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THE USE OF OPTIMIZATION OF ENERGY-SAVING MICROCLIMATE CONTROL IN SELECTED AGRICULTURAL OBJECTS

Summary

The aim of the study was to investigate the possibility of using optimization methods for the design of energy-saving microclimate control system in specialized agricultural buildings, such as mushroom-growing cellars or storage of potatoes as well for the microclimate control in these facilities. The results of simulation studies have shown that the use of optimization in microclimate control systems in specialized agricultural buildings enables implementation of the variables depending on the needs of the control strategy (e.g. control during which energy consumption is minimized or technological losses are minimized). This is not possible in the systems currently in use.
Key words: *specialized agricultural buildings, microclimate, optimization*

WYKORZYSTANIE OPTYMALIZACJI PODCZAS ENERGOOSZCZĘDNEGO STEROWANIA MIKROKLIMATEM W WYBRANYCH OBIEKTACH ROLNICZYCH

Streszczenie

Celem pracy było zbadanie możliwości wykorzystania metod optymalizacji podczas projektowania energooszczędnego systemu sterowania mikroklimatem w specjalistycznych obiektach rolniczych, takich jak pieczarkarnie czy przechowalnie ziemniaków, a także podczas sterowania mikroklimatem w tych obiektach. Wyniki badań symulacyjnych wskazały, że zastosowanie optymalizacji w układach sterowania mikroklimatem w specjalistycznych budynkach rolniczych umożliwia realizację zmiennych, zależnych od potrzeb strategii sterowania (np. sterowania podczas którego minimalizowane jest zużycie energii lub minimalizowane są straty technologiczne). Nie jest to możliwe w aktualnie stosowanych układach.
Słowa kluczowe: *specjalistyczne obiekty rolnicze, mikroklimat, sterowanie, optymalizacja*

1. Introduction

Currently in Poland there is a consumer market that is interested in low-cost but high-quality food and agricultural products. The owners of specialized agricultural buildings such as greenhouses, mushroom-growing cellars, storage of fruit, vegetables or potatoes are looking for ways to meet the expectations of consumers, among others, by automating production processes or storage processes. Through the introduction of automation it is possible to reduce production or storage costs, by:

- reducing the consumption of energy supply,
- reducing the cost of human labor,
- reducing the technological losses.

Automation also ensures high yield of cultivated plants and mushrooms. Currently used control methods (algorithms), known in the industry, do not always meet the expectation placed in them in the case of agricultural engineering processes. This is due to the fact that during control of agricultural engineering process there is a lack of qualitative and quantitative reproducibility of the process in successive technology cycles (storage or cultivation). This is because an important role in agricultural engineering processes is played by random factors in the form of climate parameters occurring during the growing season, such as ambient air temperature, insolation, rainfall [5]. Such phenomena do not occur during industrial process control. It is therefore necessary to search for new control algorithms of microclimate parameters in specialized agricultural buildings, fulfilling the expectations of both producers and consumers of agricultural products.

The aim of the study was to investigate the possibility of using optimization methods in the control algorithms at the stage of:

- design of energy-saving microclimate control system (on the example of mushroom-growing cellar),
- energy-saving microclimate control (on the example of potato store).

2. Optimization task carried out during the design of control system or during the microclimate control in specialized agricultural buildings

Optimization task carried out in specialized agricultural buildings is to meet the demands of producers of agricultural products and food. These tasks are:

1) minimization of regulation error, i.e. the difference between required by technologists and actual value of controlled microclimate parameter. Through the fine-tune the parameters of the microclimate, ensuring compliance with the requirements of technology, you can:

- to minimize the technological losses and get the highest quality of stored agricultural products (fruits, vegetables or potatoes) after completion of the storage process,
- get high, very good quality yields of plants grown in greenhouses or mushrooms grown in mushroom-growing cellars,

2) minimization of energy supply, thereby reducing the operating costs of specialized agricultural building (store, greenhouse, mushroom-growing cellar).

The above-mentioned optimization tasks are mutually contradictory and their technical implementation is not possible. Indeed, lowest power consumption of energy supply in the greenhouse or mushroom-growing cellar for example, we get when the ventilation and air conditioning equipment is not switched on during the process of cultivation. But then it will be impossible to guarantee required by technologists microclimate [6]. And what goes with it will not be possible to achieve a high and good quality harvest of vegetables or mushrooms.

Therefore, to meet the expectations of producers of agricultural products and food, it shoud be given to the owners of specialized agricultural buildings a choice of microclimate control strategy using optimization methods. Below three possible to implement control strategy options are presented on the example of potatoes storehouse:

1) if the owner wants to cheaply store potatoes, because he does not care for high quality and low losses at the end of storage, the microclimate control system should implement the postulate of minimizing the consumption of power supply,

2) if the owner of the luggage stored seed potatoes and cares for maintaining their high quality, the microclimate control system should implement demand of a very precise adjustment of microclimate parameters, namely the postulate of minimizing the error of regulation;

3) sometimes when operating it is necessary to find a compromise between two mutually exclusive demands of producers of agricultural products, i.e. the minimization of regulation error and minimizing energy consumption. Therefore, when the owner of the store wants to provide high quality of potatoes at the end of storage and at the same time lower energy consumption, then the control system should implement a polioptimization task.

Such an approach to the problem of microclimate control in specialized agricultural buildings was not used yet.

3. Methodology of microclimate control system design using optimization methods

Optimization methods can be applied already at the phase of design of energy-saving or guaranteeing the highest level of control accuracy microclimate control systems for specialized agricultural buildings. Below, on the example of mushroom-growing cellar, will be discussed methodology of designing such systems. The methodology may be applied only when we have a comprehensive mathematical model of mushroom-growing cellar that contains: a model of heat and mass transfer processes occuring in the building, a model of ventilation and air conditioning systems and an adopted control algorithm for microclimate parameters. This model was developed in Koszalin University of Technology and its description includes work [4].

Having available the mathematical model it should be developed a numerical model using e.g. the software environment MATLAB, and then performing a simulation study. The results of experimental research may be used for selection of the microclimate control algorithm, assuring either a minimizing regulation error or a minimizing energy consumption [4].

3.1. Minimizing regulation error

If required high accuracy of control of the microclimate parameters, and thus minimizing the error of regulation, during simulation tests the waveforms of the following microclimate parameters in the mushroom farm are determined:

- internal air temperature,
- moisture in the indoor air,
- carbon dioxide content in the air inside the mushroom-growing cellar.

The difference between the desired (required by technologists) and calculated (as the results of simulation studies) waveforms of the individual parameters of microclimate inside the mushroom-growing cellar, is an regulation error (e). Quality regulation index I_{JR} for the individual microclimate parameters is the minimum integral of the square of regulation error e for each of the designated runs (formula 1) [2].

$$\min I_{JR} = \int_{t_0}^{t_k} e^2(\tau) d\tau \qquad (1)$$

where: e – regulation error [ºC], τ – time [h].

At the stage of the design of control system, waveforms of microclimate parameters are determined numerically by using in the mushroom-growing cellar model various possible to use control algorithms. The highest accuracy of regulation, and thus the highest mushrooms yield of very good quality provides the control algorithm for which total quality index has the lowest value.

Fig. 1 shows examples of simulation studies' results for indoor air temperature and desired (required by technologists) values of the parameter, obtained when at the design stage of the control system three options of control algorithm were considered: two-position control, continuous control (PID – proportional, integral, derivative) and predictive control.

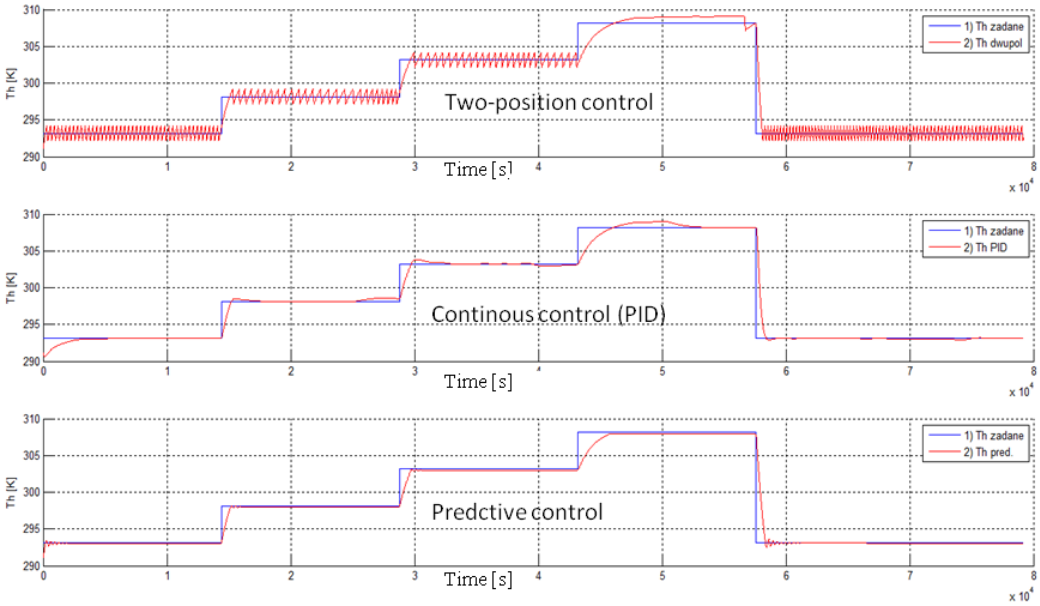
Table 1 shows designated, as described above, values of quality regulation index for different microclimate parameters and different applied control algorithms.

Control algorithm that delivers the best accuracy of microclimate regulation in the mushroom-growing cellar is a predictive control.

Tab. 1. Designated, as a result of optimizing, values of quality regulation index
Tab. 1. Wyznaczone w wyniku optymalizacji wartości wskaźnika jakości regulacji

	Values of quality regulation index I_{JR}			
	Indoor air temperature	CO_2 content in the indoor air	Moisture in the indoor air	Total index
Two-position control	86734,6	312,8	29153,4	116200,8
Continuous control	80390,0	295,1	10898,0	91583,1
Predictive control	75852,4	34,2	4804,0	80690,6

Source: Own work / Źródło: opracowanie własne



Source: Own work / Źródło: opracowanie własne

Fig. 1. Example of calculated waveforms of indoor air temperature (red lines) and required (setpoint) values of the parameter (blue lines) obtained for different applied control algorithms
Rys. 1. Przykładowe wyliczone przebiegi temperatury powietrza wewnętrznego (kolor czerwony) oraz wymagane (zadane) wartości tej temperatury (kolor niebieski) uzyskane dla różnych zastosowanych algorytmów sterowania

3.2. Minimizing energy consumption

If the investor requires low power supply, then in simulation studies using comprehensive model of mushroom-growing cellar, waveforms of control signals for devices (mainly ventilation and air conditioning) installed in the building are determined.

Power supply index I_E is the minimum integral of the square of control signal u for each device (formula 2) [2].

$$\min I_E = \int_{t_0}^{t_k} u^2(\tau)d\tau \quad (2)$$

where: u – control signal [V], τ – time [h].

At the stage of the design of control system, waveforms of control signals are determined numerically by using in the mushroom-growing cellar model various possible to use control algorithms. The lowest power consumption provides the control algorithm for which total quality index, for all installed devices. has the lowest value.

Fig. 2 shows example of waveforms of control signal for humidifier, obtained when at the design stage of control system three options of control algorithm: two-position control, continuous control (PID – proportional, integral, derivative) and predictive control were considered.

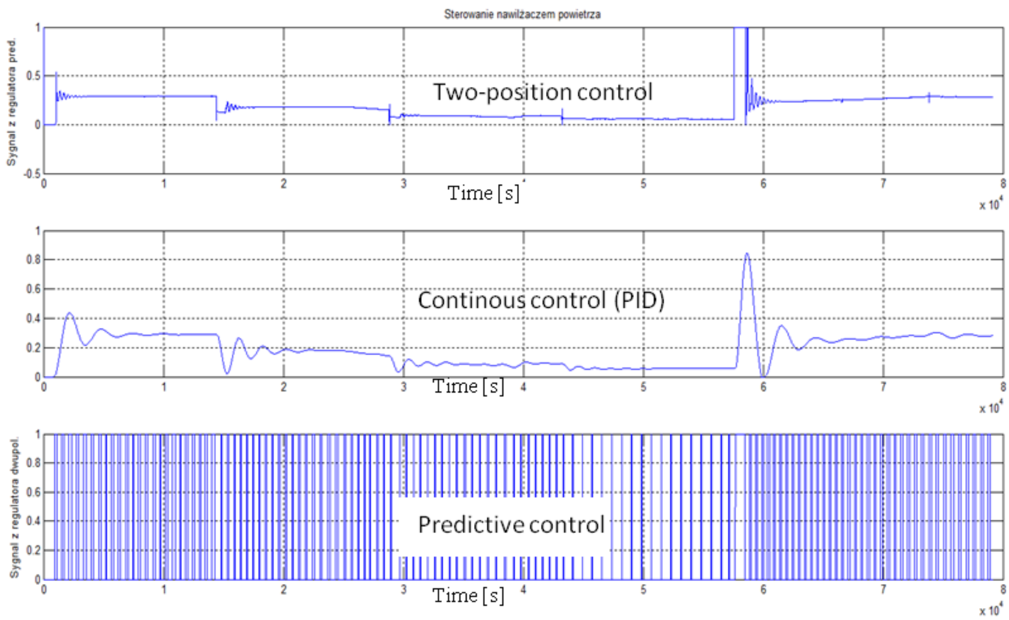


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Fig. 2. Example of waveforms of control signal for humidifier obtained for different applied control algorithms
Rys. 2. Przykładowe przebiegi sygnału sterującego nawilżaczem powietrza uzyskane dla różnych zastosowanych algorytmów sterowania

Tab. 2. Designated, as a result of optimizing, values of power supply index
Tab. 2. Wyznaczone w wyniku optymalizacji wartości wskaźnika zużycia energii

	Values of power supply index I_E				
	Control signal for cooler	Control signal for heater	Control signal for humidifier	Control signal for CO_2 installation	Total index
Two-position control	15530,9	63669,0	16360,5	12214,0	107774,4
Continuous control	315,1	37729,6	3726,1	1938,0	43708,8
Predictive control	193,9	36896,0	4179,6	2365,6	43635,1

Source: Own work / Źródło: opracowanie własne

Table 2 shows designated, as described above, values of power supply index of control signals (for different devices installed in mushroom-growing cellar) and different applied control algorithms.

Low power consumption ensures continuous control (PID) and predictive control. Analysing obtained by computer simulation aggregate values of quality regulation index and power supply index, at the stage of the design of control system for mushroom-growing cellar, to technical realization should be selected predictive control algorithm, which guarantees the lowest values of these indicators.

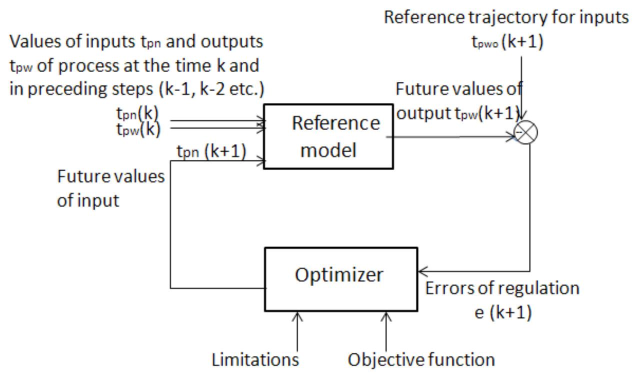
4. Use of polioptimization at microclimate control on the example of potato store

DMC control algorithm (Dynamic Matrix Control) is control algorithm that allows the use of polioptimization at microclimate control in agricultural buildings. This possibility was examined on the example of controlling of air temperature inside the potato store during potato tubers storage.

Polioptimization consists in finding a compromise in the control between two mutually exclusive demands of producers of agricultural products. These demands are:
1) minimization of technological losses and assurance of the highest quality of stored potatoes at the end of storage process through the fine-tuning the temperature of air inside the store, guaranteeing the fulfillment of technological requirements. During the technical implementation of these requirements, it is necessary, in addition to ventilation equipment, the use energy-consuming air-conditioning equipment. Air conditioners consume about 17 times more energy than ventilation devices [6];
2) minimization of energy supply, thereby reducing the operating costs of the building storage.

Fig. 3 shows a diagram illustrating the operation of the control system implementing this algorithm. Input signals in the control process are temperatures of air supply to store (t_{pn}): current (in the step k) and previously measured at a fixed frequency in steps k-1, k-2 and so on. Output signals are temperatures of inside air (t_{pw}): current (in the step k) and previously measured at a fixed frequency (e.g. every 6 hours) in steps k-1, k-2 and so on. Technological requirements regarding the temperature of the indoor air are introduced into the control system as a set points t_{pwo}. Regulation error *e(k+1)* is the projected difference between required by technologists and actual values of the internal air temperature in the next step k+1. The idea of predictive control on the example of stored potatoes temperature is discussed in detail in work [3].

To be able to use the DMC control algorithm to regulate indoor air temperature is necessary to know [1]:
- reference model,
- optimizer.



Source: Own work / Źródło: opracowanie własne

Fig. 3. The idea of indoor air temperature control in potato store using DMC algorithm
Rys. 3. Schemat obrazujący sposób funkcjonowania systemu sterowania, realizującego algorytm sterowania DMC, zastosowany do regulacji temperatury powietrza wewnętrznego

Reference model is a discrete time characteristics of technological process. The starting point for determining the characteristics is heat balance equation for the air inside the storage. This equation has the form:

$$\rho_{pw} c_{pw} \frac{dt_{pw}}{d\tau} = -\rho_{pw} c_{pw} v \frac{dt_{pw}}{dz} + \frac{a\alpha(1-\varepsilon)}{\varepsilon}\left(t_{zi} - t_{pw}\right) \quad (3)$$

where:
ρ_{pw} – density of indoor air [$kg \cdot m^{-3}$],
c_{pw} – specific heat of indoor air [$J \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$],
t_{pw} – temperature of indoor air [°C],
τ – time [h],
v – velocity [$m \cdot h^{-1}$],
z – height of the layer of potatoes [m],
a – surface area [$m^2 \cdot m^{-3}$],
α – heat transfer coefficient [$J \cdot m^{-2} \cdot h^{-1} \cdot {}^{\circ}C^{-1}$],
ε – porosity of the layer,
t_{zi} – temperature of potatoes [ºC]
with the initial conditions:

$$t_{pw}(z,0) = t_{pwo}$$

and with boundary conditions:

$$z = 0, t_{pw} = t_{pn}$$

The methodology for determining the characteristics described in detail in the work [3].

Optimizer enables the polioptimization. The objective function (4) is composed of two parts and has the form:

$$\min f = w_{t_{pw}}[t_{pwo}(k+1) - t_{pw}(k+1)]^2 + w_{t_{pn}} \Delta t_{pn}^2(k+1) \quad (4)$$

where:
t_{pwo} – the temperature of indoor air required by technologists in step k+1 [ºC],

t_{pn} – supply air temperature in step k+1 [ºC],

$w_{t_{pw}}$ – weighting factor reflecting the relative importance of the accuracy of regulation,

$w_{t_{pn}}$ – weighting factor reflecting the relative importance of energy consumption,

k, k-1, k-2,…N – time steps.

The first term of this function is responsible for the accuracy of regulation, and the second term for energy consumption during the internal air temperature control. Assigned to both terms weighting factors enable the realization of company management strategy adopted by the owner of the storage. Thus:

- if in the store are stored seed potatoes of high quality and value, then it is advisable to increase value of weighting factor $w_{t_{pw}}$ (in formula 4), accepting thereby increased energy consumption and hence higher operating costs of the storage building. By providing precise regulation of air temperature high quality of stored tubers is maintained;
- if the owner of the store intends to reduce the operating costs of the object, he can increase value of weighting factor $w_{t_{pn}}$ (in formula 4), taking into account the fact that the quality of stored tubers after storage is lower.

5. Summary

The results of simulation studies have demonstrated the benefits of using optimization methods both for design of energy-saving control system in specialized agricultural buildings and during the microclimate control in these buildings. The aim of implemented in these facilities optimization task is to minimize the regulation error and minimizing energy consumption. At the stage of design microclimate control system for mushroom-growing cellar, after analysis of obtained by computer simulation aggregate values of quality regulation index and power supply index, to technical realization it should be selected predictive control algorithm, which guarantees the lowest values of these indicators. Simulation tests conducted on the example of potato store also showed that it is possible to use poliopti-mization methods at stage of microclimate control in agricultural buildings by using DMC control algorithm (Dynamic Matrix Control). Weighting factors assigned to terms of objective function, which is integral part of these control algorithm, enable the realization of company management strategy adopted by the owner of the storage.

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