The analysis of the dynamic properties of the wastewater treatment process in a recirculating aquaculture system

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Abstract

The paper deals with the analysis of the dynamic properties of the wastewater treatment process in a recirculating aquaculture system. The goal of this analysis was to investigate the control possibilities of the nitrification processes that take place in the biological filter of trickling type, which is a component of the aquaculture plant. The analysis has been done on the basis of two experiments, made on a pilot plant located in the aquaculture laboratory of “Dunarea de Jos” University of Galati. The species Cyprinus carpio, which has an intense metabolism, was considered in order to obtain significant results regarding the use of control methods in increasing the efficiency of the aquaculture process. Thus the influence of the two control variables (water recirculation rate and aeration rate) has been investigated, but also the influence of the main disturbing variables of the aquaculture system. The results obtained in this work led to the conclusion that - due to the great complexity of the nitrification process and the specific of the trickling biofilter - a realistic approach of the recirculating system control consists in developing a rule-based system that uses qualitative descriptions and some "local" crisp models, established within the two mentioned experiments.

Keywords: Recirculating aquaculture system, Trickling biofilter, Nitrification and denitrification processes, Monitoring and control systems.

Introduction

Nowadays, modern aquaculture technologies are developed in recirculating systems, which require the use of high performance methods for the recirculated water treatment [1], [2], [3], [4]. Such a system includes the following essential subsystems: 1) tanks for the aquaculture biomass growth (fish); 2) a drum filter for the removal of solid particles from the water exhausted from the tanks; 3) a nitrification biological filter and 4) a denitrification filter. The aquaculture biomass produces organic matter in the tanks that must be removed. Through an aerobic process the heterotrophic bacteria convert the organic matter into more simple organic products, the final product being ammonium. The aerobic nitrification process that takes place in biofilter develops in two phases: ammonium is oxidized by the autotrophic bacteria (Nitrosomonas), resulting (NO₂⁻), and the nitrities are oxidized by another category of autotrophic bacteria (Nitrobacter), resulting nitrates (NO₃⁻). The two oxidizing processes are followed bu nitrification processes that lead to the nitrate conversion in gaseous nitrogen. The denitrification can be achieved by biological or chemical means.

The quality of the treated and recirculated water largely depends on the nitrification process performances [5]. Therefore, there is a justified interest for the nitrification modeling and simulation in the wastewater treatment plants [6], [7]. An approach that offers significant solutions to the modeling problem of the nitrification process consists in describing the nitrification through a modified version of the model ASM3_2N [8], including the situation when the nitrification is treated as a controlled process [9]. A constructive version of the
biological filter, essential in recirculating aquaculture systems, is the trickling filter. Its modeling is very difficult because the basic nitrification processes occur at a biofilm scale [10], [11]. The model of this filter is given by a set of partial derivatives equations with respect to two spatial coordinates [11].

A topical issue in modern aquaculture technology consists in the control of the recirculating systems. The main objective of such a monitoring and control system is to ensure the quality parameters of the recirculated water. Designing this monitoring and control system requires the knowledge of dynamic properties of the nitrification process, within a recirculating aquaculture system equipped with a biofilter of trickling type. The cited literature, concerning the dynamic properties of the trickling filter is not able to provide significant information, suitable for this task. The present work aims to obtain experimentally such information.

Materials and methods

Figure 1 presents the recirculating system scheme for fish intensive growth. The wastewater from the four aquaculture tanks is collected through natural flow to the mechanical treatment (drum filter), that is carrying out the slime separation and removal. Here the slime removal is done periodically and the exhausted water is replaced with water from the public network. Further on, the water from the drum filter is transferred with the pump P1 to the two filters (with sand and active carbon respectively) and then to the top of the trickling biofilter. The water collecting at atmospheric pressure is done in the tank located below the biofilter. From this point, the water is circulated by pump P2 through the chemical denitrification and UV filters, and then it is transferred under pressure in the aquaculture tanks. During operation, the sand and active carbon filters switch periodically into a washing regime, then they return to the normal working regime.

Figure 1. The structure of the recirculating system including the control equipments
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The aquaculture plant is equipped with a monitoring and control system which ensures the acquisition of the following process parameters: level, temperature and dissolved oxygen concentration in all four tanks, the inflow in each tank and the total flow measured to the tank output, the ammonium concentration measured to the tank output and after the biofilter, the nitrite and nitrate concentrations of the water in the four tanks, the dissolved oxygen concentration measured to the biofilter output, the pH - in the drum filter tank and to the recirculated water inputs in the four tanks. The plant is equipped with control systems for the following process variables: the dissolved oxygen concentration and the water level in each tank, the pH in the drum filter tank. The levels in the tanks located after the drum filter and after the biological filter are controlled by on/off controls of the pumps P1 and P2 respectively. The trickling filter was provided with an aerator, for the eventual control of the nitrification regime using the valve R9 (see Figure 1). The modification of the water recirculation flow in the aquaculture system is done through the level changing in the aquaculture tanks. For this purpose the relationship between the level steady-state values and the recirculation flow has been experimentally identified.

Figure 1 presents the main field equipments of the monitoring and control system. The objective of the control system is to maintain between the prescribed limits the values of the main parameters of the water quality in aquaculture tanks: the dissolved oxygen, ammonia, nitrite and nitrate concentrations.

The present paper aimed with priority the control possibilities of the nitrification process. It has been a priori admitted that this process can be controlled using two variables: the biofilter aeration rate and the water recirculation rate in the aquaculture system. Since the objective of determining the possibilities of biofilter control, the choice of a fish species with an intensive metabolism, aiming to produce significant variations of the main parameter followed in the biofilter (the ammonium concentration) was necessary. As a consequence the four tanks of the aquaculture pilot plant have been populated with the species *Cyprinus carpio*, which fully meets the purpose of experiments. The fish biomass consists in 2427 juvenile individuals of carp, with an average body mass of 22.68 g/individual. The biomass was randomly distributed in the four tanks of the recirculating system, the populating mode being presented in detail in Table 1. For the fish biomass feeding the fodder Optiline 1P of 2 mm with 44% protein (Table 2), distributed in two ratios, was used: 10% BW for the first two growth tanks, B1 and B2, and 5% BW for B3 and B4.

<table>
<thead>
<tr>
<th>Tank number</th>
<th>Quantity (kg)</th>
<th>Individual number</th>
<th>Average weight/individual (gr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1=13,616</td>
<td>665</td>
<td>20.47</td>
</tr>
<tr>
<td>2</td>
<td>C2=13,614</td>
<td>557</td>
<td>24.44</td>
</tr>
<tr>
<td>3</td>
<td>C3=13,855</td>
<td>614</td>
<td>22.61</td>
</tr>
<tr>
<td>4</td>
<td>C4=13,710</td>
<td>591</td>
<td>23.19</td>
</tr>
</tbody>
</table>

Table 1. The populating mode of the aquaculture tanks with juvenile carp

| Protein | 44 %                          |
| Grease  | 20 %                          |
| Cellulose| 3.0%                         |
| Ash     | 6.5 %                         |
| Phosphorus | 0.8%                     |
| Vitamin A | 9500 UI/kg                 |
| Vitamin D3 | 1500 UI/kg                 |
| Vitamin E  | 150 mg/kg                   |
| Vitamin C  | 150 mg/kg                   |
| Copper sulphate | 9 mg/kg         |

Table 2. The biochemical composition of the fodder OPTILINE 1P
The food was automatically distributed by means of two feeding conveyors with a 5 kg fodder capacity. The granules are uniformly spread by the stream, thus ensuring equal opportunities for all individuals from the tanks. For food administration two procedures were used:

1. continuous distribution of the fodder; the dispensers were loaded with food at 9 A.M. and the food was exhausted around 9 to 10 P.M. In this period, the amount of fodder had a slope variation;
2. discontinuous distribution of the feed, in 3 rounds, at 9.30 A.M., 2 and 6:30 P.M. In this case, the variation of the fodder amount was of "step" type. The goal was to observe the influence of fish feeding on the evolution the ammonium concentration measured after the biofilter.

Two experiments were performed. The first experiment was developed over the time horizon 07.10.2009-09.11.2009 and it used the continuous distribution of the fodder in the tanks. All variables of the recirculating system were recorded with a 10 minutes sample period. This experiment aimed the measuring of the influence of the ammonium concentration measured to the biofilter output on the biofilter aeration rate. The second experiment had a shorter duration (28/11/2009 - 4/12/2009) and it used the discontinuous distribution of the fodder. In this experiment a 1 minute sample period was used, aiming to observe better the dynamics of the ammonium concentration variation.

Results and Discussion

The most variables measured in the aquaculture process (ammonium, nitrite, nitrate and dissolved oxygen concentrations) are strongly affected by the following categories of disturbances:
1. disturbances generated by the feeding process of the fish biomass;
2. disturbances of noise type that affect the measured variables;
3. pseudo-periodical disturbances induced by the functioning of some components of aquaculture plant.

**Disturbances generated by the feeding process** are the most important from the control system objective point of view: maintaining in acceptable limits the quality parameters of the water in the aquaculture plant.

**Disturbances that affect the measured variables** are: the high frequency measuring noise and the slow drift of the acquired signals. The high frequency noise was practically removed by linear and nonlinear filtering procedures, implemented in the monitoring and control system. An important effect is given by the slow drift of the acquired signals in the aquaculture process, due to the biofilm deposit on the surfaces of the transducer sensitive elements. Even with a careful maintenance of the sensors aiming to reduce the measured values drift, there is a level of uncertainty regarding these values, which should not be underestimated.

**Internal pseudo-periodical disturbances** are generated by the drum filter and the filters with sand and active carbon respectively. In the drum filter the separation, the gradual accumulation and the sudden removal of the slime are done. Once the slime removal occurs, a quantity of water is exhausted from the recirculating system, with the consequence of the water level decrease in the aquaculture tanks. Level control systems ensure the compensation of the exhausted water with water brought from the public network through on/off controls. Under these conditions, the level in aquaculture tanks, but also the recirculation flow, has pseudo-periodical oscillations, which are transmitted as an internal disturbance to the other variables of the system. The filters with sand and activate carbon are cyclically by-passed and
put in washing regime. The important water lost from the plant, which accompanies this operation, is experienced when the filters are reintroduced in the recirculating system circuit, producing an appreciable decrease of the water level in the aquaculture tanks. The use of the water level control systems ensures the exhausted water completion with water from the public network.

**Results regarding the effect of the disturbances generated by the feeding process**

The experimental analysis of the water treatment process dynamics in aquaculture plants referred in the first instance to the evaluation of the biomass feeding effect, which generates the main disturbance in the recirculating system.

It is well known that the main effects of feeding and metabolic processes are:

- **a** – the increase of the organic matter concentration in the tanks from two sources: metabolism products and excreta, on the one hand, and the decomposition of the unused fodder, on the other. The heterotrophic bacteria that are growing in the tanks transform the organic matter into ammonium resulting in the ammonium concentration increasing to the biofilter input. This effect does not appear immediately after the food ratio administration, due to the biological processes at the aquaculture biomass level and to the microbiological processes in which the heterotrophic bacteria are involved;

- **b** – the increase of the oxygen consuming in the tanks.

The fodder was administrated discontinuously (as a portion), resulting the evolutions of the ammonium concentration measured to the biofilter input (NH₄C), the average concentration of the oxygen in the four aquaculture tanks (O₂) and the oxygen concentration to the biofilter output (O₂FB) that are given in Figure 2. A 1 minute sample period for data acquisition was used in the experiment. The ammonium concentration begins to increase suddenly after approximately 3 hours after the food administration, and then it returns in a steady-state regime after about 10-11 hours. Because of the water recirculation and the existence of the biological filter, the ammonium concentration does not accumulate and does not remain constantly, but gradually diminishes. The NH₄C(t) curve in Figure 2 can be interpreted as a response to a disturbance of step type of the recirculating system, representing the ratio of the food administration. The oxygen concentration in the tanks has a very important variation, since the start of the metabolic processes related to the feeding. The oxygen concentration measured to the biofilter output is affected in a lesser extent. In the experiment performed in the aquaculture laboratory, the biofilter worked having the aeration system in operation, which could explain the reduced effect of the disturbance on the variable O₂FB.

**Figure 2.** The evolutions of the ammonium concentration at the biofilter input (NH₄C[mg/l]), the average oxygen concentration (O₂[mg/l]) and the oxygen concentration at the biofilter output (O₂FB[mg/l])
Further on, the link between the variation of the ammonium concentration at the output of aquaculture tanks (NH₄C) and at the biofilter output has been examined. The subsystem corresponding to this channel was considered linear and it was identified by two methods: the least squares method and the one of the instrumental variable \[12\], resulting the following transfer function:

\[
H(z) = \frac{0.006308z^{-1}}{1 - 0.994z^{-1}}
\]  

(1)

Figure 3 presents the evolutions of the input/output variables of this subsystem, \(\Delta\text{NH}_4\text{C}(t)\) and \(\Delta\text{NH}_4\text{FB}(t)\), and the response of the identified system, \(\Delta\text{NH}_4\text{FB}_m(t)\).

![Figure 3. The validation results of the experimental identification of the interaction channel NH₄C(t)-NH₄FB(t) [mg/l]](image)

**Results regarding the control possibilities of the nitrification regime**

For the nitrification process control two control variables were considered: the recirculated water rate and the trickling biofilter aeration rate.

For economic reasons, the aquaculture plant in recirculating regime was provided with constant flow pumps that are on-off controlled by the level controllers. Under these conditions, the rate of the recirculated water rate may change indirectly through the water level in the aquaculture tanks. To illustrate the dependence: level in the aquaculture tanks - recirculation flow, in Figure 4 were graphically represented the evolutions of the water level in the four tanks (NB1 / 5,..., NB4 / 5), the inflow in the aquaculture tanks (DI) and the average value of this flow (DIₘ), obtained with a moving-average filter. Even if the inflow varies discontinuously, the average value of the recirculation flow follows the average level in the aquaculture tanks.

Therefore, the recirculation - flow-controlled nitrification process involves the modification between certain limits the water level in the aquaculture tanks. Further on the dependence: level in the aquaculture tanks - ammonium concentration measured to the biofilter output will be analyzed.

Figure 5 illustrates such a dependence, where LBₘ is the average level in the four tanks and NH₄FB, O₂BF are the ammonium and dissolved oxygen concentrations measured to the biofilter output. Although the evolutions of the mentioned variables are strongly disturbed, it can be noticed that, broadly, the dissolved oxygen concentration varies in phase with the
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water level from the tanks, whereas the ammonium concentration has a phase lag of $\pi$ in relation to the same water level (the recirculation rate). The recirculation rate decrease produces the increase of the organic matter concentration in the aquaculture tanks. As a consequence, the ammonium concentration increases and the oxygen concentration is reduced to the output of the four tanks.

![Figure 4](image1.png)

**Figure 4.** The relationship between the water level in the aquaculture tanks (NB[cm]) and the recirculation flow (DI[m$^3$/h])

![Figure 5](image2.png)

**Figure 5.** The relationship between the average level, LB$_m$[cm], and the ammonium and oxygen concentrations at the biofilter output (NH$_4$FB[mg/l], O$_2$FB[mg/l])

The second control variable provided for the nitrification process control was the biofilter aeration rate. It was experimentally found that the effect of the biofilter aeration on the ammonium concentration to its output is very low. Basically, the effects of aeration control cannot clearly discern in the very high level noise that exists in all the variables.
measured in the aquaculture pilot plant. The explanation results from the biofilter particularities used in the aquaculture system: in the case of the trickling biofilter there is an important contribution of oxygen, due to the existing space between the balls even if the aeration control is null. Since there is an intrinsic aeration, the aeration rate can be omitted as a biofilter control variable. However, the dissolved oxygen concentration to the biofilter input significantly affects the nitrification process. This statement is illustrated by the experimental recording shown in Figure 6, where the evolutions of the following variables are given: the average oxygen concentration in the aquaculture tanks (O₂B), the ammonium concentration to the tank output (NH₄C) and the concentrations of ammonium (NH₄FB) and oxygen (O₂FB) to the biofilter output. It can be noticed that the ammonium concentration to the trickling biofilter output can be controlled by the oxygen concentration in the aquaculture tanks. The oxygen concentrations in these tanks can be modified between certain limits, which are specific to the fish species that are growing in the aquaculture system. By changing the set points of the oxygen concentration control loops, the ammonium concentration to the biofilter output can be also controlled.

![Figure 6](image)

**Figure 6.** The relationship between the average of the oxygen concentrations in the tanks (O₂B[mg/l]), the ammonium concentration to the aquaculture tank output (NH₄C[mg/l]), the ammonium and oxygen concentrations at the biofilter output (NH₄FB[mg/l] and O₂FB respectively[mg/l]).

As a conclusion, the ammonium control methodology proposed in this section is illustrated in Figure 7:

![Figure 7](image)

**Figure 7:** Block diagram of ammonium control: NH₄FB[mg/l] - ammonium concentration at the biofilter output, O₂B setpoint, NB setpoint - setpoints of levels and oxygen concentrations in the aquaculture tanks [mg/l], DI – recirculated flow [m³/h], O₂B – oxygen concentration in the aquaculture tanks [mg/l].
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**Results regarding the effect of the internal pseudo-periodical disturbances**

Internal pseudo-periodical disturbances are caused by the operation of the drum filter and the sand and active carbon filters respectively. Figure 5 illustrates the cyclic variation of the water level in the aquaculture tanks, along with the slime removal, and the effect of the recirculation flow variation on the ammonium and oxygen concentrations to the biofilter output. Figure 8 illustrates the effect of the cyclic by-pass and entering of the sand and active carbon filters in washing regime. The coupling moments of these filters in washing regime are indicated by arrows. The important lost of water in the plant, generated by this operation, is experienced at the filter re-coupling in the recirculating system circuit, causing the sensitive decrease of the average recirculation flow in tanks (DIB). This decrease is compensated by the level control systems, by adding water from the public network.

The reducing of the oxygen content in the tanks (O₂B) and the slow increase of the ammonium concentration (NH₄C) are due to the system disturbing through the recirculation flow decrease. At the same time, the pulses of the oxygen concentration increase to the biofilter output (O₂FB) and ammonium concentration decrease (NH₄FB) are due to the fresh water contribution from the public network.

**Conclusions**

The obtained experimental results led to the following conclusions regarding the dynamics of the wastewater treatment process from a recirculating aquaculture system:

1. The acquired variables for process monitoring and control are affected by different and high level disturbances, caused by: high frequency measurement noise, the slow drift of the acquired signals (due to the biofilm deposited on the sensors), and the internal pseudo-periodical excitations generated by the operation of the drum filter and the sand and active carbon filters. These disturbances produce major difficulties in establishing the control model of the nitrification process.

2. The dynamic effect of the main disturbance of the system, which is the feeding rate (the fodder flow administrated to the aquaculture biomass), has been evaluated. It produces the increase of the ammonium content and the decrease of the oxygen concentration in the aquaculture tanks. The mathematical model that links the ammonium concentrations to the biofilter input and output has been identified.
3. The main control variable of the trickling biofilter is the recirculation flow. In the considered aquaculture plant, the recirculation flow is directly controlled through the set points of the level control loops in the tanks.

4. It was experimentally found that the effect of biofilter aeration on the ammonium concentration to its output is very low and therefore it does not justify the providing of an aerating system aiming to control the nitrification process to a biofilter of trickling type.

5. It was also experimentally found that the effect of the aquaculture tank aeration on the ammonium concentration to the biofilter output is significant. It was established that when needed, the oxygen setpoint in the aquaculture tanks can be used as a control variable for bringing the ammonium concentration to the biofilter output into the prescribed limits.

6. A hierarchical scheme with two control levels will be designed for increasing the efficiency of the aquaculture system. The first level (the basic control level) was mentioned in the paper. The second control level consists in an expert system that aims to give assistance to the operator about ammonium control and the decisions that must be taken in different phases of the aquaculture process.

The overall conclusion regarding the dynamics of wastewater treatment process in a recirculating aquaculture system is that - due to the great complexity of the nitrification process and the specific of the mentioned biofilter - a realistic approach of the recirculating system control consists in the developing of a rule-based system that uses qualitative descriptions and some "local" crisp models, established within the experiments performed in the aquaculture laboratory.

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