

HEAT PUMP PERFORMANCE SENSITIVITY TO HORIZONTAL AND VERTICAL COLLECTOR CONFIGURATIONS IN A MARITIME CLIMATE REGION

N. Burke, M. Greene, J. Lohan, R. Clarke, Sustainable Energy Research Group (SERG), Galway-Mayo Institute of Technology (GMIT), Dublin Rd., Galway, Ireland.

Abstract: Ground source heat pumps extract heat from the ground surface layer using either a horizontal or vertical collector. While numerous studies have characterised heat pump performance in continental climates few have focuses on maritime climates. This experimental study was carried out in Ireland's maritime climate and it utilised two identical, 15 kW_{th} heat pumps. One heat pump was connected to a 430m² horizontal collector while the other was connected to a series of three, 100m deep, single U-tube vertical collectors. The goals of this study were to identify the quantifiable differences in heat pump performance that could be attributed to either a) collector configuration; vertical or horizontal, b) climate; continental or maritime, c) operating environment; standard laboratory test environment or actual application, and d) use conditions that mimic either typical or extreme duty cycles. Experimental results are presented for 2007 and 2008 and the data highlights collector sensitivity to climate and use conditions along with ground temperature recovery rates depending on collector configuration. This study will aid the development of guides to support heat pump collector design based on measured performance under maritime climate conditions. Heat pump COP variations of between 5.1 and 2.9 were recorded with brine output temperatures of between 35°C and 50°C.

Key Words: *ground source, heat pump, horizontal collector, vertical collector, climate, thermal storage, coefficient of performance*

1 INTRODUCTION

Growing awareness of climate change, diminishing world-wide fossil fuel stocks, having possibly reached peak oil production, escalating energy costs and concerns about security of supply has united international bodies such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC), along with governments, to call for increased uptake of sustainable energy systems and improving energy efficiency (IPCC 2007; IEA 2006). Since Ireland is particularly exposed with a 91% dependency on imported fossil fuel (SEI 2007) it has responded by adopting similar policies to increase the use of sustainable energy systems and energy efficient technologies (DOCMNR 2007). This study responds to both of these calls by promoting heat pump technology, a recognised sustainable energy technology and by investigating methods of increasing its efficiency when operated in the Irish maritime climate. Ireland is very supportive of such initiatives since these sustainable technologies are relatively new to Ireland and it is likely to exceed the CO₂ emissions production level set down under the Kyoto Protocol by 23.1% (DOE 2007).

The use of heat pumps for space heating in Ireland has grown dramatically over the past number of years, initially due to natural market growth but it gained exponential growth in 2006 with the introduction of government grants for installing sustainable energy heating systems in new dwellings (SEI 2007). Furthermore, the new Irish building regulations stipulate that new dwellings must derive a minimum of 10 kWh/m²/annum of the dwelling's thermal energy needs using renewable energy sources, and also requires the dwelling to

operate within specific CO₂ emission targets. Heat pumps are included in the list of renewable energy systems, with the proviso that only the energy delivered above a COP of 2.5 can be counted (DOE 2007). These international and national developments have led to an increased interest in optimising the potential of heat pump systems, particularly under the variable, yet very favourable maritime climate conditions that exist in Ireland.

Recent statistics shows that horizontal collector, brine-to-water, heat pumps hold the largest share of the Irish heat pump market with 60%, followed by vertical collector brine-to-water (24%), air source air-to-water (14%) and water source water-to-water heat pump (2%) (O'Mahony 2007). Performance aside, horizontal collectors are less expensive to install, but vertical collectors occupy less surface space, and with Ireland low population density many new dwellings have ample space for horizontal collectors. Hence, this study focuses on the two heat pump collector designs that combined occupy 84% of the Irish heat pump market; vertical (GSHP_{VC}) and horizontal collector heat pumps (GSHP_{HC}). This study is part of a research project aiming to assess heat pump performance under the Irish maritime climate, and the study shall be referred to as "GSHP-IRL".

The Irish maritime climate is particularly favourable to heat pump technologies due to its close proximity to the influential warm Gulf Stream. It is the key control mechanism of the Irish climate, maintaining a moderate air temperature fluctuation, which is in contrast to the more pronounced temperature fluctuations of the continental climate where the land with a lower specific heat than water combines with solar irradiance to influence air temperature (Koepe *et al.* 1958). A substantive analysis of the positive and negative effects of the various climatic parameters that are likely to influence heat pump performance has been published (Lohan *et al.* 2006; Lohan *et al.* 2006; Greene *et al.* 2007).

Figure 1 presents a set of air temperatures, averaged over 30 years, for six widely dispersed locations that experience either continental or maritime climates. Three striking effects are evident; i) the amplitude of the annual air temperature fluctuation in maritime climates is less than half that of continental regions, generating greater demand for heating in winter turning potentially to cooling demand in the summer, and ii) the average air temperature shows the greatest variation in the winter, with maritime regions recording the highest temperatures, and as a result: iii) maritime regions show a +2°C higher average year-round air temperature. While all above points are positive for the GSHP_{HC}, the latter suggests the horizontal collector will, for a given collector depth, operate in the heating mode for longer periods and at a higher temperature in the maritime climate. The low peak summer temperature drives the small space heating demand for as much as 10 months of the year.

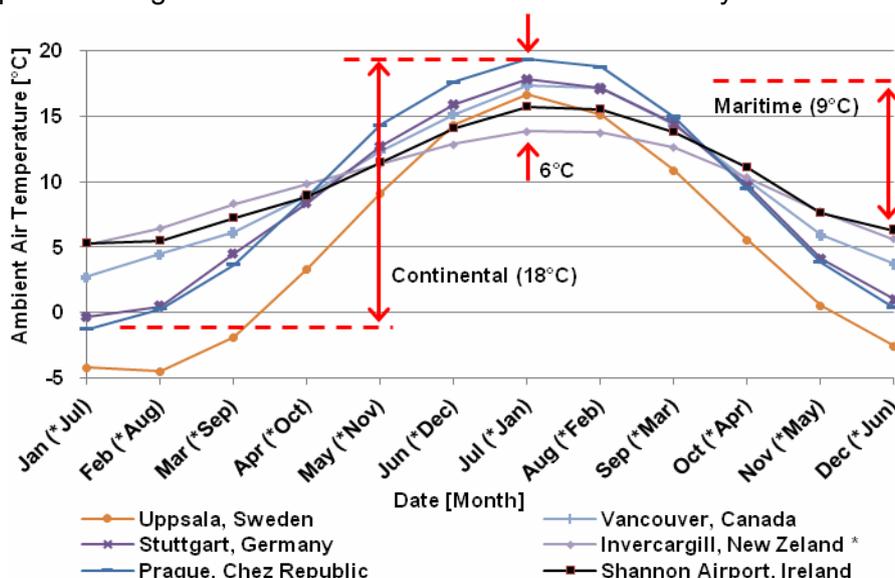


Figure 1: Continental v maritime climates – 30 year average air temperatures for six widely dispersed locations (World Climate 2007).

With an absence of accurate/reliable and neutral performance data for either GSHP_{VC} or GSHP_{HC} within Ireland, customer confidence in heat pump capabilities is still relatively low. Emphasis has been placed on the need for heat pump research and development within Ireland in a report by a European based testing facility, *Arsenal Research*, which states that there is a lack of “neutral, practical information” as “there is only information from some manufacturers and importers available” and this acts as a barrier to the long term viability and growth of heat pumps within Ireland (Arsenal Research 2004). Advocates of heat pump technology, such as the International Ground Source Heat Pump Association (IGSHPA), International Energy Agency (IEA), European Heat Pump Network (EHPN), European Heat Pump Association (EHPN), the American Society of Heating and Refrigeration and Air-conditioning Engineers (ASHRAE) have made a sizable contribution in providing quality information pertaining to the use of heat pumps throughout the world (IGSHPA 1989; Forsen 2005; IEA 2002; ASHRAE 2002). However, this information does not necessarily distinguish between climates, or subsequent collector configuration and operational characteristics. This paper recognised the development of heat pump technologies and advances made in collector design on the continent and Scandinavia but questions the validity of the direct application of this knowledge in a maritime climate region without appropriate climate modification, therefore this *GSHP-IRL* study seeks to redress the absence of such knowledge for maritime climates.

Ireland has been particularly reliant on heat pump performance data derived from either standard test laboratories or under operation in continental climates. It has been highlighted that aspects such as climate, the condition of building stock, experience of the use of heat pumps and energy mix all vary widely across Europe and it cannot be considered a homogenous market (Axell *et al.* 2005). These authors also identify that a lack of heat pump experience and knowledge contribute to the poor level of heat pump use in industrial applications which is another aspect addressed by the current *GSHP-IRL* study. It is acknowledged that rigorous laboratory testing of heat pumps in accordance with internationally recognised heat pump test standards such as EN 14511 (2004) is an essential element of characterising a system performance under similar and repeatable conditions. While this data facilitates the comparison of different heat pumps and detailed data on individual heat pumps, it ignores practical issues associated with possible performance variations associated with collector design or configuration, quality of installation, climates and operational parameters such as duty cycle and load. Dumont and Frère (2005) highlighted this anomaly by monitoring a GSHP_{HC} installed in a domestic dwelling in Belgium, where they recorded the performance over two years prior to 2005. They stated that while COP values are usually given by manufacturers for standard working conditions over a wide range of temperatures, the actual COP cannot be predicted or estimated as it can vary from climate to climate and indeed from application to application (Dumont *et al.* 2005). This indicates that the COPs yielded by standard tests are indicative as to the heat pumps capabilities over a range of temperatures but they may not indicate how a heat pump will perform under operational, building and climate specific conditions.

In order to overcome uncertainty that arises when attempts are made at the design phase to translate standardised laboratory test results to the application Bianchi *et al.* (2005) suggested a need for laboratory testing using real weather and usage data to be a viable indication of efficiency under certain climatic conditions so that potential consumers might gain an indication of potential efficiency. While accepting that it would be difficult to achieve, given that each location is climate specific, these concerns helped to motivate the current study. Laboratory testing using real weather data can also be ineffective in the evaluation of heat pumps if sufficient weather data is not available. Blanco Castro *et al.* (2005) conducted tests to determine the Seasonal Performance Factor (SPF) for an Air Source Heat Pump (ASHP) in Spain and concluded that the use of historical data to simulate heat pump demand, and performance, can be deceiving as using just average ambient air temperatures may not reflect the actual demand on the heat pump, as was discovered in their experimental evaluation.

This study therefore seeks to address the identified concerns and knowledge gaps by; a) developing a heat pump characterisation facility that would allow the performance of GSHPs with either vertical or horizontal collectors to be evaluated, b) establishing variations in performance between maritime and continental climate conditions, c) allowing different operating and duty conditions to be imposed so that the impact of heat pump operation on a collector region could be established, and d) evaluate actual operating conditions against international test standards.

2 TEST FACILITY

The test facility presented in Figure 2 was designed, installed and commissioned at the Galway-Mayo Institute of Technology (GMIT), Dublin Rd., Galway Campus, which is located at latitude 53°16'39" N and longitude 9°00'43" W. The site shown in Figures 2(a) and 2(b) is 20m above sea level and the test facility consists of two identical 15 kW_{TH} GSHPs (*Solterra 500*), which were used to heat the nearby 1200m² Innovation in Business Centre (iIBC) building via hydronic radiators, a heat distribution system that requires a minimum flow temperature of +50°C. This heat distribution system was initially designed for the use with gas condensing boilers as the sole heat supplier, and with the subsequent installation of the GSHPs the heating system can therefore be described as a retrofit system.

Figure 2(a) details the exact design and positioning of both the vertical and horizontal collectors relative to each other and the iIBC building. The GSHP_{HC} extracts heat using a horizontal collector that occupies a footprint of 430m² and submerged at an average depth of 1m. The relative position of three 100m deep single U-tube type collectors which act as the GSHP_{VC} vertical collector is also shown in Figure 2(a). Two of the three boreholes are instrumented with temperature sensors, which are mounted on the collector outer pipe wall at depths of 5m, 50m and 95m. Brine flow and return temperatures are also recorded on two boreholes, along with the overall brine flow and return temperatures to the both the GSHP_{VC} and GSHP_{HC}. The vertical boreholes are encased in limestone from a depth of 1.8m, this limestone has been karstified over time and all three boreholes reach an aquifer at 100m. As the iIBC is 20m above sea level the vertical boreholes extend 80m below sea level.

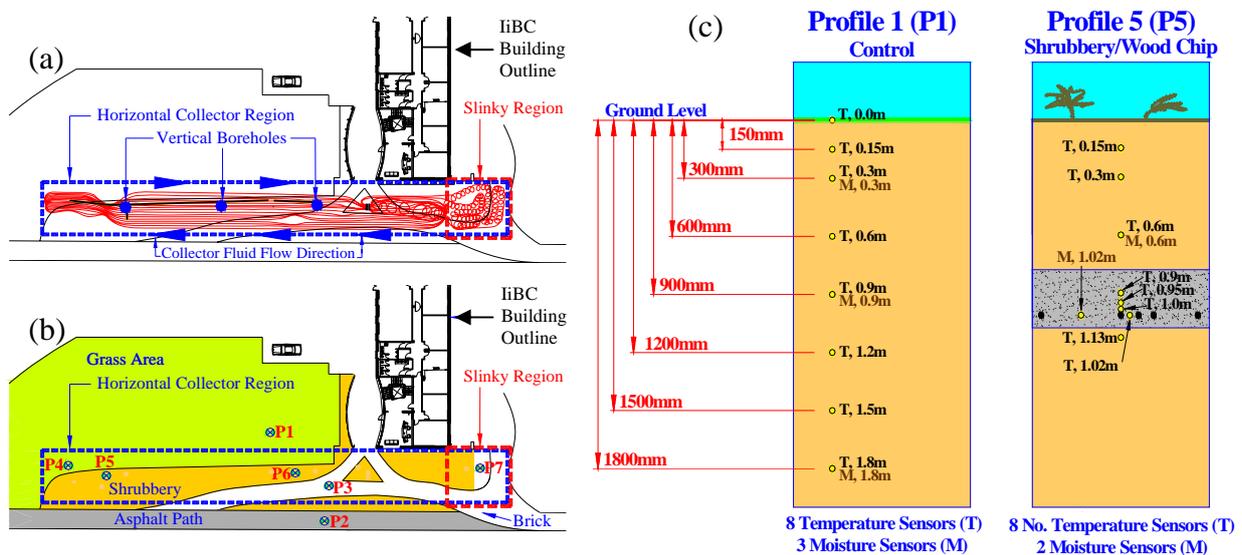


Figure 2: (a) Position of vertical & horizontal collectors relative to iIBC, (b) range of ground covers over horizontal collector, (c) cross-sectional view of two vertical measurement profiles.

Figure 2(b) presents the same plan view as in Figure 2(a) but at the ground surface level to show the range and type of ground covers that exists above the horizontal collector. The cover types include grass, shrubbery, porous brick and non-porous brick pavement and this

allows the impact of different ground covers at the ground-air interface to be investigated. Such impact, along with that of climate and heat pump operation, on ground temperatures and moisture content was investigated using a series of seven vertical measurement profiles identified as P1 - P7 in Figure 2(b) using 46 ground temperature sensors and 12 moisture content sensors. Five profiles (P3-P7) were located within the collector region and two (P1 and P2) acted as reference profiles and are positioned outside the collector region. P1 is located 6m from the nearest collector pipe. These profiles facilitated measurement to be taken to a depth of 1.8m as indicated in Figure 2(c). All heat pump data is supported by a nearby weather station.

3 RESULTS & DISCUSSION

During the 2006-2007 heating season attention focused on quantifying the performance of both heat pumps, but while operating alone, hence the supplementary gas heating was required. During the current 2007-2008 heating season both heat pumps operate simultaneously, when required, negating the need for gas. This section shows the results of these testing periods and discusses the significance.

3.1 Test instrumentation

Ground temperatures are monitored using 4-wire, PT100 Class A temperature sensors, with a nominal accuracy of $\pm 0.1^\circ\text{C}$ between -5°C and $+5^\circ\text{C}$ and $\pm 0.3^\circ\text{C}$ between $+5^\circ\text{C}$ and $+25^\circ\text{C}$. Measurement accuracy was assessed using a D55SE Jofra calibrator and the calibration method reflects best practice outlined by Stum (2006) and accounts for transducer, wire and acquisition error (Stum 2006). The dry-bulb air temperature (T_a) sensor has a calibrated accuracy of $\pm 0.35^\circ\text{C}$ at 0°C . Heat pump coefficient of performance (COP) was evaluated by means of high accuracy fluid temperature sensors: *PT100 CLASS B 1/10 Din element sensors* with an accuracy of $\pm 0.03^\circ\text{C}$ at 0°C , ultrasonic fluid flow meters: *Prosonic* ultrasonic flowmeter with an accuracy within $\pm 2\%$ of reading and electrical power monitors: *Universal Power Cell* with an accuracy within $\pm 1\%$ of reading. The overall COP accuracy is within $\pm 3.3\%$.

3.2 Operating demand

Figure 3 illustrates the monthly heating requirement of the liBC building and the actual contribution of each of the three heating systems being utilised to meet demand.

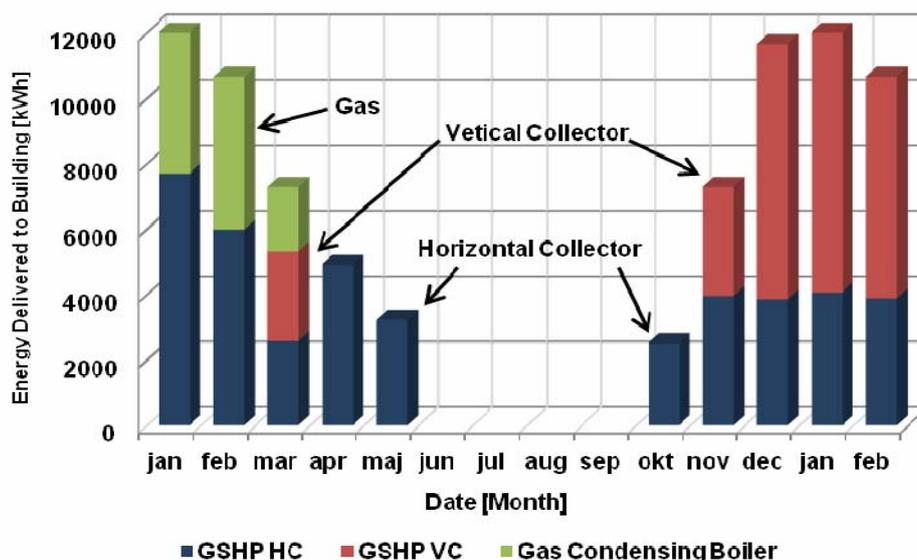


Figure 3: Combination of heating systems (GSHP_{HC}, GSHP_{VC} & Gas) deployed in the liBC, and their respective contributions to the heat demand between January 2007 and February 2008.

3.3 Test results using Horizontal Collector

Figure 4 presents a detailed overview of the performance characteristics of both the GSHP_{HC} and the impact of its operation on the ground temperature during February 2008. The average heat pump output ($T_{HPHC,F}$) temperature for this period was +48.8°C with an average brine return temperature ($T_{HC,R}$) of +4.9°C, giving a COP_{AVG} of 3.15, ranging between 2.92 to 3.35.

It should be noted that the heat pumps are not variable output and thus the variation in Q_{HC} and Q_{VC} shown in Figures 4 and 5 are due to the variation in heat pump duty over each hourly period. The operating time is recorded every minute and the extract rate is then averaged over one hour. The heat pumps brine flow ($T_{HC,F}$ and $T_{VC,F}$) and return ($T_{HC,R}$ and $T_{VC,R}$) temperatures are only plotted as hourly average values when the heat pump is operational. The ambient air temperature (T_a) and ground temperatures at P1, P4 and P5 are recorded every 5 minutes and then presented in Figure 4 as hourly averaged values. For the purpose of this study a ‘farfield’ temperature from which the collector draws its energy must be defined and as the horizontal collector is located at a depth of 1m, the control profile (P1) temperature sensor located at a depth of 0.9m is used as the farfield temperature for the horizontal collector, which will be referred to as $T_{HC,\infty}$.

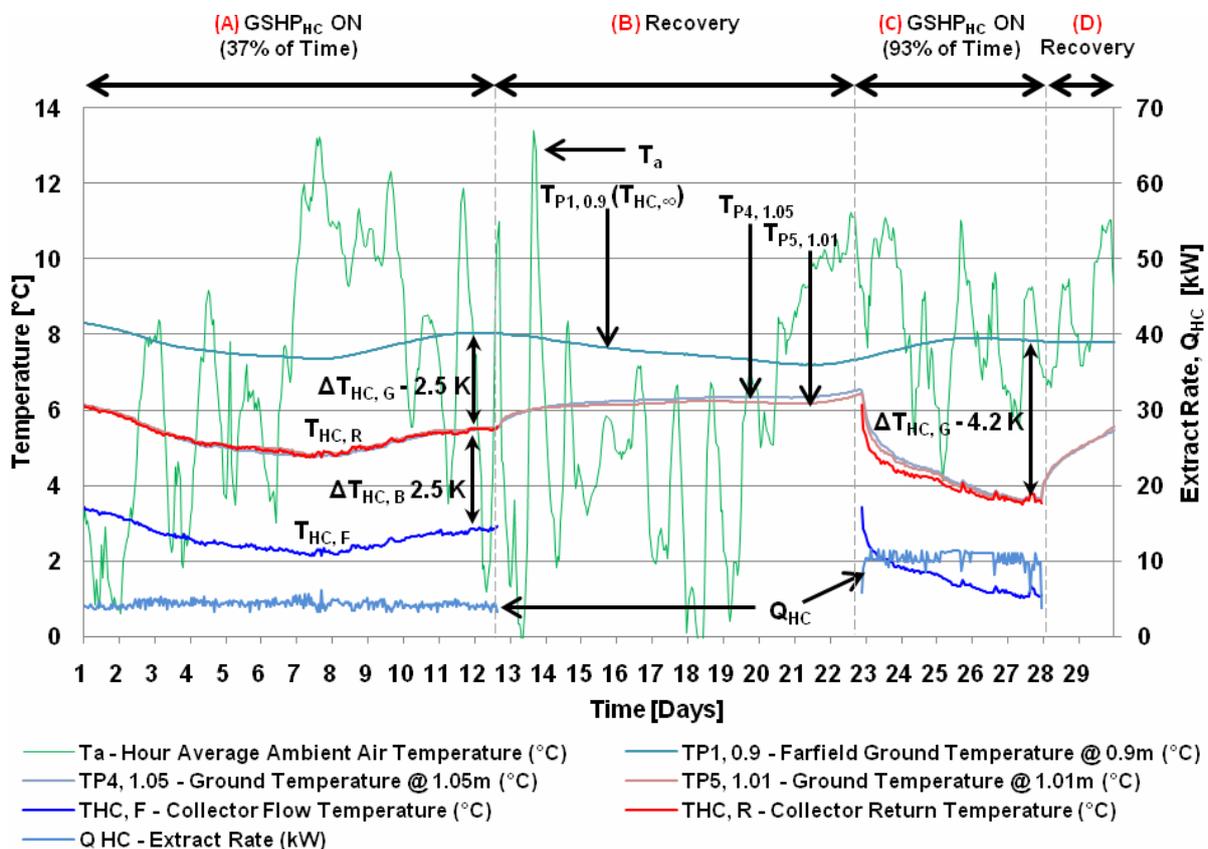


Figure 4: Drawdown and recovery of the ground temperature in the collector region of the GSHP_{HC} (horizontal collector) during February, 2008.

Prior to time period identified as ‘A’ in Figure 4, the GSHP_{HC} had been operational for the preceding 58 days and steady stage conditions existed. As can be seen that for the 12 days of Period A an average heat extraction rate of 4.3kW was delivered, and the $\Delta T_{HC,G}$ between the farfield temperature and the collector return temperature ($\Delta T_{HC,G} = T_{HC,R} - T_{HC,\infty}$) remains relatively stable at -2.5 K. This highlights that steady state conditions existed and also the extent to which heat pump operation affects ground temperature at horizontal collector depth. It is notable that the ground temperature taken from P1 at a depth of 0.9m displays a small 1°C sensitivity to the 12°C fluctuation in the ambient air temperature in time period A. This

thermal dampening effect of the ground's thermal mass minimises the impact of air temperature fluctuations, which is critical for short periods of unusually low air temperatures. Due to the nature of the Irish climate, sub-zero degree air temperatures are uncommon, especially on coastal regions, and sustained periods below 0°C are very rare, and the data in Figure 4 suggest that any low temperature swings are dampened sufficiently by the ground above and below the collector.

Between Day 12 and Day 23 (period B) the heat pump was turned off and the ground allowed to recover, reducing the $\Delta T_{HC,G}$ to less than one third (-0.8 K) of the value established during operation. On day 23 (period C) the heat pump was reactivated and requested to deliver a higher output that averaged approximately 10.3kW. It is notable that the $\Delta T_{HC,G}$ increased from -2.5 K to -4.2 K showing a sensitivity to extract rate (Q_{HC}).

It is also noticeable that the negligible thermal resistance between the ground and the brine fluid, where it can be seen that the temperature of the ground directly beside the collector pipe in profiles 4 and 5 are of similar temperatures to that of the brine fluid.

3.4 Test results using Vertical Collector

As with the horizontal collector, a 'farfield' temperature from which the collector draws its energy must be defined. One measure of the 'farfield' temperature ($T_{VC,\infty}$) was derived from recording and averaging the brine temperature in the vertical collector over a 10 month period of off-time between January 2007 and November 2007. Values ranged between 10°C (January 2007) and 10.8°C (November 2007), yielding a value of 10.4°C for $T_{VC,\infty}$. A detailed set of measured data for the vertical collector is presented in Figure 5 which depicts performance over one month of operation and recovery. This month is broken into four operational periods A, B, C and E, with one recovery period, D.

Prior to Period 'A', an extract rate of 6.5kW had been maintained for three weeks, and the temperature $T_{VC,R}$ reached steady state at +6.2°C from January 20th.

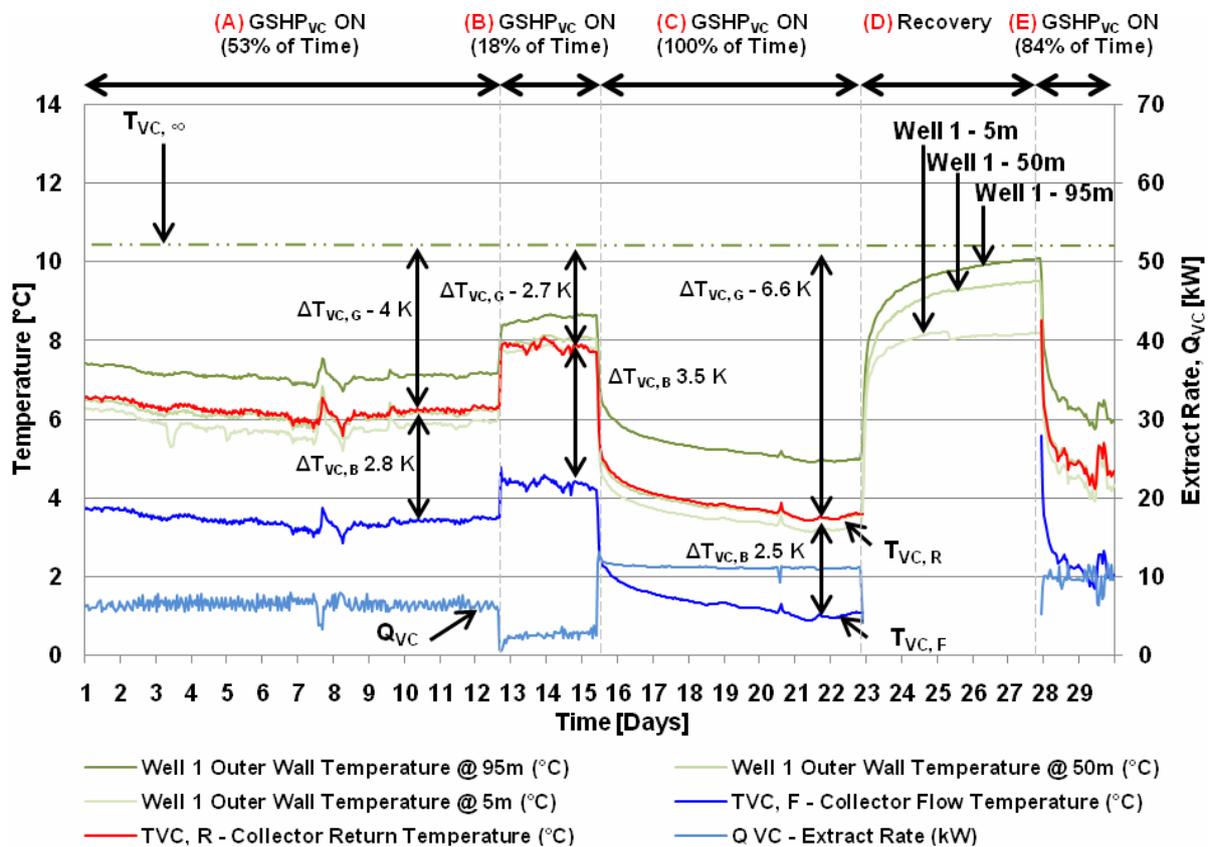


Figure 5: Drawdown and recovery of the ground for the GSHP_{VC} (vertical collector) during February, 2008.

Table 1 provides a detailed analysis of heat pump performance for the four periods of vertical collector operation. Noticeable, is the wide variation in $T_{VC,R}$ temperature depending on extract rate, given the temperature stability and size of the source. Average COPs ranged between 3.14 at +50°C output and 4.81 at +35°C output.

Table 1: Summary of the impact of varying the heat extraction rate from the vertical collector during February 2008, as presented in Figure 5.

Period	Extract Rate	$\Delta T_{VC, G}$	$\Delta T_{VC, B}$	Average $T_{VC, R}$	Average $T_{HPVC, F}$	COP_{AVG}	COP_{MAX}	COP_{MIN}
A	6.5kW	-4 K	2.8 K	+6.2°C	+50°C	3.32	3.47	3.16
B	2.6kW	-2.7 K	3.5 K	+7.8°C	+35°C	4.81	5.14	4.57
C	11.2kW	-6.6 K	2.5 K	+3.9°C	+49.3°C	3.14	3.26	3.04
E	9.8kW	-5.6 K	2.6 K	+5°C	+49.9°C	3.21	3.32	3.11

3.5 GSHP_{HC} versus GSHP_{VC}

The ability of the collector to efficiently extract thermal energy using the least possible pumping power and temperature drop in the vicinity of the collector is paramount, as both impact upon COP. Therefore, Figure 6 presents the rate at which the ground temperature surrounding the collector changes when both collectors extract at approximately 6.4kW and 10.5kW and contrasts the drawdown rate of the ground temperature in the vicinity of the collectors. While both collectors display similar drawdown rates at 6kW, the drawdown rate for the vertical collector accelerates beyond that of the horizontal collector by as much as a factor of 2 at full load (10.5kW). This highlights the ability of the horizontal collector to be up to 40% more efficient than the vertical collector at drawing as close a temperature to that of 'farfield' at full load.

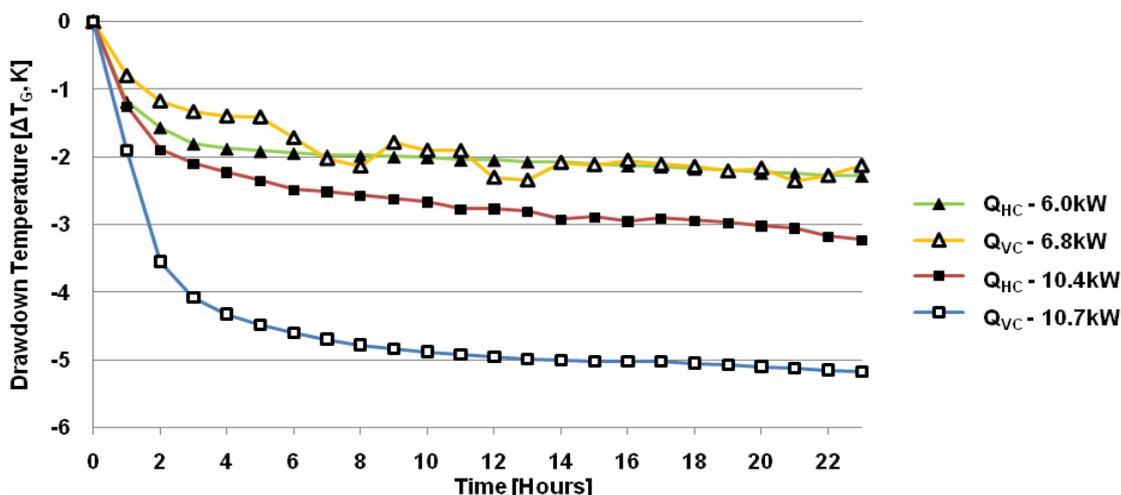


Figure 6: Comparing the drawdown of the ground temperature in the vicinity of both the horizontal collector ($\Delta T_{HC, G}$) and the vertical collector ($\Delta T_{VC, G}$) versus extract rates (Q), results were obtained from tests carried out on various dates in 2007.

Some examples of variable extract rates and the subsequent effect on the heat pump's return temperature can be seen in Figures 4 and 5 where typical brine return temperatures to the heat pumps vary between +3°C and +9°C for the horizontal collector ($T_{HC,R}$) and between +5°C and +8°C for the vertical collector ($T_{VC,R}$).

3.6 DACH rating results versus GSHP-IRL test results

The DACH rating for the heat pumps used in the *GSHP-IRL* study was established by *Arsenal Research* for brine input temperatures (T_R) between -5°C and $+5^{\circ}\text{C}$, and the results are presented in Figure 7. These input temperatures are indicative of the range of input temperatures that occur in the colder continental climate and are slightly lower than that experienced by heat pumps operating in maritime climate regions.

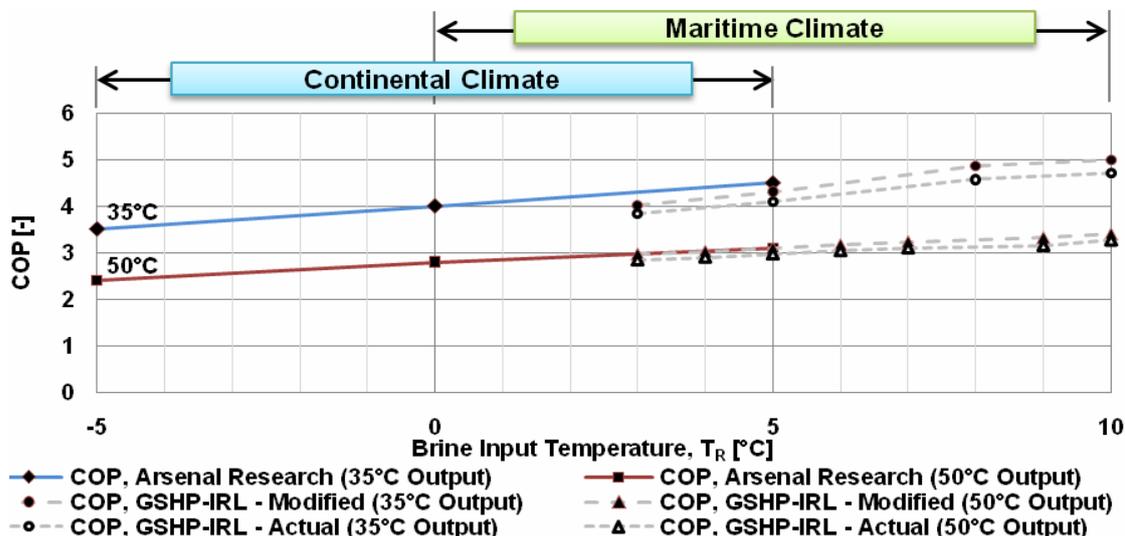


Figure 7: Comparison of heat pump performance as measured using international standards and from GSHP-IRL study.

Whilst the *GSHP-IRL* tested results correlate to within 4% of those produced by Arsenal Research to the DACH standard, it can be seen that the typical operating temperatures in the *GSHP-IRL* study ($T_{HC,R}$ and $T_{VC,R}$) are higher than those set under the standard test. The COP data from this *GSHP-IRL* study was extracted from data presented in Figure 8.

While both sets of data compared well it was noted that standards EN 255 and EN-14511 only call for a portion of the liquid pumping power to be included in the COP calculation. The *GSHP-IRL* data presents two sets of data, one that accounts for the portion of pump power recommended by the standard and the other that accounts for all the measured pumping power on the collector side and the results are summarised in Table 2.

Table 2: Impact of pumping power on COP

Test	COP, GSHP-IRL (as per EN-14511)	COP, Arsenal Research	% Difference
B5°C/W35°C	4.32	4.5	-4.0%
B5°C/W50°C	3.09	3.1	-0.3%

Test	COP, GSHP-IRL (+ Pumping Power)	COP, Arsenal Research	% Difference
B5°C/W35°C	4.09	4.5	-9.1%
B5°C/W50°C	2.98	3.1	-3.9%

The percentage differences disparity between the $+35^{\circ}\text{C}$ and $+50^{\circ}\text{C}$ outputs reflect the fact that the pumping power remains the same for both outputs but is proportionally larger in terms of total electrical consumption for the former.

Studies have shown that brine pumping power for collectors range between 14W and 40W for every 1kW of heat pump capacity (Kavanaugh 1997), and the *GSHP-IRL* study falls centrally in this range with a brine pumping requirement of 26W per 1kW of heat pump capacity.

In Figure 8, the actual COP_{DAY} results of both the horizontal collector and the vertical collector are contrasted over a winter period. The COPs for the horizontal collector (a) shows a trend upwards with a rise in ambient air temperatures, whereas the vertical collector COPs (b) remain relatively stable throughout the period.

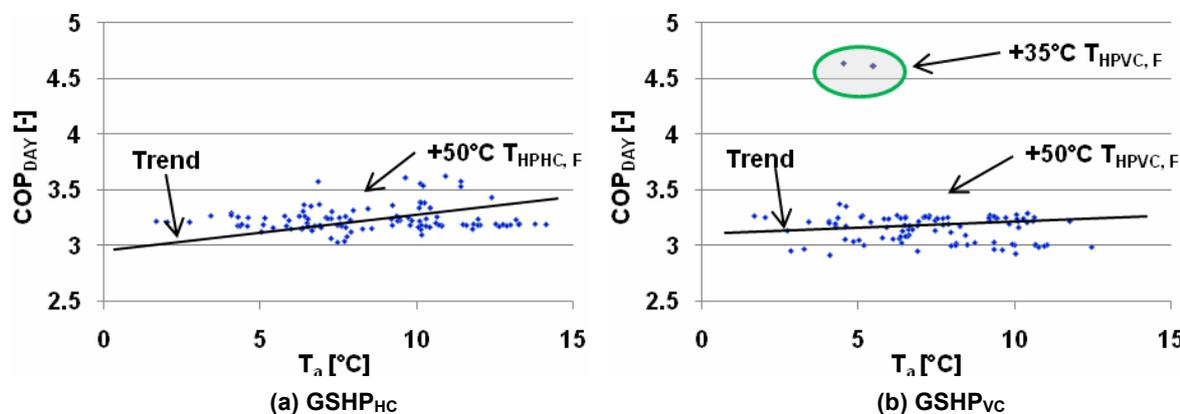


Figure 8: COP_{DAY} values for both heat pumps over the winter period from the 1st of September 2007 to the 1st of March 2008.

The SPF for the horizontal collector is 3.15 and 3.18 for the vertical collector, as recorded during the winter operating period 2007/2008.

CONCLUSIONS

This paper demonstrates that a comprehensive test facility has been established to evaluate the performance of GSHPs in maritime climates. Analysis of the test results obtained between January 2007 and February 2008 reveal that:

- a) Over the winter period, the measured COP of the horizontal and vertical collectors were 3.15 and 3.18 respectively, for a heat pump output temperature of +50°C. COP increased to 5 when the output temperature reduced to +35°C.
- b) GSHP-IRL measured COPs compare well with those from a standard laboratory test results, with average difference of between -1% and -4% indicating that laboratory data provides a reasonably accurate reflection of performance in the field. However, once all the pumping power is included, performance differences of between -4% and -9% were revealed.
- c) The rate and extent to which the brine return temperature reduces with respect to 'farfield' temperature for both collectors is a strong function of the heat extract rate, with the vertical collector showing greater sensitivity at full load (10kW).
- d) Negligible thermal resistance at the ground-horizontal collector wall interface was identified.

Further analysis will be undertaken to facilitate the completion of a guide to collector design in maritime climates and heat pump operation.

NOMENCLATURE

GSHP-IRL	abbreviation used to refer to this study	
GSHP _{HC}	ground source heat pump utilising the horizontal collector	
GSHP _{VC}	ground source heat pump utilising the vertical collector	
Q _{VC}	vertical collector thermal energy extract rate	(kW)
Q _{HC}	horizontal collector thermal energy extract rate	(kW)
T _{HC, F}	brine flow temperature from HP to horizontal collector	(°C)
T _{HC, R}	brine return temperature to HP from horizontal collector	(°C)

$T_{HC,\infty}$	horizontal collector 'farfield' temperature	(°C)
$T_{HPHC, F}$	water flow temperature to the radiators from the GSHP _{HC}	(°C)
$\Delta T_{HC, G}$	difference between $T_{HC,\infty}$ and $T_{HC,R}$ ($\Delta T_{HC,G} = T_{HC,R} - T_{HC,\infty}$)	(K)
$\Delta T_{HC, B}$	brine, temperature difference between $T_{HC,R}$ and $T_{HC, F}$	(K)
$T_{VC, F}$	brine flow temperature from HP to vertical collector	(°C)
$T_{VC, R}$	brine return temperature to HP from vertical collector	(°C)
$T_{VC,\infty}$	vertical collector 'farfield' temperature	(°C)
$T_{HPVC, F}$	water flow temperature to the radiators from the GSHP _{VC}	(°C)
$\Delta T_{VC, G}$	difference between $T_{VC,\infty}$ and $T_{VC,R}$ ($\Delta T_{VC,G} = T_{VC,R} - T_{VC,\infty}$)	(K)
$\Delta T_{VC, B}$	brine, temperature difference between $T_{VC,R}$ and $T_{VC, F}$	(K)
COP_{DAY}	daily average coefficient of performance	(-)
COP_{AVG}	average coefficient of performance over stated period	(-)
COP	instantaneous (every minute), coefficient of performance	(-)
SPF	seasonal performance factor, COP over a season	(-)

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