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The Wastewater pH Control Using an Artificial Intelligence Technique

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Abstract

In this paper it is presented an automatic system named FuzzypHControl for wastewater pH control, developed using one of the artificial intelligence techniques, namely fuzzy logic. The analyzed process is that of wastewater pH neutralization, process that takes place in a wastewater treatment plant. For process implementation in Matlab 7.9/Simulink, studying the literature, a mathematical model tested and validated on a pilot plant was chosen. Because of the process dynamic and high non-linear behavior, a robust fuzzy logic controller was developed, so that the developed system FuzzypHControl will supply the best results, in terms of the controlled variable (pH) value, the system error and transient time.

Key words: *fuzzy logic, pH, control, controller.*

Introduction

The control of the those parameters that describes the various processes, such as pH quality indicator for neutralization process, can be made using conventional methods (the Proportional-Integral-Derivative (PID) control, etc.) and also using advanced control methods, some of these belonging to artificial intelligence (AI) domain such as: fuzzy logic, artificial neural networks, hybrid neuro-fuzzy techniques, expert systems, etc. The usage suitability of a conventional or advanced control method it is given, first of all, by the analyzed process behavior (high nonlinear character, dynamic behavior, etc.). According [12], the wastewater pH neutralization process presents a high nonlinear character, wherefore we chose to use advanced control techniques that belong to AI domain, such as fuzzy logic. Fuzzy logic was chosen due to its characteristics, that according [16], are: applicability in case of high nonlinear and complex processes (such as the pH neutralization process is), fuzzy controllers are processing rules that describes the analyzed process, rules that are defined by the user and that can be modified for control improvement, etc.

In literature there are presented many examples of systems that are using AI techniques in process control, monitoring, diagnosis and analysis, such as: Aqualogic and Enerlogic systems that are using fuzzy logic [20], BIOEXPERT system that uses expert systems [11], the prototype system for control loops optimal adjustment EXPERT-AT [14], fuzzy logic system for the analysis of a wastewater treatment plant (WWTP) emissary level of pollution [4], a system that uses data mining for monitoring the effluent's quality of an industrial WWTP [5], TELEMAC system that uses data mining [7], ISCWAP that uses knowledge based systems [17], GESCONDA system developed using case base reasoning [9], EnvMAS an agent-based system for environmental monitoring and analysis that uses collaborative intelligence [15], etc.

Regarding the usage of fuzzy logic in pH control, in literature are presented systems for pH control, which are using this type of logic [3, 8, 19].

In this paper it is presented an automatic system with fuzzy logic named FuzzypHControl developed for wastewater pH control. In developing the proposed system it was necessary, first of all, the study of the pH neutralization process that takes part in a WWTP, the study of literature for choosing a validated mathematical model that better describes the analyzed process, the mathematical model implementation in Matlab 7.9/Simulink, the development of an robust fuzzy controller for our automatic system, the development of the automatic system in Matlab 7.9/Simulink environment. The paper is organized as follows: section II it shortly describes the pH neutralization process from a WWTP and the process mathematical model from literature. The implementation of the process mathematical model in Matlab 7.9/Simulink and the process response in time, are presented in section III. The fuzzy controller development, the FuzzypHControl system architecture, implementation in Matlab 7.9/Simulink and the system experimental results are presented in section IV. The final section concludes the paper.

The Wastewater pH Neutralization Process

Process description

According [18] and [1], for acid wastewater neutralization (pH<7) are used basic-type substances, as: hydroxide sodium (NaOH), calcium hydroxide (Ca(OH)2), limestone, etc. For alkaline (or basic) wastewater neutralization (pH>7), are used acid-type substances, as: sulphuric acid (H2SO4), carbonic acid (H2CO3), etc. In [12] are presented examples of dynamic characteristics (the process response in time) for pH neutralization process (fig. 1).

As we can observe in Figure 1, the pH neutralization process presents a high non-linear behavior. Also, it is observed the characteristic dependence on the input pH (curves 1 and 2). So, for an influent with pH=2 (strong acid) it is necessary to be used approximately 3.6 l/min basic type neutralizer with a concentration of 10% NaOH for 1000 l/min wastewater flow, to bring an acid pH to a neutral one (pH=7). For an influent with pH=6 (weak acid) it is necessary to be used 3.6×10-4 l/min basic type neutralizer with a concentration of 10% NaOH for 1000 l/min wastewater flow. Are highlighted the following aspects: for a pH variation in [2 6] interval, the necessary neutralizer flow is varying in a 10000:1 (3.6/3.6×10-4) ratio, the high nonlinear character of the process it leads to major consequences, such as the neutralizer dosage accuracy direct dependence on the input pH value and the process amplification it extremely high for pH=2 or 12 and it decreases for a pH about 7 [12].

Process mathematical model

Studying the literature, we chose to use for pH neutralization process a mathematical model tested and validated on a pilot WWTP, model developed by R. Ibrahim in his Ph.D. thesis [10]. In Figure 2 it is presented the schematic diagram of the pH neutralization process.

The model main equations, equations that highlights the dynamic behavior of the process, are the differential ones:

$$V\frac{d\alpha}{dt} = F_1C_1 - (F_1 + F_2)\alpha \quad (1)$$

$$V\frac{d\beta}{dt} = F_2C_2 - (F_1 + F_2)\beta \quad (2)$$

where: V is the basin volume, F_1 is the acid stream flow rate, F_2 alkaline stream flow rate, C_1 is the acid concentration in basin, C_2 is the alkalinity concentration in basin, α is the system non-reactant component for acid, while β is the system non-reactant component for base (alkaline).

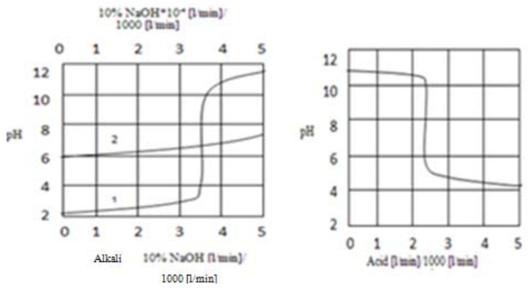

Fig. 1. Dynamic characteristics for acid and alkaline pH neutralization [12]

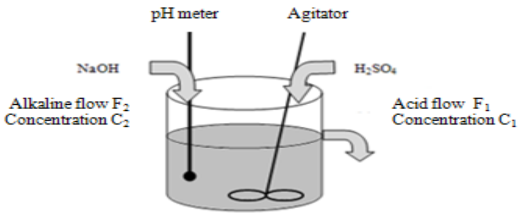

Fig. 2. Process schematic diagram [10]

Equation (3) shows the model non-linearity, equation known in literature as the pH equation:

$$[H^+]^4 + a_1[H^+]^3 + a_2[H^+]^2 + a_3[H^+]^1 + a_4 = 0 \quad (3)$$

The pH scale is the measure of the hydrogen ions concentration, the pH value being calculated with (4):

$$pH = -\log_{10}[H^+] \quad (4)$$

The main laws that are staying at the base of pH neutralization process modeling, mathematical expresses through balance equations, are presented in [2] and [13]. The meaning of equation (3) coefficients and more details about this model are presented in [10].

The Model Implementation in Matlab7.9/Simulink

In this section, it is achieved the pH neutralization process mathematical model implementation in Matlab 7.9/Simulink, being obtained the system presented in Figure 3. The goal is to obtain the process response in time (the dynamic response), namely the output (pH) variation in time at a known variation (step type) for F_1 and F_2 inputs, maintaining the others inputs (C_1 and C_2) constant in time, as it can be observed in Figure 3.

The Subsystem component from Figure 3 represents the implementation in Simulink of the pH neutralization process mathematical model (equations (1), (2), (3) and (4)), implementation presented in Figure 4 [6]. For implementing the dynamic mathematical model (DMM) model represented by equations (1) and (2) was used a Differential Equation Editor (DEE) from Simulink.

In Table 1 and Figures 5, 6 and 7 for different values (values established after process analysis) of the system inputs (C_1, F_1, F_2 and C_2), it is presented the process response in time (the controlled variable (pH) variation in time).

As it can be observed in Figure 5, applying a step input F_1 (the acid neutralizer H_2SO_4 flow increases from 17.5 l/h to 167.5 l/h), the output (pH) value decreases. The process response it's a correct one, because the neutralization of a basic pH requires the acid neutralizer flow growth.

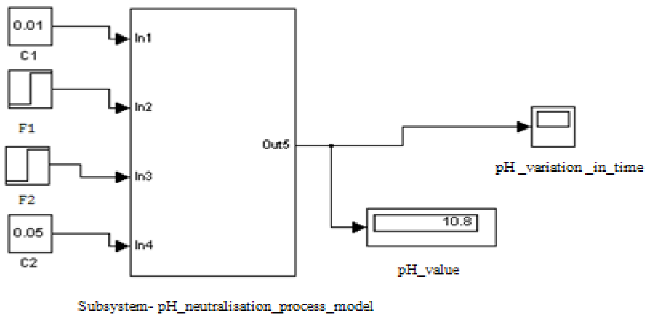

Fig. 3. The system arhitecture in Simulink[6]

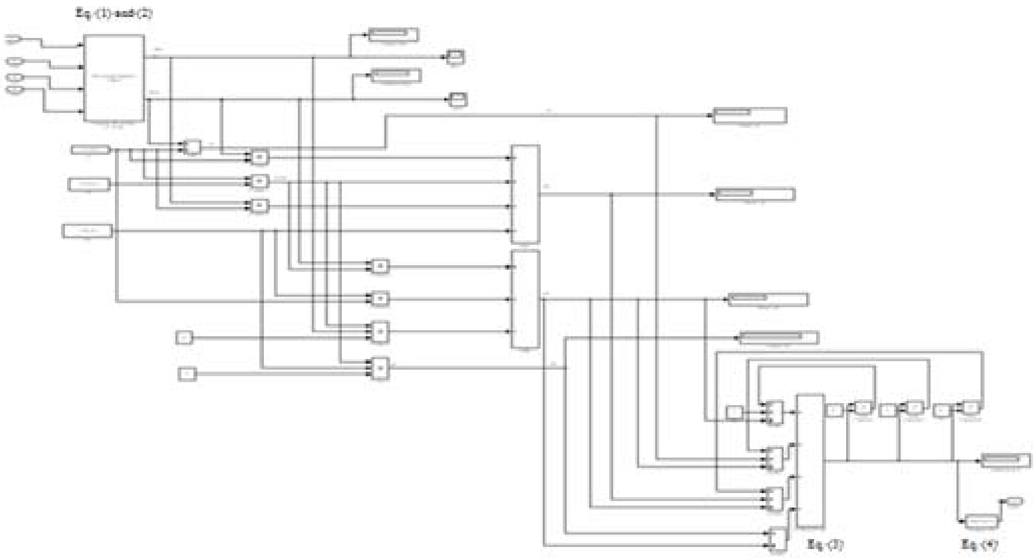

Fig. 4. Subsystem component [6]

Table 1. Process response

No.	Inputs				Outputs
	C_1 (%)	F_1 (l/h)	C_2 (%)	F_2 (l/h)	pH units
1	0.01	17.5 ↗ 167.5	0.05	70	10.8
2	0.01	0 ↗ 260	0.05	70	2.46
3	0.01	0 ↗ 260	0.05	0 ↗ 70	12.69

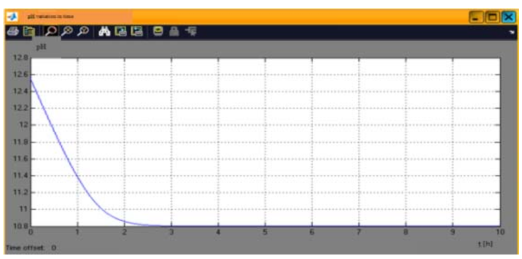

Fig. 5. Process response (Experiment no. 1) [6]

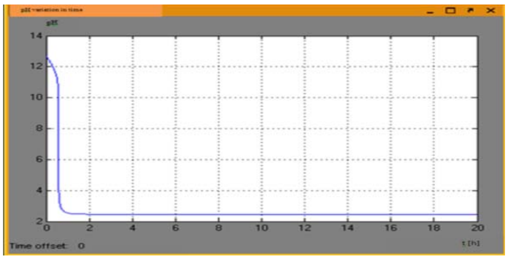

Fig. 6. Process response (Experiment no. 2) [6]

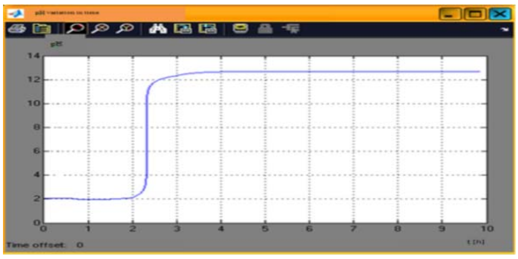

Fig. 7. Process response (Experiment no. 3) [6]

In Figure 6 it is observed the fact that starting from a basic pH (pH≈12 units), through the dosage of an increased flow of acid type neutralizer (H_2SO_4) F_1, the pH passes into the acid domain (2.46 units).

We must make the following observation: this process model needs first of all to bring the basic pH into the acid domain, and only then it is allowed the dosage of a basic neutralizer (NaOH) to bring the acid type pH to a basic one. In Figure 7, the acid pH (pH≈ 2 units), through the dosage of an increased basic neutralizer flow (NaOH) F_2, it is brought into the basic domain (≈12.69 units). The process dynamic response (figs. 5, 6 and 7) highlights its high non-linear behavior and also the correctness of model implementation in Matlab 7.9/Simulink.

FUZZYpHCONTROL System

The architecture of the developed automatic system (AS) for pH control, system called FuzzypHControl, it is presented in Figure 8.

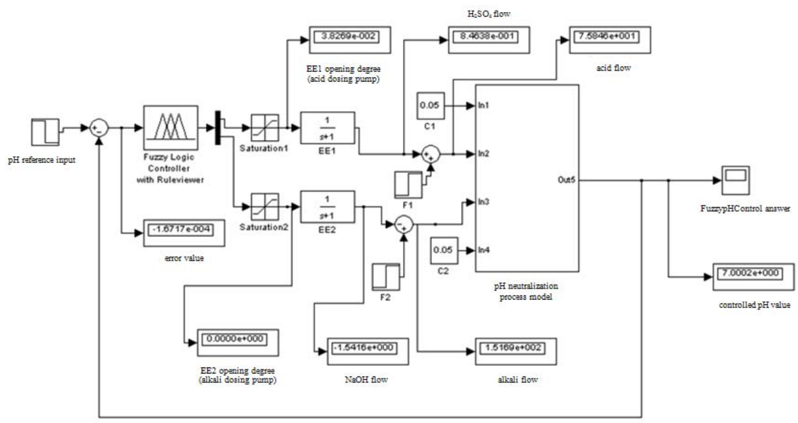

Fig. 8. FuzzypHControl arhitecture [6]

The developed FuzzypHControl system elements are:

- A fuzzy logic controller with rule viewer developed using Fuzzy Logic Toolbox from Matlab 7.9; the controller input it is represented by *error* (the difference between pH set point and pH measurement) and the output it is *command C* (the acid or alkali pumps opening degree for the dosage of the necessary neutralizer flow to bring an acid or alkali pH to the set point);
- The process represented by the mathematical model of the pH neutralization process, model whose implementation in Simulink was presented in section III;
- Two actuators: an acid (H_2SO_4) dosing pump (EE_1) and an alkali (NaOH) dosing pump (EE_2);
- The pH set point that according to the technical normative in domain (NTPA - 001/2002 [21]) is 7 pH units;
- The error defined as the difference between pH set point (i_{pH}=7) and the pH measurement at the process output (m_{pH}).

To bring the controlled variable (pH) to the set point value (pH=7) it is necessary the control of the acid or alkali (H_2SO_4 or NaOH) neutralizer flow. This implies the operation of the adequate dosing pump, for acid neutralizer EE_1 and for alkali neutralizer EE_2. The opening degree of the dosing pumps (EE_1 and EE_2) is directly dependent on the error value.

As it can be observed in Figure 8, an important element in FuzzypHControl architecture is the fuzzy controller. As we have mentioned we have developed a fuzzy controller to test it in our AS and depending on the supplied results will be improved its membership functions (MFs) and rules. In Figure 9 it is presented the architecture of the developed fuzzy controller named RpHfuzzy, where *error* is the controller input and *EE1/EE2_opening_degree* is the controller output.

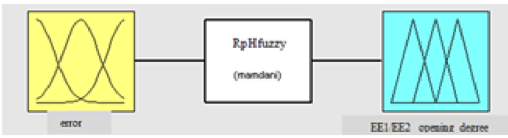

Fig. 9. RpHfuzzy architecture [6]

Studying the pH neutralization process in a WWTP, where established the membership functions (MFs) for controller input *error* and also for controller output *EE1/EE2 opening_degree* (command-C), MFs presented in Table 2 and Table 3.

Table 2. MFs for input error

pH	MF symbol	Error	MF type	MF parameters values			
				a_i	b_i	c_i	d_i
basic	erbfmare	high	trapezoidal	-5	-5	-4	-3.062
	erbmare	big	triangular	-4	-3.062	-2.125	-
	erbmed	medium	triangular	-3	-2.125	-1.25	-
	erbmica	small	triangular	-2	-1.25	-0.5	-
	erbfmica	very small	triangular	-1	-0.5	0	-
neutral	erzero	zero	triangular	-0.2	0	0.2	-
acid	erafmica	very small	triangular	0	0.5	1	-
	eramica	small	triangular	0.5	1.25	2	-
	eramed	medium	triangular	1.25	2.125	3	-
	eramare	big	triangular	2.125	3.062	4	-
	erafmare	high	trapezoidal	3.062	4	5	5

To obtain the MFs from Table 2, was used the following reasoning: when the pH value belongs to [6.8 7.2] interval, then *erzero* (error that tends to 0 value) belongs to [-0.2 0.2] interval, when the pH is strong basic (in [10 12] interval), then *erbfmare* (high error for pH basic) belongs to [-

5 -3] interval and when the pH is strong acid (in [2 4] interval), then *erafmare* (high error for pH acid) belongs to [3 5] interval. Using the same reasoning where determined all the input MFs. As it can be observed in Table 2, are eleven MFs that describe the input *error*, input that belongs to [-5 5] domain.

Table 3. MFs for output EE1/EE2_opening_degree (C)

Neutralizer	MF symbol	EE opening deg.	MF type	MF parameters values			
				a_i	a_i	a_i	a_i
Basic (NaOH)	eebfmare	high	trapezoidal	-100	-100	-90	-61.25
	eebmare	big	triangular	-80	-61.25	-42.5	-
	eebmed	medium	triangular	-60	-42.5	-25	-
	eebmic	small	triangular	-40	-25	-10	-
	eebfmic	very small	triangular	-20	-10	0	-
-	eezero	no action	triangular	-10	0	10	-
Acid (H_2SO_4)	eeafmic	very small	triangular	0	10	20	-
	eeamic	small	triangular	10	25	40	-
	eeamed	medium	triangular	25	42.5	60	-
	eeamare	big	triangular	42.5	61.25	80	-
	eeafmare	high	trapezoidal	61.25	90	100	100

For obtaining the MFs from Table 3, was used the following reasoning: a maximum opening of EE_1 (acid pump) means an opening degree in [61.25% 100%] interval, a maximum opening of EE_2 (basic neutralizer pump) means [-61.25% -100%] opening and when the pH values is close to its set point, the EE_1 and EE_2 opening degree is in [-10% 10%] interval. The symbol "-" it is used to make a difference between acid (EE_1) and alkaline (EE_2) pumps. The fuzzy rules that highlight the relations between input *error* and output *C* are presented in Table 4.

Table 4. Fuzzy rules

No.		Error		C
1	If	erzero	then	eezero
2		erbfmica		eeafmic
3		erbmica		eeamic
4		erbmed		eeamed
5		erbmare		eeamare
6		erbfmare		eeafmare
7		erafmica		eebfmic
8		eramica		eebmic
9		eramed		eebmed
10		eramare		eebmare
11		erafmare		eebfmare

The surface viewer for RpHfuzzy controller is presented in Figure 10.

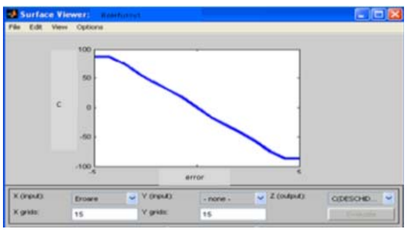

Fig. 10. Initial RpHfuzzy surface viewer [6]

In the case of RpHfuzzy as it can be observed in Table 2, Table 3 and Figure 10, when the output pH value approaches the pH set point, namely the error is in [-0.2 0.2] interval, the controller command (*C*) for opening EE1 or EE2 pump is in [-10% 10%] interval, command that can be too strong in this case. Studying [10], we improved the input and output MFs and rules for the initial developed RpHfuzzy controller. Where associated an opening degree for EE1 and EE2 in [-0.05% 0.05%] interval for an error in [-0.5 0.5] interval. In other words, it was established a lower opening degree for a bigger error, and also where modified the fuzzy rules (where refined the rules initial associated with RpHfuzzy), as it can be observed in Table 5, 6 and 7.

Table 5. New MFs for input error

pH	MF symbol	Error	MF type	MF parameters values			
				a_i	b_i	c_i	d_i
basic	erbfmare	high	trapezoidal	-5	-5	-4	-2
	erbmare	big	triangular	-3	-2	-1	-
	erbmed	medium	triangular	-2	-1.25	-0.5	-
	erbmica	small	triangular	-1	-0.5	0	-
neutral	erzero	zero	triangular	-0.5	0	0.5	-
acid	eramica	small	triangular	0	0.5	1	-
	eramed	medium	triangular	0.5	1.25	2	-
	eramare	big	triangular	1	2	3	-
	erafmare	high	trapezoidal	2	4	5	5

Table 6. New MFs for output EE1/EE2_opening_degree (C)

Neutralizer	MF symbol	EE opening deg.	MF type	MF parameters values			
				a_i	a_i	a_i	a_i
Basic (NaOH)	eebfmare	high	trapezoidal	-100	-100	-60	-45
	eebmare	big	triangular	-50	-40	-30	-
	eebmed	medium	triangular	-35	-25	-15	-
	eebmic	small	triangular	-20	-10	0	-
-	eezero	no action	triangular	-0.05	0	0.05	-
Acid (H_2SO_4)	eeamic	small	triangular	0	10	20	-
	eeamed	medium	triangular	15	25	35	-
	eeamare	big	triangular	30	40	50	-
	eeafmare	high	trapezoidal	45	60	100	100

Table 7. NewFuzzy rules

No.		Error		C
1	If	erbfmare	then	eeafmare
2		erbmare		eeamare
3		erbmed		eeamed
4		erbmica		eeamic
5		erzero		eezero
6		eramica		eebmic
7		eramed		eebmed
8		eramare		eebmare
9		erafmare		eebfmare

The graphic from Figure 11, presents all the information from the process and indicates the possible defuzified values variation domain for error.

In Figure 12 it is presented the automatic system FuzzypHControl response in time (the controlled variable (pH) variation in time), using RpHfuzzy controller with initial MFs and rules presented in Table 2, 3 and 4.

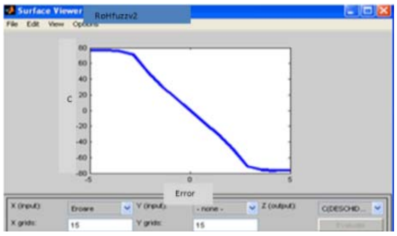

Fig. 11. Surface viewer for modified RpHfuzzy [6]

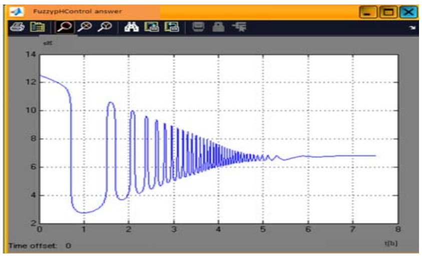

Fig. 12. FuzzypHControl response using the initial controller RpHfuzzy [6]

In Figure 13 it is presented the automatic system FuzzypHControl response, using the improved controller RpHfuzzy that uses the new MFs and fuzzy rules presented in Tables 5, 6 and 7.

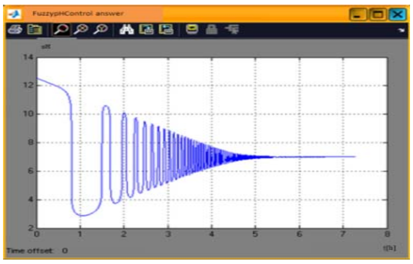

Fig. 13. FuzzypHControl response using the improved controller RpHfuzzy [6]

In Table 8 are presented the simulation results (controlled variable (pH) value at the process output, system error ($e=i_{pH}-m_{pH}$) and transient time-compressed time (T_{tr})) supplied by the developed automatic system FuzzypHControl using the initial and also the improved fuzzy controller RpHfuzzy.

Table 8. Simulations results

Fuzzy controller	**C_1 (%)**	**F_1 (l/h)**	**C_2 (%)**	**F_2 (l/h)**	**pH set point (i_{pH})**	**pH val. (units)**	**Error**	**T_{tr} (h)**
RpHfuzzy initial	0.05	75	0.05	70	7	6.8	0.19998	7
RpHfuzzy modified	0.05	75	0.05	70	7	7.0002	0.00016717	7

Conclusions

First of all, I will like to offer thanks to Senior Lecturer Dr. Rosdiazli B. Ibrahim, Doctor of Philosophy in Electrical and Electronic Engineering, University of Glasgow, and to his supervisor, Emeritus Professor and Senior Research Fellow David J. Murray-Smith, University of Glasgow, because they allowed me to use the pH neutralization process mathematical model developed by R. B. Ibrahim in his PhD Thesis [10].

The most important advantage of fuzzy logic is its successfully application in complex and high non-linear processes control, such is the pH neutralization process. As it can be observed in Table 8, the improved RpHfuzzy controller supplies the best results, the controlled variable pH being brought very close to its set point and the FuzzypHControl system error it is the lowest. The simulation results obtained denote that was obtained a robust fuzzy controller, RpHfuzzy for our developed AS FuzzypHControl.

Future work consists in developing a neuro-fuzzy controller, a neural controller and an expert controller for our automatic system (AS), in order to establish that AI technique (fuzzy logic, neuro-fuzzy, artificial neural networks and expert systems) which is the most adequate for wastewater pH control. It will also be made a comparison between these AI techniques used in pH control and conventional control techniques (such as PID), from the point of view of the controlled variable value, the AS generated error and transient time.

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Reglarea pH-ului apei uzate utilizând o tehnică de inteligență artificială

Rezumat

În cadrul acestei lucrări este prezentat un sistem automat pentru reglarea pH-ului apei uzate, numit FuzzypHControl, dezvoltat utilizând una dintre tehnicile de inteligență artificială, şi anume logica fuzzy. Procesul analizat este cel al neutralizării pH-ului apei uzate, proces care are loc într-o stație de epurare. Pentru implementarea procesului în Matlab 7.9/Simulink, studiind literatura de specialitate a fost ales un model matematic testat şi validat pe o stație de epurare pilot. Din cauza comportamentului dinamic şi puternic neliniar al procesului, s-a dezvoltat un regulator fuzzy robust, astfel încât sistemul dezvoltat FuzzypHControl să furnizeze cele mai bune rezultate, din punctul de vedere a valorii mărimii reglate (pH), a erorii sistemului şi a duratei regimului tranzitoriu.