Department of Mechanical Engineering

Characterization of the Operational Efficiency Of a Domestic Heat Pump

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Abstract

Throughout the world there has been a growing move towards using renewable technologies to replace harmful fossil fuels. The concern over fossil fuels is due to both their adverse effect on the planet's state as well as their ever diminishing quantities. In this battle to address our reliance on fossil fuels, a technology that is rapidly moving towards the forefront is the use of heat pumps. Heat pumps are particularly desirable since they promise high efficiency performance in heating and cooling applications. Although they are already being taken up by the industrial sector, in UK they still comprise only a small part of the domestic sector. With the introduction of such government schemes as the Renewable Heating Incentive (RHI) there is a large projected increase in the use of heat pumps.

This project experimentally evaluates the operational coefficient of performance of a ground source heat pump. This was done through the designing and building of a heat pump test rig that would simulate an average UK domestic household. The test rig was able to characterise the coefficients of performance through a heating cycle that could be compared with those provided in the manufacturer's manual. From this an effective COP for the specific heat pump was found. The thesis shows that the performance of the heat pump under certain test conditions did not meet the same levels of efficiency stated by the manufacturer. Consequently it was found more stringent industrial testing was required to ensure that the technology continued to be taken up. The implications of this difference would not only affect the individual heat pump user, but it is also likely to save the government a significant amount of money.

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Abbreviations

ASHP	Air Source Heat Pump
BSPT	British Standard Pipe Thread
C	Heating capacity
COP	Coefficient of performance
CO_2	Carbon Dioxide
cm	Centimetres
DECC	Department of Energy & Climate Change
FPT	Female Port Thread
GSHP	Ground source heat pump
GHX	Ground heat Exchanger
H	Enthalpy
HP	Heat Pump
HSPF	Heating Season Performance Factor
kWh	Kilo Watt Hour
kW	Kilo Watts
m	Metres
$\dot{m}$	Mass flowrate
mm	Millimetres
MUI	Medium User Interface
NPT	National Pipe Thread (Tapered Thread)
P_{INPUT}	Power Input
Q_{OUTPUT}	Heating Output
RHI	Renewable heating incentive
s	Specific Entropy
T	Temperature
WSHP	Water Source Heat Pump

1 Introduction

1.1 Project Background

As the world moves into the 21st century there are ever growing concerns about the large consumption of fossil fuels as a primary source of power due to their adverse affect on the planet through the release of greenhouse gases. A fourth climate report (Solomon & Change 2007) released by the intergovernmental panel for climate change (IPCC) has linked these greenhouse gases, most notably Carbon Dioxide (CO_2), with the warming of the earth. Fossil fuels release large amounts of CO_2 when burnt in such applications as coal-fired power plants, petrol engines and a wide variety of other means. Throughout the world there has been an ever-growing pressure, especially for 'developed' countries, to cut large proportions of their emissions through a variety of means. Therefore the United Kingdom has set an ambitious target of reducing its greenhouse emissions to less than 80% of the 1990 levels by 2050 primarily by moving towards the use of renewable technologies. For this figure to be reached drastic changes in many areas of society will need to be made as well as a shift in mentality.

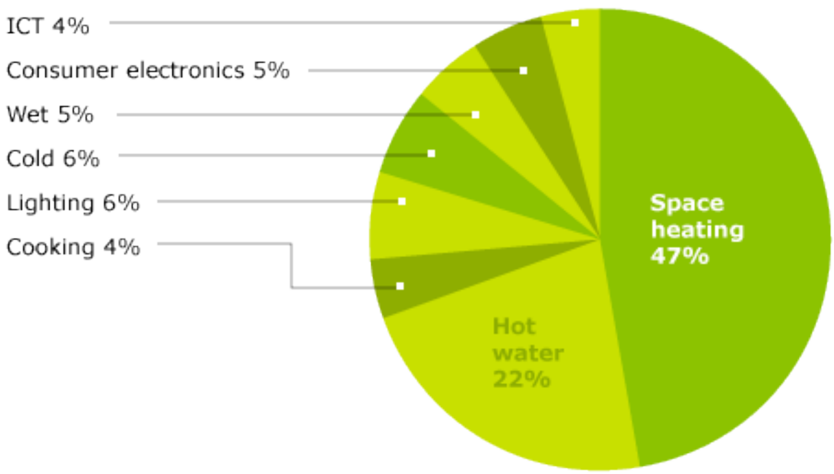


Figure 1: Domestic CO_2 emissions by end use in the UK (Guardian 2010)

One area that has been identified by the UK government as in need of particular improvement is the use of fossil fuels to deliver heating in homes and offices (Figure 1). This sector has been identified as one of the largest sources of Carbon Dioxide emissions in not only this country but also worldwide (Ochsner 2008). The reason for such inefficiency with regard to heating is primarily a result of the poor use of resources as well as poor fabric determinants (such as insulation and draught proofing) in the older buildings. The inefficiency of heating in the UK is such that at best 1kW of electricity goes to produce just less than 1 kW of heating (Figure 7). A large amount of CO2 is subsequently produced in the heating of UK buildings. If the UK is to be able to meet the ambitious emissions targets that it has set then a significantly improved form of heating will need to be utilized. One of the few developed and reliable technologies that could address this problem is the use of Heat pumps.

Heat pumps promise a much greater performance than commonly used technologies (almost 300% better), and so they deserve to be explored and potentially embraced by the government. The performance of a heat pump is measured by the coefficient of performance (COP), with higher values being more desirable. The COPs provided by the majority of heat pump manufacturers sound very promising and if they work according to the COP value specified then the desirability of them should increase massively. If the heat pumps can operate at a suitably high COP then they will provide an important stepping stone towards the 80% reduction in emissions for the UK. With that possibility in mind, this project will test a heat pump COP range and compare it with the manufacturer's data to confirm whether the promising data given by the manufacturers is in fact accurate.

1.2 Project Definition and Aims

In view of the possibility that the heat pump data provided by the manufacturers is overly optimistic, this project will aim to establish exactly what levels of COP can be achieved under test conditions. This experiment will be simulated by the setting up of a ground source heat pump (GSHP) test rig in the University of Strathclyde's laboratories and then running through a variety of controlled tests. The primary focus of the test will be to confirm the operational coefficient of performance of a specific heat pump model, the 8kW Waterfurnace Ground Source Heat Pump, and to subsequently assess the reliability of the data provided by the manufacturers (Appendix 9.5). The program RETScreen will be used to test the modelling protocols that are utilised in the prediction of the performance of the heat pump's COP in order to simulate how it will operate in a domestic environment. The COPs defined by the company are 6.1 and 4.2 for cooling and heating respectively.

2 Heat pumps

2.1 Literature Review

Lord Kelvin first described the theoretical basis for heat pumps in 1852 (Capehart 2007) but he could see no use for it as a heating device. It took three more years (1885) before his theories were used in the production of heat through the use of an open-cycle mechanical vapour compression unit. The first heat pump was developed and built between 1855 and 1857 by Peter Ritter von Rittinger (Banks 2008). Heat pumps were initially used in reverse, taking hot air away from spaces and dumping it. This method was primarily used as a means of storing food and can most commonly be seen in refrigerators. It was not until much later that the closed vapour compression cycle heat pump was used for generating useful heat in a domestic heat environment. Nowadays millions of air conditioners, chillers and fridges are manufactured and installed every year throughout the world (Ochsner 2008).

Uptake of heat pumps in the UK for the purpose transferring heat has been a lot slower than compared to the amounts being manufactured in mainland Europe and North America (Figure 2). In the UK there has been a large uptake of heat pumps in non-domestic buildings (over 60,000 units in 1996 alone (ESRU n.d.)) but the uptake for domestic heat pump units remains very slow. A survey was done by the EHPA (European Heat Pump Association) in 2006-2007 of 9 mainland European countries and it found that UK had only 3500 units in operation in 2007 (Forsén 2007). The spread can be seen in Figure 2 and illustrates how little the United Kingdom has moved in embracing domestic heat pumps. Reasons for this low uptake could be attributed to the lack of government incentives encouraging individuals to invest, and there is an expectation that if the RHI goes ahead, then the uptake is likely to improve. The same report that notices the poor uptake goes on to say that there is a large projected increase in 2008 (to 5000 units) as heat pumps become more widely available and more easily integrated into most hot water systems (Singh et al. 2010).

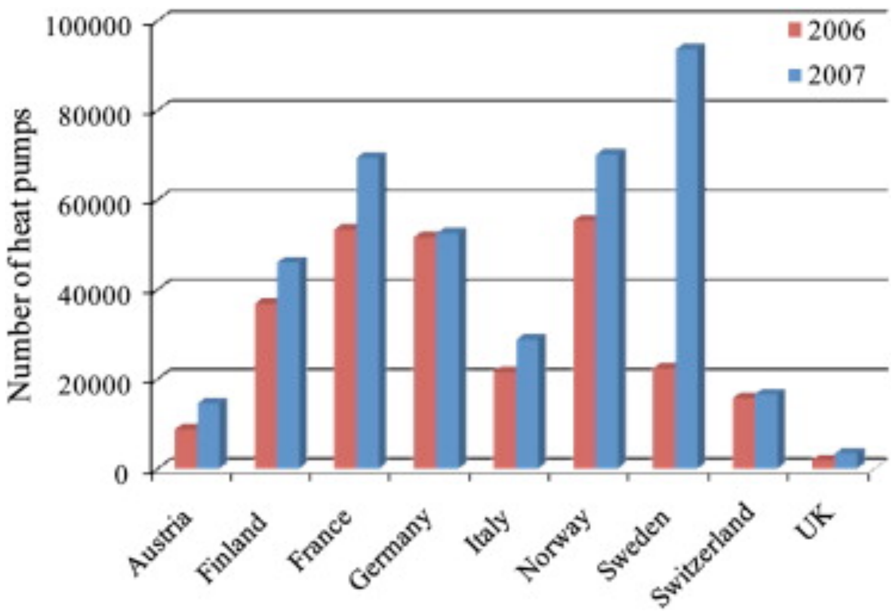


Figure 2: Number of Domestic heat pump units sold in 2006-2007 (Forsén 2007).

The graph (Figure 2) is useful for highlighting the considerable difference in numbers of heat pumps throughout Europe. Whereas most countries have a gradual increase it can be noted that Sweden has increased 3 fold in one year. This is due to a combination of high oil prices but mainly because of the state supporting the installation of heat pumps through providing tax breaks, loans and grants (Karlsson & Axell 2008).

Since most heat pumps are driven by electricity, one of their major benefits is that as more and more electricity generation is produced through the use of renewables such as wind and tidal turbines, the use of heat pumps becomes cleaner. By contrast, conventional domestic heating technologies such as gas are not affected by the move towards renewables and therefore they continue to pollute the atmosphere.

2.2 How a heat pump works

This is a brief introduction of how heat pumps operate. The heat pump has to operate within the second law of thermodynamics, which according to the Clausius statement states that 'Heat cannot flow spontaneously from a material at lower temperature to a material at higher temperature' (Howell & Buckius 1992). A heat pump is a device that is able to extract heat from a low temperature (low grade heat) source and transfer it to a high temperature load. This process requires input from some mechanical work, usually supplied by electricity, to be able to 'move' or 'upgrade' the heat. The low-grade heat can be collected from a variety of places such as the atmosphere, water sources and the ground. The heat load (sink) tends to be some internal space or domestic hot water. Most heat pumps consist of a vapour compression refrigeration device, heat exchangers and a reversing valve (so the heat flow can be reversed). The heat pump system uses a refrigerant to transfer the heat from the source (air etc) to the load (domestic hot water etc). It is a closed cycle process and there are four main changes of state,

- Evaporation
- Condensation
- Expansion
- Compression

The typical setup of how a heat pump works can be seen in Figure 3.

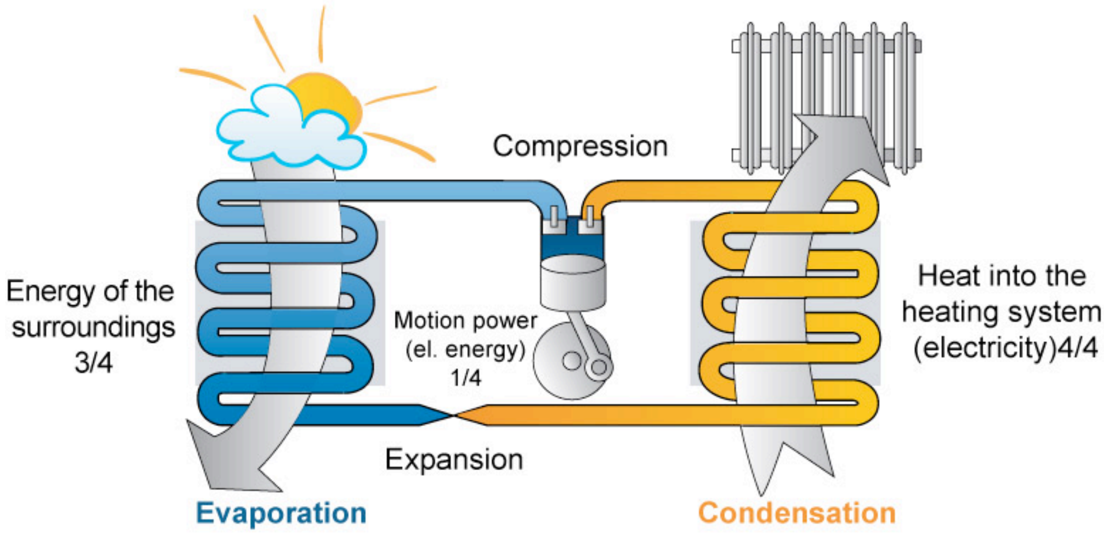


Figure 3: The heat pump cycle (Setrime n.d.)

The heat pump more or less reverses the ideal Carnot cycle for a heat engine. The working fluid (refrigerant) in its gaseous state is pressurized and circulated through the system. On the exiting side of the compressor the fluid is a highly pressurized vapour, as it is superheated, and goes through a condenser, which acts like a heat exchanger. In the condenser the vapour condenses to a moderate temperature liquid after releasing heat into the designated system. The condenser is where the heat is released into the heat sink. The condensed fluid then passes through an expansion valve (in some cases it is a turbine) so that the refrigerant's high pressure is lowered. The last stage is for the fluid to pass into the evaporator where it undergoes evaporation into a vapour through absorbing heat from the source, this again is another form of a heat exchanger. The vapour then returns to the compressor and the cycle is repeated. This cycle can be seen on the temperature (T) specific entropy (s) diagram for the refrigerant, in this case R410a (

Figure 4), where each stage is highlighted. From this diagram some key points are identified and these are useful for determining the COP of the cycle.

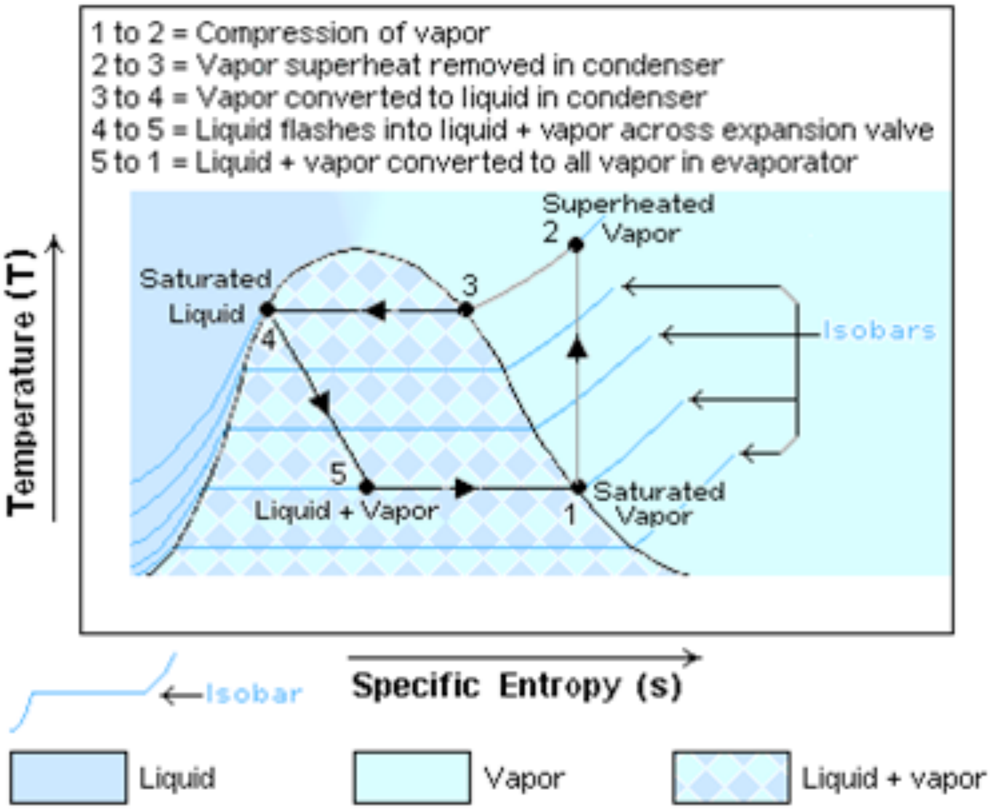


Figure 4: The T-s diagram for a typical refrigerant used in a heat pump.

2.3 Types of Heat Pumps

There are generally considered to be three main types of Heat pumps in commercial production. Each type can be subdivided into smaller groups. These smaller groups are commonly categorized by the source of their heat, but can also be categorized by function, working fluid, and unit construction. The three main types are:

- Ground Source Heat Pump (GSHP)
- Air Source Heat Pump (ASHP)
- Water Source Heat Pump (WSHP)

Each of these different technologies has advantages and disadvantages. Within each category there are many forms, which are determined not only according to the heat source medium, but also what medium the heat pump uses to transfer heat to the heat sink, i.e. ground to water, ground to air. This project focuses on the ground source form (the others types can be found in Appendix 9.1.).

The GSHP (sometimes known as the geothermal heat pump) is the type of pump being used in this specific project. It uses heat extracted from the ground through a ground heat exchanger (GHX) to warm up buildings, swimming pools, under floor heating, domestic hot water and in many other applications. It has two main forms; Ground to water and Ground to air. This means that heat is extracted from the ground, exchanged in the heat pump and then transferred into the circulating air or water.

A unique feature of the GHSPs is the option of a closed loop or open loop system. The closed loop contains two loops on the source side, one comprising of a mixture of water and anti-freeze and the other is the refrigerant loop. It is considered closed loop because the working fluid is within a closed pipe and does not come into contact with any ground water. In this case the heat is extracted through closed pipe ground loops buried either in horizontal trenches or in vertical boreholes (Figure 6a). The open loop pumps water from a well or from a nearby pond and are sometimes referred to as a ground water heat pump. The working fluid is the water in the pond/well and is circulated through a set of open pipes connected to the heat pump and has the benefit of eliminating localized chilling.

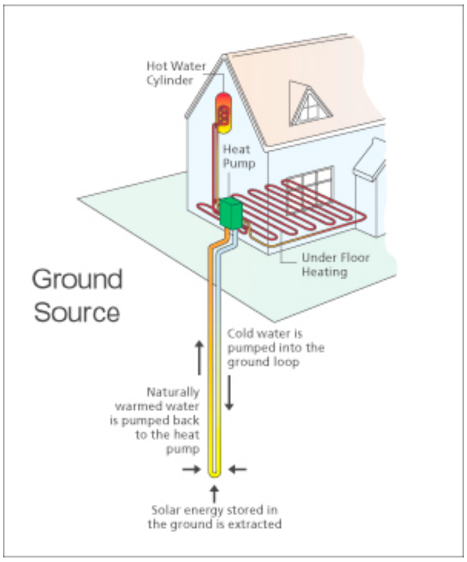


Figure 6: GSHP with ground loop water to water (HPA n.d.).

There are many advantages to GSHP method of functioning, the most noteworthy one being the consistency of the ground temperature. For most ground source heat pumps the starting temperature of the source inlet is about 10°C (Figure 7) as this is the natural temperature of the ground at a depth of six metres. Throughout the whole of the United Kingdom this temperature of around 10°C will be found, summer or winter, unless unusual conditions apply.

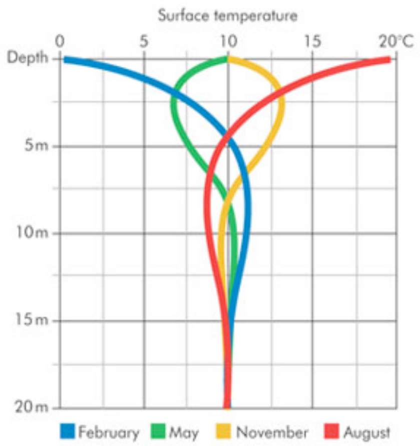


Figure 7: Ground Temperature throughout the year at different depths (Filterclean n.d.).

The reason for such consistency is that heat only moves very slowly in the ground and the earth has a huge latency. Another advantage is that during the hotter periods, any excess heat can be dumped back into the ground due to the reversibility of the heat pump. GSHP's are best suited to applications such as under floor heating or low temperature radiators due to them only being able to raise the temperature to around 40°C, although high outputs in domestic heating can be gained through using them in conjunction with a conventional boiler or immersion heater to raise the temperature to

80°C. Unfortunately one of the major drawbacks to ground source heat pumps is the financial cost of installing the ground loops, especially the vertical boreholes. The high costs are primarily due to the depth of the borehole (anywhere between 23-150m deep) and the area covered by a horizontal pipe layout. The actual installed cost ranges from £800 - £1,200 per kW of peak heat output installed (trench systems tend to be at the bottom end of that bracket), although once the system has been installed they have a life expectancy of over 40 years (ICAX n.d.).

2.4 Coefficient Of Performance

In the description of the performance of a heat pump it is better not to use the term 'efficiency' which has a very specific thermodynamic definition. A better term to use is the coefficient of performance. This is an indicator of the amount of heat that is delivered in relation to the drive power required (Ochsner 2008). It can be represented as,

$$COP = \frac{Delivered\ heat\ energy(kW)}{Heat\ Pump\ Electrical\ Input\,(kW)} \quad \text{Equ. 1}$$

Therefore a COP of 3 would mean that the thermal output of the heat pump is three times the amount of electrical input. The COP can vary greatly for different technologies that perform domestic heating (Figure 7).

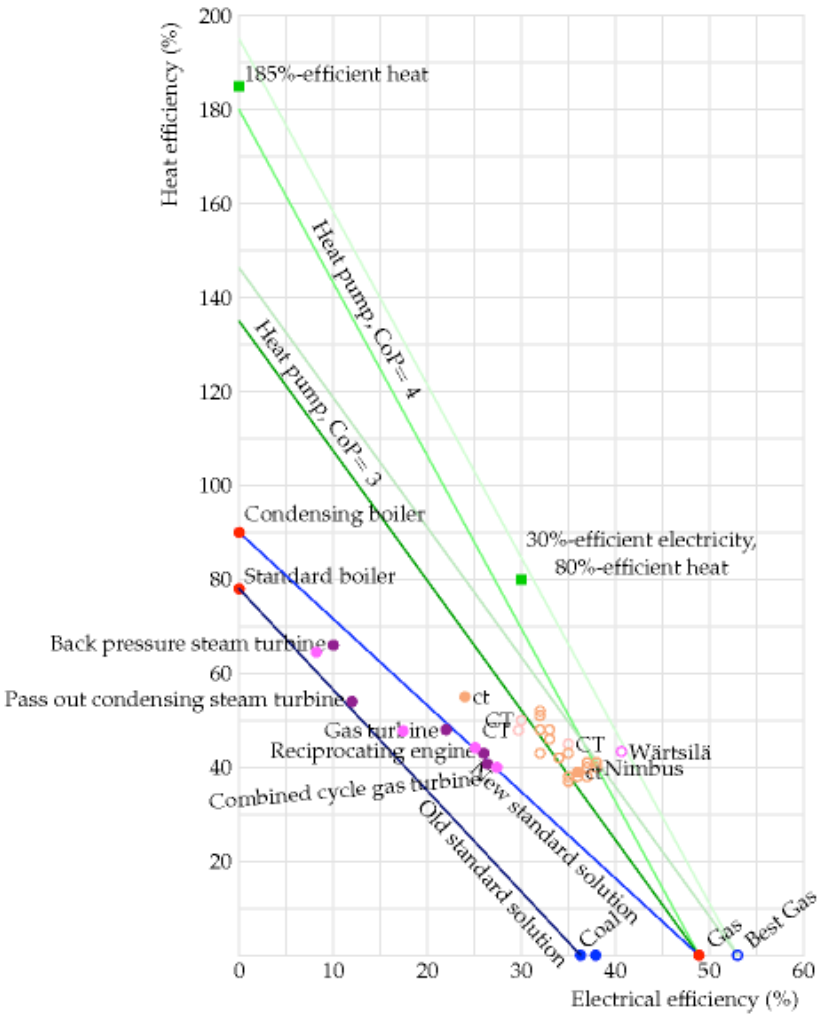


Figure 7: The Effectiveness of a heat pump compared to other technologies (MacKay 2009)

In comparing heat pumps against different technologies it can be seen that the specified COP for a heat pump is a lot higher than the alternatives. Only heat pumps have a COP higher than one. One of the added benefits of using heat pumps as a replacement for the less efficient boilers is that they use the same infrastructure. The only hardware that needs replaced is the boiler and the connections for the heat pump to be fitted. As has recently been observed in Japan, as the heat pump technology develops so the COP will increase and '*thanks to strong legislation favouring efficiency improvements, heat pumps are now available with a coefficient of performance of 4.9*' (MacKay 2009).

The reason is the heat pump is so efficient is that it draws about three-quarters of the heating energy from the solar energy stored in its surroundings. The COP is dependant on the design of the heat pump and the operating characteristics of the refrigerant. It is also dependant on the temperature difference between the source and the load. As this difference increases, the heat pumps performance will tend towards 1 due to the Carnot efficiency limits. This is because the theoretical thermal COP in a vapour compression heat pump is always greater than one (Tarnawski et al. 2009). The larger the difference in load and source temperatures the lower the coefficient of performance of the heat pump. The practical way of calculating the COP in this thesis is by finding the heat output from the heat pump by using Equ 2.

$$Q_{OUTPUT} = \dot{m}C(T_{LL} - T_{EL}) \qquad \textbf{Equ. 2}$$

Q_{OUTPUT} is the Heat Output of the heat pump, $\dot{m}$ is the mass flowrate, T_{LL} is the leaving load temperature, T_{EL} is the entering load temperature and C is the heat capacity of water (4.1855 kJ/kgK). This will give the heat output of the pump and then dividing by the electrical power measured in the experiments, the COP for that particular temperature difference can be found. As the load temperature increases due to it absorbing heat the COP can be characterised at specific 1^{0}C intervals. This will be used later in chapter 6.3 to help analyse the results and produce the COP of the system.

3 Renewable heating incentive

3.1 Description

As a way for the UK government to switch from using fossil fuels as a source of domestic heating they are going to introduce the Renewable heating incentive (RHI), also known as "the clean energy cash back". The RHI is a way of providing financial support to individuals or companies wanting to invest in renewable technologies. As part of their attempts to reduce CO_2 emissions, the government has set an energy target of 15% renewable energy in the UK by 2020 (DECC 2010). Currently there is approximately 1% of total heat demand being generated from renewable sources so there needs to be a rise of 12% to meet EU targets. The RHI is very similar to Feed-in Tariffs (introduced in 2010) that have helped to accelerate the installation of renewable technologies in Europe more than any other incentive.

The scheme works by paying individuals a certain amount a year in order to encourage them to replace their existing fossil fuel heating systems (e.g. gas, oil or coal) with a renewable technology. It is hoped that this incentive will reduce the current CO_2 emission levels and help prevent 'climate change' (Energy saving Trust). These are the technologies that are eligible:

- Air, water and ground source heat pumps
- Solar thermal
- Biomass boilers
- Renewable combined heat and power
- Use of biogas and bio-liquids
- Injection of bio-methane into the natural gas grid

This sort of initiative would really energize the heat pump market but it would be a very expensive process and at this point in time the government has not revealed where the money will come from. The tariffs are fixed for between 10 and 23 years although there are variations between each system (Table 1).

Table 1: Comparison of the tariffs for types and sizes of systems (Ownergy 2010).

Technology	Scale	Tariffs (pence/kWh)	Tariff lifetime (years)
Small installations			
Solid biomass	Up to 45kW	9	15
Biodiesel (restricted use)	Up to 45kW	6.5	15
Biogas on-site combustion	Up to 45kW	5.5	10
Ground source heat pumps	Up to 45kW	7	23
Air source heat pumps	Up to 45kW	7.5	18
Solar thermal	Up to 20kW	18	20
Medium installations			
Solid biomass	45kW-500kW	6.5	15
Biogas on-site combustion	45kW-200kW	5.5	10
Ground source heat pumps	45kW-350kW	5.5	20
Air source heat pumps	45kW-350kW	2	20
Solar thermal	20kW-100kW	17	20
Large installations			
Solid biomass	500kW and above	1.6-2.5	15
Ground source heat pumps	350kW and above	1.5	20
Biomethane injection	All scales	4	15

It can be seen from the above table that small installations of ASHP and GSHP will have a long lifetime (18 and 23 years respectively) with the ASHP having a slightly better tariff. The tariffs paid to the consumers are based on the output of the renewable energy system. For the small and medium installations the way they the level of payment is based is through a process of 'deemed' output based on what the installation is expected to produce. For the large-scale systems, they will be metered and the payments will be based on the amount of kWh produced. As the installation size increases so the tariff rate decreases. The RHI is expected to come online before April 2011 but people will be eligible for it if they have had their system installed after the 15th July 2009. The customer is expected to receive a return rate of about 12%, which amounts to about £700 - £1000 a year.

3.2 Problems

The department of energy and climate change (DECC) has stated in its consultation document that only efficient heat pumps will be eligible for the RHI. This is based primarily on the manufacturer's standard for the coefficient of performance under certain test conditions and not with what environment the heat pump is actually working in. Secondly, for the small and medium sized installations the size of the payments is dependent on 'deemed' payment output. For heat pumps this is calculated using the size of the heat pump and the COP. If the COP provided by the manufacturer is a lot higher than the actual operational COP then the owners of the heat pumps will be making a lot of money. This in turn will encourage more people to take on heat pumps but will also defeat the purpose of the RHI. People will expect the heat pump to provide a certain amount of heat but when it falls short of that they will need to rely on fossil fuels. Subsequently there will arise a situation where the government will be paying them to use fossil fuels.

4 RETScreen

A program called RETScreen Clean Energy Project Analysis Software was used to simulate the setup. It is primarily a decision support tool but can also be used to test the energy production and the efficiency of certain technologies. It was used to test the setup of the proposed system and to highlight the expected coefficients of performance. Additionally it was used to model a realistic scenario that the heat pump would be placed in to see how efficient it would be and what effective COP it would produce.

4.1 Model Construction

The model was constructed to represent the experimental setup (see 5.1) so that accurate comparisons could be made. Firstly RETScreen has certain templates available, but the user can also select and customize each model to suit their specific needs. In this case there was an option to use a heat pump but it was restricted to an industrial environment. The ground source heat pump was chosen but the characteristics of where it was located had to be changed. Firstly by using data collated from NASA, the location of the heat pump could be set to Glasgow Airport. This was useful as it contained all the vital information about Glasgow, such as the average climatic conditions, the average temperatures and perhaps most importantly the ground temperatures throughout the year (Table 2). Although these ground temperatures were only taken from just at ground level (0 metres) and should have been taken at 2 metres. These temperatures were averaged at 10^0C throughout the year.

The most important part of the model setup was next, the load and network design, as this would define how closely the model matched the test rig setup. This project has assumed an average UK domestic house setup and therefore has a floor space of $130m^2$ ($1400ft^2$) per household (Ochsner 2008). The domestic heating load for a building in the UK is 10.56 W/m^2 for hot water and 20.12 W/m^2 for hot air (MacKay 2009).

Table 2: Data provided by RETScreen on Glasgow's Climate.

Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		3.9	85.2%	0.57	99.4	5.2	1.8	437	0
February		4.3	81.4%	1.28	99.7	5.4	2.4	384	0
March		5.7	79.7%	2.29	99.6	5.3	4.5	381	0
April		7.5	75.9%	3.67	99.7	4.6	7.0	315	0
May		10.6	73.8%	4.97	100.0	4.5	10.7	229	19
June		13.0	75.8%	5.06	99.9	4.2	14.0	150	90
July		15.0	78.5%	4.71	99.9	4.1	16.3	93	155
August		14.5	79.7%	4.01	99.8	4.0	16.2	109	140
September		12.1	82.1%	2.77	99.8	4.2	12.8	177	63
October		9.5	84.2%	1.49	99.4	4.5	8.5	264	0
November		6.3	85.1%	0.73	99.4	4.3	4.7	351	0
December		4.4	86.5%	0.38	99.5	4.6	2.6	422	0
Annual		8.9	80.7%	2.67	99.7	4.6	8.5	3,311	466
Measured at	m					10.0	0.0		

The average seasonal coefficient of performance for a standard 8kW heat pump has been recorded at just over 3. This value is where the biggest error is likely to occur, as it is very dependant on the type of heat pump. Unfortunately, due to this pump being designed in America, there is no recorded data about what its seasonal performance would be in the United Kingdom. Next the main data about the heat pump needed to be inputted. The heating capacity was inputted at 8.1 kW and the cooling capacity was taken as 11.4 kW. The Design Coefficients were also put in with a heating COP of 4.2 and a cooling COP of 6.1. In the experiment only the heating COP will be explored.

The ground heat exchanger was a vertical closed loop that needed to have a compact layout because of space restrictions for domestic locations. The land area required for a vertical borehole needs to be $11m^2$ and since this was specifically designed to meet the heating capacity, it needed to be to a depth of 99m. It was assumed that the geology of the ground that the pipes were buried in was primarily a mixture of rock and soil with an average temperature of 10^0C.

For the setup to be eligible for RHI the domestic house has to meet certain energy efficiency standards. The program requires a minimum of 18 cm of glass wool insulation in the attic, 12 cm in the exterior walls and 15 cm in the unheated floor; the glass wool insulation has to have a minimum thermal conductivity of 0.045 W/Km.

These were all added to the setup to try and ensure that the most accurate representation of the setup could be found. From this the results could be produced (Chapter 6.7).

5 Experimental Setup

5.1 Design Criteria

To successfully assess the coefficient of performance of the Heat pump, a suitable test rig would have to be set up to simulate the operational characteristics of a standard home. This is the same domestic setup used in the modelling software RETScreen. As previously mentioned the heat pump is a ground source heat pump that is designed to operate with a closed loop source collector. In this case it would probably have been a vertical loop and the source ground temperature would be at roughly 10^{0}C. This is going to be effectively simulated by having a volume of water at 10^{0}C in a large cylinder so that the heat pump can absorb the heat. The water from the source must be transferred to the heat pump and back again through a closed loop heat exchanger (Figure 16). This must be insulated so that no heat is lost transporting the water and it must be a close looped circuit to effectively simulate how it would be setup in a domestic situation. The water must be pumped with a variable domestic pump that is able to circulate the water (or brine water mixture) at up to 0.76L/s so that the data from the manual can be compared. Secondly the load on the heat pump (the water that needs to be heated up) needs to be of a similar capacity to that of a standard domestic setup.

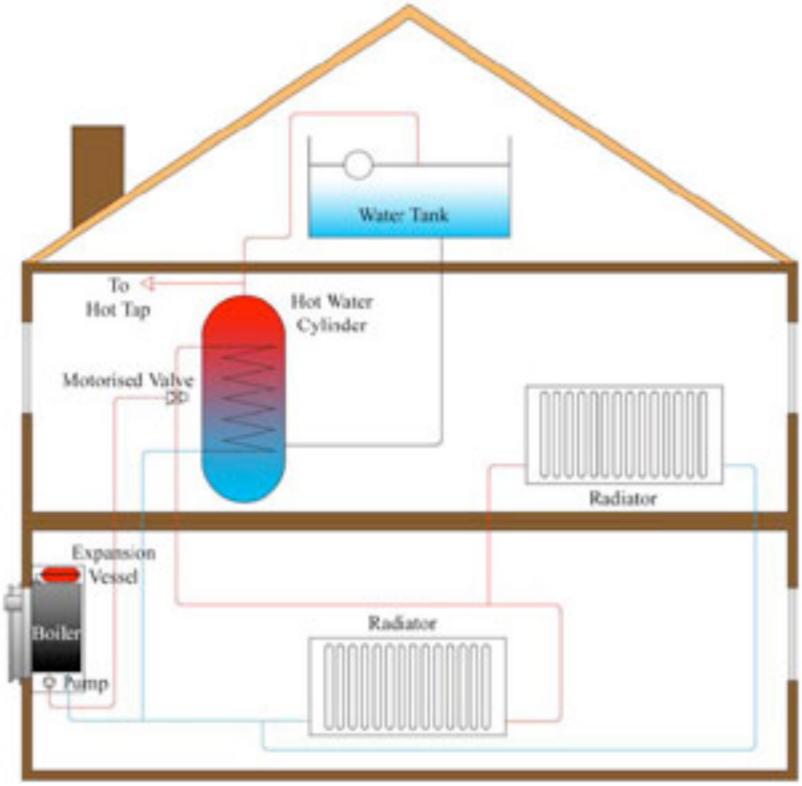


Figure 8: Gravity Fed hot water system (AquaBrand n.d.).

The domestic setup chosen is gravity fed hot water system (Figure 8) because it works with low pressures and its ease of installation. Usually the water tank is located at the top of the building so that it has a large head and therefore there is pressure in the system. Due to the experimental limitations, the only requirement is that it needs to be above the cylinder as the setup is not permanent. There are other possible setups such as unvented hot water systems and combination boilers but these were deemed to not work as well as the gravity fed in conjunction with this specific heat pump setup.

The standard size of a domestic tank in the UK is 50 Gallons (SimplifyDIY n.d.) but for this rig the tank must be large enough to be able to simulate a wide range of domestic sizes. This necessary so that it can reproduce the possible different amount of combinations of appliances that can occur in a standard house, such as 1-3 showers, multiple radiators and many parts that are connected to the domestic hot water. It is possible to make the cylinder vented or unvented. Vented means it needs to be open to atmosphere to avoid a pressure build up and requires a cold water feed tank whilst unvented is fed directly from the mains water supply and so is pressurized, eliminating the need for a water tank. Due to the selection of a gravity fed system it is better to go for a vented tank as the unvented tank capabilities would not be fully utilized and it is considerably more expensive.

Figure 9: Domestic water pump – Grundfos 15/50 selectric pump

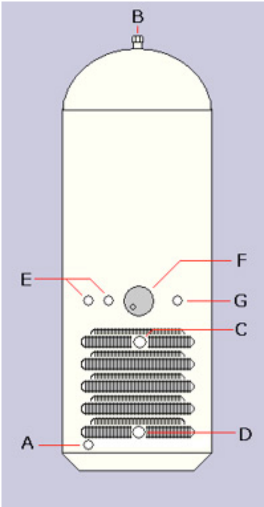
The water should also be potable so that it can be used in domestic appliances without the user risking the possibility of suffering illness. There will also need to be a variable pumped closed source circuit that will be able to transfer the heat from the HP to the source cylinder. This will need to be able to pump (Figure 9) at least 0.76 L/s and the volume flowrate will need to be known throughout the experiment. The temperature will need to be able to be measured at the source inlet and outlet to the heat pump so that the temperature difference can be calculated. The temperature at the load inlet and outlet will also need to be known to aid in the calculation of the coefficient of performance. The location of the heat pump must be indoors as the heat pump is not weatherproof. It will need to be located on a vibration proof mat to ensure that the noise levels are not too high. The amount of electricity consumed by the heat pump and the circulation pumps will also need to be measured to aid in the calculation of the COP.

5.2 Equipment Information

The equipment was purchased for this project specifically to match the design criteria. It was further influenced by the selection of the heat pump. The heat pump selected in this case was a Waterfurnace 8 kW Ground source heat pump (Figure 10). The model is known as the EKW08 and was designed for use in a domestic context.

Figure 10: Waterfurnace EKW08 Ground Source heat pump.

The heat pump is a hydronic heat pump and so uses water as a transfer medium in both the heating and cooling setups. It is also reversible so can be used to heat in the winter and to cool in the summer. This particular model was designed to be used in conjunction with a ground source loop - horizontal loops, vertical loops, pond loops or open loops - but unfortunately due to the restrictions placed on it because of its location this had to be simulated using heat pump cylinders. The heat pump cylinders used were brought from the Newark Copper Cylinder Company and were two 300 litre HPCyl vented cylinders (Figure 11). These cylinders were designed to be large enough so that the setup would not need to be temperature controlled. It was decided that although it would be useful to control the temperature in the source and load vessels doing so would be hard to regulate. Also as the readings were to be taken manually the size of the cylinders would ensure that the temperature change would not happen too rapidly. Vented cylinders are open to the atmosphere and do not require a pressure relief valve.



HPCyl Cylinder Connections	
Letter on Diagram	Connection type
A	Cold feed
B	Hot draw off
C	Heat Pump flow
D	Heat Pump return
E	1/2" Female auxillary port and/or high limit stat
F	Immersion heater (Optional 2nd Immersion available)
G	10mm Stat pocket (can be ommitted)

Figure 11: Newark Copper 300 Litre Heat Pump cylinders.

To pump water around the system two water pumps were required for each loop, the source and the load loops. The water pumps procured were two Grundfos Alpha+ 15-50 Domestic Circulating Pumps (Figure 9) that had a variable volume flowrate. This was important as it allowed different flows up to 0.83 litres per second (l/s), which was required to be able to compare with test data provided by the heat pump manufacturer (0.25, 0.5 and 0.76 litres per second). There was a variable area flow meter in each circuit so that the volume flowrate could be found with a small degree of error and to allow the pump's flowrate to be changed to the required rate. There was also a pressure gauge placed on each of the pumped circuits so they could be charged to a reasonable pressure (1.5 – 2 bar) and then disconnected. This also served as a safety measure, helping to show whether the pump pressure was too high in which case the experiment could be stopped, avoiding danger.

Figure 12: 5 Litre expansion vessels.

Another important component was the expansion tank (vessel) used in both closed loop pump systems (Figure 12), as this would ensure that if the pressure in the circuits was too high, the excess pressure would have space to escape to. There was a table supplied by the manufacturers (Figure 13) to aid in the selection and sizing of the required vessel. Alternatively a formula could be used but due to the low temperatures and pressures used in the selected system it was deemed not to be necessary as the tank size would be lower than 5 litres. Therefore the tanks purchased were two 5 Litre Heating Expansion Vessel from Reliance Water Controls. As these were placed into each closed circuit setup it was deemed not necessary to have potable vessels as the water did not mix with possible drinking water and so eliminated the chances of contamination.

Vessel Size (Litres)	Static Head (Metres)	Boiler Rating (KW)	BTU
5	5	8.90	30,366
	10	7.18	22,559
8	5	14.33	45,024
	10	11.50	36,133
12	5	21.58	67,804
	10	17.25	54,199
18	5	32.50	102,115
	10	25.83	81,157
	15	19.25	60,483
24	5	43.07	135,321
	10	34.48	108,331
	15	25.90	81,356

Figure 13: Heating expansion tank/vessel sizing guide (AWC n.d.).

To ensure that the water did not feed back into the water mains a non-return valve was placed on the water supply inlet for both circuits. These were single check valves and so only had one method of protection. There was also placed a ball valve so that each individual circuit could be charged separately due to the different lengths of pipe. A pressure gauge was attached to each of the circuits so that the status of each circuit could be found and could be charged to around atmospheric conditions by the mains water pressure.

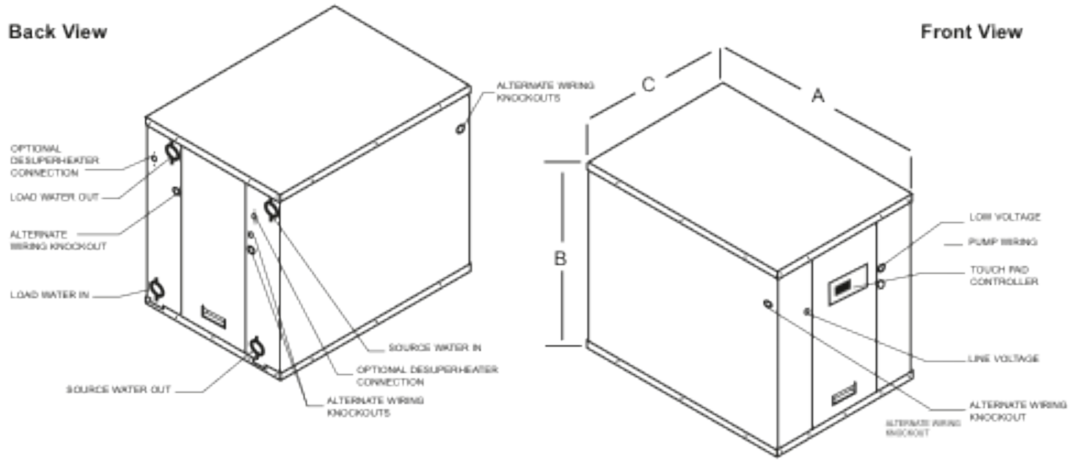


Figure 14: Waterfurnace 8kW Hydronic Heat Pump

Clip-on metallic temperature sensors were used to measure the temperature at the inlets and outlets of the source and load flows, to aid in the finding of the COP of the heat pump. This was in addition to the sensors that were already installed within the heat pump coils as an extra check to ensure the readings were correct. These were analogue as well and so had a small degree of error. A simple power meter was used to measure how much power the heat pump used during its operation, so as to know how much energy it has used in extracting the heat. The majority of the piping used in the system was 28mm copper piping that had been insulated to ensure that there was negligible heat loss. This pipe diameter was selected due to a recommendation placed in the manual (pg 5 of EKW Installation Manual) to ensure that the required volume flow rates could be reached.

Table 3: Dimensional Data for Waterfurnace 8kW Hydronic Heat Pump (See Figure 14)

Unit Model	A in [mm]	B in [mm]	C in [mm]	Load Liquid in FPT in	Load Liquid out FPT in	Source Liquid out FPT in	Source Liquid in FPT in
EKW06	25.5 [648]	26.3 [668]	18.0 [457]	0.75	0.75	0.75	0.75
EKW08	32.5 [826]	26.3 [668]	22.0 [559]	1.00	1.00	1.00	1.00
EKW12	32.5 [826]	26.3 [668]	22.0 [559]	1.00	1.00	1.00	1.00
EKW17	32.5 [826]	26.3 [668]	22.0 [559]	1.00	1.00	1.00	1.00

The water feed pipe will be fed from the plastic cistern hanging above the cylinders and will also be used to regulate the amount of water in both tanks. This cistern will be linked to the main water supply through the use of a ball float and a Portsmouth pattern float value, which halts the water supply when there is a predetermined amount of liquid in the cistern. Since the tank hot water valve (at the top of each cylinder) leads into the cistern, this also acts as a safety measure to ensure that there is never a high pressure build-up in either of the vessels. There will be isolation valves for each of the cylinders so that either one tank can be filled at a time or both can be filled together.

Figure 14 shows the layout of the ports and controls for the heat pump. The heat pump will be located on top of a wooden pallet to ensure that the vibrations from the heat pump will be absorbed and not affect the performance. The actual sizes referenced in Figure 14 can be seen in
Table 3 for the specific model EKW08. The heat pump provided by the manufacturer did not include the optional desuperheater and so those connections shown on the diagram were not open. The heat pump uses the Refrigerant R410a, which is a hydrochlorofluorocarbon (HFC) (see Appendix 9.2 for further information). The pump was controlled by a medium user interface (MUI) (see Appendix 9.3 for details on the specific model)

5.3 Building of the test Rig

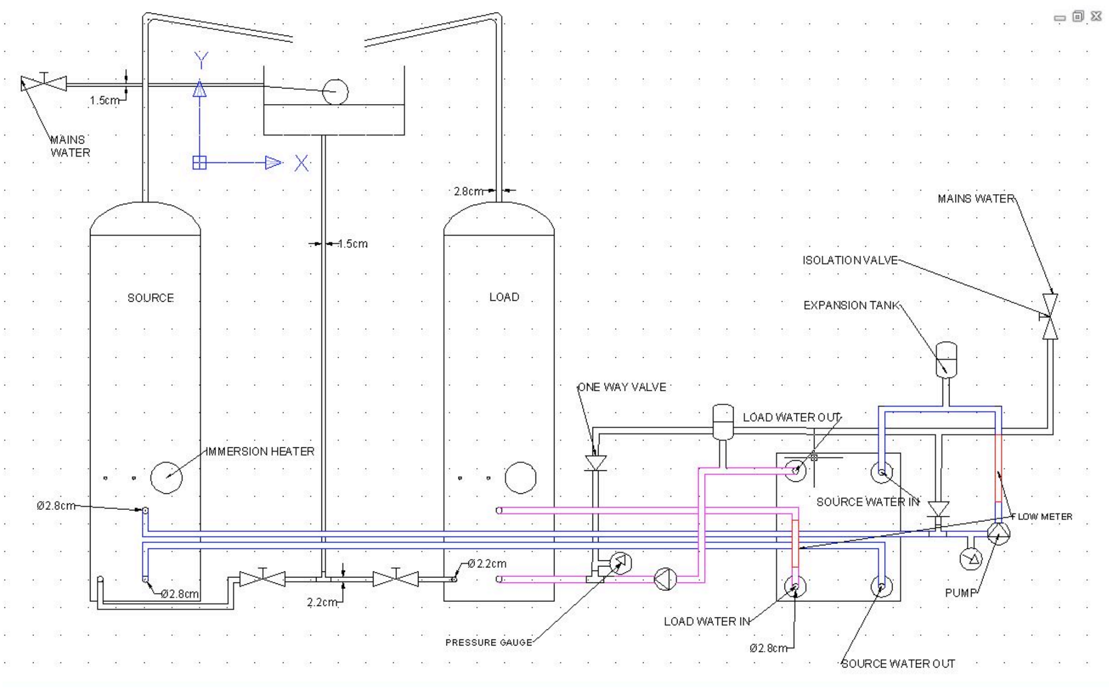


Figure 16: Basic setup of the test rig.

The test rig basic setup was designed in AutoCAD to aid in the construction (Figure 16). The setup of the test rig was the lengthiest part of the project. Due to its location in the University of Strathclyde, a number of safety precautions had to be abided to during its construction. The majority of the equipment had to be transported in from other companies due to the requirement of specialist parts. The equipment (the heat pump, the water pumps and the immersion heaters) needed to be wired to the mains supply and therefore required certified university electricians to connect them correctly as well as ensure that they were safe. Perhaps the most complicated part of this was to wire up the heat pump, as it required at least a 19.3A fuse and involved opening up the heat pump case. The complete electrical specification of the heat pump can be seen in Table 4. Consequentially this required thicker cables then the circulation pumps so as to be able to carry the larger current, as well as special wiring for the plug and a larger fuse in case it short-circuited.

Table 4: Connection details for EKW08 heat pump.

Unit Voltage	Frequency	Phase	Min Circuit Amp	Rotated Load Amps	Locked Rotor Amps
220/240 V	50 Hz	Single	19.3	15.4	82

Once these had all been fitted, then the building of the main parts of the rig could commence. {Figure 16} shows the layout of all the parts, with the magenta coloured piping being the pumped load circuit and the blue piping being the source pumped circuit.

6 Results

6.1 Completed Test Rig

Figure 16: Completed Experimental Setup.

Figure 16 shows the completed test rig that was built during this project. It was completed to the design (Figure 16). Since it is able to simulate the performance of heat pump within a domestic situation it fully meets the requirements of the design criteria.

6.2 Test Procedure

Once the first run test procedure had been carried out (Appendix 9.4) the experiments could be run. The first action taken was to record the temperatures of the load and source cylinders. The source was set at the standard temperature of water coming in from the tap (around 10^0C) and the load started at tap water temperature and increased as heat was transferred. The temperature was taken from the thermometers placed on the copper pipes located at the inlet and outlet valves for the load and source. The circulating pump flowrate was set at the required litres per second and checked by looking at the vertical flowrate measurement devices. Previously the pump circuits had been pressurized to 1.5 bar and checked by looking at the pressure gauges to ensure they were both at the same pressure. They were then isolated from the mains supply with a ball valve so that their pressure would not alter. The electricity meter was then reset and the HP was switched on. As the temperature changes due to the heat exchanges there was sufficient time to manually record the different combination of temperatures at each stage due to the sizing of the source and load. The tanks were then flushed and refilled and the experiments were repeated to ensure that the tests were robust. This allowed the coefficient of performance to be characterized over all the different evaporator and condenser temperatures for one set of flow rates. This will be the operational COP characterization.

6.3 Experiment 1

Three separate tests were run at a flowrate of 0.25 l/s and a pressure of 1.5 bar as part of experiment 1. The most important part of this was the difference in load temperatures and the power consumed in each test. The entering and leaving temperatures can be seen in Figure 17.

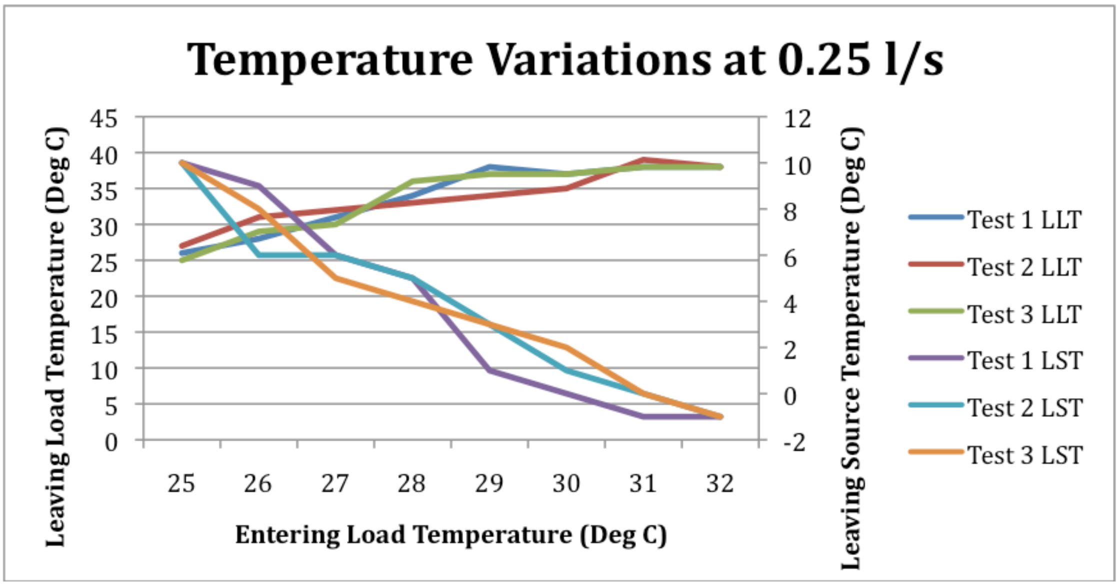


Figure 17: ELT, LLT and LST at a flowrate of 0.25 l/s for experiment 1.

The three tests produced similar results with a gradual increase in the load temperature and a steeper decrease in the source temperature. The data temperatures can be found in the appendix 9.6. The source temperatures were a lot lower then the entering load temperature, and when the ELT reached 32^{0}C the leaving source temperature was below freezing. This caused the heat pumps safety mechanisms to start up and so the experiment could not be continued.

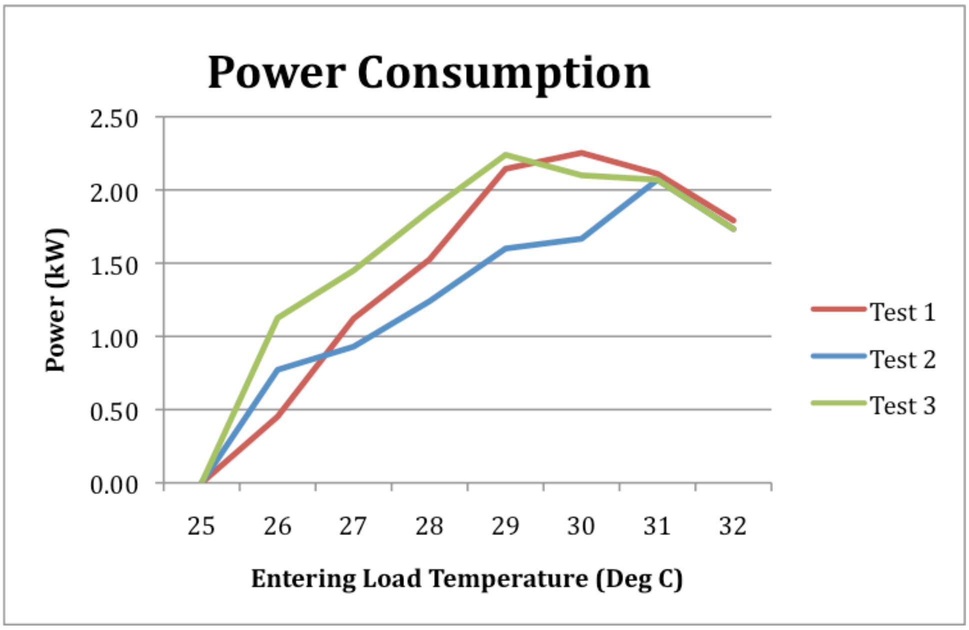


Figure 18: Power Consumed during the tests for experiment.

The power consumption (Figure 18) of the heat pump rose gradually as the entering load temperature increased. This is due to the ever decreasing source temperature and so the heat pump has to work harder to extract heat from lower temperatures. All three tests followed similar paths although in test 2 the power consumption was less than expected. With all three tests in experiment 1 it was found that there was a rapid temperature change, which lowered the accuracy of the experiment.

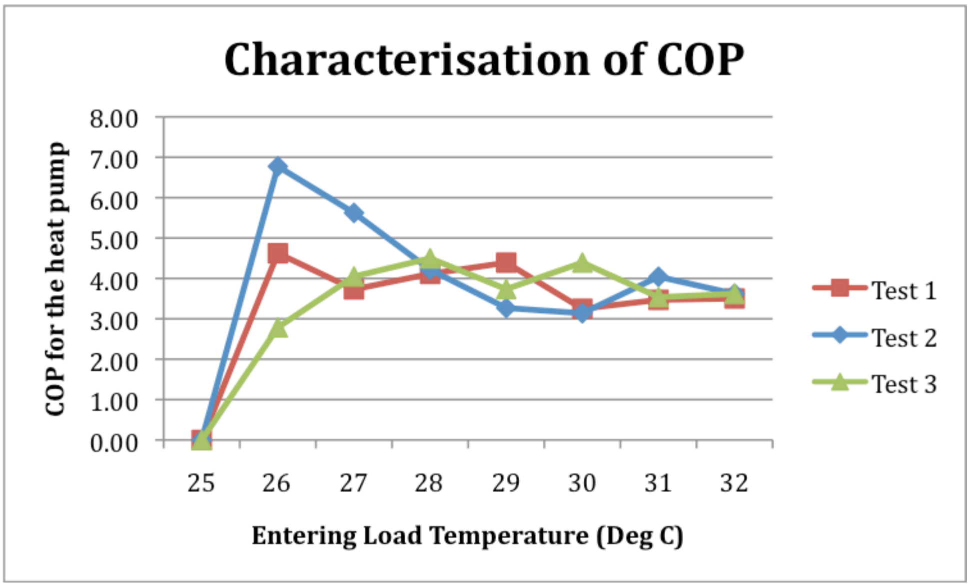


Figure 19: The Coefficient of performance of the test rig for experiment 1.

The COP of the system can be calculated by referring to the equations in chapter 2.4. Firstly by using Equation 3 to find out the heat delivered by the HP and then using Equation 1 to calculate the COP at the specific temperatures. From these calculations

Figure 19 could be produced. The three tests have significant differences in COP for the first two ELTs (25^0C and 26^0C) but as the tests continue they follow similar paths.

6.4 Experiment 2

For experiment 2 the pressure was increased to 2 bar and the flowrate for the source was increased to 0.5 l/s. This slowed down the whole process and more accurate results could be taken. Therefore it was only deemed necessary to carry out one test.

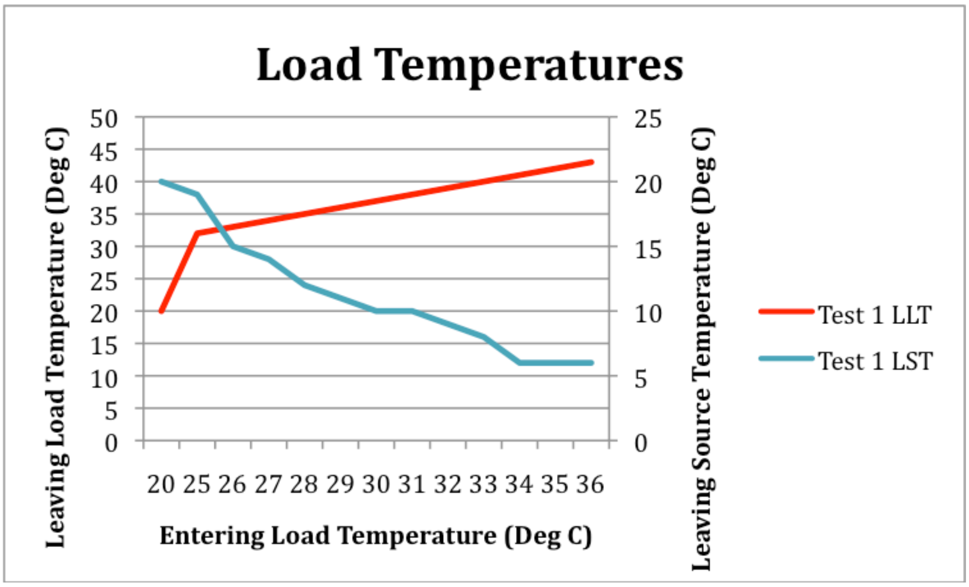


Figure 20: Load Temperature changes for experiment 2.

The entering load temperatures both started at 20^0C but within a very short space of time moved to 25^0C. There is more of a linear increase in the LLT than there was in experiment 1 and this allowed the temperature to rise above 40^0C. The LST was started at 20^0C and with a pressure of 2 bar the temperature fall was a lot more gradual than in experiment 1. This also meant that the experiment could be continued for a longer period but still was stopped to avoid freezing on the source outlet once the LLT had reached 36^0C.

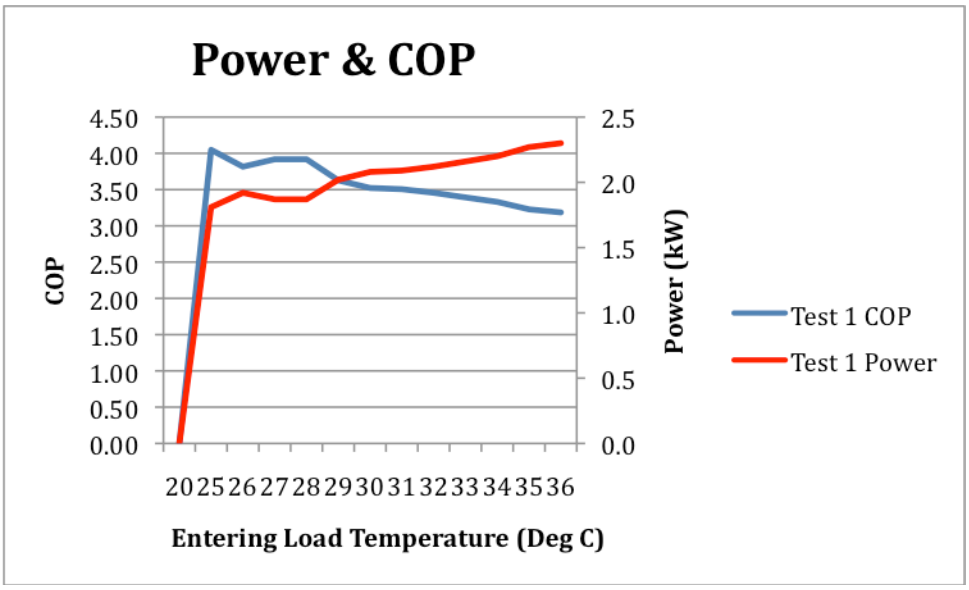


Figure 21: Power consumption and COP for experiment 2.

In experiment 2 it was found that the power and COP of the heat pump performed more consistently than in experiment 1. The COP starts off high but as the load and source temperature difference increases, the COP gradually decreases. This is the inverse of the Power graph because as the temperature difference increases more power is required to transfer the heat.

6.5 Model Comparison

The data that was found in the experiments was compared with the manufacturer's data in Figure 22.

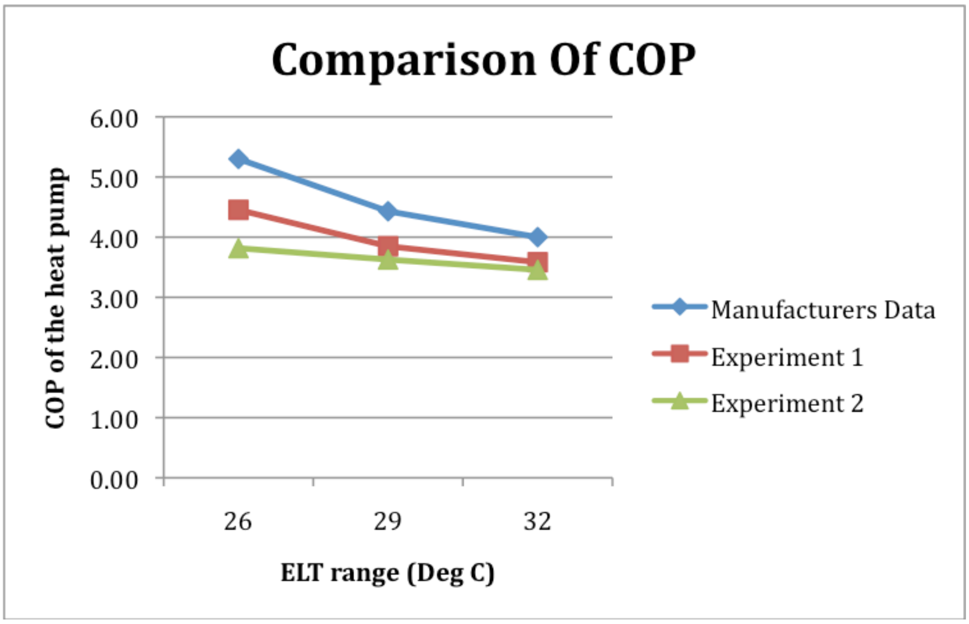


Figure 22: Comparison between experiments and manufacturers data for 0.25 l/s.

By comparing the experimental results with interpolated results taken from the manual (Appendix 9.5) and then plotting them on the graph (Figure 22) for entering load temperatures it can be seen that the COPs found in the experiment are lower then those produced by the manufacturer. Although the COP is lower in the experimental data, the COPs follow the same trend. For the higher values of COP, where the temperature difference is less, there is more error in the corresponding data but as the load temperature increases the COP the manufacturer and experimental data move closer together. Experiment 1 is closer to the manufacturers data because it is measured at the same flowrate but it has a lower level of accuracy compared to experiment 2.

There are various possible reasons for the difference in coefficient of performance of the manufacturer's data and the experimental test results. Although the manufacturers data meets BS EN 14511 standards, it been produced under ideal circumstances that could not be achieved in practice. Another error would occur from manual readings that were taken on analogue gauges for the pumped circuit flow rates, the load and source temperatures and the pumped circuit pressures. This potential error has been mitigated in this thesis by doing 3 separate tests. The heat pump setup was not designed to handle below freezing temperatures and so the whole performance range of the heat pump could not be tested.

6.6 Temperature Load Profile

The COPs found in Experiment 2 were then used to make a load profile of a typical domestic setup. This was the same setup used in the RETScreen model although it was assumed that the heating was restricted to personal usage. It was assumed that the load cylinder needed to be kept at 36^0C and that the load cylinder was fed by a cold water tap at 20^0C. There was a varying draw off rate from the load cylinder throughout the day and so the tank was sitting at a different temperature for a specified length of time. From the experimental tests a COP was found that would be able to restore the tank back to its required temperature. The following table was produced to show an average day.

Table 5: Load Profile of a Domestic Setup.

Typical Day			
Time	Draw off rate (l/h)	Temperature Of Tank (Deg C)	COP required
1-3	0	36	0.00
4-6	50	28	3.92
7-9	67	25	4.05
10-12	32	31	3.52
13	80	32	3.51
14-16	32	31	3.52
17-19	47	29	3.92
20-22	58	27	3.82
23-24	50	31	3.52

By using the data in Table 5, the overall COP of the heat pump was found to be 3.75 for this particular scenario. This was below the optimistic manufacturers COP of 4. There are many reasons for the difference in coefficient of performance of the manufacturer's data and the experimental test results. Although the manufacturers data meets BS EN 14511 standards, it been produced under ideal circumstances that could not be achieved in practice. Another error would occur from manual readings that were taken on analogue gauges for the pumped circuit flow rates, the load and source temperatures and the pumped circuit pressures but this had been mitigated through doing 3 separate tests. The heat pump setup was not designed to handle below freezing temperatures and so the whole performance range of the heat pump could not be tested.

6.7 RETScreen Simulation

The performance of the heat pump was then placed into a realistic domestic scenario to see how it would perform (Chapter 4.1). By using RETScreen to simulate the GSHP setup, the domestic load could be predicted and the actual usefulness of the heat pump could be found. The results for this particular setup were recorded so that the heat pump performance could be seen in a standard domestic house. The base caseload characteristic graph (Figure 23) highlighted the fact that the most important part of the heat pump's operation would be to pump heat in the depths of winter (note the graph axis goes up in 0.5 kW increments but the software only showed integers).

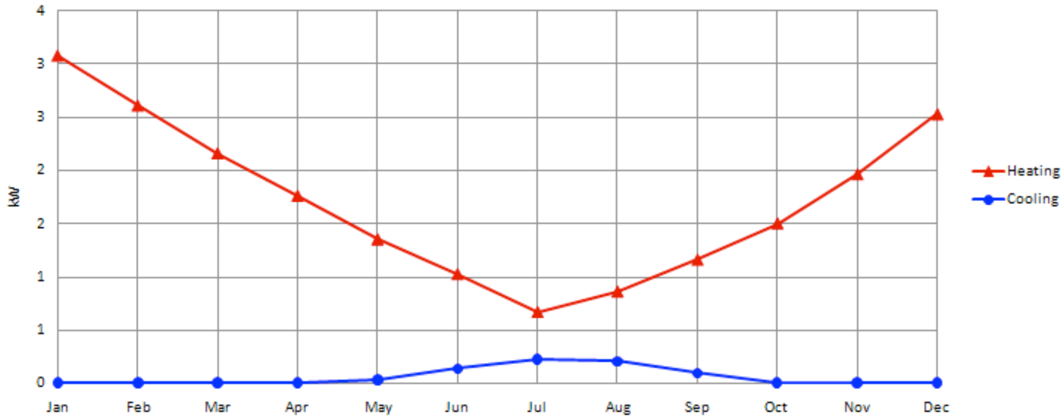


Figure 23: Base case system load Characteristic graph.

This graph highlights that it is during the depths of winter (December, January and February) that the peak heating loads occur. The total heating load required is 5 MWh and the total energy delivered annually for the heating 15 MWh. A variable load had been applied to simulate water draw-off for such operations as showering and heating. The program then predicted how effectively the heat pump would match the required heating changes (Figure 24).

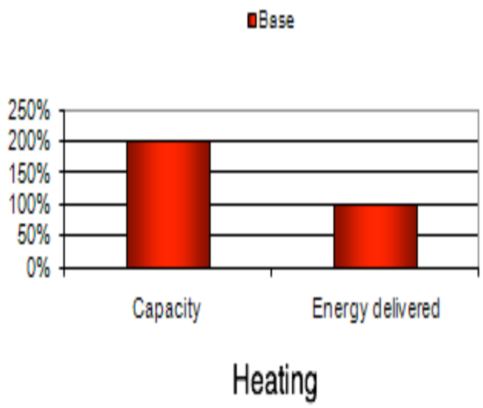


Figure 24: Heating Capacity of heat pump to amount of energy delivered.

Using the effective COP from the experiments, it was found that the heat pump capacity was nearly double what was required by the simulated setup. Although the energy delivered was dependant on some configurable factors, the program designers at RETScreen had used other constants that could not be altered. The performance of the heat pump was predicted to be almost double what was required. To fully verify the usefulness of RETScreen different scenarios would need to be modelled and then compared with the experimental tests.

7 Conclusion

As the world moves towards a more energy conscious future, renewable technologies are bound to be at the forefront of societal development. Heat pumps are at the front of the new clean energy mix and so the general uptake is expected grow rapidly. It is imperative that such an important technology is thoroughly assessed. The experiments conducted during this research have demonstrated that there are potential problems regarding the current accuracy of heat pump assessment. Such problems are particularly important in light of the UK government's intention to introduce the RHI. If there are significant differences between predicted and actual COPs, there will arise a situation where the government is actually paying people to use fossil fuels.

In this thesis a test rig was designed and built that was able to simulate the performance of a ground source heat pump. The characterization of the COP was conducted without the hard to regulate temperature control due to the design utilizing the heat capacity of two large water filled cylinders. The experimental setup was able to successfully replicate the operational conditions of the heat pump and so produce an accurate overall coefficient of performance. Using a consistent test procedure enabled the experimental results to be compared with manufacturer's data and removed a large degree of error. Conducting multiple experiments ensured the robustness of the results and the data produced was able to be made into a typical domestic load profile.

The experimental findings of this thesis do indeed suggest that this specific model of heat pump was less effective than had being advertised. Whilst it is undeniable that heat pumps have a lot of potential, what this thesis has shown is that there needs to be more work done by independent bodies to test the coefficient of performance from an objective stance. This report has found that the COP values stated by the manufacturer are approximately 13% higher than those found under experimental testing. Furthermore, whilst the performance of the tested heat pump is still better than a standard boiler, the technology is more complicated and can only be serviced by specialist technicians. If heat pumps start being placed in social developments and council housing but are not properly looked after, the situation could become even worse than it is currently.

As the heat pump technology develops, their COPs are expected to rise, but as long as they under perform the uptake will be staggered. Since the current push for renewable technologies is so strong, the unfortunate reality is that there are always likely to be slight tweaks in the data results. In the UK specifically, as the Renewable Heating Incentive comes into operation, a large proportion of manufacturers are going to portray the performance of their heat pumps to be the best, in order to encourage consumers to purchase their specific product.

Even the RETScreen software project, which tries to be more realistic and predicts a more reasonable COP, can still be seen to be overly optimistic as it encourages people to move towards renewables. In summary, this project concludes that more stringent COP measurement methods need to be devised so that the consumer knows with a more objective certainty how their heat pump is likely to perform. Not only would an improved certainty be advantageous for the individual heat pump user, but it is also likely to save the government a significant amount of money.

7.1 Further Work

This project was conducted only over a three-month period and so there are a number of possibilities for future work

- Now that the apparatus has been set-up, it is worth looking at how it meets certain requirements such as the heating load in different size houses.
- Vary parameters such as operating pressure and mass flowrate
- Make all the measurement devices digital so that the results can be recorded more accurately.
- Test the heat pumps cooling COP.
- Test what the heat pump is like under negative conditions.
- Try the heat pump in different modes, such as Setpoint and Aquastat

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9 Appendix

9.1 Other types of heat pump

The two other types of heat pump technology is air source heat pumps (Figure 6b) and water source heat pumps. ASHP require a lot less initial setup than the GSHP as they absorb heat from the outside air even to temperatures as low as -15^{0}C (EST n.d.). This is usually through the placement of an external air module. They are currently the most popular form of heat pump systems in the UK and can range from as small as 3kW to over 100kW (HPA n.d.). Air source systems have the potential to be combined to form multi-units that can perform cooling in one area of a building and heating in another. There are two main forms of ASHP, an air to water setup and an air to air setup. The air to air is generally used in heating, ventilating and air conditioning systems (HVAC) due to their versatility as reversible systems. There are relatively few moving parts so maintenance costs are not high but the outdoor heat exchanger needs to be checked frequently to ensure that there have not been any blockages at the intake by such things as debris and leaves. There is also the continuing problem that when the air temperature outside is low (below freezing) and has a high humidity, the air module extracts heat and then ice can form over it causing it to malfunction. Now unfortunately this only occurs when the heat is most needed (i.e. it is very cold outside) and so there will always need to be a backup system to be installed that is considerably more reliable. These units are expected to last for over 20 years with low maintenance requirements (Danfoss n.d.). They are also considerably cheaper to install than comparable GSHP's but do not have as high COP's due to the widely varying temperature differences.

Water source heat pumps operate in a very similar way to air source heat pumps except for the fact that the source fluid is water, mainly in the form of rivers, ponds, springs or ground water. They usually require the water to be within 5 to 8^{0}C but certain types can operate with water that is below freezing as long as it is in a fast flowing river (Cantor 2007). This setup does offer high efficiencies most of the year running but due to the amount of rules and regulations in respect to installation as well as the lack of available equipment, the other technologies are usually preferred.

As well as this its similar to the air source setup because in the depths of winter there is a chance the system may not operate so a backup source will be required. They also have the tendency to be affected by the condition and purity of the water, for instance contaminants can cause pump failure and stifle the refrigeration link.

Table 6: Comparison of the different types of heat pumps.

	GSHP	WSHP	ASHP
Typical Setup Cost (£) (Below 30 kW)	7000 – 13000	6000 - 10000	5000 - 9000
Output Water Temperature (^{0}C)	30 - 40	35 - 58	40 - 55
Source Operating Temperature (^{0}C)	~ 8 - 13	5 - 8	Above -15
Average COP	3.5 - 4.0	3 – 5 (Dimplex n.d.)	2.5 – 2.8 (Carrier n.d.)

Table 6 summarizes the facts about heat pumps and acts as a comparison for the different technologies available to the average domestic customer. The GSHP is the most expensive to setup due to the piping being laid, secondly it is the WSHP also because of the initial installation. The ASHP has the highest output temperature and also can operate in the biggest temperature range, although it does also have the lowest average COP. As previously mentioned this project is looking specifically at the GSHP and testing whether the actual coefficients of performance are achievable.

9.2 R410a Refrigerant

The most important part of the heat pump is the refrigerant as it is the primary factor in defining its operational criteria and therefore its coefficient of performance. The physical properties of the refrigerant used in the HP are defined in Table 7.

Physical Properties of R410A	
Chemical Formula	CH_2F_2/CHF_2CF_3
	(50/50% by weight)
Molecular Weight	72.58
Boiling Point at One Atmosphere	–51.58°C (–60.84°F)
Critical Temperature	72.13°C
	345.28 K
Critical Pressure	4926.1 kPa (abs)
Critical Density	488.90 kg/m3
Critical Volume	0.00205 m3/kg

Table 7: Physical Properties of R410a (DuPont 2004).

The selected working fluid has a large specific heat capacity and evaporates at low temperatures. The most commonly used refrigerants used to be chlorofluorocarbons

(CFC) (DuPont n.d.) but they were discontinued due to the damaging effect that CFC's had on the atmosphere. R410-A is a hydrochlorofluorocarbon (HFC) that does not damage the ozone layer to the same degree as CFC's due to it having less chlorine but this comes at a cost as it less efficient than the more damaging CFC's. HFC's do have a high global warming potential of 2090 (the potency compared to CO_2, i.e. CO_2 has a value of 1) (Daikin 2009), which is similar to that of CFC's, but are considered a lot less dangerous due to the lower quantity of Chlorine. Installing and sealing it during the manufacturing process protect against the release of the refrigerant and therefore it becomes incredibly unlikely that it will be lost to the atmosphere. Part of this is the consumer's responsibility, as the HP will need to be properly disposed of after it has completed its lifecycle to ensure that no refrigerant is leaked. The pressure enthalpy diagram for the refrigerant can be seen in Figure 25.

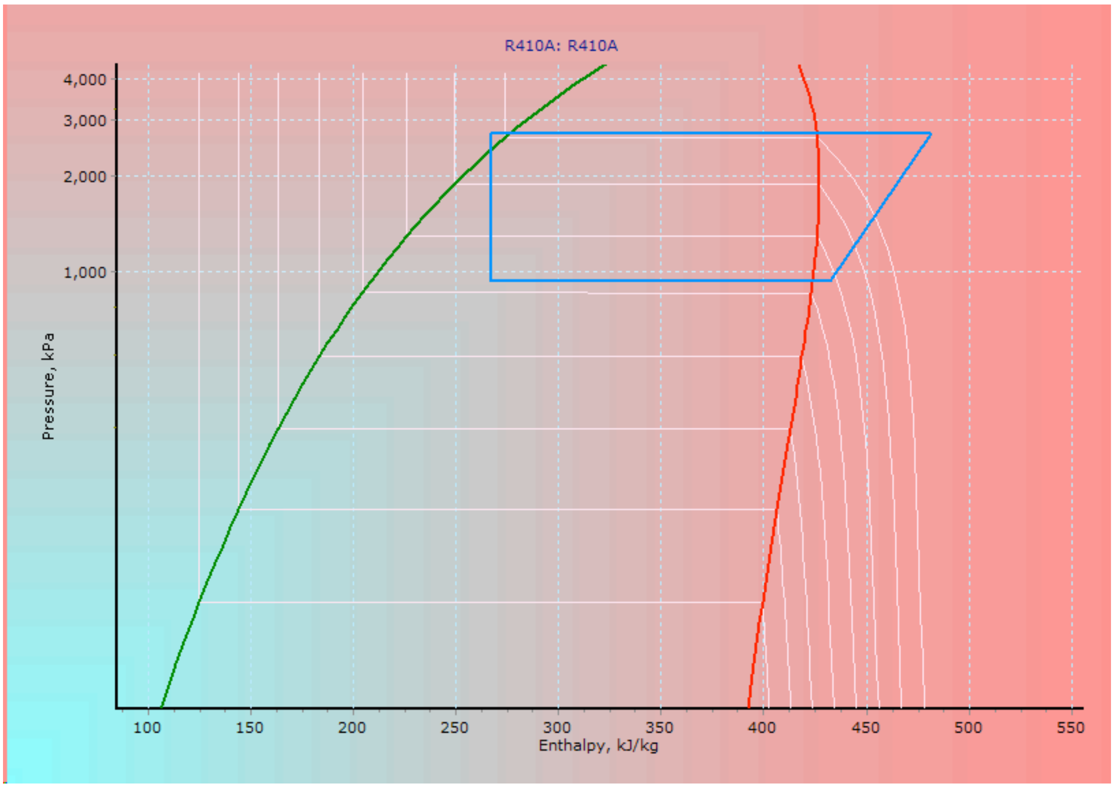

Figure 25: Pressure Enthalpy diagram for Refrigerant R401a.

The blue lines are used to show the ideal cycle that would be followed by the refrigerant. This is the standard 4-stage process that can also be seen in Figure 4. It can be noted that the working properties rely on the refrigerant having a low boiling point (–51.58°C) so that it can absorb the heat from the warmer surroundings.

9.3 LED FX-10 Heat Pump controller

The heat pumps operation is controlled by a medium user interface (MUI) that can be seen in Figure 26. This is connected directly to the FX10 mainboard, which is a high performance, programmable controller designed specifically for heat pump applications (Johnson Controls 2005). The controller is connected to the main components in the heat pump and has several layers of safety to ensure that if a fault occurs there will be no lasting damage.

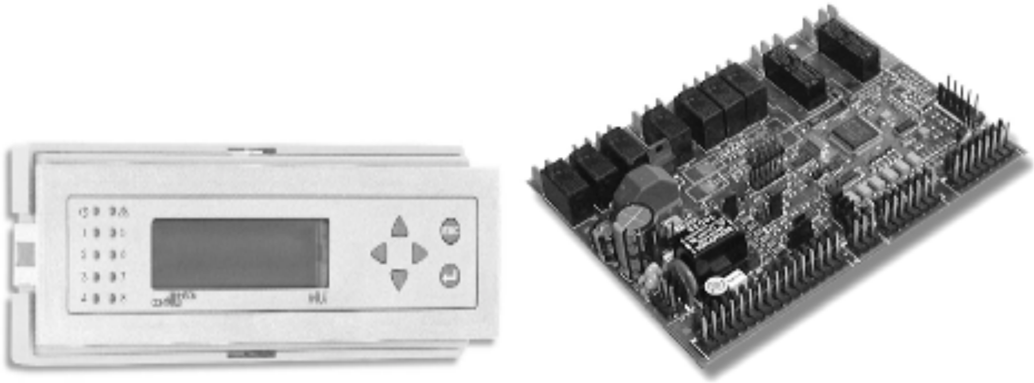

Figure 26: The medium user interface for the EKW08 and the FX10 Controller mainboard.

The default setting for the heat pump is in reversible water to water mode and is ready for operation by aqua stat calls. The aqua stat is the device used in domestic hydronic heating systems to control the water temperature. There are three operating modes, Aqua stat, Setpoint and S-Plan, and in all the cases the controller is configured slightly differently but will operate a comfort reversible load and a domestic hot water load. There are many fault alarms available to the MUI such as low pressure, low source and load temperatures, damaged sensors and high temperature limits. The controller will also have an emergency shutdown and lockout functions, to ensure that the HP is stopped because continued running will cause damage to the equipment.

9.4 First Run Procedure

When starting the equipment there is a strict procedure that has to be followed to be sure that the heat pump is operating within safe conditions, to ensure that it does not experience any faults. Before the power was switched on the following safety checks were performed (taken from the Manual),

- High voltage wiring is correct and matches the nameplate.
- Fuses, breakers and wire size are correct.
- Air is purged from the closed loop system.

- Isolation valves are open and loop water control valves or loop pumps are wired.
- Service/access panels are in place.

Once these checks had been taken the primary Unit start-up could begin. Both the heat pump cylinders were filled with standard temperature cold tap water (around 10^0C) until the ball valve stopped them overflowing. Secondly as a consequence of the pumps not being connected to the main board of the heat pump, the operator started them manually before the HP was switched on so that water was circulating. The manual lists the following 8 steps to ensure proper start-up (taken from manual).

1. Apply power to the unit. Upon power up, the unit will display the current operation mode.
2. Press the mode button. The LED screen will display the current entering water temperature. The load pump will activate after a 5minute delay. Adjust mode operation as desired by reference to MUI menu configuration on page 21.
3. Once the load pump system has been active for 35 minutes, the controller will sample the temperature of the water system. In heating mode, when the temperature of the water shown on the display is lower than the set point the compressor will activate check the system operation as shown in steps 4 through 7.
4. By using a pressure gauge and the P/T ports, check the pressure drop through both the load and source coaxes. Compare this to the capacity tables in the specification catalogue to verify the proper flow rate through the unit.
5. Verify that the compressor, load side and source side pumps are operating.
6. After determining the flow rates, use a thermometer and the PT ports to determine the change in temperature on both the load and source side coaxes.
7. Compute the formula $L/s \times \Delta T \times 4.2$ (4.2 for 100% water) = Heat of extraction on the source side in heating, Heat of Rejection on the source side in cooling. To ensure proper operation, compare these values to the capacity tables in the specification catalogue.
8. Reduce the set point below the incoming load temperature. Compressor should shut off and the load pump should shut off 30 seconds after the compressor.

As previously highlighted part of task 2 will not be performed due to the pumps not being directly connected to the HP main board. Task 7 was completed in the results section for heat extraction. A value of 4.2 was used because the transfer was 100% water and not a mixture of antifreeze and water (a value of 4.1 would have been used in this case). In a standard GSHP setup it is common practice to use a mixture of antifreeze and water to ensure that the working fluid is not affected by subzero temperatures

9.5 Manufacturers Data

Heating Capacity Data
EKW08

Load Flow				Source Flow - .25 L/s							Source Flow - .50 L/s							Source Flow - .76 L/s						
ELT °C	EST °C	Flow L/s	PD kPa	LLT °C	HC kW	Power kW	HE kW	COP	LST °C	PD kPa	LLT °C	HC kW	Power kW	HE kW	COP	LST °C	PD kPa	LLT °C	HC kW	Power kW	HE kW	COP	LST °C	PD kPa
15.6	-1.1	0.25	4.82	22.3	7.14	1.40	5.74	5.1	-6.6	5.52	22.4	7.24	1.41	5.83	5.1	-3.87	19.30	22.7	7.49	1.43	6.06	5.2	-3.0	40.70
		0.50	17.90	19.1	7.47	1.42	6.05	5.3	-6.9	5.52	19.1	7.57	1.43	6.14	5.3	-4.02	19.30	19.3	7.83	1.44	6.39	5.4	-3.1	40.70
		0.76	37.20	18.0	7.60	1.43	6.17	5.3	-7.0	5.52	18.0	7.70	1.45	6.25	5.3	-4.08	19.30	18.1	7.96	1.46	6.51	5.5	-3.2	40.70
	10.0	0.25	4.82	24.7	9.67	1.37	8.30	7.1	2.1	4.83	24.9	9.80	1.38	8.42	7.1	6.01	17.90	25.2	10.14	1.40	8.74	7.3	7.2	38.60
		0.50	17.90	20.4	10.12	1.39	8.73	7.3	1.7	4.83	20.4	10.25	1.40	8.86	7.3	5.80	17.90	20.6	10.61	1.41	9.19	7.5	7.1	38.60
		0.76	37.20	18.8	10.29	1.40	8.89	7.3	1.6	4.83	18.9	10.43	1.42	9.01	7.4	5.73	17.90	19.0	10.79	1.43	9.36	7.5	7.0	38.60
	21.1	0.25	4.82	27.2	12.30	1.38	10.92	8.9	10.8	4.83	27.4	12.47	1.39	11.07	8.9	15.86	17.20	27.8	12.89	1.41	11.49	9.2	17.5	35.90
		0.50	17.90	21.7	12.86	1.40	11.47	9.2	10.2	4.83	21.7	13.04	1.41	11.63	9.2	15.60	17.20	21.9	13.49	1.42	12.06	9.5	17.3	35.90
		0.76	37.20	19.7	13.08	1.41	11.67	9.3	10.1	4.83	19.7	13.26	1.43	11.83	9.3	15.50	17.20	19.9	13.71	1.44	12.28	9.5	17.2	35.90
	32.2	0.25	4.82	27.7	12.77	1.38	11.39	9.3	21.4	4.83	27.8	12.94	1.39	11.55	9.3	26.75	15.90	28.2	13.39	1.40	11.98	9.5	28.4	33.80
		0.50	17.90	21.9	13.35	1.39	11.96	9.6	20.9	4.83	22.0	13.54	1.41	12.13	9.6	26.47	15.90	22.2	14.00	1.42	12.58	9.9	28.2	33.80
		0.76	37.20	19.8	13.58	1.41	12.17	9.7	20.7	4.83	19.9	13.77	1.42	12.35	9.7	26.37	15.90	20.1	14.24	1.43	12.80	9.9	28.2	33.80
	43.3	0.25	4.82	28.1	13.24	1.37	11.87	9.7	32.1	4.14	28.3	13.42	1.38	12.03	9.7	37.63	15.20	28.7	13.88	1.40	12.48	9.9	39.4	31.70
		0.50	17.90	22.1	13.85	1.39	12.46	10.0	31.5	4.14	22.2	14.03	1.40	12.63	10.0	37.34	15.20	22.4	14.52	1.41	13.10	10.3	39.2	31.70
		0.76	37.20	20.0	14.08	1.40	12.68	10.1	31.3	4.14	20.1	14.27	1.42	12.86	10.1	37.24	15.20	20.2	14.76	1.43	13.33	10.3	39.1	31.70
26.7	-1.1	0.25	4.82	33.2	6.94	1.75	5.18	4.0	-6.0	5.52	33.3	7.03	1.77	5.26	4.0	-3.61	19.30	33.6	7.27	1.79	5.49	4.1	-2.8	40.70
		0.50	16.50	30.1	7.25	1.77	5.48	4.1	-6.3	5.52	30.2	7.35	1.79	5.56	4.1	-3.75	19.30	30.3	7.61	1.81	5.80	4.2	-2.9	40.70
		0.76	35.20	29.0	7.38	1.79	5.59	4.1	-6.4	5.52	29.0	7.48	1.81	5.67	4.1	-3.80	19.30	29.1	7.74	1.83	5.91	4.2	-3.0	40.70
	10.0	0.25	4.82	35.4	9.26	1.75	7.51	5.3	2.9	4.83	35.6	9.38	1.77	7.62	5.3	6.39	17.90	35.9	9.71	1.78	7.92	5.4	7.5	38.60
		0.50	16.50	31.3	9.68	1.77	7.92	5.5	2.5	4.83	31.3	9.82	1.79	8.03	5.5	6.19	17.90	31.5	10.15	1.80	8.35	5.6	7.4	38.60
		0.76	35.20	29.8	9.85	1.79	8.06	5.5	2.4	4.83	29.8	9.98	1.80	8.18	5.5	6.12	17.90	29.9	10.32	1.82	8.50	5.7	7.3	38.60
	21.1	0.25	4.82	38.0	11.94	1.70	10.23	7.0	11.4	4.83	38.1	12.10	1.72	10.38	7.0	16.19	17.20	38.5	12.52	1.74	10.78	7.2	17.7	35.90
		0.50	16.50	32.6	12.49	1.72	10.76	7.2	10.9	4.83	32.7	12.66	1.74	10.92	7.3	15.94	17.20	32.9	13.09	1.76	11.34	7.5	17.5	35.90
		0.76	35.20	30.7	12.70	1.74	10.96	7.3	10.7	4.83	30.7	12.87	1.76	11.11	7.3	15.84	17.20	30.9	13.31	1.78	11.54	7.5	17.5	35.90
	32.2	0.25	4.82	40.2	14.31	1.73	12.58	8.3	20.3	4.83	40.4	14.51	1.75	12.76	8.3	26.17	15.90	40.9	15.01	1.77	13.24	8.5	28.0	33.80
		0.50	16.50	33.8	14.97	1.75	13.22	8.5	19.7	4.83	33.9	15.18	1.77	13.41	8.6	25.87	15.90	34.1	15.70	1.79	13.91	8.8	27.8	33.80
		0.76	35.20	31.5	15.23	1.77	13.45	8.6	19.5	4.83	31.5	15.43	1.79	13.64	8.6	25.75	15.90	31.7	15.96	1.81	14.16	8.8	27.7	33.80
	43.3	0.25	4.82	41.0	15.12	1.75	13.36	8.6	30.7	4.14	41.2	15.32	1.77	13.55	8.7	36.91	15.20	41.7	15.85	1.79	14.06	8.9	38.9	31.70
		0.50	16.50	34.2	15.81	1.77	14.04	8.9	30.0	4.14	34.3	16.03	1.79	14.24	9.0	36.58	15.20	34.5	16.58	1.81	14.77	9.2	38.7	31.70
		0.76	35.20	31.7	16.08	1.79	14.29	9.0	29.8	4.14	31.8	16.30	1.81	14.49	9.0	36.47	15.20	32.0	16.86	1.83	15.03	9.2	38.6	31.70

Heating Capacity Data continued...
EKW08

Load Flow				Source Flow - .25 L/s							Source Flow - .50 L/s							Source Flow - .76 L/s						
ELT ºC	EST ºC	Flow L/s	PD kPa	LLT ºC	HC kW	Power kW	HE kW	COP	LST ºC	PD kPa	LLT ºC	HC kW	Power kW	HE kW	COP	LST ºC	PD kPa	LLT ºC	HC kW	Power kW	HE kW	COP	LST ºC	PD kPa
37.8	-1.1	0.25	4.14	44.1	6.72	2.26	4.45	3.0	-5.3	5.52	44.2	6.81	2.28	4.52	3.0	-3.26	19.30	44.5	7.04	2.31	4.73	3.1	-2.6	40.70
		0.50	15.20	41.1	7.02	2.29	4.74	3.1	-5.6	5.52	41.2	7.12	2.31	4.81	3.1	-3.39	19.30	41.3	7.36	2.33	5.03	3.2	-2.7	40.70
		0.76	32.40	40.0	7.14	2.31	4.83	3.1	-5.7	5.52	40.1	7.24	2.34	4.91	3.1	-3.44	19.30	40.1	7.49	2.36	5.13	3.2	-2.7	40.70
	10.0	0.25	4.14	46.2	8.93	2.25	6.67	4.0	3.7	4.83	46.4	9.05	2.27	6.77	4.0	6.79	17.90	46.7	9.36	2.30	7.06	4.1	7.8	38.60
		0.50	15.20	42.2	9.34	2.28	7.06	4.1	3.3	4.83	42.3	9.46	2.30	7.16	4.1	6.60	17.90	42.4	9.79	2.32	7.47	4.2	7.6	38.60
		0.76	32.40	40.8	9.49	2.30	7.19	4.1	3.2	4.83	40.8	9.62	2.33	7.30	4.1	6.54	17.90	40.9	9.95	2.35	7.61	4.2	7.6	38.60
	21.1	0.25	4.14	48.6	11.39	2.16	9.22	5.3	12.4	4.83	48.7	11.54	2.19	9.36	5.3	16.68	17.20	49.1	11.94	2.21	9.73	5.4	18.0	35.90
		0.50	15.20	43.4	11.91	2.19	9.72	5.4	11.9	4.83	43.5	12.07	2.21	9.86	5.5	16.44	17.20	43.7	12.49	2.23	10.26	5.6	17.9	35.90
		0.76	32.40	41.6	12.11	2.21	9.90	5.5	11.7	4.83	41.7	12.28	2.23	10.04	5.5	16.35	17.20	41.8	12.70	2.26	10.44	5.6	17.8	35.90
	32.2	0.25	4.14	51.1	14.09	2.17	11.92	6.5	20.9	4.83	51.3	14.29	2.20	12.09	6.5	26.49	15.90	51.8	14.78	2.22	12.56	6.7	28.3	33.80
		0.50	15.20	44.8	14.74	2.20	12.54	6.7	20.3	4.83	44.9	14.94	2.22	12.72	6.7	26.19	15.90	45.1	15.46	2.24	13.22	6.9	28.1	33.80
		0.76	32.40	42.5	14.99	2.22	12.77	6.7	20.1	4.83	42.6	15.20	2.24	12.95	6.8	26.08	15.90	42.7	15.72	2.27	13.45	6.9	28.0	33.80
	43.3	0.25	4.14	52.9	15.92	2.19	13.72	7.3	30.3	4.14	53.1	16.14	2.22	13.92	7.3	36.73	15.20	53.6	16.69	2.24	14.45	7.5	38.8	31.70
		0.50	15.20	45.7	16.65	2.22	14.43	7.5	29.7	4.14	45.8	16.88	2.24	14.64	7.5	36.39	15.20	46.1	17.46	2.26	15.20	7.7	38.5	31.70
		0.76	32.40	43.1	16.93	2.24	14.69	7.6	29.4	4.14	43.2	17.16	2.26	14.90	7.6	36.27	15.20	43.4	17.75	2.29	15.47	7.8	38.4	31.70
48.9	-1.1	0.25	4.14	54.9	6.30	2.87	3.43	2.2	-4.4	5.52	54.9	6.39	2.90	3.49	2.2	-2.77	19.30	55.2	6.61	2.93	3.68	2.3	-2.3	40.70
		0.50	14.50	52.0	6.59	2.90	3.69	2.3	-4.6	5.52	52.1	6.68	2.93	3.75	2.3	-2.89	19.30	52.2	6.91	2.96	3.95	2.3	-2.4	40.70
		0.76	30.30	51.0	6.70	2.93	3.77	2.3	-4.7	5.52	51.0	6.79	2.96	3.83	2.3	-2.93	19.30	51.1	7.03	2.99	4.04	2.3	-2.4	40.70
	10.0																							
		0.50	14.50	53.1	8.87	2.84	6.03	3.1	4.3	4.83	53.2	9.00	2.87	6.13	3.1	7.10	17.90	53.3	9.30	2.90	6.41	3.2	8.0	38.60
		0.76	30.30	51.7	9.02	2.87	6.15	3.1	4.2	4.83	51.8	9.15	2.90	6.25	3.2	7.04	17.90	51.9	9.46	2.93	6.53	3.2	7.9	38.60
	21.1																							
		0.50	14.50	54.2	11.16	2.78	8.38	4.0	13.2	4.83	54.3	11.31	2.81	8.50	4.0	17.08	17.20	54.4	11.70	2.84	8.86	4.1	18.3	35.90
		0.76	30.30	52.5	11.35	2.81	8.53	4.0	13.0	4.83	52.5	11.50	2.84	8.66	4.1	17.01	17.20	52.6	11.90	2.87	9.03	4.1	18.3	35.90
	32.2																							
		0.76	30.30	53.3	13.90	2.83	11.08	4.9	21.7	4.83	53.3	14.09	2.86	11.24	4.9	26.90	15.90	53.5	14.58	2.88	11.69	5.1	28.5	33.80
	43.3																							
		0.76	30.30	54.1	16.46	2.84	13.62	5.8	30.4	4.14	54.2	16.68	2.87	13.81	5.8	36.78	15.20	54.3	17.26	2.90	14.36	6.0	38.8	31.70

9.6 Test Results – Experiment 1

Test 1						
ELT (*C)	LLT(*C)	EST(*C)	LST(*C)	Power (kW)	Flowrate (l/s)	Cop
25	26	10	10	0.00	0.25	0.00
26	28	10	9	0.45	0.25	4.62
27	31	10	6	1.12	0.25	3.73
28	34	10	5	1.53	0.25	4.11
29	38	9	1	2.14	0.25	4.39
30	37	9	0	2.25	0.25	3.25
31	38	8	-1	2.11	0.25	3.47
32	38	8	-1	1.79	0.25	3.50

Test 2						
ELT (*C)	LLT(*C)	EST(*C)	LST(*C)	Power (kW)	Flowrate (l/s)	COP
25	27	10	10	0.00	0.25	0.00
26	31	10	6	0.77	0.25	6.77
27	32	10	6	0.93	0.25	5.62
28	33	10	5	1.24	0.25	4.22
29	34	9	3	1.60	0.25	3.27
30	35	9	1	1.67	0.25	3.14
31	39	8	0	2.07	0.25	4.04
32	38	8	-1	1.73	0.25	3.62

Test 3						
ELT (*C)	LLT(*C)	EST(*C)	LST(*C)	Power (kW)	Flowrate (l/s)	COP
25	25	11	10	0.00	0.25	0.00
26	29	11	8	1.13	0.25	2.79

27	30	10	5	1.45	0.25	2.17
28	36	10	4	1.86	0.25	4.50
29	37	10	3	2.24	0.25	3.74
30	37	9	2	2.10	0.25	3.49
31	38	9	0	2.07	0.25	3.54
32	38	9	-1	1.73	0.25	3.62

9.7 Test Results – Experiment 2

Experiment 2						
ELT (*C)	LLT(*C)	EST(*C)	LST(*C)	Power (kW)	Flowrate (l/s)	COP
20	20	20	20	0.0	0.25	0.00
25	32	20	19	1.8	0.25	4.05
26	33	20	15	1.9	0.25	3.82
27	34	20	14	1.9	0.25	3.92
28	35	20	12	1.9	0.25	3.92
29	36	20	11	2.0	0.25	3.63
30	37	20	10	2.1	0.25	3.52
31	38	20	10	2.1	0.25	3.51
32	39	19	9	2.1	0.25	3.46
33	40	17	8	2.2	0.25	3.39
34	41	15	6	2.2	0.25	3.33
35	42	12	6	2.3	0.25	3.23
36	43	8	6	2.3	0.25	3.19