Performance and Potential Applications of Direct Expansion Ground Source Heat Pump Systems for Building Energy

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ABSTRACT

The move towards a low-carbon world, driven partly by climate science and partly by the business opportunities it offers, will need the promotion of environmentally friendly alternatives if an acceptable stabilisation level of atmospheric carbon dioxide is to be achieved. This requires the harnessing and use of natural resources that produce no air pollution or greenhouse gases (GHGs) and provides comfortable coexistence of humans, livestock, and plants. Ground source heat pump systems (GSHPs) are receiving increasing interest because of their potential to reduce primary energy consumption and thus reduce emissions of GHGs. The main objective of the research is to stimulate the uptake of the GSHPs. This paper describes the details of a prototype direct expansion GSHP test rig and details of the construction and installation of the heat pump, heat exchanger, heat injection fan and water supply system. It also presents a discussion of the experimental tests currently being carried out.

Keywords: Direct expansion GSHPs, construction, development and evaluation of the system

1 INTODUCTION

Globally buildings are responsible for approximately 40% of the total world annual energy consumption. Most of this energy is for the provision of lighting, heating, cooling and air conditioning. An increase in awareness of the environmental impact of CO_2, NO_x and CFCs emissions triggered a renewed interest in environmentally friendly cooling and heating technologies. Under the 1997 Montreal Protocol, governments agreed to phase out chemicals used as refrigerants that have the potential to destroy stratospheric ozone. It was therefore considered desirable to reduce energy consumption in order to decrease the rate of depletion of world energy reserves as well as the pollution to the environment.

One way of reducing building energy consumption is to design buildings, which are more efficient in their use of energy for heating, lighting, cooling and ventilation. Passive measures, particularly natural or hybrid ventilation rather than air-conditioning, can dramatically reduce primary energy consumption [1]. Therefore, promoting innovative renewable energy applications including the ground source energy may contribute to preservation of the ecosystem by reducing emissions at local and global levels. This will also contribute to the amelioration of environmental conditions by replacing conventional fuels with renewable energies that produce no air pollution or GHGs. An approach is needed to integrate renewable energies in a way to achieve high building performance standards. However, because renewable energy sources are stochastic and geographically diffuse, their ability to match demand is determined by the adoption of one of the following two approaches [2]: the utilisation of a capture area greater than that occupied by the community to be supplied, or the reduction of the community's energy demands to a level commensurate with the locally available renewable resources. Ground source heat pump (GSHP) systems (also referred to as geothermal heat pump systems, earth-energy systems and GeoExchange systems) have received considerable attention in recent decades as an alternative energy source for residential and commercial space heating and cooling applications. The GSHP applications are one of three categories of geothermal energy resources as defined by ASHRAE [2] and include high-temperature (>150°C) for electric power production, intermediate temperature (<150°C) for direct-use applications and GSHP applications (generally (<32°C). The GSHP applications are distinguished from the others by the fact that they operate at relatively low temperatures.

The term "ground source heat pump" has become an inclusive term to describe a heat pump system that uses the earth, ground water, or surface water as a heat source and/or heat sink. GSHPs utilise the thermal energy stored in the earth through either a vertical or horizontal closed loop heat exchangers buried in the ground. Many geological factors impact directly on site characterisation and subsequently the design and cost of GSHP systems. The geological prognosis for a site and its anticipated rock properties influence the drilling methods and therefore the system cost [3]. Other factors that are important to system design include predicted subsurface temperatures and the thermal and hydrological properties of strata. GSHP technology is well established in Sweden, Germany and North America, but has had minimal impact in the United Kingdom space heating and cooling market [4].

The main objective of this research is to stimulate the uptake of the GSHPs. Direct expansion GSHPs are well suited to space heating and cooling and can produce significant reduction in carbon emissions. To design a GSHP system, the tools that are currently available require the use of key site-specific parameters such as temperature gradient and the thermal and geotechnical properties of the local area. Three main techniques are used to exploit the heat available are geothermal aquifers, hot dry rocks and GSHPs. Geothermal energy is the natural heat that exists within the earth and that can be absorbed by fluids occurring within, or introduced into, the crystal rocks. Although, geographically this energy has local concentrations, its distribution globally is widespread [5]. On average the amount of heat that is theoretically available between the earth's surface and a depth of 5 km is around 140 x 10^{24} joules [6]. Of this, only a fraction (5 x 10^{21} joules) can be regarded as having economic prospects within the next five decades and only about 500 x 10^{18} joules is likely to be exploited by the year 2020 [7].

2 HEAT PUMP

Heat pumps are a more energy efficient way to provide space heating or domestic hot water heating to a household than conventional methods of using a boiler to heat water or electric heaters. Heat pumps can either use the ambient air (air source heat pumps) as the energy source or geothermal energy (ground source heat pumps). Ground source heat pumps can be split into open loop systems; where the ground loop is circulated at the bottom of a pond or loch, or closed loop systems; where the ground loop is circulated through horizontal trenches a few feet below the frost level or vertically down through bore holes.

It is proposed for this project that closed loop, water to water ground source heat pumps would be more suitable for use on the Isle of Lewis application rather than air source heat pumps. Ground source heat pumps (GSHP) have higher coefficients of performance than air source. The coefficient of performance (COP) is calculated as the energy output from the heat pump divided by the energy input to the compressor and any auxiliary pumps. The COP of a GSHP is between 3 and 4, i.e. the produce 3 to 4 times the electrical energy they consume as heat.

The main advantage of the GSHP is that the geothermal temperature 4-6ft below the frost level remains constant throughout the year. So, in the summer, the ground temperature is generally lower than the air temperature allowing for household cooling if it is needed whereas in the winter, the ground temperature is higher than the ambient temperature. Most households on the West coast of Lewis are spaced out with room in the gardens to install the cheaper horizontal ground loop systems.

Heat pumps operate in the same way in which a refrigerator operates. Low pressure refrigerant is pumped through the closed ground loop heat exchanger (evaporator) where thermal energy is absorbed from the higher temperature soil into the system. The higher temperature refrigerant then returns to the household where it passes through a heat exchanger transferring the heat to the second closed loop system. The fluid in the second loop is then passed through a compressor which raises the temperature (and pressure) to the desired level. The high temperature fluid passes through a third heat exchanger (either another water to water or water to air heat exchanger) which delivers the thermal energy to the home. The thermal energy in the second loop decreases and is then cooled below the temperature of the ground loop through an expansion valve which allows thermal energy to once again be absorbed from the ground loop heat exchanger.

2.1 Soil Thermal Properties

One of the fundamental tasks in the design of a reliable ground source heat pump system is properly sizing the ground source heat exchanger length (i.e., depth of boreholes). Recent research efforts have produced several methods and commercially available design software tools for this purpose [8-9]. These design tools are based on principles of heat conduction and rely on some estimate of the ground thermal conductivity and volumetric specific heat. These parameters are perhaps the most critical to the system design, yet adequately determining them is often the most difficult task in the design phase.

2.2 Heat Pump Performance

The performance of the heat pump depends on the performance of the ground loop and vice versa. It is therefore essential to design them together. Closed-loop GSHP systems will not normally require permissions/authorisations from the environment agencies. However, the agency can provide comment on proposed schemes with a view to reducing the risk of groundwater pollution or derogation that might result. The main concerns are:

- Risk of the underground pipes/boreholes creating undesirable hydraulic connections between different water bearing strata.
- Undesirable temperature changes in the aquifer that may result from the operation of a GSHP.
- Pollution of groundwater that might occur from leakage of additive chemicals used in the system.

Efficiencies for the GSHPs can be high because the ground maintains a relatively stable temperature allowing the heat pump to operate close to its optimal design point. Efficiencies are inherently higher than for air source heat pumps because the air temperature varies both throughout the day and seasonally such that air temperatures, and therefore efficiencies, are lowest at times of peak heating demand.

A heat pump is a device for removing heat from one place - the 'source' - and transferring it at a higher temperature to another place. The heat pumps consist of a compressor, a pressure release valve, a circuit containing fluid (refrigerant), and a pump to drive the fluid around the circuit. When the fluid passes through the compressor it increases in temperature. This heat is then given off by the circuit while the pressure is maintained. When the fluid passes through the relief valve the rapid drop in pressure results in a cooling of the fluid. The fluid then absorbs heat from the surroundings before being re-compressed. In the case of domestic heating the pressurised circuit provides the heating within the dwelling. The depressurised component is external and, in the case of ground source heat pumps, is buried in the ground. Heat pump efficiencies improve as the temperature differential between 'source' and demand temperature decreases, and when the system can be 'optimised' for a particular situation. The relatively stable ground temperatures moderate the differential at times of peak heat demand and provide a good basis for optimisation.

The refrigerant circulated directly through the ground heat exchanger in a direct expansion (DX) system but most commonly GSHPs are indirect systems, where a water/antifreeze solution circulates through the ground loop and energy is transferred to or from the heat pump refrigerant circuit via a heat exchanger. This application will only consider closed loop systems. The provision of cooling, however, will result in increased energy consumption and the efficiently it is supplied. The GSHPs are particularly suitable for new build as the technology is most efficient when used to supply low temperature distribution systems such as underfloor heating. They can also be used for retrofit especially in conjunction with measures to reduce heat demand. They can be particularly cost effective in areas where mains gas is not available or for developments where there is an advantage in simplifying the infrastructure provided.

2.3 Ground temperatures

The temperature difference between the ground and the circulating fluid in the heat exchanger drives the heat transfer. So it is important to know the ground temperature. The temperature variation disappears at lower depth and below 10 m the temperature remains effectively constant at approximately the annual mean air temperature.

It is important to maximise the efficiency of a heat pump when providing heating, not only to have a low heating distribution temperature but also to have as high a source temperature as possible. Overall efficiencies for the GSHPs are inherently higher than for air source heat pumps because ground temperatures are higher than the mean air temperature in winter and lower than the mean air temperature in summer. The ground temperature also remains relatively stable allowing the heat pump to operate close to its optimal design point whereas air temperatures vary both throughout the day and seasonally and are lowest at times of peak heating demand. For heat pumps using ambient air as the source, the evaporator coil is also likely to need defrosting at low temperatures. It is important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity. The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger.

2.4 Economics

Heat pump technology can be used for heating only, or for cooling only, or be 'reversible' and used for heating and cooling depending on the demand. Reversible heat pumps generally have lower COPs than heating only heat pumps. They will, therefore, result in higher running costs and emissions and are not recommended as an energy-efficient heating option. The GSHP system can provide 91.7% of the total heating requirement of the building and 55.3% of the domestic water-heating requirement, although only sized to meet half the design-heating load. The heat pump can operate reliably and its performance appears to be at least as good as its specification. The system has a measured annual performance factor of 3.16. The occupants will be pleased with the comfort levels achieved and find the system quiet and unobtrusive. The heat pump is mounted in a cupboard under the stairs and does not reduce the useful space in the house, and there are no visible signs of the installation externally (no flue, vents, etc.). The GSHP system is responsible for lower CO_2 emissions than alternative heating systems (the emission figures for an all-electric system, and oil- or gas-fired boilers). For example, compared with a gas-condensing boiler, the heat pump system resulted in 15% lower CO_2 emissions (assuming a CO_2 emission factor for electricity of 0.46 kg/kWh) [10]. When compared with new oil fired boiler system or all-electric systems, the emissions of CO2 are cut by over 40% and nearly 60% respectively. Annual fuel costs, based on the fuel prices given in SAP 1998, are about 10% higher than those for a gas condensing boiler and about 20%

higher than for a new regular oil boiler, but servicing costs are likely to be lower. Running costs are substantially cheaper than for an all-electric heating system. At present, suitable products are not readily available in the UK, so the heat pump had to be imported. This had some drawbacks, e.g., limited documentation in English and possible difficulty in obtaining spare parts. The controller supplied with the heat pump was not designed for use with an Economy 7 type tariff structure. There is however potential to improve the operation of the system by scheduling more of the space and water heating duty during the reduced tariff period. The performance of the heat pump system could also be improved by eliminating unnecessary running of the integral distribution pump. It is estimated that reducing the running time of this pump, which currently runs virtually continuously, would increase the overall performance factor to 3.43. This would improve both the economics and the environmental performance of the system. More generally, there is still potential for improvement in the performance of heat pumps, and seasonal efficiencies for ground source heat pumps of 4.0 are being achieved. It is also likely that unit costs will fall as production volumes increase. By comparison, there is little scope to further improve the efficiency of gas- or oil-fired boilers.

The ground source heat pump system, which uses a ground source with a smaller annual temperature variation for heating and cooling systems, has increasingly attracted market attention due to lower expenses to mine for installing underground heat absorption pipes and lower costs of dedicated heat pumps, supported by environmentally oriented policies. The theme undertakes an evaluation of heat absorption properties in the soil and carries out a performance test for a DX heat pump and a simulated operation test for the system. In fact, these policies are necessary for identifying operational performance suitable for heating and cooling, in order to obtain technical data on the heat pump system for its dissemination and maintain the system in an effort of electrification.

3 CONCLUSIONS

Direct expansion (DX) ground source heat pump (GSHP) system are known to perform very well throughout the year mainly because of the constant nature of the earth temperature. Despite of the apparent advantages of DX GSHPs, at present geothermal energy makes a very small, but locally important, to the world energy requirements. The main barriers that restrict a wider uptake of the technology appear to be the lack of awareness of the benefit of the technology and high capital cost. The shortage of manufacturers, suppliers and installers are also among the barriers. It is likely that this situation will continue unless these problems are tackled. Direct expansion (DX) ground source heat pump (GSHP) system suitable for provision of heating and cooling for buildings have been investigated. The research efforts have been directed towards finding of environmentally acceptable replacement refrigerants and optimisation of the heat pump system. Considerable improvement in system performance has been achieved as a result of this optimisation.

REFERENCES

[1] Geothermal Engineering Ltd. First commercial- scale geothermal power plant. World Renewable World 12 (6): 14. November 2009.

[2] Abdeen M. Omer, Riffat, S. Development and evaluation of a direct expansion heat pump system. 8th International Conference on Sustainable Energy Technologies (SET2009), Aachen, Germany. August 31st to 3rd September 2009.

[3] Kalbus, E., Reinstrof, F., and Schirmer, M. Measuring methods for groundwater-surface water interactions: a review. Hydrology and Earth System Sciences 10: 873-887. 2006.

[4] Austin, W.A., Yavuzturk, C. and Spitler, J.D. Development of an in situ system and analysis procedure for measuring ground thermal properties. ASRAE Transactions 106 (1). 2000.

[5] ASHRAE. Commercial/Institutional Ground Source Heat Pump Engineering Manual. American Society of heating, Refrigeration and Air-conditioning Engineers, Inc. Atlanta, GA: USA. 1995.

[6] Rognon, F. Heat pumps and ecological balances. IEA Heat Pump Centre. Newsletter 15(2): 26-28. 1997.

[7] Van de Venn H. 'Ground-source heat pumps systems – An international review'. IEA Heat Pump Centre Newsletter Vol. 17 No. 1.

[8] Government's Standard Assessment Procedure (SAP). 1998.

[9] Clauser, C. Numerical stimulation of flow in hot aquifers. Berlin, Germany. 2003.

[10] Witte, H., Gelder, A., Spitler, J. In-situ measurement of ground thermal conductivity. ASHRAE Transactions 108 (1): 15-50. 2002.