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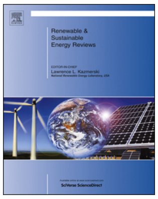

Thermal response testing for ground source heat pump systems—An historical review

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ABSTRACT

When designing ground heat exchangers used with ground source heat pump systems, a critical design property is the thermal conductivity of the ground. Thermal response tests are used to measure the site-specific thermal conductivity and are also used to measure the thermal resistance of a borehole heat exchanger as installed. Thermal response tests are commonly used today for design of multiple borehole ground heat exchangers, where knowledge of the ground thermal properties can help avoid undersizing of ground heat exchangers, leading to poor system performance, and oversizing of ground heat exchangers, leading to overly costly systems. This review covers the development of the mathematical and numerical analysis procedures, development of the hardware and test procedures, and validation of the results. We take a historical perspective, going as far back as Lord Kelvin's treatment of transient heat conduction problems in the 1880s, further development of which allowed analysis of conductivity measurements from transient needle probes by the 1950s. We focus on development of test rigs and test procedures in the 1980s and 1990s and validation of the measurements. More recent developments are covered throughout the review.

Contents

1. Introduction

The ground source heat pump system is a commonly utilized green technology (worldwide) for heating and cooling of buildings.

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Although the concept of a heat pump for heating and cooling of buildings was first suggested by Thomson [1] and use of the ground as the heat pump heat source was first patented by Zoelly [2], installations of ground source heat pumps did not begin until the 1940s. An actual installation can be seen in an article appearing in Life magazine [3] in October 1948. For reasons discussed by Spitler [4], including undersized ground heat exchangers, use of this technology waned in the 1950s, but interest increased rapidly in the 1970s and 1980s due to the energy crisis. New developments during the 1980s include development of design software which helped overcome undersizing problems.

Further development of design software sparked an interest in helping system designers to obtain the needed inputs, especially the thermal conductivity of the ground. A 1983 paper by Mogensen [5] suggested a method by which thermal conductivity of the ground and borehole resistance could be obtained in situ for a specific borehole using what we now call a thermal response test (TRT). This test is similar in principle to transient needle probes [6–14] used to measure thermal conductivity of solids. Transient needle probes typically contain an electric heating element and temperature sensors inside a metallic sheath on the order of 5–6 mm in diameter and 100–500 mm long. However, Beck et al. [15] described a probe used for making in situ measurements of rock conductivity that was 32 mm in diameter and 914 mm long—that is, much larger than a needle probe, but much smaller than the borehole-with-U-tube “probes” that are the subject of this paper. Mogensen's 1983 paper, proposing the use of the entire borehole as the probe, and using a U-tube with fluid circulating through it as the “line source” was the starting point for work in the mid-1990s in both the USA and Sweden to develop mobile thermal response test devices.

Mobile thermal response tests are primarily used to determine two quantities—the effective thermal conductivity, and, often as a secondary goal, the effective borehole thermal resistance. We emphasize the term “effective”. The ground is seldom, if ever, homogeneous and the thermal conductivity is likely to vary with depth and perhaps with direction. Furthermore, the actual heat transfer process in the ground may not be pure conduction—it can also be affected by regional groundwater flow [16] or buoyancy-driven advection [17–23]. Therefore, the thermal conductivity measured with a TRT may unavoidably include some combination of the effects of inhomogeneity and groundwater flow, and it seems better to refer to it as the effective thermal conductivity, denoted by k^*.

Likewise, the borehole thermal resistance determined with a thermal response test is an effective resistance between the mean fluid temperature and the borehole wall for the entire borehole. It will include the effects of the local borehole resistance that might be determined with a 2-dimensional analysis and the effects of short-circuiting between the legs of the U-tube. The short-circuiting effect can vary significantly with flow rate and the leg-to-leg thermal resistance. We have adopted the nomenclature used by Hellström [24] (cf. pp. 96–99) and refer to this as R_b^*.

Zhang et al. [25] and Beier [26] have recently reviewed the state-of-the-art of thermal response testing. It is our intention to complement these reviews by giving an historical review of the early development of mobile thermal response test devices along with development of analysis procedures and validation of the results. Our main focus is on work done during the 1980s and 1990s with some of the publications appearing in the first few years of the 21st century. However, our review of analysis procedures begins with Kelvin's work a hundred years earlier. Later developments are covered briefly in the main body of the review and additional developments are covered in Section 6.

2. Development of the first TRT rigs

Mobile thermal response test devices or TRT rigs were a natural development of earlier research, including transient thermal probes or needle probes mentioned earlier. Mogensen [5] suggested development of such a device for estimating borehole thermal resistance. Several thermal response tests of existing ground heat exchangers were performed and, eventually, the need for test devices that could be moved from site-to-site became clear in both Sweden and the USA. This section recounts the development of the first TRT devices.

2.1. Mogensen

Mogensen[2] [5] proposed an experimental method to determine the thermal resistance between the heat carrier fluid and the borehole wall in a full-scale vertical ground loop. His proposed apparatus, which was to provide a constant cooling rate, is shown schematically with a water chiller, circulating pump and temperature recorder. Although the aim of the method as described in the paper is to determine the borehole thermal resistance, Mogensen also mentions that the ground thermal conductivity can be estimated from the results. Mogensen's 1983 paper was the starting point for the authors of this paper when they began development of their mobile TRT rigs in the mid 1990s, even though they both concluded that it would be simpler to use a fixed heating rate to the borehole rather than a fixed heat extraction rate.

Mogensen's paper was entirely theoretical with no clear indication that a device had been fabricated or was even under development. However, in preparing this paper, we found that the work had been carried a little further. An unpublished 13-page student report [27] describes the design and fabrication of a 2.7 kW cooling machine (Fig. 1) intended to be used to support thermal response testing of horizontal ground loops. The report focuses on the scheme adopted for control of the refrigeration device—a constant speed compressor was used and the cooling rate was intended to be held constant by using a thermostatic expansion valve and another valve was used to control the water flow rate on the condenser side. This approach relies on the refrigerant mass flow rate remaining constant while the water-side temperature on the evaporator is falling. From the student report, it is difficult to know if this approach could provide sufficiently uniform heat extraction rates for TRT and the student did not report any test results for the cooling machine. According to Mogensen [28], it was built in 1982 and used in conjunction with a circulating pump, PT-100 temperature probes and a rented analog printing device to perform a test of a residential vertical borehole. But as this work was never published, it had no impact on later developments, which started with Mogensen's 1983 paper.

2.2. Full scale non-mobile thermal response tests

Several full-scale (non-mobile) response tests were performed and analyzed on existing and experimental vertical borehole plants from the mid 1980s to mid 1990s. These tests were done for several reasons including confirmation that an installation was done properly and as a check on the original design. In 1984 Mogensen performed a response test on a ground source heat pump system for a small house in Järfälla, Stockholm, by applying a constant heat extraction rate to the borehole and measuring the

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[2] Palne Mogensen is a Swedish consulting engineer, now retired. In the 1980s he worked as a consulting engineer for the Swedish heat pump manufacturer Thermia in Arvika, where he was engaged in the budding market for ground source heat pumps, primarily with horizontal ground loops, and later also for vertical ground heat exchangers.