Spent coal mines using for the industrial wastewater disposal

L Bondareva[1, 2] **and Yu Zakharov**[1, 2]

[1]Kemerovo State University, Krasnaya Street, 6, 650043, Kemerovo, Russia
[2]Institute of Computational Technologies of the Siberian Branch of the Russian Academy of Sciences, Academician M.A. Lavrentiev Avenue, 6, 630090, Novosibirsk, Russia

Abstract. Industrial wastewaters disposal, in particular wastewaters appearing from the coal extraction and enrichment, is an important national economic task of preserving environment. At the same time, the applied wastewater disposal technologies must be ecologically safe and do not requires large financial expenses. This task is quite relevant for Kuzbass due to territory saturation of the coal, metallurgical and chemical industrial enterprises. The paper discusses a mathematical model of one of these technologies - the wastewater treatment in spent workings of closed and flooded coal mines. The proposed mathematical model allows studying the treatment processes occurring in the flooded mine workings, that using numerical experiments and taking into account the slurry water characteristics and changes of the incoming groundwater volume and of the injected wastewater volume. The process of suspended in mine waters coal and rock particles sedimentation and sediment compaction is given special attention in the model. Numerical experiments results, that allowing estimating the safe time mine act as a wastewater treatment plant, are presented.

1. Introduction

More and more attention to environmental issues in the modern world is paid. Despite the growing interest in renewable energy sources, a full-scale transition to the alternative energy sources use for industry's needs and the traditional fuels abandonment, such as oil, natural gas and coal, are impossible at present [1]. Of course, the coal fuel productions, enrichment, transport and use has a negative environment impact [2]. However, currently existing technologies allow to obtain high-quality coal fuel, whose production and use will have a lesser negative impact on the environment [3]. Gasification and partial gasification should be singled out among the most promising ways of "refining" coal, which will significantly increase the economic and environmental effects [4]. Coal sludge processing technologies into commercial products [5] and new methods for deep safe cleaning and processing of coal production wastes development [6] are in particular interest.

A large amount of sinter plants wastewaters and mine industrial waters need effective treatment, so that they can not only be dumped into outdoor water sources, without breaking the ecology, but also be reused in the production cycle. The most common treatment wastewaters technologies are such methods as flotation, filtration and settling. Due to its cheapness, the last of them has gained great popularity, therefore, artificial surface ponds - so-called sludge settler are often used for treatment. They occupy large areas, their effectiveness significantly decreases because of sediment filling and during the spring flood and during heavy rains the industrial wastewaters spilling beyond the sludge settler is possible. Therefore, for the first time in Russian practice in Kuzbass, an alternative technology was used - the coal preparation plant "Komsomolets" wastewaters disposal into the spent mine workings of the closed and flooded coal mine "Kolchuginskaya". Such a disposal method is that wastewater is pumped into the flooded coal mine, where they are effectively settled due to the large length of spent mine workings, additional clarification is achieved due to the dilution with groundwater, and cleaner mine waters are pumped out of the mine as a result. This disposal method is of great economic interest, because of it not only allows to avoid additional costs for the coal sludge sediment disposal, but it is generally technologically simple. However, for this wastewaters disposal method environmentally to be safe practice use, it is necessary to study the processes occurring inside the flooded mine. This is important to know when the underground space is substantially filled with settled sediment, and further use of the flooded mine will be dangerous and also to identify those factors that can lead to volley emission of accumulated impurities.

Since it is extremely difficult to carry out measurements and observations in flooded waste mine workings, mathematical modeling can be useful for studying the processes occurring in the coal mine. It is necessary to take into account mine waters composition , coal mine features , treatment process specifics and sediment compaction possibility of suspended impurities contained in the treated wastewaters and mine waters for appropriate mathematical model choosing. Suspended impurities transport modeling can be found in various mathematical models to solve practical problems variety, such as river sediments transport and channel processes modeling [7], oil spills spreading [8], sediment formation on the coast [9] and other tasks. However, the modeling approaches used in all these tasks are not applicable for coal waste mines, since they do not take into account the slurry waters features. Therefore, a mathematical model of the industrial wastewaters treatment from suspended impurities is presented in this paper [10]. This mathematical model using numerical experimentation allowed us to obtain safe operation time estimates of a coalmine as a wastewater treatment plant [11].

2. Mathematical and numerical modelling

In this research, the coal waste mine workings is a completely flooded great length closed mining and technological facility (more than 4 km), where industrial wastewater is pumped at the inlet, and clarified mine waters are pumped out through the outlet. Through the entire top roof a rather large groundwater volume obtains into the mine. However, the total incoming water volume is such that inside the mine flow will be very slow (about 0.1 cm/s).

Suspended impurity composition will greatly influence the treatment process of industrial wastewater into a coalmine as well. Despite their content in the industrial wastewater pumped into the mine for treatment does not exceed 5 percent, they most strongly affect the safe operation time of the mine as a treatment plant. Suspended impurities consist of very small organic and mineral genesis particles with a particle size of up to 10 microns. They very slowly settle in the water under the action of gravity and are quite strongly diffuse. However, the particles sediment may eventually compact so that it will not to be blurred by the flow. This process is called mine workings siltation. Mine workings siltation may lead to such fluid flow space narrowing, that because of transport speed wastewater becomes large enough so that the impurities particles no longer stay in the mine workings space. After that, the coal mine will become unsuitable for further use as a wastewater treatment plant.

In mathematical modeling of industrial wastewater treatment in coal mine workings, we will neglect the walls influence, therefore only the two-dimensional model is under consideration (see Figure 1). And since impurity particles are very small sized, and the flow is so slow, the suspended impurities presence will not affect the mine water flow.

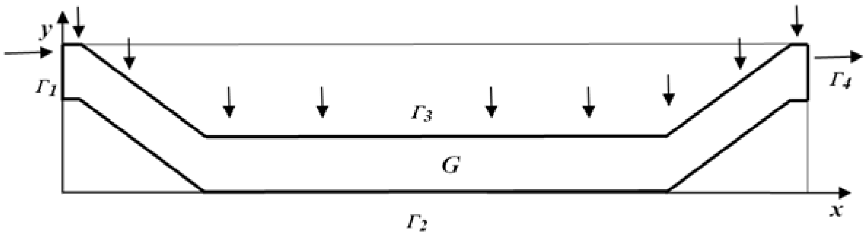

Figure 1. Solution domain

The mine water flow, filling the mine workings, is the flow of a homogeneous viscous incompressible fluid and is described by the system of Navier-Stokes equations in "stream function - vortex" variables:

$$\frac{\partial \boldsymbol{\omega}}{\partial t}+u\frac{\partial \boldsymbol{\omega}}{\partial x}+\upsilon\frac{\partial \boldsymbol{\omega}}{\partial y}=\frac{1}{\mathrm{Re}}\left(\frac{\partial^2 \boldsymbol{\omega}}{\partial x^2}+\frac{\partial^2 \boldsymbol{\omega}}{\partial y^2}\right); \tag{1}$$

$$\frac{\partial^2 \boldsymbol{\psi}}{\partial x^2}+\frac{\partial^2 \boldsymbol{\psi}}{\partial y^2}=\boldsymbol{\omega}. \tag{2}$$

The following notation is used in equations (1) – (2): $\boldsymbol{\omega}$ – vortex, $\boldsymbol{\psi}$ – stream function, u, υ – velocity vector components, Re – Reynolds number.

The boundary and initial conditions for the velocity vector components are known from the physical statement of the problem (3), and the boundary and initial conditions for the vortex and stream functions are set by differentiating and integrating the velocity profile, respectively:

$$\begin{aligned}
&\textit{at } t=0 \;\; u=0, \;\; \upsilon=0;\\
&\textit{on the boundary } \Gamma_1 \;\; u=u_0(t,y), \;\; \upsilon=0;\\
&\textit{on the boundary } \Gamma_2 \;\; u=0, \;\; \upsilon=0;\\
&\textit{on the boundary } \Gamma_3 \;\; u=0, \;\; \upsilon=\upsilon_0(t,x);\\
&\textit{on the boundary } \Gamma_4 \;\; u=u_1(t,y), \;\; \upsilon=0;\\
&\textit{across the boundary } \omega=\left(\frac{\partial \upsilon}{\partial x}-\frac{\partial u}{dy}\right);\\
&\textit{across the boundary } u=\frac{\partial \psi}{\partial y}; \;\; \upsilon=-\frac{\partial \psi}{\partial x}.
\end{aligned} \tag{3}$$

The suspended impurities distribution in the found mine water flow is determined from the solution of the impurity transport equations, and the number of these equations corresponds to the number of particle fractions considered. For one fraction of particles, the boundary value problem has the form:

$$\begin{aligned}
&\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+\left(\upsilon-\upsilon_s\right)\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right);\\
&\textit{at } t=0 \;\; C=0;\\
&\textit{on the boundary } \Gamma_1 \;\; C=C_1(t,y);\\
&\textit{on the boundary } \Gamma_2 \;\; D_1\frac{\partial C}{\partial y}+\upsilon_s C=C_D-C_{\upsilon_s};\\
&\textit{on the boundary } \Gamma_3 \;\; C=C_2(t,y);\\
&\textit{on the boundary } \Gamma_4 \;\; \frac{\partial C}{\partial x}=0,
\end{aligned} \tag{4}$$

where C – the suspended impurities concentration, D – dimensionless diffusion coefficient, υ_s – impurities settling velocity under gravity, D_1 – bottom diffusion coefficient, C_D – flow of particles detached from the bottom, C_{υ_s} – accumulated settling particles rate.

Suspended impurities sediment accumulation and compaction occurs in a rather thin layer near the bottom, which is usually called the active layer. As soon as settled impurity concentration in the active layer increases sufficiently, the sediment begins to compact and after some time completely ceases to be washed out by the fluid flow. In the proposed mathematical model, sediment compaction corresponds to a bottom shape change, due to the lower boundary moving inside the solution domain to that part of the active layer thickness in which the limit compaction concentration preserved during the limit compaction time. The fully compaction sediment does not wash out over the future.

Grid method is used to solve boundary problems. A non-uniform finite-difference grid is constructed in the solution domain (see Figure 1). The first derivatives within the solution domain are approximated using up flow differences. The stabilizing correction scheme is used to solve the transfer difference equations, and to solve the system of linear algebraic equations obtained after Poisson equation approximation for the stream function is used the minimal residuals method of incomplete approximation with global optimization of iterative parameters.

3. Numerical experiments results

In this section the industrial wastewater treatment in spent mine workings numerical simulation results are presented. The suspended impurities distribution process in the mine workings is non-stationary and as the impurities particles sediment, the lower boundary of the solution domain gradually begins to change due to sediment compaction (Figure 2a). At the initial moment, at the sloping boundary base near the inlet, a sediment beach begins to form, the mine workings channel narrows and the flow velocity locally increases.

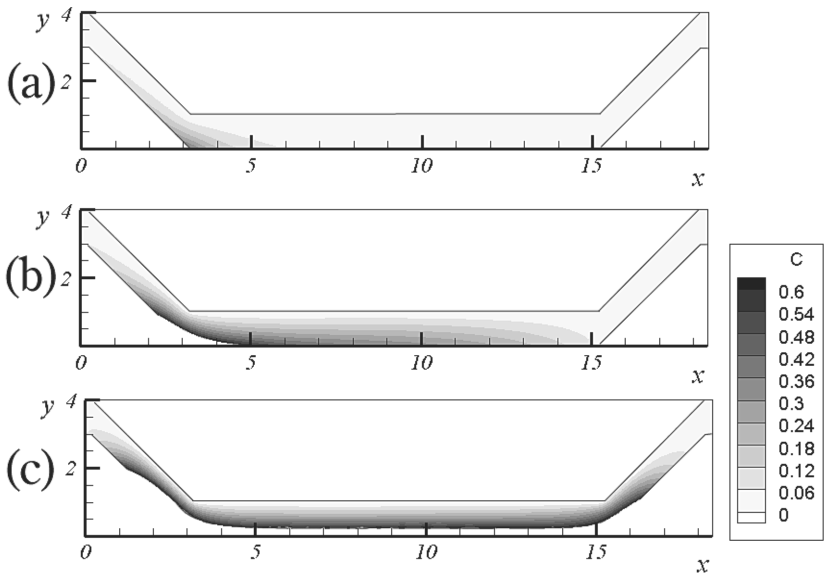

Figure 2. The mine workings filling with compacted sediments at time moments: (a) 100 months, (b) 100 months, (c) 1000 months.

Due to the increased flow velocity, impurities particles are transport further along the channel from the point of constriction towards the outlet, for this reason the channel does not overlap (Figure 2b). Since the sedimentation processes of fine slurry coal water and the compaction sediment are very slow processes, over a long time the impurity concentration remains much less than the input concentration (equal to 50 000 mg / l) and almost constant (about 20 mg / l), only over 780 months it greatly increase. This means that for a sufficiently long time, mine workings remains an effective treatment structure and only after about 1000 months it is filled with compacted sediment so that, due to the increased fluid flow velocity, the impurity particles no longer settle at the bottom and begin to wash out intensively (see Figure 3a).

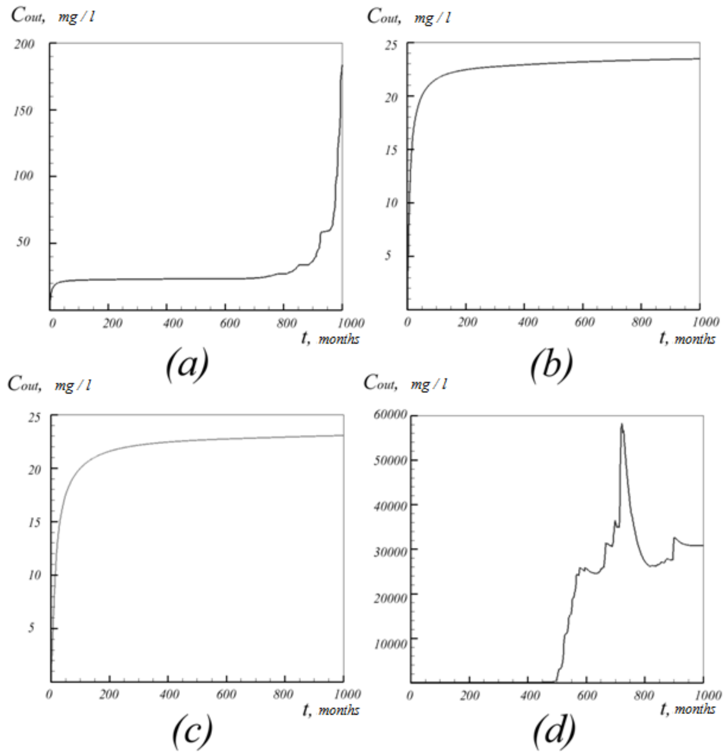

Figure 3. Diagrams of impurity quantity change in the outflow solution domain boundary. The results were obtained with a different industrial wastewater volume pumped for treatment into spent mining workings, respectively (a) “normal volume”; (b) half the “norm”; (c) four times less than the “norm”; (c) doubles the “norm”.

If the total flowing wastewater volume is reduced by two or four times, in this case the sediment accumulation is much slower and the impurities concentration at the outlet remains at an acceptable level for a long time, which significantly increases the time of possible flooded mine workings use as a sewage treatment plant (see Figure 3b, 3c). However, if the pumped wastewater volume is doubled compared with conventional volume, the volley emission will occur earlier, the peak volley concentrations will be significantly higher, and may even exceed the impurity concentration at the inlet (see Figure.3d). Thus, the industrial wastewater volume pumped for treatment directly affects the mine workings "safe operation" time as a wastewater treatment plant.

4. Conclusions

The performed numerical simulation experiments industrial wastewater treatment from coal preparation plants in spent flooded mine workings showed that this treatment method is quite effective for suspended impurities and allows treatment for a long time. However, as the coal mine workings are filled with compacted sediment, the treatment efficiency will decrease, and the probability of volley emission will increase. The proposed model makes it possible to study the treatment processes occurring in the flooded mine workings and can help the choice of optimal pumped wastewater volumes and such pumped intervals so that, taking into account the specific parameters of the taken coal slurries, to achieve the maximum safe time and cost-effective operation conditions of such treatment structures.

References

[1] Filippov S 2018 New Technological Revolution and Energy Requirements *Foresight and STI governances* **12(4)** pp 20–33

[2] Popova D S 2017 Environmental problems of coal-mining regions of Russia *International journal of applied and fundamental research Geologo-mineralogical sciences* **8** pp 126–131

[3] Drebenshedt K 2013 Modern environmental and economic approach of mining industry. Economy of region *Centre for Economic Security Institute of Economics of Ural Branch of Russian Academy of Sciences* **1(1)** pp 114–22

[4] Islamov S R 2017 Coal as a low carbon fuel *Ugol' – Russian Coal Journal* **4** pp 50 – 2
[5] Zaytsev A S, Tkachenko P P and Belonogov M V 2018 Light-Induced Gasification of Fuels Prepared from Coal-Enrichment *Wastes Coke Chem*. **61(7)** pp 274–80.
[6] Lottermoser B 2010 *Mine Wastes: Characterization, Treatment and Environmental Impacts* (Springer Verlag Berlin Heidelberg) p 400
[7] Churuksaeva V V and Starchenko A V 2015 A Mathematical model and numerical method for computation of a turbulent river stream *Vestnik Tomskogo Gosyudarstvennogo Unuversiteta Mat. Mekh.* **6(38)** pp 100–14
[8] Zhu Z, Waterman D M and Garcia M H 2018 Modeling the transport of oil–particle aggregates resulting from an oil spill in a freshwater environment *Environmental Fluid Mechanics* **18(4)** pp 967–84
[9] Sukhinov A I, Chistyakov A E and Protsenko E A 2014 Mathematical modeling of sediment transport in the coastal zone of shallow reservoirs *Mathematical Models and Computer Simulations* **6(4)** pp 351–63.
[10] Zakharov Yu and Bondareva L 2015 Simulation of Domestic and Industrial Wastewater Disposal in Flooded Mine Workings *Procedia Engineering* **117** pp 389–96
[11] Bondareva L, Zakharov Yu and Goudov A 2017 Simulation of Industrial Wastewater Treatment from the Suspended Impurities into the Flooded Waste Mining Working. *IOP Conf. series: Materials and Engineering* **189** pp 1–5