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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy
in Technology

DEVELOPMENT OF MODELS AND ALGORITHMS FOR MODELING AND CONTROL OF TECHNOLOGICAL PROCESSES OF OIL BASES THROUGH THE APPLICATION OF PETRI NETS

Speciality: 3337.01 - Information-measurement and
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GENERAL CHARACTERISTICS OF THE WORK

Relevance of the topic and level of development. Oil depots are facilities made up of a complex of buildings and infrastructure designed for receiving, storing, transporting, and delivering oil and oil products to consumers. Their main function is to ensure a continuous and reliable supply of oil and oil products to industrial enterprises, vehicles, agricultural sectors, and other users - in the required quantity and variety. Another important task is to eliminate losses as much as possible during the reception, storage, and transportation of oil products.

When petroleum products are stored in tanks, several key parameters tend to change over time: -temperature changes depending on daily fluctuations in the surrounding air temperature, or due to heating the oil during colder months; density may vary as lighter components of the oil begin to evaporate; liquid level inside the tank can change as a result of evaporation, temperature shifts, and changes in density; -pressure increases when gas accumulates and builds up in the tank's vapor space.

The density of a petroleum product at a given temperature is determined based on its standard density at 20 °C and the average coefficient of temperature-dependent density variation. Relative density is defined as the ratio of the product's density to the density of water at 4 °C. The temperature coefficient of relative density, also referred to as the temperature correction factor, indicates the change in the relative density of a petroleum product for each 1 °C variation in temperature. During these calculations, parameters such as excess pressure and the height of the product level in the tank are not taken into account. This situation highlights the necessity of developing and refining models that describe the various physical processes occurring in storage tanks, in order to enable modern methods for determining the density of petroleum products. Therefore, empirical and expert-based models must be capable of ensuring the acquisition, collection,

verification, and completion of new experimental data obtained under simulated experimental conditions.

In this context, the development of models for determining and regulating the temperature of petroleum products, calculating their density, and managing logistics under uncertain conditions - through the use of modern computing and information technologies, modeling tools, and artificial intelligence - represents a highly relevant scientific and technical challenge.

Object and subject of research. In this dissertation, the object and subject of research is an information-measuring system designed to ensure commercial accounting and logistics control by collecting and processing measurement data on the temperature, pressure, and density of petroleum products stored in tanks at oil depots under conditions of uncertainty.

Purpose and objectives of the research. The main purpose of this dissertation is to develop models and algorithms for the modeling, control, and logistics of technological processes at oil depots through the application of extended Petri nets.

An additional objective of the dissertation is to enhance the information-measuring system that enables control over the commercial accounting and logistics of petroleum products stored in tanks at oil depots under conditions of uncertainty.

Research methods. To solve the problems posed in the dissertation, the following approaches and theories were applied: the theory of Petri nets, the theory of queuing systems, matrix theory, graph theory, fuzzy set theory, formal language theory, as well as modern concepts and methods of artificial intelligence.

Main provisions for the defense:

- Classification of oil depots used for the reception, storage, and transportation of oil and petroleum products, and systematization of key parameters of technological processes;
- Network models in the form of fuzzy Petri nets and C_f - type fuzzy Petri nets for determining and regulating the temperature of petroleum products in tanks under conditions of uncertainty;

- Decision-making models for regulating the temperature and determining the density of petroleum products in tanks under uncertain conditions;
- Implementation of models for temperature regulation and density determination of petroleum products in the MATLAB/Simulink environment;
- An algorithm for automated calculation of the density of petroleum products in tanks;
- A vehicle movement model for the logistics of petroleum products at distribution oil depots;
- A logistics model for the movement of vehicles within the "Transport Vehicles - Oil Depots - Fuel Stations" system at distribution oil depots;
- Software for regulating the temperature and determining the density of petroleum products in tanks under conditions of uncertainty.

Scientific contributions

- A model for determining the temperature of petroleum products in tanks under uncertain conditions has been developed in the form of a fuzzy Petri net, while a model for temperature regulation has been implemented using a C_f - type fuzzy Petri net;
- Decision-making models have been developed for regulating the temperature and determining the density of petroleum products in tanks under conditions of uncertainty;
- An algorithm for the automated calculation of the density of petroleum products in tanks has been proposed and developed;
- Models for regulating the temperature and determining the density of petroleum products in tanks have been developed using an integrated Fuzzy-PID control system;
- A vehicle movement model for the logistics of petroleum products at distribution oil depots has been developed in the form of a colored Petri net;
- A logistics model for vehicle movement within the "Transport Vehicles - Oil Depots - Fuel Stations" system at distribution oil depots has been developed using a timed Petri net. A production rule base has

also been created to support the operation and control of the developed logistics model.

Theoretical and practical significance of the work and application of the results. The theoretical and practical significance of the dissertation lies in the fact that the obtained scientific and practical results, the proposed approach, algorithms, and the developed decision-making and logistics models can be used for the control of technological processes at distribution oil depots, improvement of the commercial accounting and measurement system of tank farms, application in artificial intelligence technologies, and research of logistics models of petroleum products under uncertain conditions.

Approbation of the work. The main results of the dissertation were discussed at the following national and international scientific and technical conferences:

International Scientific Conference “Science, Technology, Production - 2017: Applied Science as a Tool for the Development of the Petrochemical Industry” (Salavat, May 22, 2017); XXI Republican Scientific Conference of Doctoral Students and Young Researchers (Baku, October 24, 2017); I International Scientific Conference “Information Systems and Technologies: Achievements and Prospects” (Sumgayit, November 15-16, 2018); XXII Republican Scientific Conference of Doctoral Students and Young Researchers (Baku, November 22-23, 2018); XXXII International Scientific Conference “Mathematical Methods in Engineering and Technology” (St. Petersburg, June 3-7, 2019); XIII International Scientific Conference “Fundamental and Applied Problems of Mathematics and Informatics” (Makhachkala, September 16-20, 2019); I International Scientific and Practical Conference “Modern Information, Measurement and Control Systems: Problems and Prospects (MIOIS: MPP 2019)” (Baku, July 1-2, 2019); XXII International Conference “Computational Mechanics and Modern Applied Software Systems (VMSPS’2021)” (Alushta, September 4-13, 2021); II International Scientific Conference “Information Systems and Technologies: Achievements and Prospects” (Sumgayit, July 9-10, 2020); XIV

International Scientific Conference “Fundamental and Applied Problems of Mathematics and Informatics” (Makhachkala, September 16-19, 2021); IV Republican Scientific Conference “Applied Issues of Mathematics and New Information Technologies” (Sumgayit, December 9-10, 2021); III International Scientific Conference “Information Systems and Technologies: Achievements and Prospects” (Sumgayit, December 8-9, 2022).

Published scientific works. A total of 20 scientific papers have been published based on the dissertation work, including 7 journal articles and 13 papers published in the proceedings of scientific-practical conferences.

Name of the institution where the dissertation was carried out. The research was conducted at Sumgayit State University.

Volume and structure of the dissertation. The dissertation consists of an introduction, four chapters, main conclusions, a list of 107 references, appendices, and a list of abbreviations. The total length of the dissertation is 174 pages, of which the main content comprises 141 pages (198 007 characters), including 16 tables and 26 figures. The distribution of characters by chapters is as follows: Chapter 1 - 35077 characters; Chapter 2 - 31553 characters; Chapter 3 - 75683 characters; Chapter 4 - 37494 characters.

CONTENT OF THE WORK

The Introduction justifies the relevance of the conducted research, outlines the investigated issues, the object and subject of the study, the aim and objectives of the research, the research methods, the main provisions submitted for defense, the scientific innovations obtained as a result of the research, the theoretical and practical significance of the work, its approbation, the list of published scientific works, and the volume and structure of the dissertation.

In the first chapter, oil depots are classified according to their functional purpose. The expediency of their placement is demonstrated by taking into account the nature of operations, the quality of service provided to consumers, compliance with sanitary

and fire safety standards, and the necessity to minimize vehicle movement.

The operating principles of all types of oil depots are analyzed, and it is shown that the primary function of distribution oil depots is to ensure the storage, distribution, and delivery of petroleum products to consumers with maximum efficiency and minimum losses and transportation costs.

Modern measurement systems for the commercial accounting and management of oil and oil products in storage tanks are analyzed. The analysis shows that when measurement devices are used as part of the system to determine density, insufficient accuracy in measuring even one parameter can significantly reduce the overall accuracy of volume and mass calculations.

The current state of research and modeling of the management of distribution oil depots is analyzed. It is demonstrated that improving the modeling and calculation methods for key parameters related to the receipt, quality, storage, transportation, and management of petroleum products stored at oil depots requires the development of models based on modern technologies.

In this context, the use of modern artificial intelligence technologies is justified for the development of new approaches, algorithms, and models to evaluate and calculate key parameters of petroleum products-such as temperature, density, level, and pressure.

Chapter two is devoted to the classification of measurement systems used for the commercial accounting and management of tank farms at oil depots, as well as the calculation of density and uncertainties. It is shown that commercial accounting and management of the tank farm depend on the accuracy of the measurement of petroleum product parameters. For this purpose, the operating principles of industrial-standard systems equipped with high-accuracy temperature, level, and pressure transmitters, radar antennas, and supporting both wired and wireless technologies are analyzed. Their advantages and disadvantages are identified.

The second paragraph focuses on the development of an algorithm for the automated calculation of the current density of oil and petroleum products. By applying the developed algorithm, the relative density range of the tested petroleum product and the automated calculation of the temperature correction factor within this range ensure that the calculated current density of the product complies with the required accuracy. Computer experiments were conducted based on the developed software, and the current calculated values of the tested petroleum products were determined. The density of oil and petroleum products decreases as the temperature increases, and increases as the temperature decreases. This relationship is linear and is calculated using the following formula: $\mathcal{S}_4^t = \mathcal{S}_4^{20} - \alpha(t - 20)$, where: $\mathcal{S}_4^t$ - relative density of the petroleum product at the test temperature; $\mathcal{S}_4^{20}$ - relative density of the petroleum product at 20°C, based on the density of water at 4°C; α - average temperature correction factor for density variation; t - test temperature. The calculation of the density of a petroleum product at a given current temperature includes the following steps: 1. The density of the petroleum product at 20°C is retrieved from its technical passport. 2. The average temperature of the product in the storage tank is measured. 3. The difference between the measured temperature and 20°C is calculated. 4. Based on the density value at 20°C, the temperature correction factor per 1°C is found from the passport. 5. The product of the calculated temperature difference and the correction factor is determined. 6. The difference between the density value from the passport at 20°C and the result from step 5 is calculated.

The complexity and sequence of this process increase the risk of error in calculating the current density of petroleum products. Therefore, an algorithm for the automated calculation of the density of oil and petroleum products has been developed.

Algorithm for automated calculation of the current density of petroleum products

Start of the algorithm

Step 1. Set $x_{\min} = x_1$; $i = 2$.

Step 2. If the condition $x_{\min} > x_i$ is satisfied, then set $x_{\min} = x_i$, otherwise calculate $i = i + 1$.

Step 3. If the condition $i \leq n$ is satisfied, then go to **Step 2**.

Step 4. Set $x_{\max} = xx_1$; $i = 2$.

Step 5. If the condition $x_{\max} \leq xx_i$ is satisfied, then set $x_{\max} = xx_i$, otherwise calculate $i = i + 1$.

Step 6. If the condition $i \leq n$ is satisfied, then go to **Step 5**.

Step 7. Determine the lower and upper bounds of the oil product's density at 20°C: $a = x_{\min}$; $b = x_{\max}$.

Step 8. Determine the coefficient for calculating the new range of current density of the oil product: $k_1 = 0.0100$.

Step 9. Determine the temperature correction coefficient for calculating the new range of current density of the oil product: $k_2 = 0.000013$.

Step 10. Set the initial value of the oil product's temperature correction coefficient for 1°C: $TP = 0.000962$.

Step 11. Set the initial value of the oil product's density range counter: $k = 0$.

Step 12. Determine the upper scale value PT (density of oil product) and lower scale value T (temperature of oil product) from the densimeter.

Step 13. Calculate the boundary values of the new current density range of the oil product: $a_1 = a + k_1 \cdot k$; $b_1 = b + k_1 \cdot k$.

Step 14. If the condition $k > 24$ is satisfied, go to the end of the algorithm.

Step 15. If the condition $a_1 \leq PT \leq b_1$ is satisfied, then calculate the current density of the oil product: $TP = TP - k_2 \cdot k$; $P = PT - TP \cdot (T - 20)$. Proceed to the end of the algorithm.

Step 16. Set the value of the oil product's density range counter: $k = k + 1$ and go to **Step 13**.

Step 17. The current density of the oil product is determined.

End of the algorithm.

As a result of the computer experiment, the calculated current density values of the sample petroleum product - automobile gasoline - are presented in Table 1.

**Table 1. Test petroleum product: automobile gasoline
(density range: 0.71 - 0.76)**

<i>Measure- ments</i>	<i>a</i>	<i>b</i>	<i>PT</i>	<i>TP</i>	<i>P</i>
1.	0.7100	0.7199	0.7150	0.000884	0.7230
2.	0.7100	0.7199	0.7190	0.000884	0.7261
3.	0.7200	0.7299	0.7260	0.000871	0.7321
4.	0.7200	0.7299	0.7280	0.000871	0.7332
5.	0.7300	0.7399	0.7320	0.000858	0.7363
6.	0.7300	0.7399	0.7370	0.000858	0.7353
7.	0.7400	0.7499	0.7460	0.000845	0.7426
8.	0.7400	0.7499	0.7480	0.000845	0.7429
9.	0.7500	0.7599	0.7510	0.000832	0.7443
10.	0.7500	0.7599	0.7530	0.000832	0.7455

In paragraph 2.3, the calculation of measurement uncertainty for the commercial accounting of the tank farm is examined. Empirical formulas are provided for the standard uncertainty that expresses the main quantitative measurement data, as well as for its *type A and type B* evaluation methods.

The third chapter is devoted to the development of decision-making models for regulating the temperature and determining the density of petroleum products under uncertain conditions. In the first paragraph, a model for determining the temperature of petroleum products in a tank is developed in the form of a fuzzy Petri net (FPN). The structure of the model is described in the form of a matrix, the trajectory of the sequence of permissible transitions from a given initial value is determined, and the graph-scheme is constructed.

For managing the technological process of storing and releasing petroleum products in the tank, the set of positions and transitions of the temperature determination model is defined.

Set of places: p_1 - storage tank for petroleum product; p_2 - temperature of the petroleum product is within the allowable range; p_3 - temperature of the petroleum product is below the allowable range;

p_4 - temperature of the petroleum product is above the allowable range; p_5 - product level (height) in the tank is within the allowable range; p_6 - product level (height) in the tank is below the allowable range; p_7 - product level (height) in the tank is above the allowable range; p_8 - density of the petroleum product is within the allowable range; p_9 - discharge column of the petroleum product; p_{10} - heating of the petroleum product in the tank; p_{11} - cooling of the petroleum product in the tank.

Set of transitions: t_1 - determination of the temperature of the petroleum product in the tank; t_2 - determination of the product level (height) in the tank; t_3 - determination of the density of the petroleum product in the tank; t_4 - execution of the discharge process of the petroleum product; t_5 - slight adjustment of the electric heater valve to the left; t_6 - slight adjustment of the electric heater valve to the right.

The elements of the Gram matrix of the network and the diagonal conformity vector are calculated. As a result of the computer experiment, the following sequences of transitions from the initial marking μ_0 were obtained: $\tau_1 = (t_1, t_2, t_3, t_4)$, $\tau_2 = (t_1, t_5, t_1)$, $\tau_3 = (t_2, t_6, t_2)$.

Paragraph 3.2 presents a decision-making model for regulating the temperature of petroleum products in the reservoir.¹ A rule base was created based on a fuzzy production system. The elements of the term sets of the input and output linguistic variables included in the rule base were defined.

To formulate fuzzy logic inference rules for regulating the temperature of petroleum products in reservoirs, the following linguistic variables are defined:

¹ Mustafaev, V. A. A decision-making model for regulating the temperature of petroleum products under conditions of uncertainty / V. A. Mustafaev, K. A. Allahverdiyeva // Bulletin of Voronezh State Technical University. - 2022. - Vol. 18, No. 1. - pp. 29–35. - DOI: 10.36622/VSTU.2022.18.1.003. - EDN JBMTKM. Available at: <https://elibrary.ru/item.asp?id=48007172>

A-input linguistic variables “temperature of petroleum product in the reservoir”, with the term set $T_A = \{\text{below limit; within limit; above limit}\}$.

B-input linguistic variables “rate of temperature change in the reservoir”, with the term set $T_B = \{\text{negative; zero; positive}\}$.

C - output linguistic variable “reservoir heater regulator valve”, with the term set $T_C = \{\text{far left; slightly left; keep as is; slightly right; far right}\}$.

The rule base of the fuzzy logic inference system is as follows:

Rule 1. IF the temperature of the oil product in the reservoir corresponds to the low level $[-20, -20, 15]$, AND the rate of temperature change in the reservoir is negative $[-10, -10, -1]$, THEN the control valve of the reservoir should be turned to the far right corner $[70, 90, 90]$;

Rule 2. IF the temperature of the oil product in the reservoir corresponds to the low level $[-20, -20, 15]$, AND the rate of temperature change in the reservoir is close to zero $[-3, 0, 3]$, THEN the control valve of the reservoir should be turned to the slight right corner $[50, 65, 80]$;

Rule 3. IF the temperature of the oil product in the reservoir corresponds to the low level $[-20, -20, 15]$, AND the rate of temperature change in the reservoir is positive $[1, 10, 10]$, THEN the control valve of the reservoir should be turned to the slight right corner $[50, 65, 80]$;

Rule 4. IF the temperature of the oil product in the reservoir corresponds to the normal level $[-9.814, 15.185, 40.185]$, AND the rate of temperature change in the reservoir is negative $[-10, -10, -1]$, THEN the control valve of the reservoir should be kept as is $[40, 50, 60]$;

Rule 5. IF the temperature of the oil product in the reservoir corresponds to the normal level $[-9.814, 15.185, 40.185]$, AND the rate of temperature change in the reservoir is close to zero $[-3, 0, 3]$, THEN the control valve of the reservoir should be kept as is $[20, 35, 50]$;

Rule 6. IF the temperature of the oil product in the reservoir corresponds to the normal level $[-9.814, 15.185, 40.185]$, AND the rate

of temperature change in the reservoir is positive [1, 10, 10], THEN the control valve of the reservoir should be kept as is [40, 50, 60];

Rule 7. IF the temperature of the oil product in the reservoir corresponds to the high level [15, 50, 50], AND the rate of temperature change in the reservoir is negative [-10, -10, -1], THEN the control valve of the reservoir should be turned to the slight left corner [20, 35, 50];

Rule 8. IF the temperature of the oil product in the reservoir corresponds to the high level [15, 50, 50], AND the rate of temperature change in the reservoir is close to zero [-3, 0, 3], THEN the control valve of the reservoir should be turned to the slight left corner [20, 35, 50];

Rule 9. IF the temperature of the oil product in the reservoir corresponds to the high level [15, 50, 50], AND the rate of temperature change in the reservoir is positive [1, 10, 10], THEN the control valve of the reservoir should be turned to the far-left corner [0, 0, 30].

For the fuzzification of the conditions of linguistic variable A , a triangular fuzzy number membership function (Figure 1) was selected in the universe $X = [-20, 50]$, and the following fuzzy sets were defined: $\widetilde{A}_1 = [-20, -20, 15]$ - corresponds to the low level; $\widetilde{A}_2 = [-9.814, 15.185, 40.185]$ - corresponds to the normal level; $\widetilde{A}_3 = [15, 50, 50]$ - corresponds to the high level.

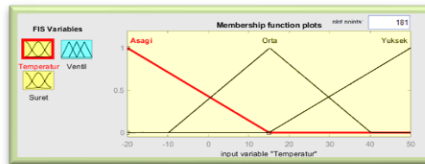


Figure 1. Graphical representation of the membership function of the input linguistic variable the temperature of the oil product in the storage tank

For the fuzzification of the conditions of linguistic variable B , a triangular fuzzy number membership function (Figure 2) was selected in the universe $Y = [-10, 10]$, and the following fuzzy sets were

defined: $\widetilde{B}_1 = [-10, -10, -1]$ - negative; $\widetilde{B}_2 = [-3, 0, 3]$ - zero, close to zero; $\widetilde{B}_3 = [1, 10, 10]$ - positive.

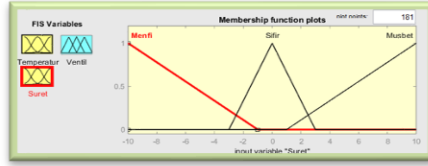


Figure 2. Graphical representation of the membership function of the input linguistic variable the rate of change of the oil product temperature in the storage tank

For the fuzzification of the conditions of linguistic variable C , a triangular fuzzy number membership function (Figure 3) was selected in the universe $C = [0, 90]$, and the following fuzzy sets were defined: $\widetilde{C}_1 = [0, 0, 30]$ - big left corner; $\widetilde{C}_2 = [20, 35, 50]$ - small left corner; $\widetilde{C}_3 = [40, 50, 60]$ - keep as is; $\widetilde{C}_4 = [50, 65, 80]$ - small right corner; $\widetilde{C}_5 = [70, 90, 90]$ - big right corner.

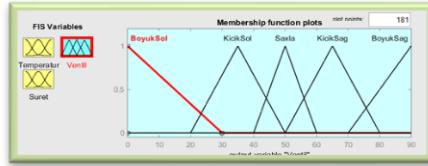


Figure 3. Graphical representation of the membership function of the output linguistic variable the density of the oil product

The fuzzy sets corresponding to the elements of the term set of the linguistic variable A are described as follows:

$\tilde{A}(x_1) = \{(1/-20), (0.857/-15), (0.714/-10), (0.571/-5), (0.428/0), (0.285/5), (0.142/10), (0/15)\}$; $\tilde{A}(x_2) = \{(0.785/-9.814), (0.400/0.186), (0.800/10.186), (0.799/20.186), (0.399/30.186), (0/40.185)\}$; $\tilde{A}(x_3) = \{(0/15), (0.142/20), (0.225/25), (0.425/30), (0.571/35), (0.714/40), (0.857/45), (0/50)\}$.

The fuzzy sets corresponding to the elements of the term set of the linguistic variable B are described as follows:

$\tilde{B}(x_1) = \{(1/-10), (0.889/-9), (0.778/-8), (0.667/-7), (0.556/(-6)), (0.444/-5), (0.333/-4), (0.222/-3), (0.111/-2), (0/-1)\}$; $\tilde{B}(x_2) = \{(0/-3), (0.333/-2), (0.667/-1), (1/0), (0.667/1), (0.333/2), (0/3)\}$; $\tilde{B}(x_3) = \{(0/1), (0.111/2), (0.222/3), (0.333/4), (0.444/5), (0.556/6), (0.667/7), (0.778/8), (0.889/9), (1/10)\}$.

The fuzzy sets corresponding to the elements of the term set of the linguistic variable C are described as follows:

$\tilde{C}(x_1) = \{(1/0), (0.5/15), (0/30)\}$; $\tilde{C}(x_2) = \{(0/20), (0.333/25), (0.667/30), (1/35), (0.667/40), (0.333/45), (0/50)\}$; $\tilde{C}(x_3) = \{(0/40), (0.5/50), (0/60)\}$; $\tilde{C}(x_4) = \{(0/50), (0.333/55), (0.667/60), (1/65), (0.667/70), (0.333/75), (0/80)\}$; $\tilde{C}(x_5) = \{(0/70), (0.5/80), (1/90)\}$.

Considering the membership function values of the terms of the linguistic variable, all sub-conditions of the rule base are calculated, and the following values are obtained: $\mu_{\tilde{A}_1}(x) = 0.285$; $\mu_{\tilde{A}_2}(x) = 0.600$; $\mu_{\tilde{A}_3}(x) = 0$; $\mu_{\tilde{B}_1}(y) = 0.444$; $\mu_{\tilde{B}_2}(y) = 0$; $\mu_{\tilde{B}_3}(y) = 0$.

As a result of the defuzzification of the output linguistic variable, the following value is obtained:

$$x = \frac{(30 \cdot 0.285 + 50 \cdot 0.444)}{(0.285 + 0.444)} = \frac{(8.55 + 22.2)}{0.729} = \frac{30.75}{0.729} \approx 42.17$$

In the developed decision-making model for regulating the temperature of the oil product, the surface of the fuzzy output has been visualized (Figure 4).

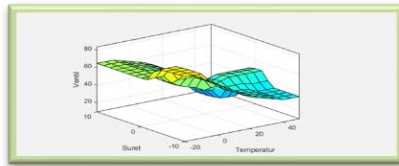


Figure 4. Graphical representation of the result of the defuzzification of the output linguistic variable the control valve of the temperature regulator in the storage tank.

In Paragraph 3.3, a control model aimed at regulating the temperature of oil products is proposed, based on the integration of

Fuzzy and PID control systems. The model has been developed in the MATLAB/Simulink environment and is equipped with a transfer function that reflects the dynamics of a real physical system.

In industrial settings - especially in processes such as oil product temperature regulation, which are complex and often accompanied by uncertainty-classical deterministic control methods are often insufficient. Therefore, hybrid approaches are applied. In this context, Fuzzy control systems offer advantages in decision-making under uncertain conditions, while PID controllers provide precise, mathematically grounded analog control algorithms (Figure 5).

In the model, the temperature signal is given by a linearly increasing Ramp function: $T(t) = T_0 + a \cdot t$; where $T_0 = 0$ - initial temperature $a = 1$ Ramp coefficient (slope).

$$T(20) = 0 + 1 \cdot 20 = 20^{\circ}C.$$

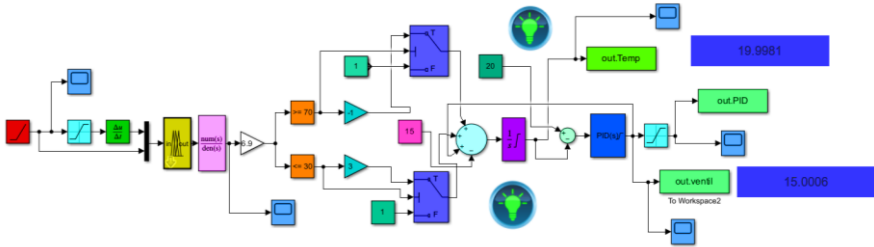


Figure 5. Control model built in the Simulink environment based on the integration of Fuzzy and PID control systems for temperature regulation of oil products in reservoirs

The Ramp function models a steady increase in temperature. The rate of this increase, expressed by the differential - i.e., the rate of change of temperature over time $\frac{dT}{dt} = a = 1^{\circ}C/s$ - is assumed to be constant. This indicates that the temperature rises by $1^{\circ}C$ every second, meaning the temperature signal has a linear growth pattern, and the system's response is regulated based on this variation.

The control is adjusted based on variability. In the control model, the Fuzzy control system operates on two input signals - the

temperature $T(t)$ and the rate of change of temperature $\frac{dT}{dt}$ - to determine the degree of valve opening. In this decision-making process, linguistic variables and fuzzy rules are used. The Fuzzy output function is defined as follows: $U_{fuzzy} = f\left(T, \frac{dT}{dt}\right)$, where: U_{fuzzy} - is the output signal of the Fuzzy controller; T - is the real temperature value; $\frac{dT}{dt}$ - is the rate of change of temperature; f - is the mapping function defined by the Fuzzy inference system (*fis*). The rule base used in the Fuzzy system is built upon 9 rules. Each rule is expressed as follows: *If $T = A_i$ and $\frac{dT}{dt} = B_j$ Then $U_{fuzzy} = C_k$* : where: A_i, B_j - are the fuzzy terms from - ($T_1 - T_9$) assigned to the input variables, C_k - is the Fuzzy output corresponding to the output variable (valve opening degree). To determine the output value, the Mamdani-type inference method is used, and the defuzzification is applied using the centroid (center of gravity) method:

$$U_{fuzzy} = u_f = \frac{\int_{\mu(x)>0} \mu(x) \cdot x dx}{\int_{\mu(x)>0} \mu(x) \cdot dx}.$$

In the control model, the Fuzzy output value obtained through simulation was $U_{fuzzy} = 15.0006$. This value is then passed to the Transfer Function block to shape the response of the real system. In addition to the Fuzzy output, a PID controller is applied in the model and is used to make corrections on the Fuzzy signal. The PID controller, based on classical control principles, responds to the error signal. The PID signal is calculated using the following formula:

$$U_{PID}(t) = K_p \cdot e(t) + K_i \cdot \int e(t) dk + K_d \cdot \frac{de(t)}{dt},$$

here, $e(t) = T_{ref} - T_{out}$ - is the error between the desired and the actual output temperature; K_p - *proportional gain*, K_i - *integral gain*, K_d - *derivative gain*. The PID parameters used in the simulation are as follows: $K_p = 9.78$; $K_i = 6$; $K_d = 0.03$; $e(t) = 0.0019$. $\int e(t) dt \approx e \cdot t = 0.0019 \cdot 20 = 0.038$;

$$U_{PID} = 1.0019 + 0.1 \cdot 0.038 = 0.0019 + 0.038 = 0.0057.$$

For the purpose of visual analysis of the simulation results, Scope blocks were added to the model, allowing the observation of both the temperature variation over time and the behavior of the Fuzzy+PID output (valve opening level) (Figure 6).

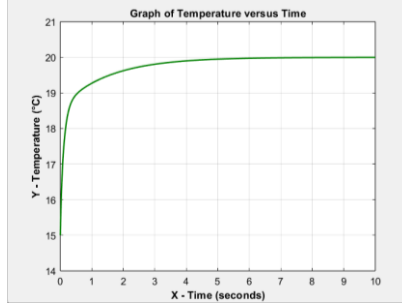


Figure 6. Graph of temperature signal variation over time

This graph reflects the system's temperature response as a result of the synchronous application of Fuzzy and PID control systems. It is clearly seen from the graph that the initial temperature is approximately 15°C . During the $0 - 3$ second interval, the temperature rises rapidly and approaches 15°C , and after the 5th second, it stabilizes near the reference value of 19.9981°C .

The system reaches a steady state with a smooth transition, without exhibiting any overshoot. This result indicates that the Fuzzy output defines the core behavior of the real system, while the PID controller adds precision based on the error signal. The temperature behavior can be modeled by the exponential function: $T(t) = T_f - (T_f - T_0) \cdot e^{-kt}$, where: $T(t)$ - temperature signal as a function of time; $T_0 = 15^{\circ}\text{C}$ - initial temperature; $T_f = 20^{\circ}\text{C}$ - final steady-state temperature; k - time constant depending on the system's response rate; t - time (in seconds). Thus, it can be stated that the temperature approaches 20°C exponentially, i.e., $T(t) \xrightarrow{t \rightarrow \infty} 20^{\circ}\text{C}$ (Figure 7).

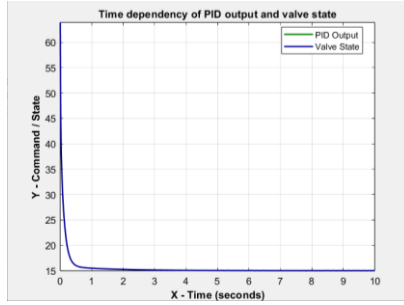


Figure 7. Graphical representation of PID output and valve output signal

The graphical representation illustrates the response of the Fuzzy control system to the valve opening. According to the observations, the valve output in the initial state of the system starts at approximately *level 70 (maximum opening)*, and during the first *2 seconds*, the output value rapidly decreases, approaching the *15 level*. After the 3rd second, the system stabilizes around 15.0006.

This decrease occurs as a result of the adaptive response generated by the Fuzzy decision-making system based on both the temperature and the rate of change of temperature. Consequently, the valve output is regulated in a smooth and stable manner, without any abrupt changes, in accordance with real heating demands. The decrease in the valve opening level, which is initially high and then converges to a steady-state value, is modeled using an exponential decay function:

$V(t) = V_0 \cdot e^{-kt} + V_{ss}$, where: $V(t)$ - represents the valve opening level over time; $V_0 \approx 55$ - is the initial additional opening, i.e., the difference between the fully open state of the valve and the steady-state value: ($V_0 = 70 - 15 = 55$); k - is the decay constant that determines how fast the valve closes; t - represents time; V_{ss} - is the steady-state value of the valve opening level, approximately 15 in this case.

From the equation, we observe that: $V(t) \xrightarrow{t \rightarrow \infty} 15$. This means that as time progresses, the valve opening level gradually approaches the steady-state value of 15. In other words: The fuzzy controller reduces the valve opening as the temperature increases and ensures the system transitions into a steady-state condition. This behavior reflects

the classic goal of control systems: to maintain stability and robustness. Therefore, the system responds not in a sharp way, but in a smooth and intelligent manner.

In Section 3.4, the temperature control model of the oil product was developed in the form of a C_f - type fuzzy Petri net (FPN). The positions, set of transitions, truth functions, and excitation threshold functions were described through corresponding vectors, and the structure of the model was obtained. Based on a given initial state, the trajectory of the sequence of excited transitions was determined, and the graph scheme of the model was constructed accordingly. Additionally, a decision-making model was developed to determine the density of the oil product stored in the tank.² A rule base was formed for this model in the form of fuzzy production rules.

The following variables are used as input linguistic variables for determining the density of the oil product: temperature of the oil product, excess pressure of the oil product, and height of the oil product level.

A - the input linguistic variable is *"the temperature of the oil product in the tank"* (which changes according to the daily ambient temperature norm or as a result of heating during cold seasons). For this variable, the term set T_A consists of the following elements: *{extremely low, significantly low, low, slightly low, normal, slightly high, high, significantly high, extremely high}*.

B is the input linguistic variable representing **"the height of the oil product level in the tank (resulting from evaporation, temperature, and density changes)"**. For this variable, the term set T_B

² Атаев, Г. Н. Модель принятия решений для определения плотности нефтепродукта в условиях неопределенности / Г. Н. Атаев, Н. М. Кязимов, К. А. Аллахвердиева // Проблемы сбора, подготовки и транспорта нефти и нефтепродуктов. - 2018. - № 4(114). - С. 110-120. - DOI 10.17122/ntj-oil-2018-4-110-120. - EDN XTUVVR. <https://elibrary.ru/item.asp?id=35290059>

includes: {near zero–very low, low, slightly low, medium, normal, slightly high, high, very high, maximum high}.

C is the input linguistic variable representing “**the excess pressure of the oil product** (*during pressure increase in the gas space*)”. For this variable, the term set T_C includes: {very low, low, medium low, medium, normal, medium high, high, very high, maximum high}.

D is the output linguistic variable representing “**the density of the oil product** (*due to evaporation of light fractions*)”. For this variable, the term set T_D includes: {very low - included in control system 1; low - included in control system 1; medium low - not included in control system; normal - not included in control system; medium high - not included in control system; high - not included in control system; very high - included in control system 2; significantly high - included in control system 2; maximum high - included in control system 2}.

The fuzzy logic inference system’s rule base is as follows:

Rule 1. IF the temperature of the oil product is extremely low ($T1$) $[-20, -20, -17, -12]$, **AND** the oil product level is near zero, very low ($S1$) $[0,0,1,2]$, **AND** the excess pressure of the oil product is very low ($P1$) $[0,0,0.1,0.2]$, **THEN** the density of the oil product is considered very low and is included in control system 1 ($D1$) $[700,700,710,720]$;

Rule 2. IF the temperature of the oil product is normal ($T5$) $[9,14,19,24]$, **AND** the level is normal ($S5$) $[11,12,13,14]$, **AND** the excess pressure is normal ($P5$) $[0.7,0.8,0.9,1]$, **THEN** the density is considered normal and is not included in the control system ($D4$) $[750,760,765,770]$;

Rule 3. IF the temperature is extremely high ($T9$) $[47,50,50,50]$, **AND** the level is at maximum ($S9$) $[19,20,20,20]$, **AND** the excess pressure is at maximum ($P9$) $[1.45,1.5,1.5,1.5]$, **THEN** the density is maximum high and is included in control system 2 ($D9$) $[799,800,800,800]$;

Rule 4. IF the temperature is significantly low ($T2$) $[-17, -12, -9, -4]$, **AND** the level is slightly low ($S3$) $[4,6,8,10]$, **AND** the excess pressure is medium low ($P3$) $[0.3,0.4,0.5,0.6]$, **THEN**

the density is medium low and not included in the control system ($D3$) [730,740,750,760];

Rule 5. *IF* the temperature is slightly high ($T6$) [19,24,29,34], **AND** the level is medium ($S4$) [8,10,11,12], **AND** the excess pressure is medium high ($P6$) [0.9,1,1.1,1.2], **THEN** the density is high and not included in the control system ($D5$) [765,770,775,780];

Rule 6. *IF* the temperature is low ($T3$) [-9, -4, -1,4], **AND** the level is low ($S2$) [1,2,4,6], **AND** the excess pressure is low ($P2$) [0.1,0.2,0.3,0.4], **THEN** the density is slightly high and not included in the control system ($D5$) [765,770,775,780];

Rule 7. *IF* the temperature is high ($T7$) [29,34,39,44], **AND** the level is high ($S7$) [15,16,17,18], **AND** the excess pressure is high ($P7$) [1.1,1.2,1.3,1.4], **THEN** the density is very high and is included in control system 2 ($D7$) [785,790,795,797];

Rule 8. *IF* the temperature is slightly low ($T4$) [-1,4,9,14], **AND** the level is slightly high ($S6$) [13,14,15,16], **AND** the excess pressure is medium ($P4$) [0.5,0.6,0.7,0.8], **THEN** the density is low and is included in control system 1 ($D2$) [710,720,730,740];

Rule 9. *IF* the temperature is significantly high ($T8$) [39,44,47,50], **AND** the level is very high ($S8$) [17,18,19,20], **AND** the excess pressure is very high ($P8$) [1.3,1.4,1.45,1.5], **THEN** the density is significantly high and is included in control system 2 ($D8$) [795,797,799,800].

To fuzzify the conditions of the linguistic variable A , a trapezoidal fuzzy membership function was selected within the universe $X = [-20, 50]$ (Figure 5). Based on this, the following fuzzy sets were defined:

$\widetilde{A}_1 = [-20, -20, -17, -12]$ extremely low ($T1$); $\widetilde{A}_2 = [-17, -12, -9, -4]$ significantly low ($T2$); $\widetilde{A}_3 = [-9, -4, -1, 4]$ low ($T3$); $\widetilde{A}_4 = [-1, 4, 9, 14]$ slightly low ($T4$); $\widetilde{A}_5 = [9, 14, 19, 24]$ normal ($T5$); $\widetilde{A}_6 = [19, 24, 29, 34]$ slightly high ($T6$); $\widetilde{A}_7 = [29, 34, 39, 44]$ high ($T7$); $\widetilde{A}_8 = [39, 44, 47, 50]$ significantly high ($T8$); $\widetilde{A}_9 = [47, 50, 50, 50]$ extremely high ($T9$).



Figure 5. Graphical representation of the membership functions for the input linguistic variable - temperature of the oil product

To perform the fuzzification of the linguistic variable B , a trapezoidal-shaped fuzzy interval membership function was selected within the universum $Y = [0, 20]$ (Figure 6), and the following fuzzy sets were defined: $\widetilde{B}_1 = [0, 0, 1, 2]$ near-zero, very low ($S1$); $\widetilde{B}_2 = [1, 2, 4, 6]$ low ($S2$); $\widetilde{B}_3 = [4, 6, 8, 10]$ slightly low ($S3$); $\widetilde{B}_4 = [8, 10, 11, 12]$ medium ($S4$); $\widetilde{B}_5 = [11, 12, 13, 14]$ normal ($S5$); $\widetilde{B}_6 = [13, 14, 15, 16]$ slightly high ($S6$); $\widetilde{B}_7 = [15, 16, 17, 18]$ high ($S7$); $\widetilde{B}_8 = [17, 18, 19, 20]$ very high ($S8$); $\widetilde{B}_9 = [19, 20, 20, 20]$ extremely high ($S9$).

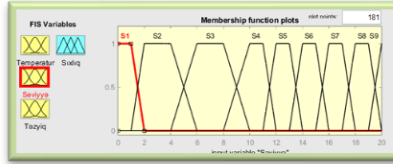


Figure 6. Graphical representation of the membership function of the linguistic input variable "height of the oil product level"

For the fuzzification of the conditions of the linguistic variable C a trapezoidal-shaped fuzzy interval membership function (Figure 7) was selected over the universe $Z = [0, 1.5]$, and the following fuzzy sets were defined: $\widetilde{C}_1 = [0, 0, 0.1, 0.2]$ very low ($P1$); $\widetilde{C}_2 = [0.1, 0.2, 0.3, 0.4]$ low ($P2$); $\widetilde{C}_3 = [0.3, 0.4, 0.5, 0.6]$ medium low ($P3$); $\widetilde{C}_4 = [0.5, 0.6, 0.7, 0.8]$ medium ($P4$); $\widetilde{C}_5 = [0.7, 0.8, 0.9, 1]$ normal ($P5$); $\widetilde{C}_6 = [0.9, 1, 1.1, 1.2]$ medium high ($P6$); $\widetilde{C}_7 = [1.1, 1.2, 1.3, 1.4]$ high ($P7$); $\widetilde{C}_8 = [1.3, 1.4, 1.45, 1.5]$ very high ($P8$); $\widetilde{C}_9 = [1.45, 1.5, 1.5, 1.5]$ maximum high ($P9$).

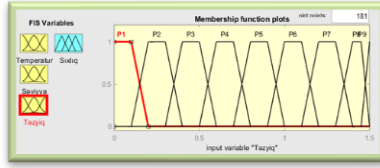


Figure 7. Graphical representation of the membership function of the input linguistic variable "excess pressure of oil product"

For the fuzzification of the conditions of the linguistic variable D a trapezoidal-shaped fuzzy interval membership function (Figure 8) was selected over the universe $K = [700, 800]$, and the following fuzzy sets were defined: $\widetilde{D}_1 = [700, 700, 710, 720]$ very low - included in control system-1 ($D1$); $\widetilde{D}_2 = [710, 720, 730, 740]$ low - included in control system-1 ($D2$); $\widetilde{D}_3 = [730, 740, 750, 760]$ medium low - not included in the control system ($D3$); $\widetilde{D}_4 = [750, 760, 765, 770]$ normal - normal - not included in the control system ($D4$); $\widetilde{D}_5 = [765, 770, 775, 780]$ medium high - not included in the control system ($D5$); $\widetilde{D}_6 = [775, 780, 785, 790]$ high - not included in the control system ($D6$); $\widetilde{D}_7 = [785, 790, 795, 797]$ very high - included in control system-2 ($D7$); $\widetilde{D}_8 = [795, 797, 799, 800]$ extremely high - included in control system-2 ($D8$); $\widetilde{D}_9 = [799, 800, 800, 800]$ maximum high - included in control system-2 ($D9$).

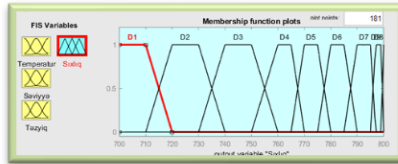


Figure 8. Graphical representation of the membership function of the output linguistic variable "density of oil product"

The degree of truth of the conditions and the results of the activation process have been determined for each production rule. The active rules are as follows:

$$\mu(p_1) = 0.0476; \mu(p_2) = \mu(p_3) = 0.1135; \mu(p_4) = 0.1190; \\ \mu(p_5) = \mu(p_6) = \mu(p_7) = \mu(p_8) = \mu(p_9) = 0.0952.$$

As a result of the defuzzification of the output linguistic variable, the following value is obtained.

$$x = \frac{\sum \mu(p_i) \cdot d_i}{\sum \mu(p_i)} = \frac{590.8875}{0.7744} = 763.026214 \text{ kg/m}^3$$

To determine the density of the oil product, the fuzzy output surface has been visualized in the developed model (Figure 9).

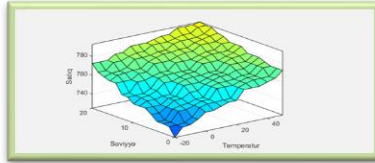


Figure 9. Graphical representation of the logical inference of the linguistic variable "density of oil product"

The developed model combines both fuzzy control and PID control methods, delivering two distinct outcomes. As shown in the block diagram, the model consists of two main parts. The first is a classical fuzzy control module, which includes a Fuzzy Logic Controller and a Transfer Function, designed in MATLAB/Simulink and tuned to match the process dynamics. The second is an advanced control module that adds a PID Controller to the sequence - Fuzzy Logic Controller → Transfer Function → PID Controller - and runs in parallel with the first module (Figure 10).

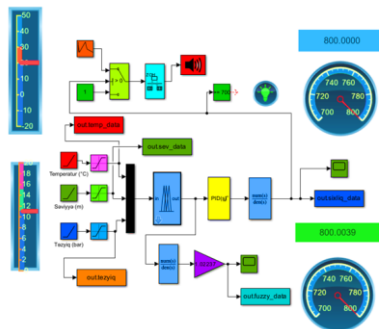


Figure 10. Block diagram of a hybrid model for determining the density of petroleum products in storage tanks in the MATLAB/Simulink environment

The Simulink model is designed to accurately determine and control the density of petroleum products under uncertain conditions. It combines fuzzy logic and PID control methods, and the system operates as follows. At the beginning of the process, the main physical parameters - temperature ($^{\circ}\text{C}$), level (m), and pressure (bar) are input by the user or received from sensors. These signals are combined in a MUX block and sent to the fuzzy logic controller. The fuzzy logic controller analyzes the input values of temperature, level, and pressure and generates a fuzzy output signal corresponding to the density. This output is then processed as an ‘estimated density’ based on nonlinear rules.

Both control outputs are fed into a transfer function that models the dynamics of the real system. This block simulates the system’s time response and transient behavior. The results obtained from the model are visualized using Gauge indicators, Display panels, and Scope plots. Thanks to this setup, both the Fuzzy and Fuzzy+PID approaches can be compared in real time. As a result, the Fuzzy+PID approach shows complete adaptation to any target value and responds with an error close to zero. Meanwhile, the Fuzzy-only output provides high practical accuracy and performs satisfactorily even without additional tuning.

The use of such a hybrid approach offers significant advantages in terms of improving the response accuracy and stability of the control system. Specifically, in the module that uses only the fuzzy output, the system makes decisions based on fuzzy rules and membership functions. In the second parallel module, however, the fuzzy result is further refined with the help of a PID controller. This structure combines the classical benefits of a PID controller with the flexibility of fuzzy control, which makes it possible to eliminate errors arising during transient states more quickly and to bring the system closer to the reference (desired) value with greater accuracy.

The input variables used in the model are the following physical parameters:

Temperature – $T \in [-20, 50] ^{\circ}\text{C}$; *Level* – $S \in [0, 20] m$;
Pressure – $P \in [0, 1.5] bar$.

These variables are provided in the Simulink model through dedicated Ramp blocks and visual indicators that are adapted to real sensors and fed into the fuzzy system. The core of the model is an output generator of the Mamdani type. For each input variable, nine trapezoidal membership functions are defined. This approach makes it possible to effectively model the system's internal dynamics even under uncertain and fuzzy conditions. The corresponding rule base is structured according to the following principle:

If $T \in T_i$ And $S \in S_j$ And $P \in P_k$ Then $D \in D_i$,

here, T_i, S_j , and P_k are the terms activated as a result of the fuzzification of the input data, while D_i is the fuzzy equivalent of the output density. In the defuzzification stage, the centroid (*center of gravity*) method is used:

$$D_{fuzzy} = \frac{\int x \cdot \mu_D(x) dx}{\int \mu_D(x) dx}$$

here, $\mu_D(x)$ is the membership function of the density. This method is notable for producing more realistic and stable results. To enable more precise tuning of the generated fuzzy output and to adapt it to the real system, a classical PID (proportional-integral-derivative) control system has been integrated into the model. This control system optimizes the system's dynamic response by minimizing the error between the fuzzy output and the desired density value:

$$e(t) = D_{ref} - D_{fuzzy},$$

here, D_{ref} is the required density value (800 kg/m^3), while D_{fuzzy} is the output density determined by the fuzzy logic system. The output of the PID control system is defined by the following mathematical expression:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int e(t) dt + K_d \cdot \frac{de(t)}{dt},$$

here, K_p , K_i and K_d - are the proportional, integral, and derivative coefficients, respectively. $u(t)$ is the control signal generated by the PID block. This control signal is ultimately fed into the transfer function block that models the dynamic behavior of the system:

$$G(s) = \frac{1}{0.5s + 1}.$$

This transfer function acts as a transition model that illustrates how Fuzzy-PID control results can be applied to a real physical process (for example, changes in the density of petroleum products). In the Simulink environment, this block is implemented in the form of $num(s)/den(s)$, where the numerator and denominator coefficients incorporate the system's delay, speed, and stability characteristics. The results obtained show that this approach minimizes both the absolute and relative errors in the system's response, making it a highly reliable and optimized control model for industrial applications. Thus, the Fuzzy-PID combination significantly improves the overall system performance by compensating for the limitations of individual control methods.

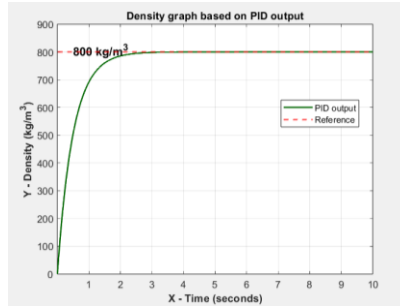


Figure 11. Graph of the density (kg/m^3) output signal versus time (seconds) in the control module enhanced with a PID controller

The graph in Figure 11 illustrates the time-dependent change in the density output signal obtained from the Fuzzy-PID control model. The density signal initially rises rapidly from zero and reaches the reference value of 800 kg/m^3 in approximately 2.5 seconds before entering a stable regime. This response demonstrates the control system's high flexibility and critically low transition time. The absence of signal oscillations in the steady-state mode and its constant value of 800 show the effective corrective capability of the PID controller. The visual representation clearly shows that the model reaches the desired density value with maximum precision and minimal error, proving that the control system performs excellently in practical applications.

Figure 12 shows the time variation of the density output signal obtained from the fuzzy logic-based control model. The output signal rises quickly within approximately 1 second, approaching the reference value of 800 kg/m^3 , and reaches a steady-state regime at around 3 seconds. The output, defined as 800.0039 kg/m^3 with a very small amplitude deviation on the graph, demonstrates that the fuzzy model operates with high accuracy. However, compared to the PID controller, there is an absolute error of only 0.0039, indicating that the system is practically satisfactory for real-time applications. In conclusion, the fuzzy model produces results very close to any desired value, accounting for complex fuzzy conditions, and stands out for its high response speed.

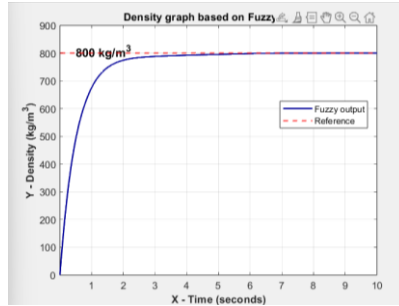


Figure 12. Graph of the density (kg/m^3) output signal versus time (seconds) in the control module with fuzzy output

The table below (Table 2) presents a comparison of the performance indicators of the Fuzzy control approach and the Fuzzy+PID combination. This table clearly shows how close the output signal gets to the desired value in the steady state and whether the errors have been minimized.

Table 2. Comparative analysis of the hybrid model

<i>Error measure</i>	<i>Results of the Fuzzy logic-based control model</i>	Results of the hybrid Fuzzy+PID control model
<i>ISE (Integral of Squared Error)</i>	0.983205	0.0001065
<i>IAE (Integral of Absolute Error)</i>	0.991533	0.0273

<i>MSE (Mean Squared Error)</i>	0.140458	0.00001521
<i>MAE (Mean Absolute Error)</i>	0.141648	0.0039
<i>Absolute error</i>	0.0039	0.0000
<i>Relative error %</i>	0.0004875%	0.000000%
<i>Reference value</i>	800	800
<i>Output value</i>	800.0039	800.000

Chapter Four is dedicated to the methods, characteristics, and the development of automated logistics models for the transportation of petroleum products. For this purpose, the features of distribution oil depots used in transporting petroleum products, along with the advantages and disadvantages of various transportation methods, and indicators of quantitative and qualitative losses, have been analyzed.

In Section 4.2, a colored Petri net (CPN) model of the movement of transportation vehicles in petroleum logistics is developed. The sets of places and transitions, the elements of the color distribution function vector at the input and output positions of transitions are described. The structural elements of the model are represented in the form of vectors and matrices, and a graphical scheme of the network is constructed.

Based on the given initial state, the sequence of permissible transitions the trajectory is determined. The vehicle movement model is described using a colored Petri net (CPN) framework.

Set of positions: P_1 - a standard-compliant empty vehicle is in the motor depot; P_2 - a standard-compliant empty vehicle is at the oil depot; P_3 - the reservoir at the oil depot is in the process of filling the empty vehicle with petroleum product; P_4 - a vehicle filled with petroleum product is at the oil depot; P_5 - the fuel station is in receiving mode for petroleum product; P_6 - a vehicle filled with petroleum product is at the fuel station; P_7 - the petroleum product has been unloaded into the storage system at the fuel station; P_8 - an empty vehicle is at the fuel station; P_9 - the vehicle's service life has not yet

expired; P_{10} - the vehicle's service life has expired; P_{11} - the fuel station has a demand for petroleum product.

In the displacement model, the possible events are represented by the following set of transitions.

Set of transitions: t_1 - the process of relocating a standard-compliant empty vehicle to the oil depot is carried out; t_2 - the process of filling the empty vehicle with petroleum product from the reservoir is carried out; t_3 - the process of receiving the filled vehicle at the fuel station is carried out; t_4 - the process of unloading petroleum product from the vehicle's cistern into the fuel station's tank is carried out; t_5 - the process of adjusting the operating mode of the empty vehicle at the fuel station is carried out; t_6 - the process of determining the fuel station's demand for petroleum product is carried out; t_7 - the process of relocating the empty vehicle back to the oil depot is carried out; t_8 - the process of returning the empty vehicle to the motor depot is carried out.

In the studied model, four color-coded states have been defined as $\mathcal{W} = (w_1, w_2, w_3, w_4)$: w_1 - an empty transport vehicle that meets the standard; w_2 - the reservoir of the oil depot; w_3 - a transport vehicle filled with petroleum product; w_4 - a gas station with demand for fuel.

Figure 13 presents the graph-scheme of the movement model of the transport vehicle. As a result of the computer simulation, a sequence of transitions was obtained from the initial state μ_0 , represented as a set of matrices: $\tau = (\mu^1, \mu^2, \mu^3, \mu^4, \mu^5, \mu^6, \mu^7, \mu^8)$.

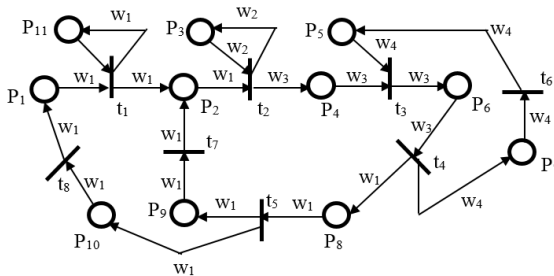


Figure 13. Graph-scheme of the transport vehicle displacement model

In Paragraph 4.3, the logistic model of the displacement from the motor transport park to the oil depot and then to the gas station was developed in the form of a time Petri net.

The structure of the model was presented in matrix form, and starting from a given initial state, the trajectory of the sequence of permitted transitions was determined, and the corresponding graph-scheme was constructed. The set of places and transitions was defined as follows.

Set of places: P_1^1 - a standard-compliant empty transport vehicle 1 is in standby mode at the oil depot; P_2^1 - transport vehicle 1, filled with fuel, is in standby mode at the loading column position of tank 1 at the oil depot; P_3^1 - transport vehicle 1, filled with fuel, is in transit mode after leaving the loading column position of tank 1 at the oil depot; P_4^1 - a standard-compliant empty transport vehicle 1 is in standby mode at the motor transport park assigned to the oil depot; P_5^1 - the loading column of tank 1 is in service mode, fulfilling the request of the fuel-transporting vehicle; P_6 - the filling station assigned to the oil depot is in fuel demand mode; P_1^2 - a standard-compliant empty transport vehicle 2 is in standby mode at the oil depot; P_2^2 - transport vehicle 2, filled with fuel, is in standby mode at the loading column position of tank 1 at the oil depot; P_3^2 - transport vehicle 2, filled with fuel, is in transit mode after leaving the loading column of tank 1 at the oil depot; P_4^2 - a standard-compliant empty transport vehicle 2 is in standby mode at the motor transport park assigned to the oil depot; P_5^2 - the loading column of tank 2 is in service mode, fulfilling the request of the fuel-transporting vehicle; P_1^3 - a standard-compliant empty transport vehicle 3 is in standby mode at the oil depot; P_2^3 - transport vehicle 3, filled with fuel, is in standby mode at the loading column of tank 2 at the oil depot; P_3^3 - transport vehicle 3, filled with fuel, is in transit mode after leaving the loading column of tank 1 at the oil depot; P_4^3 - a standard-compliant empty transport vehicle 3 is in standby mode at the motor transport park assigned to the oil depot; P_1^4 - a standard-compliant empty transport vehicle 4 is in standby mode at the oil depot; P_2^4 - transport vehicle 4, filled with fuel, is in standby mode at the loading column of

tank 2 at the oil depot; P_3^4 - transport vehicle 4, filled with fuel, is in transit mode after leaving the loading column of tank 2 at the oil depot; P_4^4 - a standard-compliant empty transport vehicle 4 is in standby mode at the motor transport park assigned to the oil depot.

A production rule base has been developed for the functioning and control of the logistics model designed in the form of a time Petri net.

MAIN RESULTS OF THE WORK

In this dissertation, models and algorithms for modeling and controlling technological processes at oil depots using Petri nets have been developed. The following results were obtained:

1. Oil depots used for the reception, storage, and transportation of oil and petroleum products were classified. The main parameters of technological processes were identified, and the selection of appropriate modeling tools for their control was substantiated.

2. For determining and regulating the temperature of petroleum products in tanks under uncertain conditions, decision-making models in the form of fuzzy Petri nets and C_f -type fuzzy Petri nets were proposed and developed.

3. A decision-making model was developed for determining the density of petroleum products in tanks under uncertainty. A rule base based on a fuzzy production system was created, and a reasoning mechanism based on the Mamdani algorithm was implemented.

4. Models for temperature regulation and density determination of petroleum products in tanks were developed within integrated Fuzzy and PID systems, and their simulation was carried out in the **MATLAB/Simulink** environment.

5. An algorithm for the automated calculation of the density of petroleum products in tanks was proposed and developed. Using this algorithm, computer experiments were conducted to calculate the densities of various types of petroleum products.

6. A colored Petri net-based model was developed to simulate the displacement of transport vehicles for petroleum product logistics at distribution oil depots.

7. A time Petri net-based logistic model was developed for simulating the displacement of transport vehicles in the “transport vehicles - oil depots - filling stations” chain at distribution oil depots. A production rule base was created for the operation and control of the developed logistic model.

8. The software implementation for regulating the temperature and determining the density of petroleum products in tanks under uncertain conditions was realized in the *MATLAB* environment using an extended program package based on the *Fuzzy Logic Toolbox*.

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The author's personal contribution in jointly authored works

The works numbered [5, 6, 8, 9, 13, 14, 15, 16, 17, 18] were carried out independently by the applicant.

The works numbered [1, 2, 3, 4, 10, 11, 12, 19] were written as a result of joint discussions among the authors and, based on the recommendations of the scientific supervisor, with the aim of comprehensively studying and mastering the theoretical aspects of the problem.

In the works numbered [7, 10], the problem statement belongs to the scientific supervisor V.A. Mustafayev, while the research, as well as the analysis and interpretation of the obtained results, belong to K.A. Allahverdiyeva.



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