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**Yakubash Ivan**

*Odesa National Technological University*

*ORCID: 0000-0002-2260-410X*

# RELEVANCE OF USING CONTROL SYSTEMS BUILT ON THE BASIS OF A FUZZY LOGIC APPARATUS FOR CONDENSATION DRYING OF FRUIT AND VEGETABLE RAW MATERIALS USING THERMOELECTRIC HEAT PUMPS

***Summary.*** *A special problem in the field of automation is the control of objects whose functions are described by nonlinear dependencies. When designing control systems for nonlinear objects, methods such as linear approximation or piecewise linear approximation are usually used. However, the application of these methods in real technical devices does not always achieve the desired effect.*

*Thus, in the presence of significant uncertainties in the static and dynamic characteristics of the drying chamber as a control object, it is difficult to formalize the tasks of synthesizing control system regulators. In this regard, the use of controllers based on fuzzy logic is appropriate (relevant).*

*The main advantage of the fuzzy approach is the possibility of forming a number of control rules depending on the combination of values of the input variables of the controller and, consequently, on changes in the operating mode and the level of disturbances.*

*In this paper, we have developed a model of an ATS with a fuzzy logic controller where the object for this case has nonlinear static characteristics. The development of the fuzzy logic controller is based on 5 rules of operation of the tabular representation. The membership functions of fuzzy sets have been* *defined. The fuzzy output algorithm was chosen as Sugeno of order 0. According to the characteristics of the fuzzy controller, the initial data for the formation and study of the neural network were determined, for further use as a neuro-regulator. The modeling resulted in the transient processes of the ACS with a fuzzy logic controller and a traditional PID controller.*

*The use of a control system built on the basis of a fuzzy logic apparatus for a condensing dryer using thermoelectric heat pumps is possible when using incomplete information on the mathematical description, or the control object is not stationary.*

***Key words:*** *object control, nonlinear static response, condensing dryer, thermoelectric heat pump, fuzzy logic, neural controller.*

**Introduction.** Fuzzy control is effective under conditions of uncertainty of information about the dynamic behavior of complex control objects. For technical systems with a random nature of the disturbing influence, the complexity of developing a dynamic model, its high order, and nonlinear nature, we can talk about the problem of control under uncertainty. The use of fuzzy controllers provides coarseness and stable convergence of processes, so this approach should be considered appropriate [1].

As an advantage of fuzzy control, one can also note the availability of modern controller programming systems with built-in fuzzy control libraries that have a good graphical interface, which very easily and clearly presents and corrects the type of membership functions and fuzzy inference. This makes it easier to set up an automatic control system.

To confirm the relevance of using a control system based on the fuzzy logic apparatus for the control object considered in this paper, it is necessary to move to its nonlinear model. Thus, the models of control channels of the considered control object should be characterized by a slightly nonlinear static characteristic.

First, let us present the insignificantly nonlinear static characteristic of the control object to move from the linear model of the control object to the initial nonlinear one. Representation of a nonlinear model of a control object [2], it is necessary to add appropriate nonlinear links to the corresponding models of control channels. The nonlinearity should be realized by including the Look up Table block in the corresponding model of the control channel.

In the Look up Table block, a nonlinear relationship (dependence) between the input variables is set in tabular form, which entails a “distortion” of the static characteristic of the control channel model.

As a result of the modeling, the static characteristic of the model of the control channel “u1 - T of the drying agent at the input, *C” was obtained, which has the form shown in Figure 1.

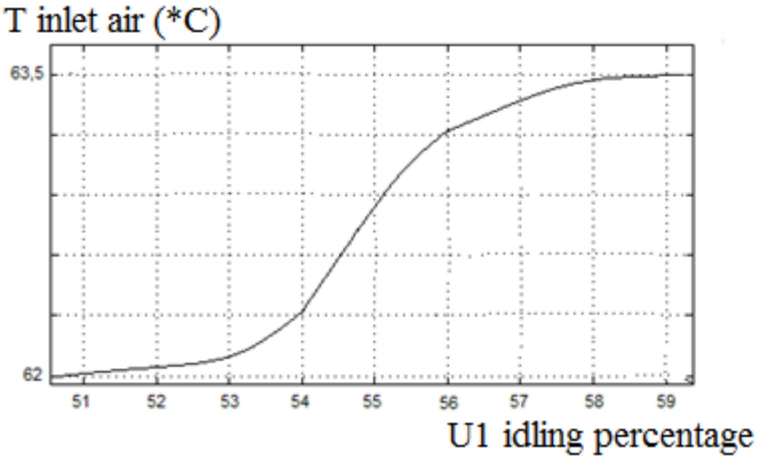


**Fig. 1. Nonlinear static characteristic of the control channel model**

Figure 1 shows that the static characteristic is insignificantly nonlinear, which makes it possible to synthesize the ACS with traditional PID controllers and obtain the required control quality indicators [3].

Taking into account the properties of the drying chamber as a nonlinear control object, it is advisable to use a fuzzy logic controller (FLC), which has the properties of a nonlinear controller, in the inlet air temperature control loop. The use of a fuzzy logic controller (Fuzzy controller) is due to the presence of a nonlinear control object, as well as a complex description of its static operating modes.

The complexity of describing the static modes of operation of the drying chamber leads to the fact that the operating modes can be described with insufficient accuracy due to the fuzzy (blurred) various experimental data [4]. Thus, in the present work, an ATS model with a Fuzzy controller was implemented.

The fuzzy controller developed in this paper is a combination of three phase control units on a certain element base: phasing, inference, and defuzzification. A simplified block diagram of the control system under development based on a fuzzy controller is shown in Figure 2.

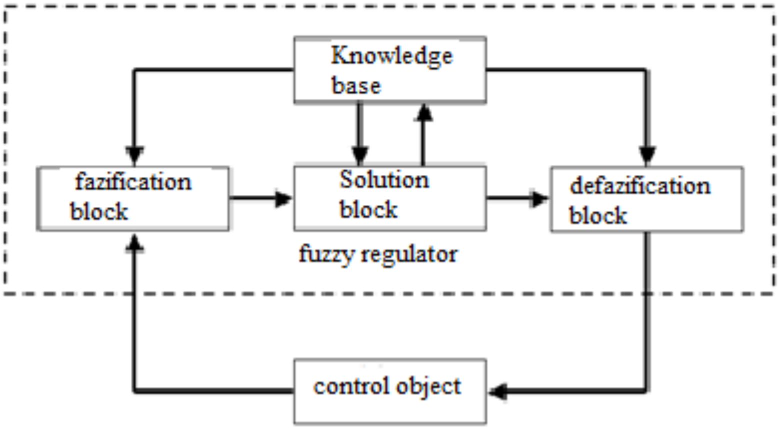
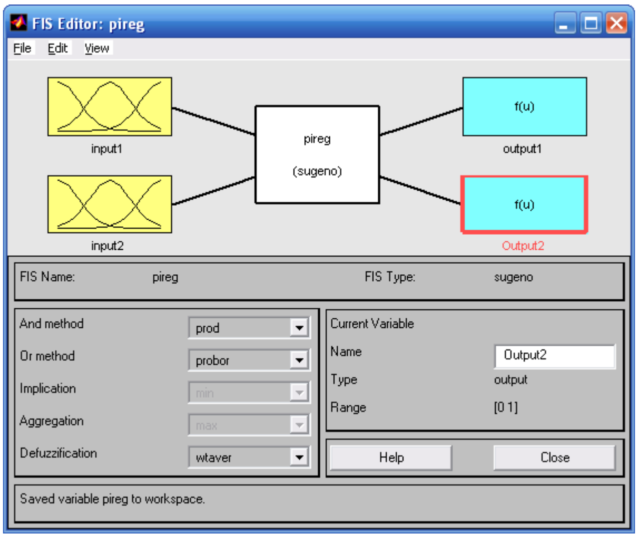


**Fig. 2. Simplified block diagram of a fuzzy logic controller**

From the point of view of structure, this controller scheme does not differ from the schemes of classical fuzzy controllers and is built according to classical models. All the defined blocks (phasing, logic solution block, defuzzification) shown in Figure 2 are edited in the corresponding FIS Editor of the MATLAB environment [5]. To launch the fis-editor window, the command "Fuzzy" was written in the MATLAB Window commander. After that, the Sugeno algorithm and two input and two output variables were selected.

Figure 3 shows the fis-file setup window for the fuzzy controller of the inlet air temperature in the drying chamber with the corresponding input and output signals.



FIS Name: pireg

FIS Type: sugeno

And method: prod

Or method: probor

Implication: min

Aggregation: max

Defuzzification: wtaver

Current Variable

Name: Output2

Type: output

Range: [0 1]

Saved variable pireg to workspace.

**Fig. 3. The editor window of the fuzzy controller with two inputs and two signal outputs**

So far, several fuzzy inference algorithms have been proposed (Mamdani, Tsukamoto, Larsen, Sugeno, etc.). In this paper, we present the 0-order Sugeno algorithm, as it is the simplest fuzzy inference algorithm.

Formally, the Sugeno algorithm proposed by Sugeno and Takagi can be defined as follows.

The rule base uses only the rules of fuzzy products in the form:

$$\begin{aligned}&\text{rule } {<}1{>}: \quad \text{if } (x \in A_1 \,/\, y \in B_1), \text{ then}, \ z_1 = f(x_1,\dots,x_n),\\ &\text{rule } {<}2{>}: \quad \text{if } (x \in A_2 \,/\, y \in B_2), \text{ then}, \ z_2 = f(x_1,\dots,x_n),\end{aligned} \qquad (1)$$

*where x, y are input variables, Ai, Bi are fuzzy sets z1=f(x1,...xn) is an arbitrary crisp function.*

If the polynomial *f(x)=Ci* is used as *f*, then we speak of a 0-order Sugeno algorithm. Then the rules will be as follows:

$$\begin{aligned}&\text{rule } {<}1{>}: \quad \text{if } (x \in A_1 \,/\, y \in B_1), \text{ then}, \ z_1 = C1\\ &\text{rule } {<}2{>}: \quad \text{if } (x \in A_2 \,/\, y \in B_2), \text{ then}, \ z_2 = C2\end{aligned} \qquad (2)$$

*where C1, C2 – are ordinary (distinct) numbers.*

Considering the governance structure, the following five rules for the functioning of the NLR can be identified in the "*if-then*" format, as shown above in:

R1: If the control error $e1$ belongs to the fuzzy set "large positive PE" and the increment of the control error $\Delta e1$ belongs to the set "approximately zero Z", then the control action $u1 = w1$, and the increment of the control action $\Delta u1 = w2$;

R2: If the control error $e1$ belongs to the fuzzy set "large negative NE" and the increment of the control error $\Delta e1$ belongs to the set "approximately zero Z", then the control action $u1 = -w1$, and the increment of the control action $\Delta u1 = -w2$;

R3: If the control error $e1$ belongs to the fuzzy set "approximately zero Z" and the increase in the control error $\Delta e1$ belongs to the set "approximately zero Z", then the control action $u1 = 0$, and the control action increment $\Delta u1 = 0$;

R4: If the control error $e1$ belongs to the fuzzy set "approximately zero Z" and the increase in the control error $\Delta e1$ belongs to the set "large positive PE", then the control action $u1 = w1$, and the control action increment $\Delta u1 = w2$;

R5: If the control error $e1$ belongs to the fuzzy set "approximately zero Z" and the increase in the control error $\Delta e1$ belongs to the set "large negative NE", then the control action $u1 = -w1$, and the control action increment $\Delta u1 = -w2$.

In accordance with the above rules, we will compile the knowledge base tables for the NLR of relative humidity in the drying chamber.

As can be seen from Figure 3, the input of this fuzzy controller will be two variables – the control error (input1) and the incremental control error (input2). For the variable input1, we define three triangular membership functions "trimf". This is a simple membership function and is the most commonly used. The triangular membership function is given by the following analytical formula:

$$\mu(x)=\begin{cases}0, & x\le a\\ \frac{x-a}{b-a}, & a\le x\le b\\ \frac{c-x}{c-b}, & b\le x\le c\\ 0, & c\le x\end{cases}. \qquad (3)$$

*[a, c] – range of change of the variable, for the present case* $a = -21$, $c = 21$;

*b – the most possible value of the variable.*

According to Table 1 of the database of rules for the functioning of the regulator, the corresponding rules were written in the window of the editor of the rules for the functioning of the fuzzy regulator of the MATLAB\Simulink environment.

*Table 1*

**Knowledge base table for the fuzzy logic controller of the input temperature to the chamber**

| $e_1$ $\Delta e_1$ | NE<br>( big negative $\Delta e_1$) | Z<br>(APPROXIMATELY ZERO $\Delta e_1$) | PE<br>(big positive $\Delta e_1$) |
|---|---|---|---|
| NE | – | $u_1 = 0.035$;<br>$\Delta u_1 = 21$; | – |
| Z | $u_1 = 0.035$;<br>$\Delta u_1 = 21$; | $u_1 = 0$;<br>$\Delta u_1 = 0$; | $u_1 = -0.035$;<br>$\Delta u_1 = -21$; |
| PE | – | $u_1 = -0.035$;<br>$\Delta u_1 = -21$; | – |

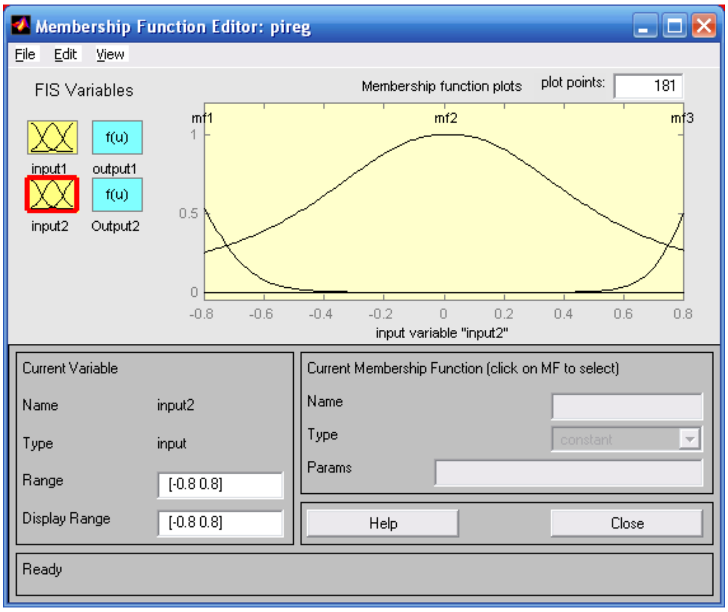
All membership functions were defined in the appropriate editor based on expert data. Figure 3 shows the window for setting the membership functions mf1, mf2, mf3 to the fuzzy sets of control error “large negative”, “approximately zero”, and “large positive”, respectively. We also defined the functions of belonging mf1, mf2, mf3 to the fuzzy sets of the incremental control error “large negative”, “approximately zero”, and “large positive”, which are shown in Figure 4.

When defuzzifying the original variables, a modified version in the form of the center of gravity method for single-point sets is used according to the following formula:

$$y_{out} = \frac{\sum_{i=1}^{n} (\alpha_i \cdot C_i)}{\sum_{i=1}^{n} (\alpha_i)} \qquad (4)$$

*where n is the total number of active fuzzy product rules, in our case – 5 rules;*

*- is the value of the degrees of truth of all conclusions of fuzzy product rules using the min-activation method.*



plot points: 181

Current Variable

Name input2

Type input

Range [-0.8 0.8]

Display Range [-0.8 0.8]

Current Membership Function (click on MF to select)

Name

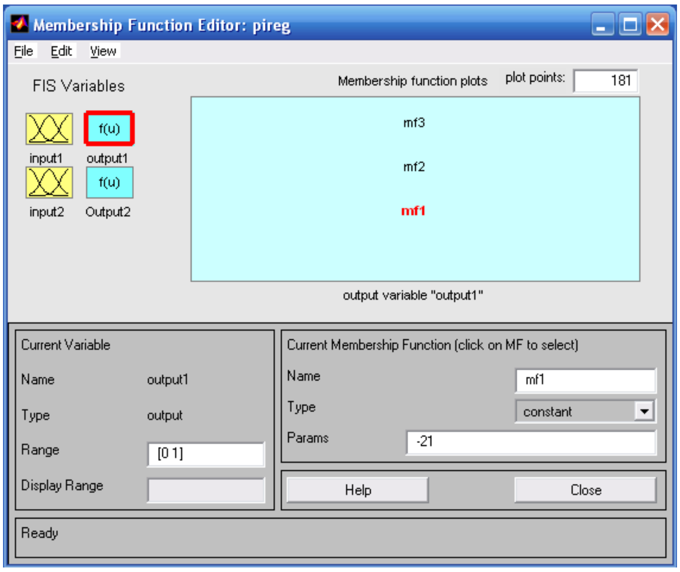
Type constant

Params

Ready

**Fig. 4. Windows for forming membership functions for fuzzy sets by increasing the error values PE, Z, NE of the MATLAB\Simulink fuzzy controller editor**

In this case, the output values of the Si signals according to the zero-order Sugeno algorithm were determined in the reactor window shown in Figure 5. The outputs of the synthesized fuzzy controller are the changes “output1” and “output2”. The output “output1” will work out the integral I-component of the controller, and “output2” will work out the P-component, respectively.



plot points: 181

Current Variable

Name: output1

Type: output

Range: [0 1]

Display Range:

Current Membership Function (click on MF to select)

Name: mf1

Type: constant

Params: -21

Ready

**Fig. 5. The window of the editor of rules for the functioning of the MATLAB\Simulink fuzzy controller**

To run the synthesized algorithm, the "Fuzzy Logic Controller" block from the standard library was dragged to the SIMULINLK model creation workspace. In the open window "Fuzzy Logic Controller", the name of the fis-file was written in the proposed field, and in the main window of setting up the fis-file, File / Save to Workspace was selected to load the fuzzy control algorithm into the MATLAB workspace.

In the final case, a scheme for modeling the ACS with a fuzzy controller was defined, a fragment of which is shown in Figure 6. Figure 6 shows that the control action of the fuzzy controller is formed from several components according to the formula:

$$u(t) = u_1(t) + (u_2(t-\tau_z) + \Delta u_2) \qquad (5)$$

*where u1(t) is the control action of the P-component of the controller;*

$\Delta u_2 = u_2(t) - u_2(t-\tau_z) -$ increase in control action from a fuzzy controller;

$u_2(t-\tau_z) -$ control action with a time delay $\tau_z$

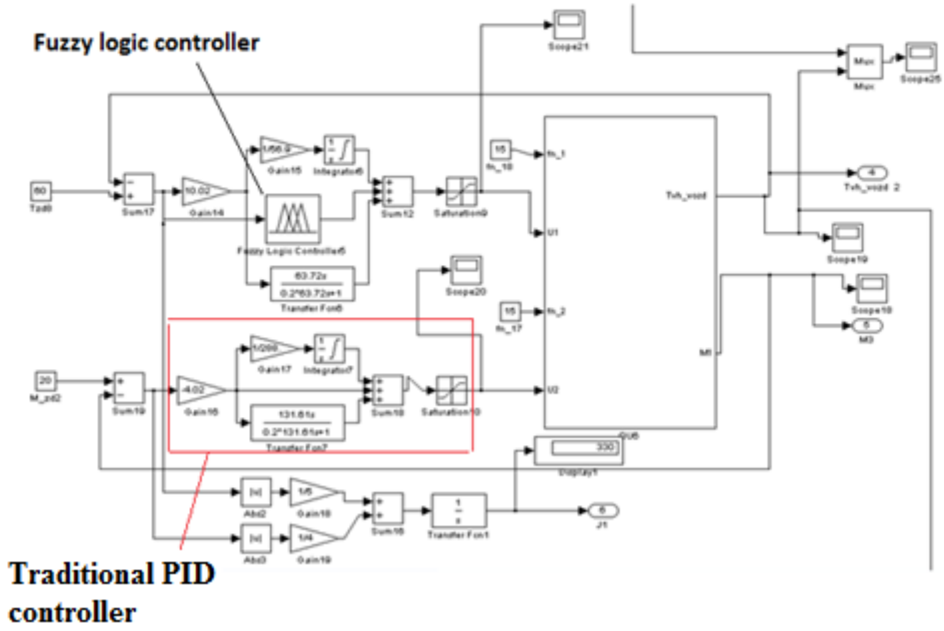


**Fig. 6. A fragment of the modeling scheme of the ACS with a fuzzy logic controller**

It should be noted that in the synthesis of the Fuzzy Logic Controller, all functions of membership in fuzzy sets and logical rules of operation are determined on the basis of expert data. And then adjusted during the modeling by trial and error. Also, the logical rules of operation were determined taking into account the rules of operation of fuzzy controllers presented in well-known scientific works, one of the first on Fuzzy control.

To implement the parametric optimization of control system regulators in the MATLAB\Simulink 5.2 software environment, a control system modeling scheme with an automatic optimizer was developed, which provides a search for optimal controller parameters according to the following compromise criterion for the quality of the system:

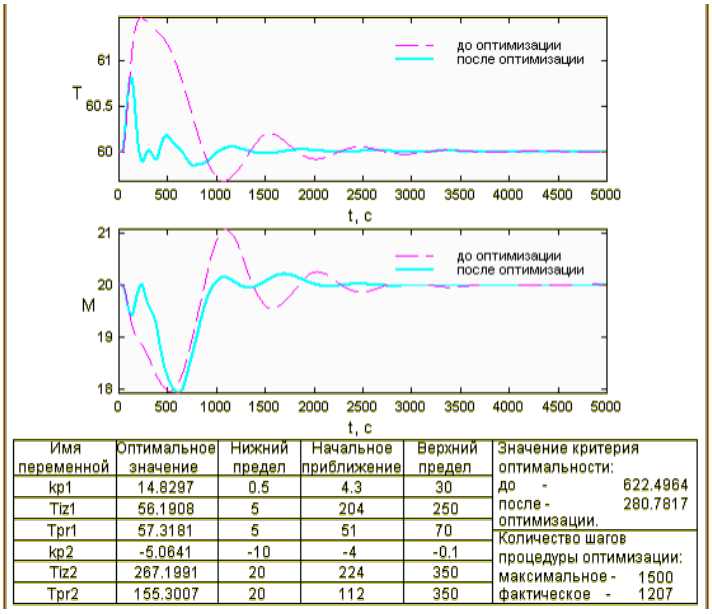
$$J = \int_0^\infty (|e_1(t)| + \beta \cdot |e_2(t)|)dt \rightarrow \min \quad (6)$$

where*: e1(t) is the time difference between the actual value of the controlled variable and the setpoint air temperature in the drying chamber;*

*e2(t) is the time difference between the actual value of the regulated value and the set value of air humidity in the drying chamber; β is the coefficient.*

The developed scheme for modeling the control system with an automatic optimizer in the MATLAB\Simulink 5.2 environment is shown in Figure 6.

As a result of the parametric optimization for the selected integral indicator of the system quality and using the corresponding module – the MATLAB\Simulink 5.2 application, we obtained the graphs of transient processes before and after optimization and the corresponding parameters of the controllers' tuning.  The initial values of the controller tuning parameters and the corresponding optimal values are presented in the optimization results window. Figure 7 also shows the corresponding transient plots obtained before and after the system optimization. The transient graphs show that the quality of control, in terms of the air temperature in the chamber, has improved significantly after the optimization of the ACS. However, it should be noted that due to the nonlinear characteristic of the control channel, such improvements can occur only under appropriate operating modes or initial conditions of the control system. Thus, the optimal tuning parameters in this case may be suboptimal otherwise, which determines the need to use nonlinear controllers.



| Имя переменной | Оптимальное значение | Нижний предел | Начальное приближение | Верхний предел | Значение критерия оптимальности: |
|---|---|---|---|---|---|
| kp1 | 14.8297 | 0.5 | 4.3 | 30 | до - 622.4964<br>после - 280.7817<br>оптимизации. |
| Tiz1 | 56.1908 | 5 | 204 | 250 | |
| Tpr1 | 57.3181 | 5 | 51 | 70 | Количество шагов<br>процедуры оптимизации:<br>максимальное - 1500<br>фактическое - 1207 |
| kp2 | -5.0641 | -10 | -4 | -0.1 | |
| Tiz2 | 267.1991 | 20 | 224 | 350 | |
| Tpr2 | 155.3007 | 20 | 112 | 350 | |

**Fig. 7.  The results of parametric optimization of the values of the parameters of the controllers of the ACS with a control channel characterized by a nonlinear static characteristic**

As a result of modeling the ACS with a fuzzy controller, transient diagrams of the system's output to the nominal mode of operation and transients under deterministic and random disturbing effects were obtained. For comparative analysis, the corresponding transient diagrams of the ACS with a traditional PID controller were also presented.

Thus, Figure 8 shows the graphs of transient processes from the system's output to the nominal mode of operation. And Figure 9 shows the graphs of dynamic processes under a deterministic disturbing influence and under a random influence introduced at 200 seconds.

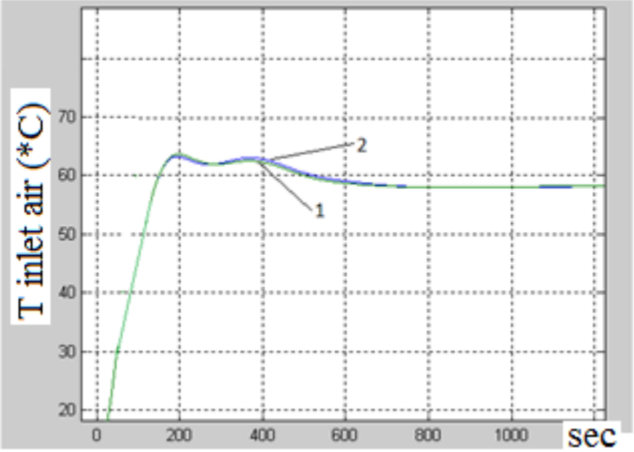


**Fig. 8. Graphs of transient processes obtained as a result of modeling different ACS**

where *graph 1 – transient process in ACS with a traditional PID controller; graph 2 – transient process in ACS with a fuzzy controller*

The figures show that the quality of control of different ACSs is identical to that of both traditional and fuzzy controllers. The transient graphs of different ACSs merge into one. This is obtained by adjusting the parameters of the fuzzy controller, as well as by comparing the functioning of the ACS with the fuzzy controller and the ACS with the traditional controller.

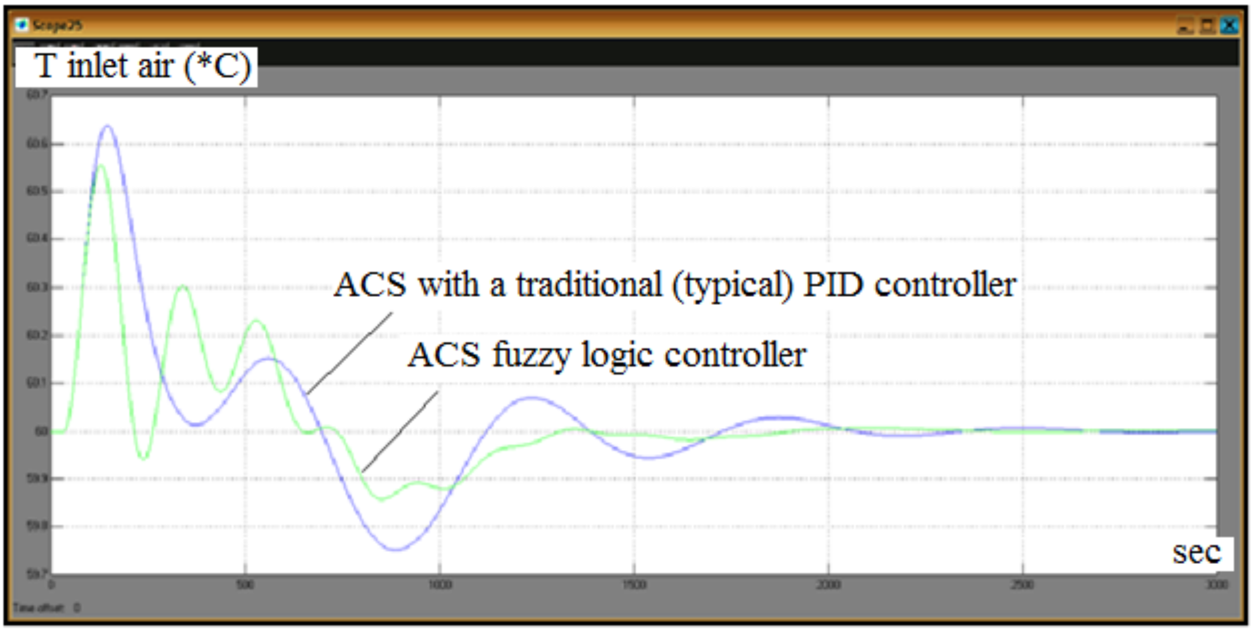


**Fig. 9. Transient diagrams of the ACS with a traditional (typical) PID controller and a fuzzy logic controller obtained as a result of modeling in Matlab Simulink**

**Conclusion.** In the process of performing the work, a model of the ACS with a fuzzy controller was developed. The fuzzy controller was developed in the appropriate editor of the MATLAB\Simulink environment. The functions of membership in fuzzy sets were defined, a database of rules for the functioning of the regulator was formed in tabular form and in the window of the corresponding editor, and a fuzzy inference algorithm – Sugeno of the 0th order – was defined.

It was found that in terms of control quality, such an ACS functions no better, and perhaps slightly better, than an ACS with a traditional PID controller for a control object with a nonlinear static characteristic along the control channel.

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