The 2012 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM' 12)
Seoul, Korea, August 26-30, 2012

Direct Geothermal Energy Research and Demonstration Projects for Victoria, Australia

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ABSTRACT

Direct geothermal energy systems use the ground within a few tens of metres of the surface as a heat source in winter and a heat sink in summer for heating and cooling buildings. In closed-loop systems, ground heat exchangers (GHEs) comprise pipes embedded in specifically drilled boreholes or trenches or even built into foundations. In Victoria, more than 85% of the electricity is generated from brown coal. Given that geothermal energy systems operate at a coefficient of performance of about 4, the substitution of commonly used electrical heating and cooling systems with geothermal systems could significantly reduce energy consumption and greenhouse gas emissions. This paper provides an overview of direct geothermal energy research and demonstration projects undertaken by the University of Melbourne in Victoria. This includes i) two recent full scale pilot demonstration projects with vertical and horizontal GHEs respectively, ii) some information of a larger scale project designed to collect detailed information from about 30 to 40 new and retrofit buildings around the state, iii) a summary of the finite element modelling of common and alternative GHEs, and iv) the potential benefits of introducing this technology in sites with temperate climate. The full scale physical and numerical models involved in these projects allow a study of the effects of GHE configuration and actual (typical) heating and cooling demand patterns in Victoria on ground energy system performance, and investigate the potential to improve existing design techniques.

1. INTRODUCTION

There are more than three million *direct* geothermal energy systems installed and in operation around the world. The vast majority can be found in North America and Europe, and an increasing number of systems are being deployed in Asia. Yet, this technology is just starting to be known in Australasia, with only a few hundred

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installations to date. In contrast, Australasia is more familiar with, and to some extent leads, *indirect* geothermal energy technology development, i.e., the use of the thermal energy of the ground (~150˚-200˚C) to generate electricity via turbines of various types.

Direct geothermal energy systems use the ground within a few tens of metres of the surface as a heat source in winter and a heat sink in summer for heating and cooling buildings respectively. The ground temperature at these depths is normally close to the mean atmospheric temperature, far from the much higher ground temperatures required for power generation. In closed-loop systems, ground heat exchangers (GHEs) comprise pipes or ground loops placed in small diameter vertical boreholes drilled to an appropriate depth (typically 30m to 100m), in shallow trenches between about 1m and 2m depth provided there is adequate space beside the building to be serviced, and for larger commercial and industrial buildings, in the foundations themselves. The key element in any direct geothermal system is the ground source heat pump or GSHP, which is connected to the GHEs. In winter, the GSHP extracts heat from water (or other fluid) circulating in the ground loops, upgrades it, and delivers it to a building. In summer, the reverse happens with the GSHP extracting excess heat from the building and rejecting it to the ground. Thus, a GSHP simply moves large quantities of heat between the building and the ground via GHEs, and it does so very efficiently due to the year-round narrow temperature range of the ground.

In Victoria, Australia, more than 85% of the electricity is generated from brown coal, a cheap source of energy, although, regrettably, not the cleanest. According to the Commonwealth Scientific and Industrial Research Organisation (CSIRO), energy use in buildings accounts for 26% of Australia's greenhouse gas emissions and heating and cooling accounts for over half of this. Given that direct geothermal energy systems operate at a coefficient of performance of about 4, the substitution of commonly used electrical heating and cooling systems with geothermal systems could significantly reduce energy consumption and greenhouse gas emissions. The introduction of carbon taxes from the 1st of July 2012 in Australia is predicted to accelerate actions to cut greenhouse gas emissions. In this context, all forms of renewable energy, as well as the continued use of coal for several years, are likely to play a part in this transition into the carbon-tax era. Moreover, the direct geothermal alternative is likely to become a major player in this space because it is abundant and renewable, it involves well established and reliable technology, and, unlike most others, it is available 24 hrs a day.

Despite the large number of direct geothermal system worldwide, and the maturity of GSHP technology, the design of these systems has been driven by the heating, ventilation and air conditioning (HVAC) industry, with little technical input from geotechnical engineers. Consequently, ground loop installations are generally over-designed leading to systems which are neither as cost effective nor competitive as they could be. Further, only a handful of these installations has been instrumented to check the applicability of the design and installation processes used, or to provide information about balanced design for optimal performance, and publicly available literature is limited. This situation is rapidly changing, and there is now an increasing number of geotechnical groups around the world, including the authors, devoted to understanding GHEs and their interactions with the ground, and to ultimately improve design.

This paper provides an overview of direct geothermal energy research and demonstration projects currently undertaken by the University of Melbourne in Victoria.

The work being undertaken aims to collect information about local conditions for the design of GSHP systems and to investigate the potential to improve existing design techniques, not only in the local but also in the global context. To this end, a number of complementary activities are taking place. This includes a fully instrumented full scale pilot demonstration project with vertical GHEs, another fully instrumented full scale pilot project with horizontal GHEs, a much larger scale project designed to collect detailed information from about 30 to 40 new and retrofit buildings around the state of Victoria, state-of-the-art finite element modelling of common and alternative GHEs, and a study of the potential benefits of introducing this technology in places with temperate climate.

2. FULL SCALE PILOT PROJECTS

Two full scale pilot demonstration projects with vertical and horizontal GHEs have been recently commissioned. Details of these follow.

2.1. Vertical GHEs: Beaurepaire Sport Centre

This demonstration project is a field laboratory where GHEs can be operated under relatively controlled conditions and is not currently connected to an occupied building. Colls et al. (2012) present a more detailed description of this project.

<u>Geographical and geological setting</u> The demonstration project is located adjacent to the Beaurepaire Sports Centre at the University of Melbourne’s Parkville Campus, approximately 1.5 km north of the Melbourne CBD.

At the site, a thin layer of topsoil overlies silty clay. Variably weathered siltstone with minor interbedded sandstone is present below 1.0m. Groundwater was encountered at a depth of 14m when the GHEs were drilled (November 2010) and has since risen to a depth of about 12.8m (May 2012).

<u>GHE layout and instrumentation</u> Five GHEs have been built (refer Fig. 1). GHEs A to C are closed-loop systems in which water circulates through HDPE pipe. GHEs D and E are direct exchange GSHP systems in which refrigerant circulates through a pair of copper U-loops embedded in the ground. The GHEs were all drilled to depths of approximately 30m with borehole diameters ranging from about 100mm (GHEs C to E) to 600mm (GHE-A and GHE-B).

GHE-A and GHE-B represent foundation piles fitted with absorber pipes (Fig. 2). Three U-loops are attached to the reinforcing cage in each of these GHEs. The spacing and size of the embedded HDPE pipe varies to allow the effect of this variation to be studied. GHEs C to E represent standalone borehole GHEs.

Six 100mm diameter boreholes (BH1 to BH6) were also drilled to monitor ground temperatures at various distances from the GHEs.

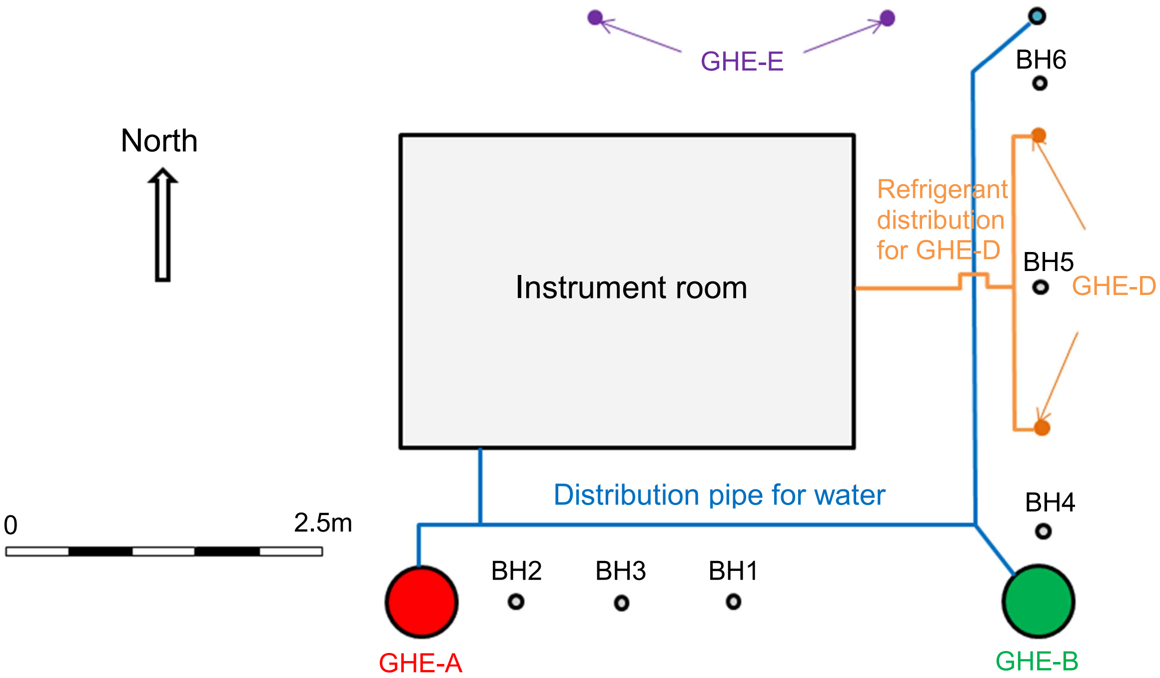


Fig. 1. Layout of the Beaurepaire Geothermal Experiment

Fig. 2. Pile reinforcement cages with absorber U-pipes attached (left) and in the ground prior to concreting (right)

Thermal loads can be applied to the water loops using either electrical resistance elements or a reversible heat pump. A second reversible heat pump can apply thermal loads to GHE-D and GHE-E.

There are 78 thermistors either connected to the GHEs or installed below ground level, to allow temperatures within and around the various GHEs to be monitored. Further thermistors, together with flow meters and a kW transducer, are installed within the instrument room to allow system output and performance to be monitored.

Experimental testing and preliminary results To date, testing has focused on the effect of GHE characteristics (such as pipe diameter and spacing, flow rate and GHE diameter) on the transfer of heat in the local ground. This assessment has primarily been based on the results of thermal response tests (TRTs) undertaken in the various GHEs. Trials of the GSHP system operation have also been performed, including a comparison of the performance of water-loop and refrigerant GSHP systems.

TRTs performed in GHE-C suggest that the average thermal conductivity of the ground over the borehole length is about 2.0 W/(mK). However, it has been observed that the use of TRTs to measure the thermal properties of the ground can be influenced by factors such as the spacing of embedded pipes, the rate of power application during the test and variations in ambient surface temperatures.

The variation in ground temperature in borehole BH1 has now been measured for over 18 months. Fig. 3 shows the measured temperature variation at selected depths in BH1. The reduction in ground temperature variability with increasing depth is clearly evident – below 10 m depth there is very little seasonal variation. While very basic, these data, to these depths, have been rarely measured or published in Australia.

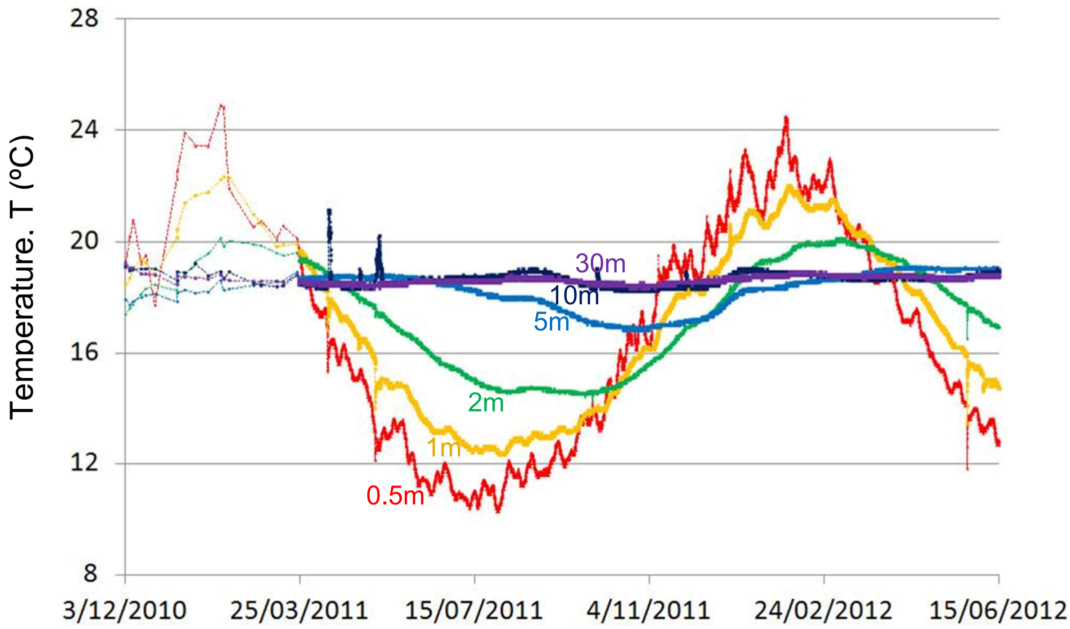


Fig. 3. Ground temperature variation over time at various depths in BH1

2.2. Horizontal GHEs: Main Ridge

This second demonstration/research project is a full scale multi-instrumented field testing site where horizontal GHEs can be remotely operated in a number of configuration combinations. It is currently connected to a large residential building. Valizadeh Kivi et al. (2012) present more details of this endeavour.

Geographical and geological setting This operational GHSP system is privately owned and is located 90km southeast of Melbourne, on the Mornington Peninsula. The building that is served by this system has an estimated heating load of 70 kW.

Sampling from 7m deep boreholes in the area shows that the ground is a clayey soil, developed on Tertiary basalts. The average moisture content at 1.8-2.0m from the ground surface is 23% and the soil unit weight is 20.5kN/m^3. For such basaltic clayey soil, the thermal conductivity is estimated to be 1.3 W/(mK) and thermal diffusivity to be 2.9 MJ/(m^{3}K). Fig. 4 shows some of installation works and the homogenous clayey soil profile underlying the topsoil.

GHE layout and instrumentation Two separate horizontal GHE circuits have been installed in trenches of 25m and 44m meters in length using a total of about 4,800 metres of HDPE 19mm diameter pipes in "slinky" configuration with two different pitches in each circuit (Fig. 4). A total of 172 temperature probes, strategically located (Fig. 5), are used to monitor the soil and water temperatures in the GSHP system, together with pipe water flows and energy use to run the compressors of the 3 GSHPs installed at this site. Most of the temperature transducers are located at the GHE depth (2m below ground surface). Two data loggers were used in the experiment, one for each GHE circuit. One of the data loggers was also used as a control device for the operation of circulation pumps and the solenoid valves installed in each "slinky" loop to study the effect of ground loop separation.

Experimental testing Using such extensive instrumentation, it is possible to test the influence of "slinky" loop length, spacing of loops, slinky pitch (just two) and monitor temperature changes along pipes and across the soil to study loop interference. Using circulation pumps with different flows, the effect of flow regime can be also studied. The heat gradient induced by the geothermal field on the ground is studied in four cross sections along the fields. Field data are becoming available only since May 2012.

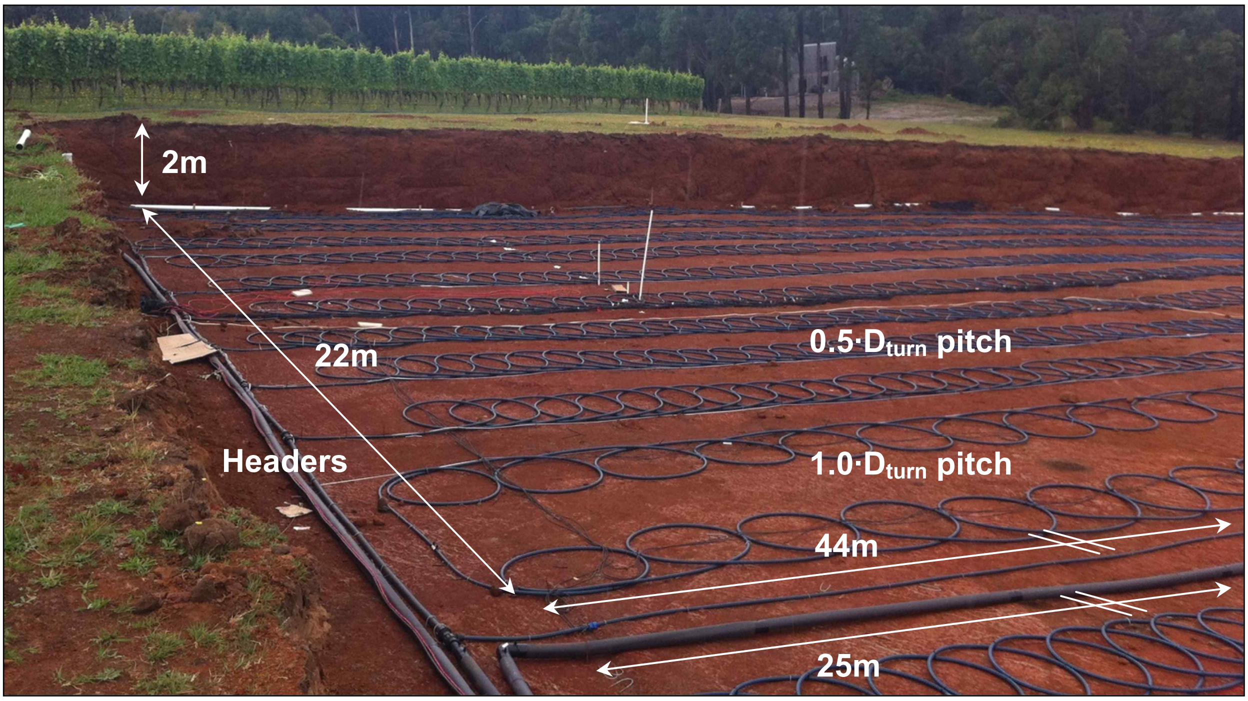


Fig. 4. Instrumented horizontal "slinky" GHEs placed 2m below the ground surface, with different pitches. There are two circuits of 44m and 25m ground loop lengths.

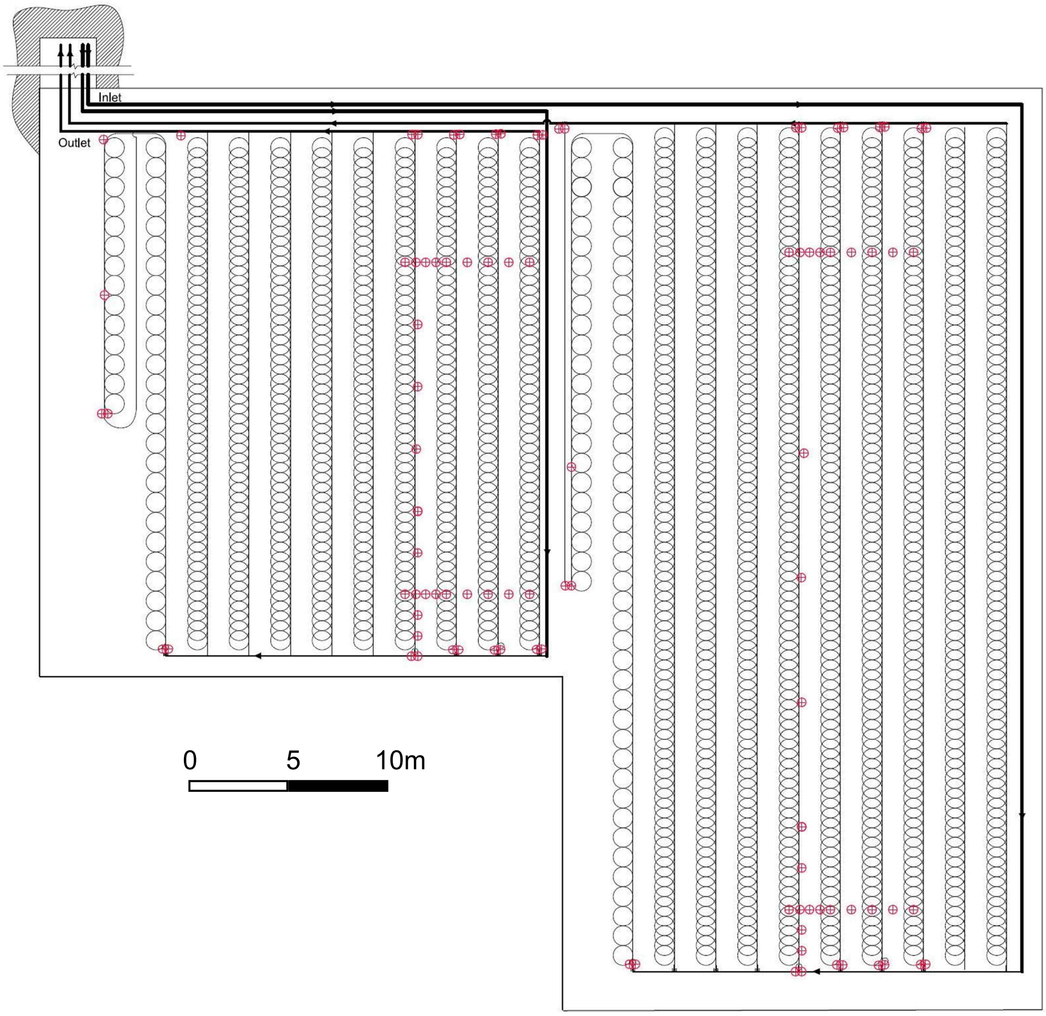


Fig. 5. Schematic view of the horizontal geothermal field, and location of the 172 temperature transducers in plan view

3. SUSTAINALBLE ENERGY PILOT DEMOSTRATION (SEPD) PROGRAM

Despite the large number of direct geothermal energy systems around the world, virtually none of these installations has been instrumented to verify and fine-tune to local conditions their design and installation guidelines. In order to correct this imbalance, the Victorian Government through the Department of Primary Industries (DPI) is funding a large scale project designed to collect detailed information from about 30 to 40 new and retrofit buildings around the state. This will help to develop comprehensive in-ground design data for Victorian conditions. The factors being investigated in real-life conditions include the geometrical arrangement of components, the materials used, the importance of orientation, depth and component spacing, ground fluid types and flow rates, and the operating characteristics of the GSHPs used. The project is also aimed at demonstrating the efficacy of direct geothermal energy in Australia.

The data will be collected from instruments in the GHEs of the direct geothermal systems that will be installed in selected buildings. Instrumentation will also be placed inside and outside each building to monitor the adequacy of these systems to provide heating and cooling and the external temperatures against which this energy is to be provided. The energy efficiency of each building will also be assessed.

The buildings involved in the project include the following:

1. A new two storey building located on the University's Parkville campus. This will be constructed on a competent founding material comprising a soft rock known locally as the Melbourne mudstone,
2. An existing commercial building located in Port Melbourne, on a quite different geological material known as Coode Island Silt. This is a very poor founding material comprising soft and very soft clays,
3. A total of up to about 40 new and retrofit buildings to cover a range of conditions typically encountered in Victoria.

3.1. New commercial building: Melbourne Mudstone

The building comprises 1,200m^2 floor area, and will be a Science Sub-School to be located at the Bio21 Institute in Flemington Road. The building is a joint venture between the University of Melbourne, University High School and Debney Park Secondary College, and will be used to teach science to pre-university students. This new 'commercial-type' building has an added advantage in that the science students using the building will have direct experience of the technology, and will be able to use the building as a living experiment in their studies with direct access to the data generated. Fig. 6 shows a provisional ground plan of the 28 x 50m deep vertical GHEs to be installed in 4 circuits that can be operated individually or in various combinations to explore ground responses to GHEs separation, alternancy (heating vs cooling) among other variables. The figure includes information about the instrumentation as well.

3.2. Existing commercial building: Clayey soils

The second building is an existing commercial building whose footprint is about 750m^2 with two floors and the retrofitted geothermal system will provide heating and cooling to one half of the building while the existing conventional system will be used for the other half. This will provide a very useful direct comparison of energy use and costs.

3.3. Existing and new residential buildings: Various ground types

Finally, there will be up to about 40 other new and retrofit buildings, mostly of a residential type, to complete the mix. The individual owners of these properties will be paying for the capital costs of the geothermal systems, while the instrumentation, and its design, installation and monitoring is funded by the DPI grant. This leg of the large project will provide important data with respect to the overall physical performance of direct geothermal systems from a range of building types at varying locations and with a number of different characteristics.

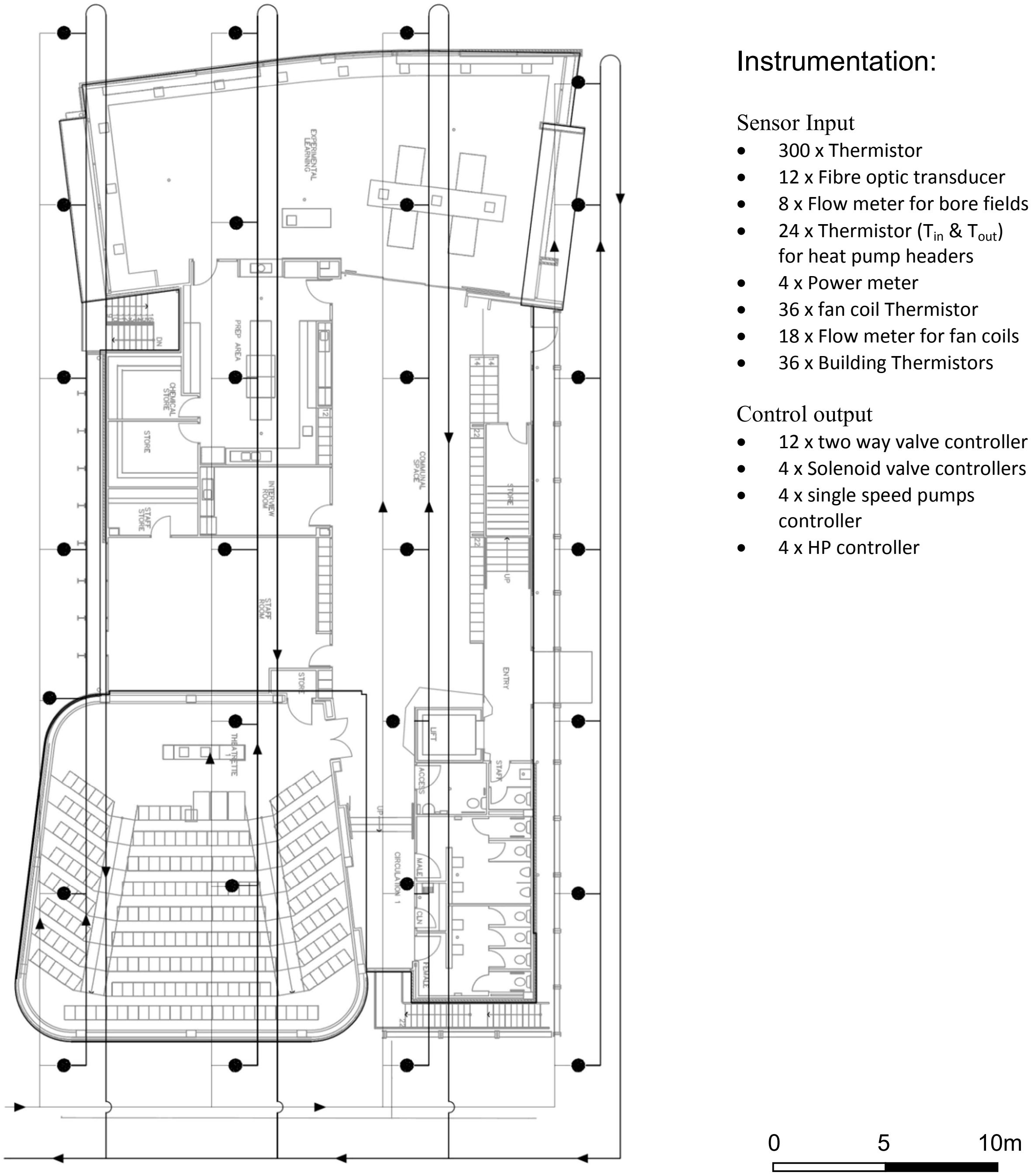


Fig. 6. Plan view of Bio21 annex building and planned geothermal system

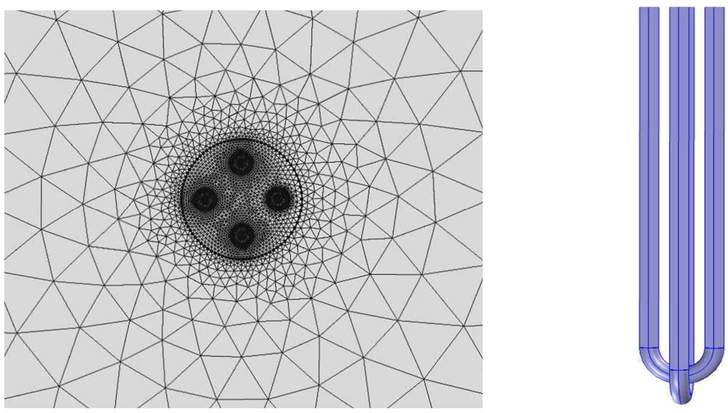
It will also provide further data about the associated capital and operating costs along with the socioeconomic energy demands of a range of buildings and the characteristics of their pattern of use by the occupiers.

Another important part of the overall program is to educate and engage the general (Australian) community about direct geothermal energy as well as provide specific training to the trades and professions so that the technology can be successfully rolled out.

4. 3D NUMERICAL MODELLING OF GHEs

GHE design requires knowledge of the ground thermo-physical parameters, as well as of the fluid circulating within the closed loops and of the backfill material (e.g., grout or concrete in vertical boreholes or energy piles). These are key inputs of any GHE model.

Despite fairly recent advances in both analytical and numerical modelling, one of the major limitations is that no detailed models of GHE components appear to have been developed and used to predict system performance and truly consider all the variables that affect the system. A few notable exceptions have only been published very recently (Al-Khoury et al., 2010; Lee et al., 2010). Without such a detailed model, it is likely that geothermal systems cannot be designed, installed and operated in a fully efficient way. Moreover, full scale prototyping and testing of all different variations and combinations of influencing parameters, even to the scale envisioned in the previous section, would be too expensive and difficult to achieve in a reasonable timeframe. To overcome these limitations, a numerical model based on first principles has been developed and implemented using finite element methods. An example of a 3D model configuration and FEM mesh is shown in Fig. 7.



(a) (b)

Fig. 7. (a) FEM mesh of a double U-pipe model – top view, (b) detail of a double cross U-pipe configuration – side view

In this model, heat transfer around and in the GHEs occurs primarily by conduction and convection. Heat conduction occurs in the ground (soil), concrete or grout and pipe wall, and partially in the carrier fluid; while heat convection dominates in the carrier fluid circulating in the pipe (i.e., water). It is assumed that there is no groundwater flow in the ground. The governing equations for fluid flow and heat transfer are coupled numerically within the finite element package COMSOL Multiphysics to produce a model to evaluate the performance of the GHEs.

The fluid flow in the pipes is described by the Navier-Stokes equations, which for an incompressible flow like water in a laminar regime can be described as:

$$\rho\nabla . u = 0 \tag{1}$$

$$\rho \frac{\partial \mathrm{u}}{\partial \mathrm{t}} + \rho(u.\nabla)u = \nabla.\left(-PI + \mu(\nabla u) + (\nabla u^T)\right) + F \quad (2)$$

where ρ is the fluid density in kg/m^3, u is the fluid velocity vector in m/s, P represents pressure in Pa, μ is the dynamic fluid viscosity in Pa.s, T is absolute temperature in °K and F is a volume force field of various origins (like gravity) in N/m^3.

In a turbulent flow, all quantities in Eq. (2) fluctuate in time and space. Obtaining detailed information about the fluctuations is computationally expensive. An averaged representation often provides sufficient information about the flow, substantially saving computational time and effort. To this end, the Reynolds-averaged representation of turbulent flows divides the flow quantities into an averaged value and a fluctuating part. Decomposition of flow fields into these parts, followed by insertion into the Navier-Stokes equation, and then averaging, results in the Reynolds-averaged Navier-Stokes (RANS) equations which are governing equations used in so called k-ε turbulent models:

$$\rho \frac{\partial u}{\partial \mathrm{t}} + \rho u + \nabla u + \nabla.\overline{(\rho u' \otimes u')} = -\nabla P + \nabla.\mu(\nabla u + (\nabla u)^T) + F \quad (3)$$

$$\rho \nabla.u = 0 \quad (4)$$

where u is the fluid velocity vector in m/s.

On the other hand, the generalized governing equation for heat transfer can be expressed as:

$$\rho_m C_{p,m} \frac{\partial T}{\partial t} + \rho_m C_{p,m} u.\nabla T = \nabla.(k_m \nabla T) + Q \quad (5)$$

where ρ_m is the density of a given medium (i.e., fluid or solid) in kg/m^3, k_m is the thermal conductivity in W/(m°K), $C_{p,m}$ is the heat capacity of the medium in J/(kg°K), and Q represents an external heat source in W/m^3. Note that solid can refer to soil, concrete, grout, steel or any other solid.

Heat transfer can be modelled using Eq. (5) in full. The velocity field u, found by solving the governing Eqs. (1) to (4), is used in Eq. (5) when modelling the heat transfer by conduction and convection within the pipes. Heat transfer in the ground, in the heat exchanger and in the pipe wall, uses a simplified Eq. (5) as the velocity field is null in the absence of groundwater flow.

This model has been recently validated against a few available analytical solutions, and full scale experimental data. It is capable of accurately predicting GHE performance in both laminar and turbulent regimes, homogeneous and heterogeneous ground profiles, and adequately flexible to explore a number of different pipe placement configurations, ranging from well known U-pipe configurations to spiral, W-pipes and others.

5. TEMPERATE CLIMATE AND INTERMITENT USE

It is important that the ground temperatures around the GHEs remain adequately stable to ensure the GSHP system operates reliably (Taylor et al., 2011). When a GSHP system is used for both heating and cooling, the total heat extracted from the ground in winter (*HE*) and the total heat rejected to the ground in summer (*HR*) are, respectively, given by:

$$HE = (HC - E) \times th \qquad (6)$$

$$HR = (TC + E) \times tc \qquad (7)$$

where *HC* is the mean heating load of the building, *E* is the mean power consumption of the compressor, *th* is the total heating period time *TC* is the mean cooling load of the building, and *tc* is the total cooling period time. Theoretically, when the total heat extracted from the ground in winter is equal to the total heat rejected to the ground in summer, i.e., *HE=HR*, the ground temperature around the underground heat exchanger will remain balanced year by year. In regions with climates such as those encountered in Northern Europe and Canada, the total heat extracted from the ground in winter is significantly greater than the total heat rejected to the ground in summer. This leads to a progressive heat deficit which causes a marked reduction in the performance of the GHEs. In tropical areas, the opposite happens and heat accumulation in the ground also leads to reduced performance characteristics. On the other hand, a balanced operation ensures that geothermal systems operate at a high efficiency. Temperate climates such as encountered in Melbourne tend to produce balanced operations.

In addition, discontinuous operation mode, such as operating the GSHP system during daytime while shutting it down at night or vice versa, can effectively alleviate the effects of heat deficit or accumulation around the GHEs to improve system performance (Cui, Yang, & Fang, 2008). For example, the coefficient of performance (CoP) of GSHP systems with a discontinuous operation mode is higher than that in the continuous operation mode by 11.6% after 40 hours of operation (Man, Yang, Wang, & Fang, 2011). Therefore, discontinuous operation provides the possibility of reducing the borehole depth of the GHEs (Miyara, 2012). This can now be further simulated using the model briefly described in Section 4.

6. CLOSING COMMENTS

There is no doubt that direct geothermal energy is becoming an important sustainable, economic and highly effective technology for heating and cooling buildings. This is particularly so as the world comes to grips with climate change and the need to considerably reduce our dependence on fossil fuels. While this relatively new technology has gained a great deal of acceptance over recent years, there is still a need to reduce the capital costs of installation to make it even more attractive. The mechanics of the above ground components of these systems including heating and cooling load prediction and optimization, heat pump technology and distribution and zoning systems are relatively well understood. While there is still always scope to improve these, it is the below ground component of geothermal energy systems which is thought to represent the best opportunity to reduce costs. Current GHE design methods are comparatively crude with clear indications that systems are often significantly overdesigned. In order to address this shortcoming, the University of Melbourne, alongside other groups around the world, has commenced a number of projects to demonstrate the effectiveness of the technology for a range of different conditions and to develop more effective guidelines for the design and operation of GHEs.

With some projects only just coming online and with many more still to commence, it is not possible to present a consolidated view of outcomes. However, it is envisaged that within the next year, data will become available to permit the overall project to significantly improve our understanding of these systems and allow us to design even more cost effective direct geothermal energy systems.

AKNOWLEDGEMENTS

Parts of these works are supported by the Victorian Government through the Department of Primary Industries, Saddleridge Pty Ltd, the Melbourne Energy Institute and The University of Melbourne. The authors would like to acknowledge a number of volunteers and helpers of various aspects of the multiple projects, including X. Han, D. Kiraly (CSIRO), M. Mahalati, O. Mikhaylova, and Z. Zhang. Assistance was also provided by Geotechnical Engineering Pty Ltd, Direct Energy Pty Ltd, the Nicholson Group, Supaflow Plumbing, Emerson Climate Technologies, Golder Associates, University of Melbourne Property and Campus Services, and Melbourne University Sport.

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