Applied Energy 147 (2015) 30–39

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Field demonstration of a first thermal response test with a low power source

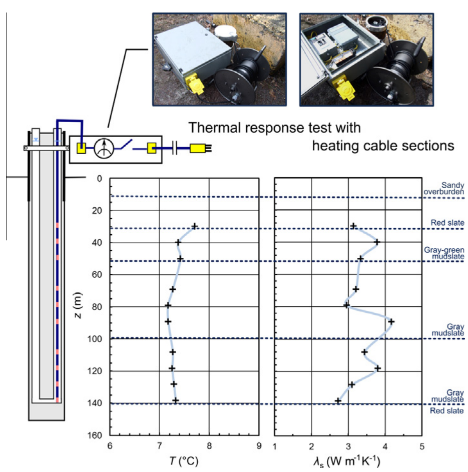
Jasmin Raymond [a,*], Louis Lamarche [b], Michel Malo [a]

[a] Institut national de la recherche scientifique, Centre Eau Terre Environnement, 490 rue de la Couronne, Québec (Qc) G1K 9A9, Canada
[b] Département de génie mécanique, École de Technologie Supérieure, 1100 rue Notre-Dame Ouest, Montréal (Qc) H3C 1K3, Canada

HIGHLIGHTS

- A field test has been conducted to assess the subsurface thermal conductivity.
- Heat was injected with heating cable sections installed in a ground heat exchanger.
- The power source needed to conduct the test was 845 W.
- Analysis of recovery temperatures was performed with a finite heat source solution.
- The thermal conductivity was evaluated at 10 locations in the ground heat exchanger.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 August 2014
Received in revised form 30 January 2015
Accepted 31 January 2015
Available online 12 March 2015

Keywords:
Geothermal
Heat pump
Heat exchanger
Thermal response test
Heating cable
Thermal conductivity

ABSTRACT

Thermal response tests conducted to assess the subsurface thermal conductivity for the design of ground-coupled heat pump systems require a power source of about 7–12 kW to heat water circulating in a ground heat exchanger. This high power is commonly supplied with a fuel-fired generator, which is an important source of cost. An alternative method relying on a power source of less than 1 kW was consequently developed and used for a first field demonstration. Heat was injected along ten short sections of heating cable standing in the water column filling the pipe of the exchanger. Recovery temperatures measured at the middle height of each heating section were analyzed with a linear heat source solution of finite length. The ten local measurements distributed over a depth of 139 m and averaged according to the site stratigraphy revealed a subsurface thermal conductivity that is within an acceptable range of the bulk value determined with a conventional test. The new method has the potential to reduce the use of generators for thermal response tests since a low power source is common to construction sites.

1. Introduction

Knowledge of the subsurface temperature and thermal conductivity helps to design ground-coupled heat pump systems, particularly in the institutional, commercial and industrial sectors of the

* Corresponding author. Tel.: +1 418 654 2559; fax: +1 418 654 2600.
E-mail address: jasmin.raymond@inrs.ca (J. Raymond).

http://dx.doi.org/10.1016/j.apenergy.2015.01.117
0306-2619/

Nomenclature

(M L T t I) *are used to denote units of mass, length, temperature, time and electric current, respectively*

d	relative thickness (–)
f	function
Fo	Fourier number (–)
g	finite heat source function (–)
H	length of heat source (L)
I	electric current intensity (I)
M	parameter
n	number of heat sources (–)
q	heat injection rate per unit length (M L t^{-3})
R	electric resistance (M L^2 t^{-3} I^{-2})
R'	thermal resistance (M^{-1} L^{-1} t^3 T^1)
r	radius (L)
V	electric potential difference (M L^2 t^{-3} I^{-1})

Greek symbols

α	thermal diffusivity (L t^{-2})
λ	thermal conductivity (M L T^{-1} t^{-3})
ω	uncertainty

Subscripts

b	borehole
h	heating
nh	non-heating
tot	total
s	subsurface
0	initial condition

building industry where the system capacity is large. This is because the length of ground heat exchangers (GHEs) required for the building heating and cooling needs is affected by the thermal sate and properties of the subsurface. Field tests are consequently carried out at the prefeasibility stage to determine parameters that impacts the economic viability of such systems.

A method to infer the subsurface thermal conductivity by reproducing heat transfer from a vertical GHE was originally proposed by Mogensen [1], which pioneered the development of mobile apparatus to conduct thermal response tests (TRTs) [2,3]. Aiming to recreate the operation of a ground-coupled heat pump system at the scale of a GHE, apparatus to conduct TRTs are generally cumbersome. A source of high power is needed to heat water with an electric resistance at surface and disturb the subsurface thermal equilibrium by circulating the heated water in a GHE under the action of a pump. A heat injection rate of 50–80 W m^{-1} is recommended in North-America industry's guidelines to create a temperature difference of 3–7 °C between the inlet and outlet of the GHE [4]. The intensity of the electric current supplied to conduct the test in a GHE that is 150 m long is at least 31–50 A, when the potential difference is 240 V. A bulk estimate of the subsurface thermal conductivity is obtained by the analysis of flow rate and temperature measurements recorded at the inlet and outlet of the GHE [5].

Despite the heavy equipment and the high power, this field test method named the conventional TRT in this manuscript has been growing in popularity. Increasing utilization of the method triggered research to improve the analysis of data commonly performed with the infinite line-source equation [6], involving simplifications of the heat transfer problem to be solved. Efforts were conducted to develop analysis methods that can take into account variable heat injection rates [5,7–11]. Among possible alternatives to resolve this problem common to all heat injection tests subject to fluctuations, the superposition principle was the solution considered for the research presented in this manuscript. Experience gained with numerical modeling of conventional TRT showed that temperature inside the pipe of a GHE departs form the assumed symmetric temperature distribution [12] and several researchers proposed solutions to the non-symmetric temperature profile along the GHE pipe [13–17]. While the temperature distribution inside the GHE is an important aspect for conventional TRT where water is flowing in the pipe, this is not a concern for TRT with heating cables where water is standing in the pipe column [18]. Further work about TRT focused on the effect of the subsurface heterogeneities, groundwater flow and temperature gradient from an analytical [19–21] and numerical [10,22–27] analysis perspectives. Parameter sensitivity [5,28–30] and optimization methods [31–33] related to conventional TRT have additionally been investigated, especially with the recent enhancement of computational methods.

While most research belonging to TRT concerned analysis methods, less work have been performed to improve the field methodology that is the scope of the manuscript. Innovative field methods were proposed to measure temperature at depth in a GHE during conventional TRT with a fiber optic cable [34–36] or a flowing sensor [37] to assess thermal properties at different elevations. Other authors reported the replacement of the heating element by a heat pump to perform the test in heat extraction mode [38]. An alternative method to determine a thermal conductivity profile of the subsurface with the measurement of the geothermal gradient using a temperature sensor that sinks in the GHE was additionally proposed [39]. This last method is based on thermostratigraphy [10] and its application is limited to deep boreholes and areas with dense measurements of the Earth's heat flow.

A new TRT field method using a low power source, which provides an estimate of the subsurface thermal conductivity at different depths and that can be carried out anywhere since it does not relies on a knowledge of the Earth's heat flow was consequently envisioned. Rather than reproducing the operation of a ground-coupled heat pump system, the new method was inspired by thermal conductivity surveys carried in the geophysical and hydrogeological sectors. The idea was to combine probes [40] and heating cables [41] used in exploration boreholes and to adapt those technologies for the tests to be carried out in a GHE. Probes can provide a measurement of the subsurface thermal conductivity with a low power source but tests have to be repeated at different depths. Continuous heating cables are better suited to measure thermal conductivity at different depths during a single test and can easily be adapted to short GHE [18,42]. However, high power is required for the tests to be conducted with continuous heating cables in conventional GHEs that are commonly 150 m long.

Interchanging sections of heating and non-heating cables are installed in the standing water column of the GHE to conduct the tests with the new method. The field apparatus, depleted of mechanical components, only encloses an electric junction box and a cable assembly. During a test, temperature is measured at distinct depths along heating cable sections. Analysis of the thermal recovery following heat injection allows an assessment of the subsurface thermal conductivity. Numerical simulations were conducted at a preliminary research phase to validate the analysis