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Design and manufacture of TDS measurement and control system for water purification in reverse osmosis by PID fuzzy logic controller with the ability to compensate effects of temperature on measurement

Seyed Kamaleddin MOUSAVI MASHHADI, Hamid YADOLLAHI, Abbas MARVIAN MASHHAD*
Faculty of Electrical Engineering - Iran University of Science and Technology, Tehran, Iran

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Abstract: Measurement and control of TDS (total dissolved solids) of water has significant importance for industry, agriculture, livestock, and health. The system designed and manufactured in this paper measures, displays, and controls the TDS of water by installation on domestic and industrial purification systems. Technology of manufacturing the TDS measurement system is such that it can compensate for the adverse effect of temperature. Calibration of the measurement system will be explained here by discussion of several examinations conducted at the Research Institute of Food Science and Technology of Iran. In order to control TDS, a mathematical model for domestic water purification devices of reverse osmosis (RO) is obtained using practical experiments. Then the controller is designed by Ziegler–Nichols oscillation and fuzzy logic methods and, after the comparison, a fuzzy logic controller is selected because it shows better response. This controller is implemented using regression analysis, which is a very good method for implementation of fuzzy logic controllers. Operation of controlling the TDS is done through real-time and continuous controlling of a mix valve. This valve is closed in parallel with a membrane filter or RO, so one can control TDS by adding or reducing inlet water into the outlet water of this filter. The system proposed in this research is tested in pilot and has received scientific approval from the relevant authorities.

Key words: Temperature turbulence, total dissolved solids measurement, total dissolved solids control, electrical conductivity, fuzzy controller

1. Introduction

Natural water usually contains a great volume of solutes due to its solubility characteristics. CO_2 of air also intensifies the corrosive behavior of water by being solved in water and producing weak carbonic acid. Thus, water solves some of the carbonates passing through different areas, especially the calcic area. These carbonates in combination with some ions such as calcium and magnesium cause temporary water hardness, which can be removed by boiling. However, ions of magnesium, calcium, and other metals that create permanent water hardness with sulfate, nitrate, and chlorine cannot be removed by heating. TDS denotes the total dissolved solids in water and is given in parts per million [1]. A high TDS content of water has detrimental effects including sedimentation and corrosion in thermal equipment and boilers, leaving stains on food products and fabrics, accelerating formation of kidney stones in the body, deteriorating the taste of tea and coffee, long cooking times of beans, and improper foaming of soap thus increasing consumption of it and disturbing hand washing. On the other hands, excessive removal of the dissolved solids in conventional domestic water purification devices

*Correspondence: a.marvian@khorasan.ac.ir

will embitter water and cause osteoporosis, which is known as a silent death. Measurement and control of TDS of water is very important for heath and industry sectors. Reverse osmosis (RO) is used daily for desalination of 100,000 m^3 seawater to make drinking water in Libya [2]. The typical operation and internal structure of the RO filter, which is the most important component of RO water purification systems, was explained in [3] comprehensively. It can be measured in order to control the TDS of water. Generally, this parameter is measured by two methods, by weight and electrical conductivity measurement [4,5]. Furthermore, [4] investigated the relationship between TDS and conductivity of water and presented a relationship that shows that TDS of water could be obtained using electrical conductivity and coefficient ke. Studies and research in [6] on the freshwater of the Indian Red Hills area to obtain the relationship between TDS and conductivity were carried out. Electrical conductivity is shown in microsiemens (μS). The experiments in [7] were performed to show the variation of electrical conductivity with temperature based on a mathematical relationship between electrical conductivity and temperature, which decreased the effect of temperature on the electrical conductivity of water.

There are several methods to control different industrial systems and processes, which were discussed in [8]. Moreover, in [9,10], accuracy of the mathematical estimation model from a RO desalination unit was investigated using feedback/feedforward techniques. The quality index of water for the Karoon River (Khuzestan, Iran), mainly including values of dissolved oxygen, TDS, opacity, nitrate, and PH, was also determined by fuzzy logic and reported quantitatively to users [11].

In this paper an innovative approach for the design and manufacture of EC measurement of water is introduced and multiple experiments show the accuracy of performance. Because of the structure of the designed sensor, it is possible to achieve the 0.5 percentage resolutions in small intervals.

The following text will mention operation of RO water purification systems. Then a brief introduction will be presented about manufacturing technology of TDS measurement and compensating the effect of temperature turbulence. Afterwards, testing and calibration of measurement systems will be assessed. The mathematical model of domestic RO purification devices will be extracted from experimental results. TDS of the outlet water will be controlled in water purification devices. With this purpose, classic PID and PID fuzzy logic controllers [12] are used. After the comparison of these controllers, because of the advantages of the PID fuzzy logic controller we select this method. We use regression analysis as the implementation method of the designed fuzzy controller. Finally, manufacturing, testing, and practical evaluation of TDS measurement and controlling systems are investigated along with scientific approval and applications in industry and health.

2. Mechanism of RO purification systems

Several filters are used in RO purification devices. The number and type of filters depend on the properties of water in that region and its application. Final filters are more accurate than initial filters, such that coarser particles are removed at the beginning while finer ones are removed at the end of purification. The RO filter is one of the initial filters in which a semipermeable membrane is devised to eliminate major chemicals and pollutants of water in addition to separate large-sized impurity particles (Figure 1). The TDS value of outlet water for this filter is about 20 ppm. It means that the content of elements in water like Ca, F, K, and fibers is decreased significantly, so the taste of natural water becomes bitter, the drinking of which is not recommended by physicians. It should be noted that the allowable concentration in drinking water is less than 300 ppm.

A mix valve is used to solve this problem and to control TDS value of the outlet water within the desired range. This valve is put parallel with the RO filter so it can be manually adjusted to add some amounts of the inlet water with greater solutes to the outlet water. Thereby, the TDS in the water leaving the system will reach the desired limit for users. However, due to high pressure of the water at the inlet of the mix valve and RO filter, small changes in the mix valve by the operator will lead to large variations in the TDS of water at the outlet of purification devices. Meanwhile, manual control of TDS is almost impossible in these devices because of the large inherent delay in them. Considering the inexistence of compensation technology for the effect of temperature turbulence in conventional TDS measurement sensors, the error arising from this turbulence will directly affect manual control of TDS.

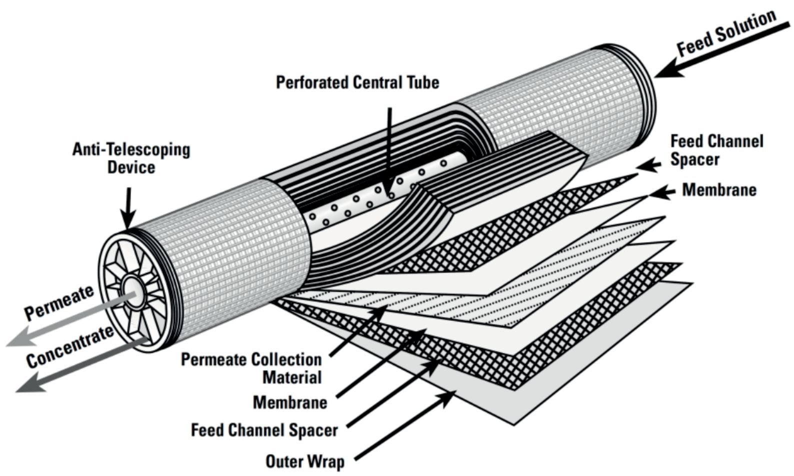


Figure 1. Schematic view of different layers in a typical RO filter.

For solving this problem in measurement, it has been tried to improve accuracy using compensation technology on the effect of temperature turbulence. Furthermore, the TDS value of the outlet water is determined and then displayed by real-time and continuous measurement. It would be possible to control the amount of solutes in the outlet water by having the exact TDS value and also proper design of the controller. Validity of system performance is determined and calibration is done scientifically in laboratories approved by the Ministry of Science of Iran.

The configuration and operation of the RO purification devices have been depicted in Figure 2 in combination with the structure proposed in this study.

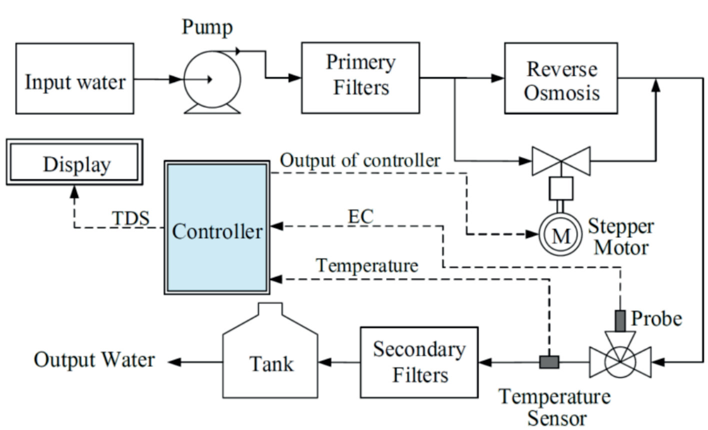


Figure 2. Schematic view of the system suggested for measurement and control of TDS by elimination of adverse temperature effects.

It can be observed in Figure 2 that the secondary filters are located close to storage tanks of water. A mineral filter is one of them, which is responsible for adding the required minerals to the water. Meanwhile, UV (ultraviolet) filters can be devised here to remove the remaining viruses and bacteria.

3. Measuring the TDS of water

Measuring the TDS of water with weight (gravimetric TDS) and electrical conductivity (EC) methods is possible. Practically, the major difference between these two methods is very important. Thus, the weight method is fully experimental and in the continuous control of industrial processes it does not have any applications. However, the electrical conductivity method, due to the high speed of its response, plays an important role in the control loops. Each of these methods is briefly described below.

3.1. Weight method for measurement of the TDS of water

This measurement method is based on the accurate measurement of the total weight of dissolved substances in a certain volume of water. Considering the fact that the amount of value of the material is less than 0.45 μm, it must pass water through the filters with the same size to remove impurities. Then, according to standards, 200 mL of this solution is poured into a beaker and heated for 24 h at a temperature 105 $^\circ C$ until completely evaporated. In addition, to remain dry it should be put for another 2 h at 180 $^\circ$C. Finally, the weight of the material must be measured with high precision using Eq. (1).

$$TDS(mg/L) = \frac{(W_2 - W_1) \times 1000}{V} \tag{1}$$

In Eq. (1), W_1 (mg) is beaker weight before heating and W_2 (mg) is beaker weight and remaining dried material after heating, and V (mL) shows the water purification volume [4,5].

3.2. TDS measurement using EC of water method

Another way to measure the TDS of water is to calculate the EC of water. The correlation between TDS and EC for water is given by Eq. (2).

$$TDS = EC\,[\mu s] \times K_e \tag{2}$$

Substituting the K_e coefficient as a constant in the range of 0.55–0.8, which is determined according to water properties for the area under study in chemical laboratories, and having the EC of water will lead one to obtain the TDS [2]. For example, the K_e coefficient was found based on 24 samples from drinking water of the Red Hills region of India (Figure 3). Results of this experiment yield 0.6507 as the best value for the K_e coefficient in this area. It must be noted that the K_e coefficient was assumed as 0.55 in all tests of the current work based on the regional water of Mashhad, Iran.

3.3. Building a sensor for EC measurement

In order to measure the EC of water in the invented system, a probe is needed to be designed and made that provides the ability to be simply installed on a T-joint in addition to being waterproof and resistant against corrosion. It would be possible to measure the EC of water in real time and continuously by installing this probe through the outlet stream of water leaving the membrane filter, exactly where the outlet water is being mixed with that of mix valve.

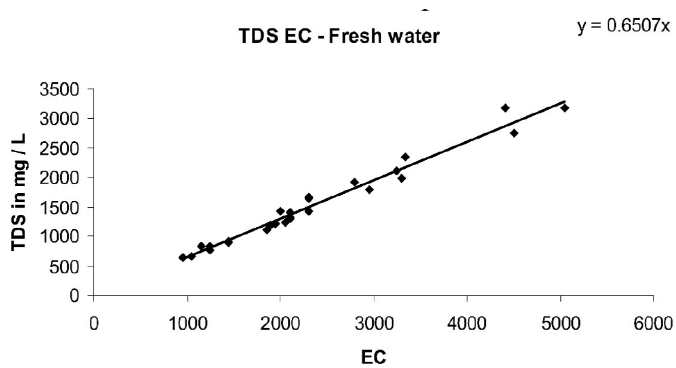


Figure 3. Results of 24 drinking water samples for finding K_e coefficient [3].

Conductors used in this probe are made of stainless steel. Selection of this material for the conductors is due to its resistance against corrosion and its immiscibility with oxygen. The whole set of these steel conductors is put inside a Teflon sleeve. Teflon is selected here because of its insulator behavior against electric current. This sleeve is manufactured by machining in CNC machines. A schematic view of the probe made is presented in Figure 4.

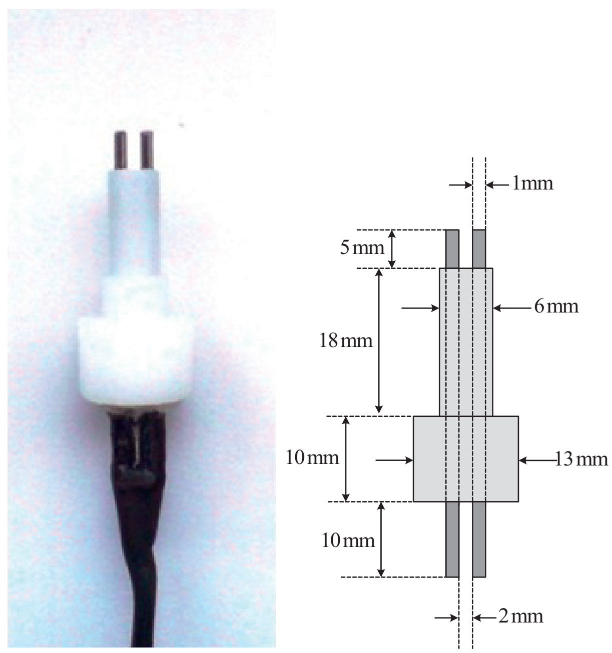


Figure 4. Front view of the probe made (left) with its technical drawing (right).

A small current is applied at two contacts of the probe by making an alternative sine electrical signal at a constant frequency of 1–10 kHz with amplitude 10 Vp-p and then introducing it into the circuit of Figure 5. Thereby, voltage of these two contacts will vary by changing the EC of water there. Having formed the following circuit, Eqs. (3) and (4) can be used to yield the EC of water.

The equations below are obtained from analysis of Figure 5.

$$R_1V_2 + R_2V_2 = R_2V_1 \tag{3}$$

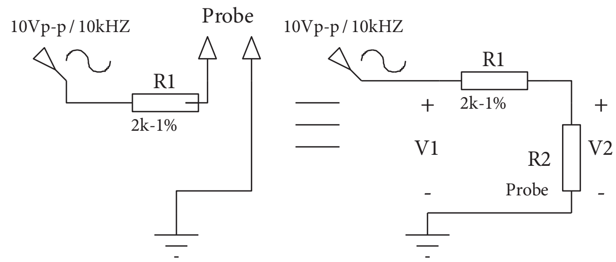


Figure 5. Main circuit for EC measurement of water.

Eq. (3) is applied to give the following.

$$R_2 \times |V_1 - V_2| = R_1 V_2 \tag{4}$$

Resistance at two contacts of the probe (R_2) is generated by measuring the voltage at two contacts of the constant resistance (R_1) and then substitution of it into Eq. (4). Measurement of this voltage is important for increasing the reliability of system. Therefore, no change will occur in the measurement of R_2 by any variation in the output voltage of the supply source. Inverse R_2 is the same as electrical conductivity at two contacts of the probe. The amount of R_1 is specified in Eq. (4) with its determination being dependent on the type of system. If the range of TDS measurement is limited, selecting the value of R_1 will have great importance. In order to achieve the best precision, R_1 and R_2 resistors should be equal, but in practice the exact amount of measured dissolved concentration is not known. However, we know the range of changes in TDS of water. Therefore, if the lower and upper bounds of water concentration corresponding shown with $TDS_{\min}$ show it as $TDS_{\max}$, α is the average concentration measured in the range of Eq. (5) and obtained as follows.

$$\alpha = \frac{TDS_{\min} + TDS_{\max}}{2} \tag{5}$$

We must determine the value of resistor R_1 taking into consideration the α point. Therefore, from Eq. (2), assuming $K_e = 0.55$, we have the following.

$$TDS = \frac{10^6}{R_2}[\mu S] \times 0.55 \tag{6}$$

The best value for resistor R_1 is thus calculated as follows.

$$R_1[\Omega] = \frac{0.55 \times 10^6}{\alpha} \tag{7}$$

A parallel resistance network having n resistances and $R_1\times$ n size can be utilized instead of a single resistance R_1 in order to enhance accuracy of the measurements. Moreover, all resistances of this network must be selected from military grade to achieve higher accuracy.

Chips of the RMS to DC convertor were used for measurement and analysis of the alternative sine voltage in R_1 and V_{R1} resistances by system processor. These chips convert the effective amount of sine signals to DC signals, which are measurable by A/D unit of microcontroller. A block diagram for preparation of the signal is depicted in Figure 6. Signals V_{R1} and V_{R2} are buffered first by op-amp circuits and become ready for analysis after conversion of them to DC signals and passing them through a low-pass filter. The level of the output voltage for this sensor is 0–5 V DC, while a PIC microcontroller (model 16F877A) is utilized to convert this analog signal to digital in addition to analyzing and evaluating them.

The TDS measurement system is quite innovative as it is designed and manufactured. Ability to achieve high precision in small intervals is important because many applications in power plants, refineries, and petrochemical plants need this precision.

4. Calibration of the constructed EC sensor

To ensure correct performance of the EC measurement system of water and also to calibrate the sensor designed and manufactured, some experiments were launched at the Research Institute for Food Science and Technology. For more accurate tests, one would need numerous samples of water with different concentrations. Therefore, the standard solution having concentration of 1000 ppm was diluted by adding distilled water in 33 steps. A higher number of these steps causes more accurate calibration. It should be noted that the temperature of water was kept constant at 25 °C during all experiments. Based on the experiments done, diagrams in Figure 7 depict the response of the TDS measurement system designed and manufactured here in comparison with the standard measurement apparatus of the Research Institute for Food Science and Technology (Conductivity/Temp/TDS Model 8302).

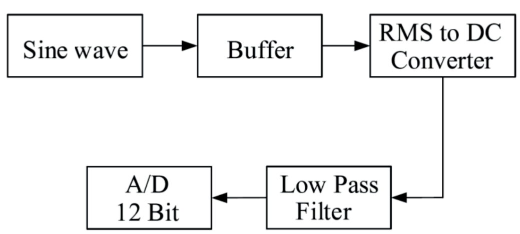


Figure 6. Block diagram of preparation steps of signal for measurement in the proposed system.

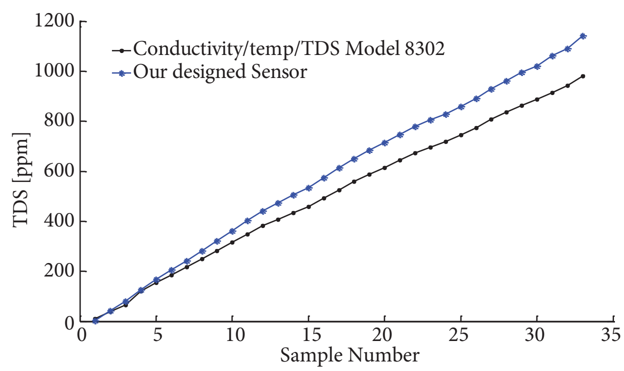


Figure 7. Illustration of outlet response for TDS measurement in the system designed and manufactured (blue curve with • points) versus that of standard apparatus (black curve with * points).

By looking at Figure 7 one can easily discover that outlet response of the designed measurement system has negligible error compared with that of the reference measurement apparatus. However, even this small amount of error can be modified by changing the equation of the curve in the system designed by software to improve accuracy of the outlet responses. The equation required for this modification of behavior is obtained using MATLAB software with numerical methods as discussed below.

$$Y = A_1 \times \sin(\omega_1 x + \alpha_1) + A_2 \times \sin(\omega_2 x + \alpha_2) + A_3 \times \sin(\omega_3 x + \alpha_3) + A_4 \times \sin(\omega_4 x + \alpha_4) \qquad (8)$$

A1 to A4, $\alpha 1$ to $\alpha 4$, and $\omega 1$ to $\omega 4$ are constant coefficients in Eq. (8), the values of which are listed in Table 1. Meanwhile, x represents the outlet response of the measurement system designed for different concentrations of water, and Y gives the modified outlet in accordance with the reference sensor. Thereby, error of measurement is refined by the software and the outlets from both systems will fit one another. Now their behaviors are examined once again in Figure 8 in order to investigate the validity of fitting the outlet responses by these two systems.

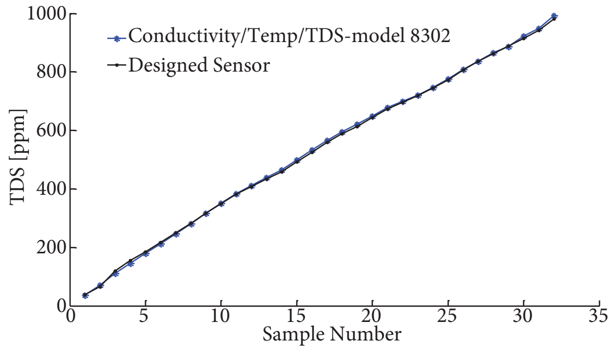


Figure 8. Comparison between the responses of designed and manufactured measurement system (blue curve with • points) and those of standard apparatus (black curve with * points) after running calibration operations using curve fitting tool.

Table 1. Constant coefficients of Eq. (8).

Constants	
$A_1 = 3064$	$A_3 = 1.543$
$\alpha_1 = -0.2052$	$\alpha_3 = 4.355$
$\omega_1 = 0.00182$	$\omega_3 = 0.01102$
$A_2 = 2255$	$A_4 = 0.6312$
$\alpha_2 = 2.86$	$\alpha_4 = -2.96$
$\omega_2 = 0.002085$	$\omega_4 = 0.02329$

As evident from Figure 8, the formula introduced in Eq. (8) leads to fitting the responses from the designed measurement systems onto those from the reference sensor.

5. Compensation of temperature turbulence in EC measurement

Since changing the temperature will cause errors in EC measurement, temperature turbulence must be compensated to properly measure and control the TDS of water.

In TDS measurement through determination of EC, variations of water temperature will alter the EC at probe contacts such that EC will increase at higher temperatures and decrease at lower temperatures. It should be noted that the TDS of water does not change by variations in temperature and remains unchanged. However, EC at probe contacts is raised due to increased speed of existing ions in water, and as a result, the measurement will contain some error. Figure 9 depicts variations of EC versus temperature.

6. Analytic theory for compensating the effect of temperature on EC measurement

To solve this problem in the designed system, EC and temperature of water can be measured precisely and then substituted into Eq. (6), in order to compensate the error arising due to the effect of temperature on the EC of water [4].

$$EC_T = EC_{25}\left[1 + \beta(T - 25)\right] \tag{9}$$

In Eq. (6), EC_T represents the measured EC of water at T temperature, while EC_{25} is its EC at 25 °C. In this equation β is a constant coefficient between 0.0175 and 0.0198, which differs depending on the existing solutes in water although the best value of it can be extracted by running tests several times. For example, by choosing $\beta = 0.0187$ the measurement error of EC at temperatures 10 and 25 °C for a specific region is lower than 2%.

7. Hardware implementation of the compensation theory for the effect of temperature

An SMT160-30 sensor with 0.7 °C accuracy and resolution limit of 0.005 °C was utilized in the system designed and manufactured for measuring temperature of water. Having measured EC and temperature of water and having built Eq. (6) into the microcontroller, this technique was implemented. Furthermore, a PT_{100} sensor was used to achieve higher accuracy.

In order to understand how temperature affects the designed system, some experiments are executed as discussed below. First, the temperature of a solution with 473.5 ppm concentration is raised to 52 °C, and then the TDS of water is recorded in 28 steps when the water is being cooled down. Figure 10 illustrates these experiments. It should be noted that coefficient β was considered as 0.0187 in all of these tests.

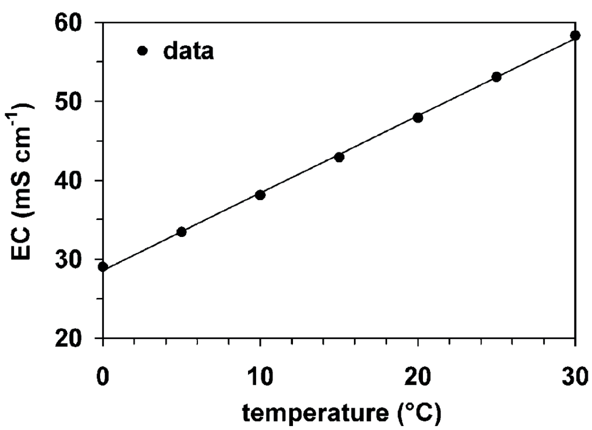


Figure 9. EC changes according to temperature changes [6].

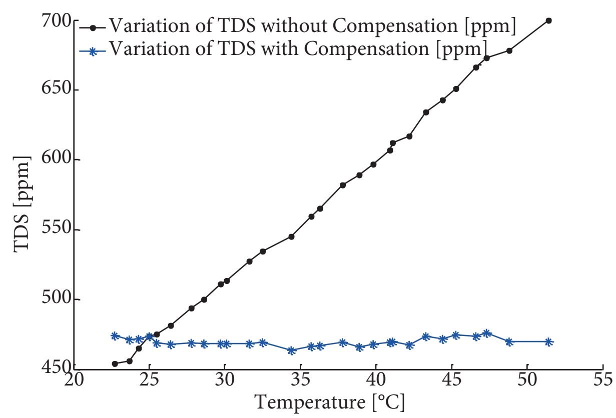


Figure 10. Variations of TDS in terms of temperature for water with technology to compensate for the effect of temperature (blue curve with * points) and without it (black curve with • points).

The black curve (•) in Figure 10 shows variations of TDS versus temperature. It can be observed that in the measurement system equipped with temperature compensation, raising the temperature has intensified EC, which can lead to incorrect increases in the TDS of water. However, the blue curve (*) is associated with the measurement system developed in this research, which has utilized the technology of temperature compensation and provides an acceptable resistance against changes in the temperature of water.

8. Modeling of RO water purification apparatuses

Having designed and manufactured the sensor for TDS measurement and having compensated the effect of temperature on it, one should control the TDS now. In order to properly control the TDS of water, the modeling of RO water purification apparatuses must be explored first. There are different techniques to identify the model of system. However, a Ziegler–Nichols open loop is utilized here to determine the mathematical modeling of these apparatuses. For this purpose, an acceptable estimation of their model is extracted by running several tests in practice.

In this regard, the probe of the designed sensor is first installed on the way of the outlet RO filter and mix valve. The outlet of the sensor is connected to a computer using a digital oscilloscope (TNM ELECTRPONICS, Model 20080A) with a sampling rate of 80 MS/s. Thereby, all samples obtained will be stored in a text file. Afterwards, the mix valve is opened just 1% in order to apply a step input to the system and variations of TDS in the outlet water are recorded. A voltage equal to 0.1 V is introduced for opening the valve 1% due to using a 0–10 V range control valve with the linear performance as the mix valve. This experiment is conducted at 25 °C.

Data processing was rather extensive and time-consuming in MATLAB software because of the great number of samples. Thus, the average of each 10 samples was found and stored by statistical techniques. Then data preparation and processing were implemented on this set of new samples.

Figure 11 illustrates the open loop behavior of a typical RO water purification apparatus for the command of 1% opened mix valve. It should be noted that the inlet and outlet of the system are the same as the voltage applied to the control valve and the TDS of water that leaves the RO purification apparatus, respectively.

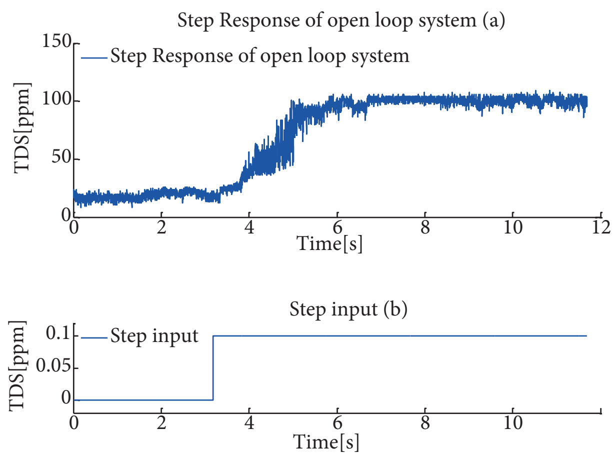


Figure 11. Open loop behavior of the RO water purification apparatus at 25 °C (a); 1% change in the control (mix) valve as the step input (b).

Severe distortion observed in the curve is not due to the measured noise in sensors. The TDS and process behavior changes also fundamentally are not abrupt. The cause of these changes is only the low-resolution oscilloscope card of the TNM Company. It is equipped with 8-bit resolution compared with the 10-bit designed measurement system for the TDS, so then accuracy is reduced 3.99 times. Therefore, the observed noise is very low and it is negligible in practice.

After extracting the reaction process curve of the open loop system, the quadratic approximate model of the process is determined. For this purpose, the System Identification tool in the toolbox menu of MATLAB software is used and the transfer function of the system model is approximated as in Eq. (7) using the data collected from experiments.

$$G(s) = \frac{823.71}{0.7316s^2 + 1.2021s + 1} \times e^{-0.0070017S} \tag{10}$$

To ensure validity of the approximate model, its step response is compared with the real behavior of the RO water purification apparatus (Figure 12).

It can be seen that the step response of the obtained approximate model predicts behavior of the water purification apparatus accurately upon changes in the mix valve.

9. Design of controlling the system for the TDS of water

Now it seems possible to design an appropriate controller based on the model of the RO water purification system. The current work has focused on designing classic P, PI, and PID and also PID fuzzy logic controllers. In order to choose the most appropriate controller, design of P, PI, and PID controllers is conducted by Ziegler–Nichols step response method. Then the best performance qualities of these controllers will be compared with the PID fuzzy logic controller to find the most appropriate method and controller.

9.1. Design of system controller by Ziegler–Nichols step response method

In this method, two parameters are used to determine system characteristics. The maximum slope of the curve plotting the step response parameters, as shown in Figure 13, is obtained.

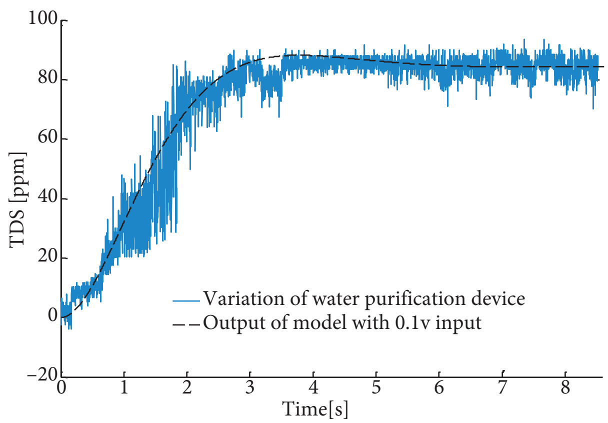


Figure 12. Comparison between the model developed and the real behavior of a typical RO water purification apparatus.

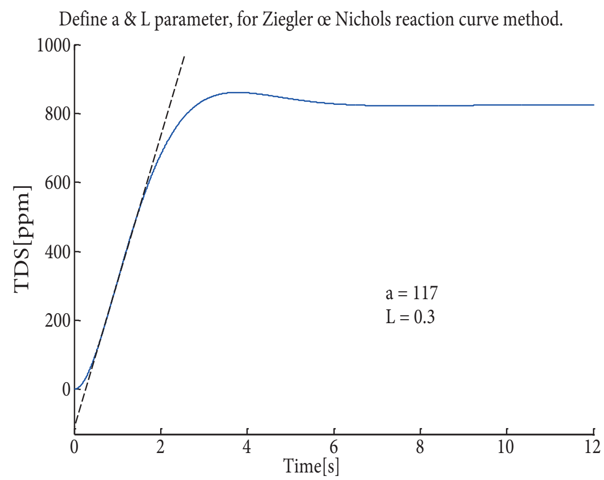


Figure 13. Determination of Tu parameter in Ziegler–Nichols frequency method for unit input of reference and controller output.

According to Figure 13, $a = 117$ and $L = 0.3$. The step response method for PID controller parameters is shown in Table 2.

Table 2. Parameters of PID controller in Ziegler–Nichols frequency method.

Controller	K	T_i	T_d
P	1/a	-	-
PI	0.9/a	3L	-
PID	1.2/a	2L	L/2

With parameters a and L and Table 2, the coefficients can be calculated. In Table 3, the coefficients in the control system for all types of P, PI, and PID are shown.

Table 3. Controller parameters of PID in Ziegler–Nichols frequency method.

Controller	Proportional	Integral	Derivative
P	0.0085	-	-
PI	0.0077	0.0085	-
PID	0.0103	0.0171	0.0015

In order to compare the behavior of the controllers, they are simulated in MATLAB software like in Figure 14.

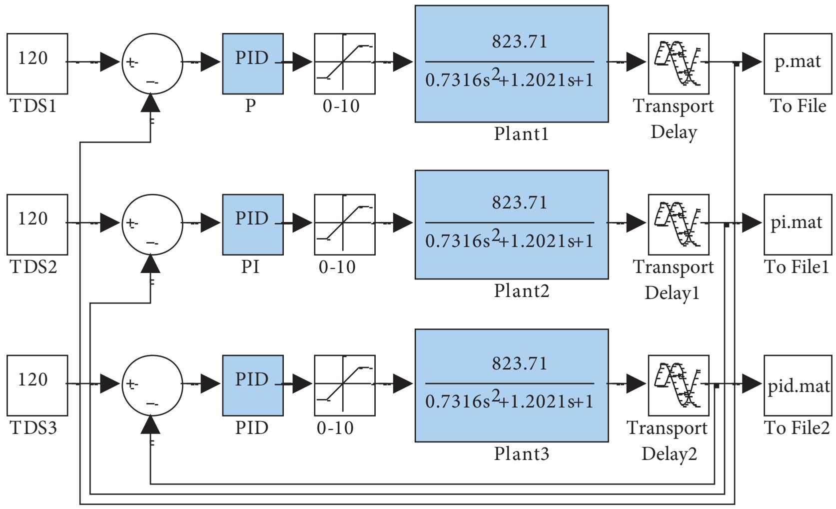


Figure 14. Simulation of the system controllers P, PI, and PID in the MATLAB Simulink environment.

As can be seen in Figure 15, the response of the PID controller is much better than that of the other controllers, but given the volatility, in order to improve the response of the system we manually adjust the coefficients (Figure 16). After implementation, it is shown that P and I values must be adjusted to reduce volatility. Under the new exhaust system with coefficients P = 0.0068 and I = 0.004, comparison with PID step response shows the technique.

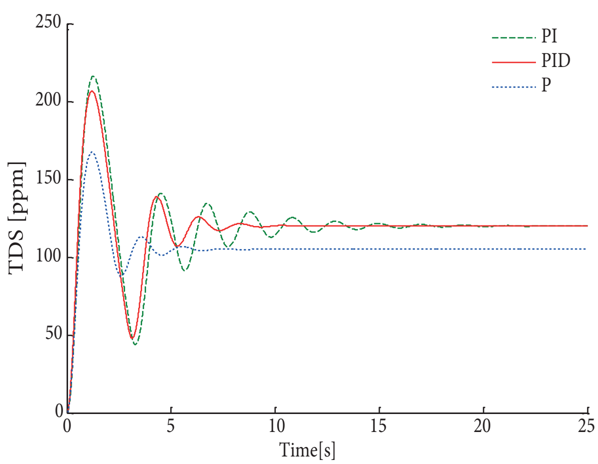


Figure 15. Behavior of water treatment systems with controllers P, PI, and PID step response method designed for Ziegler–Nichols with an ideal input for 120 ppm.

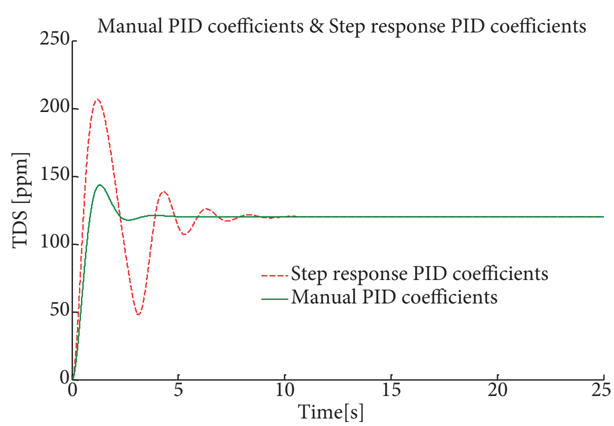


Figure 16. Comparison of the output response of the system with PID coefficients obtained from the step response using Ziegler–Nichols, ideal for TDS 120 ppm.

After selecting the most appropriate controller, it will be implemented in practice. Figure 17 depicts how the system of the controller works.

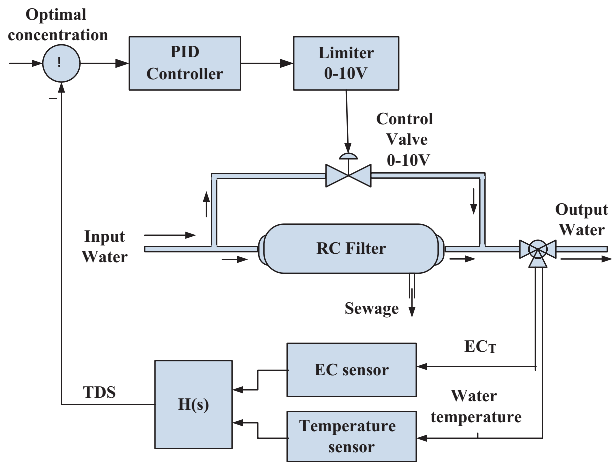


Figure 17. Implementation of TDS controller with classic PID (designed by Ziegler–Nichols frequency method) in RO water purification apparatuses.

In order to compensate for the effects of temperature turbulence on measurement of EC at the outlet of the purification apparatus and also to measure $EC_T[\mu s]$, temperature is represented as $T[^{\circ}c]$ and entered into the H(S) block. This block gives the compensated TDS of water at its outlet in ppm by Eq. (11).

$$TDS = \frac{EC_T \times K_e}{[1 + \beta(T - 25)]} \tag{11}$$

Location of installation of the sensors is an important issue that has significant importance for improving compensation of the temperature turbulence in practice. Thereby, the temperature sensor must be installed as close as possible to the EC sensor such that the measured EC at probe contacts would become proportional to the temperature of water at the same point.

9.2. Design of system controller by PID fuzzy logic method

Fuzzy rules are dependent on human science. Controllers designed based on these rules have much higher performance and reliability due to application of human experiences in their determination. Capability of the system to be developed in the future by increasing the controller inputs is another advantage of these controllers over others. In this case, just if-then rules must be modified, whereas classic control methods need more time and greater cost. These if-then rules that describe the behavior of the system are usually defined as below:

If (a set of conditions are satisfactory), then (a set of outputs can be inferred).

Therefore, such controllers are utilized to improve TDS control quality of water in domestic and industrial RO water purification systems. System response time and improved steady-state error are two basic factors in designing this controller. Now system response time to a reference input is improved by application of error and its rate of variations as the fuzzy controller inputs. Meanwhile, it is possible to reduce persistent error at the controller output by summation of signals from integration and multiplication terms. Figure 18 depicts the strategy of the PID fuzzy controller used in this paper to control the TDS of water.

In this strategy triangular membership functions with uniform distribution are used to make the input values fuzzy. For inference of rules in the fuzzy controller, the sum-product method [13] has been employed, while defuzzification techniques have been used on center of mass and triangular membership functions to obtain crisp values at the controller output. In this regard, Figures 19 and 20 illustrate the error membership function for the first fuzzy controller input and membership function of the rate of error variations for its second input, respectively.

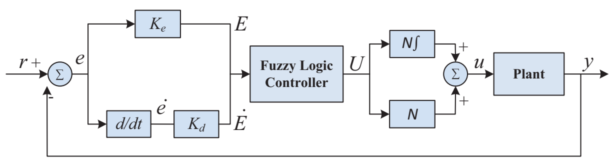


Figure 18. Strategy of PID fuzzy controller designed for controlling TDS of water [12].

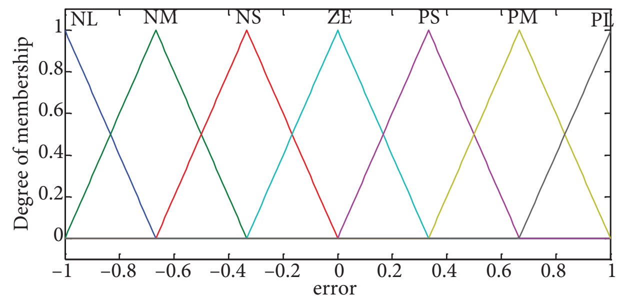


Figure 19. Membership function of the first input (error).

Moreover, the membership function of the fuzzy controller output is shown in Figure 21 for the system designed and prepared. These functions assign a degree of membership to every value of the input. Membership degrees of these functions are extracted according to the rules of Table 4 and the inference method used for the controller.

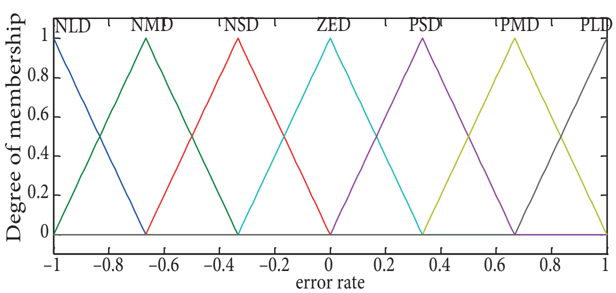


Figure 20. Membership function of the second input (error derivative).

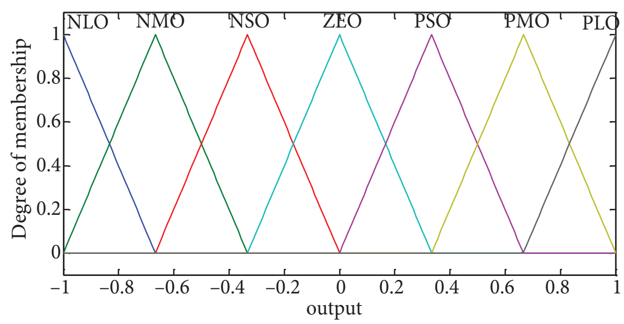


Figure 21. Output membership function.

Table 4. Rule bank.

e / Δe	PL	PM	PS	ZE	NS	NM	NL
NLD	ZEO	NSO	NMO	NLO	NLO	NLO	NLO
NMD	PSO	ZEO	NSO	NMO	NLO	NLO	NLO
NSD	PMO	PSO	ZEO	NSO	NMO	NLO	NLO
ZED	PLO	PMO	PSO	ZEO	NSO	NMO	NLO
PSD	PLO	PLO	PMO	PSO	ZEO	NSO	NMO
PMD	PLO	PLO	PLO	PMO	PSO	ZEO	NSO
PLD	PLO	PLO	PLO	PLO	PMO	PSO	ZEO

As can be seen in Figure 21, the triangular membership functions used in this system are uniform and symmetric. They accelerate evaluation of the next moment membership degree, which is calculated using final points of the membership functions. This property makes the processor not need to store all values of the sample from the membership functions.

Because of the wide range of TDS variations in the reference input, the values of error and its derivative cover a large range. Therefore, the range defined for these membership functions are considered as normalized in order to avoid increasing of the number of input/output membership functions and as a result further complexity of the rules. Definition of the membership function remains constant within a range of –1 to +1 for variations of the desired value. In this case, output signal of the controller becomes smaller in order to reach the desired response.

The fuzzy controller is called normalized when the definition of the input/output membership functions is limited to the range of –1 to +1.

Nomenclatures used in the input membership functions of the controller (including error and error derivative) as well as its output are summarized in Tables 5–7.

Table 5. Membership functions of the first input (error).

NL	Negative large
NM	Negative medium
NS	Negative small
ZE	Zero
PS	Positive small
PM	Positive medium
PL	Positive large

Table 6. Membership functions of the second input (error derivative).

NLD	Negative large
NMD	Negative medium
NSD	Negative small
ZED	Zero
PSD	Positive small
PMD	Positive medium
PLD	Positive large

Table 7. Output membership functions.

NLO	Negative large
NMO	Negative medium output
NSO	Negative small output
ZEO	Zero output
PSO	Positive small output
PMO	Positive medium output
PLO	Positive large

A control valve with input range of 0–10 V is used as the mix valve in the system designed and prepared. Thus, the required voltage is supplied for the operator by scaling the controller output within the range of 0 to 10. The correlations between inputs and output, which are determined by if-then rules, are demonstrated using the control level.

These rules written for the designed fuzzy controller have good harmony. Therefore, it can be observed in Figure 22 that the control level obtained from these rules is symmetric with no irregularity.

9.3. Implementation of designed PID fuzzy logic controller using regression analysis

Regression analysis is one of the best and most economic methods for implementation of fuzzy controllers in practice. One would need fuzzy microcontrollers for implementing the fuzzy controllers in various industries. However, application of these microcontrollers incorporates heavy costs, such that regression analysis is often utilized for implementation of the fuzzy controller. An equivalent polynomial is obtained by using this method instead of the fuzzy controllers. This polynomial estimates the control level determined from the fuzzy controller at an acceptable error. Eq. (12) shows the polynomial extracted from this method.

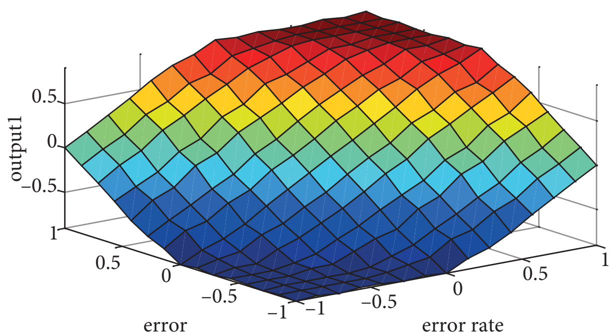


Figure 22. Fuzzy level indicative of the correlations between inputs and output.

$$\begin{aligned} f(x,y) = {} & p_0 + p_1 \times x + p_2 \times y + p_3 \times x^2 + p_4 \times xy + p_5 \times y^2 + p_6 \times x^3 + p_7 \times x^2 \times y \\ & + p_8 \times x \times y^2 + p_9 \times y^3 + p_{10} \times x^4 + p_{11} x^3 y + p_{12} \times x^2 \times y^2 + p_{13} \times x \times y^3 + p_{14} \times y^4 \\ & + p_{15} \times x^5 + p_{16} \times x^4 \times y + p_{17} \times x^3 \times y^2 + p_{18} \times x^2 \times y^3 + p_{19} \times x \times y^4 + p_{20} \times y^5 \end{aligned} \quad (12)$$

Root mean square error (RMSE) in the polynomials of Eq. (12) was just 0.0247. This considerably small error content implies an appropriate performance of the regression analysis in implementation of the fuzzy controller.

Figure 23 depicts the control surface of the polynomials obtained from regression. As we can see, lots of points fit on the fuzzy surface with small error.

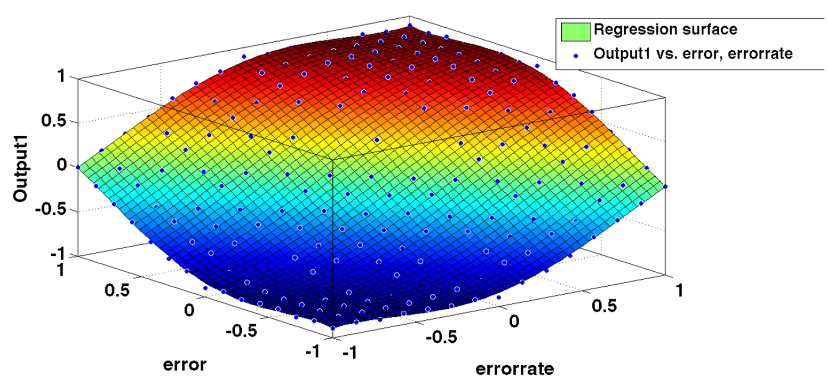


Figure 23. Resultant surface from drawing the polynomials obtained from regression.

Furthermore, coefficients of the polynomial of Eq. (12) coming from regression analysis using the Carve Fitting Toolbox in MATLAB are listed in Table 8.

Table 8. Coefficients of the polynomial obtained from regression.

P0 = 0.0098	P1 = 1.075	P2 = 1.075
P3 = 0.0063	P4 = 0.01002	P5 = 0.0063
P6 = –0.3541	P7 = –0.7955	P8 = –0.7955
P9 = –0.3541	P10 = –0.0045	P11 = –0.003
P12 = –0.0041	P13 = 0.0034481	P14 = 0.004501
P15 = –0.1291	P16 = –0.1684	P17 = 0.229
P18 = 0.229	P19 = 0.1684	P20 = 0.1291

Finding the response of the controller to the designed PID fuzzy method requires its implementation. Output control signal of the fuzzy controller is calculated as in Eq. (13).

$$u = \alpha U + \beta \int U dt \tag{13}$$

At the same time, Eq. (14) is relevant among input and output variables of the fuzzy controller [13].

$$U = A + PE + D\dot{E} \tag{14}$$

Here, E and $\dot{E}$ are defined as follows:

$$E = K_e.e \tag{15}$$

$$\dot{E} = K_d.\dot{e} \tag{16}$$

Thus, the following equation would be produced taking into account Eqs. (13)–(16).

$$u = \alpha A + \beta At + \alpha K_e Pe + \beta K_d De + \beta K_e P \int edt + \alpha K_d D\dot{e} \tag{17}$$

As a result, equivalent components of the PID fuzzy controller are found as listed in Table 9.

Table 9. Equivalent components of the fuzzy controller in the PID controller.

K_e	K_d	a	β
0.00495	0.008	0.04505	1.201

It is well known that proportional gain is increased when the system response is not quick enough. Derivative gain can prevent occurrence of overshoot and limit oscillations due to prediction of the future behavior. Although integral gain leads to removal of the steady-state error, it can also raise both the oscillations and overshoot as well.

The gain values can now be determined according to Table 10 in order to achieve the desired response of the designed and prepared PID fuzzy controller.

Table 10. Coefficients of the PID fuzzy controller.

Type of gain	Gain
Proportional	$\alpha K_e P + \beta K_d D$
Integration	$\beta K_e P$
Derivative	$\alpha K_d D$

9.4. Comparing responses of classic PID and PID fuzzy controllers

In order to make the most appropriate selection of the controllers, system response to classic and PID fuzzy controllers was assessed. As evident from Figure 24, performance of the fuzzy controller is very acceptable in comparison with the classical PID controller, which was manually configured. The maximum overshoot in this controller reaches 1.66%, while this amount is reported to be 25% average for the classic PID. Meanwhile, settlement time is almost the same for both controllers (4 s).

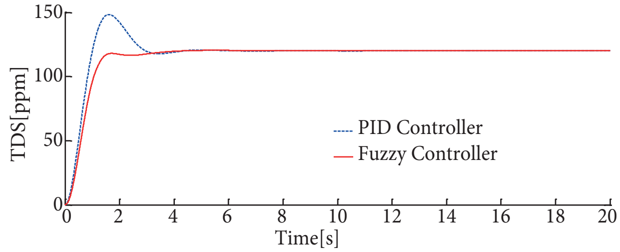


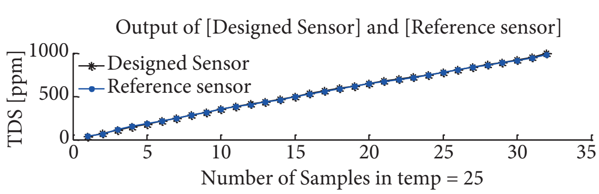
Figure 24. Comparison between step responses obtained from fuzzy controller (plain line) and PID controller (dashed line).

Thereby, system response would be much better for the case of using the PID fuzzy controller. Thus, PID fuzzy controllers are utilized in domestic and industrial RO water purification systems in order to control the TDS of the water.

10. Test and evaluation

The designed and manufactured system was tested and evaluated at the Research Institute of Food Science and Technology, which is located in the Science and Technology Park of Razavi Khorasan Province. Scientific approval of this system entitled "Measurement and Controlling TDS through Conductometry for Being Used in Water Purification Systems with the Ability to Eliminate the Adverse Effect of Temperature" was issued with No. 712 based on act M.SH/91/2 by the Scientific Council of Research Group for Food Chemistry of the Institute.

Accuracy of the TDS measurement system developed was examined within 32 steps of running tests in comparison with the reference sensor of the Conductivity/Temp/TDS Model 8302. The temperature of the water was kept constant at 25 °C during all experiments. Figures 25a and 25b illustrate the accuracy and error of the measurement system designed, respectively. Figure 25b reveals that the measurement error is different at any range. The high accuracy within the range of 250–1000 ppm is attributed to choosing $R_1 = 1K\Omega$, by which the maximum sensitivity is found near 500 ppm for the measurement system that is appropriate for agriculture and livestock applications. If the system is considered for drinking water, $R_1 = 3.5K\Omega$ will be assumed, which generates the maximum accuracy at concentrations less than 200 ppm. Finally, if industrial applications are considered, resistance value will be selected as $R_1 = 100K\Omega$, which contributes to achieving the maximum sensitivity at concentrations lower than 10 ppm.



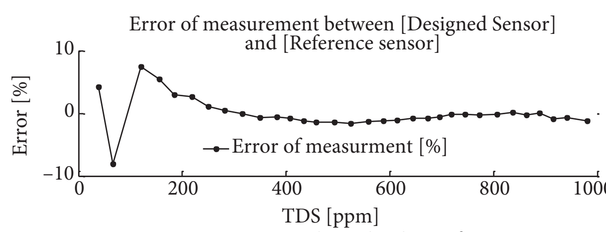


Figure 25. Investigation of behavior of the designed measurement system as compared with the reference sensor of Conductivity/Temp/TDS Model 8302 at constant temperature and different values of TDS (a); percentage of relative measurement error (b).

Scientific approval for the measurement unit of this system was issued with No. 410/A/2386 by the Research Institute for Food Science and Technology.

Furthermore, performance of the temperature compensation unit was tested and evaluated separately at the same institute. Figure 11 provides a comparison between the designed system and the reference sensor. These experiments were conducted in constant TDS of 429 ppm and 15 to 68 °C temperatures.

Blue (*) and black (•) curves in Figure 26 depict behavior of the reference sensor and the designed measurement system at different temperatures. Since standard TDS at 25 °C was 429 ppm in these tests, the ideal case entails variations of temperature causing no change in the TDS of water. As can be observed, the reference sensor does not show an ideal compensation toward temperature variations. However, performance of the developed compensation system against these changes outperforms the reference sensor even in the range of 30–40 °C. Meanwhile, regarding curves of Figure 26, the average error of compensation was limited to 3%, that is, 8.5 ppm. Thus, this amount of error is really desirable at this range.

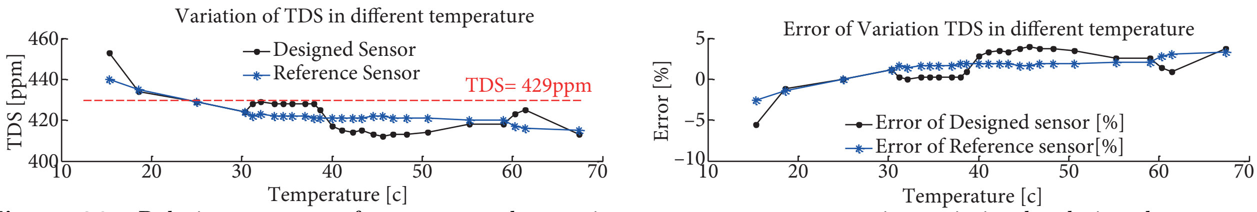


Figure 26. Relative amounts of accuracy and error in temperature compensation unit in the designed system as compared with those of the reference sensor with constant TDS but different temperatures.

Figure 27. Schematic view of the TDS measurement and control system designed and manufactured in this work.

11. Conclusion

Performance of the system and innovation of the design were investigated at the Khorasan Science and Technology Park.

The system designed and manufactured measures the TDS of water accurately with the ability to be installed on any household or industrial RO water purification apparatus. Meanwhile, with the scientific model obtained from RO water purification apparatuses, one can continuously control the TDS of water in desired ranges using a PID fuzzy controller. By using such a system, problems of conventional RO water purification apparatuses have been solved, while improved quality of the outlet water has satisfied users more than before.

One advantage of the designed system is its continuous measurement and display of the TDS of water, which has the following outcomes: confidence of the user in the quality of the purified water, no need to control the TDS of water manually, prevention of unnecessary elimination of the solutes that are useful, significant improvement in the quality of outlet water by continuous controlling of the mix valve, long life of RO filters by properly changing the state of the mix valve, considerable reduction of service and maintenance costs, and enhanced health among families.

The industrial prototype of the designed and manufactured system in this research is depicted in Figure 27.

Acknowledgment

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