ALGORITHM FOR OPTIMAL CONTROL OF ENERGY-EFFICIENT SYSTEMS ENSURING ABIOTIC FACTORS FOR ENTOMOLOGICAL PRODUCTION

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Abstract. The article is dedicated to the development of an optimal control algorithm for energy-efficient systems that provide abiotic factors. The result of the algorithm operation is a final set of conditions, instructions, and actions executed in a specific order, serving as a tool for determining methods for forming energy-efficient systems that ensure abiotic factors in adaptive technologies for cultivating maternal entomocultures. The algorithm consists of six main blocks. The first block defines an automatic air parameter regulation system in microclimate systems based on the type of the air parameter being regulated, the magnitude of the parameter deviation, the method of maintaining the parameter, and the nature of the regulator's influence on the controlled object. The types of systems that meet all the constraints of entomoproduction facilities are considered. The second block determines the conditions for optimal system control using a thermodynamic model (TDM). The analysis of these conditions allows the formulation of fundamental principles by which TDM of air conditioning systems (AirCS) ensures optimal air treatment processes, a combination of specific outdoor air parameters and indoor air parameters that minimize cooling, heating, water, and air consumption. The third block involves processing the basic information and performing key calculations and operations. The fourth block determines the types of technological schemes for maintaining environmental parameters indoors, considering options such as preheating outdoor air, operating without preheating, or using preheating for recirculated air. The fifth block is responsible for presenting the algorithm's output, defining the conditions for controlling energy-efficient systems that provide abiotic factors. The final, sixth block repeatedly performs a specific operation until a predefined condition is met. The information in this block concerns methods of controlling humidification processes – regulating water consumption, bypassing the airflow, or managing intermittent water supply. Capital costs for AirCS in entomological production amount to 20% of the total construction cost, while operating expenses range from 30% to 50% of total operating costs. Therefore, energy saving has been one of the most crucial functions of automatic control systems (ACS) in air conditioning. During the design stage of ACS and the development of technological air treatment schemes, it is necessary to refine the possibilities of process control. As a result of the research, key schemes for maintaining environmental parameters in indoor spaces have been developed to minimize air heat and moisture treatment costs. The developed algorithm enables the generation of a set of conditions, instructions, and actions that must be performed in a specific order. Given detailed initial data and knowledge of ACS equipment management methods, following each step of the developed algorithm provides a technically sound ACS solution for air conditioning systems, reducing energy consumption by approximately 25%. The algorithm's outcome serves as a tool for determining methods for forming energy-efficient systems that ensure abiotic factors in adaptive technologies for cultivating maternal entomocultures.

Keywords: air conditioning system, automatic regulation system, entomological production, optimal control algorithm, optimal control conditions.

Introduction

An integral part of the air conditioning system (AirCS), including one for entomological production, is the automatic control system (ACS). The tasks of the automatic control system are: automatic stabilization of the air parameters; a programmatic change of these parameters; the local and operational control; protection and elimination of emergency situations.

In addition, it is necessary to take into account that AirCS are energy-intensive systems [1-3]. The capital costs for AirCS make up 20% of the total cost of the buildings, and the operating costs – from 30% to 50% of the total cost of operation; therefore one of the most important functions of ACS AirCS is energy saving.

Energy saving in AirCS is a complex task [4]. Already at the designing stage of the air conditioning system, when drawing up technological schemes for air treatment, it is necessary to strictly understand the possibility to control the processes. Without a detailed consideration of the initial data, without the knowledge of the methods of control of the air conditioning units, no technically competent solution for the air conditioning system is possible [5-7]. Therefore, it is impossible to divide the task of creating of

AirCS without taking into account a competent solution for an automatic control system (ACS). Air conditioning systems in entomological production, as automation objects, are complex technical complexes.

When developing a control algorithm, it is necessary to take into account the peculiarities of AirCS: a wide range of the output data (the environmental parameters, loads, deviations of the controlled parameters) changes: heterogeneity of the controlled parameters (thermodynamic, aerodynamic, chemical); the control objects (the rooms) have complex nonlinear characteristics that have different inertia (significant in the thermal processes and insignificant in the aerodynamic ones).

When automating various technological processes, including the air treatment processes in AirCS, an information-controlled system is used as a set of technical automation tools and a set of equipment that ensure this process.

Materials and methods

To develop an algorithm for optimal control of the energy-efficient air conditioning systems in the entomological production, an integrated approach was applied, including theoretical modelling and empirical research. To analyse the air treatment processes in the air conditioning system, a thermodynamic model (TDM) was used, which allows describing polytropic processes and optimal regulation of the air parameters under the conditions of various technological schemes. The modelling was performed using air state diagrams (d-h diagram), which determine the optimal parameters (temperature, humidity, air flow, etc.) at various points in the system [8; 9].

The research was conducted considering different types of the air conditioning systems, suitable for the entomological production [10; 11]. The following systems were considered: automatic control systems for stabilizing the temperature, humidity, air flow and pressure parameters; single-zone and multi-zone air conditioning systems depending on the size of the room and the characteristics of the heat and harmful substances distribution; special and standard precision systems for a precise control of the parameters in the room, with deviations in the temperature and humidity.

The following approaches were used to determine the optimal control methods: investigation of the conditions for minimisation of the energy costs, an analysis of the minimum consumption of the heat, cold and water in the air conditioning systems, based on optimal values of the outdoor air flow, an analysis of polytropic processes of air humidification: investigation of various humidification control methods, including the water flow control, the air flow bypass and intermittent water supply control.

The research involved using various scenarios for the operation of the air conditioning system in the premises of entomological production. For each scenario parameters, such as temperature, humidity and air flow, were calculated considering various control methods. All the calculations were conducted in thermodynamic models, using diagrams of the state and algorithms of optimal control.

The results of the analysis were obtained by comparison of the air parameters in various zones of processing. In particular, optimal points on the *d-h* diagram were determined, which correspond to the required technological indicators for ensuring normal conditions in the entomological production facilities.

Results and discussion

There have been determined optimal methods for the control of the polytropic air preparation processes for the entomological production facilities, considering the characteristics and requirements for the air preparation system in this type of premises. The types of systems are identified that satisfy all the restrictions of these objects.

- Automatic control systems, based on the type of the controlled parameter (systems for stabilizing temperature t, relative humidity $\varphi(d)$, ventilated air flow G_a, pressure P).
- By the number of stabilization points (single-zone and multi-zone air conditioning systems – AirCS). Multi-zone AirCS are used in cases of large areas of premises with uneven emission of heat and harmful substances. They are more economical, compared to the single-zone ones, yet their accuracy of maintaining the parameters is lower.

- By the magnitude of the parameter deviation (automatic control systems – ACS of normal accuracy and special accuracy – the precision ones): by temperature: Δt_{add} = ± 0.02-2.5 K; by relative humidity: $\Delta \varphi_{add}$ = ± 1-15%. In the absence of special technological requirements, the standards regulate the static deviation of temperature and relative humidity. These deviations correspond to the technological or hygienic requirements.

There were investigated conditions for optimal control of the system, using a thermodynamic model (TDM) [9]. An analysis of these conditions, under which optimal air treatment processes are ensured in the TDM air conditioning system, allows to formulate three main provisions.

1. To each point in the *d-h* diagram, which characterizes the condition of the outdoor air, there corresponds only one point (•) in the zone of permissible indoor air parameters in the premises (zone (□) y or line (-) y reaching of which ensures correspondence of the technological indicators (TI) to the optimal values of AirCS. In the outdoor air zones of TDM, characterized by inevitable heat loss, one can see what will happen if this condition is not met. If the automatic control system, performing the task to maintain the air parameters on the line of the particular parameters of the room, does not provide the optimal mode and, instead of the required point (•) y_{req}, selects another point on this segment, then, when the condition of equality of the calculated outdoor air flow G_{out} and the minimum G_{min}, required according to the sanitary norms $G_{out} = G_{min}$, is met, this will require large heat costs and additional consumption of cold.
2. Minimization of heat and cold costs in AirCS is achieved only at a strictly defined value of the outside air G_{out}. A situation is possible that only with one flow rate of the outside air G_{out}, which is greater than the minimum but less than the maximum, the minimum heat consumption Q_h is achieved. Accordingly, if one tries to reduce the air flow to a minimum, then additional cold consumption will appear to achieve the required air parameters. If maximum quantity of air is used, there will increase the heat consumption and additional consumption of cold.
3. There are combinations of initial conditions in which the minimization of one technological indicator leads to an increase in the other.

There are zones of outside air in TDM where the air can be processed without the losses of heat and cold, using only adiabatic humidification. If the task is to minimize the water consumption for humidification, then under the condition $G_{out} = G_{min}$, additional cold consumption will be required. Or you can avoid additional costs of cold and heat, but this will increase the air consumption.

In this regard, in order to implement optimization, it is necessary to establish a system of priority goals for minimization of individual technological indicators. There have been studied methods of control of the air humidification processes, namely polytropic processes [12].

The first method is the water consumption control. This method is based on changing the efficiency coefficients E_a and E_n at G_a = const and $\mu = G_w/G_a$ = const, where μ is the irrigation coefficient, G_w is the water consumption. The air treatment process is shown in the *h-d* diagram. The final states of air after the irrigation chamber (IC) K1, K2, K3 are located near the line of the constant moisture content of the outside air d_{out} = const, and, when saturation is reached, – on line $\varphi_к$ = 0.9...0.95.

Thus, not every final state can be achieved under such a control. For example, to obtain the state of point *K* at $\varphi_к < 0.9$, after cooling the air in the humidification chamber, second heating will be required.

Therefore, the water flow control is a method that has a nonlinear control characteristic and limitations at low water flow rates (pressure) (Fig. 1).

The second method – control of the air flow bypass consists of installing a bypass channel with a regulating valve.

This control method is virtually inertia-free: when the valve flap is turned, the air flow and the efficiency factor change instantly. The method is used if the dimensions of the room (in particular, the height) where the air conditioner is installed allow the use of an adjustable bypass.

The minimum efficiency coefficient Emin is numerically equal to the minimum relative air flow through the humidifier $E_{min} = G_{out.min}$.

This conclusion is made under the following assumptions: The efficiency coefficient in the bypass $E_{byp} = 0$. The efficiency coefficient of the main apparatus E_{main} tends to 1 when the air flow rate decreases. With any design, especially considering the limited bypass height, it is impossible to ensure $G_{out} = 0$. The minimum value $G_{out} = E_{min} = 0.3...0.35$.

At the turning angles of the sash close to full opening ($\alpha_{key} = 0$), the air flow through the humidification zone G_{ic} and the efficiency coefficient E change insignificantly. At angles $\alpha_{key} > 200$, the air flow rates in the bypass and the main channel change along a line close to a straight line. Therefore, the nonlinearity of the control characteristic can be corrected by limiting the movement of the valve flaps to the range: $200 \leq \alpha_{key} \leq 900$.

The final state of air in a polytropic process is determined on the line connecting the initial state of air and the saturated state on the line $\varphi = 1$ at the water temperature t_w.

The method is used if the dimensions of the room (especially the height) where the air conditioner is installed allow the use of an adjustable bypass. The control is limited by condition $E_{min} = G_{out}$.

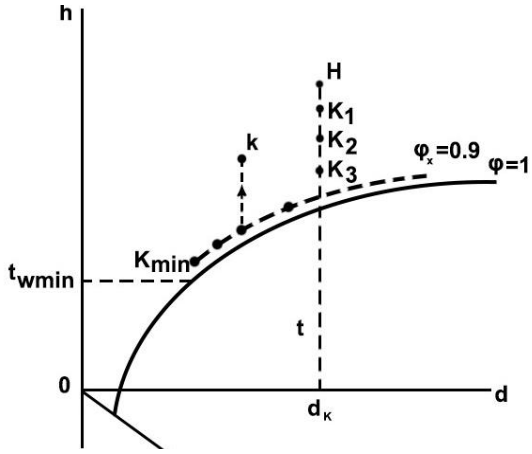

Fig. 1. **Water consumption-based process of humidity control**

The control of intermittent water supply is achieved at the expense of water, sprayed into the air flow not continuously but in pulses.

Such a control is based on the principle of mixing the air masses with different moisture content and temperature, which occurs over time in the volume of the room.

The duration of spraying changes proportionally to the deviation of the relative air humidity from the set value, while the period of the spraying pulses $\tau = \tau_{on} + \tau_{off}$ remains constant, τ_{on} is the on time, τ_{off} is the off time.

The ratio between the duration of the intervals τ_{on}, during which the water is sprayed, and the intervals τ_{off}, during which there is no spraying, determines the average value of the relative humidity of the air at the outlet of the humidification chamber φ_k (Fig. 2).

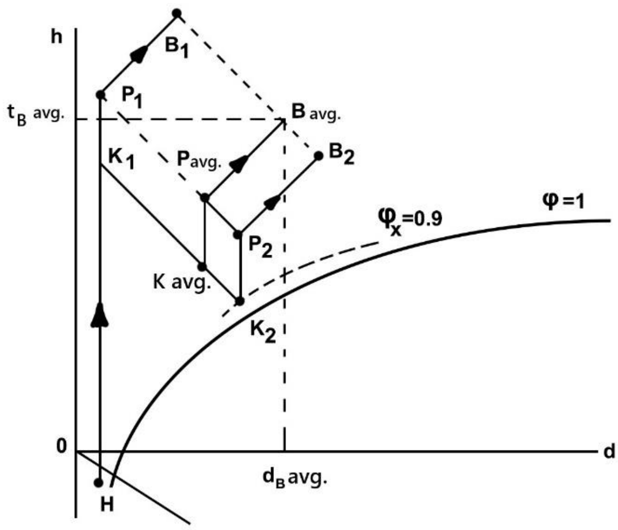

Fig. 2. **Control of the humidification process through intermittent water supply**

The duration of the time period τ for turning the spray on and off is determined based on the condition that fluctuations φ_{air} of the stabilized value do not exceed acceptable limits.

As the air continues to move, for example, through the air heater, fan, and flues, the pulsations of relative humidity are smoothed out.

The cyclical switching on and off the pump requires accounting for: the average and two boundary states of the air after the spray chamber (K_1, K_2, $K_{\cdot}$), the supply air (P_1, P_2, $P_{\cdot}$), and the room air (V_1, V_2, $V_{\cdot}$). The necessary constructions are carried out on the *h-d* diagram of the isenthalpic air treatment process in the spray chamber under intermittent water supply control. The position of point K_{avg} closer to K_2 than to K_1 corresponds to the condition $\tau_{on} > \tau_{off}$.

When constructing polytropic processes on the *h-d* diagram, the initial and final states of the air, as well as the initial state of the water, are represented on a single straight line, provided the spray coefficient is large. Otherwise, the final state will depend on μ and may correspond to different points such as K_1, K_2, etc. This method corresponds to the control chain of a humidifier: pump → valve → humidifier. However, instead of a throttling valve before the nozzles, a two-position valve is installed.

Intermittent control has the disadvantage of increased energy consumption for water pumping. To reduce energy costs, it is recommended to install an additional tank and a check valve.

The main schemes for maintaining regime parameters in the entomological production room have been developed, according to which the thermodynamic model of the air conditioning system ensures optimal air treatment processes.

Minimization of heat, cold, and water consumption is achieved through three possible equipment arrangement and airflow control schemes: preliminary heating of outdoor air (Fig. 3A); without using preliminary air heating (Fig. 3B); preliminary heating of recirculated air (Fig. 3C).

The implementation of all the above stages of analysis and control of air treatment processes in the climate system for entomological production is the result of the current stage of the research project.

The results obtained are part of an algorithm for optimal control of energy-efficient systems for maintaining abiotic factors, which enables the development of an optimal method for managing such systems.

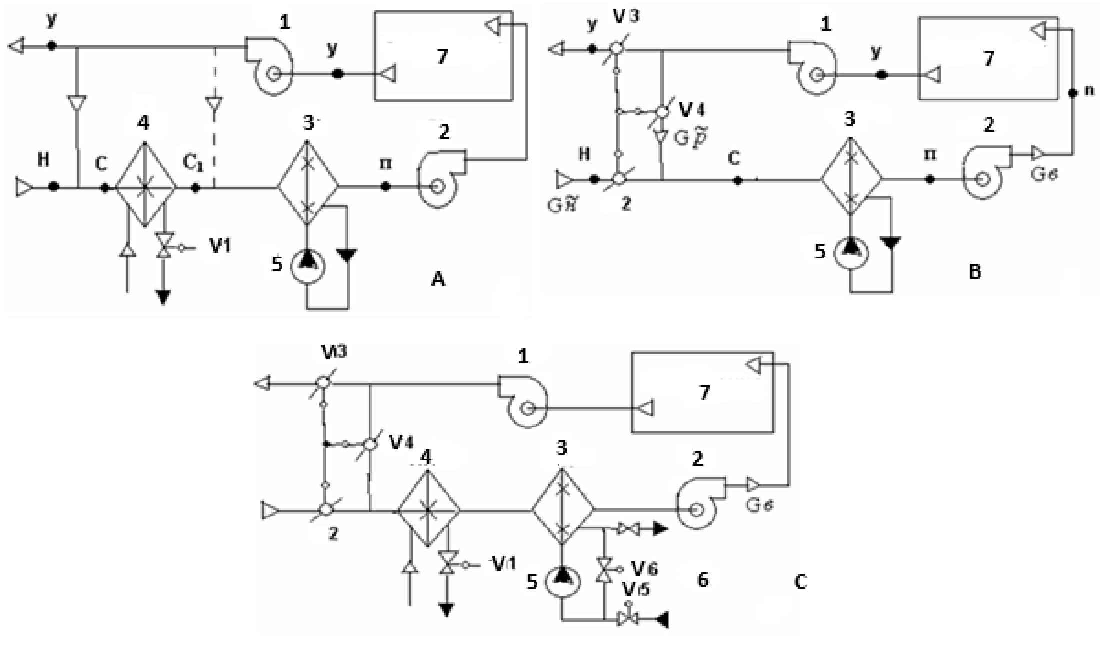

Fig. 3. **Schemes for maintaining operational parameters in an entomological production facility** (1 – exhaust fan; 2 – supply fan; 3 – humidification chamber; 4 – air heater; 5 – pump; 6 – chiller; 7 – room; V1; V2; V3; V4; V5; V6 – valves; dot u – the parameters of the exhaust air; dot N – the parameters of the outdoor air; dot C – the parameters of the mixture of the outdoor air and the recirculated air; dot C1 – the parameters of air after the air heater; dot P – the parameters of the supply air before the room)

An algorithm has been developed for the optimal control of energy-efficient systems for providing abiotic factors, which consists of the following main blocks.

1. Systems for automatic regulation of the air parameters in the microclimate systems (INPUT): by the type of the regulated air parameter, by the magnitude of the parameter deviation, by the method of maintaining the parameter, by the nature of the influence of the regulating body on the regulated object (Fig. 4).

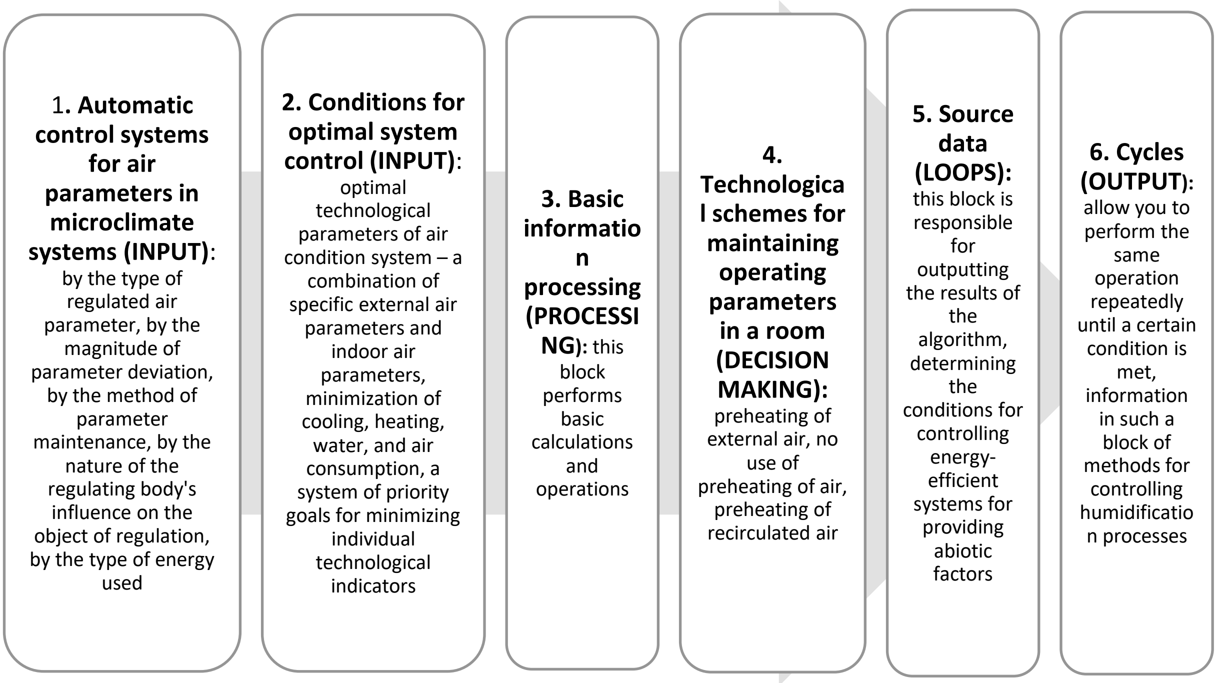

Fig. 4. **Algorithm for optimal control of energy-efficient systems for providing abiotic factors**

2. Conditions for control of optimal system (INPUT): the optimal technological parameters of the air conditioning system – a combination of certain parameters of the outside air and parameters of the indoor air, minimization of the consumption of cold, heat, water, air, a system of priority goals for the minimization of individual technological parameters.
3. Processing of basic information (PROCESSING): This block carries out the main calculations and operations.
4. Technological schemes for maintaining operating parameters in a room (DECISION MAKING): preheating of the outside air, without using preheating of the air, preheating of the recirculated air.
5. Initial data (LOOPS): this block is responsible for deriving the results of the algorithm, determining the conditions for the management of the energy-efficient system for providing abiotic factors.
6. Cycles (OUTPUT): allow the same operation to be performed repeatedly until a certain condition is reached. The information in this block concerns the methods of controlling the humidification processes.

Conclusions

1. Based on the research results, the key schemes for maintaining the operating parameters in the premises have been developed, ensuring the minimization of costs for the heat and humidity treatment of air.
2. An algorithm has been developed that allows obtaining a set of conditions, instructions and actions that must be performed in a certain order.
3. When detailed initial data and knowledge of the control methods of ACS AirCS devices are available, the implementation of each stage of the developed algorithm allows to obtain a technically sound ACS solution for AirCS, ensuring a reduction in the energy costs by approximately 25%.
4. The result of the algorithm is a tool to determine methods for the formation of energy-efficient systems to provide abiotic factors in adaptive technologies for cultivating mother entomocultures.

Author contributions

All authors have contributed equally to the study and preparation of this publication. Authors have read and agreed to the published version of the manuscript.

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