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Simulation of Domestic and Industrial Wastewater Disposal in Flooded Mine Workings

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Abstract

The paper is dedicated to the mathematical model of domestic and industrial wastewater treatment and disposal in a flooded mine working. The goal of the research is to develop and analyze the mathematical model of suspended impurities flow and distribution. Impurity sedimentation model is under consideration. Due to the sediment compaction problem solution domain can be modified. Impurities flow and distribution patterns are presented.

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Keywords: Domestic and industrial wastewater; disposal of waste; treatment; mathematical modelling

1. Introduction

Industrial and domestic wastewater emissions into water objects can cause changes of their hydrochemical conditions, biological conditions, water quality and irreversible environmental impact [1]. Urban development results in water consumption increasing as well as increasing in wastewater volume. Wastewater should be treated or disposed. Water pollution is a key problem for such industrially developed Russian region as Kuzbass [2].

Coal preparation plants exacerbate regional ecological problems. Industrial wastes normally include flotation tailing and plant slurry water. They can be identified as slurry that consists of liquid phase, solid phase and gas phase. The liquid phase mass is about 95-98% of total mass and consists of mining water or river water used by a plant to prepare coal. Gas phase consists mostly of solute air. The solid phase consists of particles of mineral or

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organic origin. However, 80-95% of solid phase appear to be particles sized up to 50μm [3]. Coal refineries wastewater may contain suspended particles (coal dust, rock dust, clay particles), salts of heavy metals, phenols, ammonia, nitrates, nitrites, free sulfuric acid, sulfur and other hazardous substances [4]. Moreover, industrial wastewater may contain remains of floatation reagents needed for coal preparation which are partially water dissolved and partially sorbed on suspended substances [3].

Large amount of electric power and capital funds needed for wastewater treatment facilities construction to pump out, purify, drain and dispose mining water. Nowadays great variety of wastewater treatment technologies are utilized depending on purification index, complexity of equipment required, energy costs and explicit costs [5 – 10]. It's well known that large amount of sediment with total suspended solids up to 5g\cubic decimeter develop while wastewater treatment facilities operating. Sewage sludge treatment usually takes place on sludge banks, in slurry ponds or sludge pits that enable to combine both its neutralization and storage. These facilities require much territory and appear to be potential pollution sources [11]. Nevertheless, this technology is widely used because of its ease of operation and simple structure.

Another method that requires treatment process with the help of flooded waste mining workings is also used for coal industry wastewater treatment in Kuzbass. This method is applied to purify slurry water of "Komsomolec", coal preparation plant in the waste mine workings of "Kolchuginskaya" coal mine. Natural purification of wastewater is supposed to take place in mine workings due to the water precipitation and mixture with influent underground water. This technology presupposes treatment as well as storage of sedimentary sludge in mined-out space [11]. This alternative approach is of great concern in Kuzbass. As a result of unprofitable coal producers closures large underground spaces are filled with technogenic underground water. Moreover, these flooded mine workings are normally situated within the city boundaries and can be potentially used as sewage treatment plants.

Although the method is quite simple and requires low costs it is essential to be researched to forecast possible effects of treatment processes. Volley emission of accumulated impurities is the highest priority danger that can result in short but intense increasing of impurities' concentration and volume in pumped out water. Changes of mine working internal structure caused by roof collapse or accumulated sediment solidifying; seasonal change of regional hydrological conditions resulting in influent underground water volume increase and other factors can be the reasons of the phenomenon described. To put this wastewater treatment method into practice safely it is highly important to avoid volley emission by in time putting mine workings out of operation like a wastewater treatment facility.

Flooded mine working can be defined to be a black box with only input and output data possible to be estimated. Thus, it is needed to apply mathematical simulation and numerical experiments in order to forecast potential evolution of the processes in flooded mine workings.

2. Selection of mathematical model of impurity subsidence and problem solution domain modifying due to the sediment packing

Slurries are identified to be unstable and segregate systems in response to falling out solid particles. This process is complex for analytical description as long as cohesion of gravity forces, environmental resistance, fluid flow effects and different falling velocities of mixed size particle produce an effect on settling velocity of polydispersed mixture that is slurry itself. As time passes while settling down the number of particles is decreasing and the balance between proportions of mixed size particles is changing in the unit volume of slurry top layer. Bigger particles sediment faster and their concentration in the top layers decreases faster compared to smaller particles. Obviously reserved tendency is registered in slurry low layers. Very fine particles can remain in top layers because their weight forces may appear to be so weak that environmental resistance and Brownian motion may balance them. Solids settling process is accompanied by sedimentation and consolidation of sediments [3].

To develop a model of the problem described existing models of suspended impurities flow and distribution were under examination. One of the problems that simulates the process of solid particles in a fluid flow transportation is the problem of dynamics of sediment load in a river bed. River water streams transport sand grains, sludge particles and grail that can result in sediment loading and riverbed erosion. Sediment loads are divided into two types: suspended sediment loads that are suspended while being transported by a flow and bed loads that move in bottom water. Water flow hydraulic elements such as flow velocity, depth and others have a great impact on sediment load transportation. Complete problem formulation of river bed evolutions dynamics is a complex problem which is focused on in several papers [12 – 15]. It is normally divided into three interdependent processes. The diffusion theory is applied to simulate suspended sediment loads. Empirical formulas are used to estimate sediment transport rate [14] and transfer equation is applied to simulate suspended sediment load transportation in a flow.

However, there are several reasons demonstrating that this method is not appropriate to simulate impurities flow and distribution in flooded mine workings. First of all a river flow is characterized by changeability of vertical and horizontal speed components. It means that particles move intermittently in a flow. They can move by bounds, roll, stop and get into flow again. Flow velocities are slow in a mine working. Main fluid volume is filtered through the roof and the flow can't switch to a turbulent mode. Moreover, size of suspended pollutant particles settlement zone is limited by mine working area. Secondly, solid phase quantity does not exceed 5% of wastewater volume and contains mainly particles sized not more than 50 μm. These impurities sediment and consolidate so eventually they are not washed out by flow. Thus, empirical formulas suitable for suspended impurities in riverbed are not applicable to estimate mass transfer between bottom and water flow in the case described. Thirdly, simplified model of bed load dynamics suggesting water saturated sludge to be viscous-plastic fluid medium is not appropriate. This method is often used to simulate landslides down the slope [16]. Flooded mine working has great extent, complex and variable topology (for example, roof collapse, cracking, etc.). Top priority target of the simulation is to analyze tendencies of impurity accumulation and emission out of mine working and local effects are of minor importance.

In the paper impurity transport equation is used to simulate impurity flow and distribution. The equation is the result of continuous and nonuniform medium conservation law [17].

We consider that industrial wastes containing only undissolved impurities with concentrations identified are supplied in a waste mine working. The problem of dissolved impurities flow and distribution was described in [18 – 22]. Underground water without undissolved impurities penetrate through the roof. Impurity particles are supposed not to affect flow, but they sediment due to gravity and spread in mine working due to diffusion and water flow transportation. Sediment impurities can cumulate and "harden" (consolidate), if water flows don't transfer them for a while.

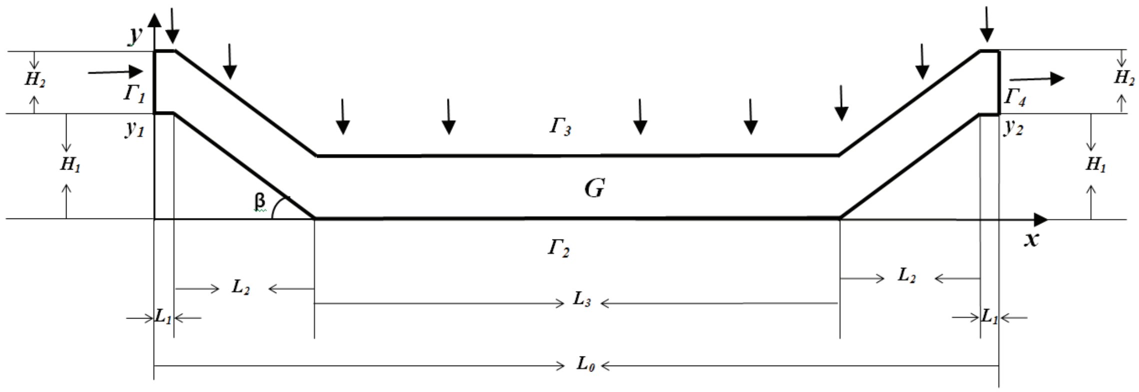

Fig. 1. Solution domain for the impurity sedimentation and sediment consolidation problem

Since fluid flow velocity is slow in a flooded mine working we consider that sidewalls don't affect sedimentation process and flowing up, so only two-dimensional model is under consideration.

We shall examine the solution domain G that represents flooded mine working form [19] with boundary $\partial G = \bigcup_i \Gamma_i$, $i = 1...4$, where Γ_1, Γ_4 – inlet and outlet holes respectively, altitudes H_2, Γ_2, Γ_3 – high and low boundaries , lengths $2L_1 + 2L_2 + L_3$ (refer with: Fig.1).

We consider fluid to be uniform, viscous and incompressible. Nondimentional Navier–Stokes equations system describes this fluid flow by variables "flow function-vortex" [23].

$$\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + \upsilon\frac{\partial \omega}{\partial y} = \frac{1}{Re}\Delta\omega; \tag{1}$$

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

Initial and boundary conditions are needed to be provided for equation system (1) – (2), but physical problem formulation suggests only two velocity conditions. The velocity of wastewater flood is known and it's possible to estimate the velocity of fluid pumping out of mine working. Taking into consideration ground water level and pumping out velocity it is possible to calculate volume of filtered underground water. Thus, initial and boundary problems are formulated for physical variables:

$$u|_{t=0} = 0; \quad \upsilon|_{t=0} = 0;$$

$$\Gamma_1: \ u = u_0(t,x,y), \ \upsilon = 0; \quad \Gamma_2: \ u = 0, \ \upsilon = 0; \tag{3}$$

$$\Gamma_3: \ u = 0, \ \upsilon = \upsilon_0(t,x,y); \quad \Gamma_4: \ u = u_1(t,x,y), \ \upsilon = 0.$$

In (1) – (3) the following identifications are used: $\vec{U} = (u(t,x,y), \upsilon(t,x,y))$ – velocity vector, defined by its components u, υ; $u_0(t)$, $u_1(t)$, $\upsilon_0(t)$ – known functions, estimated on the solution domain boundary ∂G; $Re = \frac{\tilde{u}L_0}{\nu}$ – Reynold's number; $\tilde{u}$ – reference speed, which is calculated as maximum velocity of input flow; L_0 – reference length; ν – kinematic viscosity; Δ – Laplace operator.

Velocity vector components u, υ are connected to vortex ω and flow function ψ in the following way:

$$\omega = \frac{\partial u}{\partial y} - \frac{\partial \upsilon}{\partial x}, \quad u = \frac{\partial \psi}{\partial y}, \quad \upsilon = -\frac{\partial \psi}{\partial x}.$$

Taking into consideration (3), ω and ψ on ∂G are defined as follows

$$\omega|_{t=0} = 0, \quad \omega|_{\partial G} = \left(\frac{\partial \upsilon}{\partial x} - \frac{\partial u}{\partial y}\right)_{\partial G}; \quad \psi|_{t=0} = 0, \quad \bigcup_i \Gamma_i: \ \psi = \psi_i(t,x,y); \tag{4}$$

where $\psi_i(t,x,y)$ – known functions, chosen in the way that the condition $\int_{\partial G} \frac{\partial \psi}{\partial n} = 0$ is fulfilled [24], where n – outward normal direction.

To simulate distribution of impurities transfer equation is used [16]:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+(\upsilon-\upsilon_S)\frac{\partial C}{\partial y}=D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right) \quad (5)$$

with certain initial and boundary conditions:

$$C(x,y,0)=C_0(x,y);$$

$$\Gamma_1:\ C=C_1(x,y);\quad \Gamma_2:\ D\frac{\partial C}{\partial y}+\upsilon_S C=C_D-C_{\upsilon_S};$$

$$\Gamma_3:\ C=C_2(x,y);\quad \Gamma_4:\ \frac{\partial C}{\partial y}=0. \quad (6)$$

Here $C_0(x,y),\ C_1(x,y),\ C_2(x,y)$ – the specified functions estimated at the boundary ∂G , C – concentration of impurity sedimentation, υ_s – velocity of impurity sedimentation that characterizes the mass of settling particles, D – diffusion coefficient. The "heavy" impurity flow is estimated at the low boundary of solution domain Γ_2 , that equals the difference between impurity particles taking off the bottom C_D (sedimentation outwash) and settling particles C_{υ_s} (identification of impurity accumulation at the bottom).

Subsidence impurity and slumped impurity can eventually affect bottom shape. We simulate this process in the following way: if during the time interval T^* settled impurity concentration exceeds threshold value C^* near the boundary of solution domain, then this impurity is considered not to be affected by the flow and the solution domain boundary is shifted according to concentration C^* and time T^*.

3. Problem-solving procedures and calculation results

The formulated differential problems are solved by the grid method. The initial differential boundary problems are approximated in a standard way on a difference, boundary consistent and unequally-spaced grid with step $h_{x_i},\ h_{y_j}$ with respect to space variables and step τ with respect to time [25].

The vorticity transfer equation and the impurity transfer equation are solved by the implicit scheme of stabilizing corrections with counterflow approximation of convective elements [26]. Poisson difference equation for flow function is solved by the minimal residual method of not full approximation with matrix parameter by applying componentwise and overall optimization of iteration parameters [27].

There are two stages of the solution: the boundary problem (1) – (4) is solved and components of the velocity vector are calculated at the first stage, the problem (5) – (6) is solved and patterns of impurity distribution in a channel are defined at the second stage.

It is expected that at the initial instant t=0 there are no impurities in the solution domain and polluted fluid is started to be supplied via input boundary. "Pure" underground water is filtered through a roof and liquid is pumped out at output boundary.

Fig. 2-3 shows the results in the context of the following grid and flow property values: $H_2=0.5,\ H_1=L_2=0.6,\ L_3=2,\ L_1=0.1,\ h_x=h_y=0.01,\ \tau=0.01,\ \mathrm{Re}=400,\ u_0(t)=0.001,\ C_0(t,x,y)=0.2.$

The problem of viscous uniform incompressible fluid is evolutional, thus, components of the velocity vector are calculated at every layer with respect to time. In solution domain the flow develops with low velocity and fluid streamlines are directed along the channel and vortex structures do not occur (refer with: Fig 2.1).

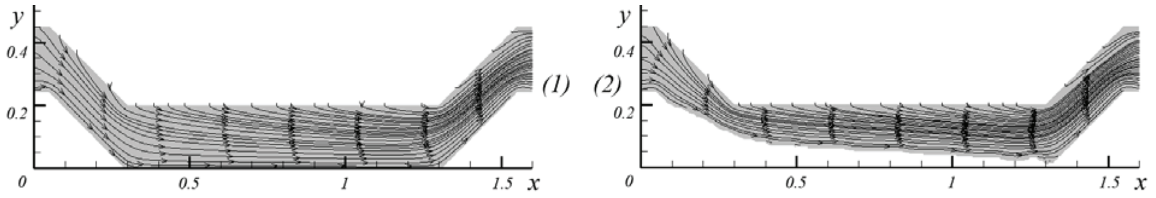

Fig.2. Fluid flow when $\upsilon_0 = -4u_0 H_2 / L_3$. 1. Initial solution domain. 2. Modified solution domain.

Due to the sediment compaction the solution domain form can change, therefore fluid flow is recalculated according to the boundary modifications (refer with: Fig.2.2).

Fig. 3 shows the dynamics of impurity distribution and sedimentation. The impurity distributes not uniformly along the streamline in a channel (t=2). Both horizontal and vertical distributions occur because of diffusion process. Forced by gravity sediment settles along the whole channel length bottom boundary. However, high concentration of impurities is defined mostly along the sloping boundaries (t=10). Fluid flow provided through the roof conduces vertical impurity sedimentation. By nondimentional time (t=5) local sediment compaction along the left bottom sloping boundary is evident. By the time (t=10) the channel appears to be more restricted. More detailed examination of problem input parameters' impact on the resulting patterns of suspended impurities flow and distribution is shown in [28].

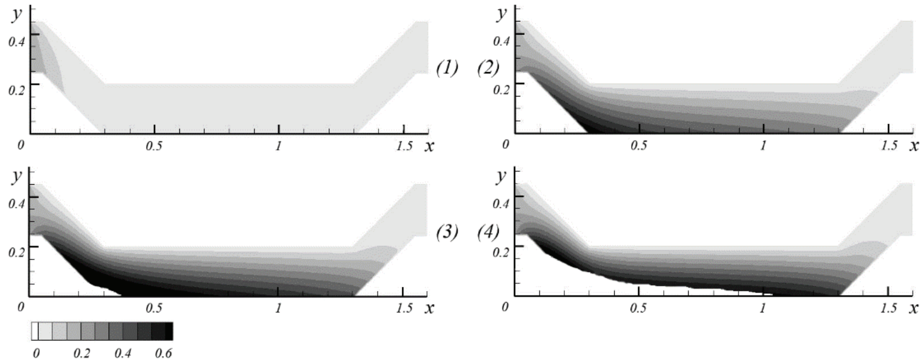

Fig. 3. Impurity flow and distribution with the following parameters' values $D = 0.1,\ C_D - C_{\upsilon_s} = 0.25,\ \upsilon_s = 0.1,\ C^* = 0.6,\ T^* = 1$

when time values:1) t= 0,05; 2) t = 1; 3) t= 5; 4) t=10; 5) t=20.

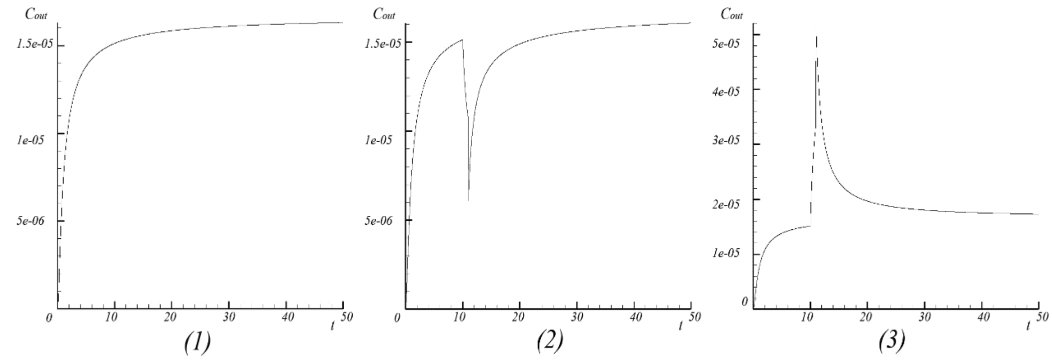

Fig. 4. Diagram of impurity quantity change leaving the solution domain.

1. Underground water flow is constant
2. Underground water flow decreases by 4 times within the following time interval $t \in (10,11)$.
3. Volley emission model. Underground water flow intensifies by 4 times within the following time interval $t \in (10,11)$.

Volume of impurities leaving the solution domain with pumped out fluid flow C_{out} is a principal characteristic that describes the “efficiency” of impurity sedimentation and accumulation. If the underground water inflow V_{in} is constant the quantity of outflowing impurities increases uniformly by a defined level (refer with: Fig.4.1)

In case of any changes of V_{in} the index C_{out} can substantially change. Though volume reduction of fluid inflow does not have any hazard effect (refer with: Fig.4.2), “emission” amount decreases correspondingly and increases uniformly as soon as flow gains its earlier volume.

Slurry sedimentation and accumulation can have hazard effect that is a so called “volley emission”, i.e. sharp increase of impurity concentration and amount that leave solution domain. This pattern can occur as a result of a sudden filtered underground water volume growth (Fig.4.3). This figure shows that within time interval from t=10 to t=11 the as soon as V_{in} increases by 4 times the impurity amount increases sharply at the solution domain output. Until t=10 C_{out} grows uniformly, as soon as t=11 its indexes drop to the value got when solving an analogous problem with constant volume of influent underground water (refer with: Fig.4.1).

4. Conclusion

The suggested mathematical model of suspended impurity flow, distribution and settling enables to change solution domain due to the deposition of sediments and analyze the process of industrial wastewater treatment in flooded mine workings. The model allows to make a forecast whether fluid flow channel can be shut off and volley emission is possible. Any drastic changes in the diagram of impurity quantity in discharged fluid may be an indication of an approaching volley emission. The carried out calculations demonstrate that the method of domestic and industrial wastewater treatment in flooded waste mine workings can be put into practice but it is very important to observe all the processes going on to avoid volley emission of accumulated impurities.

It is necessary to control treatment quality to prevent volley emission. For instance, gauges with dynamic optimization of a mechanical actuator [29] can be used to shift discharge water supply to other treatment facilities. Afterwards, if needed, dissolved impurities can be removed as well.

5. Notation

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The second chapter of the research called “Problem-solving procedures and calculation result” was carried out with support of state project 2014/64.

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