Faculty of Electrical Engineering and Information Technology STU in Bratislava

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Dissertation Thesis Abstract

The development of physical models and methods for measuring the thermal properties of natural materials suitable for the energy storage of the thermal energy in the earth's bedrock

Reg. No. FEI-104400-100084

to obtain the Academic Title of „philosophiae doctor",
abbreviated as „PhD.")

in the doctorate degree study programme: Physical Engineering
in the field of study: Electrical and Electronics Engineering
Form of Study: full-time

in Bratislava, 2021

Dissertation Thesis has been prepared at:
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Vývoj fyzikálnych modelov a metód na meranie tepelných vlastností prírodných materiálov vhodných ako energetické úložiská na skladovanie tepelnej energie v zemskom podloží

Reg. No. FEI-104400-100084

na získanie akademického titulu „doktor",
v skratke „PhD.“)

v doktorandskom študijnom programe: fyzikálne inžinierstvo
v študijnom odbore: elektrotechnika
Forma štúdia: denná prezenčná

V Bratislave, 2021

Dizertačná práca bola vypracovaná na
Fyzikálny ústav Slovenskej akadémie vied, Oddelenie fyziky kovov

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Contents

Abstract

This work aims to develop physical models and methods for measuring the thermal properties of natural materials suitable for the energy storage of the thermal energy in the earth's bedrock. The most important part of thesis is devoted to the slab model used for the parameters estimation of the measurements by pulse transient technique. The model meets the requirements of measurements without using thermal contact agent for better heat transfer in between sensors ad specimen. The parameters of nonlinear temperature response function were estimated using the Levenberg-Marquardt optimization algorithm known as the damped least squares method. In connection with the problems of very small sensitivity coefficients for two of four parameters in slab model and consequently their high relative uncertainties, the methodology of replacement of these two parameters by constants in two steps was developed.

Experimental part is represented by more than 800 measurements of Thermophysical properties of 14 rock samples. The linear dependency of Thermophysical parameters on the volume density was found. The sample planarity and surface roughness problem found at measurements was solved. Data were published in two journal papers and three papers published in conference proceedings.

Thermophysical data obtained from the experimental measurements were used for the calculation of Thermal field properties around cylindrical heat exchanger pipe. Calculations

involved radial temperature distribution, radial heat flux, the rate of heat flow in radial direction, time dependency of the temperature drop for steady and lumped cylindrical body for one-dimensional tube heat exchanger. It helped to understand the behaviour of thermal fields around pipe in bedrocks including the radial / axial temperature profile, penetration depth into rocks and critical radius of insulation. The convective and conductive thermal resistances were calculated also to know the rate of heat flow inside pipe clearly.

Abstrakt

Cieľom tejto práce je vyvinúť fyzikálne modely a metódy na meranie tepelných vlastností prírodných materiálov vhodných na ukladanie energie tepelnej energie v zemskom podloží. Najdôležitejšia časť práce je venovaná plošnému doskov0mu modelu použitému na odhad parametrov meraní impulznou prechodovou technikou. Model spĺňa požiadavky meraní bez použitia tepelného kontaktného činidla používaného pre lepší prenos tepla medzi senzormi a vzorkou. Parametre nelineárnej funkcie teplotnej odozvy boli odhadnuté pomocou optimalizačného Levenberg-Marquardt algoritmu známeho ako metóda tlmených najmenších štvorcov. V súvislosti s problémami veľmi malých koeficientov citlivosti pre dva zo štyroch parametrov v doskovom modeli a následne s ich vysokou relatívnou neistotou bola vyvinutá metodika postupného nahradenia týchto dvoch parametrov konštantami v dvoch krokoch.

Experimentálnu časť predstavuje viac ako 800 meraní termofyzikálnych vlastností 14 vzoriek hornín. Bola zistená lineárna závislosť termofyzikálnych parametrov od objemovej hustoty. Bol vyriešený problém s rovinnosťou vzorky a drsnosťou povrchu pri meraniach. Údaje boli publikované v dvoch časopisoch a troch príspevkoch publikovaných v zborníkoch z konferencie.

Termofyzikálne údaje získané z experimentálnych meraní boli použité na výpočet vlastností teplotného poľa okolo valcového potrubia výmenníka tepla. Výpočty zahŕňali radiálne rozloženie teploty, radiálny tok tepla, rýchlosť toku tepla v radiálnom

smere, časovú závislosť poklesu teploty pre stabilné a sústredené valcové teleso pre jednorozmerný rúrkový výmenník tepla. Pomohlo to pochopiť správanie sa teplotných polí okolo potrubia v podloží vrátane radiálneho / axiálneho teplotného profilu, hĺbky prieniku tepla do hornín a kritického polomeru izolácie. Vypočítali sa tiež konvekčné a vodivé tepelné odpory, aby sa dala jasne poznať rýchlosť toku tepla vnútri potrubia.

PhD Assignment

Slovak University of Technology in Bratislava
Institute of Nuclear and Physical Engineering

Faculty of Electrical Engineering and
Information Technology
2020/2021

DISSERTATION THESIS TOPIC

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Title of the thesis:	**The development of physical models and methods for measuring the thermal properties of natural materials suitable for the energy storage of the thermal energy in the earth's bedrock.**
Language of thesis:	English

Topic specifications:

Determination of thermophysical parameters of materials is a prerequisite for their use in specific purposes. Thermal parameters characterize the efficiency of the use of the materials in the required purposes whether as insulation or vice versa in the need it in the production of cooling equipment. Currently, the official governmental program supports the building up of renewable energy sources. A number of solutions are oriented to the problems of getting energy from the Sun. The next step is accumulation of this energy in a period when it's surplus and then use in the period when it is not enough. One of the ways how to complete facilities for the storage of heat energy is to build up a system of heat exchangers that are drilled into the building bedrock. Their advantage in comparison with large pools for the liquid heat medium is the low cost. For the reasons of optimization system for the seasonal heat storage, we must know the thermal properties of the materials found in the home's bedrock where the heat is stored using the drilled-in heat exchangers.

The aim of the work is to investigate rock materials taken from various geological localities and to design an optimized regime for the heat exchanger system. Develop a methodology for measuring the thermophysical properties of natural stones and relevant mathematical models for transient methods. Evaluate experimentally measured data and find suitable models for calculating fields for heat transport in the vicinity of heat exchangers for experimentally determined values of thermophysical parameters for different rocks.

Date of entry:	04. 10. 2018
Date of submission:	15. 06. 2021

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Introduction

Increasing world-wide awareness about serious environmental problems caused by the consumption of fossil fuels has highlighted the need for a reduction in the use of this energy source by using the non-polluting renewable energy. In the field of solar cooling and heating concept of seasonal thermal energy storage is very important in many industrial and commercial applications. Thermal energy storage (TES) is an environmentally friendly technology that helps to economically bridge the gap between the energy supply and end-user demand. There is a time mismatch between the availability and consumption of solar energy. Therefore, TES is very essential in solar applications. In a TES system, heat can be stored in sensible, latent and by thermochemical reaction forms. It is an economically viable technology that aids in efficiently shaping the end-user demand. It is understood from the thermodynamic principles that in any energy conversion or energy transfer process, the energy loss during the heat transfer will be increased if the temperature difference associated with the energy transport and storage process is higher. As the operational temperature difference decreases there will be reduction in the energy consumption and thereby reduce the environmental degradation. In sensible thermal storage (STS), heat energy is stored by increasing the temperature of the solid/liquid storage medium. STS characterized by temperature variation is a simpler technique, and the amount of stored energy depends on the specific heat capacity of the medium, the temperature change, and the mass of storage material. The latent heat storage is based on heat absorption or release when a phase change material (PCM) undergoes the phase transition from solid to liquid or vice versa. In thermochemical heat storage systems, the heat is stored/ retrieved in an endothermic/ exothermic chemical reaction. The time during which energy can be stored with acceptable losses is one of the important characteristics of the storage system. Due to losses by radiation, convection and conduction, storage in the form of thermal energy lasts for very short time. The next important characteristic of a storage system is energy density (or gravimetric energy density), that is the amount of energy stored per unit volume. The higher storage capacity allows smaller volume of the storage system. Therefore, a good system should have a long storage time and a small volume per unit of stored energy. The first-law efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the storage to the energy stored into it previously.

Storage materials

Material for thermal energy storage plays a vital role in the thermal performance. The performance of any engineering component is influenced by its properties. The material for thermal storage can range from unconsolidated material to rock with or without groundwater. In the case of hard rock, it can contain pores or fractures. Therefore in the field of geoscience, the thermal properties of building construction materials or rocks depending upon the composition of minerals, rock type, geometry, porosity, location, granularity, etc. plays a major role in defining its thermal interaction with the surroundings. The behaviour of heat transport and the temperature fields can be recorded through various dynamic or transient methods that are highly recommended for the measurement of the thermal properties of materials for laboratory use. These are the fundamental parameters that plays an important role in the characterizing the work and efficiency of thermal energy storage systems. The heat reservoir and its interaction with surroundings are indispensable properties for the study of the temperature distribution in the earth's subsurface. Properties like density and specific heat capacity are used extensively in the thermodynamic analysis. The following criteria needed to be satisfied by an effective storage medium. The following criteria for the medium have to be known to design the effective heat storage facility successful modelling, design, operation and economics:

The following criteria for the medium have to be known for successful modelling, operation and economics calculations to design the effective heat storage facility:

thermal conductivity (W/ m K)
thermal diffusivity (mm^2/ s)
specific heat capacity (J/ kg K)
heat transfer coefficient in between heat source and specimen (W/ m^{2}K)
thermal penetration depth (m)
heat flux [W/ m^2]

temperature range, over which the storage has to operate.

However material research done before modelling and designing of mathematical model of the thermal storage system is crucial to study these parameters. In the next chapter, the methods and techniques used for the measurement of thermal properties of bedrock material and detailed descriptions on model used to design cylindrical heat pipe are explained.

Geological Overview

The Geological Overview of the Study Area on rocks for the purpose of solar thermal energy storage using borehole heat exchangers was done on various classes of rocks. The set of more than 16 different samples of rocks were received under the project listed in acknowledgment EU Interreg Central Europe project GeoPLASMA-CE. The rocks were collected from the area located in between two countries Slovakia (367 km^2) and Austria (236 km^2) in Carpathian Mountains. The specialty of this region is that the type of rocks and sediments available creates the condition for various industrial as well as household purposes. Therefore the close distance from the region of Bratislava, highlights the need for joint future shallow geothermal energy management concepts that expand with the area of settlements in Austria (transnational suburbs of Bratislava) [1]. Example of the specimen sets of collected rocks is given in **Error! Reference source not found.**.

Figure 1.The rock samples for the measurement of thermophysical parameters collected from Carpathian Mountains

Methods and Model

Pulse transient technique

The principle of the Pulse Transient Method [2] is based on generation of the heat pulse by the plane heat source and recording the thermal response to this heat pulse by thermocouple that is placed at the distance h apart from the heat source (Figure 2). The distance h represents the active part of the specimen thickness in a form of the slab, cylinder or cuboid.

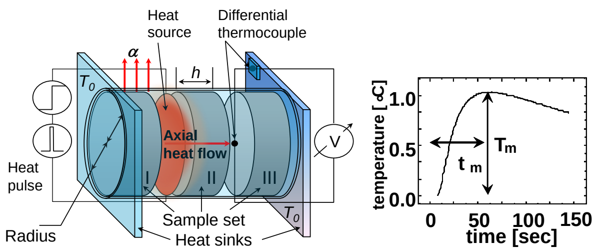


Figure 2. Experimental setup of the Pulse transient technique for cylindrical model (left) and example of the thermal response, T_m and t_m serve for one point evaluation procedure (right).

PTT was used in diverse published papers to check the data reliability by the inter-comparison measurements of different samples at different laboratories. The most papers published in the last period have been focused on the thermophysical study of natural rocks and stones [3]. The next papers were oriented to the thermal properties measurements of different materials [4], the problems of the heterogeneous structures and the surface effect influences [5, 6]. In addition, the contributions were devoted to the problem of developing a methodology for testing procedures of various models for PTT and the application of this methodology to the analysis of a reliable estimation of thermophysical parameters [7, 8].The results of experimental work obtained during my PhD study was published in several papers given in List of publications [3, 4, 7].

Slab Model

The theoretical model for Slab geometry used for Pulse Transient Technique (PTT) is a one-dimensional model with the infinitely large plane heat source having non-zero heat capacity located between two semi-infinite parts of the specimen body (Figure 3).

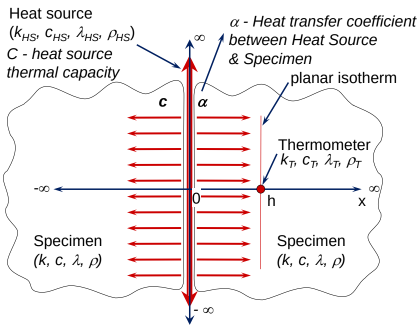


Figure 3. The Slab model for infinitely large specimen geometry accounts heat capacity of the heat source as well as the heat transfer coefficient between the heat source and specimen body. It is drawn with the experimental parameters and geometry of arrangement.

The generated heat pulse is split into two halves due to the symmetrical geometry of the heat source and specimen, thus only one half of the semi-infinite specimen is used for the theoretical calculations in the model. The model accounts the heat transfer coefficient between heat source and specimen, and the heat capacity of the heat source. Both parameters cause deformation of the thermal response curve.

The temperature function for the slab was derived from the basic heat transfer equation solution is written in the form.

$$T(t,x) = T_1(t,x) + \Delta T(t,x) \quad 1.1$$

$$T_1(t,x) = T_0 e^{-u^2}\left[\frac{1}{\sqrt{\pi}u} - w(iu)\right] H(t) \quad 1.2$$

The heat transfer coefficient is an important parameter to study, as it is connected to the heat transfer problems that are proportional to the contact heat resistance between the heat source and specimen and at the specimen interfaces or thermocouple.

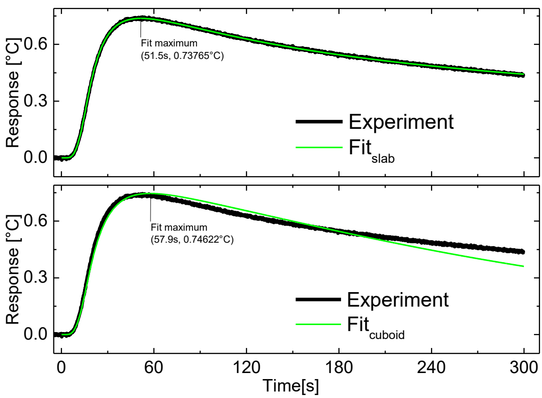


Figure 4. Fitted curve of thermal response for time window 0-300 seconds using the slab model (top) compared with the cuboid model (bottom) measured for Carbonate BDA5 sample. The sample was measured with the heat pulse duration 10 seconds.

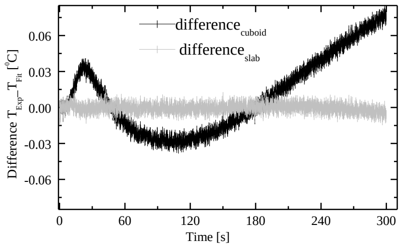


Figure 5. Comparison of residual plots of fitted curves from Figure 4 obtained using the slab and cuboid models. The slab model fits the data within the background noise on a scale of ±0.005°C (Carbonate BDA5).

The quality of the thermal response fit using the slab model compared with cuboid model is illustrated by difference of residual plots on Figure 5. Generally, uncertainty in the experiment arises from different sources and includes errors of different origin specified in [9, 10]. Moreover, we need a more sophisticated method to estimate the parameters of the theoretical model used by transient methods. Figure 6 and Figure 7 show the analysis of the sensitivity coefficients that are used while estimating the uncertainties of the free parameters (λ, k, α, C) in the Slab model. The sensitivity coefficients plotted in Figure 6 are the first derivatives of the temperature function with respect to all free parameters a_k in the model $\beta(a_k) = a_k \frac{\partial T(t,x)}{\partial a_k}$ [11]. The matrix for the uncertainty calculation (a_k) (T) given in [9, 10, 11], is equal to the matrix based on the system of equations for the couples of sensitivity coefficients.

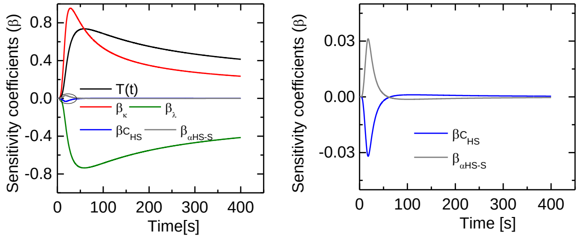


Figure 6. The sensitivity coefficients β_C and β_α on the left side highlighted in the ellipse are redrawn on the right as they are three orders of magnitude lower than β_λ and β_k. The calculated sensitivity coefficients for the thermal response to the heat pulse T (t) were plotted for time window interval 0–400 s (sample Carbonate BDA5).

The methodology for relative uncertainties was published in paper [8]. From this paper we used Eq. 1.3 for the calculation of relative uncertainties of al free parameters in model. The uncertainties plot for measurement time 400 s is in Figure 7.

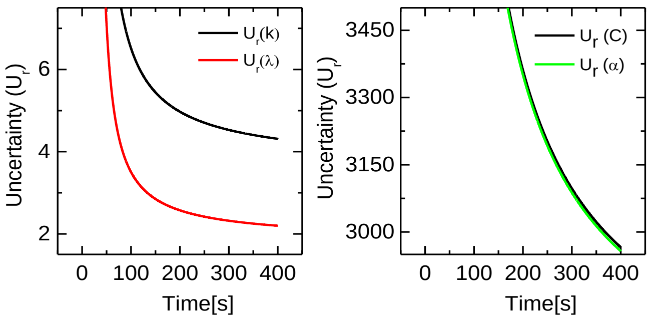


Figure 7. The relative uncertainties of the free parameters in the Slab model, e.g. the thermal diffusivity Ur (k) and thermal conductivity Ur(λ) plotted on the left, and the heat capacity of the heat source Ur (C) and the heat transfer coefficient Ur (α) plotted on the right were calculated

in the time interval of 0–400 s for the real stone sample Carbonate BDA5.

$$u_r(a_k)^2 = C_{kT}^2 \frac{u(T)^2}{a_n^2} + \sum_{j=1}^{N_b} \nu_{kj}^2 u_r\left(b_j\right)^2 \qquad 1.3$$

The analysis of the sensitivity coefficients and calculated uncertainties of estimated parameters of the slab model help to improve accuracy of parameters estimation.

Model for Steady Conduction in Radial Direction through a pipe wall (No heat generation)

Heat flow across wall of cylindrical shell considers an elemental cylindrical shell of thickness dr at radius r, inner and outer radius r_1, r_2 is drawn in Figure 8.

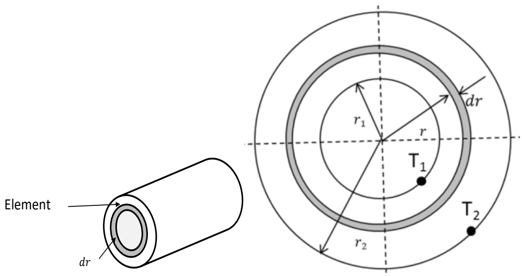


Figure 8. Heat flow across wall of cylindrical shell.

For steady state heat conduction the initial condition $\frac{\mathbf{dT}}{\mathbf{dt}} = \mathbf{0}$ is valid. This is Eq. 1.4 explains the variation of the temperature in non-dimensional form, which is an equation of logarithmic curve

$$\frac{T - T_1}{T_2 - T_1} = \frac{\ln(r/r_1)}{\ln(r_2/r_1)} \qquad 1.4$$

To find the heat flux, we use Fourier's law and by further calculations we get

$$q = -\lambda\left(-\frac{1}{r}\frac{T_1 - T_2}{\ln(r_2/r_1)}\right) \quad 1.5$$

Let recast the Eq. 1.6 to get heat flow rate from previous equation.

$$Q = -\lambda(2\pi r_2 L)\left(-\frac{1}{r_2}\frac{T_1 - T_2}{\ln(r_2/r_1)}\right) \quad 1.6$$

$$Q = \frac{T_1 - T_2}{R_{cond}} \quad 1.7$$

Conduction thermal resistance to the heat flow through cylindrical wall is $R_{cond} = \frac{ln(r_2/r_1)}{2\pi L\lambda}$.

It is possible, to include additional convective thermal resistances to heat transfer in the interior of the pipe and from the outside surface to the air surrounding the pipe. If we define a heat transfer coefficient h_i to describe convective heat transfer between the fluid flowing through the pipe at temperature T_i and the pipe wall whose inner surface is at a temperature T_1, we can write

$$Q = h_i A_i (T_i - T_1) = h_i 2\pi r_1 L(T_i - T_1) \quad 1.8$$

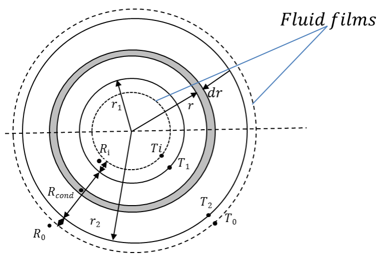


Figure 9. Radial steady-state heat conduction through a cylindrical shell considering film coefficients situated at the inner and outer surfaces.

$$Q = \frac{T_i - T_1}{1/(h_i A_i)} = \frac{T_i - T_1}{1/(h_i 2\pi r_1 L)} = \frac{T_i - T_1}{R_i} \quad 1.9$$

Where, R_i is the convective thermal heat resistance of the film situated at the inner surface of cylinder.

Unsteady Temperature profile in lumped system for cylinder

Consider a substance body which has uniform temperature throughout at any position. The temperature of these bodies is a function of time only. From the heat balance for the small body shown in [12], which is in interaction with the environment that is kept at temperature T_∞, T_i is the inner body temperature and the convection heat loss from the surface of the body at any instant will be equal to the rate of change of the internal energy of the body [12].

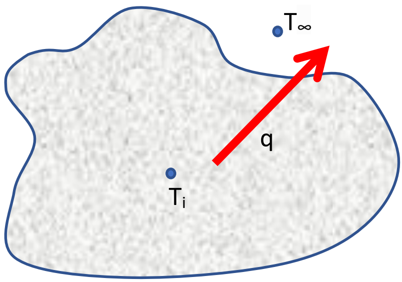


Figure 10. Lumped Body system

The assumption of uniform temperature throughout the sample is approximately valid for bodies with a very high thermal conductivity combined with a low value of the convective heat transfer coefficient. Smaller bodies with lower values of the thermal conductivity may also satisfy this condition. Mathematically, we shall assume that the thermal conductivity of the body is infinite. This analysis is called lumped heat capacity method [12].

$$Q - hA(T - T_\infty) = \rho V C_p \frac{\Delta T}{\Delta t} \tag{2.0}$$

With the initial temperature at time T(t=0) = T_i, the Eq. 2.0 can be rewritten ash

$$\frac{dT}{dt} = -\frac{hA}{\rho V C_p}(T - T_\infty) \tag{2.1}$$

The temperature of the body after some time can be determined by integration of the Eq. 2.1.

$$\int \frac{dT}{T - T_\infty} = -\frac{hA}{\rho V Cp}\int dt \tag{2.2}$$

Solving this Eq. 2.2

$$\frac{\ln(T - T_\infty)}{\ln(T_i - T_\infty)} = -\left(\frac{hA}{\rho V Cp}\right)t \tag{2.3}$$

$$\frac{T - T_\infty}{T_i - T_\infty} = \exp\left(-\frac{hA}{\rho V Cp}t\right) = \exp\left(-\frac{t}{\frac{\rho V Cp}{hA}}\right) \text{ [12 p331]} \tag{2.4}$$

From Eq. 2.4 we calculated the cooling time of the lumped body and it is evident that the temperature of the body falls exponentially with time t as shown in Figure 11.

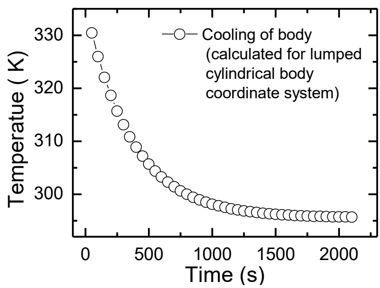


Figure 11. The graph shows the analytical solution of the temperature distribution along radius of cylindrical pipe. The cylindrical body was

considered to have equal temperature gradient in radial direction. There is sharp temperature drop after the beginning of cooling, but it is apparent that the body will get cooled after 0.5hour of duration.

Results and discussion

FUNCTIONALITY OF SLAB MODEL AND METHODOLOGY OF THE PARAMETERS ESTIMATION

The fit quality of the slab model is represented by time window analysis in Figure 12. The graph shows shifted and very low values of thermophysical parameters using cuboid model in comparison with slab model.

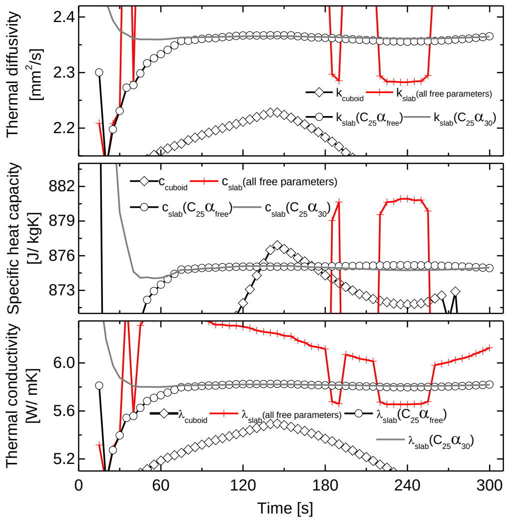


Figure 12. The time window interval analysis of the measured thermal response evaluated by of slab and cuboid model (rhombus) for thermal diffusivity (k), thermal conductivity (λ), and specific heat capacity (c). Analysis for slab model is given for fitting all four parameters as free (+,

red), then with the C parameter as constant (hollow circle), the third step of evaluation (grey line). The sample selected was Carbonate BDA5.

The time window analysis of parameters obtained by fitting the thermal response by the slab model was done using methodology of parameter estimation in 3 steps [4, 7]

THERMOPHYSICAL DATA OF SERIES OF ROCKS MEASURED BY PULSE TRANSIENT TECHNIQUE

These graphs on Figure 13 are plotted for the values of thermal diffusivity, thermal conductivity, and specific heat capacity, measured for all of the measured rocks respectively. The measurements were performed with the interfaces in dry condition, without using bentonite paste as the thermal contact agent.

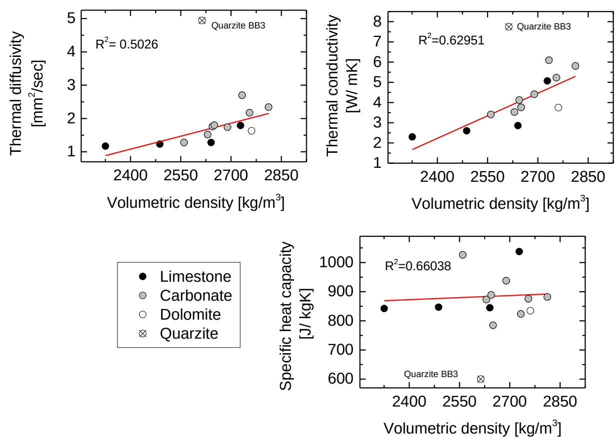
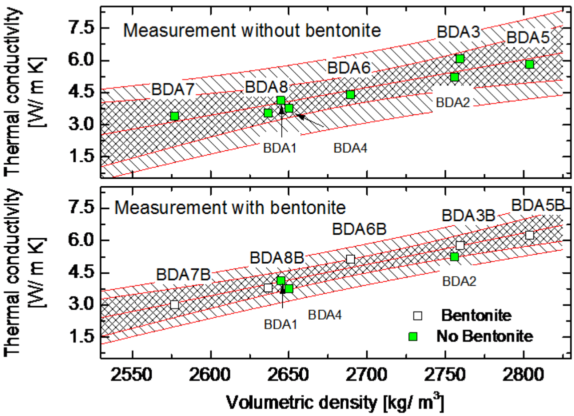


Figure 13. These graphs show a certain range of variation in the values of the thermal conductivity, thermal diffusivity, and specific heat

capacity of the rocks originate from the similar geographical place in Carpathian mountains.

INFLUENCE OF SURFACE PLANARITY ON MEASUREMENT ACCURACY

In this experiment we were facing with the problem of the surface planarity and thus the air gaps in between the specimen parts. Corresponding data are plotted in the Figure 14.



Measurement without bentonite		Measurement with bentonite	
Equation	y = a + b*x	Equation	y = a + b*x
Plot	Thermal conductivity	Plot	Thermal conductivity
Weight	No Weighting	Weight	No Weighting
Intercept	-30.24351 ± 6.96029	Intercept	-34.63629 ± 4.05048
Slope	0.01296 ± 0.00258	Slope	0.01464 ± 0.0015
Residual Sum of Squares	0.66562	Residual Sum of Squares	0.22542
Pearson's r	0.94523	Pearson's r	0.98455
R-Square(COD)	0.89345	R-Square(COD)	0.96934
Adj. R-Square	0.85794	Adj. R-Square	0.95912

Figure 14. Thermal conductivity of rocks plotted in dependency of volume density for measurements with interfaces in dry state and state when air gaps were filled by bentonite paste.

Comparison of thermal conductivity measured with and without bentonite paste on Figure 14 is similar for thermal diffusivity and specific heat capacity. Thermal conductivity vs. volumetric density plot measured with bentonite contains also 3 measurements of samples having perfect surface flatness measured without bentonite (filled in green). On the top are all data measured without bentonite paste but with good and bad surface planarity.

The rough surface planarity influence on measurement accuracy was eliminated by using Bentonite paste for filling the air gaps. This has an influence on the regular heat transfer in between the heat source and specimen as well as the thermocouple. The consequence is the increased uncertainty of measured parameters.

The volume densities for all specimens were calculated from the measured dimensions and weight of all parts of specimen sets. Total number of sets was 14. The volumetric densities of all specimens are given in Figure 15.

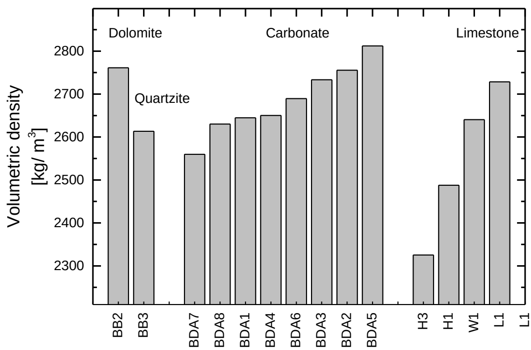


Figure 15. Volumetric densities on dolomite, quartzite, carbonate, limestone.

MODELS OF HEAT TRANSFER FOR CYLINDICAL PIPE IN ROCK SURROUNDING

Based on background details and measured thermophysical parameters of rocks given above the next calculation of the depth thermal profiles for steady and non-steady state cases were done for cylindrical pipe inserted in a rock surrounding. The data chosen for plotting the graphs below are taken from sample Carbonate BDA3. Other parameters required to design cylindrical heat pipe are initial surface temperature T_1, outer surface temperature T_2, inner radius r_1, outer surface radius r_2 and length of pipe L. The data for two sets of different radiuses r_1, r_2 of the pipes used for the calculations are the following: $T_1 = 343.15$ K, $T_2 = 303$ K, $r_1 = 0.02$ m and 1 m up to $r_2 = 0.2$ m and 10 m. The length of cylindrical pipe is assumed to be L= 1 m. The rest of parameters are given in the next table which are used for all next graphs.

Rock	λ (W/ (m K)	c (J/ (kg K))	k (mm^2/ s)	ρ (kg/ m^3)
LimestoneH3	2.30	842.098	1.17	2325.412
LimestoneH1	2.6	846.79	1.23.	2487.689
CarbonateBDA8	5.81	881.71	2.34	2630.249
Carbonate BDA2	3.53	877.46	1.52	2755.59
CarbonateBDA5	5.81	881.71	2.34	2812.201

Data in this table were used also for the problem of lumped body calculation according the Eq. 2.4. The calculations of temperature drop were done for the times up to half hour. Figure 16 and Figure 17 shows the temperature distribution and heat flux associated with radial conduction through a cylindrical wall that is logarithmic, not linear, as it is for the plane wall under the same conditions. The logarithmic distributions of temperature and het flux are sketched in these figures. It can be easy to understand that if the fluid temperatures inside and outside of the pipe remain constant, then the rate of heat transfer through the pipe is steady and only the heat flux can be changed in radial direction. Thus heat transfer through the pipe can be modelled as steady and one-dimensional.

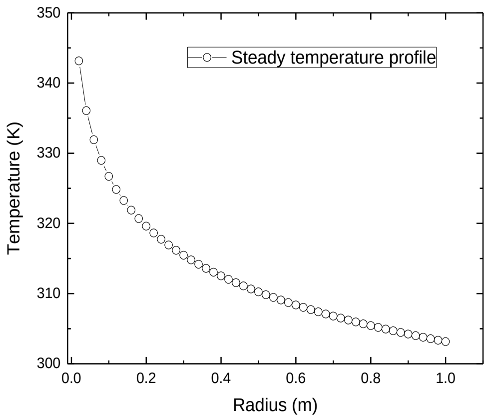


Figure 16. Temperature distribution along radius of cylindrical pipe. Calculation is based on Eq. 1.4. The data used for the plot corresponds to thermophysical data of BDA3 sample.

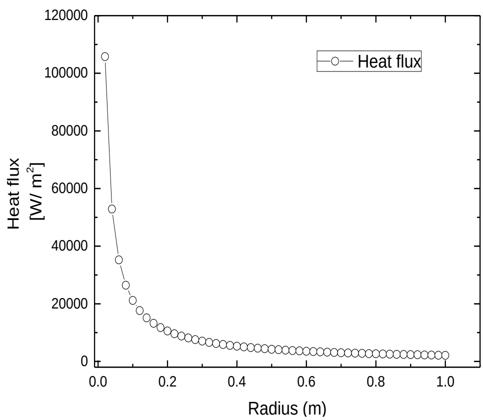


Figure 17. Heat flux along radius of cylindrical pipe. Calculation is based on Eq. 1.5. The data used for the plot corresponds to thermophysical data of BDA3 sample.

The heat loss through an insulated pipe Figure 18 was drawn. The **critical radius of insulation** of pipe around the heat source gives the information about the thermal resistance also. For an explanation of the influence of the thickness of the insulation in pipe and wall

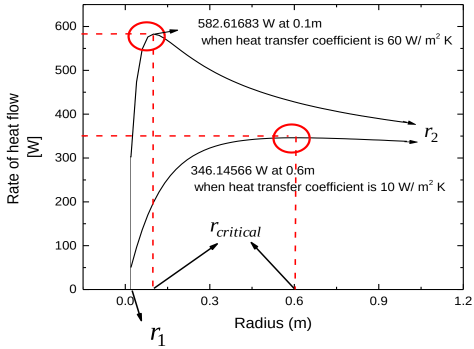


Figure 18. The rate of heat flow calculated for r_1=2 cm and the penetration depths r_2 in a range from 2 cm up to 1 m

The penetration depth calculated for Transient Plane Source [13] and Pulse Transient Technique [7] methods are in Figure 20 and Figure 21. They serve for the checking whether or not the geometry of the specimen fills the limits of the model.

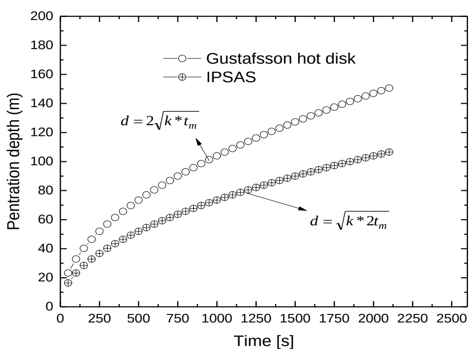


Figure 19. Thermal penetration depth vs time for hot disk (TPS) and pulse transient technique (PTT) calculated for known thermal diffusivity measured on BDA 3 rock.

In the same time it can serve for the estimation of the dimension of volume of environment exposed to heat generated by heat source. The penetration depth is increasing with the measurement time in both cases. In the case of the pulse transient method the maximum of the thermal response shifts to higher times with increasing the material thickness. This means that the time when the maximum of the thermal response is reached corresponds to different thicknesses or penetration depth when we investigate the same material.

The temperature distribution along the time dependency for cylindrical pipe was calculated for the **lumped body** theory using thermal properties of the measured rocks. The rocks were chosen in a way to cover the full scale of measured densities in Figure 15. We have to notice that α and h are the same for all calculation for a chosen samples. Cooling rate of the lumped body is directly proportional to the material volumetric density.

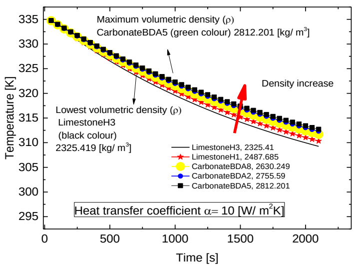


Figure 20. Time dependency of the temperature drop for lumped cylindrical body when α =10 W/ (m^{2}K) using five set of different rock sample. Based on Eq.2.4

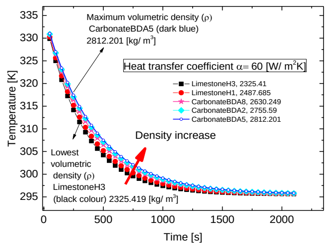


Figure 21. Time dependency of the temperature drop for lumped cylindrical body, when α =60 W/ (m^{2}K) using five set of different rock sample. Based on Eq.2.4

For the comparison in Figure 20 and Figure 21 are plotted the cases of the temperature drop in dependency of the time for chosen rock samples calculated for heat transfer coefficients 10 and 60 W/ (m^2 K).

The Table 1 below shows the data obtained from measurement for all samples used for the research study

Table 1. Thermophysical data calculated by the slab model

Rocks marks	Volume density [kg/ m^3]	Thermal conductivity [W/ m K]	Thermal diffusivity [mm^2/ s]	Specific heat capacity [J/ K kg]	Heat transfer coefficient [W/ m^2 K]
Dolomite BB2	2761.18	3.75	1.63	834.20	50.54
Quartzite BB3	2613.46	7.74	4.93	599.91	13.00
Carbonate BDA1	2644.69	4.12	1.76	888.66	26.94
Carbonate BDA2	2755.59	5.23	2.17	875.59	19.80
Carbonate BDA3	2759.12	6.08	2.70	823.40	20.00
Carbonate BDA4	2650.17	3.76	1.80	784.57	20.00
Carbonate BDA5	2812.2	5.81	2.34	881.71	42.65
Carbonate BDA6	2689.34	4.41	1.74	937.43	24.13
Carbonate BDA7	2559.71	3.41	1.28	1026.14	33.84
Carbonate BDA8	2630.25	3.64	1.58	872.90	12.00
Limestone H1	2487.69	2.6	1.23	846.79	24.59
Limestone H3	2325.42	2.3	1.17	842.00	25.63
Limestone W1	2640.56	2.86	1.28	844.65	34.00
Limestone L1	2728.39	5.07	1.79	1037.44	54.52

Table 2. Thermophysical data calculated by the slab model with and without thermal contact agent (Bentonite) [7]

Carbonate Rocks	Temperature [°C]	ρ [kg/m³]	λ [W/mK]	k [mm²/.s]	c_p [J/ kg K]	α [W/ m² K]
Carbonate BDA3	18.61	2759.12	6.09	2.70	823.40	20.00
Carbonate BDA3 Bentonite	18.61	2759.12	5.77	2.28	924.35	70.00
Carbonate BDA5	19.51	2812.20	5.81	2.34	881.71	42.65
Carbonate BDA5 Bentonite	19.51	2812.20	6.24	2.47	902.75	50.59
Carbonate BDA6	19.43	2689.34	4.41	1.74	937.43	24.13
Carbonate BDA6 Bentonite	19.43	2689.34	5.14	1.83	1041.54	61.36
Carbonate BDA7	19.85	2559.71	3.41	1.28	1026.14	33.84
Carbonate BDA7 Bentonite	19.85	2559.71	3.00	1.29	900.79	47.44
Carbonate BDA8	19.51	2630.25	3.53	1.52	877.46	12.00
Carbonate BDA8 Bentonite	19.51	2630.25	3.84	1.56	899.34	33.35

Conclusion

In PhD Study we closed the investigation on thermophysical property of carbonate, limestone dolomite, and quartzite rocks with an aim to establish and recognize characters for the possible thermal storage reservoir build in these types of bedrocks. The experiments were successfully performed and few factors influencing the measurement errors were also minimized to produce the best results using theoretical slab model. Thus, the thermophysical parameters fulfil the necessity of accurate data measurement of thermal properties of rock reservoirs and their surroundings. The examination on thermal properties of rocks in research study fills the gap of knowledge in understanding the thermal properties of rocks that can describe the temperature distribution over time and depth as it fundamentally controls the configuration of the thermal profiles and heat flow within the stone bedrock. Based on the finding of thermophysical properties of rocks we used simple one dimensional cylindrical heat exchanger assumed to be buried in earth bedrock. An analytical solution for the heat transfer in hollow cylinders for steady and Transient (lumped body system) case was done. The cylindrical pipe was assumed to be buried and surrounded by different rocks (Carbonate BDA3 was used here as an example) with the thermal properties measured in our experiments. The specific boundary condition and time-dependent heat transfer coefficient at different surfaces of the heat pipe is developed for the first time. The results in Part 5 shows the performance of cylindrical heat exchanger where we were successful in calculating the heat flux, rate of heat flow, conductive and convective thermal resistances, and penetration depth using our stone properties.

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List of publications

Research papers published in SCI Journals

[1] **R. Tiwari**, V. Boháč, P. Dieška, G. Götzl, "The non-planar surface of sample affecting the behaviour of thermal response and the Thermophysical parameters measured by pulse transient technique", Thermal Science and Engineering Progress; PII: S2451-9049(21)00089-5; (2021), Volume 24, 1 August 2021, 100927, DOI: https://doi.org/10.1016/j.tsep.2021.100927,
Q1, Impact Factor 4.947 (2019), 4.662 (5 year)

[2] **R. Tiwari**, V. Boháč; P. Dieška; G. Götzl, "Thermophysical parameters of Carbonate Rock estimated by by Slab Model developed for Pulse Transient Technique", Measurement Science Review, 20, (2020), No. 5, pp. 218-223. DOI: https://doi.org/10.2478/msr-2020-0027.
Q4, Impact Factor 0.9 (2019) 1.039 (5 year)

Papers published in conference proceedings books

[3] **R. Tiwari**, V. Boháč, P. Dieška, G. Götzl, "Thermal Properties of Limestone rock by Pulse Transient Technique using Slab Model accounting Heat Transfer Coefficient and Heat capacity of Heat Source", THERMOPHYSICS 2020, AIP Conference Proceedings 2305, 020020 (2020); DOI: https://doi.org/10.1063/5.0033924

[4] V. Boháč, G. Pavlendová, **R. Tiwari**, P. Šín, "Thermophysical Properties of Concrete Composites Mixed with Waste Materials Measured by the Pulse Transient Method Using Using Slab and Cuboid Models", THERMOPHYSICS 2020, AIP Conference Proceedings 2305, 020002 (2020); DOI: https://doi.org/10.1063/5.0035310

[5] V. Boháč, P. Dieška and **R. Tiwari**, "Measurement of Thermophysical Properties of Mortar Filled by Polymer Filaments by Pulse Transient Technique", Proceedings of MEASUREMENT 2019, *12th International Conference on Measurement*, (2019), pp. 154-157, Publisher: IEEE, **ISBN:**978-80-972629-3-8,

https://ieeexplore.ieee.org/document/8779852; **DOI:** 10.23919/MEASUREMENT47340.2019.8779852

[6] **R. Tiwari**, V. Boháč, P. Dieška and G. Götzl, "Uncertainty Analysis of Pulse Transient Model Accounting Thermal Contact Effect", Proceedings of MEASUREMENT 2019, 12th International Conference on Measurement, 2019, pp. 252-256, Publisher: IEEE, ISBN:978-80-972629-3-8, https://ieeexplore.ieee.org/document/8780095 ; **DOI:** 10.23919/MEASUREMENT47340.2019.8780095

Lecture/ Talks

1. Lecture at Thermophysics 2018 International Conference Smolenice, Slovakia. The topic "Measurement of the Stone Thermal properties *Using Pulse and Step-Wise Transient Techniques And Analysis of Model Uncertainties with an effect of heat thermal resistance and the heat capacity of the heat source."*
2. Talk at IPSAS 2018 Seminar in Smolenice, Slovakia The topic of talk was based on work done in diploma dissertation and current work in Phd "Density Functional Theory for Some Binary Compounds (Zn Chalcogenides)."
3. Poster at Measurement 2019 International Conference Smolenice, Slovakia. The topic "Thermo physical parameters of Carbonate Rock measured by Pulse Transient Technique using Slab Model accounting the Thermal Contact Effects" (Won Young Investigator Award Competition for the best poster presentations).
4. Lecture at Thermam 2019 International Conference Cesme, Turkey. The topic "Study of Thermo physical properties of Carbonate Stones by means of the Pulse Transient Technique & analysis of the Thermal Heat Resistance & Heat Capacity of Heat Source effects of accounted in SLAB MODEL"
5. Talk at IPSAS 2019 main building Bratislava, Slovakia The idea of the talk was to show the status of current work going in PhD

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6. Lecture at Thermo physics 2019 International Conference Smolenice, Slovakia. The topic "The influence of surface roughness on the Measurement of Thermo physical Properties of NATURAL STONES."
7. Lecture at NFCFA 2019 National Conference, Goa, India. The topic "Improvement of Thermo-physical Properties of Bedrock beneath Earth surface using Thermal contact agent and Analysis of the Effects of Thermal Heat Resistance and Heat Capacity of Heat Source Accounted in Slab Model."
8. Lecture at THERMOPHYSICS 2020 25th Meeting of the Thermophysical Society and Working Group of the Slovak Physical Society, Smolenice, Slovensko The topic "*Thermal properties of Limestone rocks by Pulse Transient technique using Slab model accounting Heat capacity of heat source and heat transfer coefficient*".

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[3] R.Tiwari, V. Boháč, P. Dieška, G. Götzl, Thermal Properties of Limestone rock by Pulse Transient Technique using Slab Model accounting Heat Transfer Coefficient and Heat capacity of Heat Source, AIP Conf. Proc. 2305 (2020), 020020, https://doi.org/10.1063/5.0033924

[4] R.Tiwari, V. Boháč, P. Dieška, G. Götzl, Thermophysical parameters of Carbonate Rock estimated by measured by Slab Model developed for Pulse Transient Technique, Measurement Science Review 20 (5) (2020) 218–223, https://doi.org/10.2478/msr-2020-0027

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