HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

EXPERIMENTAL EVALUATION OF THERMAL PROPERTIES OF GROUTING MATERIALS

M. Campanale*, M. Deganello, L. Moro
*Author for correspondence
Dipartimento di Fisica Tecnica,
Università degli Studi di Padova,
Padova, 35131,
Italy
E-mail: manuela.campanale@unipd.it

ABSTRACT

In recent years, the use of techniques of heating and space cooling with ground coupled heat pumps is spreading. This technology, also known as low energy geothermal cooling and heating, plans to use, as a heat source, the subsoil, due to its ability to maintain its temperature constant at values close to the average annual temperature of the locality.

The heat exchange with the ground is done by probes that generally consist of U-shaped tubes (single or double) made of plastic and placed in a vertical hole, drilled in the subsoil and filled with grouting materials. For an optimal exploitation of this technology, the use of high thermal conductivity grouting materials is fundamental to minimize thermal resistance and facilitate the heat exchange between the probe and ground.

This study is aimed at the thermal analysis of sealant mortar (usually a mixtures of bentonite and cement with addition of sand) used in geothermal cooling and heating. In particular, thermal conductivity and diffusivity measurements were performed on available materials using the so called Hot Disk Thermal Constants Analyser.

INTRODUCTION

In geothermal heat pumps design, the correct modeling of the heat exchange between the probe and the ground is fundamental in order to properly assess the amount of thermal energy that can be removed / transferred by the probes.

The probes are connected to create a closed circuit in which a fluid flows, usually mixtures of water and glycol, and allows the heat exchange with the evaporator (during winter), or the condenser (during summer), requested by the reverse cycle.

This technology can be considered renewable and efficient due to the amount of energy exchanged with the soil and the reduced temperature difference imposed on the heat pump.

With the increasing of the depth, the soil temperature becomes less variable and close to the average annual temperature of the locality.

Geothermal heat exchangers operate through these two ground's properties. During winter, the environment is heated by transferring energy from the ground to the building, otherwise, in summer, the equipment reverses its operation, extracting heat from the internal environment and transferring it to the ground. Consequently, for this type of system, subsoil appears to be an energy source more efficient than air, because of its temperature that is less variant and closer to that required for a building conditioning.

Emission reduction, related to the adoption of this system, involves a local zero release to the atmosphere and an external amount, related to the production of the electricity used by the heat pump to counteract the temperature rise between the underground storage tank and the building one.

The knowledge of the thermal conductivity of the materials used to seal geothermal probes drilled holes is basic to increase the thermal performances of the connected heat pumps. For an optimal exploitation of this technology, the use of high thermal conductivity grouting materials is fundamental to minimize the thermal resistance and to facilitate the heat exchange between the probe and the ground.

Grouting materials used to cover heat exchangers ensure an efficient thermal contact between the ground and the probe side, facilitating the energy exchange between them. Interstices in grouting materials, due to a possible faulty during the filling, reduce the thermal exchange considerably. Consequently the thermal resistance values of a geothermal probe depend not only on the construction materials but also on grouting materials [3].

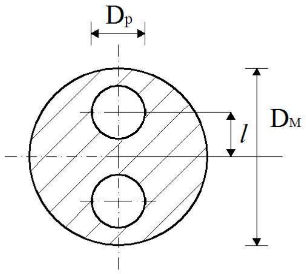

Figure 1 Geothermal single U-pipe probe.

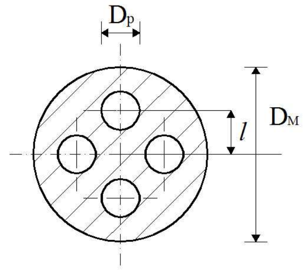

Figure 2 Geothermal double U-pipe probe.

Grouting materials can be classified into two broad categories: mortar-based and cement-based mixtures. The thermal conductivity of these compounds is a function of the ratio between water and cement, sand percentage, particles size, filling material concentration, porosity and inhomogeneity in grouting material.

NOMENCLATURE

a	[m^2/s]	thermal diffusivity
c_p	[J/(K kg)]	specific heat
D	[m]	diameter
d	[m]	hole radius
Fo	[-]	Fourier number
l	[m]	distance
m	[-]	number of concentric ring sources
P	[W]	thermal power
q	[W/m]	rate of heat transfer per unit length
R	[(m K)/W]	total thermal resistance per unit length
r	[m]	the radius of the (outermost) sensor ring source
t	[°C]	temperature

Special characters

γ	Eulero constant	[-]
λ	thermal conductivity	[W/(m K)]
ρ	density	[kg/m^3]
σ	dimensionless time	[-]
τ	real time	[s]
Θ	time	[s]

Subscripts

f	fluid
g	ground
M	mortar
m	average
p	pipe and fluid

THERMAL EXCHANGE BETWEEN THE PROBE AND THE GROUND

In geothermal heat pumps design, the correct modeling of heat exchange between the probe and ground is fundamental in order to properly assess the amount of thermal energy that can be removed/transferred by the probes.

Materials consisting of mixtures of bentonite and cement with addition of sand are commonly used.

The following relationship is used to evaluate the heat exchange process between the fluid inside the probe whose temperature is t_f and the undisturbed ground at temperature t_g:

$$q(t) = \frac{t_f - t_g}{R(t)} \qquad (1)$$

where $q(t)$ is the rate of heat transfer per unit length transferred or received from the ground at t and $R(t)$ is total thermal resistance per unit length.

If we consider a long period of time so as to assume the regime almost stationary, it can be expressed as:

$$R(t) = R_g + R_M + R_p \qquad (2)$$

where R_g is the ground resistance, R_M is the grouting material one, and R_p is the conductive/convective total resistance between the pipe and the fluid.

For the evaluation of the ground resistance, the result given in [1] was used and expressed for an infinite material with cylindrical boundary. For long enough periods, thermal resistance may be expressed as:

$$R_g(t) = \frac{1}{4\pi\lambda_g\left[\frac{1}{\ln(4Fo)-2\gamma} - \frac{\gamma}{\left(\ln(4Fo)-2\gamma\right)^2} - ....\right]} \qquad (3)$$

where γ = 0.57722 (Eulero costant), $Fo = (a\ t)/d^2$ (Fourier number), a is the ground thermal diffusivity, d is the hole radius.

The thermal resistance of the grouting material can be obtained by the following relationship [4] valid for single U-pipe heat exchanger:

$$R_M = \frac{\cosh^{-1}\left[\frac{D_M + D_p - 4l^2}{2D_M\ D_p}\right]}{2\pi\lambda_M} \qquad (4)$$

For double U-pipe heat exchanger, the relationship [4] is used:

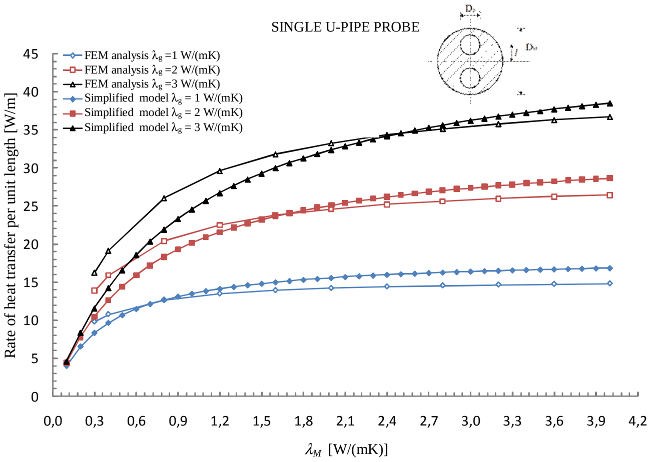

Figure 3 Rate of heat transfer per unit length as a function of thermal conductivity in a single U-pipe probe.

$$R_M = \frac{\ln\left(\frac{D_M}{2l}\right) - \frac{1}{4}\ln\left(\frac{4D_p}{2l}\right)}{2\pi\lambda_M} \quad (5)$$

where D_M, D_p and l are the geometrical dimensions represented in Figure 1 and 2 and λ_M is thermal conductivity of the grouting material. The resistance R_p is 0.05 (m K)/W.

Previous relationship have been used to evaluate rate of heat transfer per unit length q exchanged between single and double U-pipe probes and the ground.

The graphs of Figure 3 and 4 show q as a function of the thermal conductivity of the grouting material λ_M with a temperature difference t_f - t_g = 10°C after 90 days and with different ground thermal conductivities λ_g. The results are related to:

D_M = 0.15 m, D_p = 0.032 m, l = 0.0375 m

The heat flow was evaluated by the heat transfer study in 2D in the plane normal to the hole using the finite element method to obtain the conduction equation solution. The simulation was carried out by discretizing the horizontal section by a two-dimensional mesh using 8-node isoparametric finite elements. A variable time step from 1800 s to 86400 s was given according to the process development stage. In the Figures 3 and 4 is also plotted the rate of heat transfer per unit length as obtained by using the simplified model given by equations (2), (3), (4) and (5).

To set the boundary conditions used in calculations, we assumed the cylindrical surface (placed at 20 m from the axis of the excavation) as isothermal at 15°C and the probe pipe external surface at 5°C.

The results, obtained by the two different proceedings, show how the thermal exchange of the ground is a function of the thermal conductivity of the grouting material.

Particularly, if the thermal conductivity of the grouting material is less than half the one of the ground, the rate of heat transfer per unit length is reduced by 20% compared to the asymptotic value.

The thermal conductivity measurements were carried out on different sealant mixtures by using Hot Disk equipment in order to identify the interesting thermal properties of grouting materials.

DESCRIPTION OF THE EQUIPMENT AND EXPERIMENTAL PROCEDURE

The so called Hot Disk equipment works with a transient procedure and generates a constant thermal power in a disc-shaped sensor of a suitable chosen beam R, composed of a number m of concentric coils that are placed in contact with two specimens of the same material (Figure 5). This equipment is able to determine the thermal conductivity, the thermal diffusivity and the volume specific heat of the sample.

The Hot Disk Sensor consists of a probe composed of a double spiral heating element etched into a thin nickel sheet, coated with two layers of insulating material, kapton or mica, the latter particularly suitable to operate with sufficient sensitivity and accuracy up to 200°C.

During the test, the sensor generates a heat flow and at the same time measures the temperature increase of the specimen active surfaces. This method requires the measurements in times of test suitable to make negligible the influence of the boundary conditions applied to a sample of finite size.

Thermal analysis, on the contrary, is done by considering the sample as an infinitely extended one. This means that the test should end as soon as the sample outline influences the measurements.

Applying the general equation solution of the conduction and working iteratively with the Hot Disk measured temperatures, we can determine, independently, the thermal conductivity and diffusivity of the material under study. The increments of temperatures detected during the heating of the active surfaces of the sample are compared with a dimensionless time function, σ, obtaining the linear response shown in Figure 6, from which it is possible to evaluate the thermal conductivity and diffusivity [1].

The material linear response is the following one:

$$\Delta t = \frac{P}{\pi^{3/2}\lambda r m^2 (m+1)^2} \cdot F(\sigma) \qquad (6)$$

where:

Δt the average temperature rise of the sample active surfaces at generic instant;
P the thermal power generated by the sensor;
λ the thermal conductivity;
r the radius of the (outermost) sensor ring source;
m number of concentric ring sources.

The function $F(\sigma)$ is defined as:

$$F(\sigma) = \int_0^{\sigma} u^{-2} du \sum_{l=1}^{m} l \sum_{k=1}^{m} k e^{-\left(\frac{l^2+k^2}{4u^2m^2}\right)} \cdot I_0\left(\frac{lk}{2u^2m^2}\right) \qquad (7)$$

where:

I_0 Bessel amended function of order 0;
σ dimensionless time, defined as $\sigma^2 = \tau/\Theta$;
τ real time;
Θ time $\Theta = r^2/a$;
a the thermal diffusivity $a = \lambda/(\rho c)$.

Equation (6) is linear:

$$\Delta t = \frac{C}{\lambda} \cdot F(\sigma) \qquad (8)$$

where C is a constant depending on the instrument properties and on the thermal power generated by the sensor.

The regression experimental data against the increase of temperature as a function of time, allows to evaluate the thermal conductivity and diffusivity best values as soon as the chosen parameters verifies the linear equation (8).

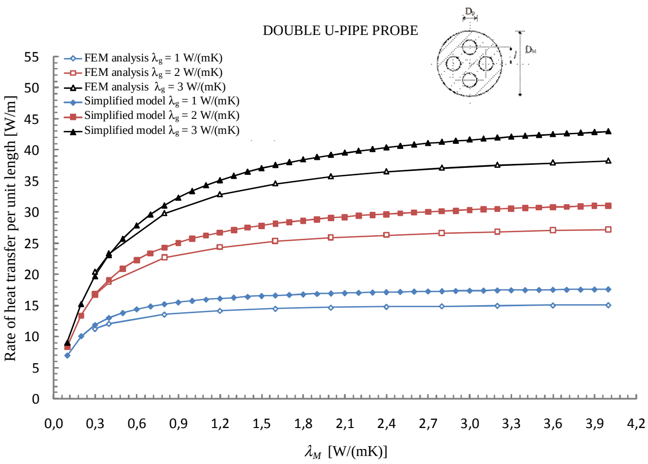

Figure 4 Rate of heat transfer per unit length as a function of thermal conductivity in a double U-pipe probe.

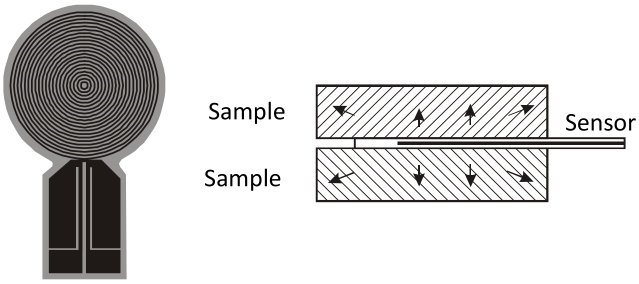

Figure 5 Hot Disk sensor and its placement between the two samples.

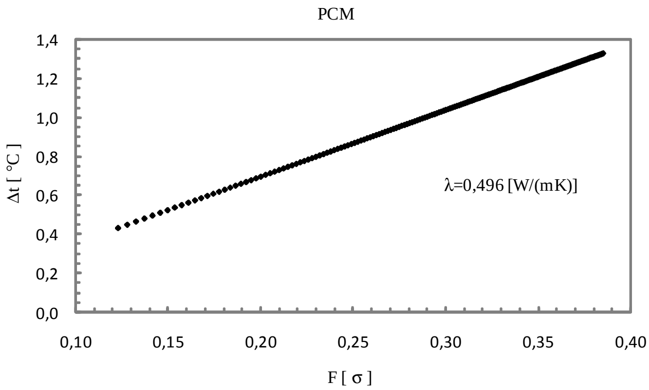

Figure 6 Thermal response in thermal conductivity measured with the Hot Disk method for PCM at 313 K.

EXPERIMENTAL RESULTS AND DISCUSSION

The grouting materials that we considered are of porous nature and, if used in the presence of groundwater, have different levels of imbibition. These materials are PCM (*Portland Cement Mortar*, that is a mixture of Portland cement, used as standard) and GM, *Grouting Material*, that is an experimental mixture of concrete, bentonite and quartz sand to which an amount of graphite equal to 1% by weight was added in order to increase the solid matrix thermal conductivity. We assumed that it was important to know the thermal behavior of these materials at different water content.

A first set of measurements was performed on samples not yet soaked, at room temperature; then the samples were taken in saturation conditions by contact capillary imbibition with a cotton wool layer moistened in water (Figures 7 and 8).

The determination of the thermal conductivity in these test conditions appears to be critical compared to measurements on not soaked sample. The evaporation of water contained in the samples, in fact, initially involves the exterior surfaces of the samples, then affects the internal area. This leads to a diversity of moist conditions of the tested specimen, leading the have dispersed values of the thermal conductivity.

Figure 7 PCM sample during imbibition.

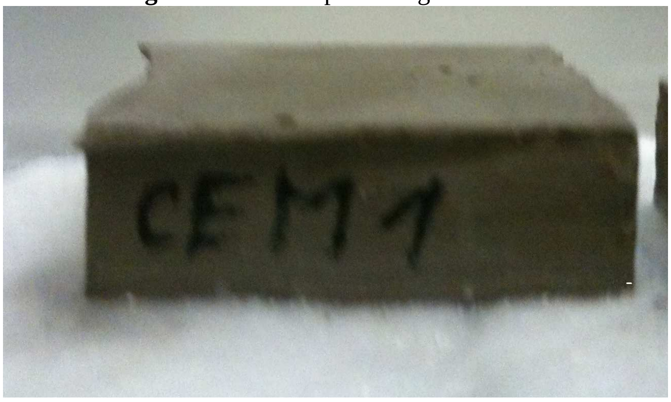

Figure 8 Soaked PCM sample.

The thermal conductivity tests have revealed how the thermal behaviour of the analyzed samples is essentially determined by the water content of the material. In not soaked conditions, grouting material with higher thermal conductivity is made with Portland concrete, λ_M = 0.51 W/(m·K) differently from λ_M = 0.38 W/(m·K) of the bentonite-based mixture. The first value is due to the higher density of the PCM sample (1647 kg/m^3) compared to the GM sample (1289 kg/m^3).

In saturation conditions, bentonite-based mixture thermal conductivity is higher than the one of cement-based mixture. This behavior is motivated by the lower water quantity inside the PCM. The sample of GM, in fact, being more porous than the sample of Portland cement, has a greater number of interstices and, in water saturation conditions, these empty spaces are completely filled with liquid. Being water conductivity about 20 times higher than the one of air, the GM thermal conductivity is higher when compared with the one of PCM (1.210 W/(m·K) compared to 0.949 W/(m·K)). Comparison results are shown in Figure 9.

CONCLUSION

The grouting material thermal conductivity can significantly affect the efficiency of heat exchange between the probe and the ground.

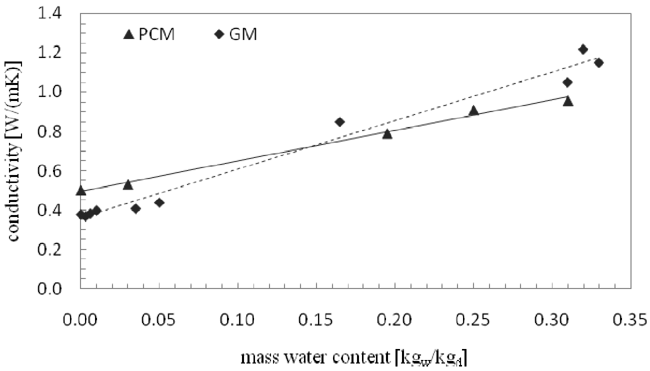

Figure 9 Parallel of PCM and GM thermal conductivity at different water content.

By numerical simulations we have seen that the grouting material restricts the heat exchange when its thermal conductivity is lower than the one of the ground; the increase of the heat flux is also small when the conductivity value exceeds one and a half times the value of the thermal conductivity of the ground, making ineffective any further increase of the grouting material thermal conductivity.

The materials analyzed are porous and having to work underground in presence of groundwater, will have high values of water content. However, the water content is a variable key in time and depends on the presence of groundwater, on evaporation, on the ground's nature and on the temperature difference in the ground itself.

The materials studied showed a thermal conductivity increase from two to three times the value of the no soaked material. This behavior is due to the replacement of the air in the pores with water.

The values of the thermal conductivity of the studied materials and the marked dependence on the imbibition conditions, suggest a greater focus on the influence of the cement mortar properties such as porosity, waterproofing and composition on the thermal conductivity and diffusivity, in order to prepare suitable mixtures to optimize the efficiency of the geothermal.

REFERENCES

[1] H.S. Carslaw e J.C. Jaeger, "Conduction of heat in solids", Oxford University Press, 1959.

[2] M. M. Yovanovich, "A General Expression for Predicting Conduction Shape Factors", Thermophysics and Spacecraft Thermal Control, AIAA Progress in Astronautics and Aeronautics, Vol 35, pp 265-291, MIT Press, Cambridge, MA, 1974.

[3] F. Tinti, "Geotermia per la climatizzazione", Dario Flaccovio Editore, 2009.

[4] E. Hahne, U. Grigull, "Formfaktor und formwiderstand der stationären mehrdimensiolanen wärmeleitung", Journal of Heat and Mass Transfer, Vol 18, pp 751-767, Pergamon Press, GB, 1975.