Measurement and Simulation of Underground Heat Collecting Processes with COMSOL Multiphysics

Martin Pies, Stepan Ozana, Radovan Hajovsky, and Petr Vojcinak

***Abstract*—The paper deals with analysis of temperature processes within the experimental borehole located at the mining dump. It consists of heat collector and measurement system for temperature measurement and wireless data transfer. The paper focuses on creation of 2D and 3D model of the heat collector and the solution of heat transfer equation by use of finite element method in COMSOL Multiphysics.**

***Index Terms*—measurement, computational modeling, mining industry, finite element methods, data processing.**

I. Introduction

THE issue of mining dumps is very extensive. The heaps are made from waste and tailings from coal mines. Waste rocks can catch fire spontaneously any time and mining dump starts to burn. Temperatures can change immediately. Fast change of temperature has a bad effect on the environment, whether it is the fauna, flora, or the surrounding buildings and humans. CO and CH_4 arise as a secondary product of combustion. It is dangerous for living organisms due to exhaust fumes and high temperature that can reach to the buildings on the ground. It is one of the main reasons why the presented data model is being developed. Currently we are monitoring temperature changes in the mining dump. It is a large network made up of tens of sensors. The sensors measure temperatures at depths of 3 and 6 meters. Temperature distribution throughout the heap is determined with using mathematical interpolated methods based on the temperature measurements [1].

Current situation illustrated in Fig. 1 has been changed by adding one more experimental borehole with more additional equipments than the other borehole have at these days. The reason of adding this experimental borehole is applied research in the field of heat collection, it is assumed that its results will be applied to the whole mining dump area. All of the data, as the same as for the other sensors, is transferred to the MySQL database by GPRS, then it is accessed and processed by MATLAB and Simulink environment [2].

The block scheme of the measurement system which is used for whole boreholes (both standard and experimental) is shown in Fig. 2.

The simulation model described in this paper handles one particular experimental borehole but it can be applied for the entire set of all boreholes provided all necessary parameters are predefined.

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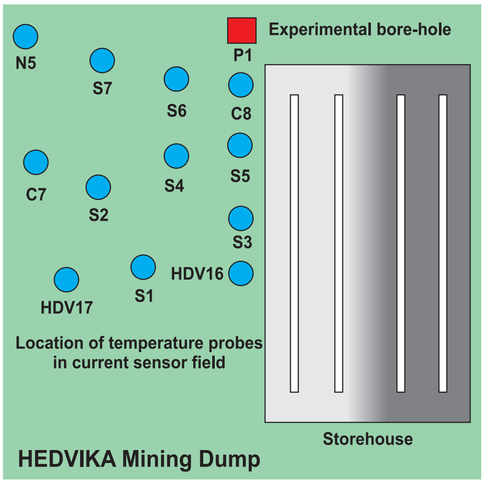

Fig. 1. Current sensoric network with experimental borehole

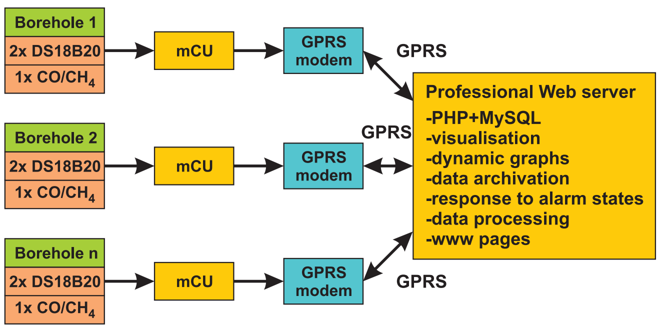

Fig. 2. Block scheme of autonomous measurement system

II. Mathematical Description

The experimental borehole was modeled as 4-chamber heat collector, its 2D and 3D model have been created with the use of COMSOL Multiphysics that allows solving more complex tasks by finite elements method [1], [3].

2D model is a basic model which is consequently transferred into 3D model by use of axial symmetry.

Nominal solution in 2D model is related to the heating power of particular heat sources (measured in watts; parameter $Q_1 - Q_5$), as follows:

- parameter Q_{src} and P_{tot} (the heat power of surrounding waste-rock mass)
- parameter Q_1 (lowest chamber, inlet)
- parameter Q_2 (second chamber)
- parameter Q_3 (third chamber)
- parameter Q_4 (fourth chamber, outlet)

Within the solution of 2D we will consider so called *general heat source*, where user-defined heat sources related to the volume is considered as $\left[\mathrm{W} \cdot \mathrm{m}^{-3}\right]$, representing alternative parameters of target objects $Q_1 - Q_5$. General forms of resulting non-homogeneous partial differential equations (as inner heat sources are included) for heat transfer in solid bodies are given in the following form, considering Hamilton and Laplace operators:

- for heat source with total heat power (in watts; parameter P_{tot})

$$\rho \cdot C_p \cdot \mathbf{u} \cdot \nabla T = \nabla (k \cdot \nabla T) + Q$$
$$Q \equiv \frac{P_{\text{tot}}}{V} \tag{1}$$

- for general heat source (in watts per square cubic meter; user-defined value), parameter Q_{src}

$$\rho \cdot C_p \cdot \mathbf{u} \cdot \nabla T = \nabla (k \cdot \nabla T) + Q$$
$$Q \equiv Q_{\text{src}} \tag{2}$$

where equation's coefficients are described in table I.

TABLE I
DESCRIPTION OF THE PARAMETERS

$T \equiv T(x, y, t)$	thermodynamic temperature (in 2D model, time-dependent)	[K]
$T \equiv T(x, y, z, t)$	thermodynamic temperature (in 3D model, time-dependent)	[K]
t	continuous time	[s]
ρ	density (in particular domain)	$\left[\mathrm{kg} \cdot \mathrm{m}^{-3}\right]$
$C_p \equiv c_p$	relative heat capacity of particular substance	$\left[\mathrm{J} \cdot \mathrm{kg}^{-1} \cdot \mathrm{K}^{-1}\right]$
$\mathbf{u} = (u_1, u_2, u_3)$	velocity vector field	$\left[\mathrm{m} \cdot \mathrm{s}^{-1}\right]$
$\mathbf{i} = \mathbf{e}_x$	unit direction vector (x-coordinate)	[1]
$\mathbf{j} = \mathbf{e}_y$	unit direction vector (y-coordinate)	[1]
$\mathbf{k} = \mathbf{e}_z$	unit direction vector (z-coordinate)	[1]
$\nabla T \equiv \text{grad}\,(T)$	gradient of thermodynamic temperature	$\left[\mathrm{K} \cdot \mathrm{m}^{-1}\right]$
$\nabla (\nabla T) \equiv \text{div}\,(\nabla T)$	divergence of thermodynamic temperature	$\left[\mathrm{K} \cdot \mathrm{m}^{-2}\right]$
$k \equiv \lambda \equiv \kappa$	coefficient of thermal conductivity	$\left[\mathrm{W} \cdot \mathrm{m}^{-1} \cdot \mathrm{K}^{-1}\right]$
$Q_1 - Q_4$	volume heat sources	$\left[\mathrm{W} \cdot \mathrm{m}^{-3}\right]$
P_{tot}	total heat power of heat source	[W]
Q_5	heat power of heat source	$\left[\mathrm{W} \cdot \mathrm{m}^{-3}\right]$
V	volume of heat source	$\left[\mathrm{m}^3\right]$
∇	Hamilton operator (Hamiltonian)	$\left[\mathrm{m}^{-1}\right]$
$\Delta \equiv \nabla \cdot \nabla = \nabla^2$	Laplace operator (Laplacian)	$\left[\mathrm{m}^{-2}\right]$

The basic scheme of 2D model, shown in Fig. 3, includes the following items:

- location and labels of the domains in 2D model;
- heat sources - values of all positive and negative heat power (in Watts);
- boundary condition - the value of temperature T_0 (in Kelvins) at the interface inlet tube/heat source Q_1 (in Watts);
- materials of domains - list of materials in a given 3D model (propylene glycol, steel, sand and waste–rock);
- coordinate system - it is chosen based on 3D model and it projects chosen slice in xz workplane, thus y-coordinate represents the third dimension in the form of unit length (it has no effect on nominal heat power per particular volumes of the domains as it only formal replace of coordinates y and z);
- other data - chosen coordinates are Cartesian and square-biased, measured in meters.

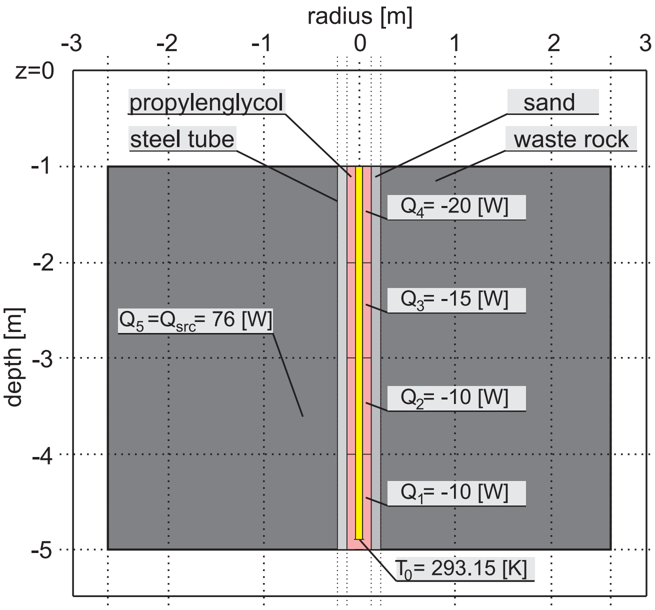

Fig. 3. 2D model - location of the domains, their labels and materials, boundary thermodynamic temperature and chosen coordinates system (xz workplane)

III. Measurement and Modeling of the Thermal Processes in Experimental Borehole

A. Physical setup

Modeling of thermal processes in experimental borehole was carried out as four-chamber model that summarizes heat sources into four volumes.

Fig. 4. Real experimental apparatus located in Hedvika mining dump

Fig. 4 shows the heat collector used for verification of measured values with simulation results from COMSOL Multiphysics. The heat collector is inserted inside experimental borehole. The main purpose of this experiment is to measure heating, resp. cooling of a small area in close surroundings of the experimental borehole by use of temperature sensors Pt100. Inside there are four interconnected chambers with cooling media. The overall height of the apparatus is 4 meters, having its top 1 meter under the ground, which works out 5 meters of the depth altogether. Around the borehole itself there is a cross-cylindrical system of sensors for temperature measurement, the distance between sensors are 0.3 m and 0.5 m horizontally and they are located in three levels vertically, corresponding to the centers of particular chambers, see Fig. 5. It is supposed that temperature changes caused by enforced cooling happen at least 100 times faster than temperature changes caused by burning of the mining dump.

Fig. 5. Installation of measurement system around the heat collector

Before the start of the experiment the temperature in the borehole surroundings can be considered as constant (and can be measured within the borehole). By control intervention the temperature in a close surroundings of the borehole will be affected, ant the temperature trend lines can be stored.

B. Modeling of four-chamber model in COMSOL Multiphysics

Setting of the partial differential equation describing the model into COMSOL Multiphysics can be seen in Fig. 6.

The created model is linear time invariant with variant space parameters. Therefore, is not necessary to deal with absolute values of temperature, but it is enough to compute relative temperature differences related to initial or steady state [4], [5].

The top and sides of the modeled object will have zero Dirichlet boundary condition that determine the ambient temperature, or Neumann condition computed from zero (relative) ambient temperature, simulated temperature of cooled object and heat transfer coefficient (iteration computation).

The sequence of computation is as follows:

- setting of initial condition
- setting of Dirichlet boundary condition
- input of step change of the power $Q_{\mathrm{src}}(x, y, z, t)$ is brought to the system

C. Results of 2D model

Post processing of the task makes it possible to provide many plots resulting from the computation, such as the one in Fig. 7 representing stationary solution of 2D model.

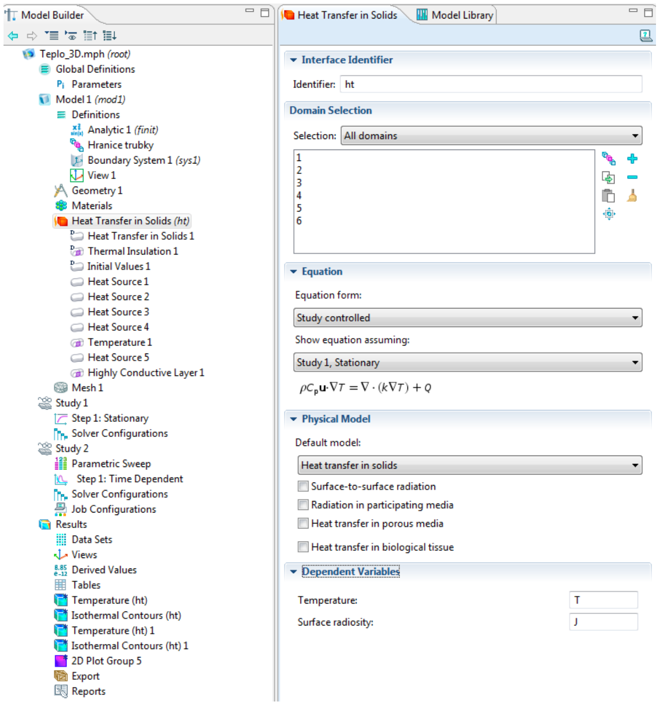

Fig. 6. Defining the task in COMSOL Multiphysics.

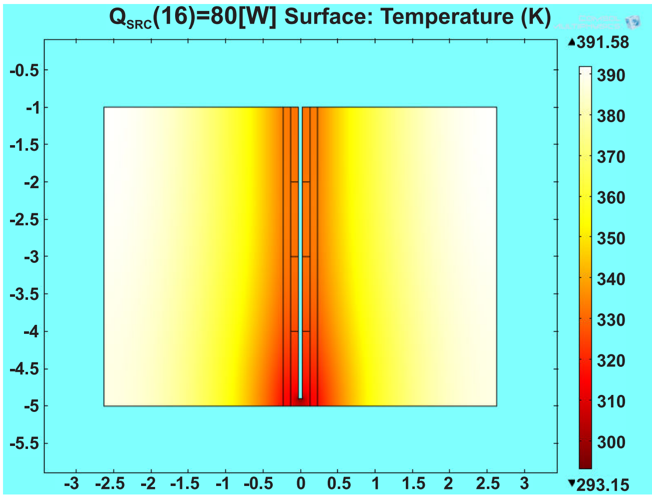

Fig. 7. 2D model - stationary solution ($Q_{\mathrm{src}} = +80$ [W]) in the form of temperature distribution (Surface in the range from 293.15 K to 391.58 K, slice in yz workplane).

D. Results of 3D model

As it was already mentioned, 3D model is created by adjustments of 2D model, particularly by the use of axial symmetry. This approach is always recommended for complex tasks as it is much easier first to tune 2D stationary and time-dependent model and then turn it to 3D solution which is incomparably more fastidious to compute regarding hardware and software requirement. Apart from stationary task the model also provides solution in particular given time or in the time range, always with the possibility of exporting video sequence showing the progress of the quantities in time, displaying gradients, contours or heat flux. For illustration we present two graphical outputs, for stationary task, presented in Fig. 8 and Fig. 9.

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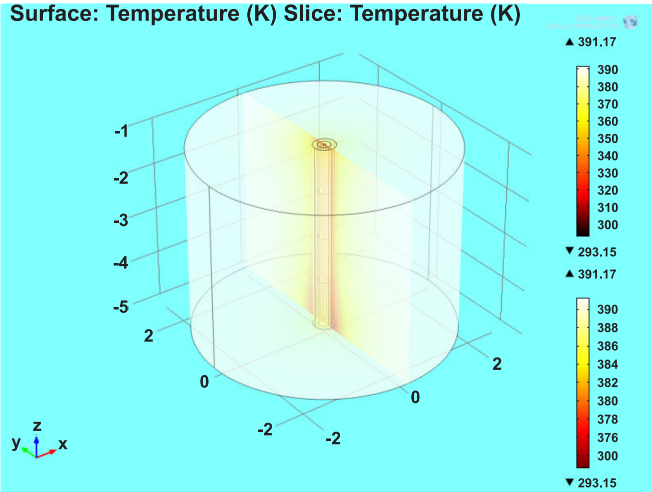

Fig. 8. 3D model - stationary solution in the form of temperature field (Surface, in the range from 293.15 K to 391.17 K, orientation xyz, slice in yz workplane, its scale can be seen in lower legend).

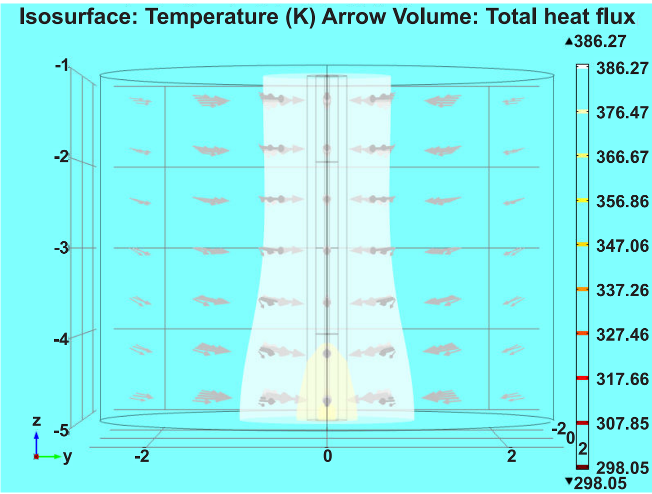

Fig. 9. 3D model - stationary solution in the form of temperature field (Isosurface, in the range from 298.05 K to 386.27 K, orientation yz, slice in yz workplane) and total heat flow (*Arrow Volume*).

IV. Conclusion

The paper presented main idea of modeling of thermal processes in experimental borehole at particular location. This model can be then extended and applied for large areas of mining dumps provided we have sufficient information about crucial parameters of area of interest. The verification between simulated and measured data is just in the primal phase, but it has been proven that the concept of the model and the methodology of experiment are valid. The most crucial fact that has to be explored in detail in future phases of the project is the heat source represented by the component $Q_{\mathrm{src}}(x, y, z, t)$, whose precise value is essential for model results but its determination is quite a challenging issue.

The heat source Q_{src} can be evaluated either in total power per area or power per cubic meters $[\mathrm{W} \cdot \mathrm{m}^{-3}]$. Originally the model assumes the knowledge of this parameter and calculates the others. Further work of the project supposes setting up of inverse task: based on measured data and their time courses it will be possible to find the heat source Q_{src} so as the simulated data match the measured data.

This is achieved by defining the optimization task with the use of COMSOL Livelink for MATLAB. The proposed approach will be the objective of a patent application.

The COMSOL Multiphysics appears to be the most appropriate tool for solution of such complex model due to the fact that it allows to model nonlinear phenomena even in heterogeneous materials with time and space variant coefficient, while the partial differential equations are already predefined in this environment. Of course, it lets user easily define 1D, 2D or 3D plots with computed signals [6].

As for future work, we will mainly focus on several issues:

- Detail specification, adjustment and tuning of the parameters of the model
- Advanced validation and accordance of the model with regard to measured data
- Creation of prediction model for the spread of underground thermal processes at mining dumps based on 3D COMSOL Multiphysics model

Within the solution of this project a unique measurement system has been designed and implemented. The problematic introduced in this paper is up-to-date with respect to environmental policy and government interest, particularly in the Ostravian industrial region. However, the solution can be used and applied abroad. As a result of several surveys in surrounding European countries, we have found similar areas and already contacted owners and administrators of several mining dumps regarding possible cooperation. The computational results of the model can be also used for determination of total calorific value (total heat power) of such affected area and collected heat can be then used to heating of residential areas and buildings.

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