods for developing of algorithmic support of IMS by multidimensional objects based on the theory of optimal processes, methods of variational calculus, dynamic programming method do not meet practical needs from the point of view of the efficiency of developing algorithmic support of IMS by multidimensional objects that characterizes the scientific relevance of the work.

2. Formalization and mathematical formulation of the problem of optimal control of a drying installation at a lot of functioning states

The control object is a drum shell-and-tube dryer of the “Vetter” brand. The design of the drying unit is shown in fig. 1. Structurally, the drying unit is a fixed body frame I, inside which there is a rotating...
drum 2. The drum and, accordingly, dreg are heated by using steam and it is carried out according to the countercurrent principle (the direction of movement of steam in pipes is opposite to the direction of material flow in the drying unit). The steam supply to the dryer and condensate drainage is ensured by means of automatic sealing steam heads 3 and 5, respectively. On the outer circumference of the rotating drum, there are lifting and feeding scrapers 6 that transport the material to be dried from inlet 7 to outlet 4. Air enters through the existing air intake windows 8. Vapor is discharged by means of an exhaust fan 9.

![Figure 1](image1.png)

**Figure 1.** 1 - body frame; 2 - drum; 3 - steam supply; 4 - dry dreg output; 5 - exhaust steam output; 6 - scrapers; 7 - dreg input; 8 - air intake windows; 9 - exhaust steam

The block diagram of the drying unit as a control object is presented in fig. 2. The following actions are considered as control actions: control of steam supply $u_1(t) = p(t) \cdot us(t)$ (where $p(t)$ is vapor pressure, $us(t)$ is the degree of the steam head opening, 0 - 100% and exhaust fan power control is $u_2(t)$. Controlled state variables are: $z_1(t)$ is the temperature of the output material; $z_2(t)$ is the temperature of the exhaust vapor; $z_3(t)$ is the air temperature in the dryer; $z_4(t)$ is the oxygen content in the air of the dryer. The output variable is dreg humidity $y(t)$.

![Figure 2](image2.png)

**Figure 2.** Structural diagram of the drying installation as a control object

The mathematical formulation of the problem was carried out taking into account several assumptions:

1) considering that the optimal control is calculated from the point of view of a program strategy (before the start of control, the entire control trajectory is calculated for the entire transition), as well as the net delay ratio (1.5-3.5 min for various types of control and state variables) to the time of the transition process (1.5-2h / 90-120 min), the net control delay in the model is neglected;

2) considering the large number of possible operating states of the control object and transitions between them, it is impossible to carry out identification for all possible models when developing IMS, which leads to the need to develop a module for automatic identification of the dynamics models of the control object. Taking into account the dispersion offset dilemma, the automatic identification module of a mathematical model of the control object dynamics uses linearized models in the form of systems of differential equations with a discontinuous right-hand side for each of the transitions, with the determination of discontinuity points using Bellman's dynamic programming. The training of the model takes place on the first few transitions in the manual mode; upon repeated transition, the model
is checked. If the structure of the model coincides and the required accuracy is obtained, after testing, automatic control can be used with control of the accuracy of the installation state compared to the model during the transition.

The mathematical formulation of the optimal control problem (OCP) can be represented as follows:
- the mathematical model of the control object, described by a system of differential equations (in matrix form) is given
\[
\dot{z}(t) = az(t) + bu(t)
\]  
(1)
- it is required to transfer the system from the initial to the final state
\[
z(t_0) = z_0 \rightarrow z(t_e) = z_e
\]  
(2)
for a fixed period of time, taking into account the restrictions to the control actions at each time point
\[
\forall t \in [t_0; t_e]: u(t) \in [u_l; u_u].
\]  
(3)
subject to achieving a minimum of functional
\[
J = \int_{t_0}^{t_e} u(t) dt \rightarrow \min
\]  
(4)

based on an array of details
\[
R = (a, b, u_l, u_u, z_0, z_e, t_0, t_e)
\]  
(5)

In the OCP (1–5), a and b are matrices of parameters of the dynamics model of the control object of dimension \(n \times n\) and \(n \times m\) respectively, where \(n\) is the number of state variables; \(m\) is the number of control actions; \(u_l, u_u\) - vectors of lower and upper admissible values of control actions of dimension \(m\); \(z_0, z_e\) - vectors of initial and final values of state variables of dimension \(n\); \(t_0, t_e\) - boundaries of the time interval of control.

For state variables, the rate of change of which is incommensurably less than those indicated above, the factors affecting the change in the state of functioning of the drying unit were selected. In general terms, the following factors can be identified that affect the state of functioning:
- kind of raw material \(H_{rm} = \{h_{1r}, h_{2r}^{m}, h_{3r}^{m}, h_{4r}^{m}, h_{5r}^{m}, h_{6r}^{m}\}\), where \(h_{1r}\) - wheat, \(h_{2r}\) - rye, \(h_{3r}\) - barley, \(h_{4r}\) - oats, \(h_{5r}\) - sugar beet, \(h_{6r}\) - potato;
- mass fraction of dry stillage on the dryer outlet, \(\%, H_{m2}^{ef} = \{h_{12}^{mef}, h_{22}^{mef}, h_{32}^{mef}\}\), \(h_{12}^{mef} \in [91; 95], h_{22}^{mef} \in [89; 91]\); 
- mass fraction of stillage from mixing screw, \(\%, H_{m2}^{ms} = \{h_{12}^{ms}, h_{22}^{ms}\}\); \(h_{12}^{ms} \in [20; 23], h_{22}^{ms} \in [23; 25]\), \(h_{12}^{ms} \in [25; 27]\), \(h_{22}^{ms} \in [27; 28]\), \(h_{32}^{ms} \in [28; 29]\), \(h_{42}^{ms} \in [29; 30]\), \(h_{52}^{ms} \in [30; 31]\), \(h_{62}^{ms} \in [31; 33]\), \(h_{72}^{ms} \in [33; 35]\);
- power of exhaust fans, \(\%\) from maximum power \(H_{\phi}^{ef} = \{h_{12}^{\phi ef}, h_{22}^{\phi ef}\}\); \(h_{12}^{\phi ef} \in [50; 65], h_{22}^{\phi ef} \in [65; 80], h_{12}^{\phi ef} \in [80; 95], h_{22}^{\phi ef} \in [95; 100]\), \(h_{32}^{\phi ef} \in f(t)\), if \(H_{\phi}^{ef} = h_{22}^{\phi ef}\), power of exhaust fans using as additional control;
- steam temperature in the system, °C, \(H_{st}^{st} = \{h_{12}^{st}, h_{22}^{st}\}\), \(h_{12}^{st} \in [160; 165], h_{22}^{st} \in [165; 170], h_{32}^{st} \in [170; 175], h_{42}^{st} \in [175; 180]\);
- steam pressure in the system, atm., \(H_{sp}^{sp} = \{h_{12}^{sp}, h_{22}^{sp}\}\), \(h_{12}^{sp} \in [5; 6], h_{22}^{sp} \in [6; 7]\);
- ambient temperature, °C, \(H_{at}^{at} = \{h_{12}^{at}, h_{22}^{at}\}\), \(h_{12}^{at} \in [5; 10], h_{22}^{at} \in [10; 17], h_{32}^{at} \in [17; 25]\);
- serviceability of sensors for monitoring air temperature, evaporation temperature, air humidity
$H^{st} = \{h_1^{st}, ..., h_8^{st}\}$, combinations of factor values $H^{st}$ are presented in table 1.

**Table 1.** The combinations of values of factor $H^{st}$

|                     | $h_1^{st}$ | $h_2^{st}$ | $h_3^{st}$ | $h_4^{st}$ | $h_5^{st}$ | $h_6^{st}$ | $h_7^{st}$ | $h_8^{st}$ |
|---------------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Air temperature sensor | 0          | 1          | 0          | 0          | 1          | 0          | 1          | 0          |
| Vapor temperature sensor | 0          | 0          | 1          | 0          | 1          | 0          | 1          | 1          |
| Air humidity sensor | 0          | 0          | 0          | 1          | 0          | 1          | 1          | 1          |

* 0 - the sensor is in good condition, 1 - the sensor is faulty

Each state of operation is described by a set of parameters described above. The estimate of the total number of functioning states is the vector product of the specified sets

$$H^d = H^s \times H^{md} \times H^{min} \times H^{st} \times H^{sp} \times H^{at} \times H^{st}.$$ 

The number of possible operating states is at least $6 \times 3 \times 9 \times 3 \times 5 \times 4 \times 3 \times 8 = 155520$. The number of states can be increased by adding new types of raw materials, new working conditions, making changes to the design of the drying unit (changing angles tilt scrapers, etc.).

3. Algorithmic support of information and management system

One of the most labor-intensive and “knowledge-intensive” stages of IMS development is the creation of its algorithmic support. The algorithmic support of IMS includes algorithms that provide a solution for the OCP for various states of operation of the control object, including algorithms that allow analyzing the possibility of the existence of a solution of the OCP for the given initial data and determining the type and parameters of the optimal control functions.

The algorithm for analyzing the domain of existence of the OCP solution contains the following steps:

1. The calculation of the values of synthesizing variables based on the array of details $L_4(R), L_3(R), L_3(R), L_4(R)$.

2. Consideration of the cross-section of the domain of existence of the OCP solution, fixing the value of one of the coordinates, for example $L_4$. Definition of auxiliary variables, $T_i, u_i, T_h$ and $u_h$ from the condition $L_4(R) = L_4(T_i, u_i)$). Determination of maximum and minimum allowable values of synthesizing variables at pressure $h^{sp} \in H^{sp}$.

3. Determination of the conditions for the guaranteed existence of the solution of the OCP. If the system of inequalities is satisfied, then the solution of the OLS is guaranteed to exist.

$$
\begin{align*}
L_{1,i}^{\min} & \leq L_4(R) \leq L_{1,i}^{\max}, \\
L_{2,i}^{\min} & \leq L_3(R) \leq L_{2,i}^{\max}, \\
L_{3,i}^{\min} & \leq L_3(R) \leq L_{3,i}^{\max}
\end{align*}
$$

(6)

4. Determination of the conditions for the possible existence of a solution of the OCP. If the system of inequalities (6) is not satisfied, and for auxiliary variables determined from the condition $L_4(R) = L_4(T_h, h^{sp})$, the system of inequalities...
3. Determination of elementary functions of synthesizing variables.

4. Development of an algorithm for synthesizing systems of equations based on elementary functions for determining the parameters of CP functions.

5. Development of an algorithm for transitions between objects that implement various kinds of CP functions.

For single-extremal functions of a CP, 17 types of functions of an CP $U^0 - U^{16}$ can be distinguished, which can be summarized as the following expression

$$
U^s(t) = \begin{cases}
    f^s_1(t), t \in [t_{0}, t_{1}^s]; \\
    f^s_2(t), t \in [t_{1}^s, t_{2}^s]; \\
    f^s_3(t), t \in [t_{2}^s, t_{3}^s]; \\
    f^s_4(t), t \in [t_{3}^s, t_{4}^s]; \\
    f^s_5(t), t \in [t_{4}^s, t_{5}^s].
\end{cases}
$$

where $s = 0, 1, \ldots, 16$ – number of OC function; $f^s_i(t), t = 1, 5$ – components of OC functions represented in Table 2 ($u^s_i, u^s_{i-1}$ – lower and upper permissible values for $i$-th control; $u^s_i(t)$ – value in the form of a function $i$-th control); $t_1^s, t_5^s$ – switching times.

| $s$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|-----|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|
| $f^s_1(t)$ | $u^s_0(t)$ | $u^s_1(t)$ | $u^s_2(t)$ | $u^s_3(t)$ | $u^s_4(t)$ | $u^s_5(t)$ | $u^s_6(t)$ | $u^s_7(t)$ | $u^s_8(t)$ | $u^s_9(t)$ | $u^s_{10}(t)$ | $u^s_{11}(t)$ | $u^s_{12}(t)$ | $u^s_{13}(t)$ | $u^s_{14}(t)$ | $u^s_{15}(t)$ | $u^s_{16}(t)$ |
| $f^s_2(t)$ | $u^s_0(t)$ | $u^s_1(t)$ | $u^s_2(t)$ | $u^s_3(t)$ | $u^s_4(t)$ | $u^s_5(t)$ | $u^s_6(t)$ | $u^s_7(t)$ | $u^s_8(t)$ | $u^s_9(t)$ | $u^s_{10}(t)$ | $u^s_{11}(t)$ | $u^s_{12}(t)$ | $u^s_{13}(t)$ | $u^s_{14}(t)$ | $u^s_{15}(t)$ | $u^s_{16}(t)$ |
| $f^s_3(t)$ | $u^s_0(t)$ | $u^s_1(t)$ | $u^s_2(t)$ | $u^s_3(t)$ | $u^s_4(t)$ | $u^s_5(t)$ | $u^s_6(t)$ | $u^s_7(t)$ | $u^s_8(t)$ | $u^s_9(t)$ | $u^s_{10}(t)$ | $u^s_{11}(t)$ | $u^s_{12}(t)$ | $u^s_{13}(t)$ | $u^s_{14}(t)$ | $u^s_{15}(t)$ | $u^s_{16}(t)$ |
| $f^s_4(t)$ | $u^s_0(t)$ | $u^s_1(t)$ | $u^s_2(t)$ | $u^s_3(t)$ | $u^s_4(t)$ | $u^s_5(t)$ | $u^s_6(t)$ | $u^s_7(t)$ | $u^s_8(t)$ | $u^s_9(t)$ | $u^s_{10}(t)$ | $u^s_{11}(t)$ | $u^s_{12}(t)$ | $u^s_{13}(t)$ | $u^s_{14}(t)$ | $u^s_{15}(t)$ | $u^s_{16}(t)$ |
| $f^s_5(t)$ | $u^s_0(t)$ | $u^s_1(t)$ | $u^s_2(t)$ | $u^s_3(t)$ | $u^s_4(t)$ | $u^s_5(t)$ | $u^s_6(t)$ | $u^s_7(t)$ | $u^s_8(t)$ | $u^s_9(t)$ | $u^s_{10}(t)$ | $u^s_{11}(t)$ | $u^s_{12}(t)$ | $u^s_{13}(t)$ | $u^s_{14}(t)$ | $u^s_{15}(t)$ | $u^s_{16}(t)$ |

The considered types of functions are caused by six types of violation of restrictions: 1. $f_i(t_0) > u^s_0$; 2. $f_i(t_0) < u^s_1$; 3. $f_i(t_0) = u^s_0$; 4. $f_i(t_0) < u^s_1$; 5. $f_i(t) > u^s_2$, $t \in [t_1^s, t_2^s]$; 6. $f_i(t) < u^s_1$, $t \in [t_1^s, t_2^s]$.

It should also be noted that from the considered types of functions, only $U^0(t)$ is a type of function that does not have switching points.
The hierarchical transition graph for single-extremal types of CP functions is shown in Figure 3.

![Hierarchical transition graph for various types of CP functions by a multi-dimensional object](image)

**Figure 3.** Hierarchical transition graph for various types of CP functions by a multi-dimensional object

Different types of CP functions differ in the number and location of switching points. Switching points are included as unknowns in non-linear equations and make the main contribution to the time spent in calculations. Search by various types of CP is conducted from simple to complex depending on the violated restrictions on control actions.

4. **Software and hardware of the information management system**
The structure of IMS within the framework of the existing production management system is shown in Figure 4.

![The structure of IMS TD](image)

**Figure 4.** The structure of IMS TD
IMS modules have the following functional purpose.

The coordinator is used as a graphical interface for operator interaction with IMS modules, as well as an intermediary between the knowledge base of IMS and the production management system database for obtaining archival information and accumulating statistics into the archive.

The accuracy control module is called by timer and is used to assess the accuracy of the current model of object dynamics.

The module of identification of the state of functioning determines the values of automatically measured parameters affecting the state of functioning of the object.

The module for setting up and selecting states of functioning allows the engineer of instrumentation and automation to make changes to the knowledge base and to supplement a set of states of functioning.

The structural and parametric identification module identifies the model of the dynamics of the drying unit.

The CP synthesis module based on the array of attributes determines the possibility of the existence of the OCP solution, as well as the type and parameters of the CP functions based on the structural synthesis method of the algorithm for determining the parameters of the CP functions by a multidimensional object.

The knowledge base contains a set of production rules for each type of model used, allowing to synthesize the elementary functions necessary for the synthesis of a finite system of equations, the solution of which determines the parameters of the CP functions.

5. Experimental results

Comparison of the results of manual control and control with IMS using is shown in Figure 5.
For the considered example, the fuel economy when drying the dreg was about 7% with ensuring the required final humidity of the product (4 ± 1%).

6. Discussion
Conducted research have shown that the classical approach used in a number of cases to the development of algorithmic and IMS software based on the imperative programming paradigm with an increase in the number of control actions and the impossibility of performing a “junction” on state variables leads to a sharp increase in the complexity of solving an OCP by a multi-dimensional object.

It should be noted that the use of modern programming paradigms and an appropriate approach to the development of algorithmic and software can significantly reduce the time spent on the development of IMS TD.

In this paper, the formalization of the OCP is carried out and the functioning states of the control object are highlighted. The method of structural synthesis of the algorithm for determining the parameters of the CP functions by a multidimensional object has been developed, taking into account restrictions on control actions based on the Pontryagin maximum principle and the method of synthesizing variables. This method provides automatic construction of systems of equations whose solutions determine the parameters of all possible types of CP functions.

An IMS system was developed for the dreg drying process, integrated into the existing production management system, which includes the following modules: structural and parametric identification of the dynamics model of the control object; setting and highlighting the functioning states; identification of the current state of functioning; CP synthesis; control of the accuracy of the dynamics model, and a knowledge base containing information on the structure and parameters of the dynamics models of the control object and ratios for calculating the parameters of the CP functions.

Perspective directions for further research are: obtaining more accurate non-linear models of dynamic modes of the control object and expanding possible operating states with regard to typical non-critical malfunctions of drying units.

7. Conclusion
The article discusses the theoretical and practical aspects of the development of algorithmic and software of IMS TD. The algorithmic support of the system was developed using an approach based on the joint application of the Pontryagin maximum principle, the method of synthesizing variables, the method of analysis and synthesis of systems on a set of operating states, and graph theory. Software of IMS system is implemented on the basis of the existing production management system.

The use of the developed IMS system allows reducing the energy costs in the dynamic modes of the TD by 3-10% while observing the technological modes and ensuring the required product quality.

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