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FUZZY-NEIGHBORHOOD MODEL OF THE PLANT FOR MAINTAINING POLYOL TEMPERATURE

Shmyrin Anatoly Mikhailovich [a], **Yartsev Alexey Gennadievich** [a*]

[a] *Department of Higher Mathematics, Lipetsk State Technical University, Lipetsk, RUSSIA.*

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ABSTRACT

A fuzzy-neighborhood bilinear model of the plant for maintaining polyol temperature is considered. A fuzzy-neighborhood model was identified in which the fuzziness coefficients facing the bilinear members the product of the corresponding fuzziness coefficients is facing the linear members. A comparison was made of the deviations of the system obtained as a result of identification, and a comparison of the values of the heat transfer coefficient obtained as a result of the mixed control of fuzzy and the traditional neighborhood model.

1. INTRODUCTION

Previously, the work considered the neighborhood models, where the structure of connections between the nodes of the system was clearly defined and did not change in the process of control. In reality, there are mechanisms that allow you to change connections between system nodes, for example, valves, switches, etc. That is, to describe real technological processes, it is advisable to use fuzzy neighborhood models [1, 2], where fuzziness is the change in the structure and quality of connections between system nodes.

In this paper, a fuzzy-neighborhood bilinear model of the plant for maintaining polyol temperature is considered. Similar plants are applied at the enterprises for the production of refrigerators. For thermal protection polyurethane foam is applied to the walls of refrigerators, and polyol is one of the two main components of polyurethane foam [3,4]. Refrigerator production is an uneven process, and therefore, the required amount of polyurethane foam changes and, accordingly, the polyol consumption. A change in polyol consumption, its initial temperature, as well as the consumption and temperature of the heating agent can lead to a change in the quality and structure of the connections between the nodes of the system.

*Corresponding author (A.G. Yartsev). E-mail: yartsev.ag@yandex.ru

2. FORMULATION OF THE PROBLEM

The structural model of the plant for maintaining polyol temperature is represented as a graph in Figure 1, where 1 – polyol storage container; 2 – polyol transfer pump; 3 – heat exchanger; 4 – polyol consumer; 5 – refrigerator.

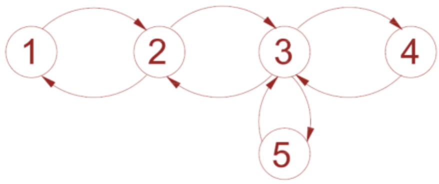

Figure 1: Structural model of a plant for maintaining polyol temperature

Essential parameters for state and control of the plant for maintaining polyol temperature are presented in Table 1.

Table 1: Parameters of state and control.

Designation	Parameter
x_1	Polyol temperature in the storage container, °C
x_2	Polyol consumption, tons/day
x_3	Heat transfer coefficient of the heat exchanger, W/(m^2·K)
x_4	Temperature of polyol transferred to the consumer, °C
x_5	Temperature difference of the heating agent before and after the heat exchanger, °C
v_1	Polyol reserve in the storage container, tons
v_2	Rotation speed of the pump shaft, rpm
v_3	Polyol temperature after the heat exchanger, °C
v_4	Consumption of polyol transferred to the consumer, tons/day
v_5	Heating agent consumption, tons/day

The fuzzy-neighborhood bilinear model of the plant for maintaining polyol temperature has the form:

$$\left\{ \begin{array}{l}
k_{x11}\cdot w_{x11}\cdot x_1 + k_{x12}\cdot w_{x12}\cdot x_2 + k_{v11}\cdot w_{v11}\cdot v_1 + k_{v12}\cdot w_{v12}\cdot v_2 + k_{xv111}\cdot w_{xv111}\cdot x_1\cdot v_1 + \\
+k_{xv112}\cdot w_{xv112}\cdot x_1\cdot v_2 + k_{xv121}\cdot w_{xv121}\cdot x_2\cdot v_1 + k_{xv122}\cdot w_{xv122}\cdot x_2\cdot v_2 = 0; \\
k_{x21}\cdot w_{x21}\cdot x_1 + k_{x22}\cdot w_{x22}\cdot x_2 + k_{x23}\cdot w_{x23}\cdot x_3 + k_{v21}\cdot w_{v21}\cdot v_1 + k_{v22}\cdot w_{v22}\cdot v_2 + \\
+k_{v23}\cdot w_{v23}\cdot v_3 + k_{xv211}\cdot w_{xv211}\cdot x_1\cdot v_1 + k_{xv212}\cdot w_{xv212}\cdot x_1\cdot v_2 + k_{xv213}\cdot w_{xv213}\cdot x_1\cdot v_3 + \\
+k_{xv221}\cdot w_{xv221}\cdot x_2\cdot v_1 + k_{xv222}\cdot w_{xv222}\cdot x_2\cdot v_2 + k_{xv223}\cdot w_{xv223}\cdot x_2\cdot v_3 + \\
+k_{xv231}\cdot w_{xv231}\cdot x_3\cdot v_1 + k_{xv232}\cdot w_{xv232}\cdot x_3\cdot v_2 + k_{xv233}\cdot w_{xv233}\cdot x_3\cdot v_3 = 0; \\
k_{x32}\cdot w_{x32}\cdot x_2 + k_{x33}\cdot w_{x33}\cdot x_3 + k_{x34}\cdot w_{x34}\cdot x_4 + k_{x35}\cdot w_{x35}\cdot x_5 + k_{v32}\cdot w_{v32}\cdot v_2 + \\
+k_{v33}\cdot w_{v33}\cdot v_3 + k_{v34}\cdot w_{v34}\cdot v_4 + k_{v35}\cdot w_{v35}\cdot v_5 + k_{xv322}\cdot w_{xv322}\cdot x_2\cdot v_2 + \\
+k_{xv323}\cdot w_{xv323}\cdot x_2\cdot v_3 + k_{xv324}\cdot w_{xv324}\cdot x_2\cdot v_4 + k_{xv325}\cdot w_{xv325}\cdot x_2\cdot v_5 + \\
+k_{xv332}\cdot w_{xv332}\cdot x_3\cdot v_2 + k_{xv333}\cdot w_{xv333}\cdot x_3\cdot v_3 + k_{xv334}\cdot w_{xv334}\cdot x_3\cdot v_4 + \\
+k_{xv335}\cdot w_{xv335}\cdot x_3\cdot v_5 + k_{xv342}\cdot w_{xv342}\cdot x_4\cdot v_2 + k_{xv343}\cdot w_{xv343}\cdot x_4\cdot v_3 + \\
+k_{xv344}\cdot w_{xv344}\cdot x_4\cdot v_4 + k_{xv345}\cdot w_{xv345}\cdot x_4\cdot v_5 + k_{xv352}\cdot w_{xv352}\cdot x_5\cdot v_2 + \\
+k_{xv353}\cdot w_{xv353}\cdot x_5\cdot v_2 + k_{xv354}\cdot w_{xv354}\cdot x_5\cdot v_4 + k_{xv355}\cdot w_{xv355}\cdot x_5\cdot v_5 = 0; \\
k_{x43}\cdot w_{x43}\cdot x_3 + k_{x44}\cdot w_{x44}\cdot x_4 + k_{v43}\cdot w_{v43}\cdot v_3 + k_{v44}\cdot w_{v44}\cdot v_4 + k_{xv433}\cdot w_{xv433}\cdot x_3\cdot v_3 + \\
+k_{xv434}\cdot w_{xv434}\cdot x_3\cdot v_4 + k_{xv443}\cdot w_{xv443}\cdot x_4\cdot v_3 + k_{xv444}\cdot w_{xv444}\cdot x_4\cdot v_4 = 0; \\
k_{x53}\cdot w_{x53}\cdot x_3 + k_{x55}\cdot w_{x55}\cdot x_5 + k_{v53}\cdot w_{v53}\cdot v_3 + k_{v55}\cdot w_{v55}\cdot v_5 + k_{xv533}\cdot w_{xv533}\cdot x_3\cdot v_3 + \\
+k_{xv535}\cdot w_{xv535}\cdot x_3\cdot v_5 + k_{xv553}\cdot w_{xv553}\cdot x_5\cdot v_3 + k_{xv555}\cdot w_{xv555}\cdot x_5\cdot v_5 = 0.
\end{array} \right.$$

The fuzzy-neighborhood bilinear system includes model coefficients – w_x, w_v, w_{xv}, and fuzziness coefficients – k_x, k_v, k_{xv}, characterizing the connection between the nodes of the system. It is worth noting that the fuzziness coefficients facing the bilinear members k_{xv}, can be either independent of the values of the coefficients facing the linear members k_x и k_v, or have a certain dependence on them, for example $k_{xv}=k_x \cdot k_v$. This article discusses a fuzzy-neighborhood model where the coefficients k_{xv} are equal to the product of the corresponding fuzziness coefficients facing the linear members.

The aim of this work is to conduct identification and mixed control of fuzzy-neighborhood model; comparison of system deviations resulting from identification and mixed control; comparison the results of determining the heat transfer coefficient of the heat exchanger in the process of mixed control of fuzzy-neighborhood model and the traditional neighborhood model, analyzing the behavior of the fuzziness coefficients in the process of mixed control.

3. IDENTIFICATION OF THE FUZZY-NEIGHBORHOOD MODEL

For identification [5], the values of the state and control components were selected corresponding to the nominal operating mode of the plant for maintaining polyol temperature. These values are presented in Table 2.

Table 2: Nominal values of state and control components

x_1, °C	40	v_1, tons	22
x_2, tons/day	13.2	v_2, rpm	319
x_3, W/(m^2·K)	71.2	v_3, °C	22
x_4, °C	22	v_4, tons/day	11.88
x_5, °C	5	v_5, tons/day	27.5

The identification procedure was carried out in the Mathcad program, where the normalized values of the state and control components [6] and part of the predefined model coefficients [7] were entered. Part of the values of fuzziness coefficients were also set equal to one:

$$k_{x11} = 1,\ k_{x22} = 1,\ k_{x33} = 1,\ k_{x44} = 1,\ k_{x55} = 1;$$

$$k_{v11} = 1,\ k_{v22} = 1,\ k_{v33} = 1,\ k_{v44} = 1,\ k_{v55} = 1.$$

In the identification process, the values of the model coefficients w and the fuzziness coefficients k are determined. In this case, the fuzziness coefficients can take values in the range from 0 to 1.

The choice of the initial approximation value has a great influence on the identification results. The initial approximation for the model coefficients was assumed to be zero. The deviations of the fuzzy-neighborhood model equations and the traditional neighborhood model equations obtained as a result of identification are presented in Table 3. The results of determining the coefficients k for the initial approximation for the fuzziness coefficients from 0.5 to 0.9 are presented in Table 4.

Table 3: Deviations of system equations for fuzzy-neighborhood model with dependent fuzziness coefficients

Initial approximation	0.5	0.6	0.7	0.8	0.9	Traditional model
Deviation of the first equation	$3.03 \cdot 10^{-9}$	$1.32 \cdot 10^{-10}$	$6.83 \cdot 10^{-13}$	$3.05 \cdot 10^{-9}$	$3.81 \cdot 10^{-8}$	$1{,}44 \cdot 10^{-8}$
Deviation of the second equation	$5.72 \cdot 10^{-8}$	$1.23 \cdot 10^{-9}$	$1.81 \cdot 10^{-8}$	$2.36 \cdot 10^{-9}$	$3.62 \cdot 10^{-9}$	$1{,}17 \cdot 10^{-8}$
Deviation of the third equation	$9.61 \cdot 10^{-10}$	$1.32 \cdot 10^{-8}$	$2.26 \cdot 10^{-11}$	$1.8 \cdot 10^{-9}$	$3.22 \cdot 10^{-10}$	$4{,}44 \cdot 10^{-8}$
Deviation of the fourth equation	$2.93 \cdot 10^{-9}$	$2.09 \cdot 10^{-10}$	$7.39 \cdot 10^{-10}$	$1.31 \cdot 10^{-9}$	$1.79 \cdot 10^{-10}$	$1{,}11 \cdot 10^{-6}$
Deviation of the fifth equation	$4.78 \cdot 10^{-13}$	$1.14 \cdot 10^{-9}$	$2.19 \cdot 10^{-8}$	$5.2 \cdot 10^{-10}$	$6.1 \cdot 10^{-8}$	$7{,}13 \cdot 10^{-8}$

Table 4: Identification results for fuzzy-neighborhood model with dependent fuzziness coefficients

Initial approx.	0.5	0.6	0.7	0.8	0.9
k_{x12}	0.12501	0.59932	0.6223	0.80004	0.22471
k_{v12}	0.25049	0.59739	0.43686	0.80012	0.43993
k_{x21}	0.5001	0.14879	0.17488	0.79854	0.22478
k_{x23}	0.50171	0.1284	0.33343	0.77417	0.41862
k_{v21}	0.50006	0.14939	0.17494	0.79848	0.22487
k_{v23}	0.50006	0.29511	0.3495	0.79848	0.44894
k_{x32}	0.12496	0.14984	0.69351	0.80058	0.22497
k_{x34}	0.24993	0.2997	0.69848	0.80014	0.44995
k_{x35}	0.12492	0.14965	0.68579	0.80128	0.22494
k_{v32}	0.24425	0.27667	0.63438	0.80555	0.44772
k_{v34}	0.12494	0.14976	0.69459	0.80046	0.22498
k_{v35}	0.24972	0.29885	0.69676	0.80027	0.44989
k_{x43}	0.12376	0.14608	0.57929	0.7988	0.59377
k_{v43}	0.24931	0.2978	0.68274	0.7998	0.84299
k_{x53}	0.50057	0.1503	0.68302	0.75744	0.90054
k_{v53}	0.5001	0.30035	0.69625	0.78977	0.90013

When choosing the optimal initial approximation, one should be guided not only by the minimum value of the system deviations, but also the requirement to get the obtained values of the fuzziness coefficients in the existing production ranges of connections between the nodes of the system. Based on this, the initial approximation equal to 0.8 is optimal for the considered case. In this case, sufficient accuracy of the system is observed – deviations are an order of magnitude lower than the deviations of the traditional neighborhood model, and the obtained fuzziness coefficients satisfy the existing range of connections.

4. MIXED CONTROL OF THE FUZZY-NEIGHBORHOOD MODEL

The purpose of mixed control is to determine the heat transfer coefficient at varying values of the polyol consumption and the temperature difference of the heating agent. The procedure of mixed control with variable coefficients [8-10] was applied, where the coefficient $q=k \cdot w$ was used as a variable. The model coefficients w, found in the identification process remain constant during the mixed control. The change in the coefficient q in the process of mixed control indicates a change in the value of the fuzziness coefficient k, i.e. indicates a change in the quality of the connections between the nodes of the system. The new value of the fuzziness coefficient is defined as:

$$k' = \frac{q'}{w} \quad (1),$$

where q' – is the value of the variable coefficient found in the process of mixed control. Mixed control was carried out in the Mathcad program, in which there are restrictions on the number of parameters of the function, so only the coefficients q_x and q_v were used as variables. The q_{xv} coefficients remained constant, i.e. the product of $k_x \cdot k_v$ remained constant.

The results of determining the heat transfer coefficient in the process of mixed control of a fuzzy-neighborhood model with dependent fuzziness coefficients are presented in Table 5. The obtained values of the fuzziness coefficients are presented in Table 6.

Table 5: The obtained values of the heat transfer coefficient

Temperature difference of the heating agent x_5, °C	Polyol consumption x_2, tons/day				
	5	10	15	20	25
5	43.2	57.32	73.13	77.58	81.68
10	42.51	55.57	73.07	77.58	81.68
20	40.91	52.03	73.14	77.58	81.68

Table 6: The obtained values of fuzziness coefficients at the the value x_5=5°C

Fuzziness coefficients	Polyol consumption x_2, tons/day					Identification results
	5	10	15	20	25	
k_{x11}	0.9899	0.99	1	1	1	1
k_{x12}	0.8056	0.7919	0.8	0.8	0.8	0.80004
k_{v11}	1	1	1	1	1	1
k_{v12}	0.8025	0.8163	0.7921	0.7921	0.7921	0.80012
k_{x21}	0.7906	0.8064	0.798	0.7994	0.8003	0.79854
k_{x22}	1	1	1	1	1	1
k_{x23}	0.7666	0.7819	0.767	0.7819	0.7819	0.77417
k_{v21}	0.7984	0.7985	0.7979	0.7985	0.7985	0.79848
k_{v22}	1	1	1	1	1	1
k_{v23}	0.7984	0.7985	0.7979	0.7985	0.7985	0.79848
k_{x32}	0.7944	0.7926	0.8006	0.8006	0.8006	0.80058
k_{x33}	1	0.99	1	1	1	1
k_{x34}	0.7955	0.7923	0.8	0.8001	0.8	0.80014
k_{x35}	0.8012	0.7932	0.8013	0.8013	0.8013	0.80128
k_{v32}	0.8037	0.8056	0.7975	0.7975	0.7975	0.80555
k_{v33}	1	1	1	1	1	1
k_{v34}	0.7985	0.8164	0.7963	0.7965	0.7924	0.80046
k_{v35}	0.8083	0.8161	0.7979	0.7984	0.7972	0.80027
k_{x43}	0.7981	0.8068	0.7916	0.7908	0.7908	0.7988
k_{x44}	1	1	1	1	1	1
k_{v43}	0.7979	0.7996	0.7989	0.7996	0.7996	0.7998
k_{v44}	1	1	1	1	1	1
k_{x53}	0.765	0.765	0.7499	0.765	0.765	0.75744
k_{x55}	1	1	1	1	1	1
k_{v53}	0.7898	0.7898	0.7898	0.7898	0.7898	0.78977
k_{v55}	1	1	1	1	1	1

When analyzing the behavior of the fuzziness coefficients, it should be noted that due to the restriction associated with the constant value of the product $k_x \cdot k_v$, the fuzziness coefficients facing the linear members change slightly and take values close to the value obtained during identification.

5. COMPARISON OF RESULTS

The results of determining the heat transfer coefficient in the process of mixed control of fuzzy-neighborhood model and the traditional neighborhood model [11] are compared with the results of thermotechnical calculation [12]. The relative deviations of the results of mixed control are presented in Figures 2–4.

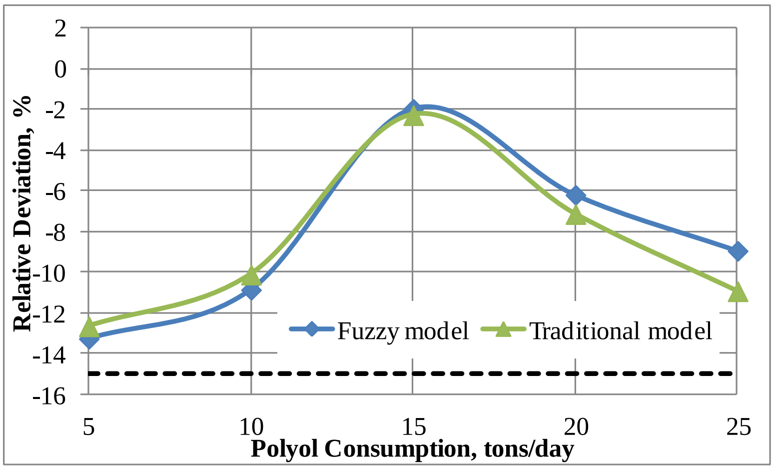

Figure 2: Relative deviation of the results of mixed cotrols at the value x_5=5°C

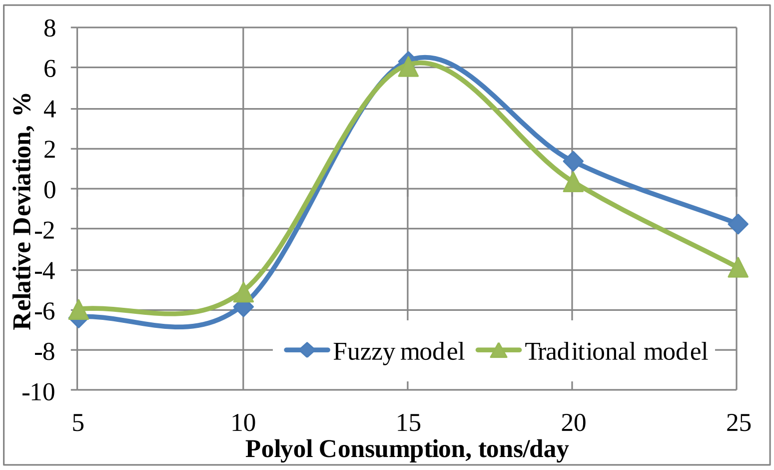

Figure 3: Relative deviation of the results of mixed cotrols at the value x_5=10°C

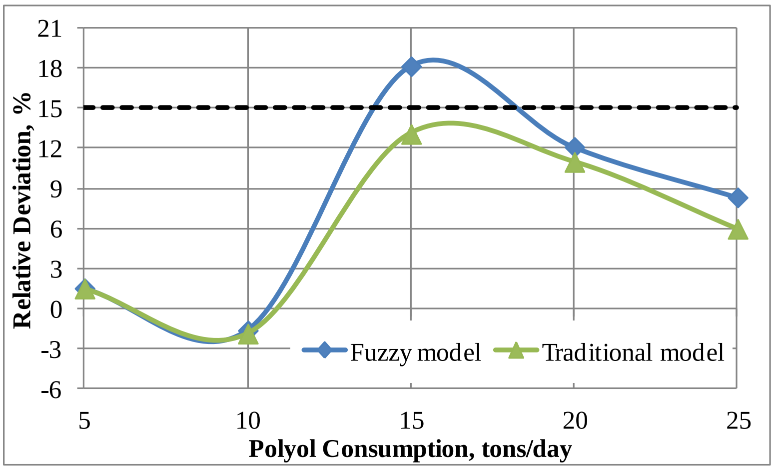

Figure 4: Relative deviation of the results of mixed cotrols at the value x_5=20°C

Most values of the heat transfer coefficient found in the process of mixed controls satisfy the error of ±15%, which characterizes the criterial equations for determining the heat transfer coefficient [13]. The values of mean-square deviations obtained during the mixed control are presented in Table 7.

Table 7: Values of mean-square deviations

x_2, tons/day	x_5, °C	Traditional model	Fuzzy model
5	5	0.32133	0.31171
10	5	0.23505	0.22468
15	5	0.16258	0.15785
20	5	0.63522	0.65035
25	5	1.12057	1.17634
5	10	0.26477	0.25418
10	10	0.19382	0.18566
15	10	0.19507	0.21036
20	10	0.66179	0.70127
25	10	1.14159	1.23139
5	20	0.20926	0.20497
10	20	0.33537	0.31598
15	20	0.27709	0.24146
20	20	0.62237	0.71252
25	20	1.06536	1.22257

The traditional neighborhood model and the fuzzy-neighborhood model show approximately equal results.

6. CONCLUSION

In this paper, identification and mixed control of fuzzy-neighborhood model was carried out. The fuzziness coefficient facing the bilinear members is the product of the corresponding coefficients facing the linear members. The deviations obtained in the identification process for fuzzy model are an order of magnitude lower than the deviations for the traditional neighborhood model. Most values of the heat transfer coefficient found in the process of mixed controls correspond to the values obtained in the thermotechnical calculation.

The use of mixed control with variable coefficients for neighborhood systems with fuzzy neighborhoods allows enhancing the control effect and improving the accuracy of the model. The fuzziness coefficient characterizes the connection between the nodes of the system, indicating whether the combination of state and control components is permissible. If the fuzziness coefficient takes on a value that is inconsistent with the permissible limit of change determined by the technological instruction, this indicates a possible appearance of risks in the system.

7. AVAILABILITY OF DATA AND MATERIAL

Information used and generated from this work is available by contacting the corresponding author.

8. ACKNOWLEDGEMENT

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Professor Dr.Shmyrin Anatoly Mikhailovich is Head of the Department of Higher Mathematics at Lipetsk State Technical University, Lipetsk, Russia. Professor Shmyrin Anatoly Mikhailovich holds a Doctor of Technical Sciences degree. His research encompasses Structural neighborhood modeling, neighborhood structures, mathematical modeling of complex distributed systems; methods of multidimensional optimization and adaptive parametric identification; mathematical theory of optimal control systems.

Yartsev Alexey Gennadievich is a graduate student of the Department of Higher Mathematics at Lipetsk State Technical University, Lipetsk, Russia.