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Saqib Javed, Per Fahlén and Johan Claesson

Gothenburg
April 2014

CHALMERS UNIVERSITY OF TECHNOLOGY
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Executive summary

Ground-source heat pump systems use ground as a source or sink of heat for space heating and cooling of buildings. The use of these systems for space conditioning of buildings has increased manifold in the last decade or more. An obvious reason for this rapid growth is the high energy efficiency of these systems, which can reduce the purchased energy by a factor of 7-8 compared to district heating and cooling systems. The energy efficiency of the ground-source systems can be further enhanced by optimizing the design and operation of these systems.

Most building energy simulation software available today offer limited capabilities to model ground-source heating and cooling systems for design and simulation purposes. This is because existing borehole heat exchanger models are mostly based on complex numerical methods, which makes their implementation into building energy simulation software quite challenging. There is also scarcity of mathematical models that can rapidly, yet accurately, simulate the dynamic thermal response of the borehole system. The lack of suitable dynamic ground heat exchanger models has also limited the development and implementation of appropriate controllers and control algorithms for ground-source system applications.

In this project, various aspects of modelling for design, simulation and control of ground-source heat pump systems have been studied comprehensively. Specific focus has been placed on the development of analytical models and predictive tools for simulating and optimizing performance of ground-source systems. All models and methods developed in the project can be easily implemented in any building energy simulation software to optimize the design and overall performance of ground-source heat pump systems.

Another important aspect studied in detail in this project is the analysis and evaluation of borehole systems. Several parameters critical to design and operation of ground-source heat pump systems have been identified and analysed using experimental and field studies. Over forty tests have been conducted in a state-of-the-art laboratory. Field studies have been carried out in various buildings including a single family house, a clubhouse, a police station, a university building and a shopping centre. Various recommendations have been suggested to improve the current design and operation practices of ground-source heat pump systems.

Keywords: ground source heat pump, GSHP, ground heat exchanger, borehole, BHE, thermal response test, TRT, optimization, design, simulation

Optimering av Marklageranslutna Värmepumpsystem för Klimatisering av Byggnader

Saqib Javed, Per Fahlén and Johan Claesson
Installationsteknik, Institutionen för Energi och Miljö
Chalmers Tekniska Högskola AB

Sammanfattning

Markvärmepumpsystem använder marken som källa eller sänka för rumsvärmning eller rumskylning av byggnader. Denna tillämpning har ökat mångfalt under den senaste 10-årsperioden. En uppenbar anledning till denna snabba ökning är systemens höga energieffektivitet. Jämfört med fjärrvärme och fjärrkyla kan behovet av köpt energi minska med en faktor 7-8. Marksystemens prestanda kan förbättras ytterligare genom optimering av deras utformning, dimensionering och drift.

De flesta av dagens simuleringsprogram för byggnaders energibehov erbjuder begränsade möjligheter att inkludera markbaserade värme- och kylsystem för konstruktion och användarsimulering. Detta beror på att befintliga modeller av borrhålsvärmeväxlare mestadels är baserade på komplexa numeriska metoder, vilket gör deras användning i byggnadssimuleringsprogram ganska besvärlig. Det finns också en brist på matematiska modeller som snabbt, men ändå noggrant, kan simulera det dynamiska förloppet i ett borrhålssystem. Bristen på lämpliga dynamiska markvärmeväxlarmodeller har också begränsat utvecklingen och tillämpningen av lämpliga styrsystem för markvärmetillämpningar.

I detta projekt har olika aspekter av modellering för konstruktion, simulering och styrning av markrelaterade värmepumpssystem studerats ingående. I synnerhet har fokus varit på analytiska modeller och predikterande verktyg för simulering och optimering av prestanda för markvärmesystem. Alla modeller och metoder som utvecklats i projektet kan enkelt implementeras i simuleringsprogram för byggnaders energianvändning för att optimera utformning och prestanda för markkopplade värmepumpssystem.

Ytterligare en viktig aspekt, som studerats i detalj i detta projekt, är analys och utvärdering av borrhålssystem. Flera parametrar, som är kritiska för utformning och drift av markkopplade värmepumpssystem, har identifierats och analyserats med hjälp av laboratorie- och fältundersökningar. Över fyrtio tester har genomförts i ett toppmodernt laboratorium. Fältstudier har genomförts i olika byggnader som inkluderar ett enfamiljshus, en klubbstuga, en polisstation, en universitetsbyggnad och ett affärscentrum. Olika rekommendationer föreslås för att förbättra dagens metoder för konstruktion och drift av markkopplade värmepumpssystem.

Nyckelord: markvärmepump, GSHP, markvärmeväxlare, borrhål, BHE, termisk responstest, TRT, optimering, utformning, simulering

Foreword

This is the final report of the project titled "Optimization of Ground-Storage Heat Pump Systems for Space Conditioning of Buildings" carried out between September 2010 and December 2013 at Division of Building Services Engineering, Department of Energy and Environment, Chalmers University of Technology.

This work has been funded by the Swedish Energy Agency through their national research program EFFSYS+. It has also been supported by in-kind contributions from many industrial and research partners including Akademiska Hus, Andersson & Hultmark, Carrier, Enertech (CTC), Donghua University, Equa Solutions, Fastighetsägarna, Geotec, Grundfos, IFLA, IVT, Lafor, NCC, Nibe, Oklahoma State University, Palne Mogensen, Sweco, Schneider Electric (TAC), SP, Thermia, Uponor, Vänersborgsbostäder, Wilo and ÅF-Infrastruktur.

We thank all participating companies and research partners for their generous support and enthusiasm throughout this project.

Gothenburg
April 2014
Saqib Javed, Per Fahlén and Johan Claesson

Contents

1 Introduction

In the last two decades Ground Source Heat Pump (GSHP) systems have emerged as an attractive alternative to conventional heating and cooling systems. Today, the worldwide thermal energy use of GSHP systems has exceeded 200,000 TJ/year. The installed capacities of GSHP systems have increased from 5,300 MW_{th} in 2000 to over 33,000 MW_{th} in 2010. In Sweden, the thermal energy use of GSHP systems is approximately 46,000 TJ/year, which is third highest in the world after China and USA. Sweden also has world's third largest installed capacity of GSHP systems, amounting to 4,600 MW_{th} [20]. There are approximately 400,000 GSHP systems installed at single family houses in Sweden. In addition to these small residential systems, there are approximately 600 other installations of large GSHP systems at commercial and office buildings [1].

In Sweden, the most common application of GSHP systems is with vertical boreholes. Over 75 % of the residential GSHP systems use vertical boreholes as ground heat exchangers. Similarly, two thirds of the GSHP systems installed at commercial and office buildings use borehole heat exchangers [1]. The attraction of GSHP systems with 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 or a heat sink. 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.

Nowadays, many office and commercial buildings in Sweden have cooling requirements during the day and heating requirements during the night. Other commercial buildings, like super markets and shopping centres, have simultaneous requirements of heating and cooling. For these systems, a significant amount of thermal energy is just pumped up and down the borehole heat exchanger with the heat transfer mainly occurring in the borehole. Consequently, adaptive control and dynamic optimization of these systems involve thermal processes varying from short-term heat exchange inside the borehole to long-term heat injection or extraction from the ground.

1.1 Background

Previously, buildings in Sweden only had heating demands and the GSHP systems were designed only to extract heat from the ground. Today, with better insulation and higher levels of air tightness, many office and commercial buildings have a cooling demand during the day and heating demand at night. Many other buildings, like shopping centres and super-markets, have simultaneous heating and cooling demands. Figure 1.1 shows the trend of changing heating demands and energy use for Swedish buildings since 1970s. The figure indicates reduction in heating demand and increase in electricity demand, especially for non-residential buildings. The decline in the heating demands of Swedish buildings and the concurrent surge in their cooling demands have led to significant interest in using ground as a heat sink, in addition to its common use as a heat source. The possibility of using ground for seasonal or short-term heat storage has also engendered considerable interest. One important reason for this growing interest is certainly the high energy efficiency of GSHP systems, which can reduce the amount of purchased energy by a factor of 7-8 compared to district heating and cooling systems.

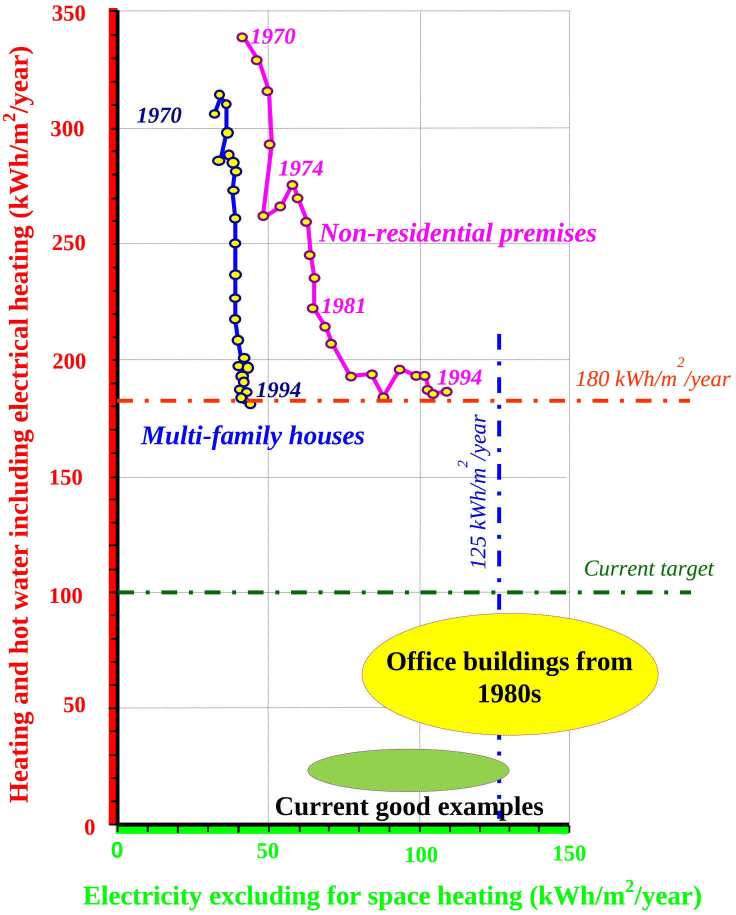

Figure 1.1 Changes in heating and electricity use of Swedish buildings [5].

The changing patterns of heating and cooling demands of buildings require modelling methods that take short-term thermal response of the borehole heat exchangers into account when designing and simulating GSHP systems. Energy flow in the earlier installations of GSHP systems in Sweden was mostly unidirectional, i.e. heat moving from ground to building. The modelling approach for these systems was to determine the long-term thermal response of the surrounding ground to heat extractions over a period of time. However, in modern buildings a significant amount of thermal energy is just pumped up and down the borehole heat exchanger on a hourly to seasonal time scale. For these systems, the thermal response of the borehole heat exchanger also depends on short-term heat transfer inside and just around the borehole. In the framework of this project, we focused on developing unified solutions that can model the borehole thermal response in both short and long time-scales. The project also addressed the issue of complete system modelling of GSHP systems. The ground models developed in this project were used in conjunction with building loads and heat pump models to develop design and simulation tools for complete system optimization of GSHP systems. Until now, such tools for dynamic modelling and optimization of GSHP systems have been conspicuously scarce.

Another important aspect addressed in this project was the analysis and evaluation of water-filled boreholes. Groundwater-filled boreholes are common in Sweden and other Scandinavian countries. The underground structure in these countries is mostly solid bedrock, which allows the boreholes to be filled naturally with groundwater, eliminating the need for grouting. Heat transfer between the borehole and the surrounding ground is mostly by conduction and buoyancy-driven natural convection, which is sometimes assisted by advection. Analysis and evaluation of the groundwater-filled boreholes present challenges which are somewhat different to those of grouted boreholes. In this project, among other things, we examined the role of convective heat transfer in groundwater boreholes. The evaluation of multi-injection rate tests on groundwater-filled boreholes was also investigated.

Various past and on-going research activities at the Division of Building Services Engineering provided a framework for this project. The project was based on an initial study [22] carried out to investigate the use of GSHP systems for both heating and cooling. It was also supported by the following projects conducted at Division of Building Services Engineering.

- Energy efficiency in shopping malls with an improved indoor climate *(EFFSYS)*.
- Heat pump water heaters – Alternative solutions for hot water and space heating *(EFFSYS)*.
- Cooling demand and daylight in commercial buildings *(Various)*.
- Demand control ventilation systems in commercial buildings *(Swedish Energy Agency, Nordic Innovation Centre)*.
- Efficiency of building related pump and fan operation *(Swedish Energy Agency, Formas, Göteborg Enery)*.
- Deep Green Cooling *(Swedish Governmental Agency for Innovation Systems)*.

1.2 Project Aims and Objectives

The project had two primary goals: one research-oriented and the other application-oriented.

Research-oriented goal:
The research goal was the development of computational tools for complete system modelling of GSHP systems. This included modelling of ground heat exchanger, heat pump, and the heating and cooling demands of the building. A specific aim was to develop analytical solutions for single and multiple borehole systems, which can model ground heat exchangers accurately when performing multi-year simulations of GSHP systems. The academic goal was a PhD dissertation.

Application-oriented goal:
The second goal of the project was to identify system solutions that use less purchased energy than 20 kWh_{el}/m^2/year and 5 kWh_{th}/m^2/year for heating and cooling of buildings. The identified solutions should be competitive with district heating and cooling systems. Another objective was to demonstrate the competitive advantage of GSHP systems for residential buildings. The goal was to find system solutions, which would reduce energy use in residential buildings from the current level of 150 kWh_{th}/m^2/year to no more than 20 kWh_{el}/m^2/year.

1.3 Research Group and Project Participants

This report presents the results from the project: Optimization of ground-storage heat pump systems for space conditioning of buildings. The project was carried out in a close collaboration between a research group at Chalmers University of Technology and 22 private companies. Five international universities also contributed significantly to the project.

Project Research Group

The research group at Chalmers was based in the division of Building Service Engineering at the department of Energy and Environment. The group also included representation from the division of Building Technology, department of Civil and Environmental Engineering. The research group consisted of the following people.

Project Leader,
Professor Emeritus
Per Fahlén
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Researcher,
Dr. Saqib Javed
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Research Group Expertise

The project group at Chalmers had strong expertise in the research area. The division of Building Services Engineering has significant research capabilities in design, operation and control of building heating and cooling systems. The division of Building Technology has extensive research expertise in energy modelling and thermal analysis of building structures and ground. This research project also had direct links to other projects at Building Services Engineering including “Heat Pump Water Heaters for Domestic Hot Water and Space Heating” and “Energy Efficiency in Shopping Malls”.

- Professor Per Fahlén has worked with heat pumps and ground heating system for more than 30 years. He has developed and validated many advanced dynamic computational models for buildings. He initiated this project and led it until he retired from Chalmers University in May 2012.

- Professor Johan Claesson is an internationally renowned and pioneering researcher in the field of GSHP systems. He is the mathematical brain behind much of Sweden’s ground breaking research on ground heat transfer. He has developed the Dynamic Thermal Network approach for modelling of transient conduction, which was also used in this project.

- Saqib Javed was the PhD candidate working on this research project. Previously, he has worked with York International on large heating and cooling projects. After completing his PhD in Jan 2012, he also led the project due to the retirement of Professor Per Fahlén.

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

Companies

- AB Vänersborgsbostäder, Vallgatan 13, 462 85 VÄNERSBORG
- Akademiska Hus AB, Box 483, 401 27 GÖTEBORG
- Andersson & Hultmark AB, Elof Lindälvs gata 1, 414 58 GÖTEBORG
- Carrier AB, Box 8946, 402 73 GÖTEBORG
- CTC, Division of Enertech AB, Box 309, S-341 26 LJUNGBY
- EQUA Simulation AB, Råsundavägen 100, 169 57 SOLNA
- Fastighetsägarna, Box 12871, 112 98 STOCKHOLM
- Geotec, Box 1127, SE-221 04 LUND
- Grundfos AB, Box 333, 431 24 MÖLNDAL
- IFLA HB, Brännabbenvägen 80, 44896 TOLLERED
- IVT AB, Box 1012, 573 28 TRANÅS
- Lafor Energientreprenader AB, Hägernäsvägen 25, 183 60 TÄBY
- NCC Construction Sverige AB, NCC Teknik, 405 14 GÖTEBORG
- Nibe AB, Box 14, 285 21 MARKARYD
- Palne Mogensen AB, Emblavägen 29, SE-182 67 DJURSHOLM
- Schneider Electric, Jägershillgatan 18, 213 75 MALMÖ
- SP, Box 857, SE-501 15 BORÅS
- SWECO AB, Box 340 44, 100 26 STOCKHOLM
- Thermia Värme AB, Box 950, 671 29 ARVIKA
- Uponor AB, Box 101, 730 61, VIRSBO
- Wilo AB, Box 3024, 350 33 VÄXJÖ
- ÅF-Infrastruktur AB, Kvarnbergsgatan 2, 401 51 GÖTEBORG

Universities

- Donghua University, College of Environmental Science and Engineering, 1882 West Yan'an Road, 200051 SHANGHAI, P. R. of China.
- Lund University, Mathematical Physics, Box 118, 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.
- Vrije Universiteit, Department ELEC, Pleinlaan 2, 1050 BRUSSELS, Belgium.

Research Sponsors

- Research Program Effsys+ (Effective systems for refrigeration and heat pumps). Swedish Energy Agency, Kungsgatan 43, Box 310, 631 04 ESKILSTUNA.

2 Implementation of the project

The project was executed in close collaboration between Chalmers University of Technology and over 25 national and international industrial and academic partners. The research group at Chalmers was responsible for implementation of the project as well as for achieving the overall project objectives. The industrial partners were actively involved in the project and provided valuable inputs, guidance, and support throughout the project. In addition to sharing their knowledge and practical experiences in the project group meetings, the industrial partners also supported the project in-kind by providing equipment and invaluable measurement data from field and test measurements.

2.1 Project plan

In order to achieve its objectives, the project was divided into six smaller but logical phases. These phases were not separate, distinct series of activities, but were integrated together. The work plan for different phases of the project is described in the following sections in more detail.

2.1.1 Compilation of Existing Knowledge and Practices

A comprehensive overview of literature and state-of-the-art practices used in industry was designed as the first phase of the project. The literature review was planned to be carried out using leading academic search engines (e.g. Science Direct, Compendex, Scopus, Google Scholar etc.). The state-of-the-art practices within the industry were aimed to be identified by consulting stakeholders and asking them for their feedback in various formal and informal ways. The stakeholders identified as relevant to the project included (but were not limited to) property owners and managers, consultants, heat pump manufacturers, borehole drillers, energy companies, trade organizations, and testing and research institutions.

2.1.2 Critical Analysis of Existing Knowledge and Practices

The second phase of the project was planned to be a critical analysis of existing knowledge and contemporary practices related to design and simulation of GSHP and borehole energy storage systems. The objective of this phase was to focus on strengths and weaknesses of the existing practices and to identify areas requiring improvements. The results of the analysis were to help determine the required course of actions for developing mathematical models and computational tools required for complete system modelling of GSHP systems.

2.1.3 Experimental and Field Measurements

Studies focused on energy use in different types of buildings and energy savings from GSHP systems were planned as the third phase of the project. A combination of field measurements and laboratory experiments were to be performed for this research project. It was planned that detailed field measurements would be carried out to collect energy usage data for a number of case study buildings. A blend of old, renovated and new residential and commercial buildings would be measured. Existing data from previously measured buildings would also be used.

The experimental studies were planned to be carried out at the GSHP test facility of the division of Building Services Engineering. The experiments were to be used for investigating different aspects of GSHP systems under controlled laboratory conditions. The experimental data and results were also to be used for designing and validating simulation studies.

2.1.4 Theory Development

The fourth phase of the project was designed to involve theory development. The following mathematical models were planned to be developed in this phase of the project:

- An analytical model to study the short-term response of a borehole,
- A long-term response model for multiple boreholes,
- Temperature response functions of the borehole field valid for time-scales from minutes to decades,
- A load aggregation technique to speed up multi-year simulations of GSHP systems.

The project was also aimed at generating new knowledge on thermal response testing and evaluation of borehole heat exchangers. Issues like random errors between tests, repeatability and reproducibility of tests, and sensitivities of test results were planned to be addressed comprehensively in this phase of the project.

2.1.5 Development of Modelling and Design Tools

Development of new modelling tools for design and simulation of GSHP systems was planned as the fifth phase of the project. The major objective of this phase was to develop an analytical tool to perform multi-year simulations of complete GSHP system. In addition, it was also planned to develop the following:

- A tool to predict the short-term response of a borehole system.
- A program to generate temperature response functions for a given borehole heat exchanger field,
- A program to evaluate thermal response tests on water-filled boreholes.

2.1.6 Dissemination of Results

Reporting and dissemination of results was regarded as the sixth and final phase of the project. It was planned that results from this research project would be presented at various forums, including:

- Project meetings with participating companies,
- Effsys-day seminars, and other national and international seminars,
- Swedish trade magazines e.g. Energi & Miljö, Kyla etc.
- International conference proceedings e.g. IIR conference, REHVA conference, ASHRAE meetings etc.
- Accredited journals e.g. Renewable Energy, International Journal of Heat and Mass Transfer, HVAC&R Research, ASHRAE Transactions etc.
- Research reports and a doctoral thesis.

3 Experimental and Field Studies

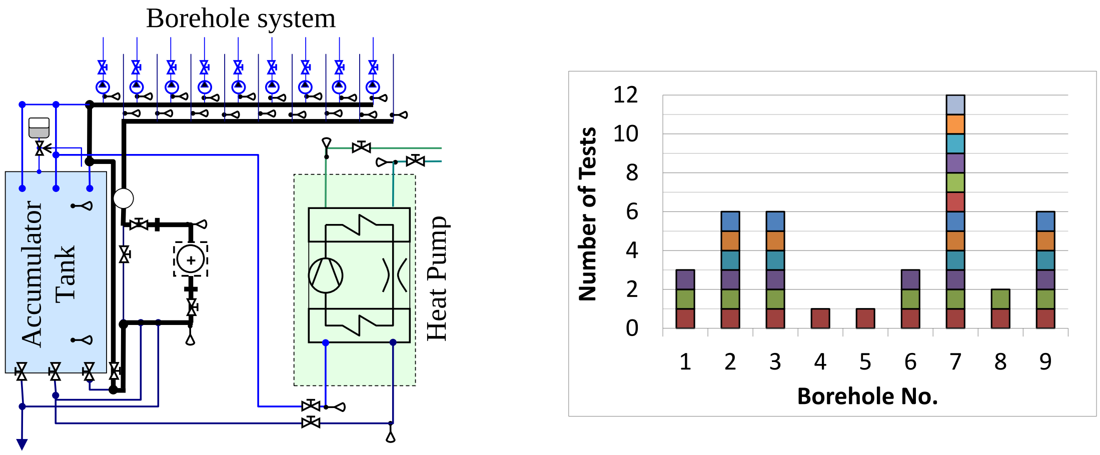
Within the framework of this project, several case studies were conducted in different types of buildings. The focus of these case studies were on ground-source heating and cooling, energy use of GSHP systems, and thermal response of the ground heat exchanger in long and short time-scales. The study cases included laboratory and field studies performed both in Sweden and abroad, in collaboration with our local and international partners. However, this report includes only those cases which were studied directly by the project group at Chalmers. These included a full-scale test facility, a single family house, a small clubhouse, a medium-sized police station, a standard-sized academic building, and a large shopping centre.

3.1 Chalmers Test Facility

In this research project, a series of experimental studies were conducted at a full-scale test facility [13] at the division of Building Services Engineering, Chalmers University of Technology. An integral part of Chalmers test facility is its GSHP system, which consists of nine 80-m-deep boreholes, three heat pumps, two dry coolers and a number of thermal storage tanks.

The test facility was used to perform over forty thermal response tests under different experimental conditions. Figure 3.1a shows the schematic diagram of the test facility's response testing setup. The tests performed on each borehole are summarized in Figure 3.1b.

The experiments were used to study thermal properties like undisturbed ground temperature, ground thermal conductivity and borehole resistance of nine boreholes in close proximity. Issues like repeatability and reproducibility of the response tests were comprehensively studied using various alternative approaches. Such investigations have rarely been conducted on an academic level in controlled laboratory conditions.



(a) (b)

Figure 3.1 Chalmers testing facility: (a) Experimental setup [14] (b) Tests performed on each borehole [9].

3.2 Single Family House in Borås

The considered house is a single family unit located in Borås. It was built in 1977 and has a total heated area of 150 m^2. In the original installation, electric resistance heaters were used to meet both the heating and the hot water demands of the house. In 1996, the heating system of the house was replaced with a GSHP system. An exhaust air recharging system was later added to the GSHP system in 2000. The hot water system of the house was also replaced in 2006 and a new integrated heating and hot water thermal energy storage system was installed. Figure 3.2 shows the schematic of the GSHP system with recharging, free cooling and heat recovery possibilities.

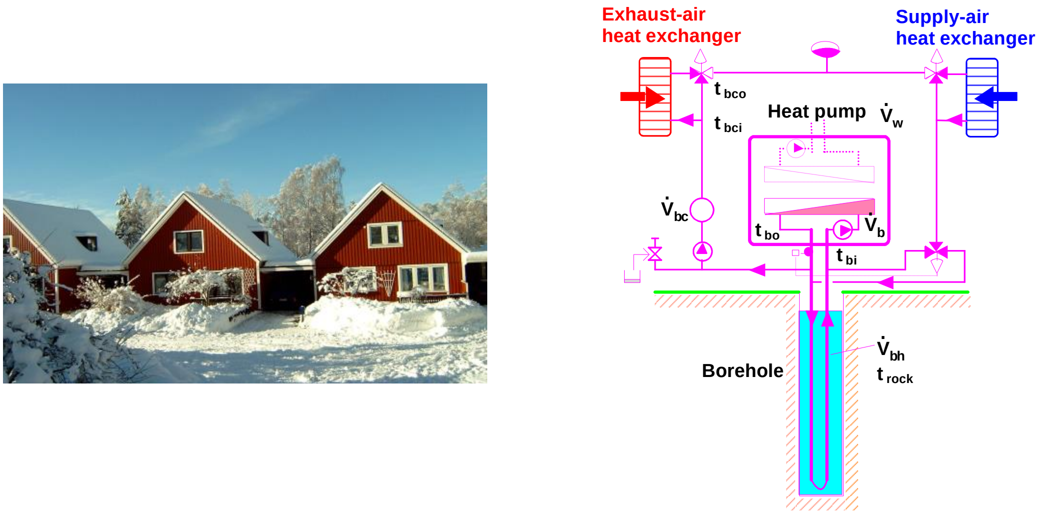


Figure 3.2 The GSHP system (right) installed at a single family-house (left) in Borås with recharging, free cooling and heat recovery possibilities [6].

The purchased energy for heating, hot water and household electricity has been measured for this installation since 1977. Figure 3.3 shows these data for several years. The combined electric input for heating and hot water has decreased from approximately 20 MWh/year (~130 kWh/m^2/year) before the modifications to less than 5 MWh/year (~30 kWh/m^2/year) after the modifications. The total energy use of the installation, including heating, hot water and household electricity, has reduced to only 9 MWh/year (~67 kWh/m^2/year) after the modifications.

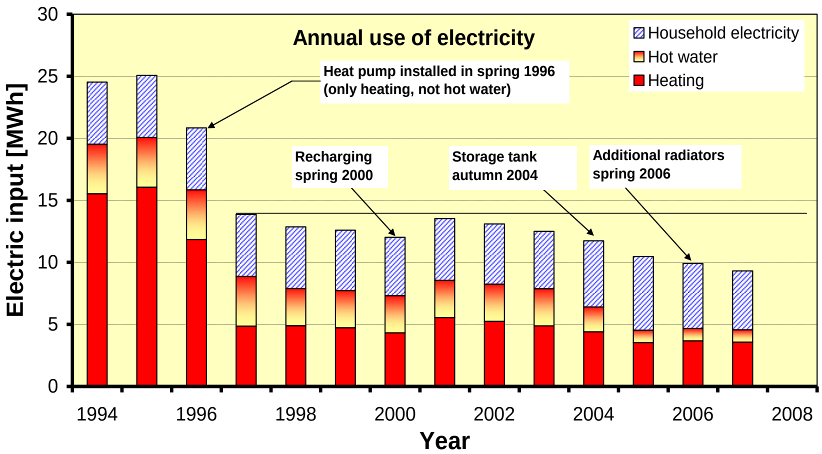


Figure 3.3 Annual use of energy for heating, hot water and household electricity [6].

3.3 Clubhouse in Sisjön

The clubhouse in Sisjön belongs to the orienteering club 'Frölunda Ol'. The building, which has an area of about 240 m^2, was constructed in 2004. The clubhouse serves as a meeting and starting point for club's outdoor activities. The clubhouse has a multipurpose community room, and locker rooms with hot showers, and saunas.

The clubhouse uses a GSHP system to provide space heating and hot water. The installation has relatively high hot water consumption because of frequent use of showers. Figure 3.4 describes the system diagram of the GSHP system at clubhouse. As shown in the figure, the ground-source heat pump is coupled to two 500 litre storage tanks. These buffer tanks make provision for the high hot water demand of the clubhouse. The energy use of the clubhouse is summarized in Table 3.1.

Table 3.1 Annual energy use of Clubhouse.

Annual Energy Use	MWh/year	kWh/m^2/year
Heating demand (including DHW)	23	97
Heating supply (including DHW)		
Heat pump	21	89
Supplementary (electric)	2	9
Electricity		
Compressor	7	30
Resistance Heaters	2	9
Pumps	1	5

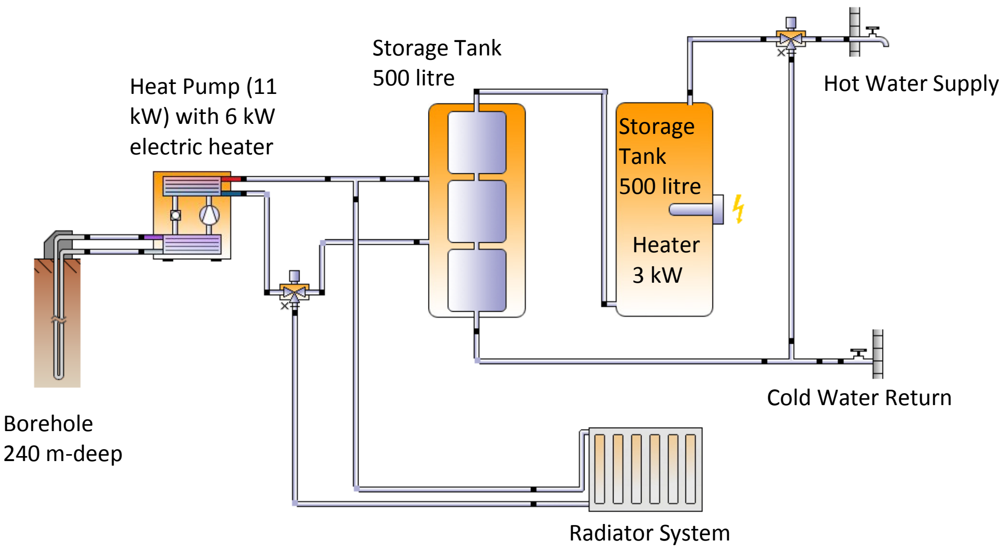


Figure 3.4 Space heating and hot water system at Frölunda Ol's Clubhouse.

3.4 Police Station in Malmö

The newly constructed police station in Malmö is a 4-storey custom-built building with a total floor area of approximately 3,500 m^2 and a temperature-controlled area of about 3,000 m^2. The building has been designed to accommodate approximately 80 police. The police station uses Skanska's patented Deep Green Cooling™ method to provide cooling and pre-heating of out-door supply air.

Photo: http://malmo.se/

This is done by connecting twelve 195-m deep boreholes directly to chilled beams and air handling units without a heat pump. Figure 3.5 shows the schematic diagram of the direct cooling system installed at the building. Table 3.2 presents projected energy-use of the building based on measurement data of 6 months. It is to be emphasized that unlike normal office buildings, the station is operational round the clock and the HVAC system is functioning 24 hours a day all year long.

Table 3.2 Annual energy use estimated from measurement data of 6 months.

Annual Energy Use	MWh/year	kWh/m^2/year
Heating demand	275	94
Heating supply Free heating (without heat pump) Supplementary (bought)	 25 250	 9 86
Cooling demand	100	34
Cooling supply Free cooling (without heat pump)	 100	 34
Electricity Pumps	 5	 2

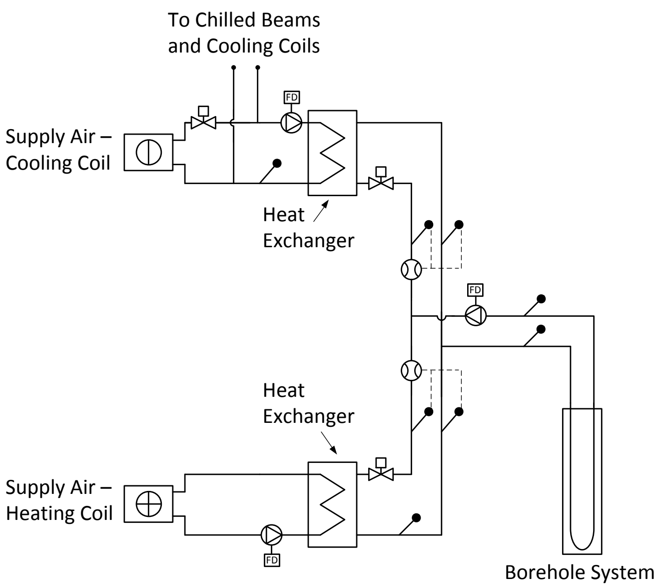


Figure 3.5 Schematic diagram of direct ground cooling and heating system of police station in Malmö.

3.5 University Building in Lund

The Astronomy-House building at Lund University has a gross floor area of about 5,300 m^2. The building houses offices, lecture halls, laboratories and a library. The building was renovated in 2001 and a GSHP system consisting of twenty, 200-m-deep boreholes, was installed in a 4x5 rectangular configuration.

The energy use of the Astronomy-House is summarized in Figure 3.6 and Table 3.3. A key element of the Astronomy-House GSHP system is free cooling, which is obtained from the borehole system without using a heat pump.

Table 3.3 Annual energy use of the Astronomy-House [22].

Annual Energy Use	MWh/year	kWh/m²/year
Heating demand	515	97
Heating supply Heat pump Supplementary (bought)	 475 40	 89 8
Cooling demand	155	29
Cooling supply Free cooling Heat pump (heating + cooling) Heat pump (cooling)	 130 15 10	 25 3 2
Electricity Compressor Pumps	 104 7	 19.6 1.3

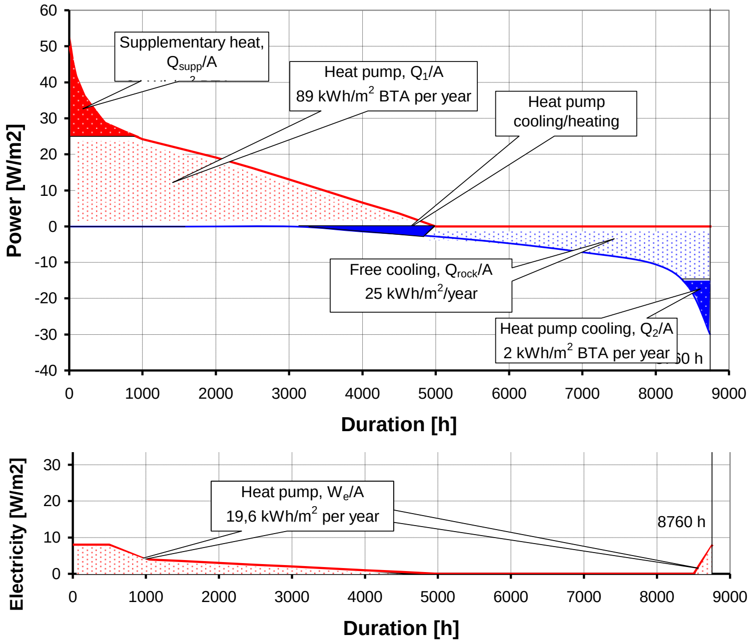


Figure 3.6 Duration diagram for heating and cooling energy use of the Astronomy-House building [22].

3.6 Shopping Centre in Vällingby

“Vällingby City” is a large shopping centre in west Stockholm. It houses 125 shops, 58 offices, 16 services and amenities centres, 30 restaurants and cafes, and many other businesses. The shopping centre was renovated in recent past, among other things with the installation of a new GSHP system.

Photo: http://vallingbycity.se/

The GSHP system at Vällingby City is designed to meet the cooling energy needs of its 86,200 m^2 shopping and commercial area. Additionally, the GSHP system also provides a major part of the required heating demands. The ground system consists of 153 boreholes with a depth of nearly 200 m. Figure 3.7 shows the schematic diagram of the GSHP system installed at Vällingby City.

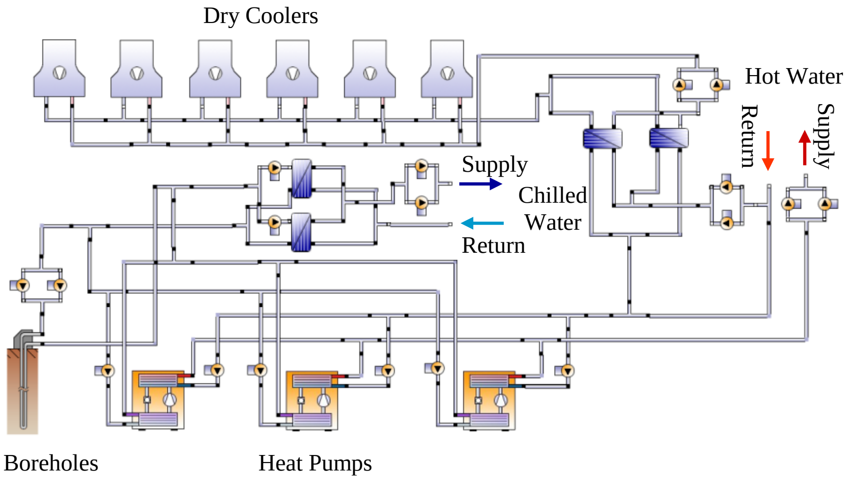


Figure 3.7 The GSHP system at Vällingby City.

The GSHP system at Vällingby City was monitored for almost 2 years. The monitoring was carried out in partnership with another EFFSYS+ project “Energy efficiency in shopping malls with an improved indoor climate”. Table 3.4 provides summary results of the annual energy use for space heating and cooling.

Table 3.4 Annual energy use of Vällingby City.

Annual energy Use	MWh/year	kWh/m²/year
Heating demand	12187	141
Heating supply		
Heat pump	8064	94
Supplementary (bought)	4122	48
Cooling demand	5367	62
Cooling supply		
Heat pump	5367	62
Electricity (heat pump)		
Heat Pump (heating)	2165	25
Heat Pump (cooling)	1327	15

4 Project Results and Dissemination

Results from this project have been presented in detail in Saqib Javed's PhD thesis "**Thermal modelling and evaluation of borehole heat transfer**" (Building Services Engineering, PhD Thesis, D2012:01, 80 pages, Chalmers University of Technology, Gothenburg.). More recent results have also been reported in Damien Casetta Master's thesis "**Implementation and validation of a ground source heat pump model in MATLAB**" (Building Services Engineering, Master's Thesis, E2012:11, 73 pages, Chalmers University of Technology, Gothenburg.) and research papers published in years 2012, 2013 and 2014. The following section provides a summary of the project results.

4.1 Overview of Results

The project included a combination of mathematical modelling, field measurements, and laboratory experiments with a goal to develop knowledge and tools necessary to perform design and performance optimization of GSHP systems.

Compilation of Existing Knowledge and Practices

A detailed collection of existing knowledge and practices of GSHP system design, operation and analysis was compiled and annotated within the scope of the project. A state-of-the-art review of analytical and numerical models of borehole heat exchangers was provided in references [12] and [16]. Various building energy simulation software were discussed in references [7] and [8] from a GSHP system modelling perspective. Different approaches to calculate temperature response functions for short- and long-term modelling of boreholes were studied in reference [3]. The account of various types of controllers and control schemes for adaptive control and dynamic optimization of GSHP systems was given in reference [21]. A survey of load-aggregation methods to perform multi-year simulations of borehole heat exchangers was reported in reference [4]. Existing methods and tools to evaluate thermal response tests were presented and compared in references [14], [17] and [18].

Critical Analysis

In this project we carried out critical analyses of existing theories, models and practices used for design and operation of GSHP systems. The conclusion of these analyses is summarized here. The analysis of existing analytical models indicated that none of the previously developed solutions is valid for short-time modelling of borehole heat exchangers. Use of these models for multiple borehole heat exchangers is also not viable. The existing analytical models can, however, be used with reasonable accuracy to predict the long-term response of a single borehole heat exchanger. The analysis of multi-year simulations of borehole heat exchangers suggested that these simulations are mostly performed using superposition of temperature response functions. At present, calculation of the temperature response functions is a complicated time-consuming process based on intrinsically complex numerical simulations. For this reason, these functions are only available for some very particular and limited configurations of borehole fields. The analysis of control strategies developed for GSHP system applications illustrated that existing controllers and algorithms to optimize borehole heat transfer are based on oversimplified models. The analysis of thermal response tests on Swedish groundwater-filled boreholes showed that the test results are affected by heat-injection rates used during the test. Most existing thermal response test evaluation methods are not designed to evaluate tests performed on groundwater-filled boreholes. These methods are also unable to evaluate multi-injection rate tests performed on groundwater-filled boreholes.

Experimental and Field Measurements

In the framework of this project, field measurements were carried out at a number of different buildings. The case study buildings were briefly described in Chapter 3 of this report. The emphasis of the field studies was primarily on the energy use of heating and cooling systems installed in the buildings. The field cases present energy-efficient applications of ground-source heating and cooling in buildings ranging from a single family house to large office and commercial buildings.

The project also generated a substantial amount of experimental data from the GSHP test facility at Chalmers. Over forty tests were designed and conducted at the Chalmers laboratory to obtain quantitative data for studying various aspects of borehole heat transfer.

Theoretical Analysis

Within the scope of this project, various aspects of borehole heat exchanger modelling were investigated in detail. Many new mathematical models were developed and validated. New analytical and numerical solutions to model the dynamic thermal response of a borehole on short time scales were presented in references [10] and [15]. An innovative analytical approach to perform dynamic, multi-year simulations of borehole heat transfer was presented in reference [4]. The approach uses the analytical solution of reference [10] together with a new finite line-source solution [3] to develop temperature response functions. These functions were used in reference [8] for performing multi-year simulations of borehole systems with prescribed heating and cooling loads. A new load aggregation scheme for multi-year simulations of GSHP systems was developed that drastically reduces the computational time requirements without compromising the accuracy of the simulation results.

In this project, many unresolved issues of thermal response testing were also studied. Over forty tests were performed in a state-of-the-art GSHP laboratory with nine 80-m-deep boreholes. Tests with durations between 48 and 320 hours were conducted. All nine boreholes were first tested under similar conditions in reference [14] to check random uncertainties between tests. It was shown in reference [18] that the random uncertainties in test results can affect the length requirements of borehole heat exchangers by approximately 10 %. Several other tests with diverse conditions were also performed to study the sensitivity of test results and to quantify their uncertainties. Some tests were also repeated to ascertain reproducibility of the results. It was shown in reference [19] that length requirements of a single borehole heat exchanger can be affected up to 25 % because of convective heat transfer inside a borehole. In a summary paper [9] on thermal response testing, it was concluded that tests shorter than 50 hours and evaluated using simple line-source approximation methods give substantially inaccurate results. For groundwater-filled boreholes, tests performed with higher power input resulted in significantly lower borehole resistance estimations. Temperature measurements in the borehole annulus indicated a recovery time of 2–3 weeks after a 50-hour test conducted with an injection rate of 50–70 W/m. Tests repeated under identical conditions gave reproducible results.

Development of Modelling and Design Tools

This project resulted in the development of a number of modelling tools for design and simulation of GSHP systems. The thermal response test evaluation method presented in reference [17] was implemented as a stand-alone computer program called TEP. The program can be used to evaluate both single and multi-injection rate tests conducted on water-filled boreholes. The analytical method [3] to calculate fluid temperatures from minutes to decades was implemented both as a Mathcad worksheet and a MATLAB tool. The tool can be used to generate temperature response functions for any configuration of boreholes. A MATLAB tool was developed for modelling and simulation of the complete GSHP system. The tool is based on three separate mathematical models: an analytical ground heat exchanger model with multiple boreholes, a curve-fit model for heat pump, and a load-aggregation model for building heating and cooling demands. All the tools were tested and validated against field measurements, experimental data and other programs.

4.2 Dissemination of Results

Dissemination of the project results was realized in many different ways. Throughout the project duration, the results were regularly presented in project-group meetings. The results were also presented in scientific journals, international conferences, EFFSYS seminars, and other national and international forums on a regular basis. The dissemination of results is described in more detail below.

4.2.1 Project Meetings

Following is a list of project meetings held during course of the project. The key discussion points and presentations made at each meeting are also listed. Detailed minutes from each meeting are available but this report confines itself only to the most notable items.

2011-04-06 Chalmers, Gothenburg (13 participants)

Presentations:

- Javed, Saqib (Chalmers). Phase 1 conclusion.
- Javed, Saqib (Chalmers). Phase 2 plans.

Discussion points:

Study visit to building services engineering laboratory, decline in fluid temperature over time; thermal resistance of groundwater-filled boreholes; effects of borehole configuration and groundwater advection on borehole fluid temperatures; future research.

2011-09-07 Chalmers, Gothenburg (15 participants)

Presentations:

- Claesson, Johan (Chalmers). Response solutions for borehole temperature.
- Nakos, Helena (Chalmers). Testing of groundwater-filled boreholes.
- Javed, Saqib (Chalmers). Project publications.

Discussion points:

Development and validation of analytical step-response solutions; differences in evaluation of grouted and groundwater-filled boreholes; injection rate dependence of groundwater-filled boreholes; heat pump manufacturer data; hourly load profiles for residential and commercial buildings.

2012-01-13 Chalmers, Gothenburg (50+ participants)

Presentations:

- Javed, Saqib (Chalmers). Optimization of heat pump systems.

Discussion points:
Dissertation seminar, analytical methods; short- and long-term response; complete system modelling; response testing; experimental results; collaboration; future research.

2012-01-19 Oklahoma State University, Stillwater, USA (25+ participants)

Presentations:

- Javed, Saqib (Chalmers). Ground-source heat pump systems.
- Claesson, Johan (Chalmers). Past, present & future of borehole modelling.

Discussion points:
Curve-fit modelling of heat pumps; differences between American and Swedish systems; development of simulation tools; current modelling approaches; experimental testing; possible research collaborations; laboratory visit.

2012-05-22 Chalmers, Gothenburg (13 participants)

Presentations:

- Spitler, Jeff (Oklahoma University). Alternative ground heat exchangers.
- Monteyne, Griet (Vrije Universiteit). Frequency domain modelling.
- Claesson, Johan and Javed, Saqib (Chalmers). Thermal modelling.

Discussion points:
American systems including foundation heat exchangers, standing column wells, surface water heat pumps; modelling approaches (black box modelling of borehole heat transfer, multipole method); design uncertainties from numerical and analytical approaches; principle of super-positioning; load-aggregation.

2012-10-25 Chalmers, Gothenburg (3 participants)

Presentations:

- Lamarche, Louis (ÉTS Montreal). Geothermal heat pumps in Canada.
- Javed, Saqib (Chalmers). Project presentation.

Discussion points:
Laboratory visit; Canadian and Swedish systems; analytical modelling of multiple borehole systems; simulation software including TRNSYS and CAN-Quest; collaboration possibilities.

2012-12-10 Chalmers, Gothenburg (3 participants)

Discussion points:
Convection and advection in boreholes; limitations of analytical approaches when designing borehole systems; superposition borehole model; inter-model comparisons.

2013-02-20 Chalmers, Gothenburg (3 participants)

Discussion points:
Uncertainties in borehole thermal resistance estimations; energy piles; modelling of Swedish heat pump systems with integrated tank and electric heater; future publications.

4.2.2 Project Publications

Following is the complete list of publications resulting from this project, sorted by category.

Research Theses:

1. Javed, S, 2012. Thermal modelling and evaluation of borehole heat transfer. Building Services Engineering, PhD thesis, D2012:01, 80 pages. (Chalmers University of Technology.) Gothenburg.

2. Casetta, D, 2012. Implementation and validation of a ground source heat pump model in MATLAB. Building Services Engineering, Master's thesis, E2012:11, 73 pages. (Chalmers University of Technology.) Gothenburg.

3. Nakos, H, 2011. Response testing and evaluation of groundwater-filled boreholes – Development and validation of a new calculation tool. Building Services Engineering, Master's thesis, E2011:18, 53 pages. (Chalmers University of Technology.) Gothenburg.

Journal Articles:

1. Monteyne, G, Javed, S, Vandersteen, G, 2014. Heat transfer in a borehole heat exchanger: Frequency domain modelling. International Journal of Heat and Mass Transfer, vol. 69(2014), pp. 129-139.

2. Javed, S, Nakos, H, Claesson, J, 2012. A method to evaluate thermal response tests on groundwater-filled boreholes. ASHRAE Transactions, vol. 118(1), pp. 540-549.

3. Claesson, J, Javed, S, 2012. A load-aggregation method to calculate extraction temperatures of borehole heat exchangers. ASHRAE Transactions, vol. 118(1), pp. 530-539.

4. Liebel, H, Javed, S, Vistnes, G, 2012. Multi-injection rate thermal response test with forced convection in a groundwater-filled borehole in hard rock. Renewable Energy, vol. 48(2012), pp. 263-268.

5. Claesson, J, Hellström, G. 2011. Multipole method to calculate borehole thermal resistances in a borehole heat exchanger. Journal of HVAC&R Research, vol. 17(6), pp. 895-911.

6. Claesson, J, Javed, S, 2011. An analytical method to calculate borehole fluid temperatures for time-scales from minutes to decades. ASHRAE Transactions, vol. 117(2), pp. 279-288.

7. Javed, S, Fahlén, P, 2011. Thermal response testing of a multiple borehole ground heat exchanger. International Journal of Low Carbon Technologies, vol. 6(3), pp. 141-148.

8. Javed, S, Spitler, J, Fahlén, P, 2011. An experimental investigation of the accuracy of thermal response tests used to measure ground thermal properties. ASHRAE Transactions, vol. 117(1), pp. 13-21.

9. Javed, S, Claesson, J, 2011. New analytical and numerical solutions for the short-term analysis of vertical ground heat exchangers. ASHRAE Transactions, vol. 117(1), pp. 3-12.

Conference Proceedings:

1. Javed, S, 2013. Thermal Response Testing: Results and Experiences from a Ground Source Heat Pump Test Facility with Multiple Boreholes. Proceedings of 11th REHVA World Congress (Clima 2013), Prague, Czech Republic.

2. Javed, S, Claesson, J, Beier, R, 2011. Recovery times after thermal response tests on vertical borehole heat exchangers. Proceedings of 23rd IIR International Congress of Refrigeration (ICR2011), Prague, Czech Republic.

3. Javed, S, Fahlén, P, 2010. Thermal response testing of a multiple borehole ground heat exchanger. Proceedings of 9th International Conference on Sustainable Energy Technologies (SET 2010), Shanghai, China.

Popular Science Articles/Presentations:

1. Javed, S, 2013. Optimization of ground source heat pump systems. Effsys+ day 2013, Gothenburg, 2012-10-18.

2. Javed, S, 2012. Optimization of ground source heat pump systems. Effsys+ day 2012, Gothenburg, 2012-10-19.

3. Javed, S, 2012. Analytical methods for modelling and simulation of ground source heat pump systems. Invited presentation, IEA-SHC Task 44 and HPP Annex 38: Solar and Heat Pump systems, meeting 6, Technical University, Lyngby, Denmark, 2102-10-10.

4. Javed, S, 2012. Modelling and evaluation of borehole heat transfer. (Project group meeting, 2012-05-22), Gothenburg.

5. Javed, S, 2012. Thermal modelling and evaluation of borehole ground source heat exchangers. Invited seminar presentation, Building and Environmental Thermal Systems Research Group (BETSRG), Oklahoma State University, Stillwater, USA, 2102-01-19.

6. Claesson, J, 2012. Thermal modelling of borehole ground source heat exchangers: Past, present and future. Invited seminar presentation, Building and Environmental Thermal Systems Research Group (BETSRG), Oklahoma State University, Stillwater, USA, 2102-01-19.

7. Javed, S, 2012. Thermal modelling and evaluation of borehole heat transfer. (Dissertation Presentation, 2012-01-13), Gothenburg.

8. Javed, S, 2011. Optimization of ground source heat pump systems. Effsys+ day 2011, Gothenburg, 2011-10-14.

9. Claesson, Johan, 2011. An analytical method to calculate borehole fluid temperatures for time-scales from minutes to decades. (Project group meeting, 2011-09-07), Gothenburg.

10. Javed, S, 2011. Optimization of GSHP system project - Publications. (Project group meeting, 2011-09-07), Gothenburg.

11. Nakos, H, 2011. Testing and evaluation of groundwater-filled boreholes. (Project group meeting, 2011-09-07), Gothenburg.

12. Javed, S, Fahlén, P, 2011. Termisk modellering och utvärdering av borrhålssystem. Energi & Miljö, No. 6-7/11: 51-54.

13. Javed, S, 2011. Optimization of ground-source heat pump systems – Effsys+ project. (Project group meeting, 2011-04-06), Gothenburg.

14. Javed, S, 2011. Optimization of ground-source heat pump systems – Effsys2 project. (Project group meeting, 2011-04-06), Gothenburg.

15. Javed, S, 2011. Modelling and evaluation of ground-source heat pump systems. 2nd European Geothermal PhD Day (EGPD 2011), Reykjavik, Iceland, 2011-03-02.

5 Discussion and Conclusions

Modelling of GSHP systems for design and simulation purposes is an intricate process. It involves modelling of several sub-systems including building, heat pump and borehole system, among others. Of these, modelling of the borehole system is of particular interest as the fluid temperature exiting the ground heat exchanger affects the performance and efficiency of the whole GSHP system. Also, the knowledge of fluid temperature exiting the borehole system is the principal prerequisite for technical, economical and operational optimization of GSHP systems. The fluid temperature exiting a borehole system depends, among other things, on thermal responses of the borehole heat exchanger and the ground surrounding the borehole field, and the thermal interactions between the boreholes. In this project, all these factors were studied extensively through experiments, mathematical modelling, simulation studies, and field monitoring.

The main results were presented and discussed in detail in previous publications from the project (see Section 4.2.2). However, an overview of the project results and a summary of the major findings are presented in the following.

5.1 Discussion

Sweden has a long tradition of using GSHP systems for heating of single family houses. The design of these small systems is relatively straightforward and is often based on experience, simple analytical methods and/or standard design tools. However, in the last decade or so, the use of GSHP systems in commercial and office buildings has increased significantly. In general, most traditional and slightly older commercial and office buildings in Sweden have fairly high heating demands in winter and some cooling requirements during the summer. For such buildings, the application of GSHP systems is focused on the long-term heat extraction or seasonal storage of heat in the ground. On the other hand, for a contemporary office or commercial Swedish building the shift between heating and cooling demands is far more frequent. Many modern buildings have cooling demands during the day-time and heating demands at night-time. Some buildings even have simultaneous heating and cooling requirements in different areas. For these modern and contemporary buildings, borehole heat exchangers of the GSHP system mostly act as short-term heat storage.

The main objective of this project was the design and performance optimization of GSHP systems for existing and new installations. A key parameter in this regard is the temperature of the fluid circulating in the borehole heat exchanger, which greatly affects the efficiency, performance and economics of the whole system. Calculating the accurate borehole fluid temperatures is a multifaceted procedure which involves thermal processes that vary from short- to long-term intervals, with time resolutions ranging from minutes to years. Due to its large thermal capacity, thermal response of the ground to an overall heat extraction or injection is a slow process, occurring over months or even years. On the other hand, due to its small thermal capacity, thermal response of the borehole heat exchanger itself is quite rapid, occurring within minutes to hours. Another significant factor is development of thermal interactions between neighbouring boreholes over time. Although, the development of thermal interactions between boreholes depends on the size and configuration of the borehole field, but in most typical cases, it is a long-term process, occurring over weeks and months.

In this project, the specific focus was on the development of new analytical methods and tools to address above-mentioned issues of short-term borehole response, long-term ground response and thermal interaction between boreholes. The major reason of our choice to focus our attention on analytical approaches was the time-efficiency and flexibility of these approaches to model GSHP systems. Within the scope of this project, we firstly developed an analytical solution to model the short-term response of the borehole. Next, the analytical solution was used together with a newly developed finite line-source solution to perform dynamic multi-year simulations of borehole systems. A load aggregation scheme was also developed to reduce computational time requirements with little penalty in terms of simulation accuracy. All these methods were presented in detail in a PhD thesis. The newly developed borehole models were coupled to heat pump and building load models in a Master's thesis to perform complete system simulations of GSHP systems. The models developed within this project were shown to effectively capture the dynamics of borehole heat transfer and were used for adaptive control and dynamic optimization of GSHP systems.

Another significant research contribution of this project was in the area of thermal response tests, which are conducted to determine ground thermal properties when designing medium- to large-sized GSHP systems. Sweden is somewhat unique in the fact that it uses groundwater-filled boreholes. The heat transfer in these boreholes is driven by natural convection and advection, and not conduction as is the case with grouted boreholes. This project dealt with various uncertainties and unresolved issues in testing of groundwater-filled boreholes. These included test accuracy, sensitivity of borehole system design to uncertainties in test results, role of natural convection, evaluation of multi-injection rate tests, and recovery times after a test. A new tool to evaluate thermal response tests on groundwater-filled boreholes was also developed.

All the models and control strategies developed within the project were tested and validated using simulation, experimental and field studies. Simulations were performed using state-of-the-art research and commercial tools. Experiments were conducted in a carefully controlled experimental setup that was developed in the initial phase of the project. Field studies were conducted in several buildings ranging from a single family house to large office and commercial buildings. The field studies chosen for this project, and presented in chapter 3 of this report, are examples of good practices in ground heating and cooling systems.

5.2 Conclusions

This project dealt with various aspects of ground-based heating and cooling in detail. The main outcome of the project was the development of analytical methods and tools for dynamic modelling and simulation of GSHP systems. The tools developed in this project can be used to design more energy-efficient systems. The mathematical models from the project can also be implemented in existing building energy simulation software. These models can also be used to develop controllers and control schemes to maximize the performance of the GSHP system. The project also identified several examples of good practices of implementing ground heating and cooling systems. The results from the project were presented in one PhD and two Master theses, and 12 journal and conference proceeding papers.

The major achievements of the project are summarised in the following.

- A validated analytical solution to model short-term heat transfer in the borehole.
- A new finite line-source solution, which has been reduced to one integral only.
- Step-response functions for both single and multiple borehole systems, which are valid for time-scales from minutes to decades.
- A new analytical approach to perform dynamic, multi-year simulations of heat transfer in multiple borehole fields.
- A load aggregation technique to reduce computational times when performing multi-year simulations of GSHP systems.
- Analysis of random errors between tests, borehole finishing effects and possible inhomogeneities for thermal response tests performed on nearby boreholes.
- Sensitivity analysis of ground thermal conductivity and borehole thermal resistance estimations from thermal response tests for various test and parameter uncertainties.
- Quantification of effects of convective heat transfer on required length of borehole heat exchanger.
- Borehole recovery times for various sets of ground formation, heat injection rates and test durations.
- A new method to evaluate multi-injection rate tests on grouted and water-filled borehole heat exchangers.
- New mathematical models for adaptive control and dynamic optimization of GSHP systems.
- Best practices and state-of-the-art examples of ground heating and cooling systems.

6 References

1. Andersson, O, Bjelm, L, 2013. Geothermal Energy Use, Country Update for Sweden. Proceedings of European Geothermal Energy Congress (EGC) 2013, Pisa, Italy.

2. Casetta, D, 2012. Implementation and validation of a ground source heat pump model in MATLAB. Building Services Engineering, Master's thesis, (Chalmers University of Technology.) Sweden.

3. Claesson, J, Javed, S, 2011. An analytical method to calculate borehole fluid temperatures for time-scales from minutes to decades. ASHRAE Transactions, vol. 117(2), pp. 279-288.

4. Claesson, J, Javed, S, 2012. A load-aggregation method to calculate extraction temperatures of borehole heat exchangers. ASHRAE Transactions, vol. 118(1), pp. 530-539.

5. Fahlén, P, 2005. Teknik och goda exempel finns - Varför bygger vi inte mera energisnålt (Swedish). Proceedings of SVR Samhällsbyggnadsdagar 2005, Gothenburg, Sweden.

6. Fahlén, P, 2008. Efficiency aspects of heat pump systems - Load matching and parasitic losses. Newsletter IEA heat pump centre, vol. 26(3), pp. 38-49.

7. Javed, S, 2010. Design of ground source heat pump systems - Thermal modelling and evaluation of boreholes. Building Services Engineering, Licentiate thesis, (Chalmers University of Technology.) Sweden.

8. Javed, S, 2012. Thermal modelling and evaluation of borehole heat transfer. Building Services Engineering, PhD thesis, (Chalmers University of Technology.) Sweden.

9. Javed, S, 2013. Thermal Response Testing: Results and Experiences from a Ground Source Heat Pump Test Facility with Multiple Boreholes. Proceedings of 11th REHVA World Congress (Clima 2013), Prague, Czech Republic.

10. Javed, S, Claesson, J, 2011. New analytical and numerical solutions for the short-term analysis of vertical ground heat exchangers. ASHRAE Transactions, vol. 117(1), pp. 3-12.

11. Javed, S, Claesson, J, Beier, R, 2011. Recovery times after thermal response tests on vertical borehole heat exchangers. Proceedings of 23rd IIR International Congress of Refrigeration (ICR2011), Prague, Czech Republic.

12. Javed, S, Claesson, J, Fahlén, P, 2010. Analytical modelling of short-term response of ground heat exchangers in ground source heat pump systems. Proceedings of 10th REHVA World Congress (Clima 2010), Antalya, Turkey.

13. Javed, S, Fahlén, P, 2010. Development and planned operation of a ground source heat pump test facility. Newsletter IEA heat pump centre, vol. 28(1), pp. 32-35.

14. Javed, S, Fahlén, P, 2011. Thermal response testing of a multiple borehole ground heat exchanger. International Journal of Low Carbon Technologies, vol. 6(3), pp. 141-148.

15. Javed, S, Fahlén, P, 2011. Termisk modellering och utvärdering av borrhålssystem. Energi & Miljö, No. 6-7/11: 51-54.

16. Javed, S, Fahlén, P, Claesson, J, 2009. Vertical ground heat exchangers – A review of heat flow models. Proceedings of 11th International Conference on Thermal Energy Storage (Effstock 2009), Stockholm, Sweden.

17. Javed, S, Nakos, H, Claesson, J, 2012. A method to evaluate thermal response tests on groundwater-filled boreholes. ASHRAE Transactions, vol. 118(1), pp. 540-549.

18. Javed, S, Spitler, J, Fahlén, P, 2011. An experimental investigation of the accuracy of thermal response tests used to measure ground thermal properties. ASHRAE Transactions, vol. 117(1), pp. 13-21.

19. Liebel, H, Javed, S, Vistnes, G, 2012. Multi-injection rate thermal response test with forced convection in a groundwater-filled borehole in hard rock. Renewable Energy, vol. 48(2012), pp. 263-268.

20. Lund, J W, Freeston, D H, Boyd, T L, 2011. Direct utilization of geothermal energy 2010 worldwide review. Geothermics, vol. 40, no. 3, pp. 159-180.

21. Monteyne, G, Javed, S, Vandersteen, G, 2014. Heat transfer in a borehole heat exchanger: Frequency domain modelling. International Journal of Heat and Mass Transfer, vol. 69(2014), pp. 129-139.

22. Naumov, J, 2005. Optimization of ground-coupled systems for heating and cooling of buildings. Licentiate thesis, (Chalmers University of Technology.) Sweden.

23. Nakos, H, 2011. Response testing and evaluation of groundwater-filled boreholes – Development and validation of a new calculation tool. Master's thesis, (Chalmers University of Technology.) Sweden.