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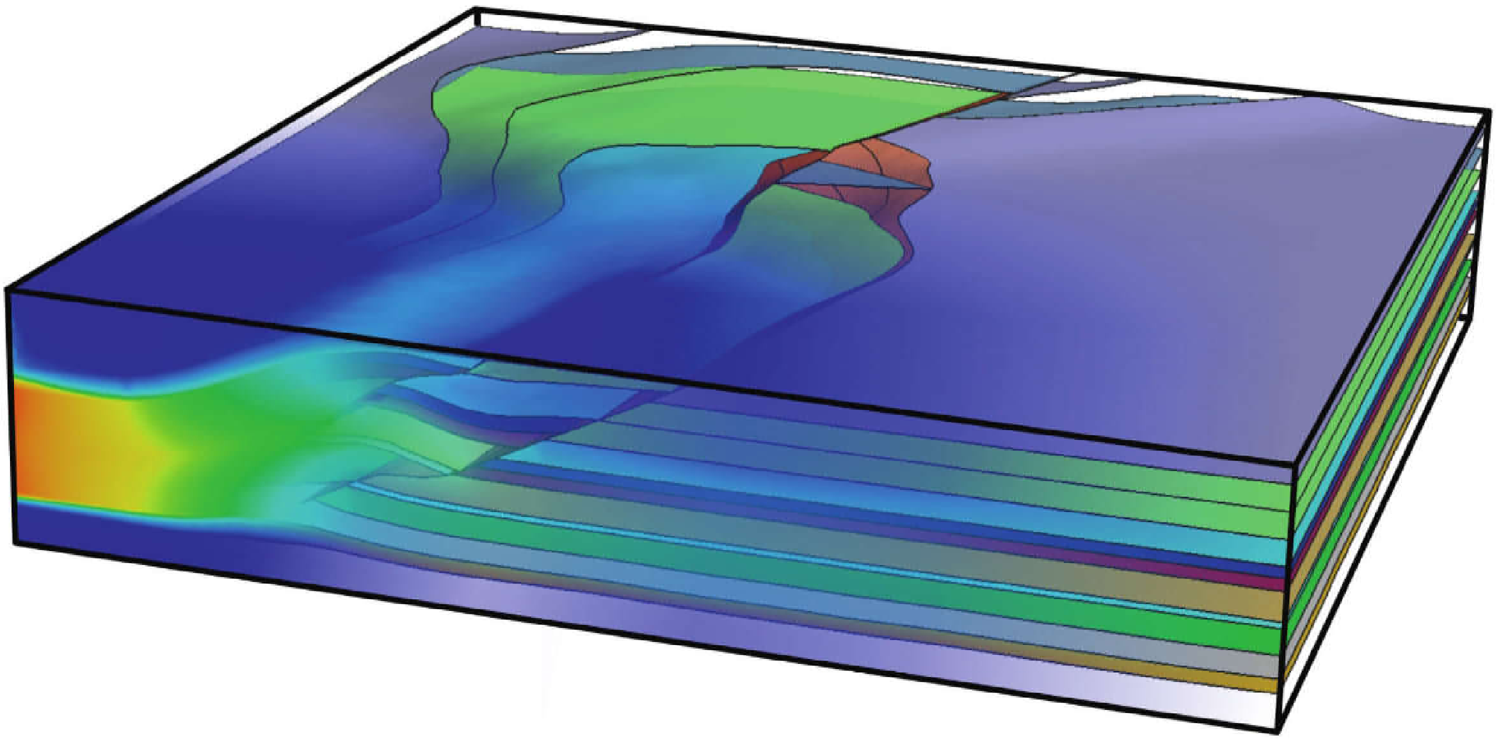

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Impact of Gravity Effect on Flows in Porous Media

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Abstract

When density of leaching solution and groundwater are different, gravity becomes an important factor that affects the hydrodynamics of in-situ leaching process. Therefore, the leaching solution flows in the porous medium noticeably at a lower rate than expected which might introduce difficulties for recovering the metal trapped in the upper part of the geological layers. This paper investigates this gravity effects on the flow regime by including it in the Darcy equations. Overall, the modeling consists of calculation of the pressure and density distribution and the filtration Darcy velocity with gravity effect, although leaching kinetics also impact on the density of the porous medium. The density of the porous medium in a couple parameter that affects the hydrodynamics of the leaching process. The full coupled differential equations are numerically solved using the CUDA (Compute Unified Device Architecture) parallel computing platform facilities provided by Nvidia. Results show that the pressure equation is solved by CUDA on graphics processing unit (GPU) an order of magnitude faster than on central processing unit (CPU).

Introduction

In-situ leaching (ISL) is a very common method used to recover metal in the mining industry, especially for uranium deposits such as those exploited in Kazakhstan. This paper investigates the sulfuric acid ISL method due to its economic effectiveness when applied to uranium recovery. As the leaching agent (sulfuric acid) density is slightly greater (about $\rho_l = 1.15$) than groundwater density ($\rho_w = 1$) gravitational effect has to be accounted for as it may affect the flow direction. Due to this gravitational effect, the denser fluid tends to flow downward while the lighter fluid flows directly to the production well. The acid fluid water interface (density of acid + water compared to pure water) is more or less tabular near the injection well, but this density contrast produces a drawdown of this interface near by the production well as shown on Figure 1. Thus, during the leaching process some regions (residual zones) are not leached because of this gravitational effect, an effect often neglected in numerical simulation of the ISL process [1]. Therefore, any hydrodynamic modelling of ISL process should take into consideration the gravity forces in the Darcy Law (1):

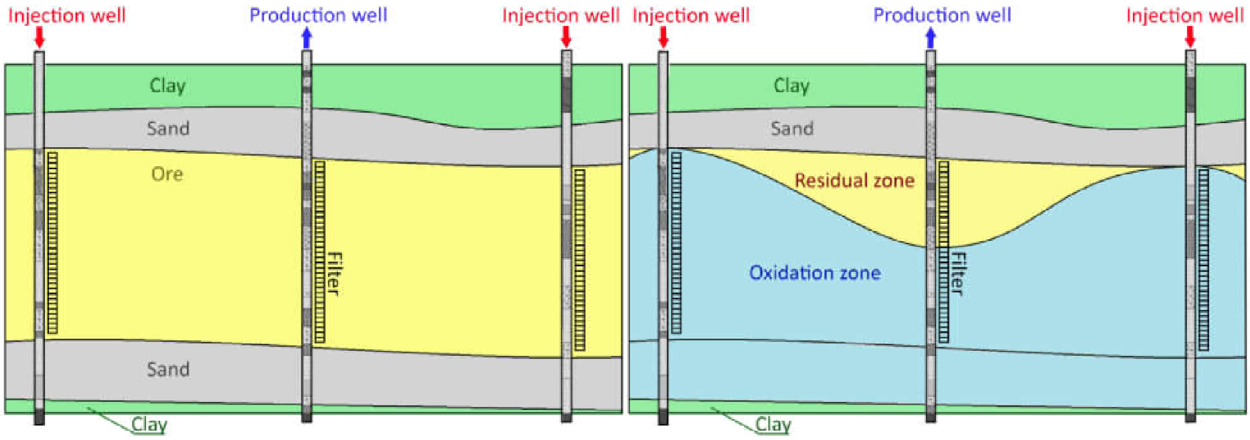
$$\mathbf{U}\phi = -\frac{\mathbf{k}}{\mu} \cdot \left(\mathbf{grad}(p) + \rho\,\mathbf{g}\right) \tag{1}$$

where **U** is the filtration velocity (in m.s^{-1}), ϕ the porosity (notice that $\boldsymbol{v} = \boldsymbol{U}\,\phi$ is the classical Darcy velocity), $\boldsymbol{k}$ the permeability tensor (in m.s^{2}) of porous medium ($\boldsymbol{k} = k\,\boldsymbol{I}$ for the isotropic case), μ the dynamic viscosity (in Pa.s) of fluid, p the fluid pressure (in Pa), ***grad*** the gradient vector, ρ the fluid density (in kg.m^{-3}), and $\boldsymbol{g}$ the gravitational acceleration (m.s^{-2}) vector [2]. The mass Conservation Equation (2) of the injected fluid can be written as [3]:

$$\frac{\partial \rho}{\partial t} + div\left(\rho\,\mathbf{U}\phi\right) = q \tag{2}$$

where t is the time (in s), and q the total source rate[1] (in kg.m^{-3}.s^{-1}) terms counted positively in the case of an injection of fluid, and negatively for the production of the fluid. After expansion, Eq (2) can be rewritten as:

$$\frac{\partial \rho}{\partial t} + \phi\,\mathbf{U} \cdot \mathbf{grad}(\rho) + \rho\, div(\mathbf{U}\phi) = q \tag{3}$$



a) b)

Figure 1 : Sketch explaining the in-situ leaching technique used to recover uranium in roll-fronts , a) before uranium extraction b) after uranium extraction

Assuming that fluids are incompressible $\left(\frac{d\rho}{dt} = 0\right)$, it comes:

$$\frac{\partial \rho}{\partial t} + \phi\,\mathbf{U} \cdot \mathbf{grad}(\rho) = 0 \tag{4}$$

And, thus the mass balance equation Eq (3) can be simplified into the following form:

$$\rho\, div(\mathbf{U}\phi) = q \tag{5}$$

Substituting the Darcy Law (Eq. 1) into the mass balance equation Eq (5), it comes (assuming a non-zero fluid density ρ):

$$div\left(-\frac{\mathbf{k}}{\mu} \cdot (\mathbf{grad}(p) + \rho\,\mathbf{g})\right) = \frac{q}{\rho} \tag{6}$$

After some arithmetic, Eq. (6) can be developed as (assuming Eq. (4) stands true i.e. fluid properties are spatially stationary):

$$div\left(\frac{\mathbf{k}}{\mu} \cdot \mathbf{grad}(p)\right) + \frac{1}{\mu} div(\rho\,\mathbf{k} \cdot \mathbf{g}) = -\frac{q}{\rho} \tag{7}$$

Eq. (7) describes the general case when permeability tensor is anisotropic. However, in sedimentary medium, the permeability tensor is often assumed to be constant in case of isotropic media or diagonal (after choosing an appropriate coordinate system). In last case, the permeability tensor can be written as:

[1] The total source rate q is the sum of in-flow q_{in} and out-flow q_{out} in a volume element: $q = \sum q_{in} + \sum q_{out}$

$$\mathbf{k} = \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix} \tag{8}$$

where k_{ii}, $i \in \{x, y, z\}$ are the permeability in the i direction. In a Cartesian coordinate grid system, the gravity vector $\boldsymbol{g}$ is directed downward along the Z axis, Eq. (6) can be simplified into:

$$div\left(\frac{\mathbf{k}}{\mu}\cdot\mathbf{grad}(p)\right)+\frac{1}{\mu}\mathbf{g}\cdot\mathbf{grad}(\rho k_{zz})=-\frac{q}{\rho} \tag{9}$$

The scalar product of Eq. (9) can be simplified into:

$$div\left(\frac{\mathbf{k}}{\mu}\cdot\mathbf{grad}(p)\right)+\frac{g}{\mu}\frac{\partial(\rho k_{zz})}{\partial z}=-\frac{q}{\rho} \tag{10}$$

Furthermore, assuming that the vertical permeability k_{zz} is spatial quasi constant in the layer, the derivative against z can be assumed as null, and Eq. (10) can simplified into:

$$div\left(\frac{\mathbf{k}}{\mu}\cdot\mathbf{grad}(p)\right)+\frac{gk_{zz}}{\mu}\frac{\partial\rho}{\partial z}=-\frac{q}{\rho} \tag{11}$$

Isotropic case: when the porous medium is isotropic, the permeability tensor is diagonal $\boldsymbol{k} = k\boldsymbol{I}$ where $\boldsymbol{I}$ is the identity and k the scalar intrinsic permeability; thus, Eq. (11) is still valid substituting the term k_{zz} by the scalar permeability k:

$$div\left(\frac{\mathbf{k}}{\mu}\cdot\mathbf{grad}(p)\right)+\frac{gk}{\mu}\frac{\partial\rho}{\partial z}=-\frac{q}{\rho} \tag{12}$$

Consequently, Eqs. (1), (4) and (11) constitute a partial differential equations system with three unknowns including the filtration velocity $\boldsymbol{U}$, the fluid density ρ which depends on the acid concentration and amount of metal dissolved in the leaching fluid, and the fluid pressure p, respectively.

1. Problem to be solved

A three-dimensional well pattern consisting of six injection and one production wells (Figure 2) is considered. It is assumed that the uranium ore is trapped between two impermeable layers, with thickness[2] greater than 12 m. The filtration open section for each well is about 6-8 m in length imposed as a Dirichlet boundary condition in the numerical simulation. Figure 3 illustrates a vertical cross-section passing along the wells 1,7,4 (Figure 2).

[2] For smaller thickness the gravity effects can be neglected.

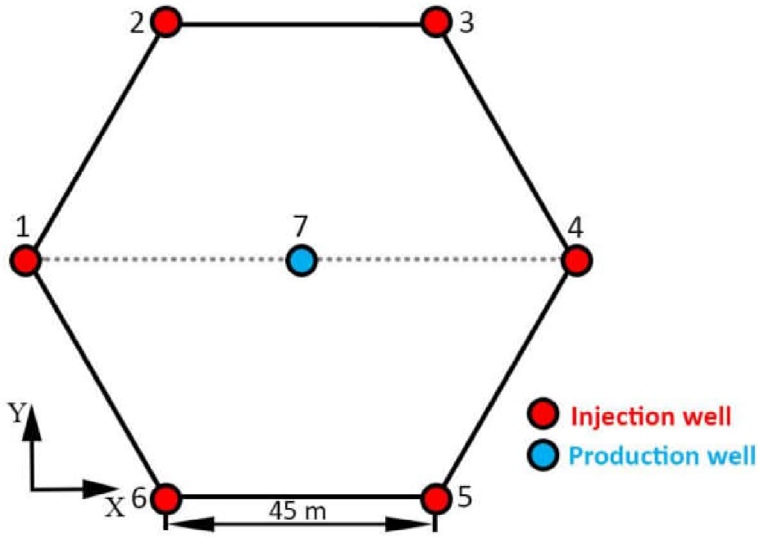


Figure 2 - Plane view of the injection and production wells with considered hexagonal cell.

2. Boundary conditions

For the pressure, a null Van Neumann boundary condition was applied to the top and bottom impermeable layers (no flow passing through). The boundary pressure conditions applied to each vertical sides of the domain are functions of depth and chosen as constant (assuming a constant pressure along the vertical of the layer), i.e. as shown on Figure 3, the distance from the injection well to the boundary is 100 m.

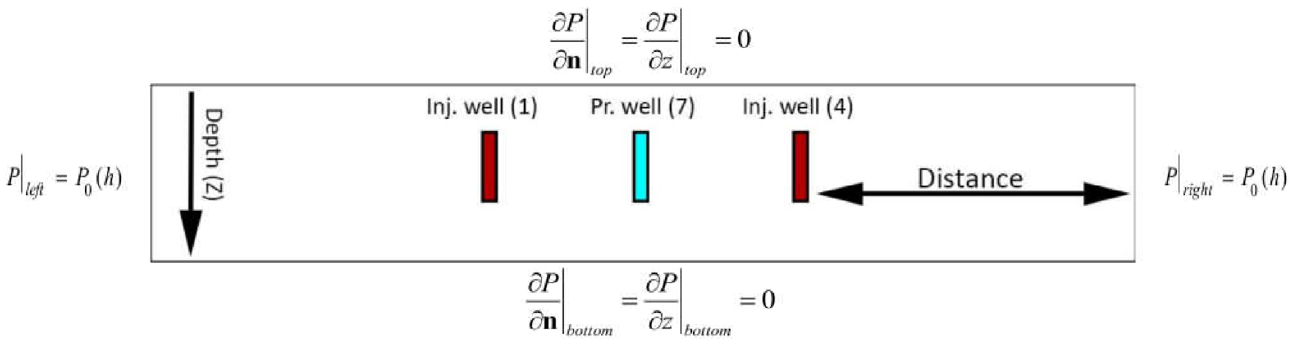


Figure 3 - Vertical cross section of the production cell with boundary conditions.

3. Numerical experiment

The numerical experimentation was implemented in three main steps: (I) estimation of the pressure field accounting for the gravity term and the above given boundary conditions by solving Eqs. 12; (II) estimation of the velocity fields using Eqs. 1; (III) density calculation from Eqs. 4. The first step was solved on the CPU and the GPU. The CUDA parallel technology was used to accelerate the calculation time.

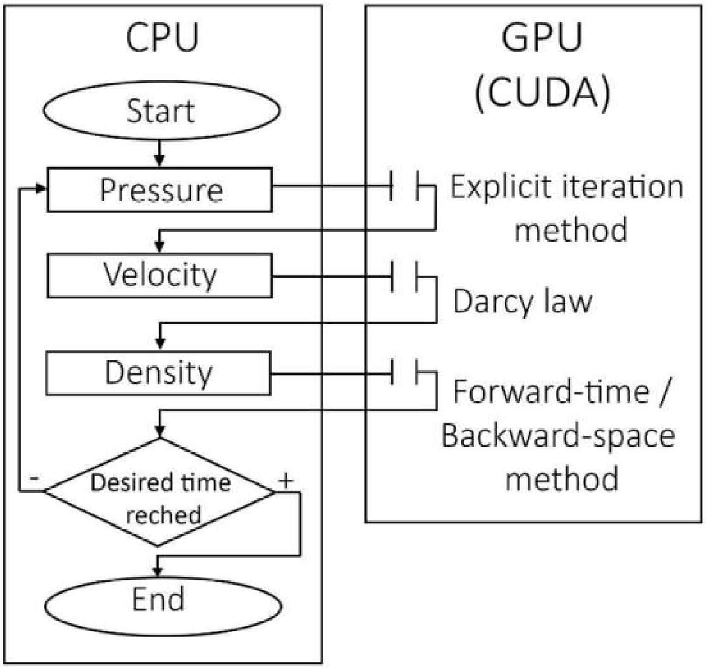


Figure 4 - Main calculation steps using the CUDA technology

Explicit iteration method was used to calculate the pressure distribution, velocity distribution and density in the horizontal layer, since it can be easily parallelized. For comparison the calculations were made with and without gravity consideration.

4. Results and discussion

Two different calculating technologies are used to provide comparison analyses:

- Intel(R) Core(TM) i7-4790 CPU 3.6 GHz
- NVIDIA GeForce GTX 980 GPU 1.2 GHz (CUDA)

The pressure distribution field calculated using these technologies is reported on Figure 5.

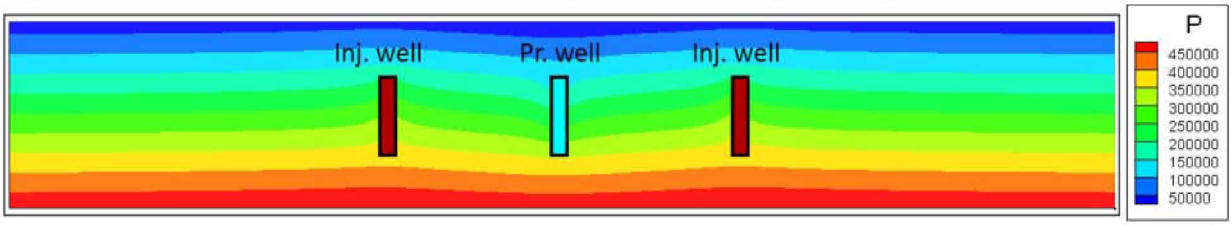


Figure 5 - Pressure distribution before reagent injection (pressure in Pa)

The calculation is performed for different mesh sizes listed in Table 1.

Table 1 - Computing time for CPU and GPU

№	Grid	Computing time [s] on CPU	Computing time [s] on GPU	Ratio
1	64x64x64	14.75	1.89	8
2	128x128x64	66.96	5.1	13
3	192x192x96	413.7	48.12	9
4	256x256x96	772.05	98.3	8
5	256x256x128	1389.9	117.2	12

As shown on table 1 calculation using GPU allow to reduce the computing time an order of magnitude compared to the use of the CPU.

Figure **6** illustrates the difference observed in the pressure distribution and streamlines between results with and without gravity effect. In the first case where the gravity effects are neglected, the streamlines are distributed symmetrically. In the second case, where the gravity effect is taken into consideration, the streamlines are curved downward and are no longer symmetrical along the depth. The difference of density leads to curve downward of the streamlines leading to an undrained zone near the top of the layer, and an over-circulation of the acid fluids at the bottom of the layer. In consequence, as expected, the uranium will be correctly leached in the lower part of the layer, and under leached in the top part.

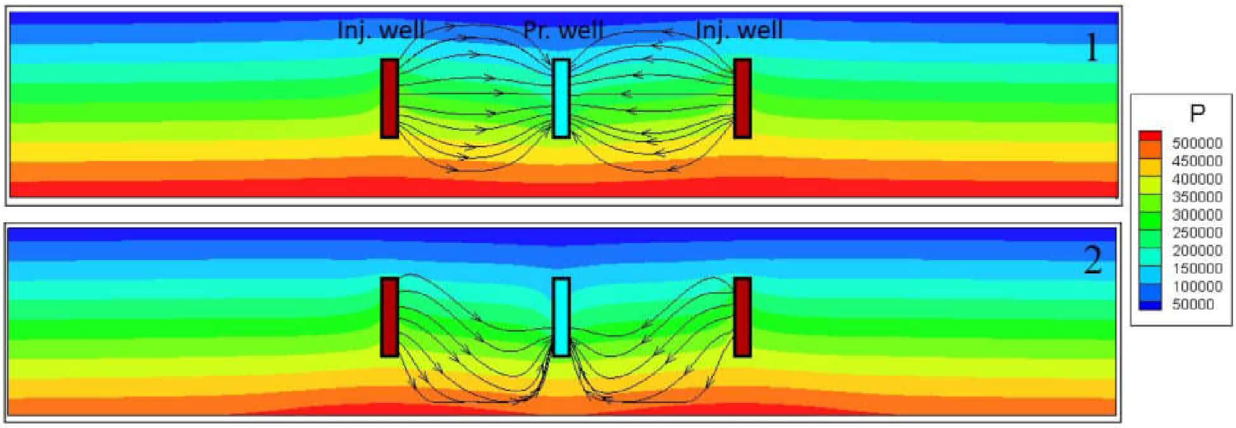


Figure 6 - Pressure distribution 1) without gravity effect, 2) with gravity effect

Therefore, the upper half of the area surrounding the producing well is not being oxidized by the leaching solution as shown in Figure 7- 2. At the same time, Figure 7-1 illustrates density distribution without gravity effect which is unrealistic physical results.

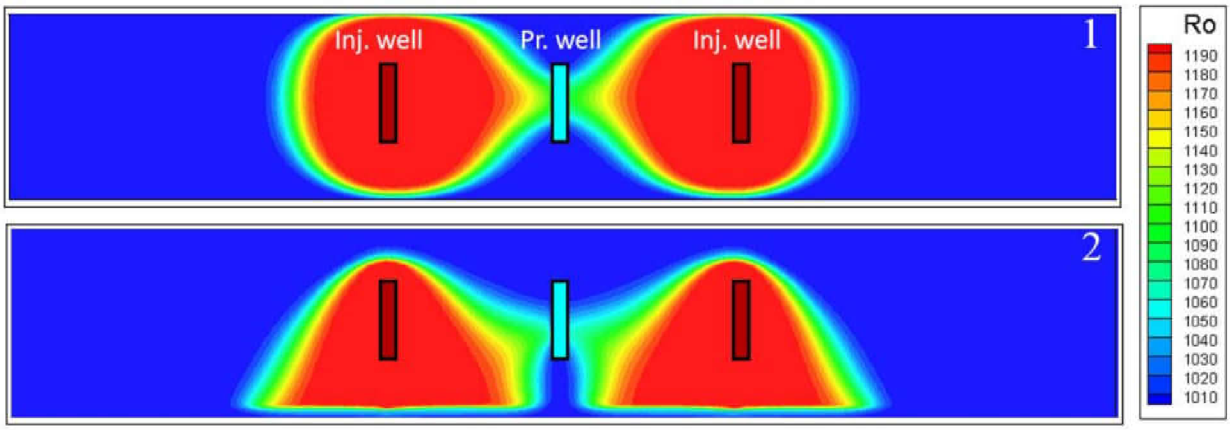


Figure 7 - Density distribution along a vertical cross-section 1) without gravity effect, 2) with gravity effect

Conclusion

Accounting for gravity effect can seriously change the way a horizontal layer is being oxidized, and consequently leached during an ISL process. In present work this change has been demonstrated by conducting hydrodynamic calculations using a parallelized CUDA - based numerical solver. When gravity effects are accounted for, consequent changes in the spatial distribution of the density (and so in acid concentration) around the injection wells are observed, and lead to a very different pressure gradient field. As a consequence, the way leaching solution flows in the stratum is changed. Resource intensive pressure calculations had to be solved on each density changing, which leads to increasing calculation times. Therefore, CUDA parallel technology was successfully used in each step in order to accelerate these calculations. A speed factor of 8 to 12 is thus obtained, depending on the mesh size used.

Future work requires the implementation of the chemical kinetics reactive transport, planned to be solved along the streamlines, in order to estimate the amounts of uranium left over in the underground. Modeling of such process with account for the gravity effect can help in determining the optimal well pattern and their filtration zone positions for a most cost effective production.

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