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Shranjevanje toplote z geosondami in testi za ugotavljanje toplotnih lastnosti zemlje - Primer uporabe v Turčiji ter stanje v Sloveniji

Borehole Thermal Energy Storage Applications and In-Situ Thermal Response Test – Example from Turkey and Situation in Slovenia

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V prispevku je predstavljena metoda sezonskega shranjevanja toplote z geosondami ter test toplotne odzivnosti, ki se uporablja za določanje parametrov tal. Predstavljene so analizne metode za dejanski izračun toplotne prevodnosti tal ter določevanje njene negotovosti. V nadaljevanju so predstavljene meritve, ki so jih opravili med raziskavami tal v Turčiji, ter stanje na področju sezonskega shranjevanja toplotne energije v Sloveniji.

(Ključne besede: hranjenje toplote, hranjenje podzemno, geosonde, prevodnost toplotna)

In the paper we present a method of seasonal heat storage with boreholes and thermal response test for determination of ground parameters. Analysis methods for concrete calculations of thermal conductivity as well as error determination are explained. In the continuation measurements made in research of the ground in Turkey and situation in a field of seasonal thermal energy storage in Slovenia are presented.

(Keywords: underground thermal energy storage, borehole heat exchangers, thermal conductivity)

0 UVOD

Podzemno shranjevanje toplotne energije (PSTE - UTES) je zanesljiva in energetsko varčna tehnologija shranjevanja toplote in je namenjena hlajenju in ogrevanju v stavbnih objektih in industrijskih postopkih ter je sedaj že široko razširjena po vsem svetu.

Gre za tehnologijo shranjevanja toplote v zemlji pod površjem ali v vodonosnikih oz. podzemnih jezerih. V poletnih mesecih se odpadna toplota ali toplota, pridobljena s sončno energijo, na različne načine shranjuje, v zimskih mesecih jo lahko uporabimo za ogrevanje. Podobno poteka tudi hlajenje.

V zadnjih dvajsetih letih je bila ta metoda uporabljana že v več različicah. Na podlagi Mednarodne agencije za energijo (IEA) ter ohranitvi energije s shranjevanjem energije (OESE - ECES) je bila temu namenu strokovno razvita znanstvena oprema. V splošnem se za metodo podzemnega shranjevanja toplotne energije uporablja kratica PSTE,

0 INTRODUCTION

Underground thermal energy storage (UTES) is a reliable, sustainable, and energy-saving technology for the cooling and heating of buildings and industrial processes all over the world. In the past 20 years, various applications of UTES have been introduced. Within the IEA Implementing Agreement, Energy Conservation through Energy Storage (ECES) program, much of the expertise on UTES has developed.

UTES is a technology for storing energy in the ground, in aquifers or in underground pools. In the summer time waste heat or heat from solar energy is saved in different ways, in the winter time this heat is used for heating. Cooling is performed in similar way.

In the past twenty years this method was applied in many applications. Scientific equipment has been developed in the frame of International Energy Agency (IEA) and Energy conservation through energy storage (ECES). The acronym UTES ki je pogosto razdeljena na podskupine glede na tip uporabljenega sredstva za shranjevanje energije. Ena takšnih je metoda z vrtinami za shranjevanje toplotne energije (VSTE - BTES), ki se nanaša na sistem shranjevanja energije z uporabo vrtine v zemlji in vanjo nameščenih cevi.

Toplotna prevodnost zemlje in toplotna upornost prenosnika toplote v vrtini (PTV - BHE) sta dva najbolj pomembna sestavna parametra sistema VSTE. Njuno vrednost je mogoče določiti prek merilnih instrumentov, katerih podatki naj bi bili dovolj natančni. Takšni testi so ekonomsko upravičeni le takrat, če imamo zgrajenih že več takšnih sistemskih enot z vrtinami. Merilno metodo pa so v zadnjem desetletju naglo razvijali in dopolnjevali in se danes navadno omenja kot “test toplotne odzivnosti” (TTO).

1 POTEK TESTA TOPLOTNE ODZIVNOSTI

Za pravilno dimenzioniranje toplotnega sistema je odločilnega pomena, poleg zadovoljivega vira energije, naše znanje in vedenje o toplotni prevodnosti tal. Oceno takšne učinkovite toplotne prevodnosti tal, primerne za naš sistem, pridobimo z meritvijo toplotne odzivnosti vira energije v tleh, ki jo izvajamo na terenu s premično napravo, v kateri je nameščen sistem za merjenje toplotne odzivnosti (sl. 1).

Test toplotne odzivnosti je prvič javno predstavil danski raziskovalec Palne Mogensen na mednarodni konferenci za »shranjevanje energije« v Stockholmu leta 1983 [1]. Prvo takšno premično napravo za izvajanje meritev so samostojno razvili na Švedskem na Univerzi za tehnologijo v Luleå in tudi na ameriški državni univerzi v Oklahomi v letih 1995-96. Takšne vrste meritev se sedaj že izvajajo v ZDA, Kanadi, Norveški, Nemčiji, Nizozemski, Angliji in Turčiji.

Naprava za TTO sestavlja črpalka z močjo 1 kW, ki poganja grelno sredstvo prek hranilnika toplote

refers to underground thermal energy storage in general, and is often divided into subgroups according to the type of storage medium that is used. The acronym BTES (Borehole Thermal Energy Storage) refers to storage systems using boreholes or ducts and pipes in the ground.

The thermal conductivity of the ground and the thermal resistance of the borehole heat exchanger (BHE) are the two most important design parameters for BTES systems. The two parameters may be determined from in-situ measurements, which give reliable design data. Such tests are usually economically feasible when designing BTES systems comprise more than just a few boreholes. The measurement method has rapidly developed in the past decade, and is now usually referred to as the Thermal Response Test (TRT).

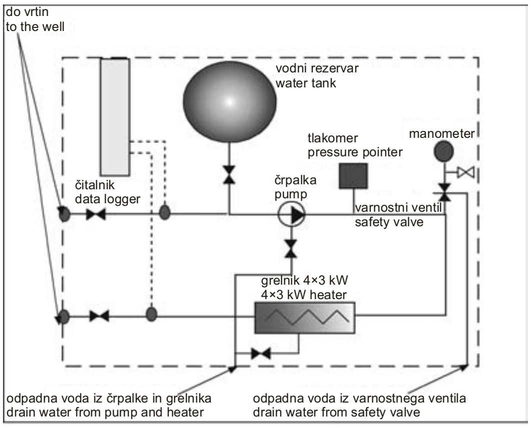
1 THE HISTORY OF THE THERMAL RESPONSE TEST

Knowledge of the thermal conductivity of the ground surrounding an energy well is crucial for the appropriate dimensioning of an underground thermal energy system. By measuring the ground thermal response of a well, the effective in-situ thermal conductivity for the system can be estimated. Field tests are done with a mobile thermal response test (TRT) apparatus (Figure1).

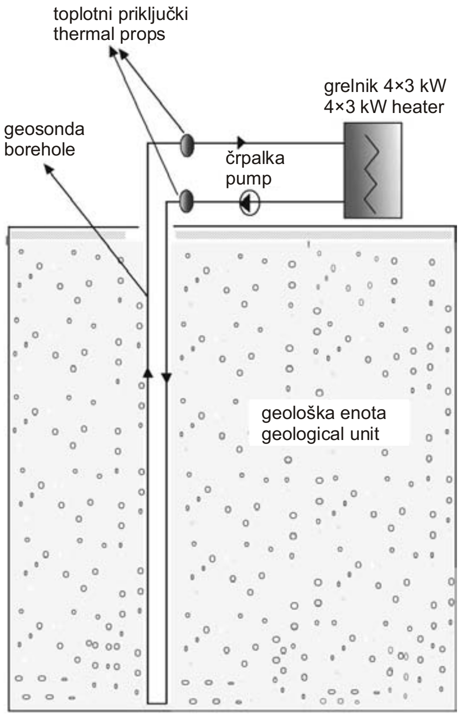
The thermal response test was first proposed by the Danish researcher Palne Mogensen at an international conference on energy storage in Stockholm, in 1983 [1]. The first mobile measurement devices for thermal response tests were developed independently at Luleå University of Technology, Sweden, and at Oklahoma State University, USA, in 1995-96. These types of measurements are now used in the USA, Canada, Norway, Germany, the Netherlands, England and Turkey.

The TRT apparatus consists of a 1-kW pump circulating the heat through the borehole

Sl. 1. *Naprava za merjenje TTO*
Fig. 1. *In-situ TRT apparatus*



Sl. 2. *Načrt merilne naprav*
Fig. 2. *TRT flow diagram*



Sl. 3. *Osnovna zamisel TTO*
Fig. 3. *Basic concept of TRT*

v vrtini naprej v prenosnik toplote s prilagodljivo in stabilno toplotno močjo v razponu od 3 do 12 kW. Temperatura vode se meri na vstopu in izstopu iz vrtine s termistorji, katerih točnost je ± 0,2 K. Stanja teh temperatur se nato hkrati shranjujejo v podatkovni pomnilnik. Celotna naprava je dimenzionirana za električni tok 16 A (sl. 2).

Načelo delovanja TTO je v tem, da v naš iskani vir energije v zemlji vnašamo znano toplotno moč v časovnem obdobju, ki je večje od 50 ur, z uporabo tekočega sredstva, ki kroži po cevnem sistemu, medtem ko se mu dovaja stalna toplotna moč. Temperaturni odziv tal merimo nato posredno prek vstopne in izstopne temperature ogrevalnega sredstva, pri čemer so toplotne značilnosti tal in pa vgrajenega hranilnika toplote sorazmerne temperaturni spremembi tal med meritvijo (sl. 3).

Slika 3 predstavlja sistem shranjevanja energije TTO, pri katerem se temperatura v vrtini spreminja zaradi shranjevanja ali črpanja toplotne energije iz nje. Zaradi tega se zemlja, ki obdaja vrtino, bodisi ohlaja ali segreva. Matematičen popis takšne temperaturne funkcije v snovi so razvili Hellström (1994) [2], Mogensen (1983) [1] in Eskilson (1987) [3].

2 ANALIZNE METODE

Splošno znane metode za oceno toplotnih lastnosti talne sestave je mogoče razdeliti v neposredne metode, kakršna je metoda enocevne

collector and through a cross-flow heater with an adjustable and stable heating power in the range 3-12 kW. The fluid temperature is measured at the inlet and the outlet of the borehole with thermistors that have an accuracy of ± 0.2 K. The temperatures are recorded at a set time interval by a data logger. The equipment is installed for 16A electricity (Figure 2: In-situ thermal response test system scheme).

The principle of the thermal response test is to inject a known amount of power into the energy well over a certain period of time (>50 hours), by circulation of the heat-carrier fluid through the energy well piping system while a certain power rate is transferred to the fluid. The temperature response of the ground is measured by recording the inlet and outlet temperatures. The thermal properties of the ground and collector installation are proportional to the temperature change in the ground over the measurement period (Figure 3) .

The thermal response test of a BTES borehole is described by the temperature change in the boreholes when heat is injected or extracted. The transfer of the heat to/from the boreholes causes a change in the temperature in the surrounding ground. The mathematics are described by Hellström (1994) [2], Mongesen (1983) [1] and Eskilson (1987) [3].

2 ANALYSIS METHODS

Currently used methods to estimate the thermal properties of the ground formation may be divided into direct methods, such as line source and kače za prenos grelnega sredstva ali valjna sestava cevi v cevi, ter metode določitve parametra z našo oceno. Na podlagi tega je bilo predstavljenih šest vrst metod:

1. teorija črtnega vira, kakor sta jo uporabila Eklöf in Gehlin (1996) [4] ter Gehlin in Nordell (1998) [5];
2. črtna teorija vira, ki jo je uporabil Smith (1999a) [6];
3. črtna teorija vira, ki jo je uporabil Curtis (2001) [7];
4. valjni model, uporabila sta ga Kavanaugh in Rafferty (1997) [8];
5. ocena parametra z enorazsežnim modelom končnih prostornin, uporabila sta ga Shonder in Beck (1999) [9];
6. ocena parametra z dvorazsežnim modelom končnih prostornin vrtine z znano prostornino, ki ga je uporabil Austin (2000) [10].

V nadaljevanju sta predstavljeni metodi črtnega vira in valjni model.

cylinder source approaches, and methods that use formal parameter-estimation techniques. The following six methods are based on four theoretical approaches and methods that use formal parameter-estimation techniques.

1. Line source theory, as used by Eklöf in Gehlin (1996) [4], ter Gehlin in Nordell (1998) [5],
2. Line source theory, as used by Smith (1999a) [6],
3. Line source theory, as used by Curtis Curtis (2001) [7],
4. Cylinder source theory, as used by Kavanaugh and Rafferty (1997) [8],
5. Parameter estimation with a 1D finite-volume borehole model, as used by Shonder in Beck (1999) [9],
6. Parameter estimation with a 2D finite-volume borehole model, as used by Austin (2000) [10].

In the rest of the paper the line-source and cylinder-source models are presented.

2.1 Teorija črtnega vira

Za izračun porazdelitve temperature (T^q) v odvisnosti od časa (t) in polmera (r) okoli enocevnega sistema s stalnim toplotnim tokom (q) lahko vzamemo približek na podlagi računske izpeljave toplotnega toka v sistemu prenosnika toplote v tleh [11]:

2.1 Line source

The equation for the temperature field as a function of time and radius around a line source with constant heat-injection rate can be used as an approximation for the heat injection from a BHE [11]:

$$T^q(r,t) = \frac{q}{4\pi\lambda}\int_{\frac{r^2}{4at}}^{\infty}\frac{e^{-u}}{u}du = \frac{q}{4\pi\lambda}E_1\left(r^2/4at\right) \qquad (1).$$

S povečevanjem časa se bo povečal tudi mejni polmer segrevanja tal okoli cevi. Ingersoll in Plass [12] sta leta 1948 pokazala, kako je takšna enačba koristna za preračun valjnega grelnika v kanalu vrtine, pri katerem se pojavi napaka, manjša od 2 %, če ob tem velja pogoj:

With increasing time, the radius of influence will increase. Ingersoll and Plass (1948) [12] showed that the equation can be used for cylindrical heat-injection ducts with an error of less than 2% if:

$$t > \frac{20r_b^2}{a} \qquad (2).$$

Pri običajnih meritvah v vrtinah je čas merjenja dolg in znaša med 10 do 20 ur.

E_1 je tako imenovani eksponentni integral. Za večje vrednosti parametra at/r^2 je E_1 lahko približan s preprosto funkcijsko odvisnostjo:

For a normal borehole, t is in the range 10-20 hours.

E_1 is the so-called exponential integral. For large values of the parameter at/r^2, E_1 can be approximated with the following simple relation:

$$E_1\left(r^2/4at\right) = \ln\left(\frac{4at}{r^2}\right) - \gamma \qquad \frac{at}{r^2} \geq 5 \qquad (3),$$

kjer je $\gamma = 0{,}5772$ Eulerjeva konstanta. Največja napaka za vrednosti $at/r^2 \geq 20$ znaša 2,5 %, za vrednosti $at/r^2 \geq 5$ pa 10 %.

Merjena temperatura med izvajanjem TTO je temperatura tekočine, medsebojno povezavo med temperaturo tekočine (T_f) in temperaturo sten vrtine (T_b) pa tako zapišemo v odvisnosti:

where the term $\gamma = 0.5772$ is Euler's constant. The maximum error is 2.5% for $at/r^2 \geq 20$ and 10 % for $at/r^2 \geq 5$.

The measured temperature during a response test is the fluid temperature, and the relationship between the fluid temperature and the temperature at the borehole wall (T_b at R_b) is:

$$T_f^q(t) = T_b^q(t) + q \cdot R_b \qquad (4),$$

kjer R_b pomeni toplotno upornost med sredstvom za prenos toplote v cevi in pa steno vrtine, ki obdaja cev. Temperaturni indeks q pomeni, da se je v toplotnem sunku q spremenila temperatura za točno določeno vrednost. Tako se temperatura tekočine kot funkcija časa lahko zapiše v obliki:

where R_b is the thermal resistivity between the fluid in the pipes and the borehole wall. The index q in the temperatures denotes that it is the temperature change due to the heat pulse q. Thus the fluid temperature as a function of time can be written as:

$$T_f(t) = \frac{q}{4\pi\lambda} \cdot \left(\ln\left(\frac{4at}{r^2} \right) - \gamma \right) + q \cdot R_b + T_o \qquad (5),$$

kjer je T_o nespremenljiva temperatura tal.

Raziskovalci so v praksi sproti razvijali lastne postopke metod, vendar se niso bistveno oddaljevali od teorije Mogensena, ki jo je razvil leta 1983.

Teoretikom, kakršni so bili Eklöf, Gehlin, Nordell, Sanner in Cruickshanks [13], je v preteklih letih uspelo dognati bistvo, kako opredeljevati toplotno prevodnost tal v preračunih metode shranjevanja toplotne energije. Razvili so metodo, pri kateri padanje povprečne temperature tekočine oziroma njeno strmino krivulje podamo z naravnim logaritmom časa:

where T_o is the undisturbed ground temperature.

In practice, researchers have made use of this approach in somewhat different ways, although they essentially follow Mogensen (1983).

Gehlin and Eklöf, Gehlin and Nordell, Sanner et al. and Cruickshanks et al. [13] have applied the line source solution to determine the thermal conductivity of the ground formation for an underground thermal energy storage system. The implementation is done by determining the slope of the curve of the average fluid temperature development versus the natural log of time:

$$T_f(t) = k \cdot \ln t + m \qquad (6)$$

$$k = \frac{q}{4\pi\lambda} \qquad (7),$$

kjer k pomeni faktor strmine krivulje.

Toplotno prevodnost zemlje določimo praktično takole: na geosondo priključimo grelnik znane moči in zapisujemo temperature vode. Narišemo diagram poteka temperature v odvisnosti od časa. Če na osi časa izberemo naravni logaritem, lahko iz strmine premice določimo k po enačbi (6). Nato pa še toplotno prevodnost λ iz enačbe (7).

2.2 Valjni model

Takšen model, ki sestoji iz sistema cev v cevi, je poenostavljena različica sistema toka grelnega sredstva po eni cevi. Njegov namen je pridobivanje približkov parametra PTV, kar mu omogoča njegova velikost ter zagotavljanje stalnega toplotnega toka. Navadno je notranji premer toplotnega prenosnika enakomeren po vsej dolžini. Matematično lahko takšen stalen tok toplote, ki ga dovajamo v tla, popišemo kot:

where k is the slope of the curve.

The thermal conductivity of the ground is practically determined in the following way: on the borehole the heater is connected and the temperatures of water are collected. The diagram of temperature changes versus time is produced. If the natural logarithm is used on the time axis, the parameter k can be determined from Eq. 6. Then we can easily calculate the thermal conductivity λ from Eq. 7.

2.2 Cylindrical model

The cylinder-source model, of which the line-source model is a simplified variation, can be used for an approximation of the BHE as an infinite cylinder with a constant heat flux. The heat-exchanger pipes are normally represented by an "equal diameter" cylinder. The cylindrical-source solution for a constant heat flux is as follows:

$$T^q(r,t) = \frac{q}{\lambda} \cdot G(z,p) \qquad \begin{cases} z = \dfrac{at}{r^2} \\ p = \dfrac{r}{r_o} \end{cases} \qquad (8),$$

kjer je $G(z,p)$ funkcija, ki popisuje valjno sestavo grelnika po metodi Ingersolla (1954) [14]:

where G(z,p) is the cylindrical-source function as described by Ingersoll (1954) [14]:

$$G(z,p) = \frac{1}{\pi^2} \int_0^\infty f(\beta) \; d\beta \qquad (9)$$

$$f(\beta) = \left(e^{-\beta^2 z} - 1 \right) \cdot \frac{\left[J_0(p\beta) Y_1(\beta) - Y_0(p\beta) J_1(\beta) \right]}{\beta^2 \left[J_1^2(\beta) + Y_1^2(\beta) \right]} \qquad (10),$$

kjer so J_o, J_1, Y_o, Y_1 Besselove funkcije prvega in drugega reda.

Deerman, Kavanaugh in Rafferty ([8] in [15]) so predlagali iterativni postopek reševanja valjne metode kot obratno določevanje toplotne prevodnosti tal. Dejanska prevodnost (in difuzivnost) talne sestave je računana z reverzibilno matematično operacijo, ki vsebuje preračun dolžine cevne zanke toplotnega prenosnika v vrtini. Če gledamo naš test kratkoročno, potem je postopek tak, da našo toplotno prevodnost tal in pa dnevni toplotni sunek, ki sta preračunana s Fourierjevim številom (z) in funkcijo valjnosti $G(z,p)$, primerjamo s pričakovano vrednostjo toplotne prevodnosti in difuzivnosti talne sestave toliko časa, dokler med sabo niso izenačene.

2.3 Analize napak

Merilna negotovost določanja toplotne prevodnosti je posledica več vzrokov. Prvi so naključne in pa sistemske eksperimentalne napake, uporabljeni približki v analitičnem ali numeričnem modelu, groba ocena pričakovane temperature v preračunih ter doba trajanja testa. To negotovost so razložili Austin leta 1998 [16], Austin s sodelavci 2000 [17] ter Witte in Van Gelder leta 2002 [18]. Celotna negotovost, ocenjena z različnimi analiznimi postopki, se giblje v razponu 10 %. Austin je tako leta 1998 pokazal, da je napaka pri meritvi prenosa toplote v sorazmerju s odstotno napako storjeno pri oceni toplotne prevodnosti tal. Potemtakem mora biti pozornost usmerjena na pravilno meritev obeh različnih temperatur natančno na vhodu in izhodu vrtine, te namreč nastanejo zaradi prenosa toplote na izvrtino, v primeru ko je merilno mesto oddaljeno stran od vhoda v izvrtino, je treba cevi dobro izolirati za preprečitev morebitnih toplotnih izgub skozi stene cevi v okolico.

Negotovost približkov, dobljenih v analiznih postopkih, je primerna za predpostavljanje stopnje ustaljenega prenosa toplote. Austin je med drugim leta 1998 tudi pokazal, kako veliko je nihanje dobljene toplotne prevodnosti pri črtnem modelu, za kar je mogoče iskati vzrok v velikem nihanju stopnje prenosa toplote na vrtino. Za dosego bolj natančnih ocen se uporablja v ta namen metoda ocenitve parametra.

3 IZKUŠNJE IZ TURČIJE

3.1 Švedska aparatura, namenjena meritvam v Turčiji

Takšno vrsto merilne naprave za izvajanje testa toplotne odzivnosti (Eklöf in Gehlin 1996 [4], Gehlin in Nordell 1998 [5]) so razvili na Univerzi za tehnologijo Luleå v letih 1995-1996. Med samim razvijanjem tehnološke opreme pa sta intenzivno in učinkovito začeli med seboj sodelovati prav Univerza

where J_o, J_1, Y_o, Y_1 are Bessel functions of the first and second kind.

Deerman, Kavanaugh and Rafferty ([8] and [15]) suggested an iterative procedure that uses the cylinder-source method to inversely determine the ground's thermal conductivity. The effective thermal conductivity (and diffusivity) of the ground formation is computed by reversing the process used to calculate the length of the ground-loop heat exchanger. Based on a short-term in-situ test, the effective thermal resistivity of the ground of a daily heat pulse is compared to a value computed from the Fourier number (z) and the cylinder-source function $G(z,p)$ with an assumed value for the thermal conductivity and the diffusivity of the ground formation until the ground resistance values are the same.

2.3 Error Analysis

Uncertainties in the estimated ground thermal conductivities come from several sources: random and systematic experimental error, approximations made in the analytical or numerical model, estimates of the far field temperature, and the length of test. These uncertainties have been discussed by Austin in 1998 [16], Austin et al. 2000 [17] and Witte and Van Gelder 2002 [18]. The overall uncertainties of the estimations made by different analysis procedures with different test equipment are of the order of ±10%. Austin has shown that the error in the measurement of heat-transfer rate to the borehole results in a similar percentage error in the estimation of the ground's thermal conductivity. Therefore, care must be taken to either measure the heat-transfer rate using a temperature difference at the borehole inlet and outlet or, if the heat rate is measured elsewhere, to minimize any unmeasured heat losses or gains.

Uncertainties due to an approximation in the analysis procedure may be due to an assumption of a constant heat-transfer rate. Austin showed very variable thermal conductivity predictions made with the line-source procedure, when there were significant variations in the heat-transfer rate to the borehole. In this situation, the parameter-estimation procedure, which does not assume a constant heat-transfer rate, can provide more accurate estimates.

3 EXPERIENCES FROM TURKEY

3.1 Application of the Swedish Apparatus for the Thermal Response Test in Turkey

The Swedish mobile thermal response test equipment, TRT (Gehlin and Nordell 1998 [5], Eklöf and Gehlin 1996 [4]), was constructed at Luleå University of Technology in 1995-1996. During this period, Luleå University of Technology and Çukurova University Centre for Environmental Research began v Lulei ter Univerzitetni center za okoljske raziskave Çukurova v Turčiji z izmenjavo študentov ter združitvijo nekaterih projektov, vse v okviru Mednarodne agencije za energijo na področju shranjevanja energije. Kot rezultat dobrega sodelovanja je Univerza v Lulei nato v novembru leta 2000 podarila eno takšnih merilnih enot Univerzitetnemu centru Çukurova, eden od konstrukterjev merilne opreme (Singhild Gehlin) pa je tudi obiskal ta center v Turčiji.

3.2 Opravljene meritve

TTO je bil izvajan od leta 2000 na dveh različnih lokacijah v Turčiji (sl. 4) [19]. Tako so v mestih Istanbul in Adana v vrtine vstavili posamič enkrat 100 m dolgo dvojno cev U ter 75 m enojno cev U. Meritve toplotne prevodnosti in pa toplotne upornosti so bile ocenjene na podlagi črtnega modela (1) z namenom poiskati primeren talni vir energije. Ta test se je v Adani ponavljal vsak mesec v časovnem obdobju od julija 2001 do februarja 2002, pri čemer so sproti določali učinke spreminjanja okoliških razmer na umerjanje meritve.

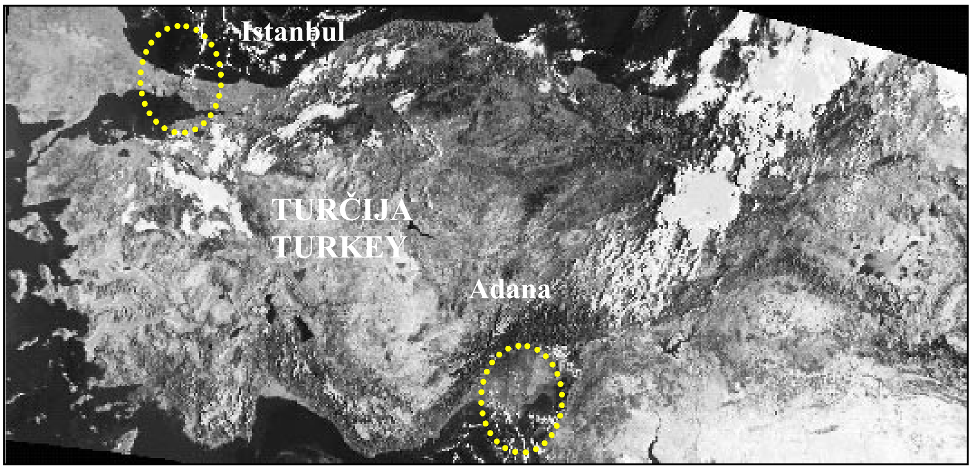
Meritve so se izvajale v vrtini z geosondo, ki so jo povezali s toplotno črpalko na primerni lokaciji v pokrajini Marmara v okolici Istanbula. Geološko sestavo površinskih plasti te pokrajine sestavljajo predvsem sedimentne kamnine, ki sestoje iz glinovca ter gline v menjavanju z apnencem. Vrtina je približno 100 m globoka, vodostaj v njej pa 80 m pod površjem. Vanjo so namestili dve cevi U dolžine 100 m in notranjega premera 2,4 mm. Da bi preprečili prožnost cevi, ki so iz nerjavnega jekla in tehtajo skoraj 50 kg, so jih obdali poprej s plastičnimi cevmi. Po koncu vgradnje cevi v vrtino so le-to zasuli in zalili z naravnim granulatom zemlje ter vodo. Konca cevi so med seboj mehansko ločili med črpalko, nameščeno v prikolici ter glavnim grelnikom tekočine. Nato so zagnali

an effective and efficient cooperation (exchange of students, some projects partnership, etc) within the frame of the International Energy Agency, Energy Conservation through Energy Storage Implementing Agreement. As a result of this successful cooperation, Lulea University of Technology donated TRT equipment to the Çukurova University in November, 2000. One of the TRT developers, Singhild Gehlin, visited Çukurova University Centre for Environmental Research for technology transfer.

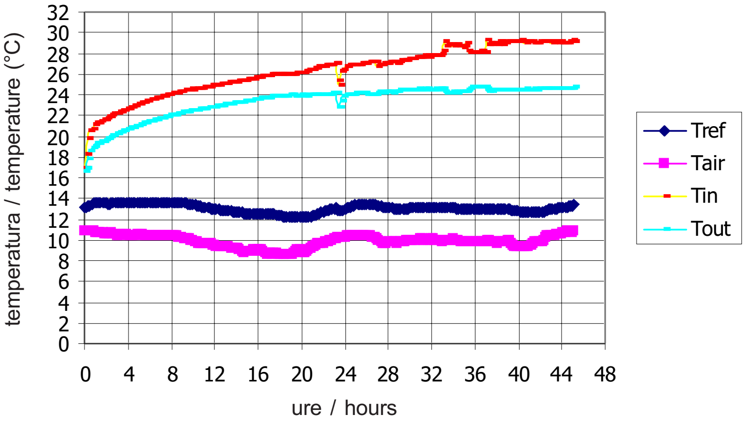
3.2 Measurements Performed

TRT has been used at two different locations in Turkey (Figure 4) since 2000 [19]. The depth and configuration for Istanbul and Adana are 100-m double U-pipe and 75-m single U-pipe, respectively. For these two sites, thermal conductivity and thermal resistance values are evaluated using the line-source model (1). The thermal response tests in Adana have been repeated every month during the period July 2001-February 2002 to evaluate the effect of the change in ambient conditions on the measurements matching.

Measurements are made in the boreholes drilled to be used with GSHP in a new residential area in the Marmara region Ýstanbul-Hadýmköy, Turkey. The research area is geollogically mostly chacterized by sediments: claystone, clay with limestone and marl succession, known as Sazlýdere Formation. The borehole is approximately 100-m deep. The water level in the borehole was 80 m from the surface. Two U-pipes, 100-m long with an inner diameter of 2.4 mm, were installed in the borehole. To counteract the flexibility, approximately 50 kg of stainless-steel weight was strapped to the plastic pipe assembly. When the U-piping was completely installed, the borehole was grouted with the natural geological formation and water. The two ends of U-pipe were insulated between the pump trailer and the fluid heater. The pump was



Sl. 4. *Satelitski posnetek Turčije*
Fig. 4. *Satellite picture of Turkey*



Sl. 5. *Izmerjeni časovni diagram temperature tekočine v kraju Istanbul-Hadýmköy*
Fig. 5. *Istanbul-Hadýmköy fluid temperature profile measurements*

črpalko, ki je potisnila ogrevalno sredstvo po cevnem sistemu, pri tem pa je bilo treba paziti na pravilen tlak, ki se je meril na sekundarni strani črpalke in se je gibal v mejah od 1,5 do 2 barov.

Merjenje vstopne in izstopne temperature sredstva je potekalo v rednih časovnih korakih po 10 min, pri čemer so njegov tlak v cevi sprotno spremljali na monitorju. Podatki so se hkrati s tem shranjevali v podatkovni pomnilnik.

Registriranih je bilo 273 ločenih meritev temperatur z 10 minutnimi koraki v časovnem obdobju dveh dni, 2. in 4. decembra leta 2000. Na sliki 5 je grafično izrisana meritev vhodne temperature (T_{in}) in izhodne (T_{out}), temperature zraka (T_{air}) ter referenčne temperature (T_{ref}).

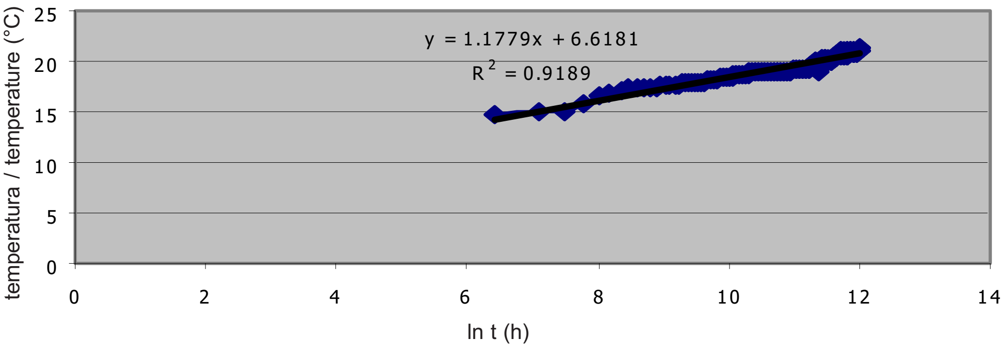
Naraščanje temperature v odvisnosti od časa v urah, kakor je prikazano na sliki 6, je sorazmerno spreminjanju toplotne prevodnosti geološke plasti med njenim segrevanjem. Glede na dobljene rezultate v Hadimköyu so toplotno prevodnost (λ) in toplotno upornost (R_b) izračunali s uporabo iterativnega približka , kjer je λ podana kot začetna ocena, R_b pa izračunana na podlagi enačbe (5). Iteracijo so ponavljali toliko časa, dokler se izračunana vrednost temperature tekočine ni ujemala z izmerjeno

then turned on and the fluid was circulated in the tubing system. Attention was paid to the pressure in the system. During the pumping, the water pressure measured at the outlet of the pump was 1.5-2 bar.

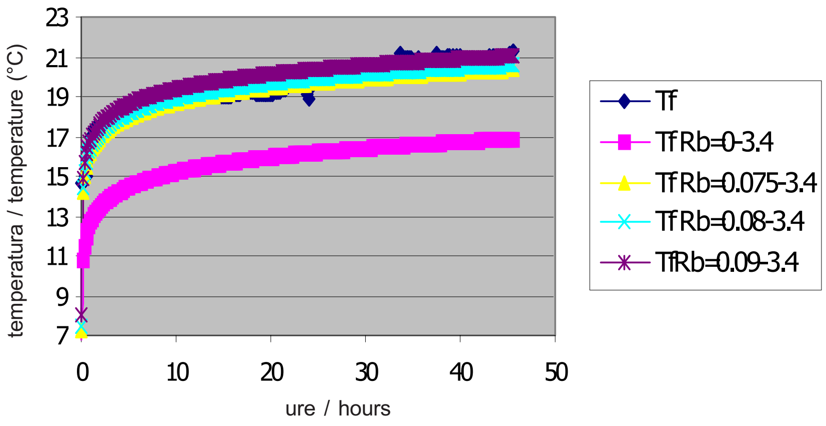
Measurements of the inlet (T_{in}) and outlet (T_{out}) temperatures were made at regular intervals of 10 minutes. The pressure of fluid circulation was also monitored. Data were recorded on a data logger.

A total of 273 separate measurements of temperature were recorded at 10 minute intervals over a period of two days, December 2-4th, 2000. Figure 5 shows the measured temperatures of T_{in}, T_{out}, T_{air} and T_{ref}.

The slope of the mean temperature data versus the natural log of time in hours, given in Figure 6, is proportional to the thermal conductivity of the rock and filled material through which the heat is transfered. According to this model for Hadýmköy, thermal conductivity (λ) and thermal resistance (R_b) are calculated with an iterative approach, where λ is given an initial estimated value and R_b is calculated from Eq. 5. The iteration is continued until the calculated fluid temperature distribution fits the experimental distribution for 2 days in December 2-4,



Sl. 6. *Odvisnost srednje temperature tekočine od časa, strmina premice k je 1,1779 in se uporabi v enačbi (6)*
Fig. 6. *Mid to late stage time / temperature data. Slope (k) of linear relationship is 1.1779. This value is substituted into Eq. 6*



Sl. 7. *Srednja temperatura tekočine dobljena iz TTO zbiralnika toplote v cevi U, ki se je ujemala s preračuni po enačbi 5, kjer so bile vrednosti spremenljivk* λ*= 3,4 W/mK in* R_b*= 0,075 – 0,08 – 0,09 K/(W/m).*

Fig. 7. *Mean fluid temperature from the response test on the U-pipe collector fitted to Eq. 5 with* λ*=3.4 W/mK and* R_b *=0.075 – 0.08 – 0.09 K/(W/m)*

Preglednica 1. *Mesečni izmerki TTO, dobljeni v Adani*

Table 1. *Monthly TRT results from measurements carried out in Adana*

Mesec **Month**	**Toplotna prevodnost** **Thermal conductivity** **λ (W/mK)**	**Toplotna upornost** **Thermal resistance** **R $(W/mK)^{-1}$**	**Trajanje testa** **Duration of the test** **(h)**
junij June	-	-	-
julij July	2,5	0,09	50
avgust August	2,1	0,05	76
september September	2,2	0,06	72
oktober October	2,2	0,06	53

temperaturo v dneh meritev od 2. do 4. decembra 2000. Slika 7 prikazuje najboljši iterativni približek za prevodnost λ in upornost R_b.

V nadaljevanju so predstavljeni izmerjeni podatki, dobljeni na podlagi meritev v Istanbulu, ki so podani v preglednici 1 in predstavljajo toplotno prevodnost in pa toplotno upornost konglomerata in gline v časovnih korakih meritev.

4 STANJE V SLOVENIJI

Popis o stanju izkoriščanja geotermalne energije za neposredno uporabo v Sloveniji je bil izveden leta 1999 za Zbornik svetovnega geotermalnega kongresa leta 2000. Pri tem je bilo treba zbrati, kolikor se je pač dalo, tudi podatke o izrabi energije iz podtalnice in plitvega podpovršja za geotermalne (talne) toplotne črpalke. Tu gre za število enot geotermalnih toplotnih črpalk, ki delujejo v odprtem ali zaprtem sistemu (obtoku). Kot odprti sistem je mišljena vgradnja na vodni vir, recimo podtalnico, ki je zajeta z vrtino (vodnjakom) ali tudi jezersko vodo. Kot zaprti sistem so mišljene vgradnje naslednjih dveh tipov: vodoravni zbiralni sistem v tleh in navpični sistem z energetsko vrtino. Ker je tovrstne podatke zelo težko pridobiti, smo zvedeli le za

2000. Figure 7 shows the best iterative approaches for the thermal conductivity (λ) and the thermal resistivity (R_b)

The same evaluation based on the line-sources model for Istanbul was used here. The monthly TRT results (thermal conductivity and borehole resistance) in a conglomerate and clay formation are given in Table 1.

4 PRESENT STATUS IN SLOVENIA

A description of geothermal energy use in Slovenia was made in 1999 for the proceedings of the World Geothermal Congress in 2000. At this point, data for geothermal (ground-cource) heat pumps was also collected. These heat pumps operate in an open or closed system. As an open source it is an installation that operates with the aquifer or lake water. Closed installations are as follows: a horizontal system in the ground or a vertical system with an energy well. As those data are difficult to obtain we have collected approximate data from three manufacturers in Slovenia for the period to 1992. Data for the period približne številke izdelanih enot takih geotermalnih toplotnih črpalk pri treh izdelovalcih v Sloveniji, za obdobje do leta 1992. Pridobili pa smo še podatke o vgrajenih enotah v zadnjem obdobju do leta 2000 od instalaterja švedskih toplotnih črpalk in nekaterih posameznikov po državi. Ob koncu leta 1999 je bilo pri nas torej vsaj 63 enot geotermalnih toplotnih črpalk, delujočih v odprtem sistemu na vodni vir (iz vrtine), ter vsaj 7 enot geotermalnih toplotnih črpalk, delujočih v zaprtem vodoravnem zbiralnem sistemu (Kralj in Rajver, 2000) [20]. Tipična imenska moč ali zmogljivost črpalk je različna, pri tistih v odprtem sistemu se giblje med 8 in 25 kW, pri tistih v zaprtem sistemu pa med 3,4 in 11 kW. Dosežen koeficient izkoristka (COP) je za oba tipa med 2,4 in 3,85. Omenjenih 63 enot na vodni vir izrablja skoraj 20 TJ letno, 7 enot v zaprtem sistemu pa še 2 TJ letno (sl. 8).

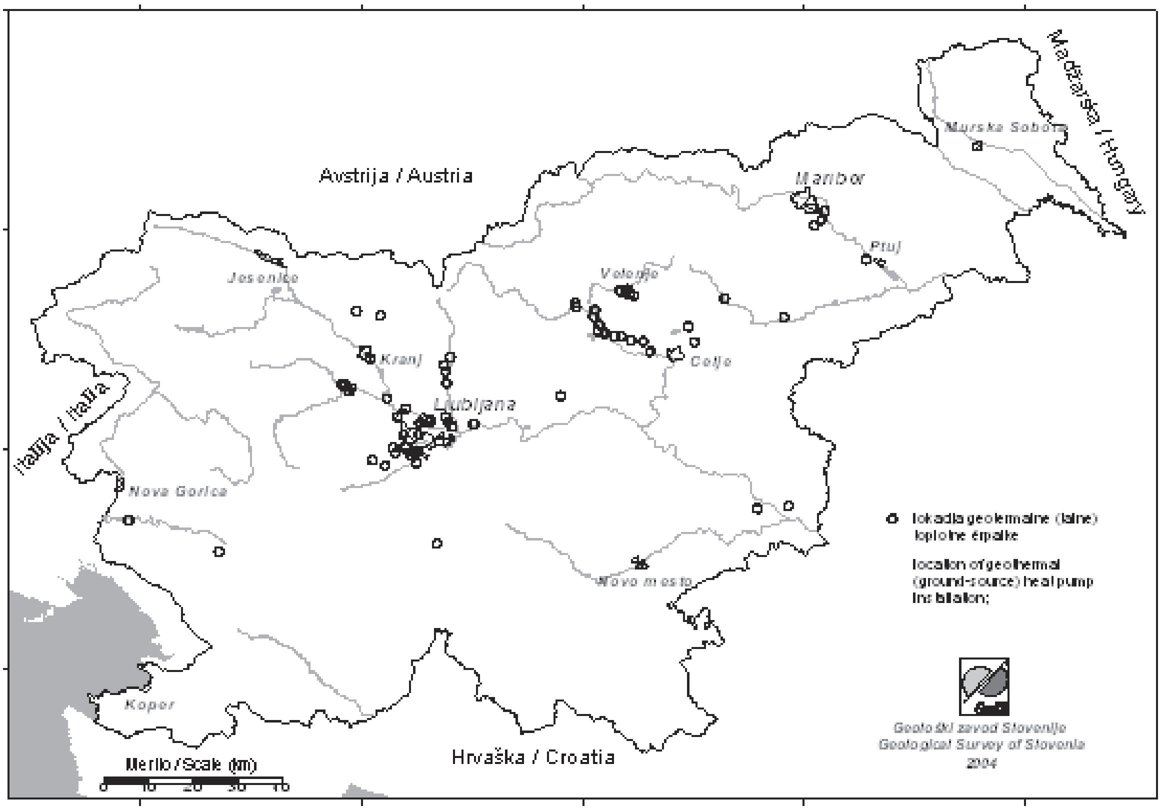
Tu seveda niso upoštevane geotermalne toplotne črpalke večjih zmogljivosti, ki se uporabljajo v sedmih naših termah in/ali rekreacijskih središčih v odprtem sistemu za dvig temperature termalne vode za nadaljnjo izrabo v bazenih in balneologiji ter za ogrevanje prostorov. Te toplotne črpalke izrabljajo 27 TJ geotermalne energije letno.

Po informacijah Škantelja (ustno sporočilo) se je v zadnjih letih število vgrajenih geotermalnih toplotnih črpalk za odprti sistem voda/voda in vodoravni zaprti kolektorski sistem precej povečalo, vendar za zdaj niti njihovo približno število ni znano. V letih 1990 do 2000 se je zanimanje zanje nekoliko zmanjšalo zaradi nizkih cen nafte

to 2000 have been obtained from the installer of Swedish heat pumps and from other installers in Slovenia. At the end of 1999 there were 63 units of geothermal heat pumps operating in open system (with water) and 7 units of geothermal heat pumps operating in closed horizontal systems (Kralj and Rajver, 2000) [20]. Typical nominal powers and the capacities of the pumps are different, the open systems have from 8 to 25 kW, and the closed systems from 3.4 to 11 kW. The coefficient of performance (COP) is for both types from 2.4 to 3.85 kW. The 63 pumps used 20 TJ of energy per year, and the other 7 units 2TJ per year (Figure 8).

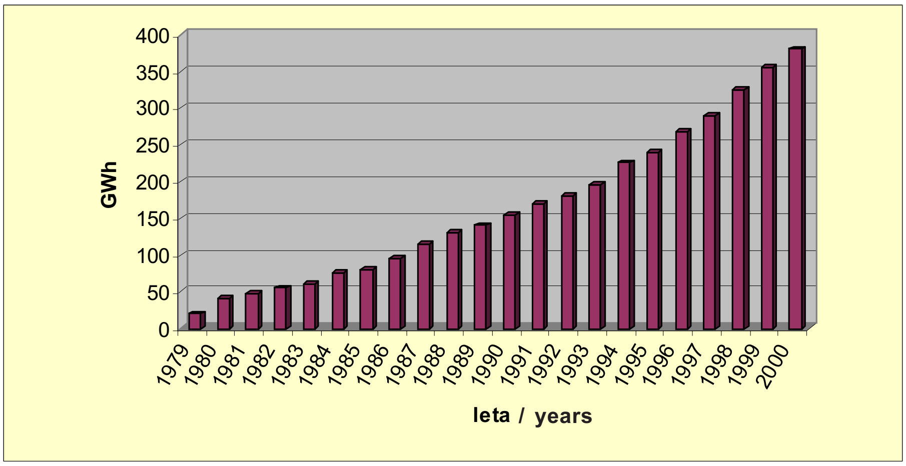
The geothermal pumps with larger capacities that are used in our seven spas and/or recreation centers for use in the swimming pools and for space heating are not included. These heat pumps use 27 TJ of geothermal energy per year.

Based on information from Škantelj (oral information) the number of installed heat pumps on open or closed systems has been increasing in recent years, but the actual number is not known. In the years 1990 to 2000 the level of interest has decreased because of the lower prices of oil and gas and the high price of



Sl. 8. *Porazdelitev enot geotermalnih toplotnih črpalk na energijo plitvega podpovršja v Sloveniji po popisu leta 1999. Geotermalne toplotne črpalke večjih zmogljivosti v termah in rekreacijskih centrih niso upoštevane.*

Fig. 8. *Units of geothermal heat pumps in Slovenia from the year 1999. Geothermal heat pumps of higher capacities in spas and recreation centers are not included.*



Sl. 9. *Vrednost pridobljene toplote v Švici*
Fig. 9. *Geothermal heat production in Switzerland*

in plina ter visokih začetnih stroškov in visoke cene električne energije. Vendar pa kaže, da so postali ti sistemi toplotnih črpalk spet nekoliko bolj zanimivi in privlačni.

5 SKLEP

Shranjevanje toplote z uporabo geosond se v svetu izjemno širi. Tako lahko na sliki 9 vidimo vrednost pridobljene toplote z geosondami v Švici [21].

V Sloveniji imamo vgrajenih zelo malo enot. Uporaba je odvisna od geotermalnih razmer zemlje do globine 100 m. Kot perspektivna območja so za postavitev geosond in drugih tipov zaprtih sistemov zanimive večinoma vse kotline z ugodno geološko sedimentacijo: Panonska nižina, Kranjsko polje, Ljubljanska kotlina v celoti, Celjska kotlina, Krško-Brežiško polje, Mariborsko-Ptujsko polje, Vipavska dolina, območje Slovenj Gradca in Raven na Koroškem. Tu je mišljeno, da površinski sedimenti nimajo prenizke toplotne prevodnosti, torej da so vsaj nekoliko peščeni ali prodnati in ne samo glinasti. Za večjo uporabo bi bile potrebne predvsem raziskave tal na področju, kjer želimo namestiti geosonde. Podatke lahko dobimo s testi za ugotavljanje toplotne odzivnosti zemlje, ki se v nekaterih državah v Evropi že nekaj let uporabljajo.

electrical energy. But it seems that these systems have become interesting again.

5 CONCLUSION

Geothermal heat storage is rapidly increasing in the world. Figure 9 shows the BHE systems in Switzerland [21].

Only small number of units are installed in Slovenia. The utilization depends on the geothermal conditions of the earth to a depth of 100m. The best areas for boreholes and other types of closed systems are basins with suitable geological sedimentation: Pannonian basin, Kranj plain, Ljubljana valley, Celje valley, Krško basin, Maribor-Ptuj plain, Vipava valley, the area around Slovenj Gradec and Ravne na Koroškem. We suppose that the thermal conductivity is not too low in these places, which means that they include sand and gravel and not only clay. For greater utilizations investigations should be made in the place where we would like to install the heat pumps. Data could be collected with tests for the thermal response of the earth, which in some European countries have been used for some years.

6 SIMBOLI
6 SYMBOLS

toplotna difuzivnost	a	m^2/s	thermal diffusivity
eksponentni integral	E_1	-	exponential integral
strmina premice	k	K/h	slope of the line
konstanta (začetna temp.)	m	K	constant (begin temp.)
gostota toplotnega toka	q	W/m^2	heat flux
toplotna upornost	R_b	mK/W	thermal resistivity
polmer	r	m	radius
čas	t	s	time
temperatura	T	k	temperature
integracijska spremenljivka	β	-	integral parameter
Eulerjeva konstanta	$\gamma=0,5772$		Euler constant
toplotna prevodnost tal	λ	W/mK	ground thermal conductivity

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