

Water level control of small-scale recirculating aquaculture system with protein skimmer using fuzzy logic controller

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ABSTRACT

The recirculating aquaculture system (RAS) is a land-based aquaculture facility, either open-air or indoors, that minimizes water consumption by filtering, adapting, and reusing water. Solid organic matter from fish waste and food waste directly becomes waste that needs to be eliminated because it is a source of increasing total ammonia nitrogen (TAN), total suspended solids (TSS), total dissolved solids (TDS), and also has an impact on reducing dissolved oxygen (DO). RAS requires a water level control system so the fish tank does not experience water shortages or floods, disrupting the aquatic aquaculture ecosystem. In this study, small-scale RAS is modeled using a 3-coupled tanks system approach with a tank configuration that follows the most straightforward RAS water recirculation process (fish tank, mechanic filter, biofilter). Clean water from the reservoir flows into the fish tank through a protein skimmer. This study applies the fuzzy logic controller (FLC) to control the water level in the protein skimmer and biofilter tanks by controlling the position of several valves where the placement positions of the valves have been determined according to system requirements. The study results show that the tuned single-input FLC has the best average output response characteristics with $t_s=50$, $h_{1SS}=49.98$, $e_{SS}=0.02$ in protein skimmer and $t_s=4700$, $h_{1SS}=39.75$, $e_{SS}=0.25$ in the tank system.

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1. INTRODUCTION

The recirculating aquaculture system (RAS) is a land-based aquaculture facility, either open-air or indoors, that minimizes water consumption by filtering, adapting, and reusing water. Compared to a traditional pond or open-water aquaculture, the water recirculation process in RAS allows for the control of culture conditions and the collection of wastes. In addition, land-based aquaculture avoids fish escapes and limits the transmission of diseases and parasites from outside [1].

RAS technology tends to be like a water treatment system where the recirculation process aims to control the quality of RAS water. Solid organic matter from fish waste and food waste directly becomes waste that needs to be eliminated because it is a source of increasing ammonia nitrogen (TAN), total suspended solids (TSS), total dissolved solids (TDS), and also has an impact on reducing dissolved oxygen (DO) [2]. TSS can be reduced by using mechanical filtration. TAN is lowered by using biological filtration through a nitrification-denitrification process. Meanwhile, TDS is lowered using a protein skimmer through a foam fractionation process. Proper aeration is necessary for the nitrification-denitrification and foam

fractionation processes. Foam fractionation is the process of converting fine solids and protein residues in the form of fat into foam which is removed as FOAMATE [3]–[7].

RAS requires a water level control system so the fish tank does not experience water shortages or floods, disrupting the aquatic aquaculture ecosystem. Small-scale RAS can be analogous to a tank system so that controlling the water level requires a mathematical model approach to the tank system, which can be obtained empirically or experimentally [8]–[10] and the control strategy used [11]–[17].

The number and configuration of tanks in a tank system depend on the needs of the process to be modeled. The complexity and nonlinearity of a tank system model tend to increase with the number and configuration of tanks used. The selection of the control strategy and the type of controller used is crucial [9], [10], [13]–[15], [18]–[25]. In addition, this study involved a protein skimmer in RAS. The positioning of the protein skimmer in relation to the circulating water system in the RAS adds to the complexity of level control.

In this study, small-scale RAS is modeled using a 3-coupled tanks system approach with a tank configuration that follows the simplest RAS water recirculation process (fish tank, mechanic filter, biofilter). Clean water from the reservoir flows into the fish tank through a protein skimmer. This is intended so that clean water is completely free of TDS. In this case, the protein skimmer can be assumed as a supplier of clean water for the tank system. Meanwhile, the output water from the last tank (biofilter) is channeled into the reservoir. The purpose of control is to condition the water level in the protein skimmer at a certain level so that the foam fractionation process can work properly and control the water level in the biofilter tank in such a way that the fish tank does not run out of water or experience flooding.

This study applies the fuzzy logic controller (FLC) to control the water level in the protein skimmer and biofilter tanks by controlling the position of several valves where the placement positions of the said valves have been determined according to system requirements.

2. METHOD

This section explains the proposed research design and methods used. The proposed research design is the 3-coupled tank system and water level control. FLC is used as the method.

2.1. The 3-coupled tank system

The small-scale RAS built in this applied research is modeled using a 3-coupled tank system, as shown in Figure 1. The balance of water volume in the recirculating system is a problem in itself. Fish tank volume is usually larger than the volume of the water reservoir, with specific technical considerations. This difference needs to be anticipated so that the fish Tank does not experience water shortages, thereby disrupting the aquatic aquaculture ecosystem. By comparing the water level in the fish tank and reservoir and considering the water pump's capacity, the water volume balance in the recirculation system can be conditioned according to needs.

In this study, the reservoir is assumed to have free dimensions, so a balanced review based on water level is focused on the water level in tank 3. By conditioning the water level in tank 3 (bio-filter), it is hoped that tank 1 (fish tank) will not run out of water or experience flooding. Meanwhile, to ensure that the protein skimmer can carry out the foam fractionation process, the water level in the protein skimmer must be maintained at the specified liquid level. If the water level in the protein skimmer changes, it will disrupt the FOAMATE production process at the FOAMATE outlet.

Modeling a small-scale RAS with a protein skimmer in a 3-coupled tank system is carried out by observing the mass balance of water between tanks, with the primary supply source coming from the protein skimmer water outlet. From Figure 1, we can get (1).

$$\begin{aligned} q_p &= k_1 \cdot q_{pump} \\ q_{in1} &= k_3 \cdot q_1 \\ q_{in2} &= k_2 \cdot (1 - k_3) \cdot q_1 \end{aligned} \quad (1)$$

k_1 , k_2 and k_3 is the constant valve position ($0 \leq k \leq 1$). k_1 and k_2 are controlled using actuators. k_3 controlled based on the change k_1 and k_2 ($k_3 = k_1 \cdot k_2$). The pump water discharge specification is stated by q_{pump} . In protein skimmers, Bernoulli's principle applies as (2).

$$P_1 + \frac{1}{2} \cdot \rho \cdot v_p^2 + \rho \cdot g \cdot h_1 = P_2 + \frac{1}{2} \cdot \rho \cdot v_1^2 + \rho \cdot g \cdot h_o \quad (2)$$

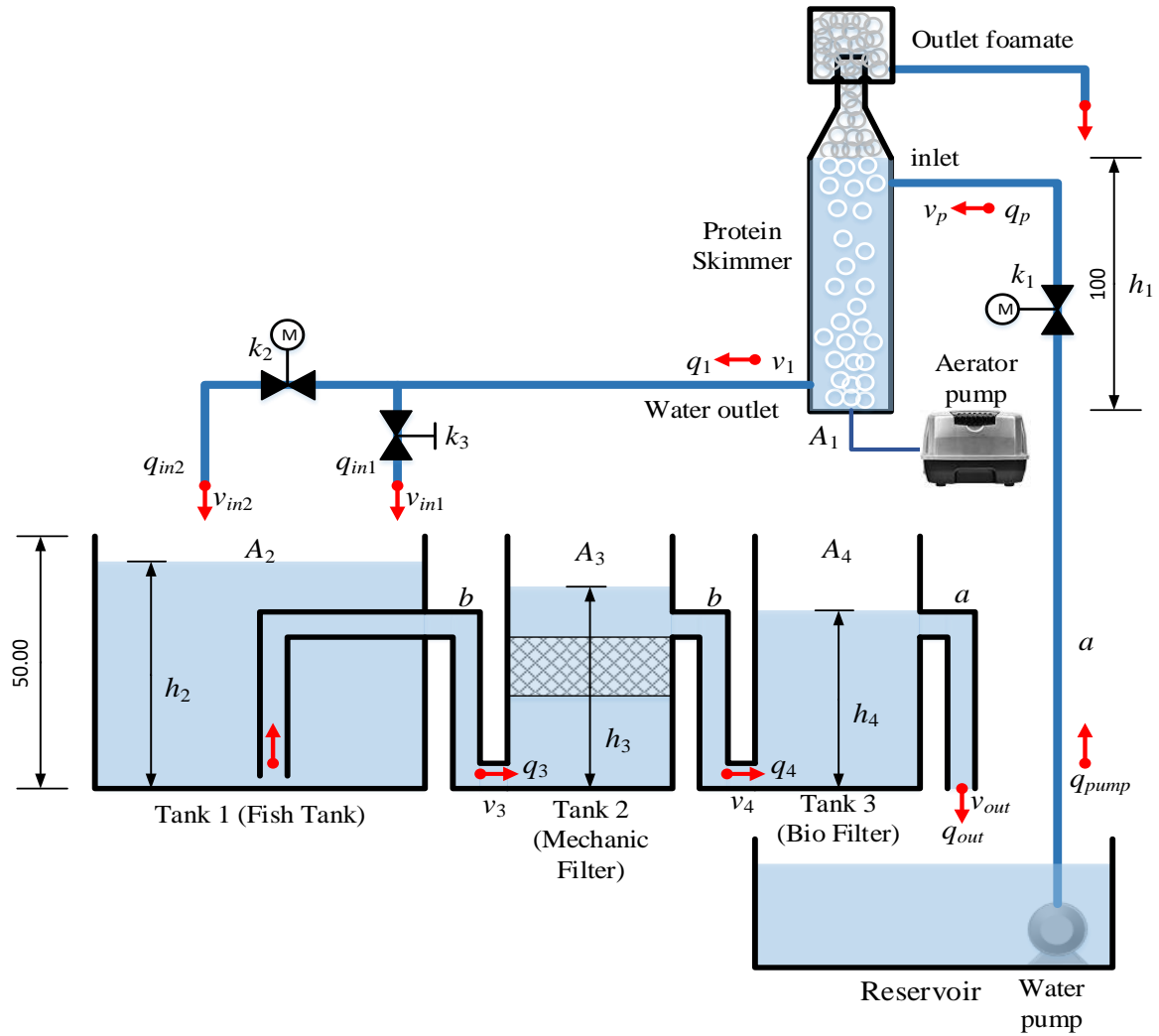


Figure 1. Small-scale RAS with protein skimmer in the 3-coupled tank system model

The applicable pressure is the aeration pressure of the aeration pump, thus $P_1 = P_2$. v_p is the velocity of water flow at the protein skimmer inlet with a cross-sectional area $k_1 \cdot a$. Because $A_1 \gg k_1 \cdot a$ then it can be assumed $v_p \approx 0$. The outlet portion is at the bottom of the protein skimmer, so that can be assumed $h_o = 0$. Then, (2) become (3).

$$g \cdot h_1 = \frac{1}{2} \cdot v_1^2 \rightarrow v_1 = \sqrt{2 \cdot g \cdot h_1} \tag{3}$$

The water discharge flowing at the outlet through cross-section a can be expressed by (4),

$$q_1 = a \cdot v_1 = a \cdot \sqrt{2 \cdot g \cdot h_1} = \alpha \cdot \sqrt{h_1} \tag{4}$$

where $\alpha = a \cdot \sqrt{2 \cdot g}$. The mass balance of the protein skimmer can be expressed by (5).

$$\begin{aligned} A_1 \cdot \frac{dh_1}{dt} &= q_p - q_1 = q_p - q_1 \\ A_1 \cdot \frac{dh_1}{dt} &= k_1 \cdot q_{pump} - \alpha \cdot \sqrt{h_1} \end{aligned} \tag{5}$$

MATLAB Simulink Model from (5) is shown in Figure 2.

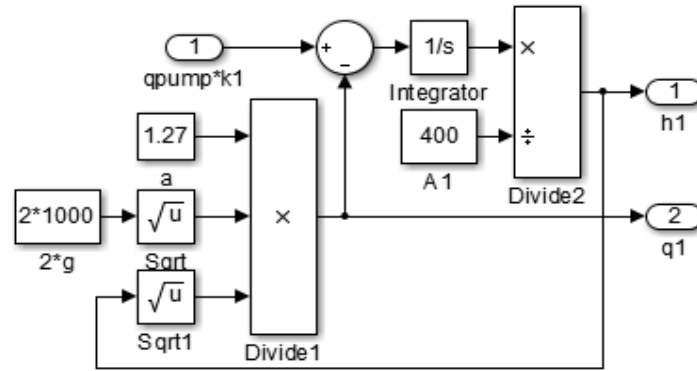


Figure 2. MATLAB Simulink model sub-system protein skimmer

The flow of water from Tank 1 to Tank 2 creates energy, where the total energy in Tank 1 equals the total energy in Tank 2. This can be expressed by Bernoulli's principle as (6).

$$P_1 + \frac{1}{2} \cdot \rho \cdot v_{in1}^2 + \frac{1}{2} \cdot \rho \cdot v_{in2}^2 + \rho \cdot g \cdot h_2 = P_2 + \frac{1}{2} \cdot \rho \cdot v_3^2 + \rho \cdot g \cdot h_3 \tag{6}$$

Because Tank 1 and Tank 2 are open, the applied pressure is atmospheric pressure, so $P_1 = P_2$. v_{in1} and v_{in2} are the velocity of the water flow from the circulation pipe with the cross-sectional area of the valve $k_3 \cdot a$ and $k_2 \cdot a$. Because $A_2 \gg \{k_3 \cdot a; k_2 \cdot b\}$ then it can be assumed $v_{in1} = v_{in2} \approx 0$. Then, (6) become (7).

$$g \cdot h_2 = \frac{1}{2} \cdot v_3^2 + g \cdot h_3 \rightarrow v_3 = \sqrt{2 \cdot g \cdot (h_2 - h_3)} \tag{7}$$

The water discharge flowing into Tank 2 through cross-section b can be expressed by (8),

$$q_3 = b \cdot v_3 = b \cdot \sqrt{2 \cdot g} \cdot \sqrt{h_2 - h_3} = \beta \cdot \sqrt{h_{23}} \tag{8}$$

where $\beta = b \cdot \sqrt{2 \cdot g}$ dan $\sqrt{h_{23}} = \sqrt{h_2 - h_3}$. With reference to (1) and (8), the mass balance in Tank 1 can be expressed by (9),

$$\begin{aligned} A_2 \cdot \frac{dh_2}{dt} &= q_2 - q_3 = q_{in1} + q_{in2} - q_3 \\ A_2 \cdot \frac{dh_2}{dt} &= k_3 \cdot q_1 + k_2 \cdot (1 - k_3) \cdot q_1 - q_3 \\ A_2 \cdot \frac{dh_2}{dt} &= (k_3 + k_2 \cdot (1 - k_3)) \cdot \alpha \cdot \sqrt{h_1} - \beta \cdot \sqrt{h_{23}} \end{aligned} \tag{9}$$

where $k_3 + k_2 \cdot (1 - k_3)$ are multi-valve. MATLAB Simulink model from (9) is shown in Figures 3 and 4.

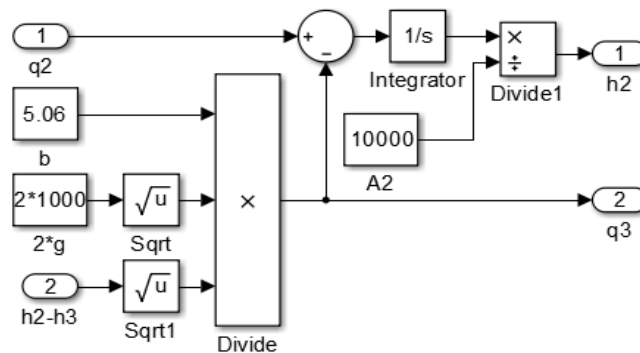


Figure 3. MATLAB Simulink model sub-system Tank 1

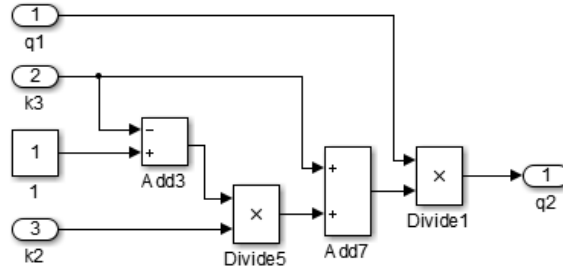


Figure 4. MATLAB Simulink model sub-system multi-valve

In the same way, obtained (10).

$$v_4 = \sqrt{2 \cdot g} \cdot \sqrt{h_{34}} \tag{10}$$

The water discharge flowing into Tank 3 through cross section b can be expressed by (11).

$$q_4 = b \cdot v_4 = b \cdot \sqrt{2 \cdot g} \cdot \sqrt{h_{34}} = \beta \cdot \sqrt{h_{34}} \tag{11}$$

The mass balance in Tank 2 can be expressed by (12).

$$A_3 \cdot \frac{dh_3}{dt} = q_3 - q_4 \tag{12}$$

$$A_3 \cdot \frac{dh_3}{dt} = \beta \cdot \sqrt{h_{23}} - \beta \cdot \sqrt{h_{34}}$$

MATLAB Simulink Model from (12) is shown in Figure 5.

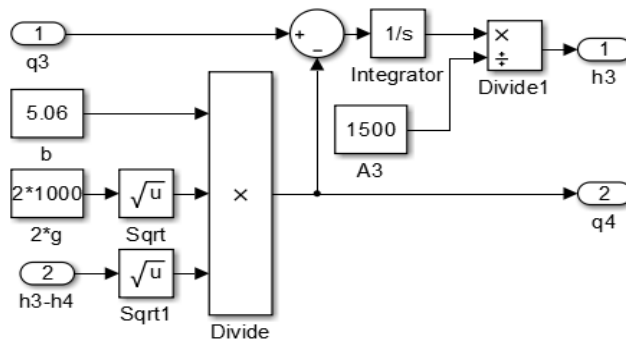


Figure 5. MATLAB Simulink model sub-system Tank 2

In Tank 3, around the outlet pipe, it can be assumed that $h_{out} = 0$ so that the applicable Bernoulli's principle is as (13).

$$g \cdot h_4 = \frac{1}{2} \cdot v_{out}^2 \rightarrow v_{out} = \sqrt{2 \cdot g} \cdot \sqrt{h_4} \tag{13}$$

The water rate in the outlet pipe is expressed by (14).

$$q_{out} = a \cdot v_{out} = a \cdot \sqrt{2 \cdot g} \cdot \sqrt{h_4} = \alpha \cdot \sqrt{h_4} \tag{14}$$

The mass balance in Tank 3 can be expressed by (15).

$$A_4 \cdot \frac{dh_4}{dt} = q_4 - q_{out} \tag{15}$$

$$A_4 \cdot \frac{dh_4}{dt} = \beta \cdot \sqrt{h_{34}} - \beta \cdot \sqrt{h_4}$$

MATLAB Simulink model from (15) is shown in Figure 6, while the valve position variables, k_1 and k_2 are modeled as shown in Figure 7.

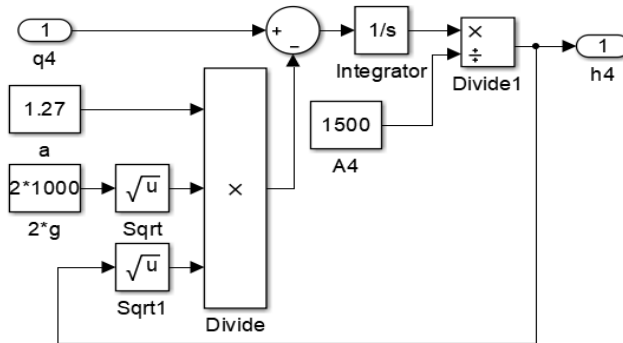


Figure 6. MATLAB Simulink model sub-system Tank 3

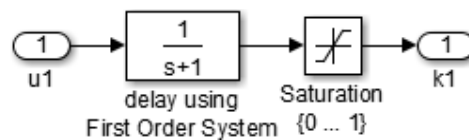


Figure 7. MATLAB Simulink model sub-system k_1 dan k_2

2.2. Water level control

In this study, k_1 is the variable valve position used to adjust the water level in the protein skimmer (h_1). k_2 is used to adjust the water level in tank 3 (h_4), while k_3 is used to adjust the multi-valve manually. The multi-valve regulates the water flow transition from the protein skimmer to the tank system. The water level in the protein skimmer is expected to reach $h_1 = 50\text{ cm}$, while the water level in tank 3, $h_4 = 40\text{ cm}$. The specifications of small-scale RAS with a protein skimmer are shown in Table 1.

Table 1. Specifications of small-scale RAS with a protein skimmer

Description	Notation	Value	Unit
Cross-sectional area of circulating pipe	a	1.27	cm^2
Cross-sectional area of interaction pipe between Tank 1, Tank 2, Tank 3	b	5.06	cm^2
Cross-sectional area of outlet pipe in Tank 3	a	1.27	cm^2
Cross-sectional area of protein skimmer	A_1	400	cm^2
Cross-sectional area of Tank 1	A_2	10000	cm^2
Cross-sectional area of Tank 2 and Tank 3	$A_3 = A_4$	1500	cm^2
The flow rate of pump	q_{pump}	694	cm^3/sec

2.3. Fuzzy logic controller

FLC is a fuzzy logic-based controller that implements the fuzzy inference system (FIS) in its reasoning. FIS consists of four parts: fuzzification, inference engine, knowledge-based, and defuzzification. Fuzzification is the process of transforming crisp values into fuzzy values using fuzzy sets for each of the variables involved. Fuzzy sets are constructed using membership functions (triangular, trapezoidal membership functions, etc.) that represent the linguistic variables used. The linguistic variable is a representation of human reasoning over many values within a specific range. An illustration of the fuzzification process is shown in Figure 8. The range of values $\{0 \dots 100\}$ is represented linguistically as low, medium, and high. the low and high linguistic variables are represented by the trapezoidal membership

function and the triangular membership function for medium. The value of crips 35 is fuzzified into linguistic low with a fuzzy value of 0.75 and medium with a fuzzy value of 0.25.

An inference engine is a reasoning process based on the logic of human linguistic knowledge (knowledge-based) packaged into a rule-based set. The inference engine applies fuzzy operators, implications, and aggregations. All three use the AND/min or OR/max method, as needed.

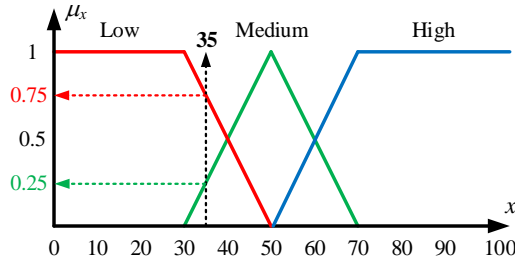


Figure 8. Fuzzification

FIS Mamdani applies IF (input) THEN (output) rules. If the input is more than one, then the fuzzy operator needs to be applied to each rule-based line. The implication is the transformation of the result of using the IF (input) THEN (output) rules to each rule line into a set of fuzzy outputs. The implication method can be AND/min or OR/max. As the illustration shown in Figure 9. Aggregation is the process of combining all output fuzzy sets into a single fuzzy set. Typically, aggregation uses the AND/max method. Finally, defuzzification is the process of transforming a single fuzzy set into one crisp value as the FIS output. Usually using the centroid method. This is illustrated in Figure 10.

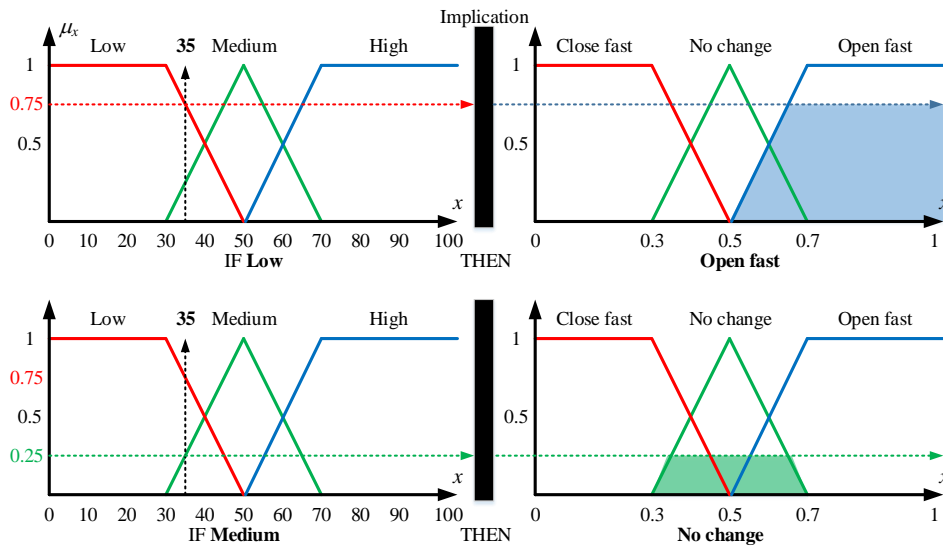


Figure 9. Application of IF (input) THEN (output) rules and their implicit

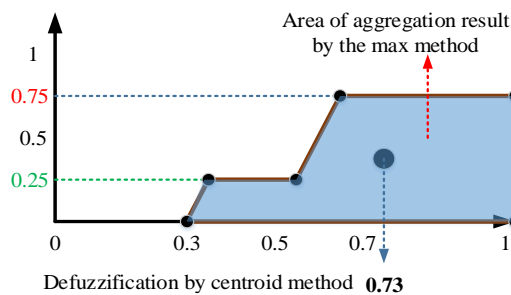


Figure 10. Aggregation and defuzzification

3. RESULTS AND DISCUSSION

These results are obtained from the simulations carried out using the MATLAB/Simulink software. The results are divided into five parts, single-input FLC, single-input FLC with setpoint, gained single-input FLC with setpoint, tuned single-input FLC with setpoint, and setpoint change experiment.

3.1. Single-input FLC

Single-input FLC is an FLC that utilizes water level output data at any time as input. While the FLC output is a constant valve position ($0 \leq k \leq 1$). Linguistic variables for the fuzzy input set (Level) are *VL* (very low), *L* (low), *M* (medium), *H* (high), and *VH* (very high). Linguistic variables for the output fuzzy set (valve) are *CF* (close fast), *CS* (close slow), *NC* (no change), *OS* (open slow), and *OF* (open fast). The target water level is set on a linguistic variable *M* where the valve condition is *NC*. Reasoning based on linguistic logic is: i) IF Level is *VL*, THEN Valve is *OF*, ii) IF Level is *L*, THEN Valve is *OS*, iii) IF Level is *M*, THEN Valve is *NC*, iv) IF Level is *H*, THEN Valve is *CS*, and v) IF Level is *VH*, THEN Valve is *CF*. Fuzzy sets (input and output) are built using trapezoidal and triangular membership functions in the range of values $\{0 \dots 1\}$ as shown in Figure 11.

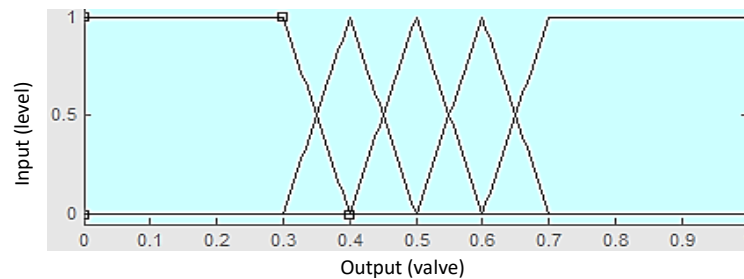


Figure 11. Fuzzy set of input (level) and output (valve)

The range of values for the fuzzy output set (valve) is directly related to the range of valve position values ($0 \leq k \leq 1$). The range of values for the fuzzy input set (level) represents the normalized value of the water level in the protein skimmer (h_1) and tank 3 (h_4). In this case, the crisp input value is expressed by (16),

$$level = h/N \quad (16)$$

where N is the normalizer value.

FLC with one input was built using FIS MATLAB with some design characteristics: i) FIS: Mamdani, ii) Implication method (AND): min, iii) aggregation method: max, and iv) defuzzification method: centroid.

MATLAB Simulink model for water level control small-scale RAS with protein skimmer using single-input FLC is shown in Figures 12 and 13, with output response water level in the protein skimmer as in Figure 14(a) and water level in Tank 3 as in Figure 14(b) with criteria $\pm 2\%$ from the final value.

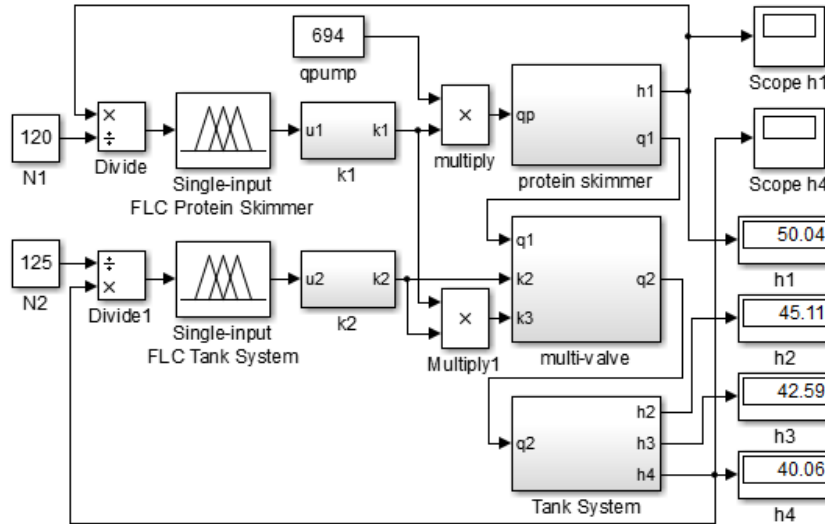


Figure 12. MATLAB Simulink model for water level control of small-scale RAS using single-input FLC

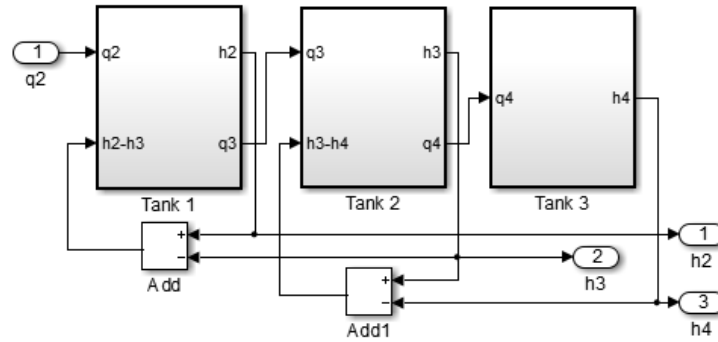


Figure 13. MATLAB Simulink model for tank system sub-system

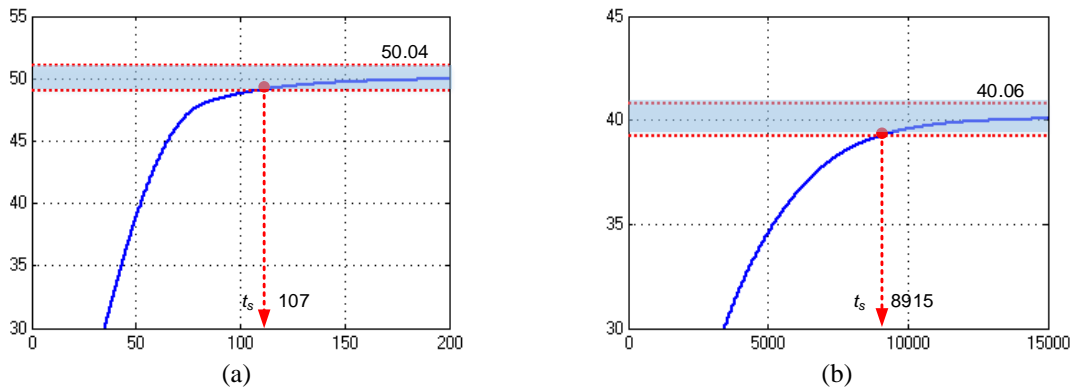


Figure 14. Output response for (a) h_1 $t_s = 107$ sec, $h_{1ss} = 50.04$ and (b) h_4 $t_s = 8915$ sec, $h_{4ss} = 40.06$ using FLC one input

3.2. Single-input FLC with setpoint

If a setpoint is included for each water level (h_1 dan h_4) then it is necessary to consider the presence of an error level, which is expressed by: $e_h = h_{setpoint} - h_{output}$. With $h_{setpoint}$ acting as a normalizer such that $error_level = e_h/h_{setpoint}$, then $error_level$ will be within the value range $\{-1 \dots 1\}$. The set of fuzzy inputs (error level) used is shown in Figure 15. The linguistic variable used is *NB* (negative big), *NS* (negative small), *Z* (zero), *PS* (positive small), and *PB* (positive big). Reasoning based on linguistic logic

used is: i) IF Level is *NB*, THEN Valve is *CF*, ii) IF Level is *NS*, THEN Valve is *CS*, iii) IF Level is *Z*, THEN Valve is *NC*, iv) IF Level is *PS*, THEN Valve is *OS*, and v) IF Level is *PB*, THEN Valve is *OF*.

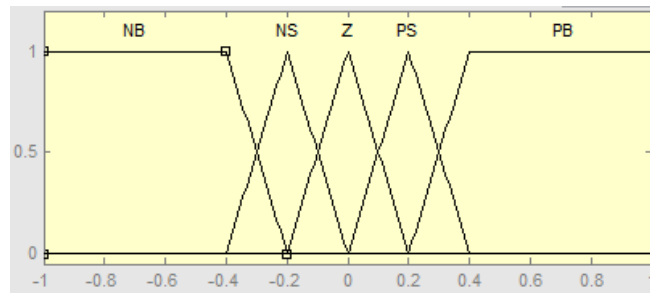


Figure 15. Set of fuzzy input (error level) for one input FLC with setpoint

MATLAB Simulink model of small-scale RAS water level control using a single-input FLC with setpoint shown in Figures 16 and 17 with output response as shown in Figure 18. It appears that the system response output produces a steady state error, $e_{ss-h1} = 4.94$ and $e_{ss-h4} = 9.77$.

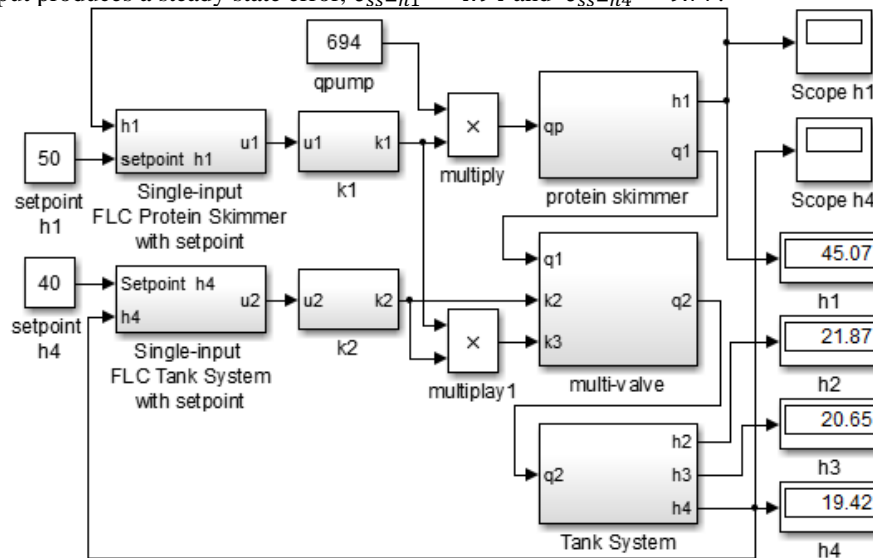


Figure 16. MATLAB Simulink model for water level control of small-scale RAS using single-input FLC with setpoint

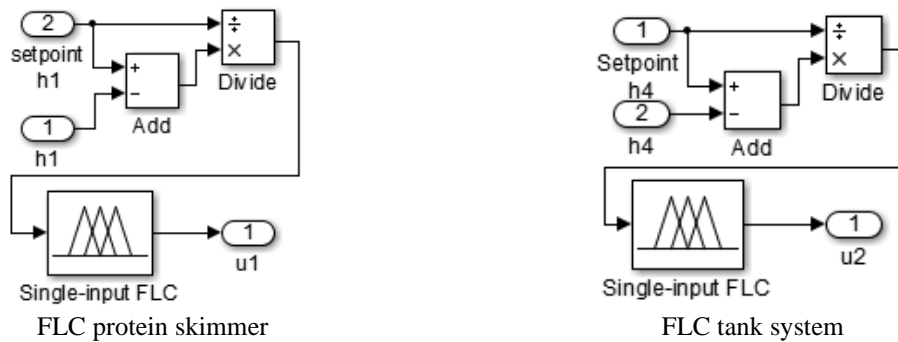


Figure 17. MATLAB Simulink Model for sub-system FLC one input with setpoint

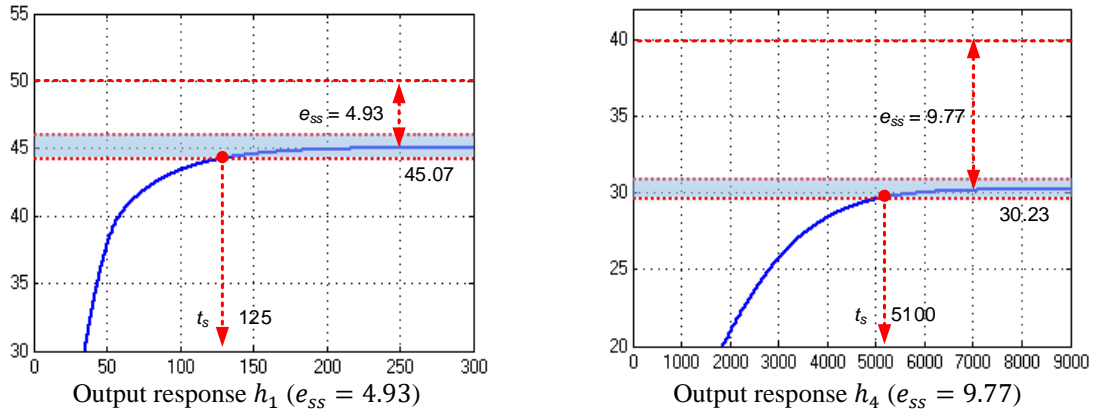


Figure 18. Output response using FLC one input with setpoint

3.3. Gained single-input FLC with setpoint

To reduce e_{ss} the FLC gain is used, which is placed on the output side of the FLC, as shown in Figure 19. In this case, the controlled signal is expressed as (17).

$$u = FLC \left(\frac{e_h}{\text{setpoint}} \right) \cdot G_{FLC} \tag{17}$$

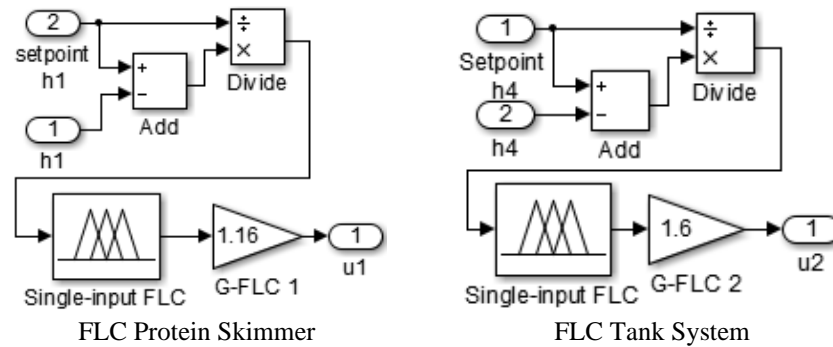
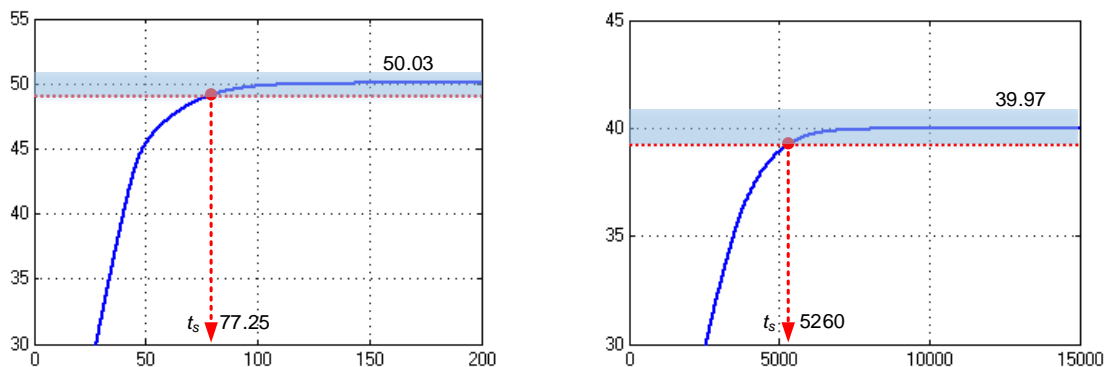


Figure 19. MATLAB Simulink model for sub-system gained single-input FLC setpoint

The system response output is shown in Figure 20. By setting $G_{FLC1} = 1.16$ and $G_{FLC2} = 1.6$ a protein skimmer water level steady state value can be achieved, $h_{1ss} = 50.03$ with $t_s = 77.25$ sec, as can be seen in Figure 20(a). Meanwhile the water level in Tank 3, $h_{4ss} = 39.97$ with $t_s = 5260$ sec. In this case, G_{FLC} serves to minimize the steady state error (e_{ss}) outside the $\pm 2\%$ area of the final value, as shown in Figure 20(b).



(a) (b)

Figure 20. Output response using gained single-input FLC with setpoint for (a) h_1 ($t_s = 77.25 \text{ sec}$, $h_{1ss} = 50.03$) and (b) output response h_4 ($t_s = 5260 \text{ sec}$, $h_{4ss} = 39.97$)

3.4. Tuned single-input FLC with setpoint

Next, e_{ss} is reduced by tuning the input and output fuzzy sets (without FLC gain). Tuning the fuzzy input set is done by changing the range of values for each linguistic variable, as shown in Table 2. The form of the membership function is the same as in Figure 15. Meanwhile, the output fuzzy set tuning is shown in Table 3 and Figure 21. The system response output is shown in Figure 22.

Table 2. Tuning the range of linguistic variable values, set of fuzzy input (error level)

Linguistic variable	before		after	
NB	-1	-0.2	-1	-0.01
NS	-0.4	0	-0.02	0
Z	-0.2	0.2	-0.01	-0.01
PS	0	0.4	0	0.02
PB	0.2	1	0.01	1

Table 3. Tuning the range of linguistic variable values, set of fuzzy output (valve)

Linguistic variable	before		after	
CF	0	0.4	0	0.05
CS	0.3	0.5	0	0.5
NC	0.4	0.6	0.495	0.505
OS	0.5	0.7	0.5	1
OF	0.6	1	0.95	1

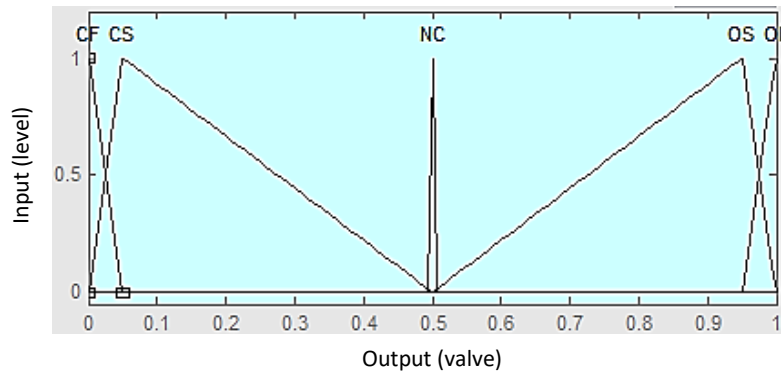


Figure 21. Tuning fuzzy output set (valve)

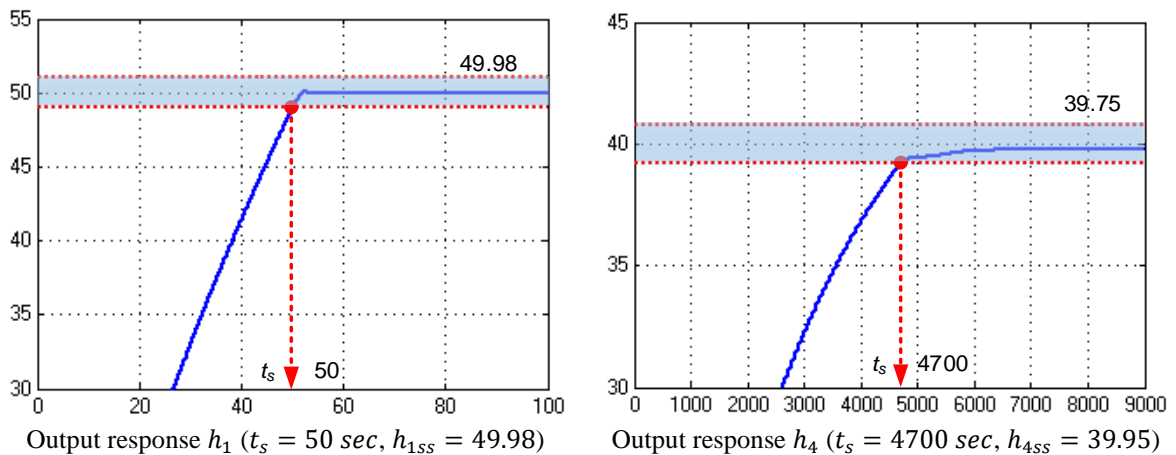


Figure 22. Output response using tuned single-input FLC with setpoint

By applying a tuned single-input FLC then it is obtained $h_{1ss} = 49.98$ with $t_s = 50 \text{ sec}$, while the water level in Tank 3, $h_{4ss} = 39.75$ with $t_s = 4700 \text{ sec}$. The appearance of overshoot in the response output h_1 is still acceptable because it is still within the $\pm 2\%$ area of the final value.

A summary of the experimental results of dynamical system models using several types of single-input FLC with setpoints is shown in Table 4. From the table, it can be seen that the tuned single-input FLC has the best average output response characteristics.

Table 4. Summary of the experimental results of dynamic system model using single-input FLC with setpoint variations

Single input FLC	Protein Skimmer			Tank System		
	t_s	h_{1ss}	e_{ss}	t_s	h_{4ss}	e_{ss}
original	125	45.07	4.93	5100	30.23	9.77
gained	77.25	50.03	0.03	5260	39.97	0.03
tuned	50	49.98	0.02	4700	39.75	0.25

3.5. Setpoint change experiment

Furthermore, both types of FLC (gained and tuned FLC) controllers were tested with changing setpoints. This test is intended to simulate the condition of the small-scale RAS water level, which under certain conditions, may change because the mechanical filter material begins to saturate with TSS. The test results, which are shown in Figure 23, show that tuned FLC can follow setpoint changes well, and vice versa for gained FLC.

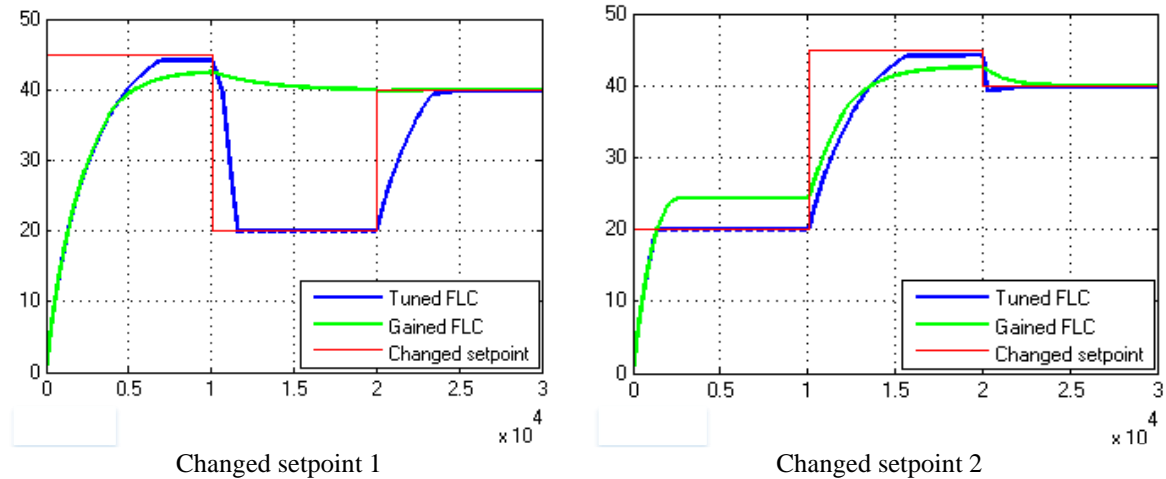


Figure 23. The results of the gained FLC and tuned FLC tests with changing setpoints

4. CONCLUSION

The small-scale RAS mathematical modeling in this study is approached by analogy with a 3-coupled tank system (fish tank, mechanic filter, biofilter). System dynamic models become complex when protein skimmers are involved. In order for the foam fractionation process in the protein skimmer to function properly, the water level in the protein skimmer needs to be conditioned in such a way as not to change. In this study, clean water from the reservoir flowed into the fish tank via a protein skimmer to ensure that TDS was completely removed. This means protein skimmer is a source of fish tank supply. Because the biofilter tank is the last tank where the water outlet goes to the reservoir, the water level of the biofilter tank needs to be controlled in such a way that the fish tank does not lack water or otherwise flooding occurs. Control of the water level at these two points is carried out simultaneously through the configuration of several predefined valves where the opening/closing position of the valves is controlled using FLC. This study uses a single-input FLC with a setpoint designed in two modes: gained and tuned FLC. The study results show that the tuned single-input FLC has the best average output response characteristics. Tests were also carried out by providing a changing setpoint, where the results showed that the tuned FLC could follow the setpoint changes well and vice versa for the gained FLC.

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