Direct GeoExchange Cooling for the Australian Square Kilometer Array Pathfinder – Field Trial

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Direct Geoexhange Heat Pumps (DGHPs) provide chilling via refrigerant-carrying copper loops buried in the ground which act as a condenser and achieve higher efficiency than equivalent air source heat pumps because of the ground's constant heat capacity. DGHPs are particularly suited to desert environments with more extreme ambient temperatures. The Australian Square Kilometer Array Pathfinder (ASKAP) radio telescope will be an array of 36 x 12-m diameter parabolic dish antennae situated in Boolardy, WA each requiring 5 – 9 kW_{th} cooling for computer equipment and pedestal. Following successful tests of a prototype installation at Marsfield, NSW (ground temperature 17 C) a DGHP is installed at antenna site #29 (the first erected). The DGHP provides chilling to a variable test load (3.6, 4.8, 8.4, 9.6, 13.2 kW) via a 200 L water buffer. 6 x 30m bores containing copper loops deliver up to 14 kW of chilling to maintain 13 - 15 C water temperature in the buffer. 5 data bores monitor ground temperature variation in the centre of the 6 active bores and at 0.3, 0.6, 3.0, 6.0 m (outside the bore field). System pressures & power are also monitored. A higher-than-expected baseline ground temperature of 27 C is measured and verified by three methods. The nominal 14 kW DGHP can maintain 15 C water temperature at all loads including 13.2 kW. Note that 0.5 kW pump heating means the effective load is 13.7 kW. We describe the results from this field installation in detail and present an abridged set of data.

Keywords:
Direct Geoexchange, Direct Use, Geothermal Heat Pump

Direct Geoexchange

The emerging geothermal industry in Australia is focused on producing electricity ("indirect use") and should begin delivering substantial results over the next decade. *Direct Use* geothermal energy is more efficiently available as it entails only one energy conversion (absorption or radiation of heat), rather than the several that occur in electricity generation and usage, with each step losing a percentage on conversion. Geothermal Heat Pumps (GHPs) are a direct use of geothermal energy which involve circulating a fluid (water, brine or refrigerant) through earth loops (poly pipe or copper) a few tens of metres deep (Fig. 1, Payne et al. 2008).

Direct Geoexchange Heat Pumps (DGHPs) which circulate refrigerant through copper loops have greater efficiency than water-loop GHPs because:
- (i) copper is more thermally conductive than insulating plastic;
- (ii) latent heat transfers directly with the ground on evaporation or condensation; and
- (iii) an intermediate water-to-refrigerant heat exchanger between the ground loops and compressor is not required.

DGHPs transfer heat via 30-metre deep, 75-mm diameter bore holes compared with 100-metre deep, 150-mm diameter bores used for water-loop GHPs. A continuous, closed loop of copper piping is inserted and sealed with a thermally conductive grout (cement). Below 5 metres the Earth remains at a stable temperature all-year-round (27^o C at Boolardy, WA). The smaller temperature difference between the heat source/sink and the building or water to be heated/cooled results in lower head pressure and energy requirement of the compressor compared to conventional heating and cooling systems. A "desuperheater" may be employed in chilling applications to further optimise the performance and produce hot water or air which can be used usefully elsewhere.

ASKAP

The Australian Square Kilometer Array Pathfinder (ASKAP) radio telescope is an array of 36 x 12-m diameter parabolic dish antennae situated in Boolardy WA (Fig. 2) whose construction commenced in early 2010 and is a precursor to the Square Kilometer Array (SKA) of several thousand 12-m dishes. A prototype of the Electronics Systems (ES) and Phased Array Feed (PAF) package to be cooled has been installed at the CSIRO Australian Telescope National Facility (ATNF) headquarters in Marsfield, NSW. These two components should not exceed 20 - 30^o C under all operating and weather conditions and require an estimated heat dissipation of 5 – 7 kW_{th}. Various cooling methods have been considered and the extreme desert temperatures and high price of diesel generated power strongly favour a DGHP solution. The results of testing of a DGHP at Boolardy are summarised in this paper.

System Design

Cooling is provided by a 14 kW_{th} DGHP which circulates refrigerant (R407C) through 6 x 30-m copper earth loops to a refrigerant-to-water, coil-in-tank heat exchanger. Water in the 200 L buffer tank is chilled to 7 – 15^{o} C. Water is circulated from this buffer tank to the PAF & ES to deliver the required cooling to the heating load (the "secondary" circuit). The design of the secondary circuit is beyond the scope of this paper – here the performance as a function of thermal load is explored by a test load. The test load is a 50 L water tank with three elements (3.6, 4.8, 4.8 kW) that can be switched on to produce 3.6, 4.8, 8.4, 9.6, 13.2 kW. A circulation pump continually circulates water through this test load and contributes circa 0.5 kW of heating. A controller achieves the specified water temperature.

Earth Loop Installation

The 14 kW_{th} system requires 6 x 30-m copper earth loops (½-inch vapour and ¼-inch liquid) with PVC insulation on the upper 15-m of the liquid line to minimise heat transfer between the two and stop flashing of the liquid refrigerant. 70-mm diameter holes are drilled vertically 30-m deep in a hexagonal configuration around a point 10m from the pedestal foundation edge with 3-m spacing between them to allow sufficient thermal diffusion through the ground. After insertion of the loops the holes are filled with a thermally conductive (geothermal) grout (e.g. 111-mix, Therm-Ex, IDP-357, Barotherm) ensuring that there are no air pockets. The liquid & vapour lines from the earth loops are brazed to their respective manifolds (½-inch liquid & 7/8-inch vapour) using a 15% silver brazing alloy. The liquid line is insulated with ½-inch non-corrosive insulation material (e.g. Armaflex, Insul-Lock) and run towards the heat pump (compressor) with a maximum length of 40-m. 5 data bores were also drilled. The location of all bores was logged by triangulation to GPS pegs on the foundation (as shown below).

Figure 1: Loops, liquid & vapour manifold and trenches.

Buffer Tank, Heat Exchanger & Test Load

Chilling is delivered through a submerged copper evaporator coil inside a 200 L buffer tank – this is in contrast to the brazed-plate heat exchanger used in the Marsfield installation. Water flows over the coils via a central perforated copper pipe to ensure effective heat transfer. A minimum flow rate of 0.6 L/s (36 L/min) is required to achieve this. A 50 L test tank equipped with three switchable heating coils (4.8, 4.8 & 3.6 kW) simulates the load. The test tank is connected to the buffer tank via 32mm polyethylene pipe.

Figure 4: Evaporator coil & load tank

Heat Pump Design & Refrigeration

The DGHP installed at Boolardy differs from that installed Marsfield in the following ways:

- The desuperheater coil is built into the unit
- The unit is cooling only having no reversing valve
- It has a nominal capacity of 14 kWth (cf. 10.5 kWth) to cater for pedestal cooling

The components are described in turn.

Compressor: A 3-phase Scroll compressor drives the heat pump with compression ratio of 4. Its efficiency is a function of the evaporating and condensing temperatures (pressures).

Active Charge Control (ACC): This:

- prevents liquid refrigerant from reaching the compressor by acting as a reservoir;
- evaporates refrigerant to keep the system properly charged and to eliminate superheat;
- improves volumetric efficiency, reduces power draw, and lets compressor run cooler;
- enables passage of oil entrained in refrigerant;
- indicates refrigerant level via 3 sight glasses.

Liquid Flow Control (LFC): This is an efficient Thermal Expansion Valve (TXV) which:

- Sets proper refrigerant flow rate based on condenser (upstream) operating conditions;
- Ensures zero sub-cooling so condenser is fully active;
- Reduces compressor discharge pressure and lowers power requirement;
- Prevents vapor from "blowing through".

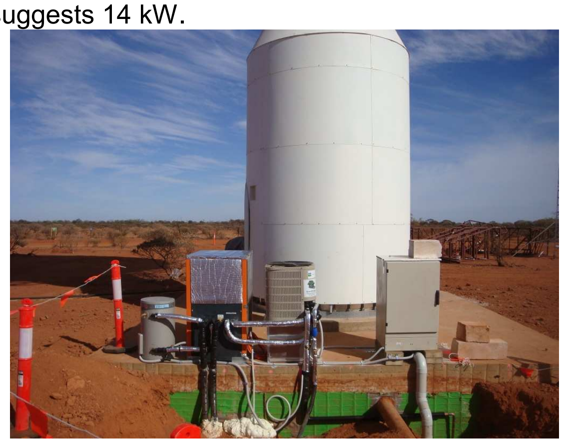
Oil Separator: Oil lubricates the compressor and the oil separator acts with the ACC to prevent oil from migrating down the earth loops.

Dryer: This filters and dries the refrigerant before it enters the LFC.

Refrigerant: R407C [HFC azeotrope: R32 (23%) + R125 (25%) + R134a (52%)]. Future work will explore other HFC and hydrocarbon refrigerants.

Expected Performance

The Air-Conditioning, Heating and Refrigeration Institute (AHRI) has a well-established standard for DGHPs: ANSI/ARI Standard 870, 2001. Also, DGHPs are EnergyStar rated, endorsed by the Environmental Protection Authority (EPA) and Electrical Testing Laboratories (ETL) tested. The DGHP manufacturer, EarthLinked, provides performance tables which are derived from both the Scroll compressor's performance and field trials. For an earth temperature of 27^{o} C and chilling water to 15^{o} C, the expected Coefficient of Performance (COP = thermal energy removed/ electrical energy input) is 4.5 – 5.0 depending on load. The theoretical maximum (Carnot cycle) performance for cooling is given by T_{evap} /(T_{cond} – T_{evap}) where T_{cond} is the condensing temperature and T_{evap} the evaporating temperature (Kelvin) and is 7.7 for T_{cond} = 42^{o} C and T_{evap} = 6^{o} C which correspond to the above conditions. Select7 software from Emerson Climate Technologies (manufacturer of Copeland Scroll compressors) suggests 14 kW.



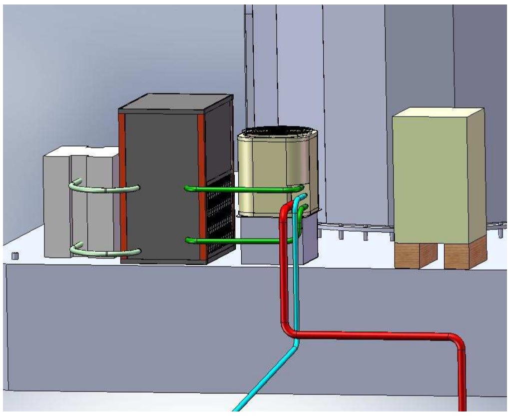


Figure 5: Final setup

Methodology

To find the most efficient means of cooling, the COP is measured as a function of the controllable aspects of the system. The key controllable variables are:

Buffer Set Point ($T_{b\text{-}set}$): the temperature to which the buffer tank is controlled to be chilled – it is measured inside the buffer tank.

Buffer Maximum ($T_{b\text{-}max}$): the buffer tank temperature at which the controller switches on the chilling DGHP.

Cabinet Set Point ($T_{cabinet}$): the temperature to which the cabinet is cooled.

Secondary Load (P_{load}): the thermal power which is simulated with a set of heaters.

Tank Load (P_{tank}): there are no elements in the tank.

Other input variables include:

Ambient Temperature: this includes both the wet (T_{wet}) and dry (T_{dry}) bulb temperatures.

Environmental Gain (P_{envt}): the tank & pipes are insulated but there is still environmental gain.

Tank Volume (V_{tank}): the buffer tank volume.

Water Volume (V_{water}): volume of water in the system: tank, primary & secondary pipes.

Output variables include:

Compressor Electrical Power (P_{comp}): the electrical power used by the compressor.

Cycle Time (t_{cycle}): the time between compressor start-ups.

Compressor Time (t_{comp}): the time the compressor is on during a cycle.

Duty Cycle (D): the percentage of time the compressor is on (t_{comp}/t_{cycle}).

Earth Loop Temperatures ($T_{5\text{–}30m}$): The temperatures measured at 5, 10, 15, 20, 25 & 30m.

Refrigerant liquid & vapour temperature (T_{liq}, T_{vap}): the temperatures to and from the earth loops

Suction, Head & Return Pressures (P_{head}, P_{suc}, P_{ret}): The pressures in & out of the compressor and returning from the earth loops.

Results

COP Calculation

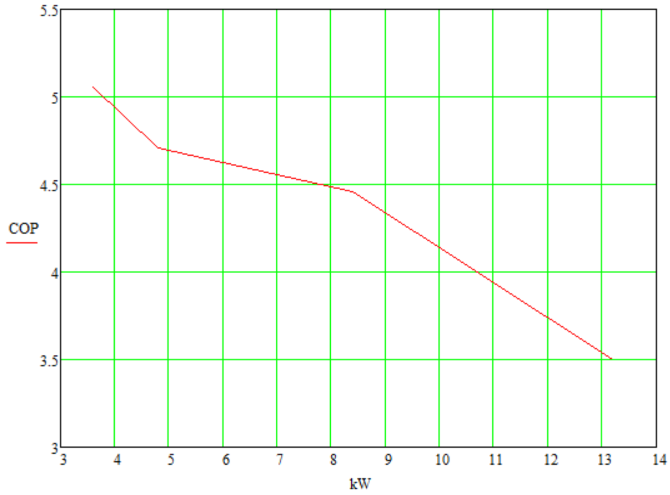
The default input values are: $T_{b\text{-}set}$ = 13° C, $T_{b\text{-}max}$ = 15° C, $T_{cabinet}$ = 23° C, P_{load} = 8.4 kW_{th}, P_{tank} = 0, V_{tank} = 200 L, V_{water} = 273 L. The ambient temperature varies between 10 and 35° C during the test periods and future results will be calibrated against this. An estimate of the environmental gain was determined by cooling the buffer to 15° C, leaving the system off and measuring the time taken (t_{envt}) for the temperature to increase a known amount (ΔT_{test}). $P_{envt} = C_{pw}.V_{water}.\rho_w.\ \Delta T_{test}/t_{envt}$ where C_{pw} = 4.2 kJ/(kg.K) is the specific heat of water, ρ_w = 1 kg/L is the density of water. It was found that for ΔT_{test} = 2 K, t_{envt} = 135 min giving P_{envt} = 208 W.

Figure 5 shows the temperature and pressure outputs for the above input conditions. From these results, the COP can be derived. We find t_{cycle} = 1160 sec, t_{comp} = 780 sec, giving D = 67.24%. There is a temperature overshoot of typically 0.3 – 0.5 K below $T_{b\text{-}set}$ and above $T_{b\text{-}max}$ giving ΔT = 2.8 K. The power required to reduce the system water temperature is $P_{water} = C_{pw}.V_{water}.\rho_w.\ \Delta T/t_{comp}$ = 4.12 kW_{th}.

The electric power consumed by the compressor + pump + monitoring equipment is measured continuously along with the electric power required for the pump alone. This allows the total electrical energy consumed over a known number of cycles to be computed. For this run, E = 3.081 MJ is consumed over n_{cycle} = 3 cycles (19.33 min) and the average power (directly monitored) $P_{comp} = E/(t_{comp}.n_{cycle})$ = 3.95 kW_{elec}.

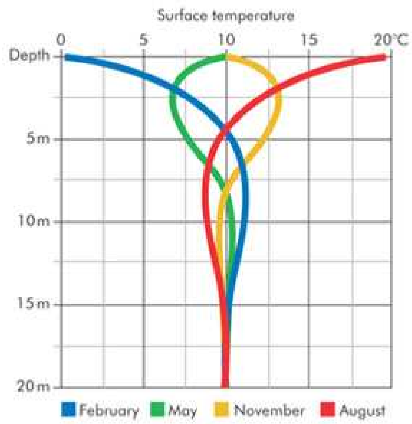
$COP = [P_{water} + (P_{load} + P_{envt})/D]/P_{comp}$ = 4.46. Note that D accounts for the fact that the load and environment are constantly delivering heat to the system which must be dissipated by the heat pump whilst on.

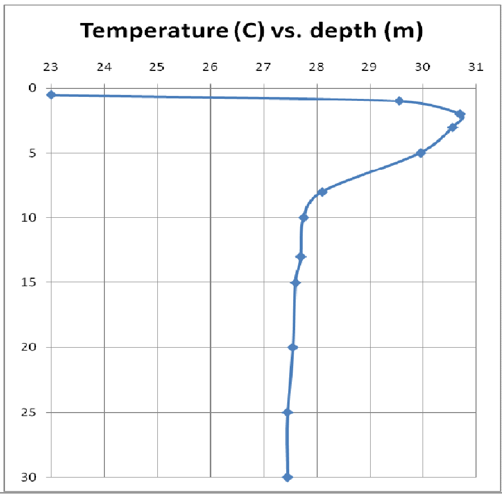
Using this method (see appendix), the COP is calculated as a function of load and DGHP configuration and plotted below. It is clear that the system should not be designed to run with a 100% duty cycle. An initial configuration of the system had the heat pump unit 30 m away from the earth loops. After moving the DGHP to within 4 m of the earth loops, the pressure drop across the earth loops was 5 – 15 PSI lower. Also, the manifold pit was initially exposed for testing and thus about 15 m of the copper earth loops was exposed to air and thus not efficiently dissipating heat. Backfilling the manifold pit boosted the performance.

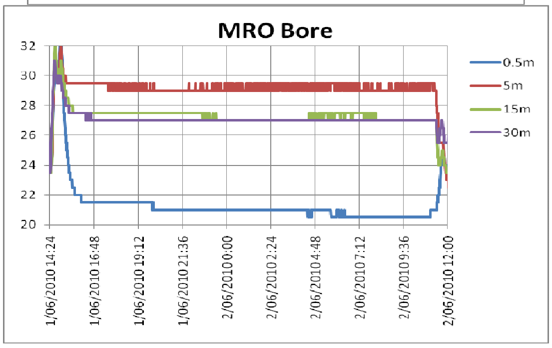


Mean Earth Temperature

The undisturbed mean ground temperature was measured every 5m to 30m down six bore holes (two active and four data) via temperature sensors. One of the bore holes (B5) has sensors at 1, 2 and 3m also. Initial temperature readings were measured on 4th May 2010 and they were corroborated with data loggers (LASCAR EL-USB-2) on 2nd June 2010 (late Spring in Australia, equivalent to November in the Northern Hemisphere). The temperature is plotted as a function of depth below and corroborates with what is expected. Independent verification of temperature data has been important as the expected mean earth temperature was 23 C. A 120m test hole for water geoexchange was drilled at the Murchison Radio Observatory central site approximately 2 km away from the DGHP installation at antenna #29. Bore water inhabited this hole at a depth of 31.3m. The data loggers were hung down the hole to a depth of 30m on a rope at depths 0.5,5,15,30 m and left for 20 hr with resultant mean earth temperatures of 21, 29.5, 27.5, 27 respectively (see figure). A sample of the bore water (jar down rope) was taken and its temperature upon extraction was just under 27 C measured with a probe thermometer. This provides a third means of verifying the bore temperature and corroborates.





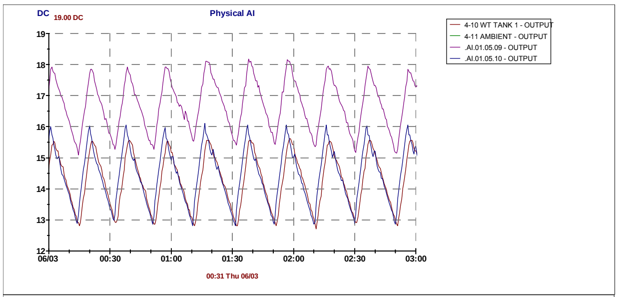


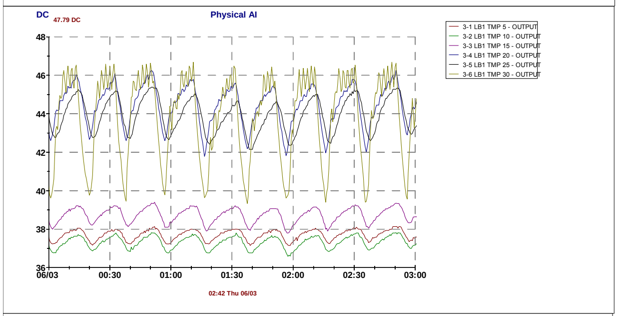
Ground pH & Bore water salinity

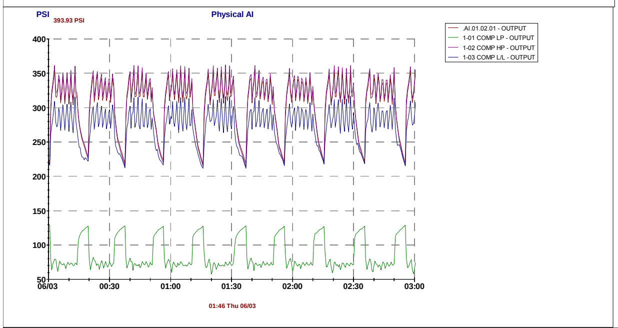
The pH and salinity of bore water used for the thermal grout was measured with testing strips. pH = 7.8 - 8.2 - acidity is thus not an issue for corrosion of the copper loops. The chloride levels are circa 850 mg/L. This is a borderline reading of the bore water. The aquifer was not penetrated by the site #29 bores and the ground is probably benign. Taking a conservative approach, a Cathodic Protection System will be installed for this system – a solar solution for its power is being exploring.

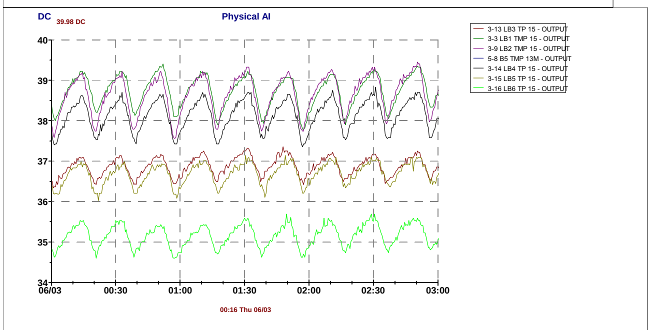
Abridged Results

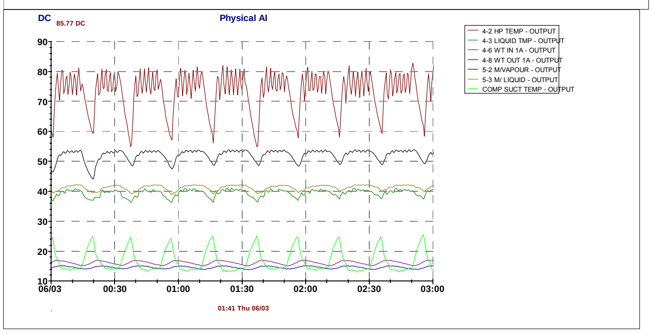
For the presentation of data, a period from 12:00 – 3:00am on 3rd June 2010 was chosen. Below appear the water (buffer tank) temperatures, temperatures down LB1, pressures, 15m bore temperature for all active bores, refrigerant temperatures throughout the system, and electric power. Also initially available temperatures from the data bores are plotted: B5 0.3m data bore, 15m bore temperature for all data bores, B4 6m data bore.

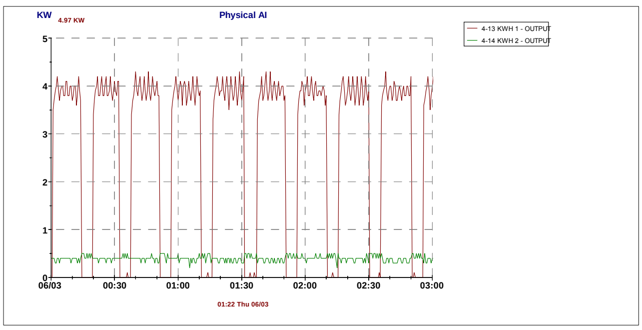


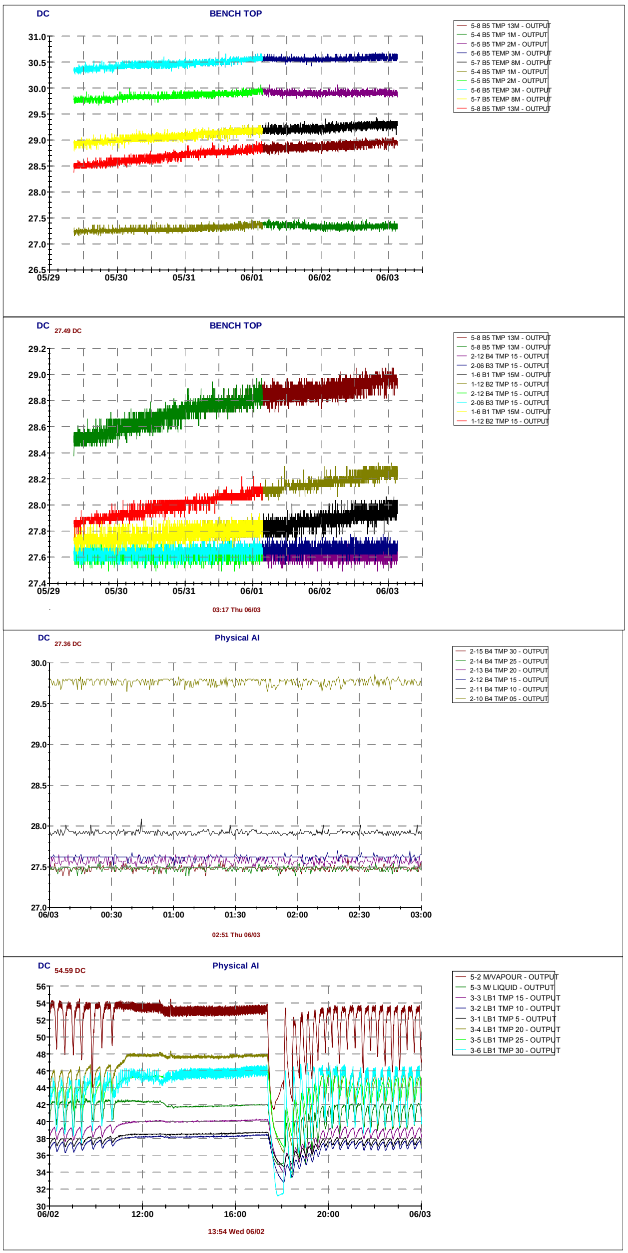












Analytic derivation of the expected ground temperatures will be presented in a future paper. As seen above, after the compressor starts, the ground temperatures rise asymptotically towards saturation at which thermal output matches thermal dissipation in the ground. Maximum load (13.2 kW_{th}) was applied from 10:38am to 17:17 and the water temperature was held down to 15 C. After switching off the load, the ground recovers. At 18:11 a 3.6 kW load is applied, at 18:45, 4.8 kW and at 19:26:30, 8.4 kW.

Conclusions & Further Work

DGHPs are an efficient solution for heating and cooling and are particularly suitable for cooling in a desert environment with no power infrastructure. It has been shown that a DGHP is able to deliver 13-15 C chilled water despite high ground temperatures of 27.5 C. It does with a COP between 4 and 5 for the expected load range. This corroborates with data obtained from Marsfield – it was expected that the higher ground temperature would slightly reduce output & performance. As in Marsfield, it has been demonstrated that COP decreases as a function of load in the secondary circuit (which determines the duty cycle) simulated by a test tank. Further results are being obtained for this configuration and additional experiments include the use of alternative refrigerants. The thermal conductivity & other properties of the ground will be calculated by comparison with analytic and numerical models.

Acknowledgements

This scientific work uses data obtained from the Murchison Radio-astronomy Observatory. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site. We acknowledge the CSIRO, CASS team including Grant Hampson, Evan Davis, Antony Schinckel, Graham Allen, Steve Broadhurst along with Robert Rechtman & Mike Francis of Direct Energy, David & Peter Manoni from Geothermal WA, Hugh Campbell & Nigel Foster of Dongara Drilling and Shannon Lovett, Nick Holt & Mark Alden of Emerson Climate Technologies.

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