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# Optimisation of EDM Process for Water Purification

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This paper discusses the process of water purification from harmful impurities by using electrical discharge machining (EDM) metal balls in an aqueous solution. The mathematical model has been developed for the water purification process. The control action was optimised using a mathematical model. To achieve the optimisation an extremal controller has been used. As a result of the process water purification optimisation, the electricity cost was minimized.

## 1. Introduction

Nowadays people are pay much attention to green energy and environmentally friendly technologies. Proof of this is the large number of publications on these topics. For example, the article Karacan et al. (2015) reviews the problems of optimisation for biodiesel production in a reactive distillation column and also the article Ibric et al. (2014) reviews the problems of optimisation of water and energy within integrated water networks. At the same time, the purification of water from contaminants is getting more and more relevance. The scientific articles describe a several methods for the purification of water sources. The most widespread processes include the following: reverse osmosis, reagent coagulation, aeration, sedimentation, and distillation. For instance, the article Lutchmiah et al. (2014) reviews the problems and prospects the use of reverse osmosis membranes for wastewater treatment. Each of the foregoing methods has its advantages and disadvantages. One can identify the following disadvantages dealing with these methods: a large consumption of reagents; the need for periodic replacement of membranes; high cost of reagents and membranes; large areas needed for equipment installation; and the main disadvantage of these methods is the lack of opportunity (or ineffective) to clean water sources by toxic substances (arsenic) and dissolved salts. In the scientific literature, there are articles, which presented different approaches to optimise these methods and the development of automatic control systems. The article from Bartman et al. (2009) is devoted to the development of a nonlinear control system based on a reverse osmosis membrane model obtained from experimental data. The article from Absar et al. (2008) deals with the development of a simplified model of a reverse osmosis membrane, which will be used to investigate the effectiveness of the hollow fiber. In the paper from Manenti et al. (2015) an optimisation work of reverse osmosis module with recycle is developed using MPC approach. However, the proposed system of control and optimisation cannot eliminate the disadvantages inherent to these methods. Therefore, it is necessary to develop new energy-saving and resource-efficient methods of water purification.

One of such methods, based on the use of electric energy, is water purification using the EDM process with metal balls in treated water. The EDM process with metal workpieces has been known for more than 70 years, but the use this method for water purification is a novelty. The benefit in the use of EDM process for water treatment is that this method is based on cheap raw materials (metal balls) and characterized by low power consumption. Since this is a new and poorly known method, it is necessary to develop an adequate mathematical model for the optimisation of this method and the development of a control system.

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The objective of this work is the optimisation of the water purification with EDM process. To achieve this objective the authors developed a mathematical model of the water purification process. The developed mathematical model is presented in this article and reflects dependence of the controlled variable (output) from the control action (input). The control variable is the concentration of harmful impurities in purified water, and the control actions consist in electrical impulses, that are skipped through a layer of metal balls. Using the developed mathematical model the authors designed a control system through the use of an extremal controller. With the use of extremal controller the cost of electricity for water sources purification was reduced.

## 2. Analysis of the object modelling and optimisation

Water purification systems are complex multi-step processes. The paper from Abdulgader et al. (2013) describes the possibility of combining ion exchange with membrane methods such as reverse osmosis, microfiltration, ultrafiltration and nanofiltration. Gabelich et al. (2007) describe technological scheme of water purification, which consists of two stages of reverse osmosis, with an intermediate chemical desalination and preliminary microfiltration. The proposed method for water purification using EDM process is also one of the stages of the water purification process. More precisely, EDM method is preparatory for water purification. The objective of this step to make the toxic substances and dissolved salts, contained in the feed water, precipitate in the insoluble fraction.

In this paper, the object of modeling and optimisation is the EDM process of metal balls in contaminated water. The main process idea lies in the fact that a layer of metal balls from pulse generator transmits electrical pulses of short duration. When electrical pulses pass in the gaps between balls, electrical discharges, which are characterized by high energy, arise. The electrical erosion process occurs as a result of the discharges on the surface of metal balls, i.e. ultrafast change of aggregate state of the surface of metal balls (melting) takes place, and erosion products are released in the intergranular spaces filled with the treated water. The erosion products go through the liquid phase with oxidation of water and dissolve therein oxygen. Active metal hydroxides and oxides, which are active coagulants, are formed in the oxidation. Oxidation proceeds according to the following chemical reactions:

$$
\begin{aligned}
&Fe + H_2O \rightarrow FeO + H_2 \uparrow \\
&Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2 \\
&4FeO + O_2 + 2H_2O \rightarrow 4FeOOH \\
&2Fe(OH)_2 + 0.5O_2 + H_2O \rightarrow 2Fe(OH)_3
\end{aligned}
\qquad (1)
$$

The formed hydroxides and oxides effectively adsorb the impurities, which are contained in water and form insoluble salts, which are precipitated. The precipitation of impurities, for example arsenic (As) and silicon (Si), proceeds according to the following chemical reactions:

$$
\begin{aligned}
&FeOOH + H_3AsO_4 \rightarrow FeO(H_2AsO_4) + H_2O \\
&2Fe(OH)_3 + 3H_2SiO_3 \rightarrow Fe_2(SiO_3)_3 + 6H_2O
\end{aligned}
\qquad (2)
$$

The adsorbed and coagulated impurities are removed from the treated water by means of membrane techniques or using of classical settling. To develop a mathematical model, which will be used to optimise the EDM process of water purification, it is necessary to allocate manipulated, controlled and disturbing variables. The controlled variable of the process is the concentration of harmful substances in the water to be treated ($C_{c.w.}$, mg/L). The manipulated variable modelling object are the parameters of the electrical discharges: pulse current ($I$, A), pulse voltage ($U$, V), pulse duration ($t_{on}$, s). The disturbance is the concentration of harmful substances in feed water ($C_{f.s.}$, mg/L).

## 3. Mathematical model for EDM process of water purification

To determine the change in impurity concentration in the treated water it is necessary to determine the erosion products concentration, which are formed during the EDM process. Since the duration of the electric discharges is small (some μs), the released heat does not have time to spread into the interior of the metal balls. Nonetheless, this heat is enough to warm up, to melt and evaporate a small amount of metal from the surface of the balls. The erosion products are formed as result of the metal evaporation and holes are formed on the metal balls. The volume of the formed holes is proportional to the mass of the erosion products. Thus, to determine the concentration of erosion products in the treated water, it is necessary to determine the parameters for the holes and to evaluate approximate number formed holes. The following assumptions have been made for the development of a mathematical model of EDM process for water purification:

- the spark radius ($R_s$) is assumed to be a function of pulse current and pulse duration. An analogous assumption is made in the work Mohanty et al. (2013).

- the heat source is assumed to have Gaussian distribution of heat flux on the workpiece surface;
- the volume of the formed hole (crater) is equal to the volume of a paraboloid of revolution. This assumption is substantiated in the work Shabgard et al. (2012);
- the modelling object is viewed as a model with concentrated parameters.

**3.1 Thermophysical model EDM process**

The heat flux, which is formed by electric discharge, on the surface of metal balls is defined as follows:

$$q(r) = \left(\left[4.45 \cdot f \cdot U \cdot I\right] / \left[\pi \cdot R_S^2\right]\right) \cdot \exp\left(-4.5 \cdot \left(r/R_S\right)^2\right) \tag{3}$$

In Eq.(3), $U$ is pulse voltage (V); $I$ pulse current (A), $R_S$ spark radius (μm). The spark radius is defined by:

$$R_S = 2.04 \cdot exp(-3) \cdot I^{0.43} \cdot t_{on}^{0.44} \tag{4}$$

In Eq.(4), $t_{on}$ is the pulse duration (μs). The effective portion of the heat ($f$) arrives in metal balls. It is determined by the following equation:

$$f = 5.672 + 0.2713 \cdot I^{0.5598} \cdot t_{on}^{0.4602} \tag{5}$$

Eq.(5), determines the proportion of supplied heat (Wuyi Ming et al. 2014). $f$ is expressed in %.
To determine the volume of erosion products, it is necessary to determine the hole (crater) depth, which depends on the thermal conductivity of material, the boiling temperature and of heat flux at the surface:

$$h_{crater} = q(r) / \left[K \cdot (T_{melt} - T_0)\right] \tag{6}$$

In Eq.(6), $K$ is the thermal conductivity of the metal balls (W/(K·m)); $T_m$ is the boiling temperature (K); $T_0$ is the initial temperature in the apparatus (K). Based on the considered assumptions, the holes volume is defined:

$$V_{crater} = 1 / \left[2 \cdot \pi \cdot R_S \cdot h_{crater}\right] \tag{7}$$

The mass of the resulting erosion products can be determined if the number of discharges occurring between all the balls is known. We used experimental data presented in the work by Scherba et al. (1991), about the distribution of number discharge in layer metal balls. The paper shows that the presence of 550 contacts (gaps between the balls) results in approximately 525 discharges. As a result, if one impulse generates $N$ discharges, $2 \cdot N$ holes are formed, because they formed on both balls acting as contacts. As a result, the mass of erosion products can be determined from the expression:

$$M_{Fe}^{EDM} = 2 \cdot N \cdot V_{crater} \cdot \rho \tag{8}$$

In Eq.(8), $\rho$ is the density of the metal, of which are made balls (kg/m$^3$). Knowing the volume water to be treated ($V_{f.w.}$, L), one can determine the concentration of the erosion products in apparatus:

$$C_{Fe}^{EDM} = M_{Fe}^{EDM} / V_{f.w.} \tag{9}$$

**3.2 Kinetics of the chemical reactions EDM process of water purification**

Chemical reactions (1, 2) describe the chemical processes, which occur during EDM process of water purification. As can be seen from reactions in Eq.(1), oxidation of iron by water and oxygen are parallel, resulting in two different substances: iron oxide (FeO) and iron hydroxide(II) ($Fe(OH)_2$). Then, the successive oxidation reactions form iron metahydroxide (FeOOH) and iron hydroxide(III) ($Fe(OH)_3$). The kinetics of the chemical oxidation reactions (1) is described by the following system of equations:

$$\begin{cases} dC_{Fe}/dt = C_{Fe}^{EDM} - k_1 \cdot C_{Fe} \cdot C_{H_2O} - k_2 \cdot C_{Fe} \cdot C_{O_2} \cdot C_{H_2O}^2 \\ dC_{H_2O}/dt = -k_1 \cdot C_{Fe} \cdot C_{H_2O} - k_2 \cdot C_{Fe} \cdot C_{O_2} \cdot C_{H_2O}^2 - k_3 \cdot C_{FeO}^4 \cdot C_{O_2} \cdot C_{H_2O}^2 - k_4 \cdot C_{Fe(OH)_2}^2 \cdot C_{O_2}^{0.5} \cdot C_{H_2O} \\ dC_{O_2}/dt = C_{O^-}^{EDM} - k_2 \cdot C_{Fe} \cdot C_{O_2} \cdot C_{H_2O}^2 - k_3 \cdot C_{FeO}^4 \cdot C_{O_2} \cdot C_{H_2O}^2 - k_4 \cdot C_{Fe(OH)_2}^2 \cdot C_{O_2}^{0.5} \cdot C_{H_2O} \\ dC_{FeO}/dt = k_1 \cdot C_{Fe} \cdot C_{H_2O} \cdot G_{diff} - k_3 \cdot C_{FeO}^4 \cdot C_{O_2} \cdot C_{H_2O}^2 \\ dC_{Fe(OH)_2}/dt = k_2 \cdot C_{Fe} \cdot C_{O_2} \cdot C_{H_2O}^2 \cdot G_{diff} - k_4 \cdot C_{Fe(OH)_2}^2 \cdot C_{O_2}^{0.5} \cdot C_{H_2O} \\ dC_{FeOOH}/dt = k_3 \cdot C_{FeO}^4 \cdot C_{O_2} \cdot C_{H_2O}^2 - k_7 \cdot C_{FeOOH} \cdot C_{H_3AsO_4} \\ dC_{Fe(OH)_3}/dt = k_4 \cdot C_{Fe(OH)_2}^2 \cdot C_{O_2}^{0.5} \cdot C_{H_2O} - k_8 \cdot C_{Fe(OH)_3}^2 \cdot C_{H_2SiO_3}^3 \end{cases} \tag{10}$$

In Eq.(10), $C_{Fe}^{EDM}$ is the concentration of erosion products in the apparatus (mg/L); $C_{Fe}$ is the concentration of iron in the apparatus (mg/L); $C_{H2O}$ is the concentration of water in the apparatus (mg/L); $C_{O2}$ is the concentration oxygen in the apparatus (mg/L); $C_{FeO}$ is the concentration iron oxide in the apparatus (mg/L); $C_{Fe(OH)2}$ is the concentration of iron hydroxide(II) in the apparatus (mg/L); $C_{FeOOH}$ is the concentration iron metahydroxide in the apparatus (mg/L); $C_{Fe(OH)3}$ is the concentration of iron hydroxide(III) in the apparatus (mg/L); $C_{H3AsO4}$ is the concentration arsenic acid in the apparatus (mg/L); $C_{H2SiO3}$ is the concentration metasilicic acid in the apparatus (mg/L); $k_i$ is the chemical reaction rate constant (mg/(s·L)), calculated from the Arrhenius equation. The variable $G_{diff}$, in Eq.(10), represents the diffusion coefficient on surface ball (mg/(L·s)). This variable is determined by the expression:

$$G_{diff} = h_m \cdot \Delta C \cdot n \cdot 2 \cdot N \cdot \sqrt[3]{6 \cdot V_{crater} / (n \cdot \pi)} \quad (11)$$

In Eq.(11), $h_m$ is the constant mass transport of molecules across the outer surface of the oxide; *ΔC* concentration pressure, measures the difference of the chemical potentials of the diffusing component on surface and in volume ball; $\sqrt[3]{6 \cdot V_{crater} / (n \cdot \pi)}$ factor allows to estimate approximately the size of the dispersed erosion products. Increasing the power discharge and reducing the amount of dispersed particles (*n*) can cause an increase in their size. The number of dispersed particles (*n*) depend on the pulse power (12). This relationship was obtained by approximation of experimental data with the expansion pack Curve Fitting Toolbox MATLAB:

$$n = a_2 \cdot P^2 + a_1 \cdot P + a_0 \quad (12)$$

In Eq.(12), $a_2$=-6·10$^{-4}$; $a_1$=5.79; $a_0$=-1.011·10$^4$. Thus, the variable $G_{diff}$ describes dependence of reaction rate from the dispersion of products erosion. If the discharge energy is small, a small amount of highly dispersion erosion products is formed. Instead, a significant increase in the discharge power makes the erosion products formation of larger dimensions. Depending on the size and from the material balls dispersion described by the Eq.(12), the formation can have a variation in direction (left and right, up and down).

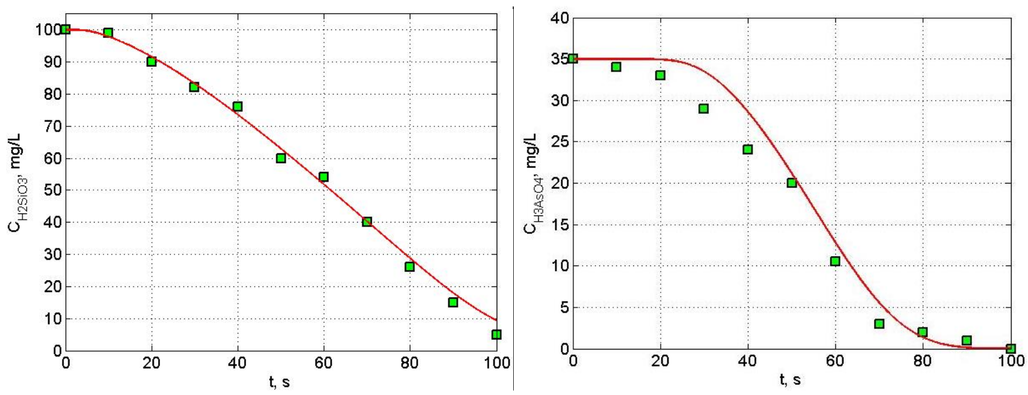


*Figure 1: The modelling results*

Then, the precipitation of impurities (arsenic and metasilicic acid) depends on the obtained oxidation products. The process occurs as described by reactions in Eq.(2) and by the following system of equations:

$$\begin{cases} dC_{H_3AsO_4} / dt = -k_5 \cdot C_{FeOOH} \cdot C_{H_3AsO_4} \\ dC_{H_2SiO_3} / dt = -k_6 \cdot C^2_{Fe(OH)_3} \cdot C^3_{H_2SiO_3} \end{cases} \quad (13)$$

This mathematical model was implemented in the MATLAB package. To check the adequacy of the developed model, the modelling results were compared with experimental data, which were taken from the work of Shakhova et al. (2013). The obtained results are shown in Figure 1. The discrepancy between the experimental and calculated data is: 4.37 % for metasilicic acid ($H_2SiO_3$) and 5.28 % for arsenic acid ($H_3AsO_4$).

## 4. Optimisation of EDM process for water purification

During the analysis EDM process of water purification, it was concluded that to reduce the electric power consumption and to increase rate of purification, it is necessary to optimise the power supplied to the electric pulse. For this reason, it is necessary to change the pulse duration ($t_{on}$). As a result, a change in $t_{on}$ resulted in different transient processes (see Figure 2).

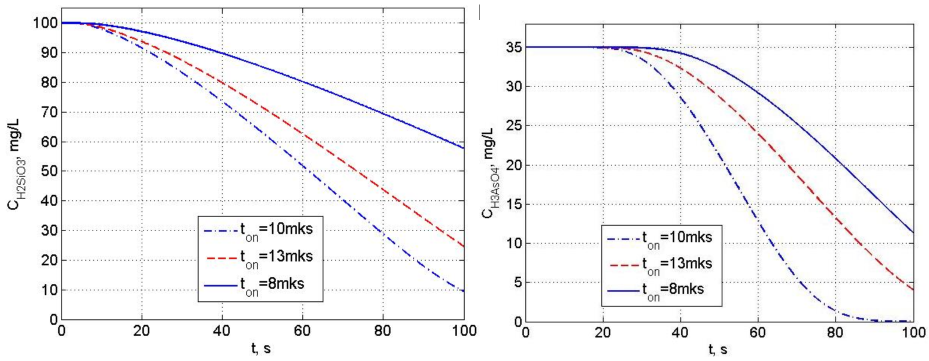


*Figure 2: The modelling results for different values of pulse duration ($t_{on}$)*

As one can see from the graphs represented in Figure 2, if $t_{on}$ is reduced, the processing time of the water and energy consumption increase. If $t_{on}$ is increased, processing time of the water also increases, because the power applied on electrical pulse is higher, leading to the formation of large size erosion products. Large size erosion products do not react completely, but only on the surface. As consequence, the rate of extraction of impurities from water is reduced. It is necessary determine the optimum pulse duration ($t_{on}$), to optimise the power applied with electric pulses. These pulses will produce the maximum number of highly dispersion erosion products to ensure maximum recovery of impurities. One extremal controller is used for the optimised $t_{on}$ value. The structure of the developed control system is shown in Figure 3. Extremal controllers tend as quickly as possible to bring a controlled variable to the level set point.

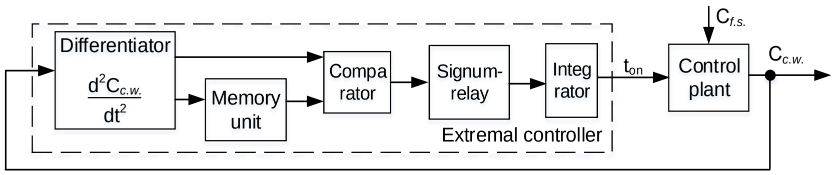


*Figure 3: The control system with extremal controller*

The control system (Figure 3) has been implemented in MATLAB/Simulink. The control plant used the mathematical model EDM process of water purification. As a disturbance on plant, a parabolic dependence have been set (Eq.(12)). Modelling reaction of control plant was carried with and without regulator. The obtained transient processes are shown in Figure 4.
As one can see from the graphs in Figure 4, at displacement characteristics – Eq(12) there is a decrease of erosion products on which adsorption occurs, therefore the reaction rate decreases. Thus, it is necessary to change power so, to find the extremum for the expression in Eq(12). This allows to receive the maximum number of highly dispersion products erosion, thereby increasing the rate of recovery impurities. Using extremal controller allows solving this problem, increasing the cleaning rate and reducing costs electric energy by 18.6 %. The implementation of the developed control system (Figure 3) will give a positive economic effect.

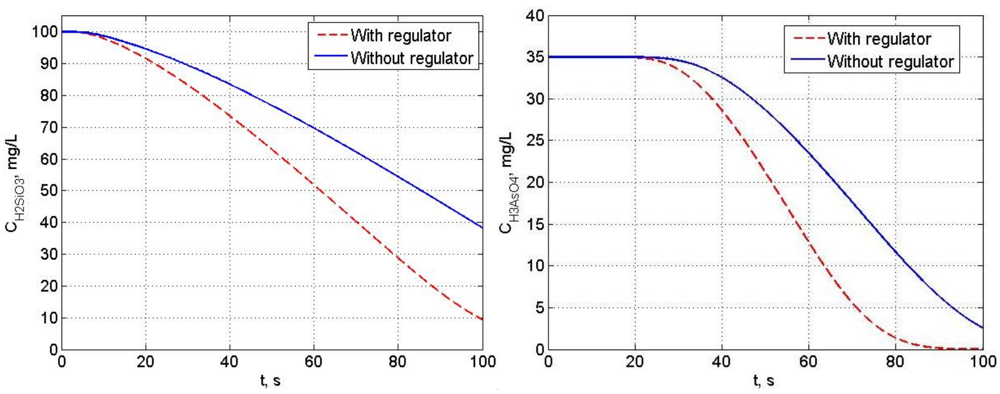


*Figure 4: The modelling results*

## 5. Conclusions

The paper presents a mathematical model of EDM process for water purification. The model describes thermo-physical processes, which occur on surface of metal balls that are processed with using electrical impulses. Furthermore, the model describes the kinetics of the reactions during the deposition of impurities. The developed mathematical model has been implemented in the package MATLAB/Simulink. The modelling results were compared with experimental data. The discrepancy between the data was around 5 %, testifying the adequacy of the developed model. The developed mathematical model was coupled with a control system with extremal controller (Figure 3). The use of an extremal controller allowed reducing the energy consumption by 18.6 %. The developed control system will give a positive economic effect for practical implementation. The future work will be devoted to a more in-depth experimental study of the dependency between the dispersion of erosion products and the power electric discharge Eq(12). The use of an extremal controller has its disadvantages: first, the complexity of implementation, since it is necessary to calculate second derivative, second, the proposed control algorithm has low noise immunity. For this reason, a nonlinear MPC controller in future research will be used for optimisation purposes.

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