

BIO-FILTRATION STEP USE IN DRINKING WATER TREATMENT

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Abstract

The paper presents a case study, for the drinking water plants which involve a bio-filtration step used to reduce simultaneously, certain pollutants (iron, manganese, ammonia) in a single stage filtration. The bio-filtration step, with microorganisms multimedia doped layers was compared with a classic filtration step. The new approach shows the advantage of: higher yields of water pollutants reduction at low specific energy consumption. The bio-filtration process is preceded by an electrochemical pre-treatment whose role is: oxidation of dissolved substances from water, turn non biodegradable organic substances in biodegradable, favour coagulation and flocculation processes, bio-filtration process improvement. In order to optimize the process, was developed and validated a mathematical model of bio-filtration process.

Keywords: bio-filtration, electrochemical treatment, multiple oxidants, ammonia, drinking water

INTRODUCTION

Given the implementation of the water supply programme in the current phase for many rural human settlements from Romania whose consumption does not exceed 100...300 m³/day, the only source of water available in the neighbourhood is the under-ground water extracted from medium depth wells (150...200 m). These sources of water have constant parameters in time for many regions (Crişana, Banat, Oltenia, Bărăgan, Moldavia, Dobrogea) and they are impurified with iron ions, manganese, ammonia, nitrates and arsenic, in a higher concentration than the maximum value allowed by the legal norms. Water drinking stations have to run several treatment stages, which use quite difficultly purchasable chemical reacting agents that call for experienced water operators and all this effort is not justified for these relatively area where the water consumptions is relatively low. In order to meet these requirements and to mitigate the aforementioned pollutants, the biofiltration stage within the water drinking station is suitable for relatively because of is relatively easy to automate energetic and chemical consumptions. The process of biofiltrating the pollutants from the water meant to make drinkable water was highlighted by chance in certain water drinking stations when no reacting agents were added during the chemical treatment stage and the filters were cleaned more rarely, and an improvement of

the processed water parameters has been noticed. When the processed water parameters (in-out) were correlated to the population of bacterial cultures developed in the filtrating environments, the processes began to be understood. They were subsequently applied in order to enhance the performances of certain existing processes and especially for being used as a basis for a new generation of biological treatment processes, providing a sudden improvement of the biofiltrating performances. Technically speaking, drinkable water obtaining by biofiltration consists in 'preparing the water for biofiltration', which most of the times means airing the water, with holding the unwanted substances (the water pollutants) in the filtrating layers by developing specific bacterial cultures that feed on these pollutants, followed by a stage of enriching the water in oxygen in order to enhance the stability of the water parameters in its distribution system and the disinfection stage, for hindering the water from transmitting diseases.

WATER POTABILISATION FLOW PRESENTATION

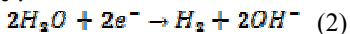
The water potabilisation process generally used by authors for the three treatment stages was implemented in the township station. The stations supply water to the human settlements where the sources of water are the wells from the second source of ground water.

The '*Water Preparation for Biofiltration*' by ozonisation or electrochemical treatment supplemented with water aeration under pressure were used. The process of ozonisation or electrochemical treatment followed by aeration aims at oxidising the ions dissolved in the water at a superior valence condition, in order to retain them in the filtrating materials. The aim is to diminish the natural organic matter (NOM) by total or partial oxidation until inorganic oxides or a biodegradable organic matter and to enrich the water with oxygen for favouring the nitrification-denitrification reactions in the biofilter. In the water treatment electro-chemical process, the electrodes (at least one cathode and an anode) are inserted either directly in the amount of water that needs treating or in a by-pass pipe. A direct or pulsating current is applied between the electrodes, thus giving birth to water electrolysis and causing the reaction to take place in situ.

At the anode, the main product is oxygen and water acidification takes place near the anode :



At the cathode, hydrogen gets formed, the water near the cathode thus becoming alkaline :



The utilisation of current pulses and the turbulent flow on small radius edges lead to local areas with high density dissipated energy, which make possible certain chemical reactions that do not take place under normal conditions, followed by a nanometrical dispersion of the reaction products. Electro-chemical oxidation is an efficient electro-chemical technique, which is used to oxidise various water compounds. This technique is also environmentally friendly, as no chemical reacting agents are used. Electrochemical oxidation depends on the anode selection. This can be initiated by the direct transfer of one or several electrons from the sublayer to the anode or the sublayer can be indirectly oxidised by the intermediaries formed as a result of water oxidation. The electrochemical treatment at the cathode leads to hydrogen release in small amounts (approx. 0.4 l of hydrogen under normal conditions are generated by an

amper*hour), which in most cases does not cause problems.

The following effects arise after the electrochemical treatment: water pre-disinfection, organic substances, ammonia and nitrates reduction.

One-stage '*Biofiltration*' was applied in a filter doped with specific target pollutant-mitigating bacteria, at an adjusted concentration of the oxygen from the water. The granular active carbon (GAC) filters with quartz sand were noticed to be able of eliminating NOM beyond the adsorption capacity, which has led to the development of certain biofiltration processes for treating drinkable water. Seeing the low maintenance costs and the pollutant mitigation efficiency, biofiltration has become an attractive treatment process. When new biofilters are commissioned, they undergo the colonisation phase for a full biodegradation activity. Biofilm increase in the new filters is a slow process, which takes months. In order to reduce the biofilter generation time, the filtrating materials upon mounting are doped with specific pollutant mitigation bacteria.

'*Water Disinfection and Oxygen Enrichment*' take place in a stage with ozone obtained from oxygen. In case that the drinkable water supply systems do not seem safe, namely they are old, full of deposits and run a high risk of infesting the water in the mains, the water disinfection flow is supplemented by dosing the sodium or calcium hypochlorite.

PRESENTATION OF A BIOFILTER WITHIN THE POTABILISATION STATION

In nature, bacteria do not exist as isolated cells, but they grow and survive in organised communities. In suspensions they can generate flakes, liquid films and the germ communities that get developed at such stage interfaces as solid-liquid or air-liquid are called biofilms. Generally speaking, biofilms can be used to treat waters, to perform biological purifications – to remove unwanted substances from the water, in food – for food digestion, but they can also be harmful – for instance the biofilms that get formed on the dental plate and the medical prosthetics or in the drinkable

water tanks and conveying pipes. The aggregates of cells and other particles accumulated on the surfaces are called biofilms. They can inevitably get formed at any interface (liquid or solid) in contact with water. In the drinkable water, the biofilms are composed of functionally organised complex microbial communities incorporated in a jelly matrix of extracellular polymers excreted by microorganisms. Any inorganic or organic substances that pass close to biofilms (corrosion products, clay, sand) may also be incorporated into biofilms. Biofilm development can take days or even months, subject to the organic concentration of the influent. The critical point for a successful biofilter operation consists in controlling and maintaining the biomass in a good condition on the surface of the supporting medium. Since the biofilter performance depends on the microbial activity for a long-lasting operation, a constant quantity of sublayer (organic substances and nutrients) is needed in the influent. According to the manner of using energy, the biochemical processes from the living cell, called metabolism, can be divided into: a) dissimilation or catabolism processes, which consume organic matters and produce energy as a result of substance degradation (exothermal); b) assimilation or anabolism processes, which encompass the reactions that lead to the synthesis of a new cell material according to the energy released in the catabolism phase (endothermal). In both phases, the extremely complex biochemical reactions take place in successive stages, each stage being catalysed by specific enzymes. The biofilm development on the surface of the solid matters in contact with water undergoes four evolution phases

- the formation of the conditioning film;
- the initial microorganisms adhesion onto the surface;
- biofilm increase;
- biofilm maturation – a balance between accumulation and detachment.

The biofilms development, morphology and physical stability are influenced by several factors: temperature and pH, the chemical and hydrodynamic conditions, the sublayer nature and nutrient supply. Any changes in the water chemistry can destabilise

the biofilm, causing its fracture. Any high flowing speeds (turbulent flow rates) can lead to biofilm shearing. Both processes may lead to the mobilisation of the microbial material through the pore system, thus determining germ enhancement in the effluent, with negative results for biofiltration. The bacteria cultures seen in the drinkable water transport and processing are linked to the substances dissolved in the water, which alongside carbon are used by them as nutrients. They are :

- bacteria from the nitrogen cycle, especially the nitrification and denitrification ones;
- bacteria from the iron and manganese cycle;
- bacteria from the sulphur cycle.

The nitrification filter (ammonia reduction)

These cultures adhere to the surface of the filtering material and consume the ammonia, which they turn into nitrites (the specific culture of *Nitrosomonas spp.*).



In the latter stage, the nitrite-oxidising bacteria (*Nitrobacter*) oxidise nitrites at nitrates. The reaction speed of the nitrite oxidation in nitrates is lesser than the nitrification reaction, so that the speed of the entire reaction chain is determined by the speed of this reaction :



For these reactions to be able to take place, the concentration of the oxygen dissolved in the influent water must be sufficient, taking into account that each mg of ammonia needs 4.5 mg of oxygen. If the ammonia concentration in the influent is higher than 3 mg/l, the necessary oxygen is greater than the concentration dissolved in the influent and the difference is added to the basis of the filter, like in Figure 1. In order to keep the biofilm active, the filter must be filled with water all the time, even if it is not functioning (the exit piece in the figure). Moreover, the biofilm needs a source of organic carbon or carbon dioxide and phosphorus for breathing and growing. If these components do not exist in the incoming water, the indicated substances are dosed in the influent.

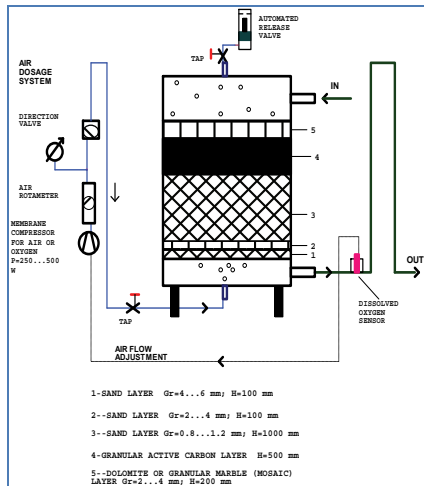


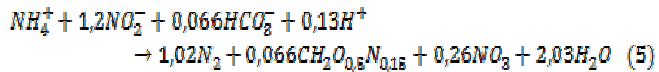
Figure 1. Theoretical scheme of the nitrification biofilter (ammonia)

The filtering layers within a nitrification filter considered from upstream to downstream are :

1. the 0.2 m high granular marble layer (granulation: 2...4 mm), meant to correct the pH and to fix the lower filtration layer – in case of acid waters
2. the 0.8 m high granulated active carbon (charcoal) layer, meant to support the biofilm and to be an additional source of carbon for it;
3. the 1 m high quartz sand layer (granulation: 0.8...1.2 mm), meant to adsorb unwanted compounds and to support the biofilm;
4. the 0.1 m high quartz sand layer (granulation: 2...4 mm), meant to support the upper filtration layers and to even the water and air flow rates;
5. the 0.1 m high quartz sand layer (granulation: 4...6 mm), meant to support the upper filtration layers and to even the water and air flow rates. Total height of the filtrating layers: 2.2 m.

In case that the amount of oxygen inserted at the basis of the filter is reduced, the afore described nitrification reaction undergoes changes: the ammonia ion reacts with the nitrite ion (resulted from the nitrification reaction, as well), the result being gaseous nitrogen and approximately $\frac{1}{4}$ of the nitrate ion, as compared to the nitrification that takes place under a sufficient concentration of oxygen. This partial nitrification reaction,

called ANAMOX, is very useful in the biofiltration step, as the concentration of the nitrate ions dissolved in the effluent is low. The Anamox reaction is given below:



In order to provide a good filter control and stability, in the sense of maintaining the partial nitrification reactions (ANAMOX), the oxygen at its basis must only be dosed as much as the process requires. This can be achieved by measuring the oxygen dissolved in the water that comes out of the biofilter and by inserting this size in a loop of adjusting the flow rate of the oxygen injected at its basis. In case that the filter is used for denitrification purposes, no air or oxygen is inserted at the basis of the filter. If there is iron and manganese in the water, they are mainly retained in the upper layers of the biofilter, in the layer of marble and active carbon. The filter is usually washed up every 2...3 weeks only with water, from the bottom upwards, under moderate conditions, that is at a flow rate approximately double the nominal one. Since the concentration of the oxygen dissolved in the effluent is lower than the minimal concentration imposed for the drinkable water, the water after biofiltration has to be enriched in oxygen, which takes place in the ozone disinfection stage, the goal being water taste correction, too.

BIOFILTRATION STAGE MODELLING

A mathematical template is a systematic attempt of conceptually translating the understanding of the real world phenomena into mathematical terms in order to assess the future statuses of the template, departing from a certain current status. That is why a template is a valuable system for testing our understanding about how a system works. By simulating various scenarios (the incoming parameters course in time), the templates allow the users to adjust such operational parameters as the processed water flow rates, the air or ozone doses, the operation times etc. at optimal levels. From the viewpoint of the course in time, the templates are static (they are not time-dependent or they are templates that reach

equilibrium) and dynamic (templates in transition).

For modelling a process produced in a bioreactor (biofilter), like in any other case, one departs from the weight and energy conservation relation for every chemical species and for the entire system. In this case we treat all microorganisms as a system to which an average growth rate is assigned. By applying the law of conservation :

$$\frac{\text{Accumulated rate}}{\text{in the volume } V} = \frac{\text{incoming rate}}{\text{in the volume } V} - \frac{\text{outgoing rate}}{\text{in the volume } V} + \frac{\text{Reaction-derived rate}}{\text{in the volume } V} \quad (6)$$

Total weight result :

$$\frac{d(V \cdot \rho)}{dt} = \rho(Q_0 - Q_1) \quad (7)$$

where :

- V: the reactor (biofilter) volume – measured in m³ ;
- Q₀: the incoming flow rate – measured in m³/s ;
- Q₁: the outgoing flow rate – measured in m³/s ;
- ρ: the liquid (water) density – measured in kg/m³.

For a certain sublayer S (sublayer meaning a chemical substance undergoing a reaction – for instance ammonia, nitrate):

$$\frac{d(V \cdot S_1)}{dt} = Q_0 \cdot S_0 - Q_1 \cdot S_1 + r_S \cdot V \quad (8)$$

where :

- S₀: the incoming concentration – measured in kg/m³ ;
- S₁: the outgoing concentration;
- r_S: the rate of reducing the pollutant S by the biofilm X – measured in kg/(m³ sec.)

Reaction rates (speeds):

$$r_X = \mu \cdot X_1 = \frac{\mu_{MAX} \cdot S_1}{K_S + S_1} \cdot X_1$$

and

$$r_S = \frac{-r_X}{Y_{N/S}} = -\frac{\mu_{MAX} \cdot S_1}{K_S + S_1} \cdot X_1 \quad (9)$$

where:

- μ: is the specific growth rate of the microorganisms
- μ_{max}: is the maximum specific growth rate of the microorganisms
- K_S: is the "half-velocity constant"

The reaction speeds r_i are reduced from the stationary status (the equilibrium one, namely dS/dt = 0 and dX/dt = 0). The reaction rates are of the Monod-type. The system of differential equations that gets formed departing from relation 8, where the reaction rates rendered by relation 9 are inserted, turns into a system of integral equations (10), which represents the sublayer and biomass course subject to time. This is the simplest biofilter template for reducing ammonia and it expresses the template transition from the initial status to the dynamic equilibrium one.

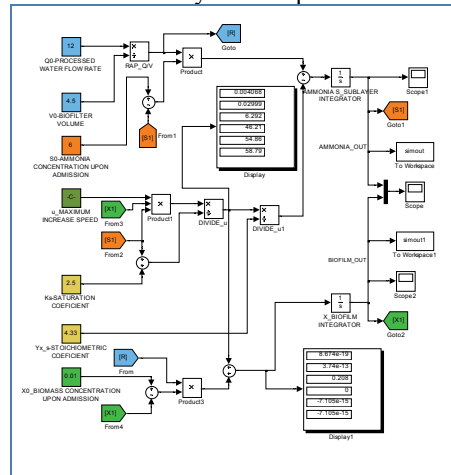


Figure 2. The Simulink template of the equation system (10)

$$dS_1 = \int \left(\frac{Q_0}{V} \cdot S_0 - \frac{Q_1}{V} \cdot S_1 - \frac{\mu_{MAX} \cdot S_1 \cdot X_1}{K_S + S_1} \cdot \frac{1}{Y_{N/S}} \right) \cdot dt$$

$$dX_1 = \int \left(\frac{Q_0}{V} \cdot S_0 - \frac{Q_1}{V} \cdot X_1 - \frac{\mu_{MAX} \cdot S_1 \cdot X_1}{K_S + S_1} \right) \cdot dt \quad (10)$$

The system of integral equations from relation 10 can be simulated by means of the SIMULINK template within the Matlab software – set out in Figure 2.

The nitrification reaction in the volume of the biofilm fixed onto the filtering material surface takes place in two steps: ammonia oxidation at the nitrites, followed by the nitrites oxidation at the nitrates. This means that the biofilter is deemed to be composed of two subsystems of micro-organisms, to which average growth rates are assigned. The sublayer penetrates inside the biofilm by diffusion. The biomass growth rates inside the

biofilm are neglected, so the biofilm is considered to be stationary. The biochemical reactions that are taken into account are rendered by the relations 3 and 4 from the paper. The oxygen requirements give rise to the stoichiometric coefficients of the reactions; thus : $Y_1 = 3.5 \text{ mg O}_2/\text{mg NH}_4^+$ and $Y_2 = 1.1 \text{ mg O}_2/\text{mg NO}_2^-$. The rates of the biochemical reactions mentioned above are rendered by relation 11 and have the form of the twofold Monod relations :

$$r_{NH_4^+} = \mu_{Max1} \cdot \left(\frac{NH_4^+}{K_{NH_4^+} + NH_4^+} \right) \cdot \left(\frac{O_2}{K_{O_2} + O_2} \right)$$

And nitrites oxidation

$$r_{NO_2^-} = \mu_{Max2} \cdot \left(\frac{NO_2^-}{K_{NO_2^-} + NO_2^-} \right) \cdot \left(\frac{O_2}{K_{O_2} + O_2} \right) \quad (11)$$

The mass result for the system constituted from the biofilm can be written as follows:

$$\frac{\text{Accumulated rate in the biofilm}}{\text{In the biofilm}} = \frac{\text{diffused rate incoming}}{\text{Incoming}} - \frac{\text{diffused rate outgoing}}{\text{outgoing}} + \frac{\text{Reaction-derived rate in the biofilm}}{\text{in the biofilm}}$$

For the water filters, so for biofilters too, the system of axes can be reduced to two sizes: a height axis, usually put down as x on the water flowing direction and a radius axis, usually put down as z , on the biofilm development direction. Deeming that the biofilm got developed evenly on the x water flowing direction, the result relation for the sublayer can be written in the following way :

$$\frac{\partial S}{\partial t} = D_S \cdot \frac{\partial^2 S}{\partial Z^2} + r_S \quad (12)$$

As a particularisation for each sub-layer chemical species :

$$\frac{\partial NH_4^+}{\partial t} = D_{NH_4^+} \cdot \frac{\partial^2 NH_4^+}{\partial Z^2} - r_{NH_4^+}$$

$$\frac{\partial NO_2^-}{\partial t} = D_{NO_2^-} \cdot \frac{\partial^2 NO_2^-}{\partial Z^2} + r_{NH_4^+} - r_{NO_2^-}$$

$$\frac{\partial NO_3^-}{\partial t} = D_{NO_3^-} \cdot \frac{\partial^2 NO_3^-}{\partial Z^2} + r_{NO_2^-}$$

$$\frac{\partial O_2}{\partial t} = D_{O_2} \cdot \frac{\partial^2 O_2}{\partial Z^2} - s_1 \cdot r_{NH_4^+} - s_2 \cdot r_{NO_2^-} \quad (13)$$

Like in case of the equation system 10, by means of the system 13 of partial derivative equations, a SIMULINK template is elaborated in the Matlab software. The time-dependent sublayer course in the biofilter complies with

relation 14. The flow of processed pollutant (sublayer) depends on the moment from which the biofilter was commissioned. For each pollutant (ammo-nium, iron, manganese), the coefficient that represents the oxygen demand has another value, namely:

$$J_{\text{pollutant}}(t) = \frac{J_{O_2 \text{ max}}}{C_{\text{need } O_2}} \cdot \left(\frac{C_{\text{pollutant}}}{K_{\text{pollutant}} + C_{\text{pollutant}}} \right) \cdot E_0 \cdot \exp(-k_N(t) \cdot H) \quad (14)$$

where :

- $J_{\text{POLLUANT}}(t)$: the flow of (POLLUTANT) that enters the biofilm ($\text{g}/\text{m}^2 \times \text{day}$) ;
- $J_{\text{OXYGEN-MAX}}$: the oxygen flow, which depends on the filtrating material characteristics ($\text{g}/\text{m}^2 \times \text{day}$) ;
- $C_{\text{OXYGEN-NEED}}$: the stoichiometric coefficient of the biochemical reaction ;
- K_{POLLUANT} : the half value of the pollutant concentration saturation value (mg/l) ;
- C_{POLLUANT} : the pollutant concentration upon admission (mg/l) ;
- E_0 the (no size) biofilter efficiency ;
- $k_N(t)$: the empirical constant for reducing the pollutant to time t since the biofiltration begins (m^{-1}) ;
- H : the biofiltrating layer height (m).

The previous relation lead to relation 15, which is a dynamic equilibrium one, used for designing purposes. In this relation, the parameter E_0 has to be known, as it represents the efficiency of reducing the pollutant by the biofilter, which is generally achieved after several days of biofilter operation and which depends on the hydraulic load of the filter (the water flow rate as compared to the filter surface). The values of this size come out after experiments.

$$C_{NH_4^+ \text{ out}}(t) = C_{NH_4^+ \text{ in}} \times \exp [-(k_{\text{real}}(t) \cdot H_{\text{real}} + k_{\text{stand}}(t) \cdot H_{\text{stand}}) \cdot Q^{0.6}] \quad (15)$$

where

Q is the specific flow rate and the value of m is -0.68 .

$C_{NH_4^+ \text{ out}}$ - ammonium concentration at the outlet

$$C_{NH_4^+ \text{ out}}(t) = C_{NH_4^+ \text{ in}} \cdot \exp [-(k_{\text{biofilter}}(t) \cdot H_{\text{biofilter}}) \cdot Q^{0.6}] \quad (16)$$

RESULTS AND DISCUSSIONS

The biofilter was tested in two stages, at a 15 m³/h flow rate. In the first stage, the height of the active carbon layer was 0.3 m and the height of the sand layer was 1.2 m. As the results regarding the concentration of the ammonia in the effluent were not satisfactory, the height of the active carbon layer was increased to 0.65 m, the height of the sand layer being the same. The concentration of the ammonia in the influent remained constant all along the water station commissioning tests and the water from the wells preserved its parameters. Figure 3 graphically renders the ammonia concentrations calculated by means of the relation 16 upon the biofilter exit, subject to time for the aforesaid water flow rate and the measured average values.

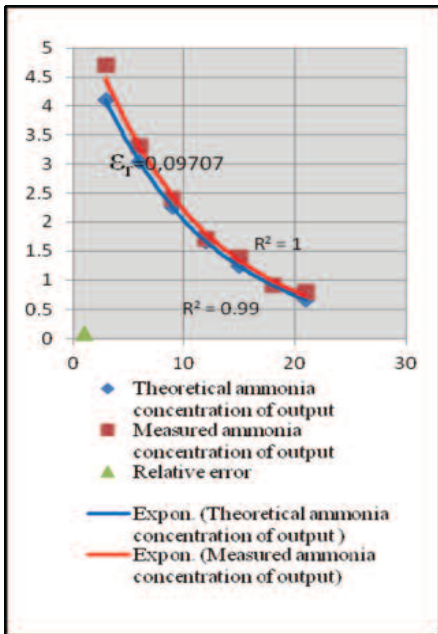


Figure 3. Calculated and measured concentration of ammonia upon exiting the biofilter : case 1

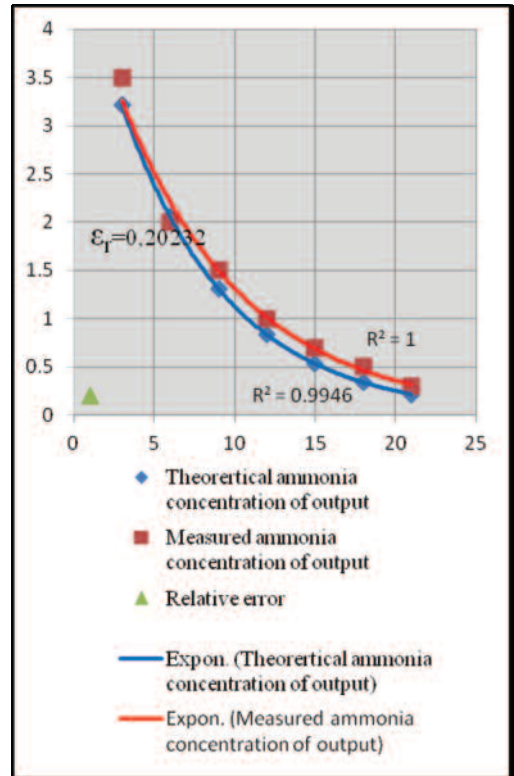


Figure 4. Calculated and measured concentration of ammonia upon exiting the biofilter : case 2

Relative error calculation formula :

$$\varepsilon_r = \sqrt{\frac{1}{n} \left(\frac{\sum (C_{outm}^i - C_{out}^i)^2}{C_{outm}^i} \right)}$$

ε_r = relative error

n = number of determinations

C_{outm}^i = measured ammonia concentration of output

C_{out}^i = theoretical ammonia concentration of output

CONCLUSIONS

The result of monitoring the potabilisation station with the ammonia reduction biofilter showed that the ammonia was better reduced in the biofilter and the amount of carbon was greater.

The concentration of ammonia obtained upon the exit from the biofilter falls into the limits imposed by Act 458/2002, as supplemented by Act 311/2004, republished in 2012.

The biofiltering stage has got the following advantages:

- ▶ No chemical reacting agents are used in the treating process, as the bacteria consume the ammonia and the nitrates present in the water; in addition, no reaction toxic by-products come out.
- ▶ It is efficient in the potabilisation process by the fact that it greatly contributes to the pollutant reduction.
- ▶ The energetic consumption versus efficiency is low.

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FOOD SAFETY

