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# Fuzzy PID Algorithm-Based External Carbon Controller for Denitrification Process Enhancement in Wastewater Treatment Plant

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Abstract — the water scarcity and drought challenge are the current issue that faced by many countries in the world. The water scarcity and drought have disadvantageous impact to agriculture, industry and the environment. Wastewater reuse method has recognized as solution to overcome water scarcity. Wastewater treatment plant (WWTP) is a widely known as water replenishment that using wastewater reuse system that integrates microbial decomposition to process the wastewater. The over limit of effluent level leads to degradation of water quality produced by the plant. The denitrification process enhancement is highly recommended to increase the quality of water disposal. The adding of carbon material has recognized as a method to enhance the denitrification process. The rising of operational cost of the plant is the direct effect of the using of carbon addition. The high-performance controller is highly suggested to control the flow of carbon material in order to enhance the denitrification process and optimizing the carbon material usage. The PID controller is widely used in industrial purposes. Due the nonlinearity and complexity of the waste water treatment plant makes the traditional PID unable to work appropriately. The real-time error correction must be performed to minimize the error. It could be achieved by combining Fuzzy controller and traditional PID controller. The Fuzzy-PID controller has been succeeded to reduce the usage of the carbon than PID controller. The implementation of Fuzzy-PID controller is able to save the usage of carbon consumption by 412 kg COD. The nitrogen concentration, aeration energy and pumping energy also decreased by 0.0029 mg N/L,87kWh and 17 kWh

Keywords – Wastewater treatment plant; External carbon controller; WWTP; PID; Fuzzy-PID



## I. INTRODUCTION

The water scarcity and drought challenge are the current issues faced by countries in the world especially for regions in Africa, Asia, the Middle East, Europe and America. The water scarcity and drought have disadvantageous impact to agriculture, industry and the environment. The high demand of the clean water and the climate change effect are possible to intensify the level of water scarcity [1]. Drought, forest degradation, floods, poor management of water supply, water contamination and population growth are the causes of water crisis [2]. Wastewater reuse method has recognized as solution to overcome water scarcity and drought [3]. Waste water treatment plant (WWTP) is widely known as water replenishment that using wastewater reuse system integrates microbial decomposition to process the wastewater [4]. Wastewater treatment plant includes two biological process namely nitrification and denitrification. Nitrification and denitrification are the most important process to perform nitrogen removal action in wastewater treatment plant [5]. Nitrification is a decomposition process of ammonia nitrogen into nitrate. It is performed by nitrification microorganism. The nitrification occurs in aeration tank compartments [6]. Denitrification process decomposes nitrate that produced by nitrification process into nitrogen gases. The decomposition process has been performed by denitrification microorganism in anoxic tank compartments. Denitrification process divided into two stages of process. Firstly, pre-denitrification process including sewage water and organic materials such as carbon. The latest is the denitrification process itself [7].

The over limit of effluent level that flows into the plant affects the quality of the produced water. It leads to degradation of water quality that produced by the plant [8]. The over limit of effluent leads the rising level of nitrate that produced by nitrification process [9]. It automatically raises the nitrogen concentration of produced water. The rising of nitrogen concentration in the water environment is extremely dangerous for humans, animals, water creatures and the environments. The denitrification process enhancement is highly recommended to increase the quality of disposal water. The adding of carbon material has been recognized as a method to enhance the denitrification process [10]. The rising of operational cost of the plant is the direct effect of the using of carbon addition in denitrification process [11]. The high-performance controller is highly suggested to control the flow of carbon material in order to enhance the denitrification process and optimizing the carbon material usage.

The PID (Proportional Integral Derivative) controller is a widely used controller in industrial purposes. Simple on structure, less tuning parameter and easy to understand by engineers are the advantages of PID controller. It also has become standard controller in industrial processes [12]. The nonlinearity and the complexity of the wastewater treatment plant caused the traditional PID unable to work properly. The significant errors are highly possible to occur in control process. The real-time error correction must be performed to minimize the error. It could be achieved by combining Fuzzy controller and traditional PID controller [13]. The implementation of Fuzzy-PID controller is expected to reduce the carbon usage in the denitrification process that occurred in anoxic tanks.

The purpose of this research are to obtain lower nitrate concentration in anoxic tanks and optimizing the usage of carbon dose to reduce the operational cost since the wastewater treatment plant consumed a huge energy to process the wastewater [7]. Moreover, the involvement of the carbon addition also caused an increase in operational cost. A slight increase in efficiency level of the energy usage and operational cost are worth considering.

## II. RESEARCH METHOD

Benchmark Simulation Model No.1 is a tool for benchmarking the wastewater treatment plant aspects including effluent level, energy consumption of the plant, external carbon dose, ammonia level, nitrate level, nitrogen total level, etc. The BSM1 is a simulation environment consisting of a plant layout, the model of simulation, loads of the influent, test procedures and evaluation criterion [14]. BSM1 model is the standard simulation used by International Water Association (IWA) to analyze and evaluates the parameters that affect the performance of wastewater treatment plant [15].

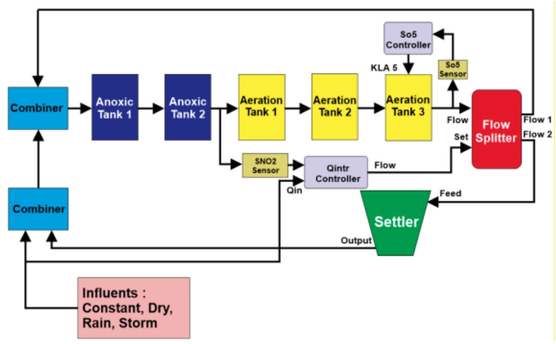



Fig.1. Benchmark Simulation Model No.1 (BSM1) Plant Layout

The BSM1 model consists of 5 reactors compartment divided into 2 anoxic compartments and 3 aeration compartments. Each compartment has a volume of 6000 m3. The BSM1 model has been designed with an average influent rate of 18446 $m^3$/day in dry condition. The average biodegradable COD amount is 300 g/$m^3$. The plant has hydraulic retention time of 14.4 hours. The rate of wastage flow equals 385 $m^3$/day. The BSM1 model has 3 different scenarios, namely dry weather, rainy weather and storm weather [14].

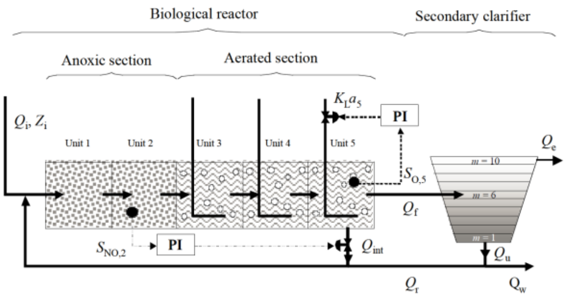



Fig.2. Wastewater Treatment Plant Schematic

The nitrification and denitrification are the most crucial process in the wastewater treatment plant [16]. The nitrate controller and dissolved oxygen controlled are included in the model. The maintaining of the nitrate level is performed by nitrate controller. The nitrate controller performs maintaining of nitrate level at 1 mg N/L. It occurs in anoxic tanks. The goal of maintaining nitrate concentration is to keep the denitrification process run properly. The maintaining process of dissolved oxygen level was performed by dissolved oxygen controller. The dissolved oxygen controller maintains the dissolved oxygen concentration at a level of 2 mg N/L to keep nitrification process works properly. The maintaining process of dissolved oxygen concentration occurs in aeration compartment [17].

The BSM1 model also supports the external carbon addition in denitrification process in order for denitrification enhancement purpose. EC refers to the consumption of external carbon source:

$$EC = \frac{COD_{ec}}{T.1000} \int_{t=7}^{t=14} \left( \sum_{i=1}^{i=n} q_{ec,i} \right) dt \quad (1)$$

Where $EC$ represents the flow rate of external carbon that to be added to compartment$i$. The amount of $COD_{ec}$ equals 400.000 g COD/$m^3$. $COD_{ec}$ is the concentration of readily biodegradable substrate in the external carbon source. The operation duration is represented by $t$ in unit of days. The BSM1 simulates the plant for 14 days period. The dosing of external carbon addition is applied between on the seventh to fourteenth day. Since the stable period of the plant starts on the 7th day [14].

The energy consumption is the important aspect to determine the feasibility of the wastewater treatment plant [18]. Reducing the energy consumption in WWTP is an important goal, since it related with carbon emission[19]. The usage of carbon addition in denitrification process affects the energy consumption in WWTP. The aeration compartments are the most energy consuming sections in WWTP.

$$AE = \frac{S_0^{sat}}{T \cdot 1.8 \cdot 1000} \int_{t=7}^{t=14} \sum_{i=1}^{5} V_i \cdot K_L a_i(t)\,.dt \quad (2)$$

Where $AE$ is the aeration energy that required by aeration system. The oxygen concentration that flows to aeration tanks represent by So. *Vi* is the tank volume. $K_L a_i$ is the aeration coefficient. Pumping section also consumes significant energy in WWTP. The enhancement of denitrification triggers the increase of internal circulation flow rate ($Q_a$). To circulate the wastewater inside the plant, it requires the pumping system.

$$PE = \frac{1}{T} \int_{t=7}^{t=14} (0.004 \cdot Q_a(t) + 0.008 \cdot Q_r(t) + 0.005 \cdot Q_w(t))\, dt \quad (3)$$

PE represents the pumping energy that required by pumping system. Internal flow recirculation rate is represented by $Q_a$. The return sludge flow rate is represented by $Q_r$ . The wastage flow rate is represented by $Q_w$. In this study, BSM1 model has been used to analyze and evaluates the consumption of external carbon and another assessment aspect in WWTP.

The denitrification enhancement has been investigated by Peng *et al.* The nitrate utilization rate (NUR) method has been used in this research. This method estimates the denitrification potential for pre-denitrification system. The addition of external carbon source has been added into denitrification process. The result shown the carbon addition has succeeded to increase the denitrification process [20]. The denitrification enhancement using carbon addition also has been done by Battistoni *et al.* Cycle analysis, nitrogen mass balance, and oxidation reduction potential are the parameters for evaluating the performance of the method. The usage of carbon addition has been succeeded to increase the performance of nitrogen removal [21]. The usage of carbon addition leads to the rising of operational cost [11]. It is necessary to maintain the carbon addition supply to increase the effectiveness the usage of carbon addition.

Fuzzy-MPC (Model Predictive Control) based carbon controller has been proposed by Libelli *et al*. This type of controller collaborates two type controller namely Fuzzy logic controller and MPC controller. The researchers involve feed-forward signal in their design. The feed-forward signal is used as reference for future state. The controller maintain the nitrate level by manipulating the carbon addition dose in the anoxic tanks [22]. The MPC controller is model-based controller. The performance of the controller depends on the model. The unpredicted conditions would be affect the controller performance [23]. The model estimation also requires time and cost.

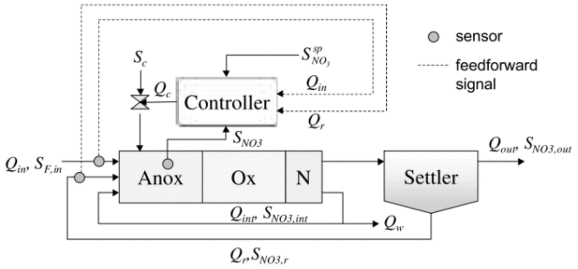



Fig.3. Fuzzy-MPC Control Strategy, Proposed by Libelli ,2002

The PI (Proportional Integral) based dissolved controller has been proposed by Revollar *et al* in 2018. This control strategy aims to increase the efficiency in the process of nitrogen removal. The controller maintains dissolved oxygen dose by manipulating the oxygen supply in aeration tanks. This research used three methods namely heating efficiency (HE), treatment efficiency (TE), nitrogen treatment efficiency (NTE), and mixing energy (ME). The result shown the control strategy has succeed to increase the efficiency of nitrogen removal process [24]. However, this control strategy is difficult to enhance significantly the pre-denitrification process, since the nitrification process only decomposes ammonia nitrogen into nitrate. The weakness of this control strategy is vulnerable to nitrate surge.

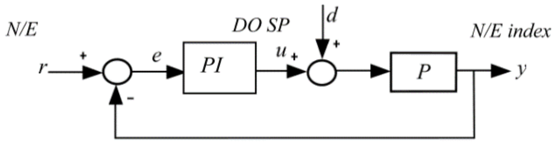



Fig.4. N/E Control Strategy, Proposed by Revoller,2018

The Fuzzy-PID based nitrate control strategy has been proposed by Gandha *et,al*. This control strategy still uses the default configuration for the plant. It involves the combination of PID controller and Fuzzy controller. The PID based-default nitrate controller has been replaced by Fuzzy-PID controller. The result of this control strategy is able to reduce ammonia and nitrogen level by 0.17 mg N/L and 0.1 mg N/L. The usage of the power consumption decreased by 193 kWh [25]. Figure 5 shows the schematic of the control strategy.

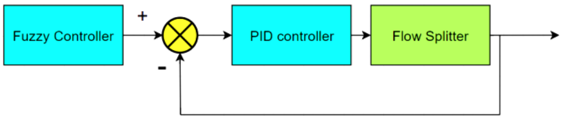



Fig.5. Fuzzy-PID Based Nitrate Control Strategy, Proposed by Gandha ,2016

This control strategy has several advantages. Firstly, the plant modification is not required. This solution is a cost-effective solution. Since this control strategy does not require additional cost to modify the plant. Secondly, this control strategy is easy to implement. However, this control strategy has a weakness in nitrate surge handling. This control strategy is unable to reduce nitrate concentration significantly when the nitrate surge occurred suddenly. This control strategy also has no features to control the carbon flow. Since this control strategy only used the constant carbon flow, the constant carbon flow dosing leads to the increase of operational cost and inefficient.

The control strategy proposed by this research has contribution to enhance the denitrification process by adding the carbon addition automatically. It expected to handle the nitrate surge. Since the carbon addition leads to the raising of the operational cost, the carbon controller has been used in this research to increase the efficiency of the usage of carbon controller.

The usage of external carbon source in water treatment process affects directly to the plant cost [11]. Therefore, it is important to examine reliability of the proposed controller. Since the PID-controller is a widely used type of controller that used by industrial process [12]. However, the implementation of traditional PID controller has several weaknesses. Firstly, PID based controller has overshoot. Secondly, the sluggish response is caused by sudden change in the system. The latest is the sensitivity to the controller gain [26][27]. The collaboration with Fuzzy controller is expected to overcome the disadvantage of PID controller. Comparing the performance of PID based-carbon controller and Fuzzy-PID based controller has been performed in this research.

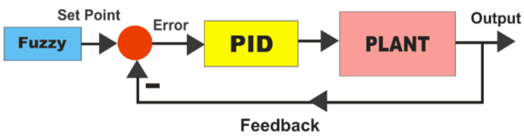



Fig.6. The Structure of Fuzzy-PID Controller

The schematic of control process is shown in the Fig.6. The input of the controller is the nitrogen total that produced by second anoxic tank. The amount of the nitrogen total would be controlled to certain value. The external carbon actuator is the object that manipulated by carbon controller. The maintaining the nitrogen amount is the aim of the actuator manipulation. This maintaining process would keep the amount of the nitrogen by dosing the carbon source to the anoxic tanks.

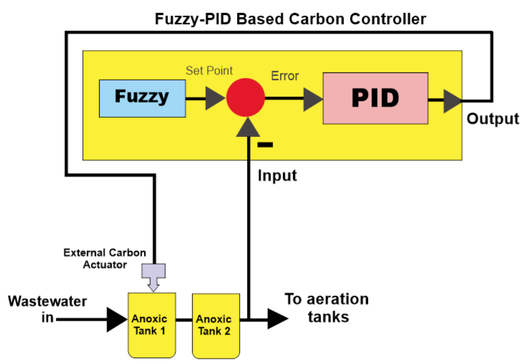



Fig.7. The Schematic of Control Process

The both scenarios of the examination have been performed in this research. Firstly, traditional PID controller was implemented to the system to control the external carbon actuator. Secondly, Fuzzy-PID based controller was implemented with the same scenario as well. Both controller attempt to maintain the amount of nitrogen total concentration by 10 mg N/L. The initial value for nitrogen total concentration is 7.49 mg N/L. In advance of examination is performed, the plant must be running in constant influent mode. The result of constant influent mode resulting the initial values for each parts of the plant. This initial values has been used to perform the simulation in dry weather.The examination scenario shown in Fig.8 and Fig.9.

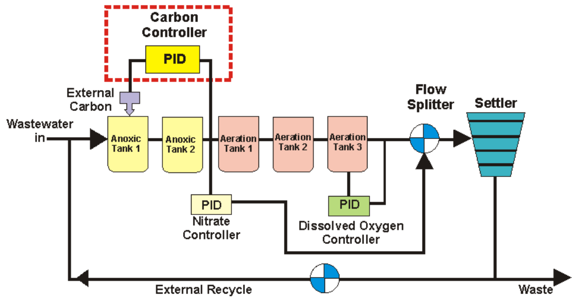



Fig.8. PID Based Carbon Controller Test Performance Scenario

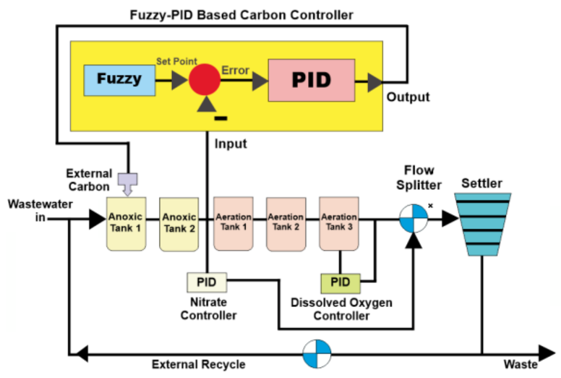



Fig.9. Fuzzy-PID Based Carbon Controller Test Performance Scenario

Several parameters have been assessed in order to evaluate the performance of the carbon controller, namely the carbon volume, the carbon mass, the power consumption and the nitrogen level.

## III. RESULT

The simulation has been carried out with initial condition where the plant had been stabilized using constant influent with no noise on the measurement. After initial condition has been accomplished then followed by weather influent data to be tested. The BSM1 simulation plant consists 3 weather influent data, namely dry, rain and storm [15]. The dry weather is the weather file that used in this research. The simulation has been tested with two scenarios. The PID parameter values of both controllers have been set to P = 2, I = 0.01, D = 0.1. The setting point value also has been set to 10 mg N/L. The performance result of both scenarios shown in the Table 1.

Table 1. Performance Comparison Result

| No | Performance comparison result | | | Unit |
|---|---|---|---|---|
| | **Evaluation Parameters** | ***PID*** | ***Fuzzy PID*** | |
| 1 | Total added carbon mass | 16611 | 16199 | kg COD |
| 2 | Total nitrogen concentration | 10.0243 | 10.0214 | mg N/L |
| 3 | Total aeration energy | 54354 | 54267 | kWh |
| 4 | Total pumping energy | 31097 | 31080 | kWh |

The implementation of Fuzzy-PID controller produces lower amount of total nitrogen concentration. It also requires lower carbon mass then PID based controller and decreases the energy consumption in aeration and pumping section by 104 kWh. A total of 412 kg COD of carbon could be saved by using the Fuzzy-PID controller for controlling the carbon addition in anoxic tanks.

## IV. DISCUSSION

The overshoot is a problem of the PID controller. The overshoot affects the stability of the controller performance. The implementation of PID controller into non-linear system leads to significant delay in response and require longer time to achieve stable state [28]. Wastewater treatment plant is a nonlinear system that involve biological reactor. Since the behavior of the microorganism inside the biological reactor is unpredictable, it could lead to the stability problem to the plant [7]. To overcome the stability problem, Fuzzy-PID based controller has been used to control the external carbon consumption. It is necessary to increase the efficiency of the usage of carbon consumption. Since the usage of carbon consumption leads to rising of operational cost plant [29].

The Fuzzy-PID controller consist two controllers namely PID controller dan Fuzzy controller. The traditional PID controller controls the nitrogen total concentration based on PID algorithm. The setting point of PID controller would be manipulated by Fuzzy controller in order to achieve the stable level of nitrogen total concentration. The discrete model of the Fuzzy-PID controller is shown below:

$$u(n) = K_p e(n) + K_i \sum_{i=0}^{n} e(n) T_s + \frac{K_D}{T_s} \Delta e(n) \quad (4)$$

$$e(n) = r_{fz}(n) - c(n) \quad (5)$$

The traditional PID controller signal $u(n)$ at any time $n$ could be expressed in equation 1. Where $T_s$ is sampling rate, $K_p$, $K_i$, $K_D$ are proportional, integral and derivative gain respectively. The manipulation of setting point of PID has been performed by Fuzzy-PID controller output. The error value ( $e(n)$ ) is the subtraction operation between setting point that generated by fuzzy ( $r_{fz}(n)$ ) and feedback value ($c(n)$).

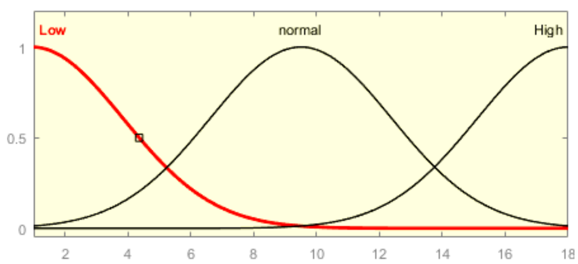
The set point manipulation of PID controller has been performed by Fuzzy controller (Fig.4) with the rules below:

If (input is low) then (output is low)

If (input is normal) then (output is normal)

If (input is high) then (output is high)

The membership functions of Fuzzy controller shown in the Fig 10.



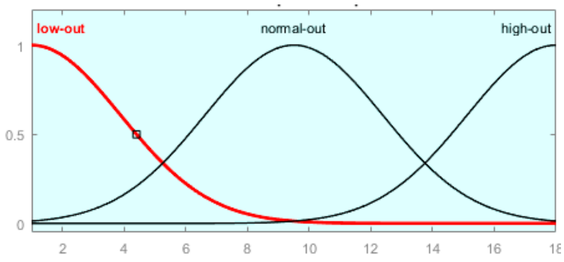



Fig.10. The Fuzzy's Membership Function of Input (Top) and Output (Bottom)

To assess the controller performance, the feedback signal has been compared in this research. The measured amount of the nitrogen concentration between PID controller and Fuzzy-PID controller show no significant differences (Fig.11). However, the significant differences occurred in the instantaneous carbon source dosing from the external carbon actuator (Fig.12).

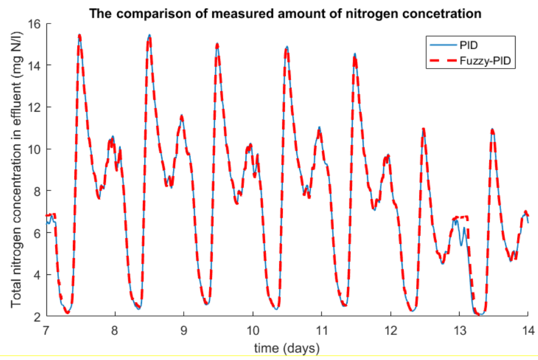



Fig.11. The Comparison of Measured Amount of Nitrogen Concetration Between PID Controller and Fuzzy-PID Controller

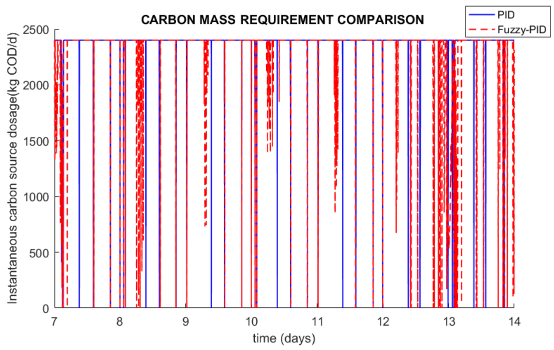



Fig.12. The Comparison of the Instantaneous Carbon Dosing Between PID Contoller and Fuzzy-PID Controller

The external carbon actuator is the object that actuated by controller (Fig.3). It doses the carbon directly into the anoxic tank. The amount of carbon dose affects the denitrification rate level in the anoxic tanks. The model of external carbon consumption is shown below:

$$EC = \frac{COD_{EC}}{t_{obs}\,.\,1000}\int_{t=7}^{t=14}\left(\sum_{k=1}^{k=n} Q_{EC,k}\right).dt \quad (6)$$

Where $Q_{EC,k}$ is the instantaneous carbon source dosing to compartment *k*. The concentration of readily biodegradable substrate in the external carbon source represent by $COD_{EC}$. The amount of $COD_{EC}$ is 400,000 g.COD/m3. The implementation of Fuzzy-PID controller saves 412 kg COD of carbon in total. The Fuzzy-PID controller has succeeded to increase the efficiency level of the carbon consumption.

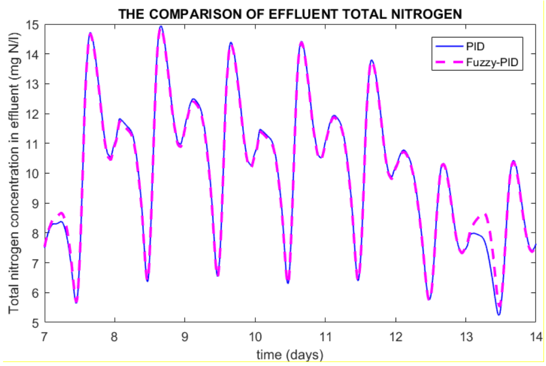



Fig.13. The Comparison of Total Nitrogen Effluent Produced by PID and Fuzzy-PID Controller

The decreased of the nitrogen total is caused by the reduced amount of nitrate nitrit nitrogen and or Kjeldahl nitrogen concentration. Since the total nitrogen ($N_{tot}$) is the sum operation of nitrate nitrit nitrogen ($S_{NO}$) and Kjeldahl nitrogen concentration ($S_{NKj}$) [1].

$$N_{tot} = S_{NO} + S_{NKj} \quad (7)$$

The Fuzzy-PID based carbon controller controls the carbon dose in order to maintain the amount of nitrogen total by 10 mg N/L in denitrification process. The effect of this control resulted in more stable amount of the nitrogen total concentration. The implementation of PID controller produces more nitrogen then Fuzzy-PID controller. Since the traditional PID controller has a sluggish response when it suddenly changes occurred [26]. The collaboration of Fuzzy controller and PID controller has succeeded to increase the speed response. To increase the time response of the PID controller, the Fuzzy will manipulates the setting point of the PID controller. By using this method, the faster response time could be achieved. The more stable control process of the denitrification leads to more efficient the usage of the carbon addition.

## V. CONCLUSSION

The denitrification process is the important process in the wastewater treatment plant. It decomposes nitrate to nitrogen gasses. Carbon addition is the material to enhance the denitrification process. However, the carbon addition leads to the raising of the operational cost. The controller is required to control the carbon dose in the denitrification process. The traditional PID controller is the widely used type of the controller. The traditional PID controller has several weaknesses when installed on the non-linear system such as wastewater treatment plant. The overshoot and sluggish response are the problems of the traditional PID controller. The collaboration between Fuzzy control and PPID control has been used to reduce the oversoot and increase the response time. The Fuzzy controller manipulates the setting point of the PID controller to achieve the faster response time and reduce the overshoot. By using such as configuration, the Fuzzy-PID controller has been succeeded to reduce the usage of the carbon than PID controller. The implementation of Fuzzy-PID controller is able to save the usage of carbon consumption by 412 kg COD. The nitrogen concentration, aeration energy and pumping energy also decreased by 0.0029 mg N/L, 87kWh and 17 kWh.

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