E3S Web of Conferences **378**, 03001 (2023) https://doi.org/10.1051/e3sconf/202337803001
IIRPCMIA 2021

Study of water purification reactor operating modes

Alexander Chuikov[1,*], *Andrey* Volkov[2,*], *Igor* Barskii[3,*] and *Dmitrii* Shabanov[4,*]

[1]Technician, Peter the Great St. Petersburg Polytechnic University, 195251, St. Petersburg, Russian Federation
[2]Professor, Graduate School of Automation and Robotics, Peter the Great St. Petersburg Polytechnic University, 195251, St. Petersburg, Russian Federation
[3]Master's degree student, Graduate School of Automation and Robotics, Peter the Great St. Petersburg Polytechnic University, 195251, St. Petersburg, Russian Federation
[4]Teaching assistant, Graduate School of Automation and Robotics, Peter the Great St. Petersburg Polytechnic University, 195251, St. Petersburg, Russian Federation

Abstract. Wastewater treatment is one of the main problems of development and urbanization of the Arctic regions. This article is devoted to the development of a method for assessing the degree of water purification in order to determine the optimum operating parameters of treatment reactors for water treatment by ferrates from industrial and household waste resulting from the development of Arctic regions. Experiments reflecting the influence of the amount of air supplied to the purification plant on the processes of mixing and distribution of water were carried out and analyzed. Based on the experimental data, a method for determining the optimum operating parameters of a new mobile water purification plant has been developed and applied. The operation of the plant is based on the use of the ferrate method. equations and dependencies describing the relationship between the reactor volume, liquid flow rate and the degree of water purification are given. The degree of water pollution is estimated as its fraction which has left the reactor before the time required for complete treatment of the liquid from the moment it enters i the reactor. Optimal parameters of the ferrate reactor, such as volume and air supply, for a mobile water treatment plant were determined.

1 Introduction

The relevance of this study is due to the need to find, select and apply an efficient, safe and cost-effective water treatment method in a harsh Arctic climate [1].

One of the most suitable methods of water treatment for this task is the ferrate method, which uses sodium ferrate. Sodium ferrate has an oxidizing and disinfecting effect [2]. It is able to decompose most of the harmful chemicals into low-toxic products (dead organic matter, salts, etc.). In addition, the ferrate decomposition product itself is low-toxic (iron hydroxide).

This method solves the technical problem of the impossibility of highly efficient treatment of wastewater of different nature, representing a mixture of water with inclusions of different types and concentrations [3]. The method also makes it possible to reduce the influence of factors causing the need for reclamation of disturbed land with industrial wastewater sludge [4].

The development of new water treatment plants is often a rather complex process, involving many areas of engineering and chemical activities. One of the stages of development is the design stage of reactors, tanks and other containers, in which the main physical and chemical processes for water treatment and purification take place. When designing new reactors, it is convenient to use pre-developed mathematical models of processes to find optimal parameters (reactor volume, treated liquid flow rate, air flow rate fed into the reactor, reaction rate, reagent feed rate, etc.) of reactor operation. The construction of mathematical models is used in conditions when the mechanism of the phenomenon being described is poorly understood Observing the reaction of the system under study, a hypothetical model of the phenomenon is drawn up, which is then empirically tested under different conditions in order to clarify its individual parameters [5].

The purpose of this article is to develop a methodology for assessing the degree of water purification during its time in the reactor, in order to find the optimal parameters of water purification plants reactors, including in relation to the ferrate method.

2 Experiments to determine the degree of water mixing in a flow reactor

For high-quality purification water must be in contact with the reagent in the reactor for a certain time Td (desired time). In a flow reactor there is mixing of the layers of the fed water, so the volume of liquid fed at a certain time t0 will leave the reactor in the time interval tA-tB. If the value of Td is within this range, the quality of water purification can be estimated by the amount of water released in the time interval tA-Td. This

* Corresponding author: a Chuikov.as16@gmail.com, Volkov-and-1@yandex.ru, barskiiigor66@gmail.com, Dsb956@yandex.ru

distribution is influenced by the speed of mixing of the liquid and the amount of air supplied to the reactor.

Experiments were carried out on a previously developed experimental unit for water purification. The experiments aim to determine the distribution of the amount of water leaving the reactor at the time interval tA-tB.

In the experiments, colored water was used to simulate polluted water. The colored liquid was fed with a membrane pump with a capacity of 7.5 L/h into the reactor pre-filled with clean water. The air was supplied using a compressor.

The experiments were carried out with the following parameters:

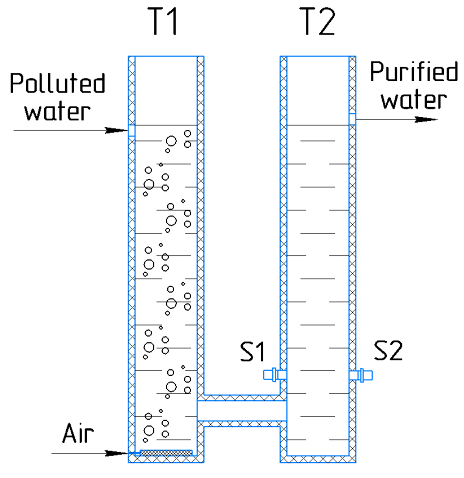
– liquid supply to the unit in the absence of air supply

– liquid supply to the unit with an air flow rate of 3.25 L/min

– liquid supply to the unit with an air flow rate of 6.5 L/min

– liquid supply to the unit with an air flow rate of 13 L/min.

The process of mixing and distribution of the colored liquid was recorded using optical sensors (Fig. 1).



T1 - first reservoir, C2 - second reservoir, S1 - optical emitter, S2 - optical receiver.

Fig. 1. Diagram of water purification technical equipment

After the experiments, the graphs of the readings from the S2 sensor were plotted (Fig. 2). To eliminate the noise on the graphs, the moving average filtering method was applied.

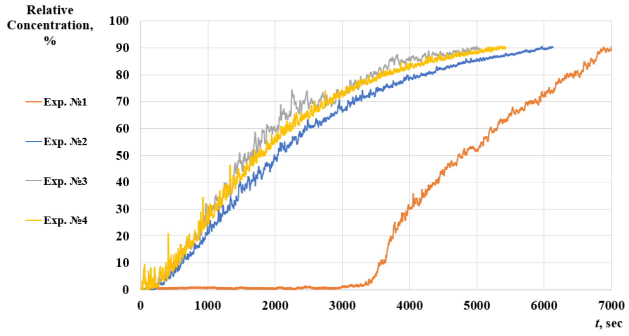


Fig. 2. Changes in dirty water concentration

The mixing process of dirty water entering the reactor can be described using a normal distribution (Fig. 3).

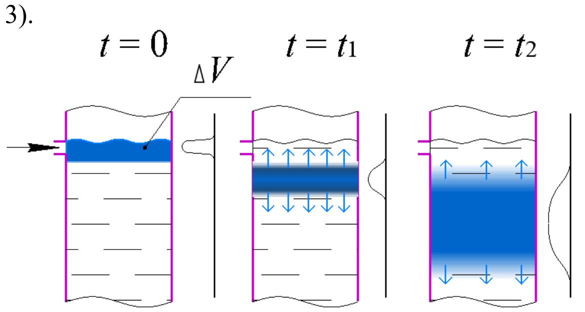


Fig. 3. Mixing liquid distribution

Let a quantity of liquid equal to ΔV be supplied at each moment of time, then the normal distribution will show what part of the liquid from the volume ΔV and at what time moment t will leave the reactor.

The normal distribution is characterized by the following function:

$$F = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\left(2\sigma^2\right)^{1/2}}\right)\right], \quad (1)$$

where μ is the mean of the distribution,
σ is the standard deviation.

The more time a water particle spends in the reactor, the more likely the particle will escape into the distant layers and the more "smeared out" the distribution will be. In this regard, it is necessary to use the variable σ, which will depend on the time that the liquid entering the reactor will spend in it.

$$\sigma(t) = k \cdot t, \quad (2)$$

where k is the empirical coefficient.

After selecting the necessary parameters, the graph corresponding to experiment No. 1 is plotted (Fig. 4).

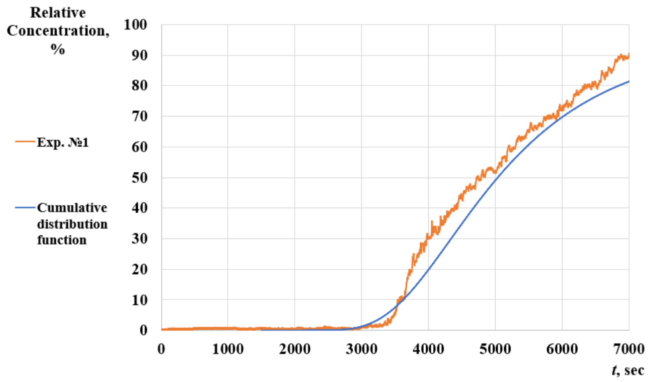


Fig. 4. Graph of the relative concentration of dirty water of experiment No. 1 and the distribution function

The graph above shows that the distribution function practically coincides with the obtained data.

The distribution graph f (t) was obtained by differentiating the plotted distribution function (Fig. 5).

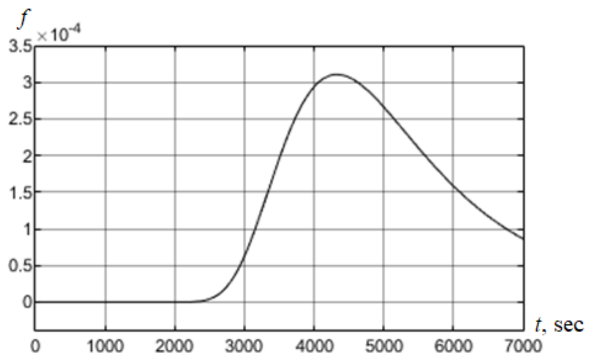


Fig. 5. Dirty liquid distribution at the reactor outlet, without air supply

The data of experiments 2, 3 and 4, in which air was supplied to the reactor, are almost identical. For one of them, we plot the corresponding distribution function. the necessary parameters are selected in advance (Fig. 6).

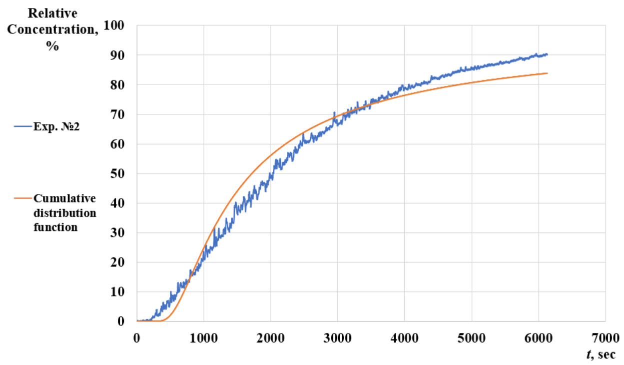


Fig. 6. Diagram of the relative concentration of dirty water of experiment No. 2 and the distribution function

A similar mixing description problem has also been described for reactive transport problems [6].

3 Mathematical estimation of the time of water passage through the reactor with perfect mixing

Based on the fact that for a given unit the supply air flow rate of more than 3.25 l/min has almost no effect on the results, we can assume that with further increase in air flow rate the mixing of liquid also occurs instantly and "perfectly".

The mathematical description of instant water mixing is shown below.

The amount of dirty water in the reactor can be found as described below.

When dirty water of volume ΔV enters the reactor, the amount of dirty water in the reactor will be equal to the sum of the amount of dirty water remaining in the reactor Vrem and the volume ΔV (Fig.7).

Dirty liquid concentration in the reactor is:

$$C_{dir}(t) = V_{dir}(t)/V \quad .(3)$$

Thus, the amount of dirty water remaining in the reactor will be equal to the product of the dirty liquid concentration and the volume of all the water in the reactor.

$$V_{rem}(t) = C_{dir}(t-dt)\cdot(V_{full}-\Delta V) = V_{dir}(t-dt)\cdot\frac{V_{full}-\Delta V}{V_{full}} \quad .(4)$$

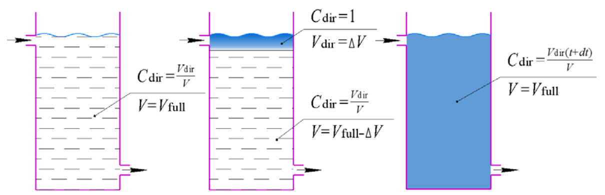


Fig. 7. Mixing the liquid in the reactor

The volume of dirty liquid in the reactor after adding ΔV can be calculated as:

$$V_{dir}(t+dt) = V_{dir}(t)\cdot\frac{V-\Delta V}{V} + \Delta V = V_{dir}(t) - V_{dir}(t)\cdot\frac{\Delta V}{V} + \Delta V \quad (5)$$

The resulting differential equation is:

$$dV_{dir}(t) = V_{dir}(t+dt) - V_{dir}(t) = -V_{dir}(t)\cdot\frac{\Delta V}{V} + \Delta V = \Delta V\cdot(1-\frac{V_{dir}(t)}{V}) \quad (6)$$

$$V_{dir}(t) = \int dV_{dir}(t)dt = \int \Delta V\cdot(1-\frac{V_{dir}(t)}{V})dt \quad . \quad (7)$$

The necessary calculations were performed in the MATLAB program (Fig. 8).

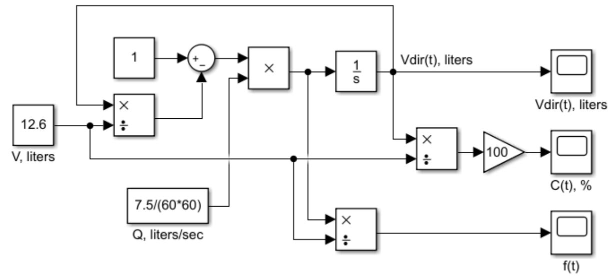


Fig. 8. MATLAB program screen

The obtained dependence of the amount of dirty water in the reactor on the time t is presented (Fig. 9).

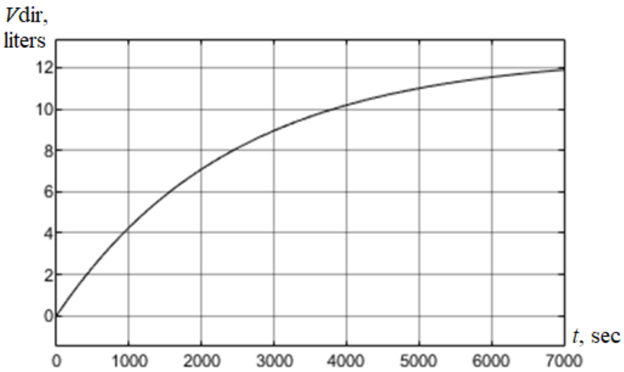


Fig. 9. The volume of dirty water in the reactor

The obtained dependence of the amount of dirty water at the reactor outlet from the moment of its supply (t = 0) on the time t in the presence of air feeding into the reactor is presented (Fig. 10).

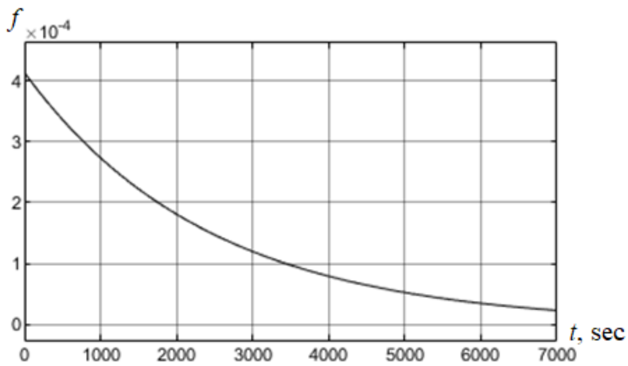


Fig.10. Distribution of dirty liquid at the reactor outlet (with air supply)

From the obtained distribution function graph it is possible to determine the fraction of particles from the fed volume of dirty water that will leave the reactor at time t. With the help of this it is possible to estimate the degree of water purification, knowing the desired time during which the water should be treated in the reactor with the known type of contamination.

4 Estimation of optimal parameters of the reactor for water purification using the ferrate method

The information obtained from the experiments is useful in the design of water treatment plants. The above equations allow us to describe the relationship between reactor volume, flow rate and quality of treated water, taking into account the air supply to the reactor.

Currently, a mobile wastewater treatment plant is being developed as part of the OneDrop project. Using the described technique, it is possible to estimate the optimal volume of the reactor in which the water is purified with ferrates [7]. One of the components of the mobile plant is a ferrate module, which allows processing of pre-purified liquid. This module consists of a ferrate reactor, an oxidation reactor and a coagulation tank (Fig. 11).

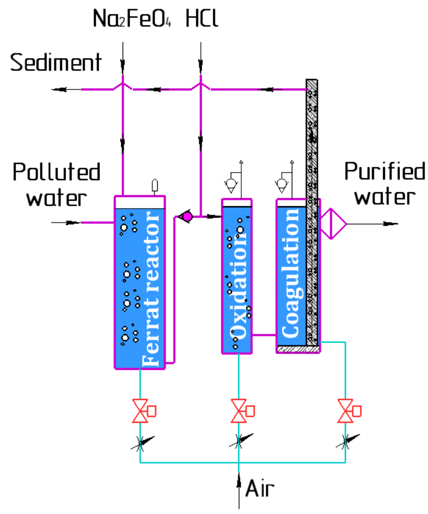


Fig. 11. The ferrate module diagram

Dirty water from the previous modules is fed from above into the ferrate reactor, and sodium ferrate (Na2FeO4) is dosed from above. During the downward circulation of the liquid, there is an interaction between the dirty substances contained in the water and the ferrate An air supply is provided in the lower part of the reactor. Air bubbles move in the direction opposite to the main flow, providing mixing of the liquid to avoid sedimentation of the reagent.

At the next stage, an oxidizing agent, hydrochloric acid (HCl), is added to the liquid before it enters the oxidation reactor. This agent separates the particles formed during the reaction between the ferrate and the water pollutants. there is also an air supply for mixing, which prevents the deposition of the resulting particles.

In the next tank, coagulated particles with a high specific gravity move down, settle and are removed from the reactor by an airlift. The purified water is filtered and discharged to the following purification stages.

The previously developed technique was applied to calculate the required reactor volume and the effect of the presence of air supply.

The average design flow rate of water is taken Q = 1 L/min; experimentally it was determined that the optimal time that water should spend in the reactor for purification is Td = 180 sec. To estimate the optimal reactor volume, two graphs are plotted as a function of the degree of water pollution at the reactor outlet on the reactor volume: with the use of air for mixing and without mixing (Fig. 12, 13). The degree of pollution C is the fraction of water (from 0 to 1) that left the reactor before the time Td after entering it.

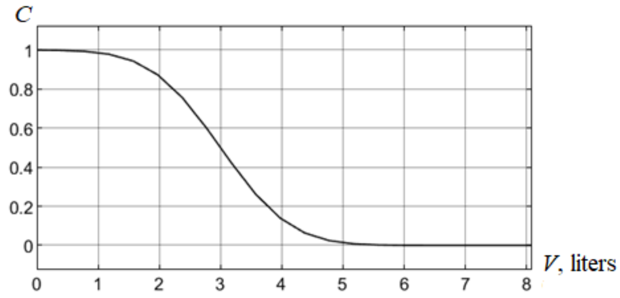


Fig. 12. Relationship between the degree of water pollution and the volume of the reactor (without air supply)

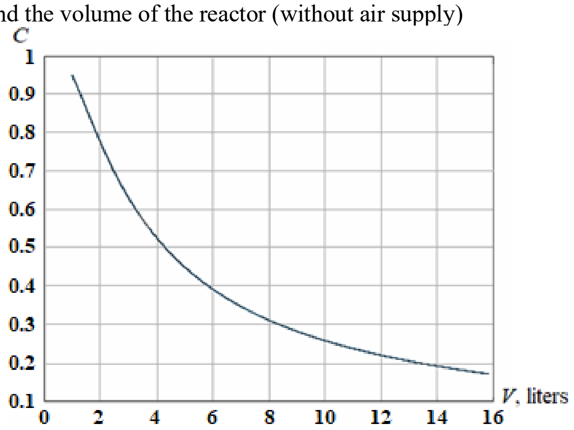


Fig. 13. Relationship between the degree of water pollution and the volume of the reactor (with air supply)

Due to the design features, it is difficult to use a reactor with a volume of more than 7 liters. The graph shows the degree of pollution of treated water when using a 7-liter reactor without air is practically 0, when using air it is about 35%.

Fig 14 also shows the graph of the dependence of the degree of pollution of the water treated in this reactor C on its flow rate and when air is used for mixing.

The graph of the dependence of the degree of water pollution C on the time Td required for water purification, when using a reactor with of 7 liters and without using air (Fig. 15). The planned flow rate is 0.6–1.3 L/min.

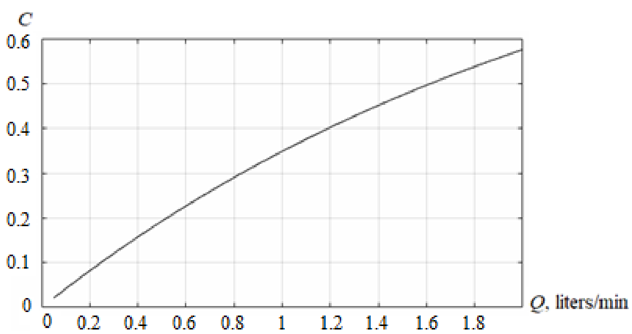


Fig. 14. Dependence of the degree of water pollution on its consumption (with air supply; reactor volume is 7 liters)

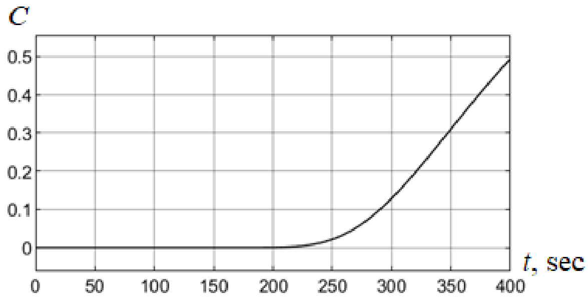


Fig. 15. Dependence of the degree of water pollution on time Td (without air supply; reactor volume is 7 liters).

5 Conclusion

Ferrate technology of water treatment is acceptable to operate in the Arctic.

The proposed methodology makes it possible to estimate the expected purity level of water with and without air supply. If air supply is not used, the mixing process is described with a distribution similar to a normal distribution. The mixing process with air supply is described by differential equation (5). Also, the relationship between water purity level, reactor volume and water flow rate allows us to choose the optimal parameters of the plant.

Graphs plotted for water purification in a ferrate reactor show that the use of air reduces the degree of water purification. In this regard, it is proposed to test the plant without air supply - perhaps the entire reagent will have time to react without settling to the bottom. mixing is then not required. Alternatively, an experiment with intermittent, periodic air supply can be performed.

Note that the k factor used in the air-free mixing calculations must be chosen individually for each reactor design. This factor is influenced by the geometry of the reactor and its size ratio.

The work was performed within the thematic project "South-East Finland - Russia CBC Program2014-2020 - OneDrop Project - KS1648".

References

1. P.E. Jensen, et al., Water, sanitation, pollution, and health in the Arctic, *Environ. Sci. Pollut. Res,* **25**, pp. 32827–32830 (2018)
2. E.N. Arakcheyev, et al., Experimental substantiation of the practicability of disinfection and purification of water and wastewaters with potassium ferrate, *Hygiene and Sanitation*, **96(3)**, pp. 216-222 (2017)
3. A.V. Karim, et al., *Advanced Oxidation Processes - Applications, Trends, and Prospects ed Bustillo-Lecompte C F* (London, IntechOpen, 2020), **chapter 5**
4. T.A. Petrova, et al,. Rehabilitation of Disturbed Lands with Industrial Wastewater Sludge, *Minerals*, **12(3)**, p. 376 (2022)

5. B. Savun-Hekimoğlu, On the Use of Mathematical Models for Wastewater Treatment: A Review and Analysis of Activated Sludge Models ASM1 and ASM3, *Int. J. Environ. Geoinformatics*, **8(1)**, pp. 1-18 (2021)
6. J. Soler Sagarra, et al., Water Mixing Approach (WMA) for reactive transport modelling, doi: 10.1002/essoar.10504136.1 (2020)
7. R.E. Nekrasov, et al., Apparatus for water purification of natural water, Patent Russian Federation no. RU 175092 U1 (1997)