

INVESTIGATION OF THERMAL PROPERTIES OF SOIL BY IMPULSE METHOD

Juraj Veselský

Faculty of Civil Engineering STU Bratislava, Radlinského 11, 813 68 Bratislava

Abstract

The thermal properties of soils is needed to study in building industry in relation to the heat loss from underground hot water pipes, heat loss from building foundations and underground constructions and relation to the effect of frost on road and airfield pavements. In a wide range of temperatures there is needed to study the thermal properties of soils in relation to application of artificial soil freezing technology. Moisture and temperature are important parameters which effect soil thermal properties.

The transient method with the line impulse heat source was used to measure the thermal properties of the soil in dependence on temperature and moisture. This method enables to measure the thermal diffusivity a , the thermal conductivity λ , as well as the volumetric heat capacity $c\rho$.

INTRODUCTION

The overall heat transfer in soils and other porous materials is realized by three modes: conduction, convection and radiation. It is very difficult to evaluate unambiguously the contributions of particular mechanisms of heat transfer. In addition, heat transfer depends also upon the particle and pore size and their arrangement. Therefore heat transfer in soils and other porous materials is very often described only by heat conduction. In this case the thermal properties contain also contribution of other two heat transfer mechanisms. Then such thermal parameters are designated as “effective”, for example the effective thermal conductivity.

Different methods are used to the thermal properties of soils measurements, steady-state and quasi-steady-state or non-steady-state (transient methods). Steady-state methods are used relatively rare, because the application of the temperature gradient for a long period of time restricts their application for measurement of dry or frozen soils only. More often the transient methods are used and from these the methods with a line heat source actuating in form of a unit jump or impulse. “Needle” probes in which is exploited any from mentioned dynamic methods are used very often [e.g. 1, 2, 3].

EXPERIMENT

2.1 Principle of the measurement method

The transient method with the line impulse heat source was used to measure the thermal properties of the soil in this study. The method enables to measure the thermal diffusivity a , the thermal conductivity λ , as well as the volumetric heat capacity $c\rho$, where ρ is the bulk density and c is specific heat. In addition, the method is possible to combine with the quasi-steady-state method in cylindrical arrangement and with the transient method, which use line step

change heat source [3, 4]. The comparison of measurements by different method provided the satisfying agreement.

The heat impulse in used measuring method is generated by passing of an electrical current during an appropriate time interval t_0 through the resistance wire. At measurement we record the time response of temperature at certain, properly selected, measuring point in sample on heat impulse of source. From point of view of evaluation of measuring, the coordinates (t_m and T_m) of

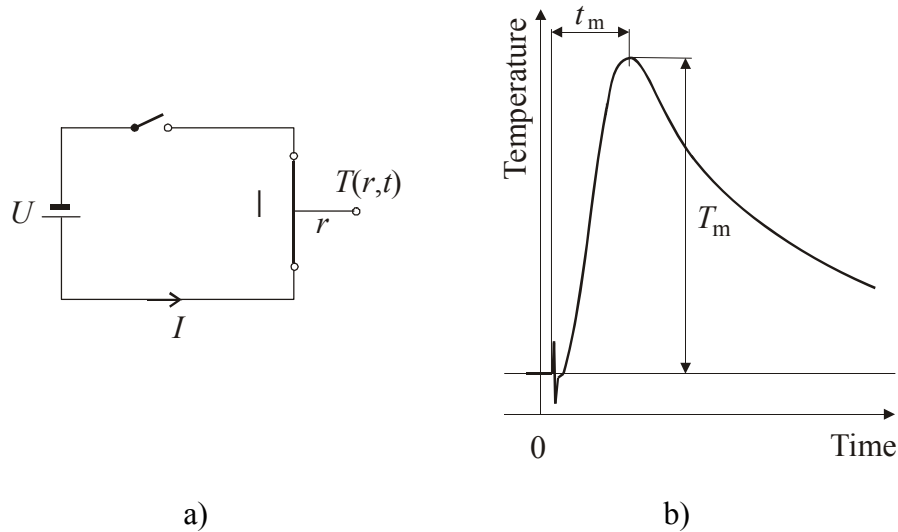


Fig. 1. a) Principle of the impulse method, b) The temperature response on the heat impulse.

maximum of time dependence of temperature are very important.

The temperature function, i.e. the function describing the temperature field in tested sample that respond to action of the linear heat impulse source under ideal propagation of heat through the sample, has a form

$$T(r,t) - T_0 = \frac{Q_0}{4\pi \lambda t} \exp\left(-\frac{r^2}{4at}\right) \cdot \Phi\left(\frac{\ell}{4\sqrt{at}}\right) \quad (1)$$

where T is temperature in time t at point of the sample (Fig. 1a), which is distant r from the heat source, T_0 – initial temperature of the sample, Q_0 – heat generated per length unit of the heat source, λ – coefficient of thermal conductivity, a – thermal diffusivity of the sample, ℓ – length of linear heat source and $\Phi(x)$ – error function.

When $\frac{\ell}{4\sqrt{at}} > 1$, the value of $\Phi\left(\frac{\ell}{4\sqrt{at}}\right) \rightarrow 1$ and temperature function (1) will be simpler

$$T(r,t) = \frac{Q_0}{4\pi \lambda t} \exp\left(-\frac{r^2}{4at}\right) + T_0 \quad (2)$$

This function has a maximum (Fig. 1b). By solving equation $T'_t(r,t) = 0$ we get relation for thermal diffusivity

$$a = \frac{r^2}{4t_m} \quad (3)$$

and for coefficient of thermal conductivity

$$\lambda = \frac{1}{4\pi\epsilon} \cdot \frac{Q_0}{t_m T_m} \quad (4)$$

where t_m is time when temperature reaches maximum value, i.e. T_m .

The volumetric heat capacity $c\rho$ is determined by the expression

$$c\rho = \frac{\lambda}{a} \quad (5)$$

2.2 Experimental apparatus

The apparatus used to measure thermal conductivity of soils is shown in Fig. 2. A sample of soil is placed in cylindrical container made of duralumin. The heat source is situated in axis of the container and is fastened at either end. The heating wire running through the box is connected to

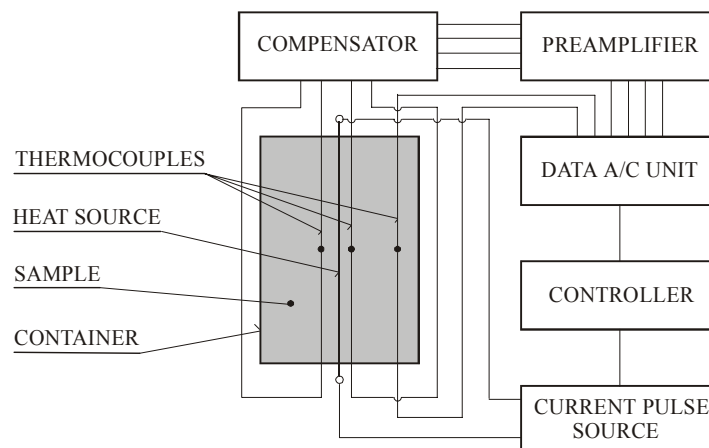


Fig. 2. Schematic diagram of the experimental apparatus.

current pulse source that heat it. The thermocouples that scan the response on heat impulse are inserted in distance r_1 and r_2 from the heat source. The third thermocouple scans temperature (T_0) of the sample before application of heat impulse. The thermocouples are attached to a data A/C unit. Change of sample temperature is achieved by inserting of sample container to Dewar vessel with liquid nitrogen.

2.3 Experimental results and discussion

In this part we present experimental data, which we acquired by measurement of the thermal parameters of fine silica sand in range from indoor temperature to temperature of boiling point of nitrogen (-196°C) at different moisture.

Thermal conductivity. The experimental results of the thermal conductivity λ are presented in Fig. 3. It is difficult to analyze the temperature dependence of the effective thermal conductivity of

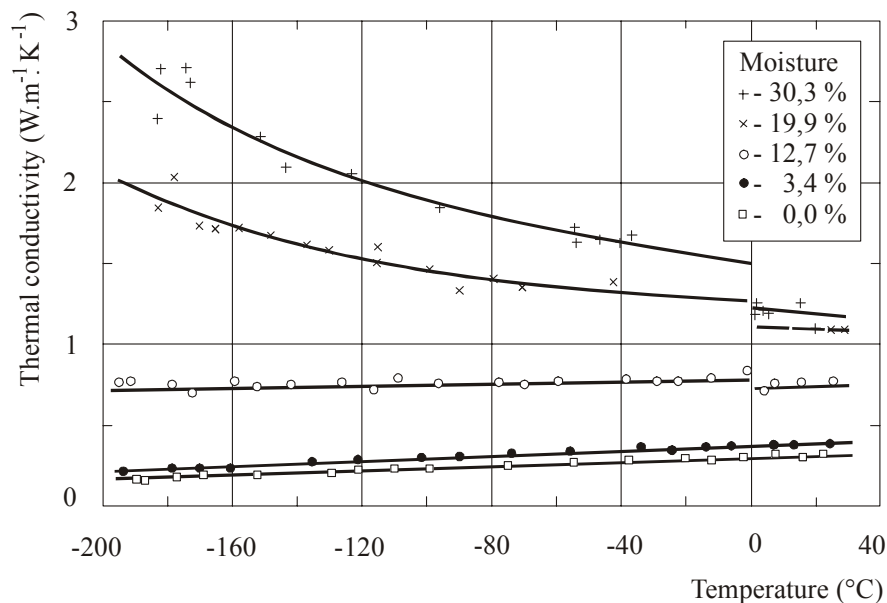


Fig.3. Thermal conductivity vs. temperature for fine silica sand.

sands and other composite materials. So, we will try to explain measured temperature dependence of the thermal conductivity λ at least qualitatively. In dry state the sand consists of solid and gaseous components. The contact thermal resistance – the thermal resistance at contact of different components – has the great effect on the thermal conductivity. It is bigger, when there are more different elastic properties of contacting components. For that reason and from idea that in the dry state the solid particles are randomly distributed in a continuous gaseous medium (air), it is possible to assume, that tendency of the temperature dependence of λ of sand will be given by behaviour of the temperature dependence of the thermal conductivity of gas, i.e. with decreasing temperature the thermal conductivity of the sand will be also decreasing.

When we will be gradually supplying air by water, the contact thermal resistance will be decreasing. In addition, water which supply air has the thermal conductivity higher than air. Consequently the thermal conductivity of the composite material will be gradually increasing up to value, which is determined only by the thermal conductivity of the solid and liquid components. If again we apply idea that solid particles are diffused in the continuous liquid component, behaviour of temperature dependence of the thermal conductivity of sand will be mainly determined by the temperature dependence of the thermal conductivity of water. The thermal conductivity of sand above temperature 0 °C will be increasing, if temperature will be increasing. This idea is experimentally confirmed in paper [5]. At temperatures below 0 °C water is in solid state, what result in additional reduction of the contact thermal resistance and, of course, also in the change of the thermal properties of the saturation matter. In this case we can treat sand as non-ideal crystal and then its thermal conductivity will be increasing and showing a peak at some temperature if temperature will be decreasing. Such vision about behaviour of the thermal dependence of the thermal conductivity well agrees with the experimental dependence (Fig. 3).

Thermal diffusivity. The experimental temperature dependence of the thermal diffusivity (Fig. 4) shows at all contents of water, as well as for dry sample the increase in values with decreasing temperature. This trend we can explain by relation

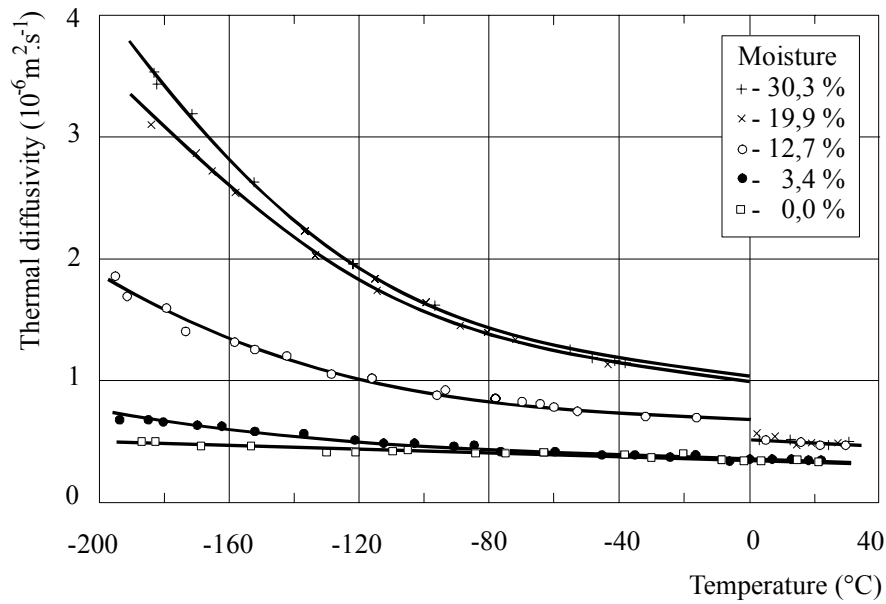


Fig. 4. Thermal diffusivity vs. temperature for fine silica sand.

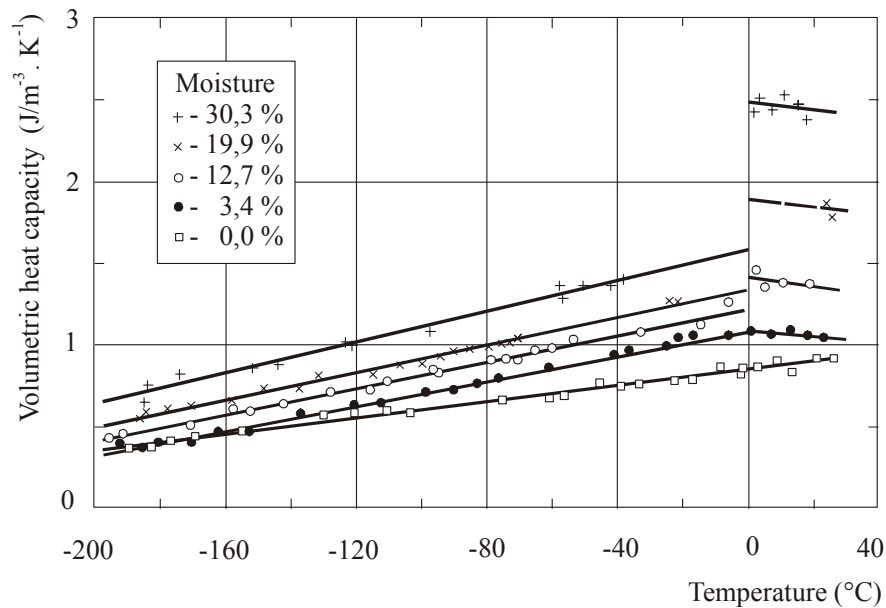


Fig. 5. Volumetric heat capacity vs. temperature for fine silica sand.

$$a = \frac{1}{3} v_f \ell_f \tag{6}$$

Although sand is a multi-component material, we can predict that average speed of phonons v_f is independent on temperature, and that the mean free path of phonons ℓ_f will be increasing consequently the wane of phonon-phonon scattering, when temperature will be decreasing. In addition, with growing content of water the thermal contact on the interface of the components will be improving and so the growth of the thermal diffusivity should be steeper with decreasing temperature at the specimens with high content of water.

Volumetric heat capacity. The experimental temperature dependence of the volumetric heat capacity $c\rho$ (Fig. 5) is decreasing with decreasing temperature. Such dependence agrees with

predictions, which Debye's theory of the heat capacity of solids provides. Debye's temperature of the basic element of sands, namely silicium is $T_{DSi} = 625 \text{ K}$. The temperature interval, in which we measured dependence, lies below this temperature and so the specific heat must with decreasing temperature decrease too.

Thermal conductivity – dependence on content of water. In next text our aim will be focused on dependence thermal conductivity of fine silica sand on content of water. Comparison of our experimental thermal conductivity λ dependence on degree of saturation S of soil by water with some models is shown in Fig. 6. From figure we can see, that the models of parallel and series arrangement of components determine the area of possible values of the effective thermal conductivity of soil. The other combinations of the "resistance" models provide the thermal conductivity lying in this area. From two more complicated models, the model presented in paper [1] better approximates whole experimental dependence. We can see that none resistance model is not able to explain s -profile of experimental dependence.

Therefore we look for the other possibility of experimental data explanation. We proposed semi-empirical model, which will be described in following section.

This model has some initial ideas as a bridge model used in work [5] but it is essentially different in physical interpretation. The model is based on the following ideas: How the content of water in soil gradually grows, water that has higher thermal conductivity as air, tread out air from pores and supply it. The molecules of water are bounded on surface of the solid particles and create water layer around them. When thickness H of water layer reaches half of the characteristic size L of pore, the pore is completely filled by water. We predict that the representative pore sizes ℓ are distributed according normal distribution law. Next, the increase of the thermal conductivity λ will be proportional to probability that the pores, which have representative size L less as ℓ are filled by water

$$\Delta\lambda = k.P(L < \ell) = k.F_1(\ell) \tag{7}$$

and resultant thermal conductivity we can express as

$$\lambda = \lambda_0 + \Delta\lambda = \lambda_0 + k.F_1(\ell) \tag{8}$$

where λ_0 is thermal conductivity of the dry sample of soil,

k – constant of proportionality,

$F_1(\ell) = P(L < \ell)$ – distributive function.

Probability $P(L < \ell)$ is equal probability $P(H < h)$ that thickness apparent water layer $H < h = \ell/2$. However the sickness of the water layer is proportional to degree of saturation S and we can write

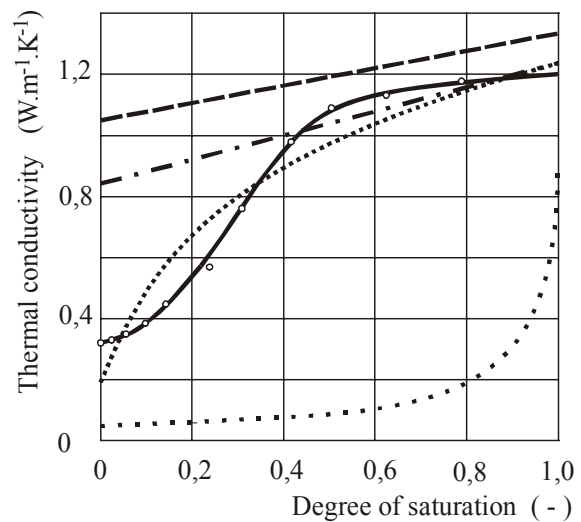


Fig. 6. Comparison of our experimental data with some models: experimental data (\circ), simple model of parallel pores (---), simple model of series pores ($\cdot \cdot \cdot$), Woodside, Messmer's model (\dashdot) [1], Chaundhari, Bhandari's model ($\dashdot\dot$) [6].

$$F_1(\ell) = F_2(h) = F_0(S) = \int_0^{\ell} f_1(\ell) d\ell = \int_0^h f_2(h) dh = \int_0^S f_0(S) dS \quad (9)$$

where functions F_i are the distributive functions and functions f_i are corresponding density functions of the normal distribution. The relation (8) we can rewrite as

$$\lambda = \lambda_0 + k.F_0(S) \quad (10)$$

The constant k we determine by following way: When degree of saturation is equal to the arithmetic mean of degree of saturation S_a (when the content of water start to have an effect on thermal conductivity) and S_b (when the content of water in soil stop to have significant effect on λ), thus

$$S_m = \frac{S_a + S_b}{2} \quad (11)$$

probability $P(S < S_m) = F_0(S_m) = 0,5$. When degree of saturation has value S_m , the thermal conductivity is

$$\lambda_m = \lambda_0 + k.F_0(S_m) \quad (12)$$

and for k we have

$$k = \frac{\lambda_m - \lambda_0}{F_0(S_m)} \quad (13)$$

So as we could calculate the values of distribution function $F_0(S)$ for different S , we need to know standard deviation σ that we determine in this manner: The thermal conductivity λ_a at degree of saturation S_a is

$$\lambda_a = \lambda_0 + k.F_0(S_a) \quad (14)$$

where

$$F_0(S_a) = \frac{1}{\sigma \cdot \sqrt{2\pi}} \int_0^{S_a} \exp\left[-\frac{(S_a - S_m)^2}{2\sigma^2}\right] dS \quad (15)$$

By substitution

$$z_a = \frac{S_a - S_m}{\sigma} \quad (16)$$

the normal distribution transforms to standard normal distribution

$$\Phi(z_a) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z_a} \exp\left(-\frac{z_a^2}{2}\right) dz \quad (17)$$

or generally for various S

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^z \exp\left(-\frac{z^2}{2}\right) dz \quad (18)$$

The density function and the distribution function of this distribution are in form of tables or the standard programs exist for their determination.

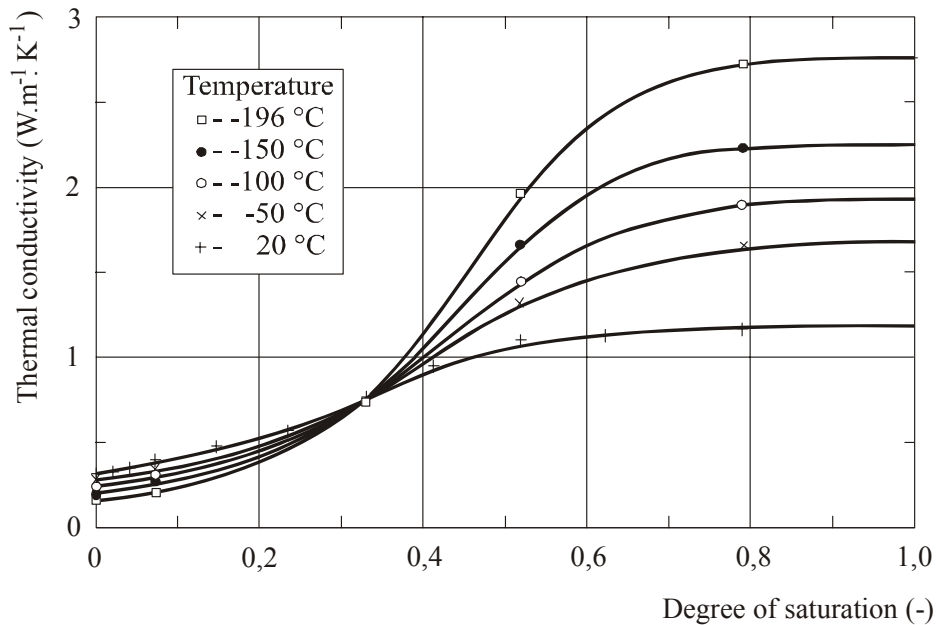


Fig. 7. Comparison of experimental data with calculated data (continual lines) by semi-empirical model.

Table 1.

$t = 20\text{ }^{\circ}\text{C}$

No.	S	z	$F_0(z)$	$\frac{\lambda}{\text{W.m}^{-1}.\text{K}^{-1}}$	Input parameters
1	0,05	-1,6281	0,0518	0,375	$\lambda_0 = 0,330 \text{ W.m}^{-1}.\text{K}^{-1}$ $\lambda_a = 0,380 \text{ W.m}^{-1}.\text{K}^{-1}$ $\lambda_m = 0,760 \text{ W.m}^{-1}.\text{K}^{-1}$ $\lambda_b = 1,140 \text{ W.m}^{-1}.\text{K}^{-1}$ $S_a = 0,06$ $S_m = 0,33$ $S_b = 0,60$
2	0,10	-1,3374	0,0905	0,408	
3	0,15	-1,0467	0,1477	0,457	
4	0,20	-0,7559	0,2248	0,523	
5	0,25	-0,4652	0,3209	0,606	
6	0,30	-0,1744	0,4308	0,701	
7	0,35	0,1163	0,5463	0,880	
8	0,40	0,4070	0,6580	0,896	
9	0,50	0,9885	0,8385	1,031	
10	0,60	1,5700	0,9418	1,140	
11	0,70	2,1515	0,9843	1,177	
12	0,80	2,7330	0,9968	1,187	
13	1,00	3,8959	1,0000	1,190	

From the relation (14) we know value of distribution function $F_0(S_a)$ to which we bind set standard variable z_a and by relation (16) we calculate standard deviation σ .

Then the thermal conductivity corresponding to degree of saturation S we calculate according term (10). We calculate the value $F_0(S)$ by known standard variable z , which we determine from relation

$$z = \frac{S - S_m}{\sigma} . \quad (19)$$

The values $\lambda_0, \lambda_a, \lambda_m, \lambda_b, S_a, S_m, S_b$ are obtained from experiment.

In this way were fitted experimentally obtained dependencies of the thermal conductivity of fine silica sand on degree of saturation by water at temperatures 20 °C, -50 °C, -100 °C, -150 °C and -196 °C. Graphical output is in Fig. 7 and the example of calculation results and values of input parameters for temperature 20 °C are in Table 1. Picture confirms a good agreement of calculated and measured values.

CONCLUSION

Investigation of the thermal properties of soils and other porous materials is still actual problem not only from interest of building practice, but also from point of view a better understanding of heat transfer in these materials. A lot of models of composite materials, which are trying to explain heat transfer through that ones were created. However, all these models are more or less successful in some limits only. The semi-empirical model proposed in this work very good fit experimental data. However this model, as follow from its name, takes input parameters from experiment. That is weakness of the model.

ACKNOWLEDGEMENT

The authors would like to thank the Grant Agency APVV (grant No. 51 – 030704) for funding this research.

REFERENCES

- [1] Woodside, W., Messmer, J. H.: J. Appl. Phys., 1961, 32, 1688
- [2] Lanciani, A. et al.: High Temperatures-High Pressures, 12 ETPC Proceedings 1991, 23, p. 501
- [3] Krempaský, J.: Meranie termofyzikálnych veličín. Bratislava, VEDA SAV 1969.
- [4] Kubičár, Ľ.: Pulse Method of Measuring Basic Thermophysical Parameters, Amsterdam, Elsevier Science 1990.
- [5] Matsumoto, J., Okubo, T.: Technology Reports Tohoku University 43, 1978, p. 151
- [6] Chaundhari D. R., Bhandari R. C.: Brit. J. Appl. Phys. D 19, 1968, p. 1.