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INTEGRATED ARTIFICIAL INTELLIGENCE TECHNIQUES APPLICATION FOR WASTEWATER pH CONTROL

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ABSTRACT

The control of the pH neutralization process has a decisive role in many industrial branches, as: wastewater treatment, biotechnology, pharmaceutical industry, chemical processing, etc. However, the pH neutralization process is a difficult one to control, due to time-varying process parameters, its high non-linearity and to the sudden variation of the pH around the equivalence point. The paper presents a device and an integrated application that uses artificial intelligence (IA) developed for dosage of the necessary reactants in wastewater pH control. The AI techniques were integrated into the application by developing an expert system (ES). For this purpose, were used the necessary *if-then* rules (rules that make up the inference engine (IE) of the ES) related to the flowrates of the reactants necessary for wastewater pH neutralization. The ES knowledge base (KB) was built based on the recorded pH values. The hardware component (the device) was created using the Arduino equipment.

Keywords: pH control, wastewater neutralization, artificial intelligence, expert system, Arduino

INTRODUCTION

The wastewater pH neutralization is the chemical process of bringing an acid or an alkaline pH to a neutral value (between 6.8 and 7.2 units), process that is applied to the wastewater discharged from different areas in order to correct the pH of the treated water before being evacuated into the emissary of a treatment plant [9].

The proposed block diagram of a pH control system is presented in Figure 1. The liquid whose pH is adjusted is fed through the wastewater pipe into a mixing tank. The neutralizing solution flows through the basic agent dosing pump, which mixed in the reaction tank with the liquid supplied through the initial pipe, should result in a desired pH value (7±0.2 units for the pH set point-SP) of the liquid in the outlet pipe (treated solution). Therefore, the pH control, in order to obtain the prescribed pH SP, is carried out by changing the flowrate of the acid or alkaline agent depending on the pH type. If the wastewater pH is acid, the reactant solution must be alkaline (hydrated lime $Ca(OH)_2$), while if the pH is alkaline the reactant solution is acid (sulphuric acid H_2SO_4).

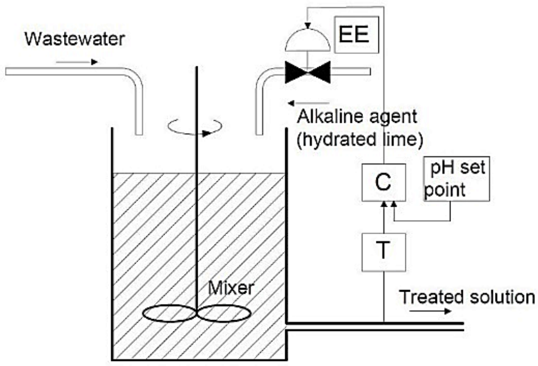


Figure 1. *Block diagram of a pH control system*

The pH neutralization process is a difficult one to control due to its high non-linearity, time-varying parameters and the influence of disturbances near the pH equivalence point (pH=7) [2, 3, 6]. According [2, 3], for the process of wastewater pH neutralization, it is very hard to find that pair of PID tuning parameters (K_R, T_i) valid for the entire domain of the controlled parameter (pH). As a result, the Proportional-Integral-Derivative (PID) controllers doesn't work over the entire pH domain, which is why it is not recommended to use PID control for the pH neutralization process. Regarding the wastewater pH neutralization process control, it is suggested the usage of the automated control systems that are using AI techniques (such as expert systems, neural artificial networks, fuzzy logic, adaptive neuro-fuzzy inference systems) due to the fact that are more efficient than PID algorithm based control systems [2, 3]. Several systems using AI techniques have been identified in the field of pH neutralization process research, such as: the SENFpHCTRL neuro-fuzzy expert system [2, 3], the fuzzy logic based controller for pH neutralization process [10], the fuzzy logic controller used in acidic control of a chemical plant [5], the ANFIS controller developed to improve pH prediction [14], the controller based on decentralized fuzzy inference developed for pH neutralization process [15].

THE DEVELOPMENT OF THE DEVICE THAT INTEGRATES AI TEHNIQUES FOR WASTEWATER pH CONTROL

The development of a device that integrates AI techniques for dosing the reactants needed to control the wastewater pH was carried out in two stages: the design of the application and the practical implementation of the device.

The following figure (Figure 2) shows the block diagram of the application that uses AI techniques (ES), added to the hardware component (the device developed using Arduino), for the reactants dosage necessary for wastewater pH control.

The ES is identified as a particular case of a knowledge-based system (KBS) which contains the human expert's knowledge in a certain field (heuristic knowledge) [8]. Any KBS contain a knowledge base (KB) - the cognitive system and an inference engine (IE) - the resolution system. To these components are added the user interface and the knowledge acquisition module [8].

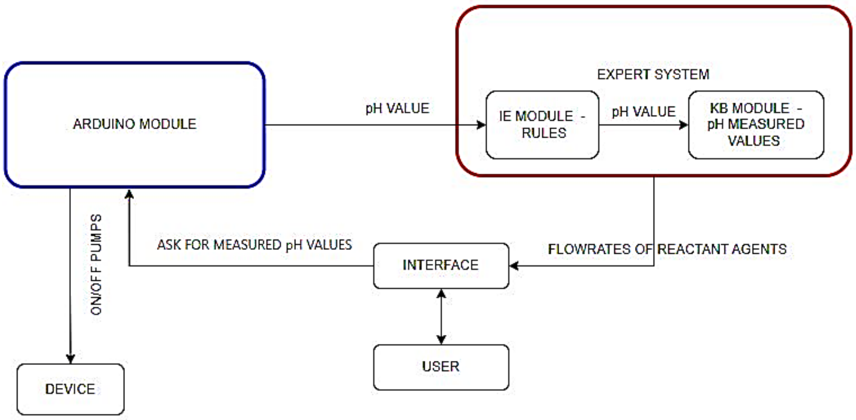


Figure 2. *Block diagram of the application*

As it can be observed in Figure 2, the component modules of the developed application are:

- The *KB module* of the ES is represented by the totality of the measured wastewater pH values. These values are provided through the Arduino module by the pH transducer and then are passed for interpretation to IE module. This module receives the pH data recorded in the IE module.
- The *IE modul*e of the ES consists of the totality of the rules (*if-then* rules) related to the flowrates of the reactants required for wastewater pH neutralization. This module receives the pH data recorded in the KB module. With the help of the controller, these values are interpreted and the pump flowrates are provided to the user via the interface module.
- Through the *Arduino module* the neutralization process is carried out. The Arduino module communicates with the user via the interface module where are transmitted the pH values measured by the pH transducer. These values reach the ES that communicates the flowrates to the user. After the comparison of the pH measured values with pH SP values [6.8, 7.2] units, the pump connected to the neutralizing solution is turned on and the mixer starts to homogenize the solution. When the pH value reaches the pH SP, the dosage pump is turned off and neutralization process is stopped. Four functions are implemented in the Arduino Uno microcontroller, which is connected to the other physical equipment (pH transducer, dosage pumps, motor for starting the mixer, motor control board, power supply and laptop):
    - The wastewater pH reading function;
    - The function for adding the acid solution by starting the pump connected to this reactant;
    - The function for adding alkaline solution by starting the pump connected to this reactant;
    - The function for activating the mixer used to homogenize the solutions.
- The *interface module* ensures the connection between the user and the application/device elements. The interface module communicates with the Arduino module via the serial port of the laptop connected to the Arduino Uno

development board. This takes the measured pH values and displays them in the specific section of the interface. At the same time, the interface module is connected to the ES, from which it receives information about the flowrates of the reactants, the type of the dosage pump (acid/alkaline) and its operating mode (on/off).

For the physical achievement of the device using AI techniques for reactants dosing, the basic structure of the automatic pH control system was considered, as it can be observed in Figure 3 that represents the block diagram of proposed system.

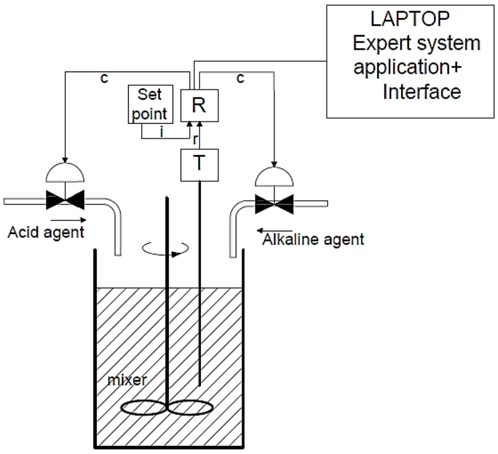


Figure 3*. Block diagram of automatic pH control system*

The developed ES was integrated into Microsoft Visual Studio using the rules for reactants dosage flowrates necessary for neutralizing an acid or an alkaline pH, presented in paper [2]. The values of the flowrates derived from the rules have been taken into the application only for information purposes and transmitted to the user through the interface. The Arduino recorded data represents the KB of the ES, while the *if-then* rules for reactants dosage flowrates necessary for an acid or an alkaline pH neutralizing represents the IE of the ES.

The wastewater pH neutralization process parameters from the considered Romanian industrial plant are presented in Table 1. The process parameters used in the developed rules were provided by the manual of the chemical, biological and wastewater treatment plant (ECBTAR) of a Romanian studied industrial plant [2, 3, 4, 7].

Table 1. *The operating parameters of the studied industrial plant [2, 3, 4, 7]*

F_1 [liters/hr] (H_2SO_4 flowrate)	C_1 (Concentration)		F_2 [liters/hr] ($(Ca(OH)_2$ flowrate)	C_2 (Concentration)		V [liters] (Volume of the admixture-reaction tank)
	[%]	[mol/liter]		[%]	[mol/liter]	
[25-300]	95	17.74	[5000-7000]	10	1.5	4000

A selection from the total number of thirty-eight rules adapted for the case of an alkaline pH neutralizing, is presented next [2]:

1. *if ((pH>11.71) and (pH<=13.42)) then F1_initial_variation=d1(180-->220 [liters/hr]);*
2. *if ((pH>11.71) and (pH<=13.42)) then F1_final_flowrate=220.9 [liters/hr];*

3. *if ((pH>11.59) and (pH<=13.13)) then F1_initial_variation =d2 (220-->220.2 [liters/hr]);*

4. *if ((pH>11.59) and (pH<=13.13)) then F1_final_flowrate =220.9 [liters/hr];*

....

37. *if (pH==7) then F1_initial_variation =0;*

38. *if (pH==7) then F1_final_flowrate =0.*

Also a selection of rules adapted for the case of an acid pH neutralizing, is presented next [2]:

1. *if ((pH>=2.7) and (pH<=2.75)) then F2_initial_variation =d1 (5704-->5750 [liters/hr]);*

2. *if ((pH>=2.7) and (pH<=2.75)) then F2_final_flowrate =6149.84 [liters/hr];*

3. *if ((pH>=2.89) and (pH<=2.98)) then F2_initial_variation =d2 (5850-->5900 [liters/hr]);*

4. *if ((pH>=2.89) and (pH<=2.98)) then F2_final_flowrate =6149.84 [liters/hr];*

....

37. *if (pH==7) then F2_initial_variation=0;*

38. *if (pH==7) then F2_final_flowrate =0.*

These rules have been added into the program developed in the C# programming language using Microsoft Visual Studio 2022 environment. The program sequence was integrated as the source code behind the "*Calculate*" button from the application interface presented in Figure 7. Behind this button, there is a function that has the role of automatically filling the spaces in the text boxes "*F_1 Initial Variation*", "*F_1 Final Flowrate*", "*F_2 Initial Variation*", "*F_2 Final Flowrate*" and to identify the pump that is operating in a certain situation. Next, is presented a selection of the source code of the function integrated in click type button "*Calculate*".

```
private void button1_Click(object sender, EventArgs e)// function name
    {   double pH;// declaration of pH variable type double
        string F1_initial_variation = ""; // declaration of string variables for the final flow rates of the reactants, respectively for the variations of the initial flowrates and their initialization with empty strings
        string F2_initial_variation = "";
        string F1_final_flowrate= "";
        string F2_final_flowrate = "";
        bool pump_a = false;// declaration of logic type variables for starting the pumps and initializing them with false value
        bool pump_b = false;
        pH = Convert.ToDouble(textBox1.Text); // initialize the pH value with the value converted to a variable of type double related to the text value taken from textBox1 (transmitted from Arduino)
        if ((pH > 11.71) && (pH <= 13.42))// defining conditions and changing parameters according to if-then rules
        {F1_initial_variation = "d1(180-->220[liters/hr])";
```

```
 F1_final_flowrate = "220.9[liters/hr]";
pump_a = true;
pump_b = false; }
```

……

```
if (pH == 7)
{F2_initial_variation = "0 [liters/hr])";
F2_final_flowrate = "0 [liters/hr]";
pump_a = false;
pump_b = false;}
```

In the experimental part of the application, because were used aquariums type reactants dosage pumps (due to high costs of industrial dosage pumps), it was not possible to integrate controllers to change the reactants flowrates. As a result of these impediments, the microcontroller only turns on/off the acid/alkaline reactant dosage pumps until the measured pH value reaches the pH SP, respectively[6.8, 7.2] units.

The program implemented on the Arduino Uno microcontroller, was written in C++ programming language in the Arduino environment. There were defined the objects *PumpA* and *PumpB* and the functions for pH reading (*pH_read*), for acid reactant dosage (*add_acid*), for alkaline reactant dosage (*add_base*) and for turning on the mixer to homogenize the solution (*start_mixer*).

The components required for the development of the proposed circuit were connected according to the wiring diagram from Figure 4.

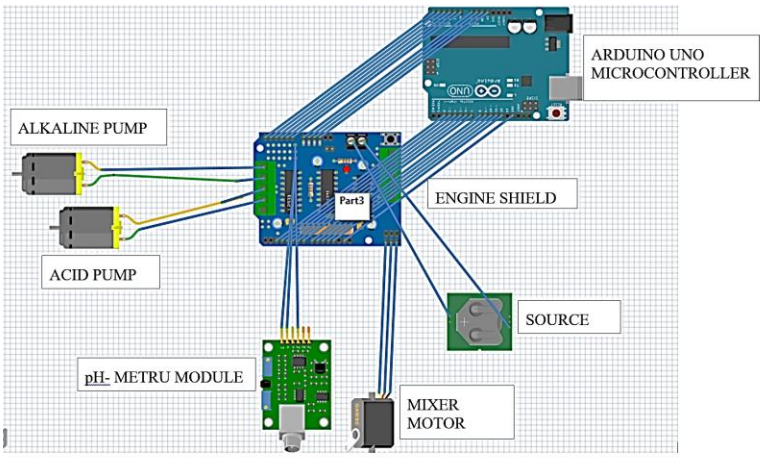
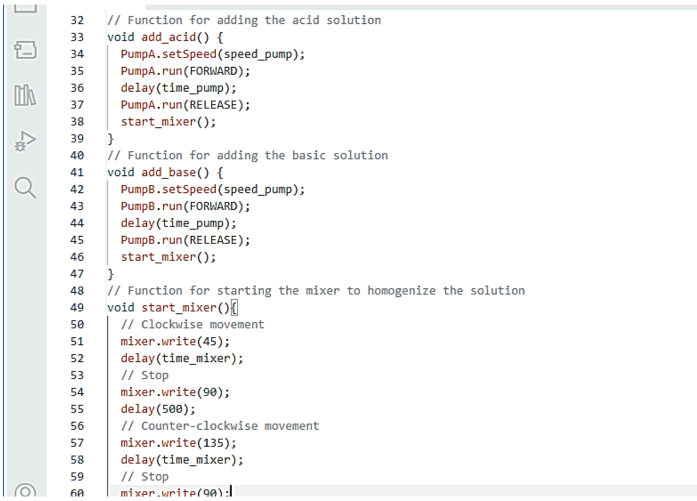


Figure 4. *Application components connection to the Arduino Board*

In Figure 5 is presented a screenshot from Arduino program containing the functions developed for alkaline/acid solution dosage and for starting the mixer for the homogenization of the solution.



```
// Function for adding the acid solution
void add_acid() {
  PumpA.setSpeed(speed_pump);
  PumpA.run(FORWARD);
  delay(time_pump);
  PumpA.run(RELEASE);
  start_mixer();
}
// Function for adding the basic solution
void add_base() {
  PumpB.setSpeed(speed_pump);
  PumpB.run(FORWARD);
  delay(time_pump);
  PumpB.run(RELEASE);
  start_mixer();
}
// Function for starting the mixer to homogenize the solution
void start_mixer(){
  // Clockwise movement
  mixer.write(45);
  delay(time_mixer);
  // Stop
  mixer.write(90);
  delay(500);
  // Counter-clockwise movement
  mixer.write(135);
  delay(time_mixer);
  // Stop
  mixer.write(90);
```

Figure 5. *Screenshot from the Arduino app*

The components used for the development of the proposed device (Figure 6) are: Arduino Uno microcontroller - through which the device is controlled, the L293D motor control board (Shield) - used to secure the connections, servo motor MG996R 13 kg 360 degrees - through which the mixer is activated for solution homogenization, 2 mini aquarium water dosage pumps R385 DC 6-12V - which takes the acid/alkaline solution and transfers it into the mixing-reaction tank, pH meter plus module - which reads the wastewater pH value, connectors, power cable with USB, 12 V power source, mixer, tanks with acid solution (Cola juice), alkaline solution (calcium hydroxide, $Ca(OH)_2$) and wastewater, hoses for transferring solutions, laptop and wooden supports [11, 12]. The engines are powered by a 12V source and the pH-transducer by a USB cable connected to the laptop with a 5V voltage.

Figure 6. *Physical connection of components*

An important aspect in the physical realization of the experiments was the calibration of the pH meter [12, 13]. For this purpose, two buffer solutions of known pH (4.00 and 7.03) were used at a temperature of 20^{o} C. Using the calibration curve from [1], was obtained the formula for determining the pH of a solution according to equation (1).

$$pH\_value = (5 \,/\, 1024.0 * pH\_analog\_val - 3.5468)/(-0.1617) \qquad (1)$$

Several substances of known pH (milk, lemon, sodium bicarbonate, degreaser, coffee, cola, hydrated lime) were used to check the calibration and the values obtained were compared with those resulting from coloring of the indicator paper.

For the implementation of the ES and of the graphical interface, Microsoft Visual Studio 2022 environment was used, where a project was created using the Windows Forms template. The source code was written in C# programming language. Visual Studio allows Arduino to be integrated into the project. Thus, the source code *Doing V04*, developed in Arduino environment, was included in the project named "*Reactants dosing*" (Figure 7).

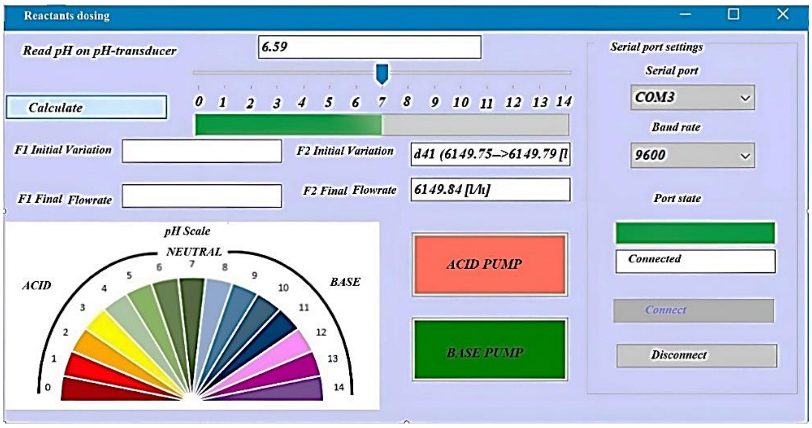


Figure 7. *"Reactants dosing" application interface*

To create the graphical interface (Figure 7), the following elements were used from the application Toolbox: *Button*, *ComboBox*, *Label*, *ProgressBar*, *PictureBox*, *TextBox*, *GroupBox*, *SerialPort* and *Form*. The following graphical interface elements have been inserted from the application toolbox:

- *Form1* named "*Reactants dosing*" representing the form on which the rest of the graphical elements are inserted;
- *Label1* named "*Read pH on pH-transducer*";
- *Label2* named "*F1 Initial Variation*";
- *Label3* named "*F1 Final Flowrate*";
- *Label4* named "*F2 Initial Variation*";
- *Label5* named "*F2 Final Flowrate*";
- *TextBox1* displaying the pH value read from the pH-meter;
- *TextBox2* displaying the initial F_1 variation derived from the imposed rules;
- *TextBox3* displaying the final F_1 flowrate from the required rules;
- *TextBox4* displaying the initial F_2 variation derived from the imposed rules;
- TextBox5 displaying the final F_2 flowrate from the required rules;
- *TrackBar1* and *progressBar1* showing the full pH value measured;
- *Label9-Label23* representing the values on *trackBar1*;
- Button1 called "*Calculate*" which with a simple click causes the change of the progress bar, the track bar, the flowrate variations, the final flowrate and the indication of the operated reactant dosing pump;
- *Button2* and *Button3* named "*Acid Pump*" and "*Base Pump*" whose color changes according to the pump being operated (green color for working dosing pump, red color for turn off pump);

- *PictureBox1* which includes a picture of the pH scale;
- *SerialPort1* which communicates with the physical device;
- *GroupBox1* called *SerialPortSettings* containing: *label6* named "*Serial Port*", *label7* named "*Baud rate*", *label8* named "*Port State*", *comboBox2* is the list box of the baud rate 9600, 38400, 115200, *progressBar2* showing the progress of the connection to the selected serial port, *textBox6* which will be given the value "*Connected/Disconnected*" depending on the status of the port, *button4* named "*Connect*" trough which connects to the selected serial port, *button5* named "*Disconnect*" trough will disconnect the serial port.

The Arduino module of the device works independently from the rest of the application. To describe the functionality of the device, from Microsoft Visual Studio 2022 application is used the Arduino menu bar, were from is selected the serial port to which the Arduino device is connected (in this case COM 3) and the *Monitor Open Serial* button is activated (Figure 8). The *Connect* and the *Start* buttons are actioned to load the application on the Arduino microcontroller. The code is compiled and if there are no errors, it will be automatically loaded on the microcontroller. Finally, the debugger will run and execute the program.

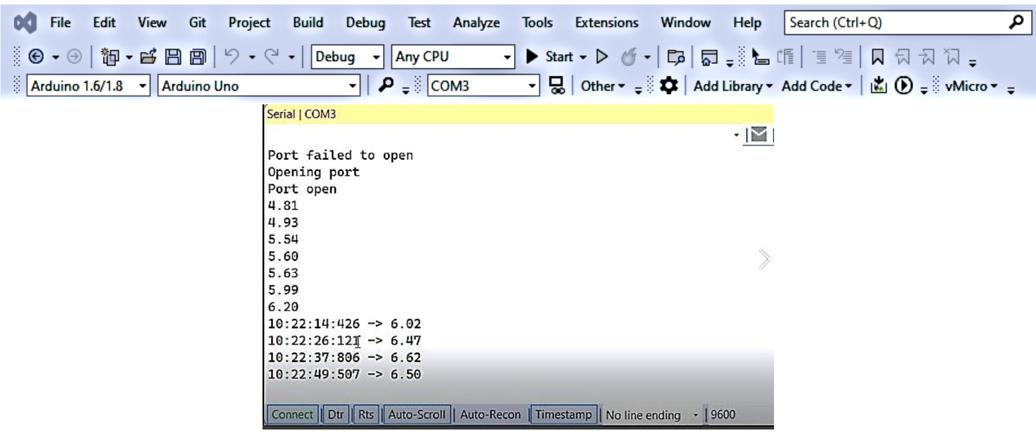


Figure 8. *Connecting the Arduino device*

If the pH value recorded by the pH-meter is less than 6.8 (acid pH) units, it will start both the pump connected to the alkaline solution and the motor driving the mixer. The pump starts for 0.2 seconds. The waiting time is five seconds until the next pH value is recorded, during which the solution in the mixing-reacting basin is homogenized. If the recorded pH is higher than 7.2 (basic pH) units, the pump connected to the acid solution and the motor driving the mixer will start.

By pressing the *Start* button in *Forum1.cs* (developed for design purposes), it is opened the device interface (Figure 7). On the right side of the form, it can be chosen the serial port through which the device is connected to the computer and the baud rate. By pressing the button "*Connect*", the interface is connected to the device. If the serial port is correct, the progress bar is activated and the message box shows "*Connected*". The pH values are automatically taken from the specially designed text box. By pressing the "*Calculate*" button the flowrates values are changed according to the ES rules, the pH value is shown on the progress bar, the tracking bar and is selected the pump being operated. If the "*Disconnect*" button is pressed, the interface is disconnected from the device. If the selected port is not the correct one, an error message will appear.

SIMULATIONS PERFORMED WITH THE DEVELOPED DEVICE FOR WASTEWATER pH CONTROL

In order to demonstrate the correct functioning of the developed device (Figure 6) and to the integrated application that uses IA (ES) (Figure 7), the neutralization of wastewater was studied through a set of simulations. For this purpose, Cola juice with an approximate pH value of 2.5 units was introduced into the acid pH solution from the mixing-reaction tank and hydrated lime ($Ca(OH)_2$) with an approximate pH value of 12 units into the alkaline pH solution tank. Five simulations (Table 2) were performed, three for acid pH solutions and two for basic pH solutions. The initial vessel volume was 750 milliliters (ml). In table 2 were recorded the start time, stop time, initial pH, final pH and final volume of liquid in the vessel. Screenshots from the performed simulations are presented in Figure 9.

Table 2. *Simulations table*

Solution pH type	Simulation no.	Initial pH (units)	Start time (minutes)	Initial volume (ml)	Final pH (units)	Stop time (minutes)	Final volume (ml)
ACID	1	4.81	10:20:24	750	6.90	10:23:01	1125
	2	6.08	10:28:31	750	6.81	10:29:29	800
	3	4.33	11:07:02	750	6.84	11:25:49	1250
BASE	1	9.80	10:41:48	750	7.14	10:52:55	1125
	2	9.01	10:58:15	750	6.93	11:02:46	900

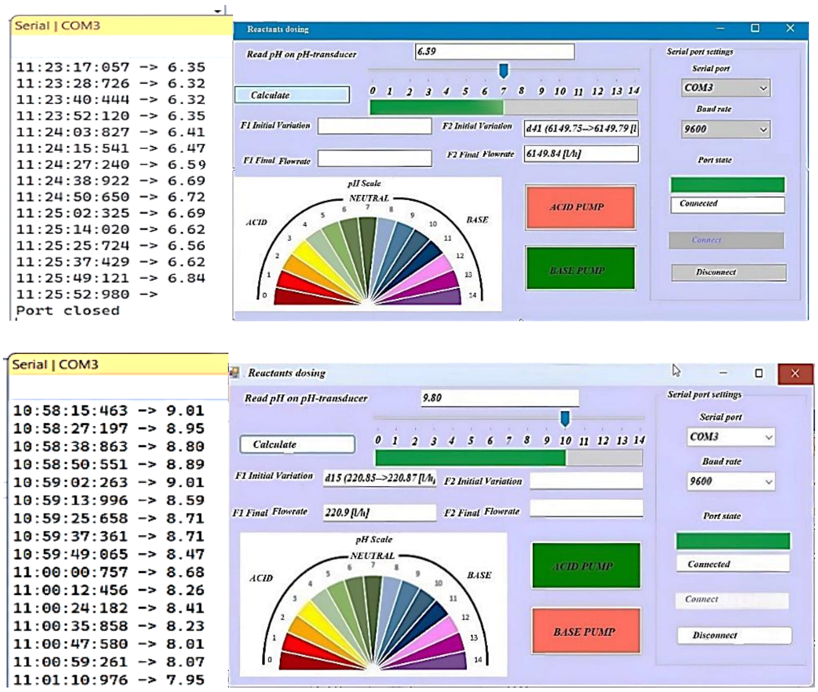


***Figure 9**. Simulations screenshots*

In the simulations carried out, was observed an increase of the time in which the pH neutralizing process was achieved, further the measured pH value was from the reference point [6.8, 7.2] units. An acceleration of the neutralizing process was observed around the area of the set point value.

At the same time, it was observed that the decrease or increase of the measured pH values during the process is not always continuous. Small variations of 0.1-0.2 of the pH value may occur depending on the measurement accuracy of the pH transducer and to the liquid homogenization degree.

CONCLUSIONS

The paper describes the design and the implementation of a device that uses AI techniques (in this case, ES) for dosing the reactants necessary for wastewater pH neutralizing. The device made with Arduino equipment achieves its goal, respectively the wastewater pH neutralizing, being an automatic control system after deviation with a closed structure.

One of the advantages of the developed device is that it can be used in industrial or domestic wastewater treatment plants to neutralize wastewater in accordance with the relevant legislation. The device can be adapted to any application involving pH control. Another advantage of the application is that it can be easily used having a user-friendly, intuitive and easy-to-use interface.

The main disadvantage is the inability to set the pump flowrates used by the device to the values derived from the rules integrated in the expert system. Among the disadvantages is the fact that disturbances (temperature, concentrations, level) were not taken into consideration in the development of the system.

Future research directions involve making improvements to the device meant to eliminate the disadvantages mentioned above:

- the usage of a level sensor within the wastewater tank to avoid exceeding the upper level of the tank;
- a more efficient mixer can be used for the for the homogenization of the solution;
- the use of high flowrate pumps and large vessels;
- integration of various sensors for possible disturbances identification;
- application interface update for the on/off command of the device.

The authors' contributions to this application are:

- development of a device for reactants dosage according to the measured wastewater pH value;
- implementation of the available rules in an expert system (KB and IE development);
- development of an application that integrates AI techniques for dosing the reactants required in wastewater pH control;
- development of an intuitive and user-friendly interface for the reactants dosing application.

In conclusion, the device developed using artificial intelligence techniques (in this case, ES) fulfils its main purpose, respectively the wastewater pH neutralizing through acid or alkaline reagents dosing.

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