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TEMPERATURE CONTROL OF POTATOES IN THE STORAGE USING DMC CONTROL ALGORITHM

Summary

The aim of the study was to investigate the applicability of DMC control algorithm to control the temperature of potatoes in the storage. Principle of regulating the temperature of stored potatoes using the above algorithm, and simulations were performed. The obtained results were compared with the effects of currently used in the storage of potatoes control algorithms: the two-position and the PID (proportional-integral-differential). Preliminary results of the temperature control system simulation of potatoes in storage, exercising control algorithm DMC indicated that this system compared with conventional control systems makes it possible to achieve the desired temperature of potatoes in less time, and also provides more accurate control without overshoot. Thus a better quality of regulation, lower technological losses and the required quality of stored potato tubers are ensured. Moreover, taking into account the weights in the objective function of optimizer allows such a process control that optimizes energy consumption.
***Key words**: preservation of potatoes, temperature control, DMC control algorithm*

REGULACJA TEMPERATURY ZIEMNIAKÓW W PRZECHOWALNI Z WYKORZYSTANIEM ALGORYTMU STEROWANIA DMC

Streszczenie

Celem pracy było zbadanie możliwości zastosowania algorytmu sterowania DMC do regulacji temperatury ziemniaków w przechowalni. Przedstawiono ideę regulacji temperatury magazynowanych ziemniaków z wykorzystaniem powyższego algorytmu, a także przeprowadzono symulacje. Otrzymane efekty sterowania porównano z efektami sterowania uzyskanymi z wykorzystaniem aktualnie stosowanych w przechowalnictwie ziemniaków algorytmów dwupołożeniowego i PID (proporcjonalno-całkująco-różniczkowego). Wstępne wyniki badań symulacyjnych układu regulacji temperatury ziemniaków w przechowalni, realizującego algorytm sterowania DMC wskazały, że układ ten w porównaniu z konwencjonalnymi układami sterowania umożliwia osiągnięcie żądanej temperatury ziemniaków w krótszym czasie, a także zapewnia dokładniejszą regulację, bez przeregulowań. Tym samym zapewnia lepszą jakość regulacji, a co się z tym wiąże niższe straty technologiczne i wymaganą jakość składowanych bulw ziemniaka. Ponadto uwzględnienie wag w funkcji celu optymalizatora pozwala na takie sterowanie procesem, które optymalizuje zużycie energii.
***Słowa kluczowe**: przechowalnictwo ziemniaków, regulacja temperatury, algorytm sterowania DMC*

1. Introduction

Owners of companies producing food or delivering agricultural products directly to consumers are today aware that customers are looking for low-cost products of the highest quality. This also applies to owners: storage (fruits, vegetables or potatoes), greenhouses or mushroom farms. If their products meet the above requirements of consumers, the company is competitive in the market.

However, we should be aware that these requirements are mutually contradictory. The highest quality of stored agricultural crops or fruits, high yield and quality of crops grown in greenhouses or in mushroom farms can be achieved in these specialized buildings, primarily by providing required by technologists microclimate. This means that in these objects must be installed expensive to operate, consuming power ventilation and air conditioning equipment. On the other hand, the prices of the products offered by traders can be reduced only if are reduced the costs of their production. In the case of food production and storage of agricultural produce costs of maintaining proper microclimate in specialized buildings are an important position.

To meet the expectations of consumers regarding the price and quality of agricultural products, it is necessary to search for new ways to control the technological parameters of the processes taking place in a specialized agricultural buildings. Control algorithms should pursue the task polyoptimization, i.e. to provide the highest level of control accuracy (and thus create the conditions for obtaining the highest quality of stored crops or high yields of good quality plants or fungi), with the lowest power consumption (which is equivalent to a reduction of costs). It seems that the demand for the implementation of the control algorithm polyoptimization meets DMC (Dynamic Matrix Control). This algorithm has not been used so far in agricultural engineering.

The aim of this study was to examine the possibility of using DMC control algorithm to control the microclimate in the specialized agricultural building, which is the storage of potatoes. The algorithm used to control the temperature of stored potatoes.

2. The idea of adjusting the temperature of stored potatoes using DMC control algorithm

During storage of potatoes is necessary to maintain the required by technologists runs of potatoes temperature and relative humidity of the surrounding tubers [1]. Since the parameters are significantly affecting the quality of stored potatoes, for example of potatoes temperature control will be presented the idea of controlling using the DMC algorithm. Figure 1. shows the input and output signals of the process while controlling the temperature of a potato. Process input signals are temperatures t_{pn} of air supply to store and output signals – temperatures of potatoes t_{zi}, considered at the time of the current steps k and in previous steps k-1, k-2 and so on.

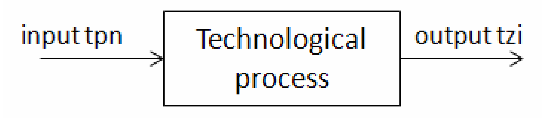

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Fig. 1. The input (control) and output (adjustable) signals of technological process while controlling the temperature of potatoes

Rys. 1. Sygnały wejściowe (sterujące) i wyjściowe (regulowane) procesu technologicznego podczas sterowania temperaturą ziemniaków

The idea of the temperature control of potato with DMC algorithm shown in Figure 2. This algorithm is an prediction algorithm. It can be technically carried out, provided that in store are performed the measurements of input and output signals of the process with a constant time step, e.g. every 10 minutes. The algorithm allows the calculation of the expected potato's temperature $t_{zi}[k+1]$ in the next step k+1 (i.e. for 10 minutes), provided that temperature values of the potatoes and the supply air temperatures measured in storage in the current time k and in preceding steps k-1 k-2 and so on, are known.

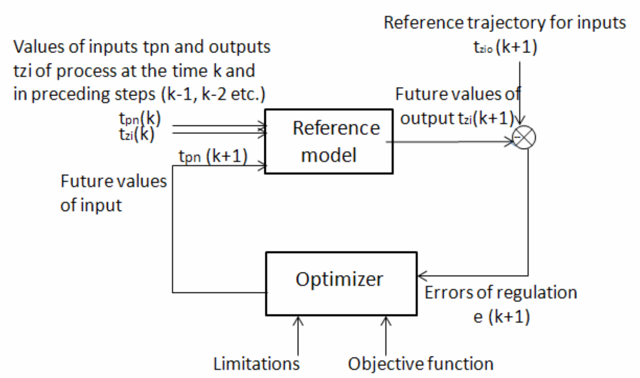

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Fig. 2. The idea of potato's temperature control using DMC algorithm

Rys. 2. Idea sterowania temperaturą ziemniaków z wykorzystaniem algorytmu DMC

The principle of operation of the DMC algorithm [2] is to minimize errors of regulation e(k+1) anticipated at the time k for the future while k+1, which are the differences between the regulated values $t_{zi}(k+1)$ anticipated at the time k for the future while k+1 and set points for these outputs t_{zio} (k+1) also for the future while (k + 1)

$e(k+1) = t_{zi}(k+1) - t_{zio}(k+1)$

for the prediction horizon N (k=1,2, ..., N).

Set points t_{zio} are strictly defined by technologists desired temperature values of potatoes in the storage. Deviation value determines the accuracy of the temperature control of stored potatoes. The smaller the deviation, the better the accuracy of regulation, and therefore less technological losses and better quality of tubers after storage.

Future values of process variables at the time k+1 are determined based on knowledge of the values of these quantities at the time k. The next time k+1 followed by a new measurement t_{zi} (k+1) and the procedure is repeated.

During the implementation of the algorithm (Fig. 2) is assigned a sequence of future values of control signal (supply air temperature), which facilitates the imposition of restrictions on the control signal [3, 4]. When the control are used: a reference model – defined by technologists reference trajectory for the manipulated variable in the form (desired by the technologists) the temperature of potatoes, as well as the optimizer. This makes it easier to take into account the future changes in the program control set point or required by technologists temperature of potatoes.

3. Reference Model

In the DMC control algorithm reference model is a discrete time characteristics of technological process. The following explains the procedure for the determining the characteristics. Taken as a starting point knowledge of the nonlinear differential equation (1) [5], describing the heat transfer in a layer of potatoes:

$$\rho_{zi} c_{zi} \frac{dt_{zi}}{d\tau} = \rho_{zi} \frac{dq_{res}}{d\tau} - \rho_{zi} r_p \frac{du_{zi}}{d\tau} - a\alpha(t_{zi} - t_{pw}) \quad (1)$$

where:

ρ_{zi} – density of potatoes [$kg \cdot m^{-3}$],
c_{zi} – specific heat of potatoes [$J \cdot kg^{-1} \cdot {}^{\circ}C^{-1}$],
t_{zi} – average temperature of potatoes [°C],
τ – time [h].
q_{res} – respiration heat of potatoes [$kJ \cdot kg^{-1}$],
r_p – vaporization heat of water [$J \cdot kg_{H_2O}^{-1}$],
u_{zi} – average water content of potatoes [$kg_{H_2O} \cdot kg^{-1}$],
a – surface area [$m^2 \cdot m^{-3}$],
α – heat transfer coefficient [$J \cdot m^{-2} \cdot h^{-1} \cdot {}^{\circ}C^{-1}$],
t_{pw} – average temperature of indoor air [°C],

with boundary conditions:

$$x = 0, t_{pw} = t_{pn}.$$

This equation is complemented by a mathematical formalism (2), describing the respiration intensity of potatoes. Equation (2) was determined on the basis of 28 varieties of potatoes during the 12 seasons of the storage [6].

$$\frac{dq_{res}}{d\tau} = 0.174 t_{zi}^2 - 1.089 t_{zi} + 41.144 \quad (2)$$

Equation (1) after taking into account the mathematical formalism (2) and after linearization is expressed in the form of following relation:

$$\frac{dZ_1}{dv} = \left(\frac{A}{T_1} - \frac{A}{T_2}\right) Z_1 + \frac{A}{T_2} Z_2 - ACZ_3 + ACZ_4 \quad (3)$$

with boundary conditions:

$$x = 0, Z_5 = Z_2$$

In the formula (3) adopted the following designations:

$$Z_1 = \rho_{zi} c_{zi} (t_{zis} - t_{zi}),$$
$$Z_2 = \rho_{pw} c_{pw} (t_{pws} - t_{pw}),$$
$$Z_3 = a\alpha(u_{zis} - u_{zi}),$$
$$Z_4 = a\beta(x_{pws} - x_{pw}), v = \tau,$$
$$A = \frac{\rho_{pw} c_{pw}}{(1-\varepsilon)\rho_{zi} c_{zi}}, C = (1-\varepsilon)\rho_{zi} r_p,$$
$$T_1 = \frac{\rho_{pw} c_{pw}}{(1-\varepsilon)\rho_{zi}}, T_2 = \frac{\rho_{pw} c_{pw}}{(1-\varepsilon) a\alpha},$$

where:

ρ_{zi}, c_{zi}, t_{zi}, t_{pw}, a, α, u_{zi}, τ, r_p, - the meaning as in formula (1)
t_{zis} – determined average temperature of potatoes [°C],
ρ_{pw} – density of indoor air [$kg \cdot m^{-3}$],
c_{pw} – specific heat of indoor air [$J \cdot kg^{-1} \cdot °C^{-1}$],
t_{pws} – determined average temperature of indoor air [°C],
u_{zis} – determined average water content of the potatoes [$kg_{H_2O} \cdot kg^{-1}$],
β – mass transfer coefficient [$m \cdot h^{-1}$],
x_{pws} – determined average water content of indoor air [$kg_{H_2O} \cdot kg^{-1}$],
x_{pw} – average water content of indoor air [$kg_{H_2O} \cdot kg^{-1}$],
ε – porosity of layer.

The solution of equation (3) as the operators has the form (4),

$$Z_1(s) = hye^{-pX} Z_5(s) \tag{4}$$

and determined according to the formula (4) Laplace transfer function G (s) is equal to:

$$G(s) = \frac{Z_1(s)}{Z_5(s)} = hye^{-pX},$$

where:

$$p = \frac{T_1T_2s^2 + A(T_1 - T_2)s + T_2s - A}{T_1T_2s + A(T_1 - T_2)},$$

$$h = \frac{T_1T_2}{T_1T_2s + A(T_1 - T_2)},\ y = \frac{A}{T_2},\ X = \frac{x}{v} \tag{5}$$

where:
T – time constant [s],
s – Laplace operator,
X – height of the bulb layer [m],
v – air flow rate [$m \cdot h^{-1}$].

Laplace transform of the time-varying step response H (s) is expressed by the relation

$$H(s) = \frac{1}{s}G(s) = \frac{hy}{s}e^{-pX} \tag{6}$$

The time-varying step response is the Laplace inverse transform applied to the expression (6)

$$t_{zi}(t) = h(t) = \Lambda^{-1}[H(s)] \tag{7}$$

Laplace transform of G(s) (formula 6) is an exponential function with the exponent in the form of a fraction. Since the row counter this fraction is greater than the order of the denominator, there isn't exist inverse Laplace transformation of the transform H (s), and thus it is not possible to determine analytically the time-varying step response of the heat exchange process in stored potatoes.

The time-varying step response of the interesting process was obtained using metod known in chemical engineering process using frequency responce [7]. The essence of this method is described below. Knowing the transfer function (5), shall designate the spectral transmittance G(jω) of the process. For this purpose the following formula is using:

$$G(j\omega) - G(s)/_{s=j\omega} \tag{8}$$

where:
j – imaginary unit,
ω – pulsation,
s – Laplace operator.

Then the Bode frequency response are calculated (Fig. 3) and based on them determines a simplified transfer function the Laplace of the heat exchange process in potatoes in storage (9).

$$G(s) = \frac{K}{Ts+1}e^{-sT_o} \tag{9}$$

where:
K – gain,
T – time constant [s],
T_o – time delay [s].

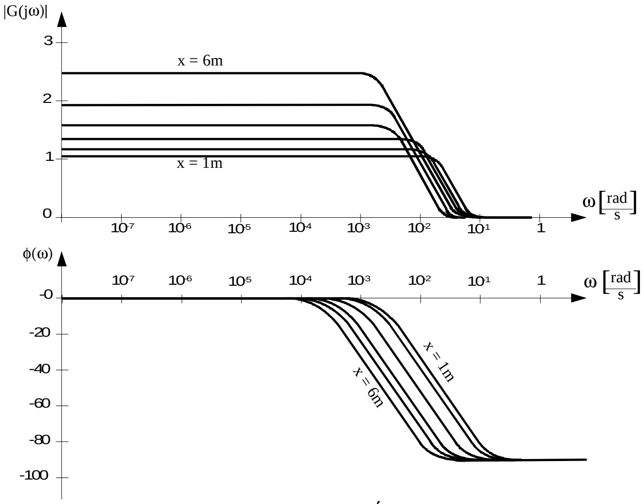

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Fig. 3. Diagrams of Bode frequency responses of heat exchange process in the potatoes in a ventilated layer depending on the height (x) of bulbs layer
Rys. 3. Przebieg charakterystyk częstotliwościowych Bode'go procesu wymiany ciepła w ziemniakach w wentylowanej warstwie w zależności od wysokości x warstwy bulw

Thus, the transform of the time-varying step response of the process takes the form:

$$H(s) = \frac{1}{s}G(s) = \frac{K}{s(Ts+1)}e^{-sT_o} \tag{10}$$

For the transmittance discrete time-varying step response of the heat exchange process in potatoes is expressed by the relationship:

$$t_{zik} = (a_1\Delta t_{pnk-1} + a_2\Delta t_{pnk-2} + \cdots + a_N\Delta t_{pnk-N})q^{-f} \tag{11}$$

where:
q^{-f} – delay operator of input signal, wherein $f = T/T_o$

4. Optimizer

Optimizer performs polyoptimization task with which we are dealing in the storage of potatoes. This task consists of finding a compromise between obtaining the required quality of stored potatoes (obtaining the required precision adjustment) with the lowest power consumption. Optimizer is part of the DMC algorithm (Fig. 2) and is designed to minimize operating costs vault. The objective function is:

$$\min J = w_{t_{zi}}[t_{zio}(k+1) - t_{zi}(k+1)]^2 + w_{t_{pn}}\Delta t_{pn}^2(k+1) \tag{12}$$

where:
t_{zio} – the temperature of potatoes required by technologists in step k+1 [°C],
t_{zi} – the actual temperature of potatoes in step k+1 [°C],
t_{pn} – supply air temperature in the step k+1 [°C],
$w_{t_{zi}}$ – weighting factor reflecting the relative importance of the accuracy of regulation,
$w_{t_{pn}}$ – weighting factor reflecting the relative importance of energy consumption.

Enclosed in parentheses (formula 12) the first term of the objective function is responsible for the deviation of the temperature value of potatoes, and thus for the accuracy of regulation. It determines the height of technological losses and quality of potato tubers at the end of their storage. The second term of formula (12), which is the square of the control signal corresponds to a value of the consumed energy supply. To the objective function introduced weights. Changing the values of weights gives the ability to make a control decisions. By introducing appropriate weight values it is possible:

- energy-efficient temperature control of potatoes when stored are potatoes of inferior quality potatoes,
- accurate control during which consumes more energy when stored are potatoes of very good quality.

5. Use of a DMC algorithm to control the temperature in the storage

The above-described DMC control algorithm was used for potatoes temperature control during storage. The obtained results were compared with the effects of currently used in the storage of potatoes control algorithms: the two-position and the PID (proportional-integral-differential). Figure 4 shows the waveforms of potatoes temperature obtained during cooling tubers layer to the desired by the technologist value 4°C by using the aforementioned control algorithms.

On the basis of the waveforms shown in Fig. 4, it can be concluded that: DMC control algorithm asymptotically and the PID algorithm in an oscillating manner allow to achieve the desired (set point) by the technologist potatoes temperature.

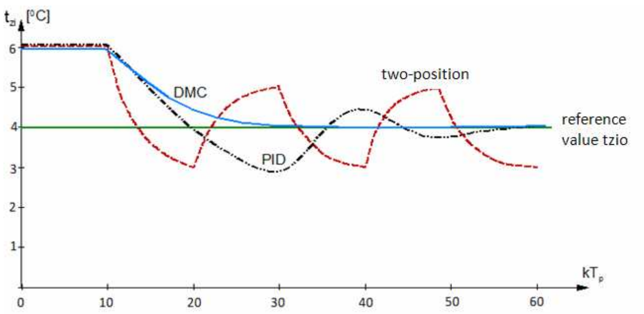

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Fig. 4. Sample diagrams of a potatoes temperature as a function of time obtained with the use of control algorithms: DMC, PID and a two-position

Rys. 4. Przebiegi temperatury ziemniaków uzyskane z wykorzystaniem algorytmów sterowania: DMC, PID oraz dwupołożeniowego

As is known from control theory, which confirms the waveform shown in Fig. 4, such possibility does not give the commonly used in the potato stores on-off algorithm. The lower the variations of storage potatoes temperature, the lower the loss of potatoes and the better their quality at the end of storage. Hence the conclusion of the advantages of using DMC algorithm compared with PID control and on-off algorithm. In addition, the DMC algorithm compared with PID control allows faster achieve the desired value of temperature of potatoes.

6. Summary

Preliminary results of simulation of the temperature control in the storage of potatoes, implementing the control algorithm DMC indicate that this system compared with conventional control systems (the most commonly used two-point system, and less used system PID):

- allows to achieve the desired temperature in a shorter time potatoes,
- provides more accurate control without overshoot.

Thus providing a better quality of regulation, and what goes with it lower technological losses and the required quality of stored potato tubers. Moreover, taking into account the weights in the objective function of optimizer allows such a process control that optimizes energy consumption.

Preliminary studies suggest that the use of the DMC control algorithm for stored can be for an entrepreneurs a tool for the task polyoptimization, i.e. to meet consumer requirements regarding the quality of agricultural products and their prices. This issue will be examined in the future.

7. References

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