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Hydraulic System Modelling for an Intensive Aquaculture Process in Recycled Regime

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Abstract

The paper deals with the mathematical model of the hydraulic system of an intensive aquaculture process in recycled regime. It is necessary to the study of the equilibrium of the entire process from the hydraulic point of view. The whole mathematical model is composed by the models of all the plant components, such as: the aquaculture tanks, the pumping subsystems, the mechanical filter, the biofilter etc. The mathematical model has been numerical simulated and the results obtained in the paper were presented in the signal diagrams corresponding to the plant functioning in automatic regime.

Key words: *aquaculture process, biofilter, model and process control.*

Introduction

The modern technologies for fish growth in super-intensive regime use water recycling systems. An important condition for obtaining a high productivity is to ensure an adequate environment (quality food, supplying with refreshed water – without substances resulted from the metabolism of fish, such as organic substances, ammonium etc.). These systems require very performing water treatment systems, aiming to obtain a high efficiency of the fish growth [2, 5, 6]. Mainly, the obtaining of the culture product imposes the achievement of a very high growth rhythm in a very short time until the fish reaches the commercial size [3].

In the intensive aquaculture process in recycled regime three main subsystems can be identified: the subsystem for the fish growth itself (macro-biologic) the biologic water treatment subsystem (micro-biologic) and the hydraulic subsystem. The subsystems 2 and 3 are designed to ensure an adequate quality of water in the fish growing tanks [1].

In principle, the problem of water quality in the intensive aquaculture systems in recycled regime is essential. Practically, for a correct operation, in terms of getting a good efficiency to the process, the system must eliminate all the substances that influence in a negative way the fish health. Therefore, in the aquaculture plant various types of filter were provided aiming to ensure an efficient cleaning of water that turns back in the aquaculture tanks. Among these a very important role (the ammonium removal) has the biological filter. The ammonium removal is carried out in two phases: ammonium is oxidized to nitrite (NO_2^-), by the autotrophic bacteria (*Nitrosomonas*), then the nitrite is oxidized to another category of autotrophic bacteria (*Nitrobacter*) to nitrate (NO_3^-) [1]. The two oxidizing processes are followed by denitrification processes, leading to the conversion of nitrate in nitrite and then the nitrite is transformed in gaseous nitrogen [3].

Through the hydraulic system the water recycling in the aquaculture plant is achieved. It aims to ensure the plant equilibrium in terms of the volume of the water balance of the plant and compensate the water losses that occur due to the elimination of substances that result from the fish metabolism.

In essence, this paper is focused on the modelling hydraulic system, in order to design the automation system of the aquaculture plant.

The paper structure is as follows: Chapter 2 presents the intensive aquaculture pilot plant in recycled regime, Chapter 3 deals with the mathematical model of the hydraulic system of the aquaculture plant. It also presents the results obtaining through numerical simulation. The last chapter is dedicated to conclusions.

The Pilot Plant of the Intensive Aquaculture Process in Recycled Regime

The pilot plant for the fish intensive growth in recycling regime is located in “Dunarea de Jos” University from Galati, Food Industry Faculty, Aquaculture Department. It is exclusively used for the scientific research purpose (Figure 1). It was designed aiming the study of the development of various fish species, starting with the less demanding species (e.g. carp, waller), until "difficult" species as trout, sturgeons (beluga, sevruga etc.).

Fig. 1. The pilot plant of the intensive aquaculture process in recycled regime.

The technological scheme of the recycling system is shown in Figure 2. The system contains 4 octagonal tanks with capacity of 1 m^3 each, in which the intensive growth of fish takes place. The tank aeration is done in the following way: through the ejection effect the air from the atmosphere in the influx is transferred with special valves which bring water into the tanks. The wastewater from the four aquaculture tanks is collected through natural flow in the system of mechanical treatment (Drum filter). Here the separation and storage of the solids substances are achieved. Together with the solids removal, a part of the water is also removed, this being used to clean the filter. The compensation of this quantity of water is achieved by approximation and it is done manually from the water network. In the next phase the water flows into a tank with buffer accumulator role. From this tank, the water is transferred using a pump, to two filters (with sand and coal respectively) and it is brought to the top of the biological filter of trickling type. The trickling biofilter performs, under aerobic conditions, the conversion of the ammonium in nitrites and then in nitrates. An important drawback consists in the fact that the air refreshing does not take place in the environment where are found the trickling balls on which the biofilm is formed.

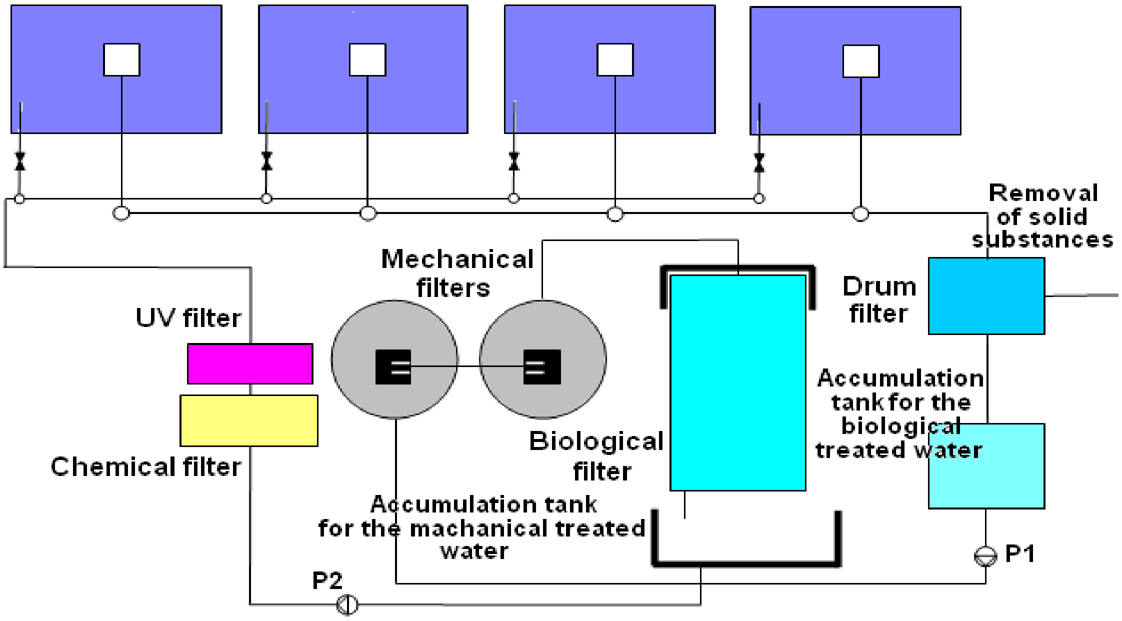

Fig. 2. The scheme of the intensive aquaculture plant in recycled regime.

Also, there is not an on-line monitoring of the efficiency of nitrification process. Collecting water at atmospheric pressure is done in the tank below the biofilter. From this point, the water is circulated, using the pump P_2, through the chemical filter (for denitrification) and UV filter, being transferred under pressure in the aquaculture tanks. A constant level is maintained in these tanks through an overflow system. Taking into account the existing technology and the elements needed for an optimal functioning of the plant the following functions must be accomplished by the automation system:

- for the aquaculture tanks: the control of the dissolved oxygen concentration and the temperature monitoring in the tanks;
- monitoring the ammonium concentration at the output of the aquaculture tanks;
- the pH control downstream the mechanical treatment;
- the control of the water level in the tank located after the mechanical treatment;
- the control of the ammonium concentration in the tank with biological filtered water;
- the control of the water level in the tank downstream the biological treatment;
- monitoring the water pH at the input of the aquaculture tanks;
- monitoring the nitrate and nitrite concentrations of the water inflow in the aquaculture tanks.

To these functions the monitoring of the whole hydraulic circuit is added.

The Model of the Hydraulic Processes in the Recycled System and Simulation Results

For modelling and numerical simulation of hydraulic system presented in Figure 2 the defining of the subsystems within whole recycled system was necessary. Between these, two subsystems will be presented separately in the following: the subsystem of the aquaculture tanks and the pumping subsystem (including the tank in which the on-off control of the level is achieved).

The aquaculture tanks subsystem

The model of the aquaculture tanks includes four state mathematical equations and algebraic equations describing the process of maintaining the water levels at the set point values. The mathematical model is the following:

$$\frac{dL_k}{dt} = \frac{1}{S}\left(Q_{in\_k}(t) - Q_{out\_k}(t)\right); \quad k = \overline{1,n};\ n = 4 \tag{1}$$

where: $Q_{in\_k}(t)$ is the water inflow in the tank *k;* $Q_{out\_k}(t)$ is the flow of the removed water from the tank *k*. The two flows are given by the following equations:

$$Q_{in\_k}(t) = \begin{cases} Q_{in}/n & if \quad L_k < h_{k\_p} \\ 0 & if \quad L_k = h_{k\_p} \end{cases} \tag{2}$$

$$Q_{in\_k}(t) = \begin{cases} 0 & if \quad L_k = h_{k\_p} \\ Q_{in}/n & if \quad L_k < h_{k\_p} \end{cases} \tag{3}$$

where Q_{in} is the inflow of the system consisting in the four tanks, ensured by the pump P_2 (see Figure 2) and h_{k_p} is the setpoint level in the tank *k*. The variable Q_{out} is the output flow of the system that is also input in the drum filter. The total inflow in the aquaculture tanks, Q_{in_b}, is:

$$Q_{in\_b} = Q_{in} - Q_{out} \tag{4}$$

The pumping subsystem

It is considered that the tank used for the water level on/off control is included in this subsystem. There are two pump systems (the pumps P_1 and P_2, see Figure 2), that have identical operating mode. The first system extracts the water from the tank located after the mechanical treatment and sends the water to the mechanical filters and trickling biofilter. The second system extracts the water from the tank located after the biofilter and sends the water through the chemical and UV filters, into aquaculture tanks. The tanks upstream the pumps are equipped with an on/off control system of the level. The inflows result through the water leakage from the aquaculture tanks and respectively from the biofilter. The exhausting flows are produced by the operating of the pumps attached to the tanks. It follows that the water flow repressed by each pump varies cyclically accordingly to the on/off operating regime of the level controllers. On the other hand, each pump is equipped with a hydraulic accumulator, corresponding to an air pillow. When the pump is starting, the hydraulic accumulator stores a volume of liquid based on the compression of the air pillow and the repression pressure increases. The pressure from the accumulator is controlled by on/off controller through the starting and stopping the electrical engine of the pump. The equivalent electrical scheme of the hydraulic circuit is presented in Figure 3.

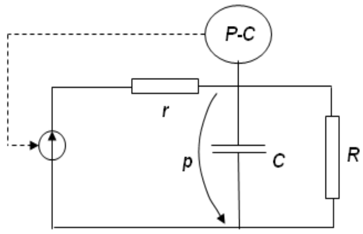

Fig. 3. The equivalent electrical scheme of the hydraulic circuit.

The following elements can be seen in Figure 3: the pump controlled by the on/off pressure controller (*P-C*); the *r-C* circuit corresponding to the accumulation system with air pillow; the pressure *p* that is on/off controlled; the load resistance, *R*, which is supplied by the pressure *p*. The resistance *R* corresponds to the hydraulic circuit consisting of: mechanical filters (for P_1), chemical and UV filters, and ejecting valves from the aquaculture tank input (for P_2). Further on, the mathematical model and numerical simulation scheme will refer to only one of the two pumping systems: the pump P_1. The pump used in the plant is of MCX200/65M type and it has a typical pressure-flow characteristic, *p(Q)*, presented in a polynomial expression, as follows:

$$p = \sum_{i=1}^{4} \alpha_i . Q^{4-i} \tag{5}$$

where the parameters α_i were calculated using the Matlab function *polyfit*. The following values have been obtained: α_1=-0.1000; α_2=0.2143; α_3=-0.2607; α_4=6.1607. The input variable of the pumping subsystem is the command 0/1 of on/off level controller. The output variable is the flow transferred to the mechanical filters and the biofilter. This flow is proportional to the pressure from the hydraulic accumulator, *p/R* (see Figure 3). The mathematical model of the system is given by the following equations:

$$p_{ref} = (\sum_{i=1}^{4} \alpha_i Q^{4-i}) \cdot u_{0/1} \tag{6}$$

$$T \frac{dp}{dt} + p = p_{ref} \tag{7}$$

$$Q_e = p / R \tag{8}$$

$$u_{pres} = His\{p, ep2, ep1, [10]\} \tag{9}$$

$$u_{0/1} = u_{pres} \cdot u_{reg\_level} \tag{10}$$

$$Q_a = C \frac{dp}{dt} \tag{11}$$

where: p_{ref} is the repression pressure of the pump. This is not equal to zero when the level controller commands the starting of the pumping system; $u_{0/1}$ – the command of the level controller; Q_e - the flow exhausted in the mechanical filters and biofilter; u_{pres} - the command given by the pressure controller attached to the pumping system; $His\{p, ep1, ep2, [10]\}$ - the hysteresis function of the pressure controller, characterized by the switching thresholds, *ep1* and *ep2*, with the commands values [10] in the states „on" and „off" respectively; Q_a - the flow to the hydraulic accumulator. Figure 4 presents the functioning of the pumping system through the following diagrams:

- the level controller command representing the input variable of the subsystem;

- the cyclic command of the pressure controller. It can be noticed that during the period when the input signal is equal to zero, the pressure controller gives the command „1", but the pump is stopped;
- the graphical representation of the repression pressure of the pump;
- the pressure *p* in the hydraulic accumulator;
- the flow towards to the accumulator. From the detailed representation it can be noticed that the flow towards to the accumulator is bidirectional: when the pump is running, the water is pumped towards to the accumulator and the main network (mechanical filters etc.). When the pump is stopped, within the on/off control cycle of the pressure controller, the water accumulated under pressure is partial exhausted from the accumulator;
- the liquid quantity stored in the accumulator.

The output variable of the subsystem is the exhausted flow. It is proportional to the pressure *p*.

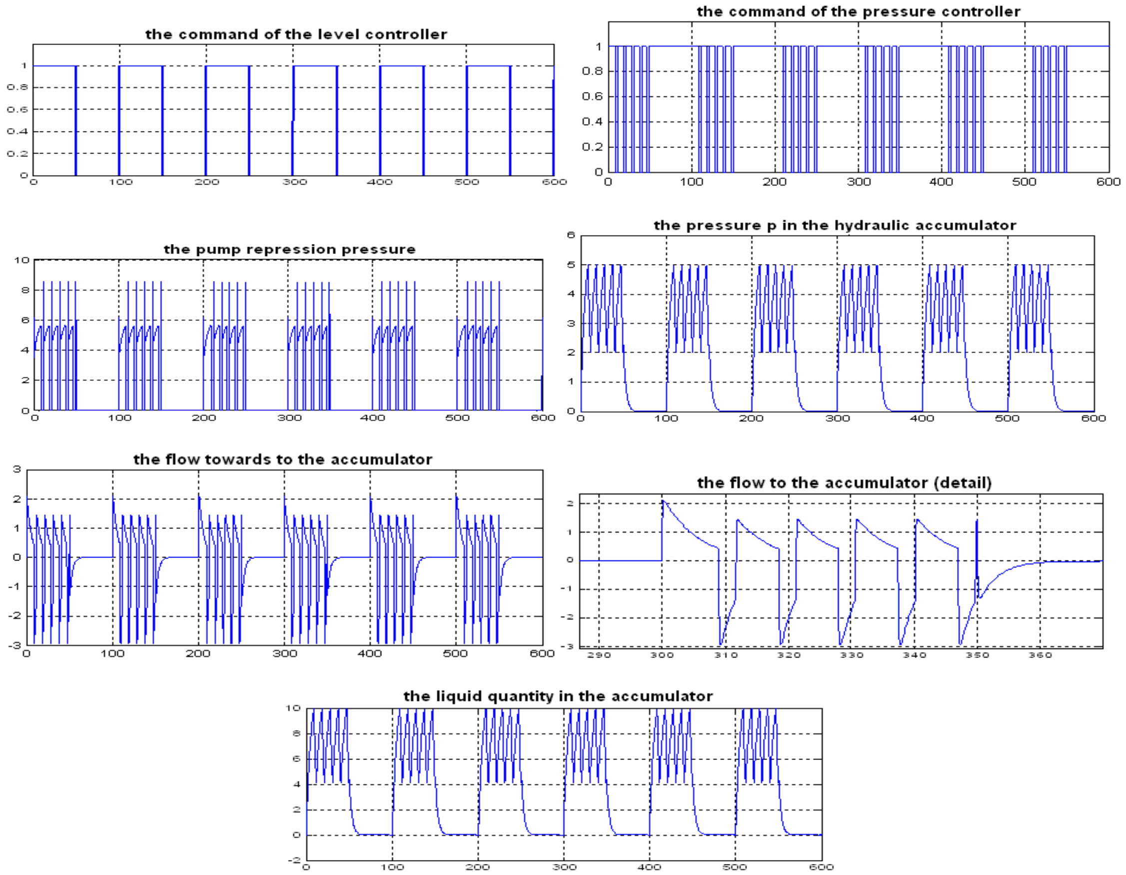

Fig. 4. Signal diagrams corresponding to the pumping system functioning.

Hydraulic recycling tank modelling and numerical simulation

For the achieving of the whole model of the recycling system the following subsystems were connected:

1. the system of the aquaculture tanks, heaving the mathematical model given by equation (1);
2. the subsystem for the mechanical treatment together with the tank attached downstream. It has been considered that the subsystem's dynamics is characterized by the following

transfer function (equation 12):

$$H_v(s) = \frac{1}{(100s^2 + 20s + 1)^2} \tag{12}$$

3. the on/off control system of the level of the tank located downstream to the mechanical treatment subsystem. The mathematical model corresponding to this subsystem is:

$$u_{n1} = His\{h_v, eps1, eps2, [01]\} \tag{13}$$

$$Q_{ep1} = u_{n1} \cdot Q_e \tag{14}$$

$$S_1 \frac{dh_v}{dt} = Q_{ev} - Q_{ep1} \tag{15}$$

where h_v represents the level of the tank located downstream to the mechanical treatment subsystem, u_{n1} is the command 0/1 of the on/off level controller P_1, characterized by the thresholds *eps1* and *eps2*, Q_{ev} is the outflow from the mechanical treatment subsystem and Q_{ep1} is the outflow from the tank;

4. the pumping subsystem P_1 (see Figure 2), heaving the mathematical model given by equations (6) – (11).
5. the subsystem corresponding to the mechanical filters and biofilter, together with the attached tank. It has been considered that its dynamics is characterized by the following transfer function:

$$H_v(s) = \frac{1}{100s^2 + 20s + 1} \tag{16}$$

6. the on/off control system of the level from the tank located downstream to the biofilter. The mathematical model of this subsystem is:

$$u_{n2} = His\{h_b, eps1, eps2, [01]\} \tag{17}$$

$$Q_{ep2} = u_{n2} \cdot Q_{ifc} \tag{18}$$

$$S_2 \frac{dh_b}{dt} = Q_{eb} - Q_{ep2} \tag{19}$$

where h_b represents the level of the tank located downstream to the biofilter, u_{n2} is the command 0/1 of the on/off level controller P_2, characterized by the thresholds *eps1* and *eps2*, Q_{ev} is the outflow from the biofilter and Q_{ifc} is the inflow to the chemical filter;

7. the pumping subsystem corresponding to the pump P_2 (see Figure 2), heaving a similar mathematical model to the one of the pump P_1;
8. the subsystem containing the chemical and UV filters. It has been considered that the dynamics of this subsystem is characterized by the following transfer function:

$$H_v(s) = \frac{1}{25s^2 + 10s + 1} \tag{20}$$

<u>Remark</u>: the transfer functions (12), (16) and (20) have been adopted on the basis of a priori information. They were not experimentally identified yet. The time constants of the transfer functions mentioned before are expressed in seconds.

For the simulation of the hydraulic recycling system a Matlab-Simulink scheme has been implemented. The signal diagrams are presented in Figure 5. The system starting is done manually. The water flow to the tanks input is firstly 4 [l/s] and then decreases, according as the tanks are filled. At the moment t=1000s (see the diagram (a)), all the tanks were filled and the filling flow becomes null. According as the level in some tanks is brought to the desired value, the outflow of the tanks increases till it becomes equal to the input one, when all the tanks are filled (see the diagram (c) in which the dynamics in the mechanical treatment unit is also reflected). Further on, till the moment $t \cong 1230s$ the outflow of the tanks is equal to the input one and in the mentioned moment the water recycling command is given. The inflows (diagram (b)) and the outflows (diagram (c)) will have an oscillatory component, but the system is stable with respect to the average value of the recycled flow. The following diagrams present the level variation in the tank downstream to the mechanical treatment subsystem (diagram (d)), the command of the level controller (diagram (e)), the exhausted flow from the pumping system P_1 (diagrams (f) and (g)), the biofilter outflow (diagram (h)), the level variation in the tank to the biofilter output (diagram (i)) and the exhausted flow by the pumping system P_2 (diagram (j)).

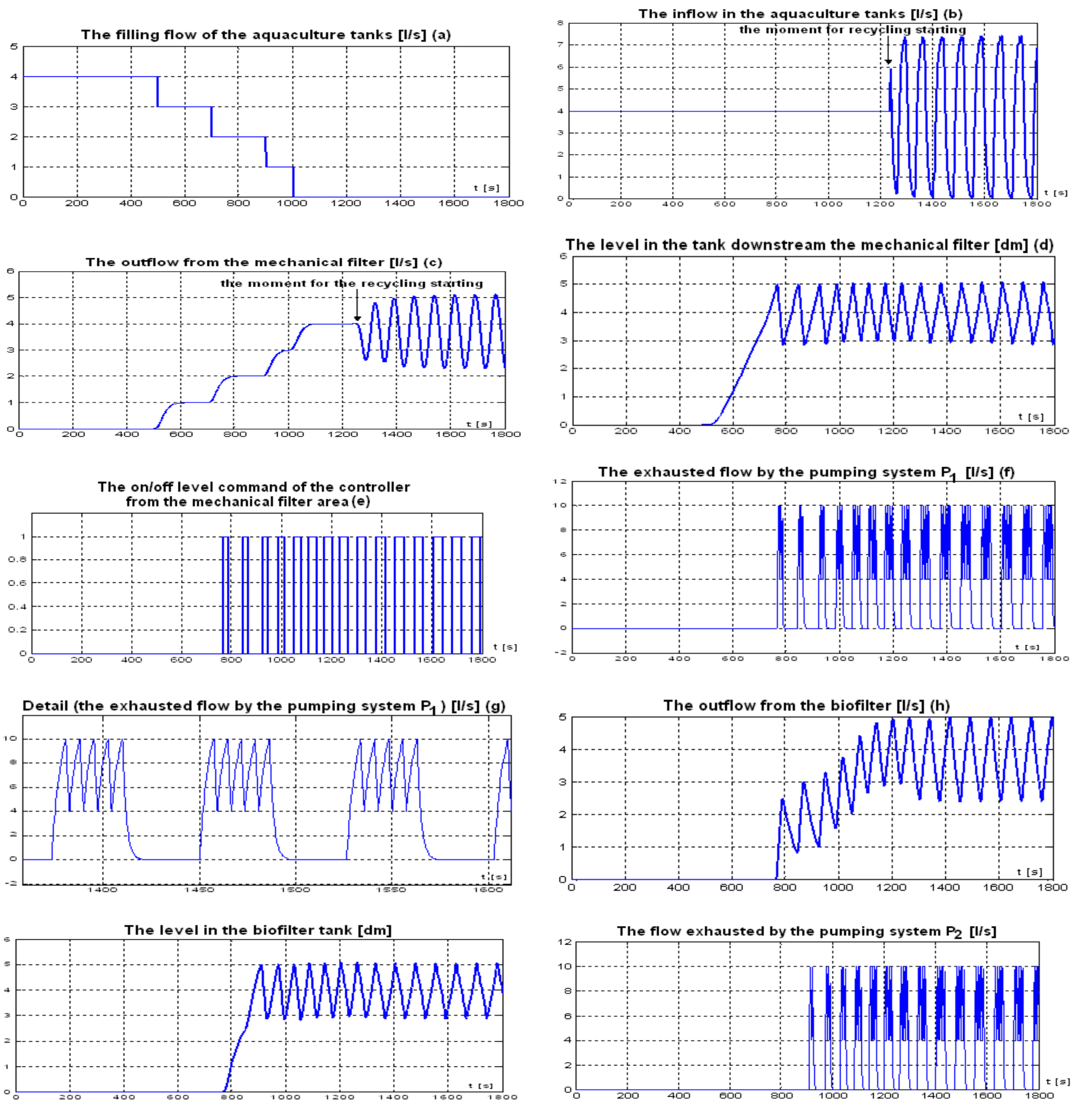

Fig. 5. The signal diagrams corresponding to the hydraulic recycling system functioning

Conclusions

Knowing the dynamics of hydraulic system is important in view of the requirement to ensure the stability in various operating regimes imposed by the aquaculture technology. The model developed in the present paper and the analysis performed through numerical simulation allowed the assessment of dynamic properties of the recycling system. In its operation, especially in the start regime, it may be obtained unstable regimes. The results presented in section three have allowed the detailing of the operating solution in the start regime of the plant, such that to ensure the stability of the recycling system.

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Modelarea sistemului hidraulic pentru un proces de acvacultură intensivă în regim recirculant

Rezumat

Lucrarea prezintă modelul matematic al sistemului hidraulic al unui proces de acvacultură intensivă în regim recirculant. Acesta este necesar pentru studiul echilibrului întregului proces din punct de vedere hidraulic. Modelul matematic de ansamblu este compus din modele ale componentelor instalaţiei tehnologice, cum ar fi: bazinele de acvacultură, subsistemele de pompare, filtrul mecanic, biofiltrul etc. Modelul matematic a fost simulat numeric şi rezultatele obţinute în lucrare au fost prezentate in diagrame de semnal corespunzător funcţionării instalaţiei în regim automat.

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