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Comparison of Performance and Effectiveness of Vertical Borehole Heat Exchanger Collectors

Saqib Javed

Gothenburg
December 2018

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COMPARISON OF PERFORMANCE AND EFFECTIVENESS OF VERTICAL BOREHOLE HEAT EXCHANGER COLLECTORS

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Comparison of Performance and Effectiveness of Vertical Borehole Heat Exchanger Collectors

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Executive summary

The number of heating and cooling system using vertical borehole heat exchangers is increasingly rapidly in Sweden. Currently, there are over 600,000 installations, mostly using U-tube ground collectors. In recent years, several new ground collectors with innovative designs and configurations have been launched. They claim to have superior performance and competitive advantages over the conventional collectors.

This project was aimed at assessing the performance and effectiveness of various types of ground collectors through full-scale experimental testing. The tested types of ground collectors included single U-tube, double U-tube configured in parallel, double U-tube configured in series, coaxial and U-tube with internally rifled pipes. The ground collectors were tested one after another in the same borehole heat exchanger over a period of two and a half years. The testing was performed in both heat-injection and heat-extraction modes with flows ranging from near-laminar to fully turbulent. A custom-built thermal response test rig was developed to perform tests of this type. To ensure similar geothermal conditions for all tests, the ground was rested long enough to allow full thermal recovery before each test.

Among all tested ground collectors, the coaxial collector had the most consistent thermal and hydraulic performance over the tested range of thermal and pumping power conditions. However, the first cost and the time and labour expense for installing the coaxial collector were substantially higher than any other type of ground collectors. A project-specific cost-benefit analysis was deemed necessary to determine if the thermal and pump energy saving from the coaxial and other new collectors are large enough to overweigh their higher first costs and installation difficulties.

Among other collectors, the U-tube collector with internally rifled pipes had inferior thermal and hydraulic performance than the ordinary U-tube collector. Double U-tube collector, configured in series, had by far the worst hydraulic performance among all tested ground collectors.

The results from this project have been presented in six technical reports, three book chapters, and eleven journal and conference proceeding papers. Some more publications are in the pipeline and will be published in 2019.

Keywords: borehole heat exchanger, ground collector, coaxial, U-tube, thermal resistance, pressure drops, comparative performance, heat transfer, loop design, ground source heat pump

Jämförelse av Prestanda och Effektivitet av Markkollektorer för Vertikala Borrhålsapplikationer

Saqib Javed
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Sammanfattning

Antalet värme- och kylsystem med vertikala värmeväxlare i borrhål ökar snabbt i Sverige. För närvarande finns det total 600 000 system, de flesta med värmeväxlare (markkollektorer) i form av U-rör. Under de senaste åren har det marknadsförts flera nya typer av markkollektorer med innovativa konfigurationer som hävdas ha bättre prestanda och andra fördelar jämfört med traditionella kollektorer.

Projektets syfte var att testa och utvärdera prestanda för olika kollektorer för borrhål i full skala. Testade konfigurationer omfattade släta och räfflade enkla U-rör, parallell- och seriekopplade dubbla U-rör och koaxialrör. Testerna genomfördes med hjälp av en speciellt utvecklad rigg för termiska responstester. Kollektorerna testades en och en i samma borrhål under en period av två och ett halvt år. Testerna utfördes både för kylning och uppvärmning (av omgivande berg) med vätskeflöden från nära laminärt till fullt utvecklad turbulent strömning. För att säkerställa likvärdiga tester fick borrhålen vila tillräckligt länge för att återhämta sig mellan testerna.

Testerna visade att koaxialrör hade bäst prestanda för alla tester sammantagna. Kostnaden för produkten och installationen av densamma var dock väsentligt högre än för alla andra testade konfigurationer. Därför krävs det en projektspecifik lönsamhetskalkyl för att utvärdera om de värmetekniska fördelarna uppväger de ekonomiska nackdelarna.

Bland övriga testade konfigurationer visade räfflad U-rör sammantaget sämre prestanda än släta U-rör. Vidare visade seriekopplade dubbla U-rör sämst prestanda med avseende på pumpenergi av alla testade konfigurationer.

Projektresultaten har presenterats i sex tekniska rapporter, tre kapitel i böcker, och elva artiklar i tekniska tidskrifter och vid konferenser. Ytterligare publikationer finns i utkast och kommer att publiceras under 2019.

Sökord: markvärmeväxlare, markkollektor, markvärmepump, koaxialrör, U-rör, värmeöverföring, termiskt motstånd, tryckfall, jämförande test, bergvärmepump

Foreword

This is the final report of the project titled "Comparative Experimental Investigation of Performance and Efficiency of Ground Collectors for vertical Borehole Applications" carried out between September 2015 and December 2018 at the Division of Building Services Engineering, Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden.

This work was funded by the Swedish Energy Agency through their national research program Effsys EXPAND. It was also supported in-kind by several industrial and research partners including Andersson & Hultmark, Asplan Viak, Bengt Dahlgren, Carrier, Danfoss, ESBE, Energy Booster, E·On, Geotec, HP Brunnsborrningar, Kronetorp Park, Lindab, Lund University, NCC, Nibe, Oklahoma State University, Qtf, Rise, Skanska, Swegon, Uponor, and Wilo.

The generous support and engaged involvement of all participating companies and research partners throughout this project has been welcomed and gratefully appreciated.

Gothenburg,
December 2018,
Saqib Javed.

Contents

1 Introduction

In recent decades, the use of ground source heating and cooling systems has increased dramatically worldwide [1]. The globally installed capacities of these systems have exceeded 65,000 MWth. The total installed capacities in Europe are over 20,000 MWth. In Sweden, the thermal energy use and the installed capacities of the ground source heating and cooling systems are both among the highest in the world. Currently, there are over 600,000 installations [2] of ground source heating and cooling systems in the country with total installed capacities exceeding 5,600 MWth [1]. Annually, approximately 15-20 thousand new systems are added to the existing stock of ground source heating and cooling systems.

The most common application of ground source heating and cooling systems is with vertical borehole heat exchangers. The attraction of vertical borehole heat exchangers is that, below a few meters depth, the ground temperature is not affected by daily or seasonal weather changes. This enables ground to be used as a heat source for heating and/or a heat sink for cooling. Alternatively, the ground can also be used for seasonal storage of heat by loading it at a time of energy surplus and extracting from it at a time of energy deficit. In Sweden, over 75 % of the installed ground source heating and cooling systems use vertical boreholes as ground heat exchangers [2]. A vertical borehole with a single U-tube collector is by far the most commonly used type of ground heat exchanger in practice. This is due to the low cost, ease of installation and small space requirements of the single U-tube collectors. Other types of commercially available borehole collectors include double U-tube and coaxial collectors. Moreover, in recent years, many new collectors with innovative designs have been launched in the market. These include, among others, U-tube collectors made of internally rifled pipes, coaxial collectors with insulated inner pipes, and coaxial collectors with flexible outer pipes. Most new collectors claim to have significant performance and energy efficiency advantages over the conventional U-tube collectors.

The primary function of any ground collector is to efficiently transfer heat between the ground and an above-ground heating and/or cooling load. The heat transfer is typically achieved through a heat carrier fluid. From an efficiency point of view, it is desirable to have the heat carrier fluid exiting the borehole heat exchanger at as high temperature as possible in winter and vice versa. Each one-degree increase in the temperature of the heat carrier fluid exiting the ground collector translates to an approximate 3% increase in the heat pump performance [3]. The temperature of the heat carrier fluid exiting a borehole heat exchanger depends upon three thermal properties: ground thermal conductivity, borehole thermal resistance, and undisturbed ground temperature. Of these properties, ground thermal conductivity and undisturbed temperature are the fixed intrinsic properties of the underground structure and can thus not be engineered. Borehole thermal resistance, on the other hand, can be manipulated by the type and the design of the ground collector. A ground collector with a low thermal resistance is paramount for good thermal performance of a borehole heat exchanger.

The borehole thermal resistance alone is, however, not an adequate criterion for characterizing the overall performance of a ground collector. When assessing the overall performance of a ground collector, both thermal and hydraulic properties of the ground collector must be taken into consideration. The thermal and hydraulic performance of a ground collector may vary significantly depending on the particular set of operating conditions. Ground collector designs optimized for one set of operating conditions (e.g. heating dominant application; using antifreeze solution as heat carrier fluid, etc.) may be far from optimum for another case (e.g. cooling dominant application; using water as the heat carrier fluid, etc.).

The aim of this project was to undertake comparative investigations of performance characteristics of various types of ground collectors. The project plan was to test the thermal and hydraulic performance of different types of ground collectors under similar thermal and geological conditions. Based on the outcomes of the comparative analysis, best performing collector types over a range of practical operating conditions were to be identified. Cost-benefit analyses were carried out to study if the benefits from the non-conventional and new types of collectors are large enough to make up for their higher first costs and installation complexities compared to the conventional single U-tube collectors.

1.1 Background

Performance and effectiveness of ground collectors have been a research topic of increasing interest during the last few years. Several experimental and simulation studies have been undertaken on this topic. Jalaluddin and Miyara [4] compared the thermal performance and pressure drop of spiral-tube and single U-tube collectors using numerical simulations. They reported that the spiral-tube collectors have significantly better thermal performance than single U-tube collectors for both laminar and turbulent flow regimes. The hydraulic performance of the spiral-tube collectors was, however, several hundred percent worse than the single U-tube collectors. Wood et al. [5] experimentally studied the comparative performance of a single U-tube collector and a pipe-in-pipe coaxial collector. They reported that the U-tube collector has better thermal performance than the coaxial collector. This was due to the turbulent flow regime in the U-tube collector compared to the laminar flow regime in the outer pipe of the coaxial collector. Cvetkovski et al. [6] also compared the performance of single U-tube and coaxial collectors using CFD simulations. Their findings were, however, contrary to those of Wood et al. [5]. They showed that coaxial collectors have better thermal performance and lower pumping energy requirements than U-tube collectors, even at laminar flow rates. Zarrella et al. [7] studied an enhanced coaxial collector with a steel helix around its inner pipe. The helix was installed to enhance turbulence in the outer pipe of the concentric collector. The authors compared the collector to a double U-tube collector and concluded that the enhanced coaxial collector has superior thermal performance than the double U-tube collector. Witte [8] also tested a similar coaxial collector, which has helical vanes on the outer wall of the inner pipe to increase the turbulence in the outer pipe. It was reported that the coaxial collector with the helical vanes had better thermal performance than a single U-tube collector. However, a major trade-off was the significantly higher pressure drop of this collector compared to the single U-tube collector. Acuna [3] studied thermal performance of a number of traditional and new collector types using field experiments and showed that the new pipe-in-pipe and multi-pipe coaxial collectors have significantly lower thermal resistances that the conventional U-tube collectors. But, Scanner et al. [9] and Wood et al. [5], among others, showed that this is not true for all coaxial collectors. Bouhacina et al. [10] used experimental and simulation approaches to show that U-tube collectors with longitudinal fins on the inner surface of the tube have better thermal performance than conventional U-tube collectors under heating mode.

The previous work carried out on the comparative analysis of the ground collectors has focused mainly on the comparison of the thermal and/or hydronic performance of one type of ground collector to another type of ground collector under certain operating conditions. However, no explicit and systematic study, comparing several ground collector types over a comprehensive range of design and operating conditions, has been reported in the literature. To fully assess the performance and effectiveness of various ground collectors, this research project titled "Comparative Experimental Investigation of Performance and Efficiency of Ground Collectors for vertical Borehole Applications" was initiated at the Chalmers University of Technology in the year 2015. The fundamental premise of this research project was to test the performance and effectiveness of various ground collectors over a wide range of prevailing thermal and hydraulic operating conditions.

Various past and on-going research projects at the Department of Architecture and Civil Engineering provided a solid foundation for this research project. These included, among others:

- Optimization of ground-storage heat pump systems for space conditioning of buildings (*Swedish Energy Agency*, *Energimyndigheten*) [11, 12],
- Efficiency of building-related pump and fan operation *(Swedish Energy Agency, Energimyndigheten; Swedish Research Council, Formas)* [13],
- Deep Green Cooling (*Swedish Governmental Agency for Innovation Systems*, *Vinnova*),
- Development of modelling and simulation tools for geothermal basements and deep foundations in soft clays (*Swedish Energy Agency*, *Energimyndigheten*) [14],
- Geothermal foundations in soft clays (*Swedish Research Council*, *Formas*),
- Thermal piles in soft sensitive clays (*Development Fund of the Swedish Construction Industry, SBUF*) [15],
- Suitable design and control strategies for high-temperature cooling of Swedish office buildings using direct ground systems (*Swedish Energy Agency, Energimyndigheten*).

1.2 Project Aims and Objectives

The primary objective of this project was to evaluate the thermal and hydraulic performance of different types of commercially available ground collectors in the Swedish market. The impetus was to facilitate the identification of the most appropriate type of ground collector for any given set of design and operating condition, for example, heating-dominant or cooling-dominant applications, or using water or brine as heat carrier fluid, etc.

The specific goals of this project were as follows:

- Full-scale field testing of different borehole collector types for assessing their in-situ borehole thermal resistance and pressure drops,
- Development of mathematical models and calculation methods for determining borehole thermal resistance of various ground collector types,
- Development of empirical correlation for computing pressure drops of different types of ground collectors.

1.3 Research Group and Project Participants

This project was carried out in a close collaboration between five universities and research institutions, and twenty-one private companies. Several other national and international stakeholders also contributed significantly to the project.

Project Research Group

The research group at Chalmers University was based at the division of Building Service Engineering at the Department of Architecture and Civil Engineering. The group also included representation from the division of Building Technology, from the same department. The research group at Chalmers University consisted of the following people.

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Research Group Expertise

The project group at Chalmers University had strong expertise in the research area. The division of Building Services Engineering has significant research capabilities in design, operation, and control of different building heating and cooling systems. The division of Building Technology has extensive research expertise in the energy modelling and thermal analysis of building structures and the ground. This research project also had direct links to other ongoing projects at Building Services Engineering including

“Development of modelling and simulation tools for geothermal basements and deep foundations in soft clays” and “Suitable design and control strategies for high-temperature cooling of Swedish office buildings using direct ground systems”.

A brief résumé of the research team and their background is presented in the following.

- Associate Professor Saqib Javed has worked on ground source heating and cooling systems for more than 12 years. He is a leading researcher and educator in the field of ground-source heat pump and thermal energy storage systems. He has published and presented extensively on these topics. He initiated this project and led it through to the conclusion.

- Professor Johan Claesson is an internationally renowned and pioneering researcher in the field of geothermal energy storage systems. He is the mathematical brain behind much of Sweden’s groundbreaking research on ground heat transfer. He has developed numerous modelling and simulation methods for ground heating and cooling, and district heating systems. He was involved in the development of mathematical models of the ground collectors tested in this project.

- Håkan Larsson is an experienced lab engineer with several years of hands-on experience in heat pumps, borehole heat exchangers, other heating and cooling technologies, and control systems. He has participated in several research and development projects at Chalmers University. He assisted with the experimental testing of ground collectors at the Chalmers test facility.

The project was generously supported by the following sponsors and research partners from industry and academia.

Companies

- Andersson & Hultmark AB, Elof Lindälvs gata 1, 414 58 GÖTEBORG,
- Asplan Viak AS, Værnesgata 17, 7503 STJØRDAL,
- Bengt Dahlgren, Krokslätts Fabriker 52, 431 37 MÖLNDAL,
- Carrier AB, Box 8946, 402 73 GÖTEBORG,
- ESBE AB, Bruksgatan 22, 333 75 REFTELE,
- EnergyBooster AB, Kvarnvägen 11, 663 40 HAMMARÖ,
- E.ON, Nobelvägen 66, 212 15 MALMÖ,
- Geotec, Västergatan 11, 222 29 LUND,
- Grundfos AB, Box 333, 431 24 MÖLNDAL,
- HP-Borrningar AB, Ravingatan 16, 264 39 KLIPPAN,
- Kronetorp Park, Kronetorps Allé 33, 232 39 ARLÖV,
- Lindab, Järnvägsgatan 41, 269 82 BÅSTAD,
- NCC Construction Sverige AB, NCC Teknik, 405 14 GÖTEBORG,

- Nibe AB, Box 14, 285 21 MARKARYD,
- QTF AB, Slöjdaregatan 5, 393 53 KALMAR,
- Skanska Commercial Development, Warfvinges väg 25, 112 74 STOCKHOLM,
- Skanska Norway, Box 1175, Centrum, 0107 OSLO,
- Swegon AB, Fallebergsvägen 17, 671 34 ARVIKA,
- Thermia Värme AB, Box 950, 671 29 ARVIKA,
- Uponor AB, Box 101, 730 61, VIRSBO,
- Wilo AB, Box 3024, 350 33 VÄXJÖ.

Universities and Research Institutions

- Lund University, Building Services, Box 118, SE-221 00 LUND, SWEDEN,
- Norwegian University of Science and Technology, Department of Geology and Mineral Resources Engineering, NO-7491 TRONDHEIM, NORWAY,
- Oklahoma State University, Building and Environmental Thermal Systems Research Group, OK 74078 STILLWATER, USA,
- RISE Research Institutes of Sweden AB, Building Services Engineering, Box 857, SE 501 15 BORÅS, SWEDEN.

Research Sponsors

- Research Program Effsys EXPAND, Swedish Energy Agency, Gredbyvägen 10, Box 310, SE-631 04 ESKILSTUNA.

2 Implementation of the Project

The project was executed in close collaboration between the division of Building Services Engineering at the Chalmers University of Technology and twenty-five national and international industrial and academic partners. The research group at Chalmers was responsible for the planning and execution of the project as well as for achieving the overall project objectives. The industrial and academic partners were highly involved in the project and provided valuable inputs, guidance, and support throughout the project planning and execution period. The project partners greatly contributed with their knowledge and practical experiences to the project group meetings. Moreover, the project partners generously supported the project by providing in-kind contributions of time and resources in form of materials, equipment, and invaluable measurement data from field and test measurements.

To accomplish its objectives, the project was divided into several smaller work packages. These work packages were tightly intertwined with each other, and several of them ran in parallel or in closely interrelated steps. The work plan for different work packages is described in the following sections in more detail.

2.1 Review of Literature and State-of-the-Art

The first work package was aimed at carrying out a comprehensive literature and market review of the ground collectors used in vertical borehole heat exchanger applications. The literature survey was carried out using leading academic search engines, including Science Direct, Compendex, Scopus, and Google Scholar, etc. The market survey was carried out by contacting various actors and stakeholders and asking them for their feedback in various formal and informal ways. The stakeholders identified for this project included but were not limited to, pipe manufacturers, borehole drillers and installers, property owners and managers, energy consultants, heat pump manufacturers, trade organizations, and testing and research institutes. During this work package, an inventory of various ground collector types, available commercially or under development in Sweden and around the world, was compiled. The state-of-the-art in the thermal and hydraulic performance assessment of the ground collectors was studied. Moreover, test methods and procedures reported in the literature were identified, and were critically analysed.

2.2 Test Plans, Procedures, and Methods

The second work package was focused on the development of test plans, procedures and methods for the in-situ testing of different types of ground collectors. Research findings and experiences learned from the first work package “*Review of Literature and State-of-the-Art*” provided the necessary background to outline the range of design and operating conditions for the ground collectors installed in the field. Based on the prevailing operating conditions, an extensive test strategy, specified by explicit test parameters, was developed.

2.3 Test Facility and Experimental Setup

The third work package dealt with the development of an appropriate test facility and experimental setup for the in-situ testing of different types of ground collectors. The development of the new testing facility and experimental setup was needed for the field testing of different types of ground collectors under similar thermal and geological conditions. During this work package, two vertical borehole heat exchangers were drilled, and a new thermal response test rig was built to simulate conditions that are representative of the ones in actual field installations.

2.4 In-situ Testing, Evaluation and Comparison of Ground Collectors

The fourth work package was focused on the in-situ testing, evaluation, and comparison of different types of ground collectors. Each ground collector was installed in the borehole heat exchangers drilled for this project and was tested individually. The tests were performed in both heat-injection and heat-extraction modes, under a wide range of thermal and hydraulic conditions. After each test, there was a considerably long waiting period to allow for the thermal recovery of the ground surrounding the borehole heat exchanger. The performance of each ground collector type was evaluated for all tested thermal and hydraulic conditions and then compared with other ground collector types.

2.5 New Theory and Mathematical Models

The fifth work package was dedicated to the creation of new knowledge in the form of theory and mathematical models. During this work package, new theories and mathematical models on the thermal and hydraulic performance of various ground collectors were developed. The basis of these new developments was provided by the in-situ measurements taken in this project and the field and test measurement data provided by the project partners. This work package was not included in the original project plan but was added later by the project team to extend the findings of this study to other borehole heat exchanger and ground collector setting, including different diameters and thicknesses of ground collectors and/or different depths of borehole heat exchangers.

2.6 Dissemination of Results

The sixth work package was attributed to the reporting and dissemination of the project results. The results from the project were presented in various forms at different national and international forums. These included, among others:

- Meetings with project stakeholders,
- National and international workshops and seminars,
- EFFSYS conferences,
- Research and thesis reports,
- International conference proceedings,
- Accredited scientific journals.

3 Project Activities and Outcomes

This project was aimed at investigating the performance of ground collectors for vertical borehole heat exchangers using experimental measurements. The study covered various types of ground collector, commercially available in the Swedish market. These included single U-tube, double U-tube configured in parallel, double U-tube configured in series, and coaxial collectors. Furthermore, ground collectors with enhanced materials and innovative design features like U-tube with internally rifled pipes and coaxial collectors with flexible outer pipes were also included. The project yielded several important results. New knowledge was created and mathematical models for the design and simulation of vertical borehole heat exchangers were developed. Detailed results from this project were presented in several journal articles, conference papers, and research reports published within the framework of this project. In the following, a summary of the most significant project activities and results, emanating from research which was either fully or partially supported by this project, are presented.

3.1 Review of Literature and State-of-the-Art

The project started with an extensive review of the literature and current practices pertaining to the design and operation of different types of ground collectors. During this work package, a detailed survey of the existing ground collector types was carried out, and the relevant information on their respective thermal and hydraulic properties was collected and analysed.

The state-of-the-art of the calculation methods for computing the borehole thermal resistance of borehole heat exchangers was established in references [16], [17] & [18]. The calculation of borehole thermal resistance of double U-tube and coaxial collectors was addressed in reference [19]. The estimation of borehole thermal resistance of groundwater-filled boreholes was presented in reference [20]. The literature review showed that several methods have been developed for calculating the borehole thermal resistance of single U-tube collectors. However, most methods presented in the literature were shown to give accurate results under certain conditions only [18]. In other situations, these methods were shown to be prone to large errors. The literature review also indicated that there is a general scarcity of mathematical models and simulation tools that can accurately calculate the thermal resistance of double U-tubes and other more complex configurations of ground collectors.

Moreover, the literature review clearly suggested that there is a serious lack of information pertaining to the hydraulic performance of different ground collectors under the full range of operating conditions. The limited available information was found to be highly contradictory, and the results were difficult to reconcile.

The analysis of the literature suggested that there were exist several contradictions and disagreements among research outcomes on the thermal and hydraulic performance of the ground collectors. It was noticed that the divergences were largely due to inconsistencies in test settings of different studies. The discrepancies among different works reported in the literature were due but not limited to differences in collectors (e.g. size, shape, geometry, material, etc.), boreholes (e.g. depth, diameter, grouting, etc.), and hydraulic conditions (e.g. flow rate, pressure loss, etc.).

3.2 Development of Test Plans, Procedures, and Methods

Development of test plans, procedures and methods was a significant step for the in-situ testing and experimental evaluation of different ground collector types. During this work package, a comprehensive test strategy was developed to fully characterize the thermal and hydraulic properties of different ground collector types. Development of the test design and procedures was based on the lessons learned from the analysis of the state-of-the-art, and the practical experiences of the project partners in designing and operating ground source heating and cooling systems with different types of ground collectors.

The field test strategy was to assess the thermal and hydraulic performance of the borehole heat exchangers with different types of ground collectors under similar experimental conditions. The heat-injection tests were designed with two levels of input power. The first level corresponded to a low-to-moderate level of heat-injection rates to the borehole heat exchanger. The second level corresponded to the peak level of heat-injection rates to the borehole heat exchanger. For each thermal input power level, two flows rates, each corresponding to a specific pumping power level, were applied. Figure 1 shows the test plan established and used to evaluate the thermal performance of different ground collectors in the heat-injection mode. After each test, the borehole heat exchanger was rested for several weeks to ensure full thermal recovery of the ground. The long rest periods between the field tests were designed to provide similar test conditions for all collectors. A test plan like Figure 1 was also developed to assess the thermal performance of different ground collectors in the heat-extraction mode.

As with the evaluation of the thermal performance, the hydraulic performance of the ground collectors was also evaluated by means of full-scale measurements. The test plan for gauging the hydraulic performance was to take measurements of pressure drop for flows covering the entire range of practical conditions. For each ground collector, the pressure drop was measured at eight different flow rates ranging from near-laminar to fully turbulent.

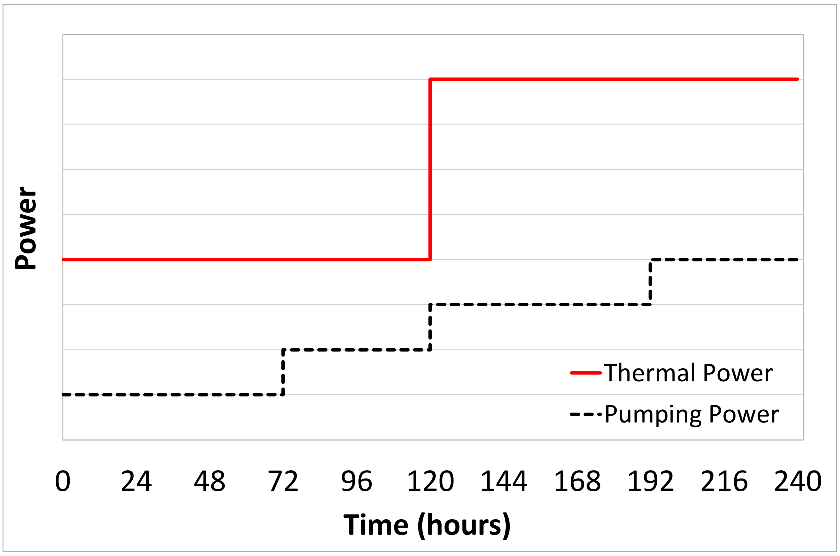

Figure 1 – Test plan in heat-injection mode with multiple thermal input and pumping power levels.

3.3 Development of Test Facility and Experimental Setup

The field testing of different types of ground collectors under similar thermal and geological conditions required the development of a new testing facility and experimental setup. During this work package, a new mobile thermal response test rig was designed and constructed to facilitate the in-situ testing of different types of ground collectors. The mobile rig was built to cover the whole range of design and operating conditions encountered in the field applications of vertical borehole heat exchangers. Figure 2 shows the layout of the thermal response test rig, whereas Figure 3 shows the pictures of the mobile rig.

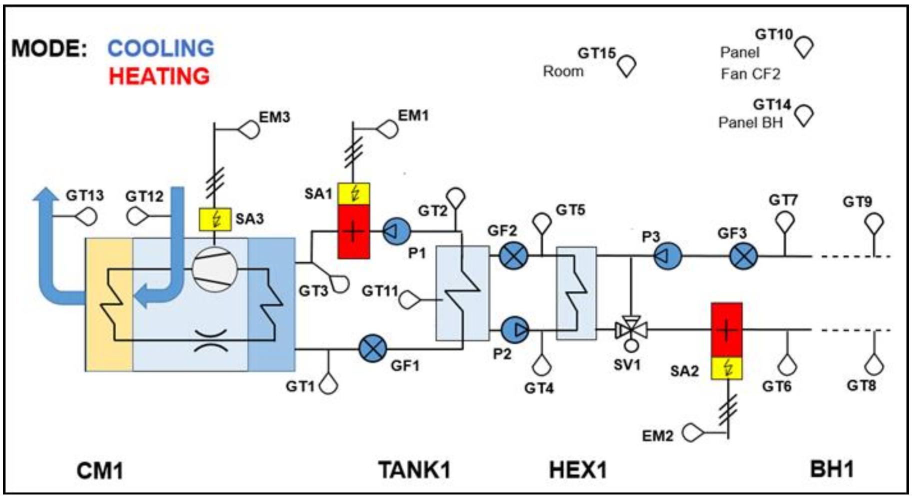

Figure 2 – Layout of the test rig.

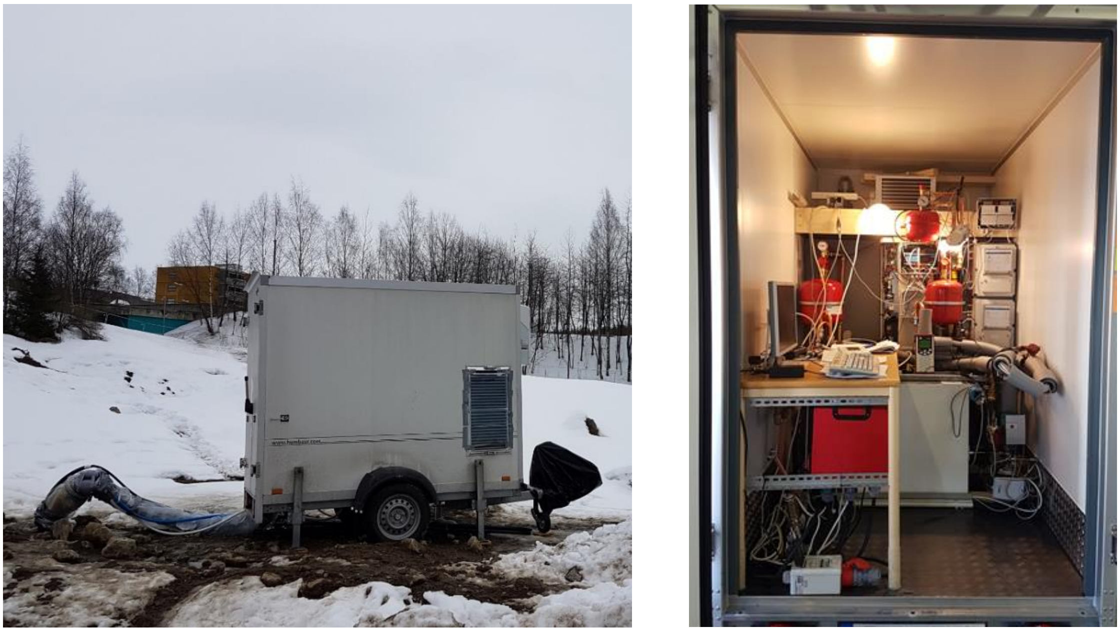

Figure 3 – Photographs of the thermal response test rig.

The thermal response testing rig was designed to operate in both heating and cooling modes. The operation of the rig to perform experimental testing of the ground collectors is briefly explained here. In heating mode, electric heater EM2 was used to inject heat into the ground. The capacity of the electric heater could be regulated between zero and the rated power of the electric heater. The flow in the borehole circuit could be adjusted by changing the pump speed between zero and 100 %. Alternatively, the air-to-water cooling machine CM1 could be operated in reverse cycle to provide heating to the ground. When operating in heating mode, the cooling machine kept the water in tank TANK1 at a set point value. Heating power in heat exchanger HEX1 was kept constant by controlling the speed of the pump P2. If needed, electric heater EM2 could be used to provide additional heating power. This way, a total heating power of up to 30 kW could be supplied to the borehole heat exchanger. In cooling mode, the air-to-water cooling machine CM1 was used to extract heating from the ground. The cooling machine CM1 kept the water in tank TANK1 at a set point value. Return water temperature to the cooling machine was kept constant by providing heating through the electric heater EM1. Cooling power in the heat exchanger HEX1 was kept constant by controlling the speed of the pump P2. The water flow to the borehole was kept constant.

In addition to the development of the thermal response test rig, two vertical borehole heat exchangers were planned and drilled at Chalmers University. These boreholes were needed to facilitate the field testing of different types of ground collectors. Both the boreholes were groundwater-filled and had depths of 100 and 200 meters, respectively. The boreholes were designed to be non-grouted and were instead filled with groundwater to allow easy insertion and removal of ground collectors to and from the boreholes. The possibility of changing the ground collector from one type to another in the same borehole made it possible to test different ground collectors under similar thermal and geological conditions.

Figure 4 – Photograph of the 200-m deep groundwater-filled borehole used for comparative testing of the ground collectors.

3.4 In-situ Testing, Evaluation and Comparison of Ground Collectors

Ground collector types tested during the in-situ testing phase of the project included single U-tube, double U-tube configured in parallel, double U-tube configured in series, U-tube with internally rifled pipes and coaxial collector with flexible outer pipes. Figures 5 and 6 show the installation process of some of these ground collectors in the 200-m deep borehole heat exchanger for experimental testing and evaluation.

Figure 5 – Installation of single and double U-tube ground collectors in the 200-m deep borehole for in-situ tests.

Figure 6 – Installation of the coaxial collector with a flexible outer pipe in the 200-m deep borehole for in-situ tests.

The experimental testing of the ground collectors was performed in accordance with the test procedures and methods developed in the second work package of the project. The thermal performance of each ground collector was tested in both heat-injection and heat-extraction modes. As an example of the experimentally taken measurements, Figure 7 shows the thermal performance of the standard U-tube collector in terms of water temperatures entering and leaving the borehole heat exchanger in the heat-injection mode. Similar data was collected for all ground collector types tested in the project. From the measured data, the effective borehole thermal resistance values were determined over the entire range of thermal and hydraulic conditions applied in the testing. These values are provided in the following in Table 1.

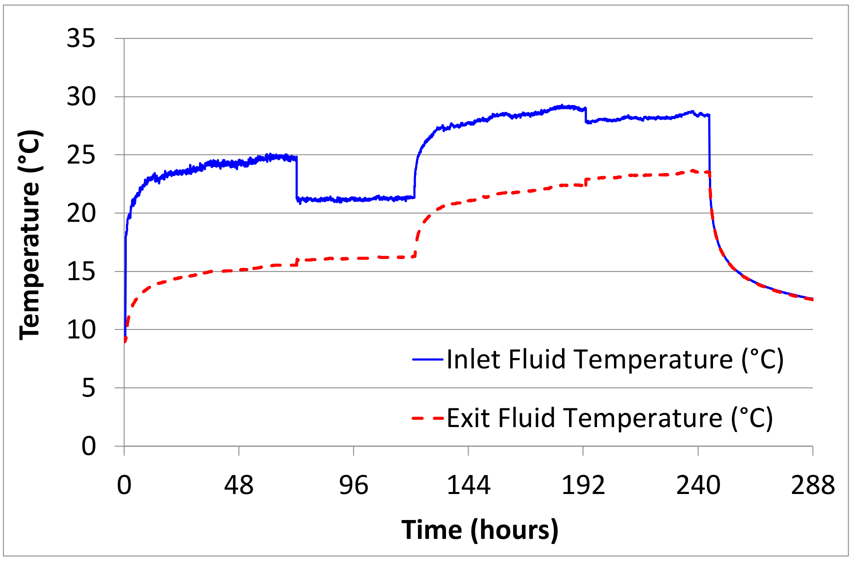

Figure 7 – Measured thermal response of the single U-tube collector (OD 40 mm, SDR 17) in the heat-injection mode.

Table 1 – Measured thermal performance of different ground collectors tested under similar thermal and pumping power conditions.

Ground Collector	**Range of Effective Borehole Thermal Resistance (m-K/W)**
Single U-tube (40mm, SDR 17)	0.077 – 0.240
Single U-tube, rifled (40mm, SDR17)	0.081 – 0.256
Double U-tube, parallel (32mm, SDR 17)	0.064 – 0.211
Coaxial (40mm, SDR 13.6)	0.060 – 0.150

The hydraulic performance of all ground collectors, evaluated in this project, was also assessed experimentally by measuring their respective pressure drop as a function of flow rate. Figure 8 presents the pressure drop measurements of various ground collector types for low and normal flow conditions.

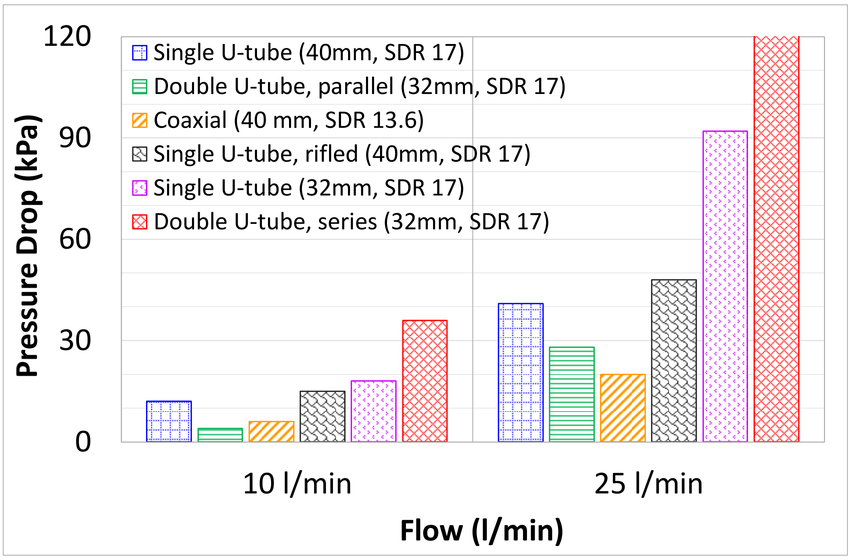

Figure 8 – Measured hydraulic performance of various ground collectors at low and normal flow rate conditions.

3.5 Development of New Theory and Mathematical Models

Various aspects of modelling different types of ground collectors were studied in detail in this project. Based on the experimental results obtained from this project, and the field and test measurement data provided by the project partners, several new methods were developed for the design and analysis of the borehole heat exchangers. The new methods covered both the thermal and hydraulic modelling aspects of the borehole heat exchangers.

As discussed in Section 3.1, the analysis of mathematical models for evaluating the thermal performance of the borehole heat exchangers showed substantial shortcomings in the existing approaches of calculating borehole thermal resistance. In this project, several new mathematical models and modelling tools were developed for accurately calculating the thermal resistance of different types of borehole heat exchangers. A new mathematical model, developed within the scope of this project, for calculating the thermal resistance of groundwater-filled borehole heat exchangers with single U-tube ground collectors was presented in reference [20]. The model was based on the experimental measurements taken over a wide range of conditions of heat transfer rates and borehole annulus temperatures. The model correlated the Nusselt numbers for natural convection in the borehole annulus against the modified Rayleigh number. It was validated by comparing the borehole thermal resistances predicted with the correlations to field measurements from a range of boreholes in Sweden and Norway. The model was implemented in an Excel/VBA spreadsheet [21] for computing the thermal resistance of single U-tube ground heat exchangers placed in groundwater-filled vertical boreholes. In references [22] and [23], new formulas for first-order, second-order and higher-order multipole were presented for calculating the borehole thermal resistance of single U-tube ground heat exchangers. These formulas provided significant accuracy improvements over the existing calculation methods for calculating the borehole thermal resistance. The accuracy of the newly derived formulas was established by comparing them to the original multipole method. In addition to these models, new explicit formulas for calculating borehole thermal resistance of multi-pipe ground heat exchangers were also developed. These models represented a major contribution to the thermal modelling of borehole heat exchangers, as previously there were no closed-form mathematical models for determining the borehole thermal resistance of multi-pipe borehole heat exchangers. A journal article on the explicit multipole formulas for multi-pipe ground heat exchangers would be published in the first half of 2019.

In addition to developing mathematical models for calculating thermal performance of borehole heat exchangers, the hydraulic performance of the vertical borehole heat exchangers was also characterised in terms of the absolute roughness of the collector pipes. The absolute roughness values for different types of ground collectors, for example, smooth and internally rifled pipes, were determined based on the experimentally measured pressure drop values. A journal paper on the characterization of pressure drop in different ground collector types would be published in the first half of 2019.

3.6 Dissemination of Results

Dissemination of the project results was realized in several different ways. Throughout the project lifecycle, the results were regularly presented in meetings with project stakeholders including industrial and academic partners. The results were also presented in scientific journals, international conferences, and other national and international seminars and workshops on a regular basis. The dissemination of results is described in the following in more detail.

3.6.1 Seminars and Workshops

The project results were disseminated nationally and internationally through interactive seminars and workshops. Following is the list of seminars and workshops attended to disseminate the results from this project through formal and informal channels.

- Svenska Kyl & Värmepumpdagen 2015 (Swedish Refrigeration & Heat Pump Day 2015), October 16, 2015, Gothenburg, Sweden.

- Second meeting and seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), December 10-11, 2015, Lisbon, Portugal.

- Third meeting and seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), March 21-22, 2016, Cluj, Romania.

- EFFSYS Expand research conference, May 17-18, 2016, Tranås, Sweden.

- Svenska Kyl & Värmepumpdagen 2016 (Swedish Refrigeration & Heat Pump Day 2015), October 21, 2016, Gothenburg, Sweden.

- Fourth meeting and seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), December 5-7, 2016, Torino, Italy.

- Fifth meeting and seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), March 20-21, 2017, Warsaw, Poland.

- Sixth meeting and seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), September 25-26, 2017, Sofia, Bulgaria.

- Geoenergidagen 2017 (Swedish Geo-Energy Day 2017), September 28, 2017, Stockholm, Sweden.

- Docent Seminar, Chalmers University of Technology, October 6, 2017, Gothenburg, Sweden.

- Svenska Kyl & Värmepumpdagen 2017 (Swedish Refrigeration & Heat Pump Day 2017), October 20, 2017, Stockholm, Sweden.

- Seventh meeting and seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), March 5-9, 2018, Alexandroupolis, Greece.

- EFFSYS Expand research conference, April 17-18, 2018, Tranås, Sweden.

- GABI sort course: How to plan a successful thermoactitve geostructure design? COST Action TU1405, September 24, 2018, Lausanne, Switzerland.

- Eight meeting and seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), September 25, 2018, Lausanne, Switzerland.

3.6.2 Project Publications

Following is the list of publications resulting for which the research was fully or partly supported by this project. The publications are sorted by category.

Journal Articles:

1. Spitler, J., Javed, S. and Ramstad, R., 2016. Natural convection in groundwater-filled boreholes used as ground heat exchangers. Applied Energy, vol. 164, pp. 352-365. http://dx.doi.org/10.1016/j.apenergy.2015.11.041

2. Bourne-Webb, P., Burlon, S., Javed, S., Kürten, S. and Loveridge, F., 2016. Analysis and design methods for energy geostructures. Renewable and Sustainable Energy Reviews, vol. 65, pp. 402-419. http://dx.doi.org/10.1016/j.rser.2016.06.046

3. Vieira, A., Alberdi-Pagola, M., Christodoulides, P., Javed, S., Loveridge, F., Nguyen, F., Cecinato, F., Maranha, J., Florides, G., Prodan, I. and Lysebetten, G.V., 2017. Characterisation of ground thermal and thermo-mechanical behaviour for shallow geothermal energy applications. Energies, 10(12), p. 2044. https://doi.org/10.3390/en10122044

4. Javed, S., Spitler J, 2017. Accuracy of borehole thermal resistance calculation methods for grouted single U-tube ground heat exchangers. Applied Energy, vol. 187, pp. 790-806. http://dx.doi.org/10.1016/j.apenergy.2016.11.079

5. Claesson, J. and Javed, S., 2018. Explicit multipole formulas for calculating thermal resistance of single U-tube ground heat exchangers. Energies, 11(1), p. 214. https://doi.org/10.3390/en11010214

6. Beier, R.A., Mitchell, M.S., Spitler, J.D. and Javed, S., 2018. Validation of borehole heat exchanger models against multi-flow rate thermal response tests. Geothermics, 71, pp. 55-68. https://doi.org/10.1016/j.geothermics.2017.08.006

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8. Javed, S., Ørnes, I.R., Myrup, M. and Dokka, T.H., 2018. Design optimization of the borehole system for a plus-Energy kindergarten in Oslo, Norway. Architectural Engineering and Design Management. https://doi.org/10.1080/17452007.2018.1555088

Conference Proceedings:

1. Spitler, J., Grundmann, R. and Javed, S., 2016. Calculation tool for effective borehole thermal resistance. Proceedings of 12th REHVA World Congress (Clima 2016), Aalborg, Denmark.

2. Javed, S. and Claesson, J., 2017. Second-order multipole formulas for thermal resistance of single U-tube borehole heat exchangers. Proceedings of IGSHPA 2017 IGSHPA Technical/Research Conference, Denver, USA. https://doi.org/10.22488/okstate.17.000535

3. Proshyn, S., Bulich, I. and Javed, S., 2018. Storage and Utilization of the Waste Heat from National Veterinary Institute (SVA), Uppsala, Sweden. Proceedings of 14th International Conference on Energy Storage (EnerSTOCK 2018), Adana, Turkey.

Technical Reports:

1. Carlsson, S., 2015. Energy piles – A Thermal Response Test on a pre-cast concrete energy pile. Master's thesis, (Lund University.) Sweden.

2. Claesson, J., 2016. Multipole method to calculate borehole thermal resistances. Additions to background report from June 2012. Mathematical report 2, (Chalmers University of Technology.) Sweden.

3. Javed, S., 2016. Development of Modelling and Simulation tools for Geothermal Basements and Deep Foundations in Soft Clays. Project report, (Chalmers University of Technology.) Sweden.

4. Proshyn, S. and Bulich, I., 2017. Waste heat storage and utilization for the case of National Veterinary Institute (SVA), Uppsala, Sweden. Master's thesis, (Lund University.) Sweden.

5. Bergström, A., 2017. In-situ testing of floating thermal piles in soft sensitive clay Licentiate thesis, (Chalmers University of Technology.) Sweden.

6. Winther, J., 2018. Power production from excess heat in a district heating system. Master's thesis, (Chalmers University of Technology.) Sweden.

Book Chapters:

1. Javed, S. and Spitler, J., 2016. Calculation of borehole thermal resistance. In: Rees S, editor. Advances in ground-source heat pump systems. Woodhead Publishing, pp. 63-95. http://dx.doi.org/10.1016/B978-0-08-100311-4.00003-0

2. Woodman, N., Loveridge, F.A., Javed, S., and Claesson, J., 2019. Evaluating the Applicability of the Radial Approximation for Pile Heat Exchangers. In: Ferrari A., Laloui L. (eds) Energy Geotechnics. SEG 2018. Springer Series in Geomechanics and Geoengineering, pp. 3-10. https://doi.org/10.1007/978-3-319-99670-7_1

3. Arghand, T., Trüschel, A., Dalenbäck, J.O. and Javed, S., 2019. Dynamic Thermal Performance and Controllability of Fan Coil Systems. In: Johansson D., Bagge H., Wahlström Å. (eds) Cold Climate HVAC 2018. CCC 2018. Springer Proceedings in Energy, pp. 351-361. https://doi.org/10.1007/978-3-030-00662-4_30

Popular Presentations:

1. Javed, S., 2015. Malmö Police House – A cool and hot Case. Svenska Kyl & Värmepumpdagen 2015 (Swedish Refrigeration & Heat Pump Day 2015), Gothenburg, Sweden, 2015-10-16.

2. Javed, S., 2015. Thermal modelling of geothermal systems. Meeting COST Action TU1405, European network for shallow geothermal energy applications in buildings and infrastructure, Lisbon, Portugal, 2015-12-10.

3. Javed, S., 2016. Comparative experimental investigation of performance and efficiency of ground collectors for vertical borehole applications. EFFSYS Expand Research Conference, Tranås, Sweden, 2016-05-17.

4. Javed, S., 2016. Comparative investigation of performance and efficiency of ground collectors for vertical borehole applications – Status update 2016. Svenska Kyl & Värmepumpdagen 2016 (Swedish Refrigeration & Heat Pump Day 2016), Gothenburg, Sweden, 2016-10-21.

5. Javed, S., 2016. Geothermal structures – Research updates from Sweden. Meeting COST Action TU1405, European network for shallow geothermal energy applications in buildings and infrastructure, Torino, Italy, 2016-12-06.

6. Javed, S., 2017. Free ground cooling. Meeting COST Action TU1405, European network for shallow geothermal energy applications in buildings and infrastructure, Sofia, Bulgaria, 2017-09-25.

7. Javed, S., 2017. Direct ground cooling – Possibilities and applications in Sweden. Geoenergidagen 2017 (Swedish Geo-Energy Day 2017), Stockholm, Sweden, 2017-09-28.

8. Javed, S., 2017. Current and future research trends in Building Services Engineering. Docent Seminar, Gothenburg, Sweden, 2017-10-06.

9. Javed, S., 2017. Comparative investigation of performance and efficiency of ground collectors for vertical borehole applications – Status update 2017. Svenska Kyl & Värmepumpdagen 2017 (Swedish Refrigeration & Heat Pump Day 2017), Stockholm, Sweden, 2017-10-20

10. Javed, S., 2018. Comparative investigation of performance and efficiency of ground collectors for vertical borehole applications – Status update 2018. EFFSYS Expand research conference, Tranås, Sweden, 2018-04-17.

11. Javed, S., 2018. Characterization of Ground Thermal Properties for Shallow Geothermal Applications. GABI short course for PhD students, COST Action TU1405, Lausanne, Switzerland, 2018-09-24.

3.6.3 Forthcoming Publications

Some publications from the project are still in the pipeline and would be published over the forthcoming months.

1. Explicit Multipole formulas for calculating thermal resistance of ground heat exchangers with multiple U-tube ground heat exchangers.

2. Measurements and modelling of pressure drops in vertical borehole heat exchangers for different types of ground heat exchangers.

3. Comparative study of borehole thermal resistance for single U-tube, double U-tube, and coaxial heat exchangers.

4 Discussion and Conclusions

The performance of ground collectors for vertical borehole heat exchanger applications is a matter of growing interest. It is particularly relevant for sizing ground heat exchangers for the optimal performance and the cost-effectiveness of the overall ground heating and cooling system. The thermal and hydraulic performance of a ground collector is characterized by its thermal resistance and pressure drop, respectively. In recent years, many new collectors with innovative designs have been introduced. These collectors claim to have superior thermal and/or hydraulic performance than their conventional counterparts. However, the available information on the actual thermal and hydraulic performance of these ground collector types is rather limited. Moreover, most new collectors are not only more expensive than conventional collectors, but often they are also more labour intensive and time consuming to install.

The performance evaluation of ground collectors is a challenging task that has not been properly addressed in literature or by industry until now. This project sought to fill the significant knowledge gap in the performance evaluation of different ground collectors. The thermal and hydraulic performance of various ground collectors was extensively studied through experiments, mathematical modelling, simulation studies, and field monitoring. Several results from the project have already been presented in various reports, articles, seminars, and conference proceedings (see Section 3.6). Many other scientific results are in the pipeline and will be published in year 2019. A summary of the main project results and findings are presented and discussed in the following.

4.1 Discussion

Sweden has a long history of using vertical borehole heat exchangers. Traditionally, single U-tube and double U-tubes in the parallel configuration have been the two most used types of ground collectors for vertical borehole applications. The typical installations of these ground collectors have been for heat-extraction applications in single-family houses. However, in the last decade or so, the use of vertical borehole heat exchangers for heating and cooling of commercial and office buildings, and energy storage applications has also increased significantly. For these installations, borehole heat exchangers are used for both heat-injection and heat-extraction applications, and in certain cases for heat-injection applications only. These new applications often require ground collectors to be designed and operated at conditions different from those used for heat-extraction applications only. Some examples of these disparities include temperature difference over the ground collector, flow regime in the ground collector, and heat transfer rate to the ground.

Many new ground collectors have been introduced in the market in recent years. Most of these collectors claim to offer better overall performance than conventional U-tube collectors. However, the survey and analysis of the literature carried out for this project showed that these claims are largely based on somewhat ambiguous results derived from a few heuristic measurements. The survey and the analysis of the literature also highlighted the need for evaluating and comparing different ground collector types in a structured, comprehensive and accurate manner.

The performance evaluation of ground collectors is a challenging task due to the wide variety of engineering, economical and practical aspects to be taken into consideration when characterizing them. A lower value of borehole thermal resistance or pressure drop doesn’t by itself imply a superior overall performance. For example, the convective resistance of the heat carrier fluid is affected by its flow rate. A higher flow rate decreases the convective resistance in the ground collector but simultaneously increases the pressure drop. This, in turn, increases the pumping energy, which negatively affects the overall performance of the ground collector. Similarly, a low flow rate of the heat carrier fluid in the ground collector decreases the pressure drop in the ground collector, but simultaneously increases the thermal short-circuiting between the collector pipes. This negatively affects the thermal performance of the ground collector as well as its overall performance. Likewise, new and innovative designs of ground collectors, offer improved thermal and hydraulic performances. However, compared to their conventional counterparts, the new types of ground collectors are generally more expensive to purchase and/or more difficult and time-consuming to install.

In this project, the specific focus was on the experimental testing of the ground collectors to measure their thermal and hydraulic performance. The thermal performance of the ground collectors was measured through a series of thermal response tests. Each ground collector was tested at multiple levels of power and flow rates, ranging from heat-injection to heat-extraction and from nearly laminar to fully turbulent. The thermal performance was characterised in terms of the thermal resistance of the borehole heat exchanger. The experimental results showed that, in comparison to other ground collectors, the coaxial collector had better thermal performance over a large range of studied design and operating conditions. Double U-tube collector, configured in parallel, also had higher thermal performance than all other ground collectors, except the coaxial one, across a broader range of design and operating conditions. The thermal performance of the double U-tube collector was, however, noticed to be adversely affected at low flows due to the thermal short-circuiting between the heat exchanger pipes. Among other collectors, the U-tube collector with internally rifled pipes had inferior thermal performance than the ordinary U-tube collector. A journal article presenting the detailed results of the comparison of the thermal performance of the tested ground collectors is in the pipeline and will be published in year 2019. Several other articles covering both the experimental and theoretical aspects of the thermal performance of the ground collectors have already been published in references [18] to [26].

The hydraulic performance of the ground collectors was measured in the full-scale measurements. Each ground collector was tested at eight different flows ranging from near-laminar to fully turbulent. As presented in Figure 8, the hydraulic performance was characterised in terms of the pressure drop of the collector. The experimental measurements of pressure drop showed that coaxial collector had the best hydraulic performance among all the tested ground collectors over a wide range of tested flow conditions. Double U-tube collector, configured in series, had by far the worst hydraulic performance of all tested ground collectors. Among other collectors, the U-tube collector with internally rifled pipes had inferior hydraulic performance than the ordinary U-tube collector. Some results on the hydraulic performance of ground collectors have already been presented in references [21], [27] and [28]. A journal article presenting detailed results of the comparative hydraulic performance of all the tested ground collectors is planned for the first half of 2019.

In addition to gauging the thermal and hydraulic performance of the ground collectors through experimental measurements, the initial upfront cost of each ground collector and the time and labour expenses necessary to install each collector were also monitored and analysed. The first costs of all ground collectors, except the coaxial one, were within a reasonably narrow range of each other. The coaxial collector had significantly higher first cost than all other ground collectors. The coaxial collector also had substantially higher time and labour expense for installation than any other ground collector. The time and labour expense required for installation of all other ground collectors were broadly similar.

To assess the overall performance of the tested ground collectors, cost-benefit analyses of the tested ground collectors were performed. The objective of the cost-benefit analyses was to determine whether the thermal and/or pump energy savings of the energy-efficient ground collectors are large enough to overweigh their higher first costs and/or the additional time and labour expense necessary to install them. The analysis was performed for various building types, including a single-family house, a school building, and a commercial building. The analyses showed that, for the studied cases, ground collectors with low borehole thermal resistance could reduce the required borehole depths up to 40 %. Moreover, ground collectors with low pressure losses could reduce the borehole pumping energy by 35 to 45 %. The required pumping power for the borehole side of the studied cases was determined to be 12−15 W/kW of the heat injection or extraction. The coaxial and double U-tube (parallel configuration) collectors were found to have most consistent thermal and hydraulic performance under the studied cases. However, despite their superior thermal and hydraulic performance in terms of borehole thermal resistance and pressure drop, it was observed that the coaxial collectors were not cost-effective in many cases, especially for small-to-medium scale applications. The initial cost and the implementation time associated with the installation and mounting of the coaxial collectors were found to be an impediment to the application of these collectors. Overall, it was noted that a project-specific cost-benefit analysis is needed to determine if the thermal and pump energy saving from a specific collector are large enough to overweigh its higher first cost and installation difficulties.

4.2 Conclusions

This project dealt with experimental testing of various types of ground collectors for vertical borehole heat exchanger applications. The thermal, hydraulic and overall performance of several ground collectors was assessed in comparison to each other. Among all ground collectors, the coaxial ground collector had the most consistent thermal and hydraulic performance over the tested range of power and flow rate conditions. However, the first cost of the tested coaxial collector was considerably higher than all other ground collectors tested in this project. The installation time and cost of the coaxial collector was also substantially higher than all other ground collectors. The double U-tube collector, configured in series, was found to have a significantly poorer hydraulic performance than other ground collectors. The U-tube collector with internally rifled pipes did not offer any significant performance advantage over conventional U-tube collectors.

A noteworthy outcome of the project was the development of new mathematical models and calculation tools for calculating the borehole thermal resistance. New models were developed for groundwater-filled borehole heat exchangers and ground heat exchangers with multiple pipes. Major improvements were suggested for grouted borehole heat exchangers with single U-tube collector. The mathematical models from the project have already been implemented in a few commercial software. The project results have been presented in six technical reports, three book chapters, and eleven journal and conference proceeding papers.

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