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Control of Wastewater Treatment Processes Using a Fuzzy Logic Approach †

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Abstract: The issue of pure water is currently one of the most critical concerns facing the global population. Wastewater treatment technologies are seen as one of the solutions to these water shortages. At present, despite the advancements in water treatment technology, there are still drawbacks in terms of energy consumption, the recovery ratio, and control. In order to solve the problems mentioned above, it is also very important to develop a control system method suitable for the water treatment process. In this work, the development and implementation of a fuzzy logic approach to control industrial wastewater treatment technology using an ion-exchange resin are presented. Initially, ion-exchange resin technology was developed in the laboratory as a pilot project and tested to purify wastewater at the Kungrad Soda Plant in Uzbekistan. According to technical instructions, the hardness of purified water should not exceed 3 mEq/L, the total dissolved solids (TDS) should not exceed 40 ppm, and the pH should remain below 7.5. Based on these data, the membership functions (MFs) of the parameters were formed, and the model of controlling the process through the fuzzy logic controller was developed. The developed fuzzy logic controller model was compared with the traditional controller (PID). The energy consumption ranged from 2 to 2.5 kJ/m^3, and the settling time was 40 s when the process was controlled by a PID controller. By implementing the developed fuzzy logic controller in the process, it is possible to decrease the energy consumption by 1.8–2.3 kJ/m^3 and the settling time by 15 s.

Keywords: wastewater treatment; ion-exchange resin; fuzzy logic controller

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1. Introduction

Only 2.5% of the water on Earth is freshwater, and the freshwater we can use makes up about 1% of the total available water. The rest of the freshwater is permafrost, inaccessible rivers, and groundwater. Almost half of the world's population is currently experiencing water scarcity in some capacity due to the growth of industry and the global population and global warning [1–3]. One of the viable solutions to the issue of freshwater is the implementation of water purification technologies. At present, there are numerous varieties of water treatment technologies. Water treatment technologies can be classified into two categories: *traditional* (Multi-Stage-Flash, Multi-Effect-Distillation, Thermal Vapor Compression, Reverse Osmosis, Nano filtration) and *emerging* (Forward osmosis, Membrane

Distillation, Solar Still Distillation, ion-exchange resin, Electro-Dialysis, Capacitive Deionization, Humidification/Dehumidification, etc.) [4,5]. In spite of its advantages over water treatment technologies, there are several drawbacks, including high energy consumption, a low recovery ratio, high operational costs, a negative environmental impact, etc. To resolve these issues, we can improve the current water treatment technologies by developing an intelligent process control system [6].

To date, intelligent control models have been developed to control the concentration of minerals in water and reduce energy consumption during the water treatment process. In the study conducted by Narges at all, a model for an adaptive neuro-fuzzy inference system (ANFIS) was developed to predict the optimal dose of coagulant in effluent. The input data consisted of pH, effluent turbidity, alkalinity, and process temperature. Issues of energy consumption reduction through concentration control were examined through this model [7,8]. According to Yel, to evaluate the primary treatment effluent at a municipal wastewater plant, a fuzzy logic-based diagnostic system was developed. Mamdani's method integrated the measured data into a fuzzy inference system (FIS). The rule base monitored key quality parameters such as pH, chemical oxygen demand, biochemical oxygen demand, and suspended solids [9]. Despite the fact that research has been conducted on the intellectual control of water treatment processes, there are a limited number of studies on the development of an automatic control system for wastewater treatment process using ion-exchange resins. In this work, an intelligent control system of water hardness and total dissolved solids based on fuzzy logic was developed in the process of wastewater treatment using ion-exchange resins.

2. Materials and Methods

Initially, test laboratory equipment for wastewater treatment using ion-exchange resins was developed, and the results were obtained by testing the industrial wastewater from the Kungrad Soda Plant. The following results were also obtained when the calcined soda production wastewater mixture was passed through a 60 L device (see Table 1) [10,11]. This pre-pilot testing scale technology is designed to treat 15 L of wastewater per hour. It is equipped with a pre-treatment filter (10 Big Blue 5 Micron Pleated Sedi-ment Whole House Water Filter), an electric pump (24 V Truck man 1501015, 75.3780-01), two solar panels (30 W 12 V monocrystalline solar panel) for powering the pump and an accumulator (two Delkor 35 Ah, 12 V), a solar charge controller (30 A, 24 V), four tanks for water storage and the regeneration of resins, two KU-2-8 cation-exchange resin filters, two AH-31 anion-exchange filters, connecting plastic tubes, and valves.

Table 1. Results of the analysis and treatment.

Name of Pointers	Unit	Plant's Requirement for Treatment of Wastewater (No More Than)	Results of Analysis of Mixed Wastewater before Treatment in Equipment	Results of Analysis of Mixed Wastewater after Treatment in Equipment
Total hardness	mEq/L	3.0	9.3	0.27
Total alkalinity	-	0.6	3.6	0.52
Calcium (Ca^{2+})	mEq/L	3.0	4.4	0.27
Magnesium (Mg^{2+})	mEq/L	-	4.9	-
Chlorides (Cl^{-})	mg/L	366.15	553	16.5
Sulfates ($SO_4{}^{2-}$)	mg/L	662.81	827	10.6
Total dissolved solids (TDS)	mg/L	1605.81	1885.0	27.3
Suspended solids	mg/L	1.5	1.014	0.042
Hydrogen carbonate indicator (pH)	-	7/7.5	9.2	7.5

According to the results obtained from the device, the total dissolved solids in the water were purified to 40 mg/L, and the total hardness was purified to 3 mgEq/L. Hardness and total dissolved solids must be automatically controlled to the specified value in accordance with the regulation. The regeneration process must be initiated and stopped automatically when these values surpass the specified value, dependent on the pH indicator's value. Compared to the conventional (PID) control method, the intellectual control method enables precise control and energy consumption reduction due to the complexities and dynamic characteristics of this process [12]. Therefore, a fuzzy logic control model was developed and applied to control this process.

As input variables, water hardness (0–4 mgEq/L), total dissolved solids (0–40 mg/L), and pH (7–9) values were determined during this process. The output parameters were the turning angle of the servo valve (4–20) that regulates the flow rate of the effluent and the on/off solenoid valve (0–1) that regulates the consumption of the regeneration solution by the pH indicator. After the input and output variables were identified, membership functions were established by converting them from crisp values to linguistic terms (see Table 2).

Table 2. Crisp and linguistic values of variables.

Input and Output Variables	Crisp Value	Membership Functions
Total hardness (H)	0–4 mgEq/L	Very Low Low Medium High Very High
Total dissolved solids (TDS)	0–40 mg/L	Very Low Low Medium High Very High
pH	7–9	Low Medium High
Servo valve (SerV)	4–20 mA	Fully Closed Mostly Closed Partially Closed Half Open Partially Open Mostly Open Fully Open
Solenoid valve (SolV)	0–1	Fully Open Fully Closed

After the membership functions were developed through the designations, we generated a rule base for the inference engine using the data obtained from the experiment.

1. **IF** H is *Very Low* and TDS is *Very Low*, **THEN** SerV is *Fully Open* and SolV is *Fully Closed*.
2. **IF** H is *Very Low* and TDS is *Low* bo'lsa, **THEN** SerV is *Fully Open* and SolV is *Fully Closed*.
3. **IF** H is *Very Low* and TDS is *Medium*, **THEN** SerV is *Partially Open* and SolV is *Fully Closed*.
4. **IF** H is *Very Low* and TDS is *High*, **THEN** SerV is *Mostly Closed* and SolV is *Fully Closed*.
5. **IF** H is *Very Low* and TDS is *Very High*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.
6. **IF** H is *Low* and TDS is *Very Low*, **THEN** SerV is *Fully Open* and SolV is *Fully Closed*.
7. **IF** H is *Low* and TDS is *Low*, **THEN** SerV is *Mostly Open* and SolV is *Fully Closed*.
8. **IF** H is *Low* and TDS is *Medium*, **THEN** SerV is *Half Open* and SolV is *Fully Closed*.
9. **IF** H is *Low* and TDS is *High*, **THEN** SerV is *Partially Closed* and SolV is *Fully Closed*.
10. **IF** H is *Low* and TDS is *Very High*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.

11. **IF** H is *Medium* and TDS is *Very Low*, **THEN** SerV is *Fully Open* and SolV is *Fully Closed*.
12. **IF** H is *Medium* and TDS is *Low*, **THEN** SerV is *Fully Open* and SolV is *Fully Closed*.
13. **IF** H is *Medium* and TDS is *Medium*, **THEN** SerV is *Half Open* and SolV is *Fully Closed*.
14. **IF** H is *Medium* and TDS is *High*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.
15. **IF** H is *Medium* and TDS is *Very High*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.
16. **IF** H is *High* and TDS is *Very Low*, **THEN** SerV is *Partially Open* and SolV is *Fully Closed*.
17. **IF** H is *High* and TDS is *Low*, **THEN** SerV is *Partially Closed* and SolV is *Fully Closed*.
18. **IF** H is *High* and TDS is *Medium*, **THEN** SerV is *Mostly Closed* and SolV is *Fully Closed*.
19. **IF** H is *High* and TDS is *High*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.
20. **IF** H is *High* and TDS is *Very High*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.
21. **IF** H is *Very High* and TDS is *Very Low*, **THEN** SerV is *Half Open* and SolV is *Fully Closed*.
22. **IF** H is *Very High* and TDS is *Low*, **THEN** SerV is *Partially Closed* and SolV is *Fully Closed*.
23. **IF** H is *Very High* and TDS is *Medium* bo'lsa, **THEN** SerV is *Mostly Closed* and SolV is *Fully Closed*.
24. **IF** H is *Very High* and TDS is *High*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.
25. **IF** H is *Very High* and TDS is *Very High*, THEN SerV is *Fully Closed* and SolV is *Fully Open*.
26. **IF** pH is *Low*, **THEN** SerK is *Fully Closed* and SolV is *Fully Open*.
27. **IF** pH is *Medium*, **THEN** SerV is *Fully Closed* and SolV is *Fully Open*.
28. **IF** pH is *High*, **THEN** SerV is *Fully Open* and SolV is *Fully Closed*.

As previously mentioned, the input and output parameters for the process's intellectual control were established per the factory's requirements and the data obtained from the experiment. Fuzzy sets and membership functions were identified, and a database was created. Briefly, the fuzzification procedure was implemented. Using the Fuzzy Logic Toolbox package of the MATLAB R2024a program, we developed a fuzzy inference system model based on the established rule base. In this model, we used the Takagi–Sugeno method to form membership functions and trained the inference engine using the rule base (Figure 1).

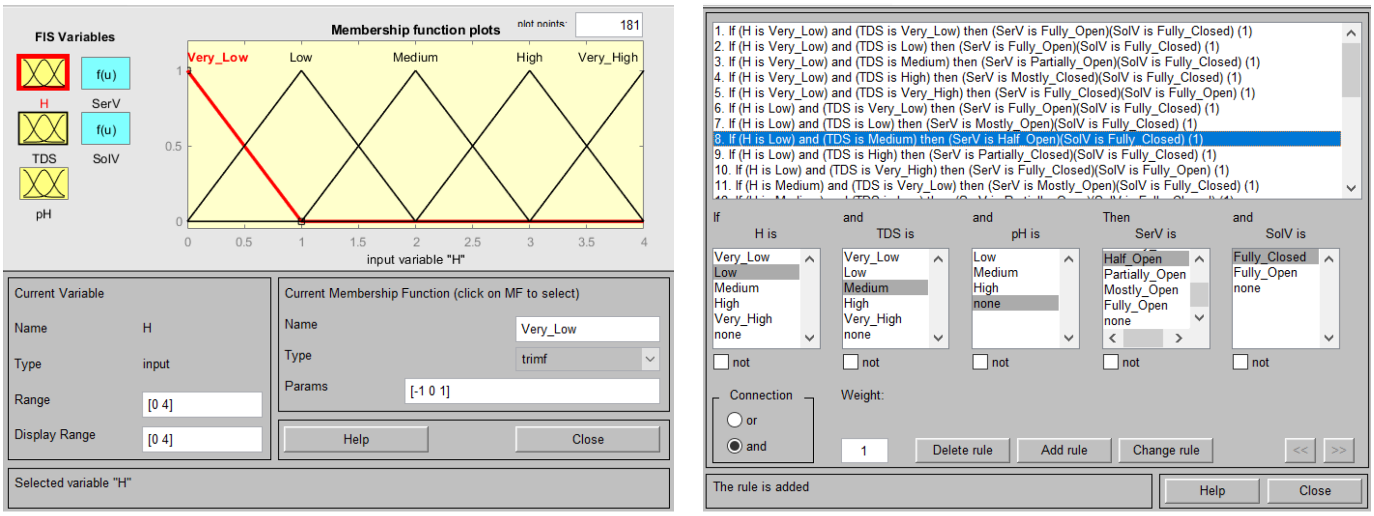
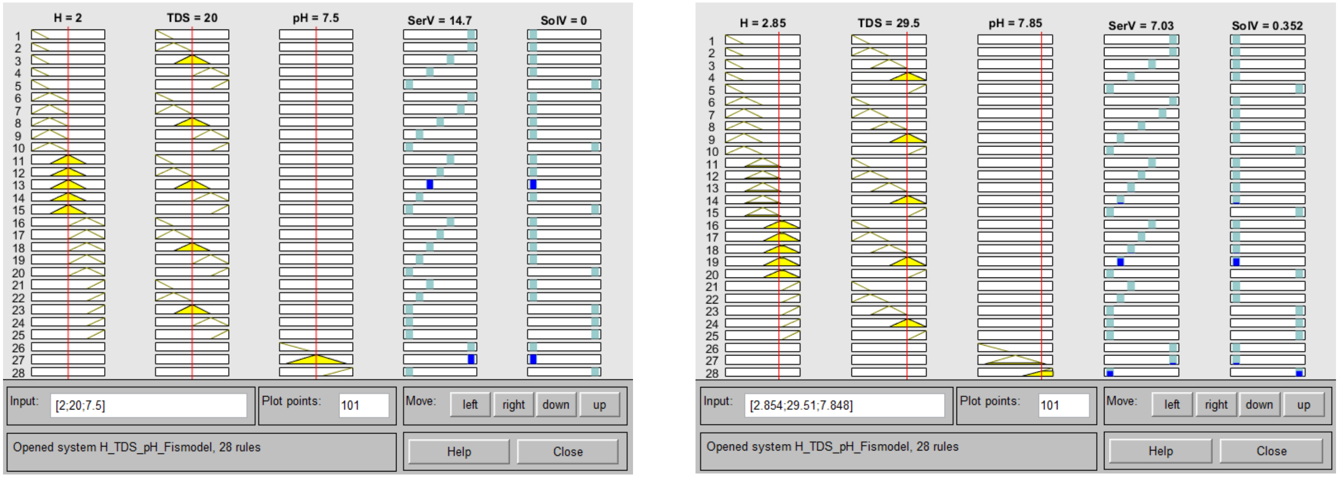


Figure 1. Membership functions of the variables and rule editor in Matlab.

3. Results and Discussion

As shown above, the membership functions and inference engine blocks were built, and input parameters were fuzzified. Using the developed model, the results of the interdependence of input and output parameters were obtained and the defuzzification process was carried out. The rule viewer in Fuzzy Logic Designer, as illustrated in Figure 2, includes the inference engine and the defuzzification value. As indicated by the results, altering the input parameters will result in corresponding changes to the output parameters.



(**a**) (**b**)

Figure 2. Values of the defuzzification by rule viewer in different values (**a**,**b**).

Figure 2a shows the input parameters as follows: the water hardness (H) is 2 mg/L, the total dissolved solids (TDS) is 3 mg/L, and the pH value is 7.5. The resulting output parameters are a turning angle of 14.7 for the servo valve and a solenoid value of 0. We assess the variation in the output parameters by changing the input parameters and comparing the outcomes with the experimental data. We can see from Figure 2b that the output parameters decrease to SerV = 7.03 and SolV = 0.352 when the input values are increased to H = 2.85 mg/L, TDS = 29.5 mg/L, and pH to 7.85. The defuzzification process is illustrated in Figure 3, and the mutual change in each input or output value is visible in this surface viewer. According to the findings in Figures 2 and 3, the wastewater consumption through the servo valve decrease as the total dissolved solids (TDS) and water hardness (H) increase. Ion-exchange resins effectively retain both positively and negatively charged ions in the water. As a result, the ion-exchange resins become fully saturated, requiring the cleaning process to be stopped and the resins to be regenerated. A solenoid valve controls the regeneration process according to the pH indicator's value.

After developing a fuzzy logic inference model, we considered applying this model to control the total dissolved solids and hardness of wastewater. First, we used the R2014 Matlab program with a traditional PID controller to control this process. Then, by changing its proportional, integral, and differential coefficients, we found the most optimal control mode and compared it to fuzzy logic–PID. Based on the conducted experiments, it was found that when $K_P = 2$, $K_I = 0.5$, and $K_D = 0.01$, the overshoot value and settling time reach the minimum and have the most optimal mode. The control structure is shown in Figure 4 for both the PID and fuzzy logic–PID controllers.

Through a control structure developed in Matlab, we controlled the total dissolved solids and the hardness in the wastewater using the input water consumption. In this case, the opening level of the servo valve controlling the water consumption was taken as an output parameter. As a result of the devised model and structure scheme, we controlled this parameter using traditional PID and fuzzy logic–PID controllers. The results indicate that the fuzzy logic–PID controller is significantly faster and has fewer errors than the PID controller (see Figure 5). The graph shows that controlling the parameter with the PID controller takes about 40 s, and controlling it with the fuzzy logic–PID takes approximately 15 s. Furthermore, the PID controller's deviation from the specified value is significantly greater than that of the fuzzy logic PID. The PID controller also exhibits a higher static error. The settling time and the large static error mean that the servo valve is constantly working to control the set value faster. The constant operation of the valve leads to an increase in energy consumption. Therefore, when using the fuzzy logic–PID controller, we can reduce energy consumption by 5–8%.

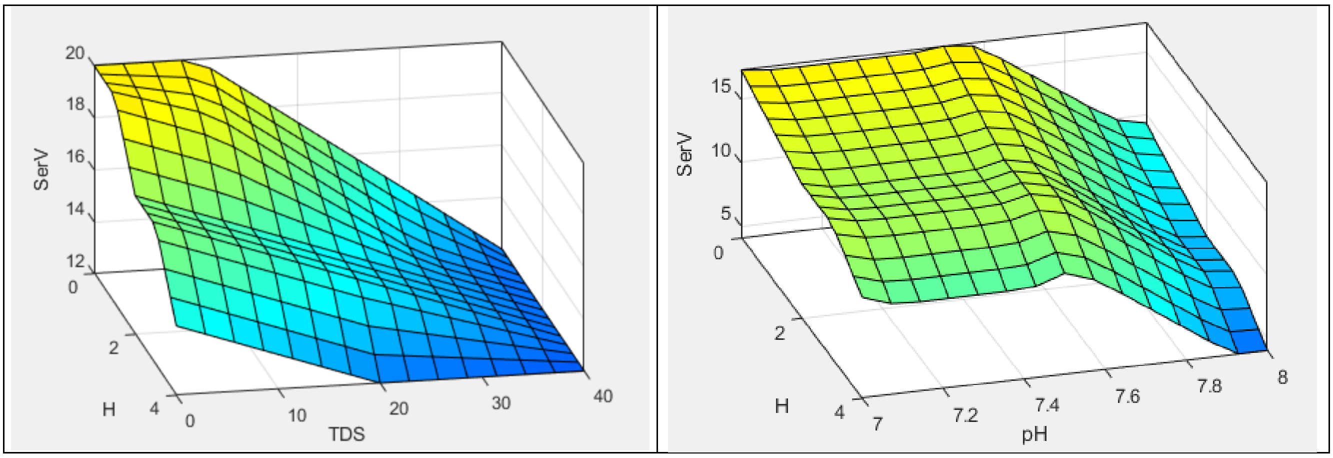


Figure 3. Surface plot of input and output values.

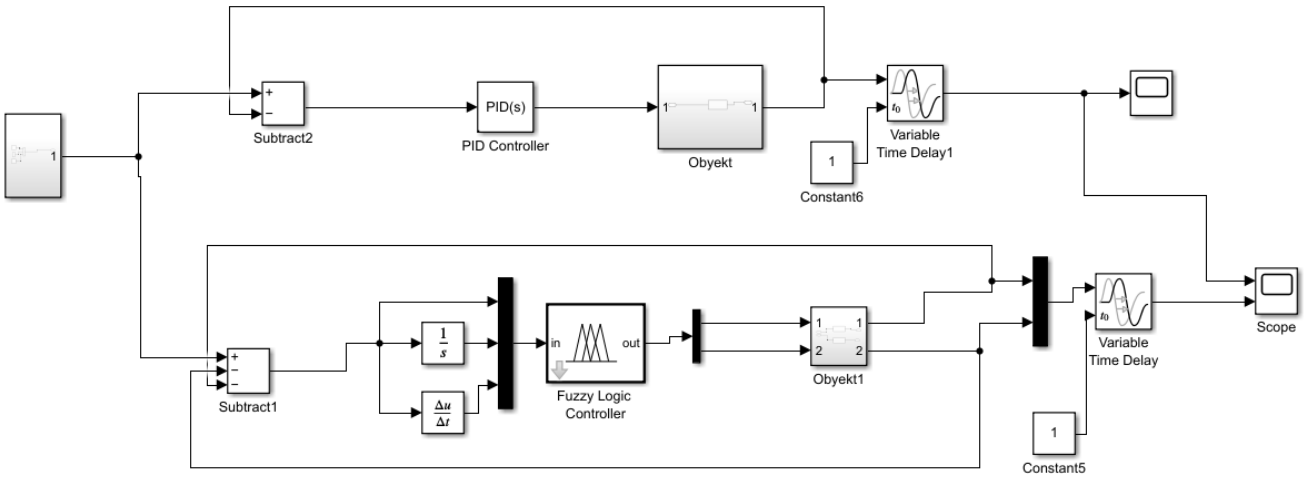


Figure 4. The control system of the PID controller and the optimal fuzzy PID controller.

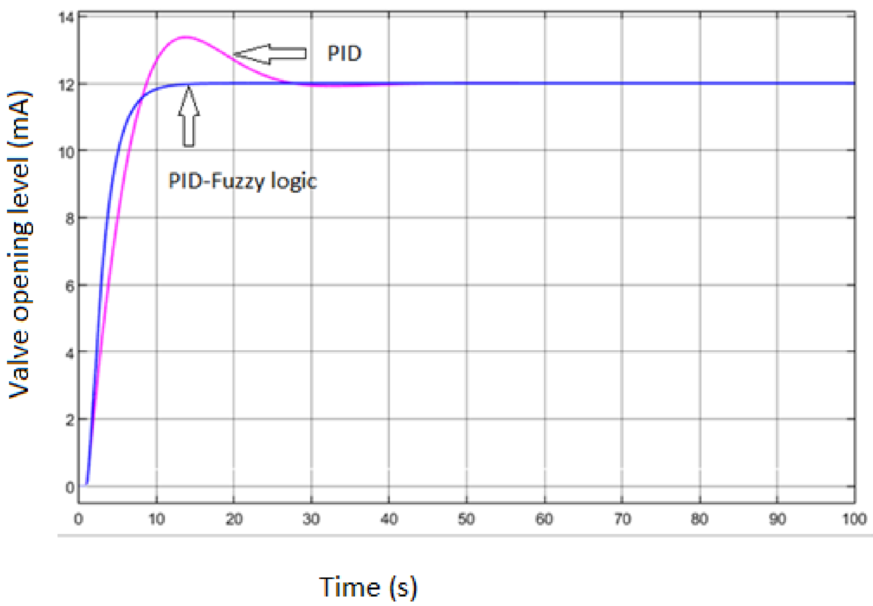


Figure 5. Valve opening level control using the conventional PID and the optimal fuzzy logic–PID controllers.

4. Conclusions

In this work, an intelligent control system for the wastewater treatment process using ion-exchange resins was developed and compared with the conventional control system. The ion-exchange resin water treatment technology results were used to determine the process's input and output parameters. According to the value of the input and output parameters, a fuzzy inference system model was developed. Using the developed model, we built a control structure scheme using the Matlab program. In order to control the amount of total dissolved solids and water hardness in wastewater, control systems for adjusting the opening level of the servo valve using PID and fuzzy logic–PID controllers were developed and compared. The obtained results suggest that the wastewater treatment process can be controlled faster and more accurately than traditional control (PID) through intelligent control (fuzzy logic controller). The energy consumption ranged from 2 to 2.5 kJ/m^3, and the settling time was 40 s when the process was controlled by a PID controller. By implementing the developed fuzzy logic controller in the process, it is possible to decrease the energy consumption by 1.8–2.3 kJ/m^3 and the settling time by 15 s. Through this, we will have the opportunity to reduce energy consumption and increase product quality.

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