INJECTED WARM OR COLD WATER AS A POSSIBLE TOOL FOR HYDRODYNAMIC CHARACTERIZATION OF SUBSURFACES

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ABSTRACT

In general, this paper presents the brief overview of the analysis of a possible tool for a hydrodynamic characterization of subsurfaces. In-situ remediation technologies involving the injection of a solution or suspension of a reagent into a subsurface of a contaminated site require the survey of hydrodynamic parameters close to an injection borehole. The characterization of the hydrodynamic parameters is crucial for assessing the usability of the selected decontamination technology. For this purpose, slug tests or chemical tracer tests are common practice. The injection of cold and/or warm water seems to be promising alternative characterization method. In this paper we present a theoretical framework and a semiempirically-based model for a homogenous isotropic porous medium. The preliminary analysis of the injection from the cylindrical tube into a permeable layer under the conditions of Darcy's law uses the governing physical laws - summarized in the following points:

- the Navier-Stokes equation $\rho_w.\frac{D\vec{u}}{Dt}=-\vec{\nabla}p+\mu_w.\vec{\nabla}^2\vec{u}+\rho_w.\vec{g}$,
- the continuity equation $\vec{\nabla}.\vec{u}=0$ which defines values of water velocities,
- the Bernoulli´s equation which is recommendable at the stream lines of a cylindrical laminar flow, where pressure drop Δp depends on Reynolds number $Re=\frac{u_w.d_p}{\nu_w}$, where the parameter d_p(the hydraulic diameter of a pore) is very important,
- the analogy between both flows in a rough channel surface and in the discrete chain of pores in a porous medium according to a common formula for the pressure drop $\Delta p_l=\xi(Re).\frac{l}{d_h}.\frac{u_w^2(r)}{2}.\rho_w$, which includes the coefficient of hydraulic friction ξ,
- the model of a real pore that substitutes its length l_p by a morfological way: an inner surface A_p, a true volume V_p, a true cross section $S_p(d_p)$, which depends on porosity,
- if the Darcy´s law, i.e. $\xi_{Dc}=\frac{const}{Re}$ is valid, named parameters A_p, V_p, $S_p(d_p)$ make possible to express the hydraulic diameter d_p of a real pore and the friction coefficient ξ by simple mathematical formulas,
- the energy equation in the Fourier-Kirchhoff form $\rho_w.c_w.\frac{DT}{Dt}=\kappa_c.\vec{\nabla}^2T+\sum_n W_{T,n}$ used in the case of a warm water injection.

The approximate mutual dependence between both heat transport and pressure drop (so called Prandtl analogy) in a porous medium can serve to obtain the more sophisticated data on the hydraulic effects of an injection by simple thermal measurement. When warm water is injected into a porous medium, the analysis of hydraulic and thermal processes provides the wider information on hydrodynamic parameters. In such a way, this analysis can actively contribute to improve the knowledge of the role of the hydraulic parameters in a subsurface. Also it can provide more detailed data for future research.

Keywords: contaminated soil, warm water, cold water, survey, pressure drop, temperature drop, hydraulic parameters

1. Introduction

In general, this paper presents the brief overview of the analysis of hydrodynamic characteristics of subsurfaces as a recommendable tool for its implementation. In-situ remediation technologies involving the injection of a solution or suspension of a reagent into a subsurface of a contaminated site require the survey of the hydrodynamic parameters close to an injection borehole. The characterization of hydrodynamic parameters is crucial for assessing the usability of the selected decontamination technology. For this purpose, slug tests or chemical tracer tests are common practice. However, slug tests provide only vague integral information about the vicinity of a borehole and chemical tracer tests introduce artificial substances into the subsurface. The injection of cold and/or warm water seems to be promising alternative characterization method. The advantages of this method are that the injection of pure water does not contaminate the subsurface, that it is easy to operate with and that it is not absorbed in the aquifer. In this paper we present a theoretical framework and a semiempirically-based model for a homogenous isotropic porous medium. The feasibility of our method was preliminary tested by calculations using data from (Idelchik, 1960). Results are presented in graphs.

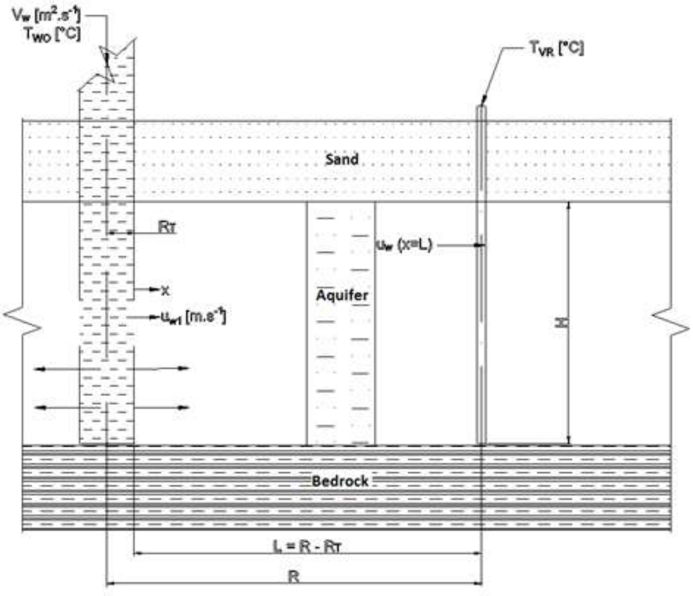

Figure 1: Illustration of real and/or modelled arrangement

2. Theoretical framework and scheme of problem

2.1. Governing equations

The equations of incompressible fluid flow (Logan, 2012; *et al*.), an analogy between flow in a tube and flow in a porous medium and semi-empirical similarity relations are used for the description of the flow in the vicinity of an injection borehole. The energy equation in the Fourier-Kirchhoff form is applied in the case of a warm water injection. So may be written:

$$\underset{(I)}{\rho_w.\frac{D\vec{u}}{Dt}}=\underset{(II)}{-\vec{\nabla}p}+\underset{(III)}{\mu_w.\vec{\nabla}^2\vec{u}}+\underset{(IV)}{\rho_w.\vec{g}} \qquad (1)$$

the vectorial Navier-Stokes equation,

$$\vec{\nabla}.\vec{u}=0 \qquad (2)$$

the continuity equation,

$$\Delta p_l=\xi(\mathrm{Re}).\frac{l}{d_h}.\frac{u_w^2(r)}{2}.\rho_w \qquad (3)$$

the general formula of pressure drop in a tube,

$$p_{B2}=p_{B1}-\sum_{1-2}\Delta p_{1-2} \qquad (4)$$

with terms

$$p_B=p+\frac{u_w^2(r)}{2}.\rho_w+\rho_w.g.h \qquad (5)$$

the Bernoulli´s equation of a water flow through a model of the tubular arranged sequence of homogenous pores,

$$\rho_w.c_w.\frac{DT}{Dt}=\kappa_c.\vec{\nabla}^2T+\sum_n W_{T,n} \qquad (6)$$

the energy equation in the Fourier-Kirchhoff form,

$$p_W=\alpha_w.(T_w-T_m) \qquad (7)$$

the heat flux density as a boundary condition of the Eq. (6), where

$$\alpha_w\big(\mathrm{Nu}(\mathrm{Re}_p)\big) \text{ and } \mathrm{Re}_p=(u_w.d_p)/\nu_w \qquad (8)$$

represents the convection heat exchange between water and a material of an aquifer.

2.2. Assumptions

A model is approximate and is based on the following key assumptions:

Eq. (1)	a.	the inertial term (I) can be neglected because of low velocities $\vec{u}$. The terms (II) and (IV) can be considered as a common pressure p_c, which implies that the pressure p_c is equal to the viscosity term (III)
	b.	the term $\vec{\nabla}^2\vec{u}$ corresponds to the continuity equation
Eq. (2)		the continuity equation in the 2D flow satisfies Cauchy-Riemann relations, i.e. the 2D potential flow
Eq. (3)		the term l/d_h in the formula for pressure drop can be substituted by the informal operation $l_p.d_p/{d_p}^2=A_p/4S_p$, that enables the determination of the original ratio l/d_h by using values of a specific surface area of a porous material and its volumetric porosity. The number of pores in bulk N_p is equal to the number of particles N_z, then $A_p\equiv A_z$ and $V_p\equiv V_z.(1-\Gamma_p)$
Eqs. (4), (5)		a flow through a sequence of pores is considered as a streamline satisfying the use of the Bernoulli´s equation
Eqs. (6), (7)		the experimental data in the case of warm water injection enable to apply Prandtl analogy which satisfies in a range of $1<Pr<3$

3. Model

Utilization of mentioned assumptions and equations supposes forming of a geometric and morphological model. The model is the attribute of a method and leads to the authentic numerical results. Primarily, the method deals with the coefficients in semi-empirical formula of the coefficient $\xi=\sum_i k/\mathrm{Re}^{n_i}$ etc. This is equivalently valid for both warm and cold water injection.

The tubular model consisting of the sequence of individual pores, see Figure 2.a, is based on assumptions Eq. (3) in Par. 2.2. To satisfy the continuity equation in the azimuthal direction the pore can be arranged, see Figure 2.b. So, eventually, the azimuthal flows can be included in the pressure drop.

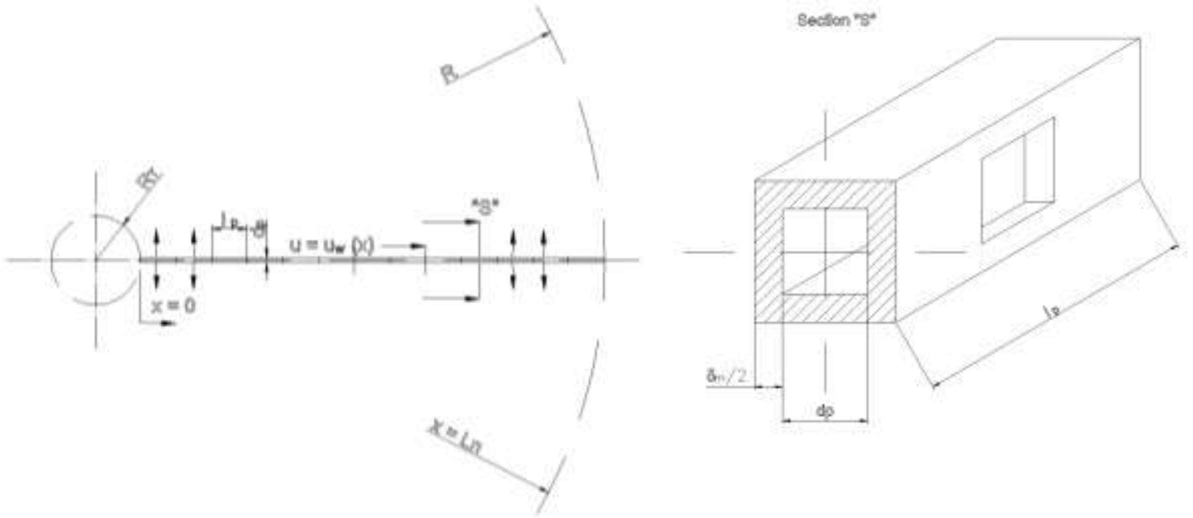

Figure 1: The arrangement of the tubular model of the set of pores

a) The illustration of the sequence of the pore b) The single shape of the pore

4. Preliminary tests

Some preliminary calculations were made (Figs. 3, 4, 5), input data from (Idelchik, 1960) were used. Figure 3 presents the water flow velocity, the pressure drop $\Delta p(x)$ and the time dependence $t \leftrightarrow x$ when the cold water is injected into coarse sand of the pore hydraulic diameter $d_p=0,5.10^{-3}$ m.

The continuity equation as the governing natural law determines the values of the coefficient $\xi = k/Re_p$. In (Idelchik, 1960), the k=180 defines the upper limit of the validity of the Darcy´s law, not only when cold water is injected. The injection of warm water, wherein the new variable i.e. the temperature of water, enables the use of Prandtl analogy. Figures 5 and 4 illustrate the course of computed temperature fields.

Parameters: grain diameter $d_z=1,6\ .10^{-3}$ m, hydraulic diameter of pore $d_p = d_z/3$ (Idelchik, 2006), length of pore $l_p=d_z$ (Figure 1.b), Nusselt number - laminar flow $Nu = \alpha_w.d_p/\kappa_w = 6,5$ (Kutateladze, 1963; Sazima, 1993; *et al*.), porosity $\Gamma_p=0,445$ (Idelchik, 1960), thickness of material $\delta_m = d_p/\sqrt{\Gamma_p} - d_p$ (Figure 1b) - thermal thin material was assumed, i.e. its temperature $T_m(x)$ as the medium value was supposed. The 80°C warm water was supplied in volume $V_{RT}=0,1.10^{-3}\ m^3.s^{-1}$ by the injection tube of an outside diameter $2R_T=120.10^{-3}$ m of the length H=1 m.

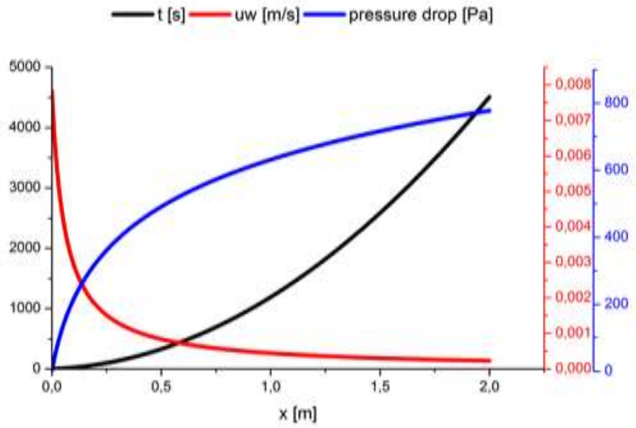

Figure 2: Flow velocity, pressure drop and the time dependence of the length x

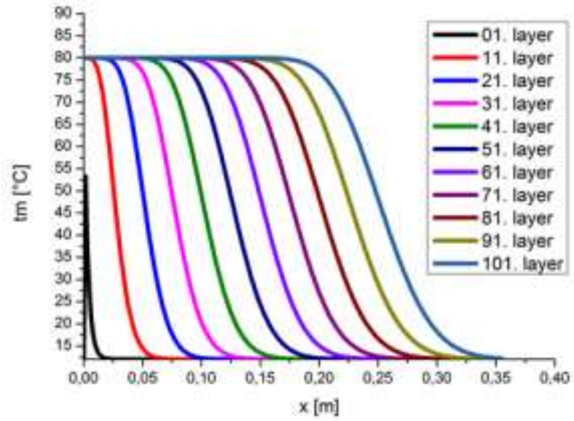

Figure 3: The injection of warm water (T_{w0} = 80°C, T_{m0} = 12°C) into the layer of a given thicknes

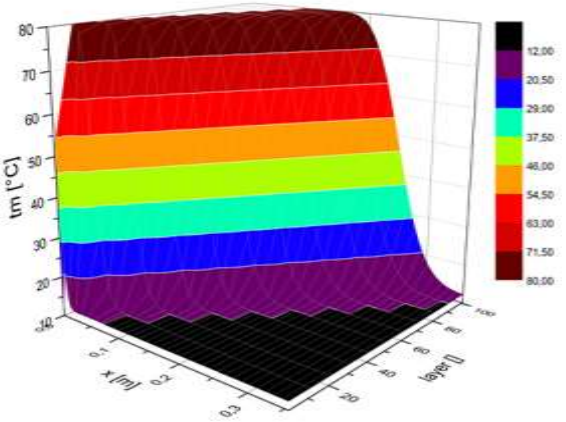

Figure 4: 3D color map of temperatures

The Figure 4 shows also the successively passage of the partially volumes $V_p=d_p.l_p$ over the coordinate x as the warming of the material given by the set of curves T_m. It proceeds as it is denoted by numbers listed on the right side of the graph and it expresses the temperature T_m development of single one-pore water volumes whose consequently enters the boundary x=0.

Prospectively, approximate Prandtl hydro-thermo-dynamic analogy (Michejev, 1952; *et al*.), can be used at $1<Pr<3$ to expand the information about the coefficient $\xi(Re_p)$ obtained by the warm water injection. The information can be expected also for the factor k_a that expresses the specific surface area of grained materials.

5. Conclusions

The model arrangement (Fig. 1) was analyzed from the point of view of the governing equations (Par. 2.1.), using the important assumptions (Par. 2.2.). The both listed in Pars. 2.1., 2.2., have to mostly satisfy the model of porous systems.

The cold water injection using the suggested geometrical and morphological model, real input data and physical similarity relations promise the hydrodynamic classification of different porous layers. The preliminary tests illustrate the principles of the research method and also shows the need of desired future research.

Particularly, it concerns either the course of coefficients $\xi(Re_p)$ and the determination of the hydraulic diameter d_p of pores etc. (see Par. 2.2.), or hydraulic parameters of vertically layered non-homogenous aquifers.

Analogically, the hydraulic classification could be extended using the data obtained by injection of warm water using the approximate Prandtl analogy between both temperature and velocity fields. This extends, on the one side, the cold-water-hydraulic-classification of aquifers and, on the other side, it can contribute to the determination of the flow velocity, which is governed by the continuity equation.

The character of the term $\vec{\nabla}^2\vec{u}$ in the Navier-Stokes equation will extend the research of the 2D flow by the method using complex variable of potential fields.

The attention has to be paid on to the determination of the coefficient $\xi(Re_p)$ by solving an inverse problem. The coefficients in the relation $\xi=\sum_i k/Re^{n_i}$ have to be, probably, computed as the results of the analysis of the experimental data either experiments in-situ or in laboratory.

The projected laboratory model will serve either to the demonstration of physical processes and classification of fine grained materials or to training and teaching purposes.

In our opinion, the presented study serves as the first step for the proposed research.

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