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Broadening the Scope: Low and High Temperature Geothermal Utilization in Iceland

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ABSTRACT

Iceland is sitting on a vast amount of various energy resources. The high temperature geothermal systems are being used for both electrical generation and direct use. Due to the accessibility of this high temperature energy source there is generally less focus on fully utilizing the low temperature systems. Presently, the low temperature systems are used for direct use such as house heating and growing of produce. The innate differences between these areas result in these different utilization capabilities and general requirements. The MEET project looks to increase the utilization of low temperature systems in Europe for electricity production through binary cycles designed to be more compact, have higher efficiency and lower cost. The use of such cycles could greatly increase the capability of utilizing these resources more efficiently and lead to greater development of renewable energy. In this paper the different conditions in low temperature areas compared to high temperature areas are looked at. The high temperature Reykjanes and low temperature Grásteinn II areas are focused on specifically as these locations will be used for testing of Organic Rankine Cycles (ORC) within the MEET project. Material requirements can vary between areas giving grounds for different material being needed and this will be looked with components for binary cycles in mind.

1. INTRODUCTION

Renewable power generation is the future. As we strive to increase utilization of more environmentally friendly resources all viable possibilities must be explored. Low temperature geothermal areas are widely available making them a vast relatively untapped resource. Being able to utilize these areas for power generation could drastically change the future of the energy sector. Increasing the use of binary cycles is a key to obtaining this reality.

Organic Rankine Cycles, or ORCs, are binary cycles that can utilize medium and low temperature geothermal resources to create electricity. To increase the reach of ORCs and make them a more viable option they have to be compact and cost effective. Part of making them cost effective is adapting them to the required environment to minimize downtime and failure on account of material damage.

This paper explores high and low temperature geothermal areas with focus on utilization. The potential of increasing use of ORCs is explored along with their limitations, specifically with adaption to different areas and their challenges in mind.

2. GEOTHERMAL RESOURCES

Geothermal resources in Iceland and abroad are split into two main sections, high temperature geothermal resources (HTGR) and low temperature geothermal resources (LTGR). HTGR is where temperatures at 1000 m depth are higher than 200 °C. LTGR is where the temperature at the same depth is lower than 150 °C. While HTGRs are mainly used for generating electricity, the focus of LTGRs has rather been on direct heat use.

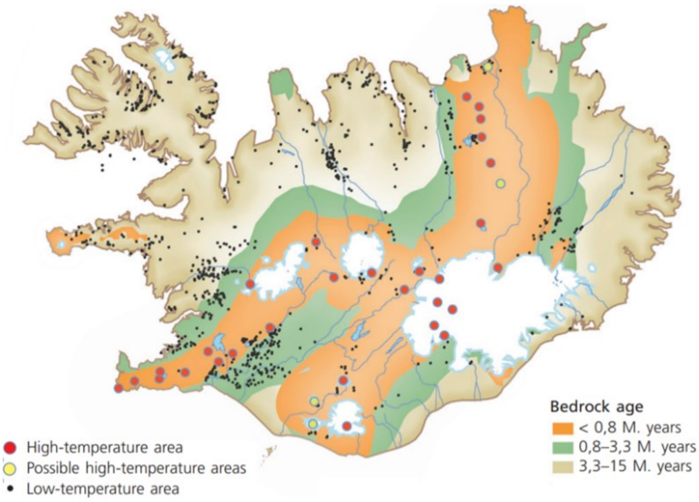

Figure 1: Distribution of geothermal resources in Iceland and the age of mineral layers (Loftsdóttir, et al., 2013).

The high volcanic activity in Iceland is a result of its unique location on the Mid-Atlantic ridge which is a divergent tectonic plate boundary. Because of tectonic activity and fracturing in the crust, water from the surface is able to travel below the earth's surface and come into contact with magma which significantly raises the water's temperature, see heat distribution in Iceland in Figure 1. The temperatures are highest in volcanic zones but lower further away where the crust is older and less volcanic activity is present. LTGRs are present where the temperatures in the earth's crust are high enough to heat water up to 50-150 °C.

2.1 High-temperature geothermal resources

The heat source for HTGRs is shallow magma or recently solidified lava that still holds considerable heat. HTGRs are created when a magma intrusion initiates a circulation of groundwater. This circulation causes hot water above the intrusion to rise and cold water to sink towards the heat source. This upstream circulation heats up higher mineral layers (Arnórsson, 2011). On the surface, indicators of HTGRs are hot springs, presence of sulphur and mud springs, to name a few. The deep water driving the HTGRs in Iceland is generally rainwater which circulates within underground cracks. Because of the high temperature of the fluid and the gasses emitting from the magma the fluid, once at the surface, it is usually quite sour and holds a lot of dissolved chemicals (Ketilsson, et al., 2011). Iceland has three major geothermal sites; the Krafla area that is owned by Landsvirkjun, Reykjanes owned by HS Orka and the Heillisheiði area that is owned by ON Power.

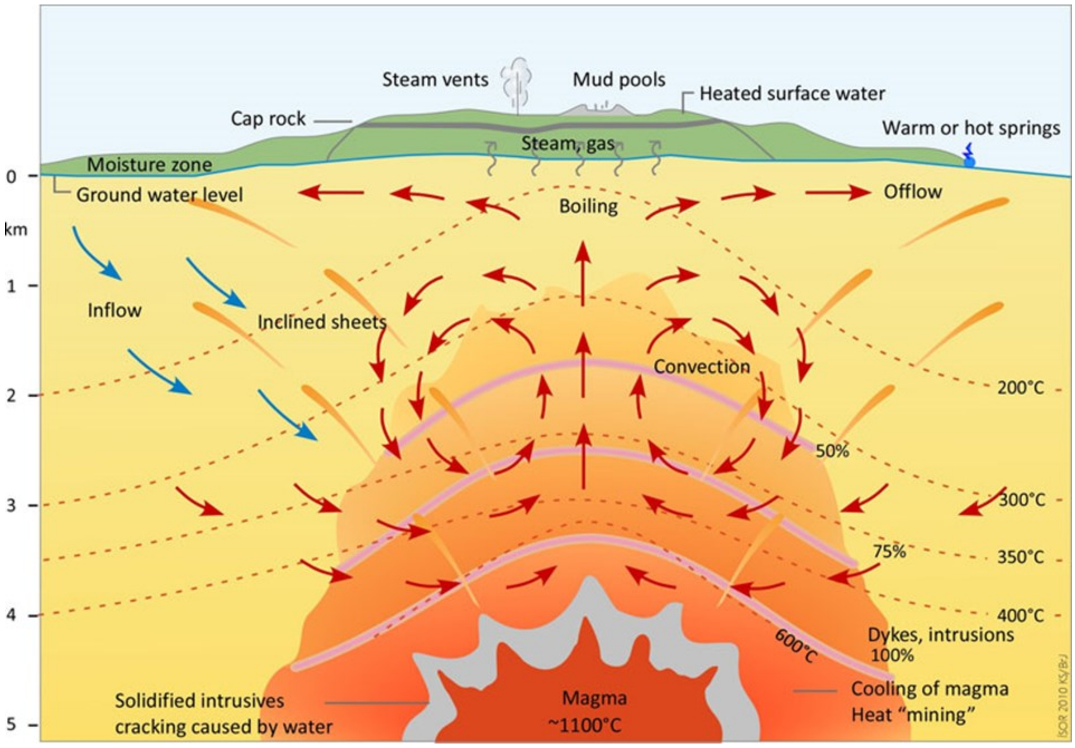

Figure 2: A diagram of a high temperature geothermal resource showing the circulation of groundwater. The heat source is a magma chamber and magma intrusions. The heat from the source warms up the nearby rock and water which flows around it. It then rises up and is replaced by colder water. Courtesy of ÍSOR.

Reykjanes geothermal system is located in the Southwest of Iceland on the Mid-Atlantic Ridge. The Reykjanes geothermal system is different from the other geothermal areas in Iceland, for the fluid in the system is a seawater-recharged hydrothermal system rather than meteoric water that is more commonly found in hydrothermal system in Iceland (Sigurðsson, 2012). In the Reykjanes geothermal system the heat comes though dikes intruded at depth, because the system lacks central volcanoes with shallow secondary magma chambers (Gudmundsson & Thórhallsson, 1986; Gudmundsson, 1995).

2.2 Low-temperature geothermal resources

The water in LTGRs is rainwater that flows down to 1-4 km depth through cracks and permeable mineral layers, warms up and then rises again to the surface. A cycle such as this can either be stationary or have a long flow path for the water. An example of a system with a long flow path are the fresh water pools in islands in Breiðafjörður, where the water flows to from the highland areas in the Westfjords, over 20 km away. Due to the lower heat of the water in LTGRs they dissolve less gasses and solids. Thus, it is often deemed suitable for consumption and heating purposes without further treatment. The most powerful LTGRs in Iceland are those close to rift zones, for example in Mosfellssveit, Árnessýsla, Borgarfjörður and Reykjahverfi, where the thermal gradient and permeability is high (Ketilsson, et al., 2011). In recent decades, hidden LTGRs have been found in Iceland where there are no signs of thermal activity on the surface. These recently found systems are now over thirty and are mostly used for heating purposes. These systems have for example been found in Eyjaförður, west of Stykkishólmur, in Hvalfjörður and north of Selfoss (Axelsson, 2004).

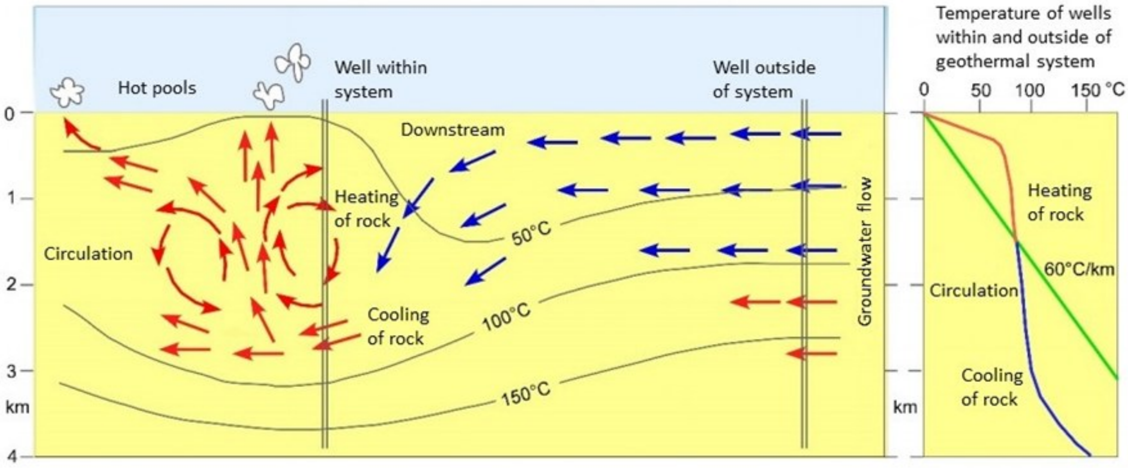

Figure 3: Typical low temperature geothermal system in Iceland. Localized circulation of groundwater occurs in permeable cracks where hot water rises to the surface and cold water sinks down. On the right side is an unchanged temperature gradient, 60°C/km, outside of the geothermal system (green) and temperature inside a well within the system (red and blue) (Björnsson, et al., 1990).

Grásteinn II is an Icelandic farm, situated in the municipality of Ölufus in southern Iceland on top of the Suðurland transverse fracture zone. The farm is located over a LTGR area and has a geothermal well which was first drilled in 1995 with depth of around 400 m. Due to unsatisfying production the well was made deeper in 2010, 586 m, which resulted in higher flow rates and higher temperatures. The maximum flow rate of the well is between 8-9 l/s although now it is kept at a minimum flow, 3.3-3.5 l/s. Further development of the well and area will be performed to increase the flow rate to facilitate an ORC. The maximum fluid temperature at the wellhead is 115 °C.

3. GEOTHERMAL ENERGY UTILIZATION

Utilization possibilities of resources are dependent on the energy present in the medium. Traditionally, higher enthalpy geothermal fluid has been used for electricity production while lower enthalpy geothermal fluid has been used directly for purposes such as district heating. The energy present in geothermal fluid can also be used in stages so that different processes, each requiring lowering temperatures, can be use the same stream hence increasing the efficiency of utilization. This is referred to as cascading use and the “Resource Park” on the Reykjanes peninsula is an example of a large system based on this design (Resource Park, n.d.).

In 2018, the global energy output of geothermal resources was estimated to be at 630 PJ. Around half of this is in the form of heat while the rest, 13.3 GW, indicates the global geothermal power capacity (Adib, 2019). In 2017 the geothermal electricity capacity in Europe was at 2.8 GW, having increased by 330 MW from the year before. The district heating capacity increased by over 75 MW and was over 4.9 GW (EGEC, 2017). In Iceland in 2017 the installed power capacity of geothermal energy was 25,6% of the market, or 708 MW, and thermal use at 97%, or just under 34 PJ (Hjaltason, et al., 2018).

3.1 Direct use

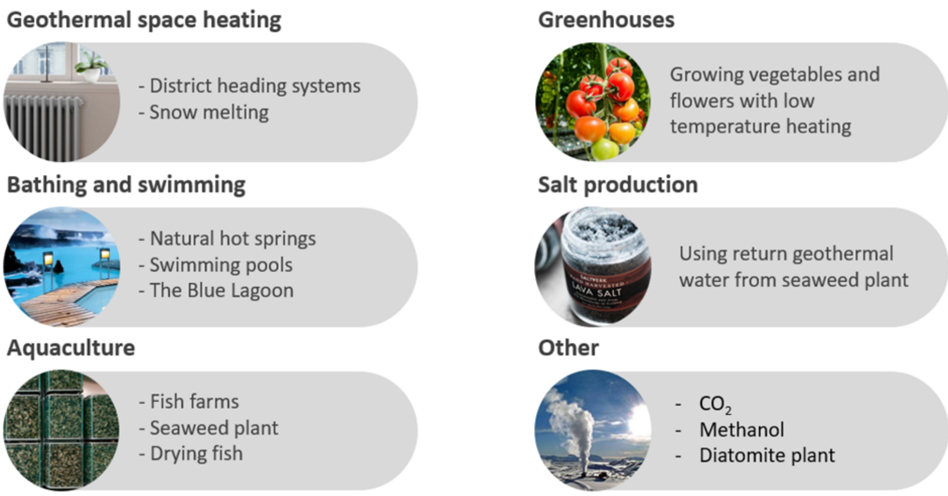

Figure 4: Examples of direct use of geothermal energy in Iceland

Low enthalpy geothermal fluid can be employed for the purpose of direct-use; the oldest and most common form of use for geothermal energy. Even in Roman times geothermal energy was used for the purposes of cooking, bathing and heating up buildings and spas.

The Lindal diagram gives examples as to how geothermal fluid can be used in industry based on the temperature of the resource. This includes drying of various products, growing of produce and washing (Patsa, et al., 2015).

Low temperature geothermal systems are wide spread over Europe. LTGRs in Austria, Bulgaria, France, Germany, Greece, Poland, Romania and Slovakia, are used for space heating, greenhouse heating, swimming pools and spas, fish farming and more (Enex and Geysir Green Energy, 2008). For over 80 years, geothermal district heating systems using LTGR have been used in Iceland. The applications of direct use are similar to those in Europe with additional stages such as snow melting. At first, the usage of these systems was based on free-flowing hot water from shallow wells or hot springs but today most LTGRs are exploited using down-hole pumps (Axelsson, 2010). Figure 4 shows examples of various utilization processes being employed in Iceland.

3.2 Electricity production

Geothermal energy can be harnessed for electricity production through the use of turbines and generators. The working fluid that drives such systems is usually steam, and the enthalpy of the resource determines how this steam can be acquired. For high enthalpy systems, the fluid is either in a dry steam phase or two-phase flow when exiting a well. After cleaning and separating, the steam from these fluids can then be used directly to run the turbine. This describes the processes used in dry steam and flash power plants. In 2007 there were 61 dry steam systems operational in the world and 233 flash systems. Together they accounted for a global capacity of 8,7 GW, which was 90% of the global geothermal electricity production at the time (DiPippo, 2007).

Medium to low enthalpy geothermal resources can however also be used to produce electricity. This is accomplished though binary systems such as Organic Rankine Cycles (ORCs) that use a closed system with a secondary fluid vaporized by the geothermal fluid to drive a turbine. Using ORC technology, European countries have begun using their LTGRs for electrical production as well. In countries such as Austria, Croatia, France and Germany, LTGRs are utilized for electricity production using ORC technology (Bertani, 2010; Weber, et al., 2016; Richter, 2018). Presently, ORC systems have a smaller capacity than the geothermal steam turbines but their potential distributional use across the world is much greater, particularly with future development of enhanced geothermal systems (EGS). The MEET project aims at making geothermal energy more accessible worldwide through small-scale plants, specifically ORC plants, that are designed to be compact and cost effective.

4. ORGANIC RANKINE CYCLE

Organic Rankine Cycle systems use an organic fluid, with a boiling point lower than that of water, to generate electricity out of heat energy. The ORC is a variant of a binary cycle power plant which is the most commonly used technology for low to medium temperature heat sources that are not able to efficiently use water as a working fluid. What separates binary cycle power plants from conventional ones is the use of a secondary working fluid. The primary working fluid, geothermal fluid coming from the geothermal reservoir, never comes into contact with the turbine. Hydrofluorocarbons such as R245fa and R134a are commonly used as the secondary working fluids.

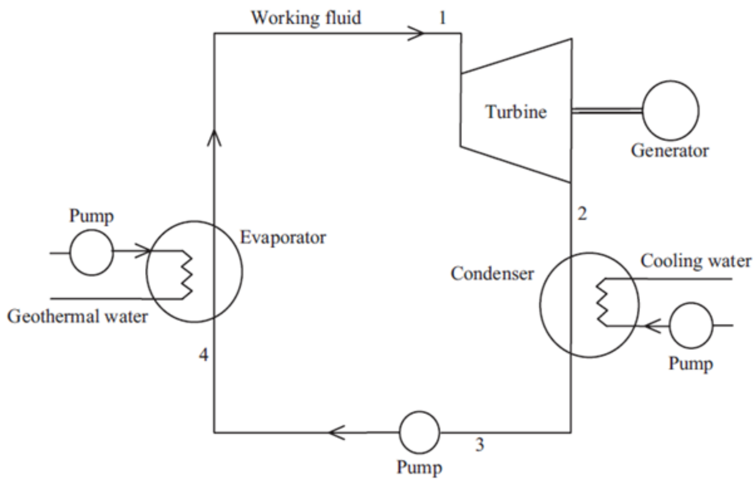

Figure 5: A simplified diagram of the ORC. Geothermal fluid runs through an evaporator (heat exchanger) heating the organic fluid. The organic fluid vaporizes and the vapor drives the turbine, generating electricity. The organic working fluid is then condensed and a pump sends it back to the evaporator, closing the cycle (Hettiarachchi, et al., 2007).

The efficiency of ORC power plants varies, depending on the temperature and properties of the hot fluid that carries the heat energy. For low-temperature heat sources (70-100 °C) the efficiency of binary power plants is approximately 5-9% while medium-temperature heat sources (90-160 °C) have efficiencies around 10-15% (Hettiarachchi, et al., 2007).

4.1 System design

As seen from Figure 5, the ORC system is made up of a few main components. These are the evaporator and condenser, which are both heat exchangers, the turbine and the generator that it turns as well as the pump which pumps the condensed working fluid into the evaporator. The evaporating heat exchanger uses hot fluid to evaporate the working fluid while the condensing heat exchanger uses cold water. Using cold air is also possible but less efficient. Alternative designs are also possible and replacing an evaporator with a preheater and vaporizer, is an example of one. These components are also heat exchangers that are in contact with both working fluids and utilize heat present at different stages within the cycle to make heat extraction the most efficient.

One of the most critical parts of the system are the heat exchangers. The evaporating heat exchanger or the preheater and vaporizer, are the only components of the system in direct contact with the outside hot fluid. When the hot fluid is from geothermal sources it often has properties, which can have damaging effects on the heat exchanger such as corrosion and scaling. There are numerous designs for heat exchangers including shell and tube, plate, parallel flow, pure counterflow, multiple-pass counter flow and crossflow (DiPippo, 2015). Which design is chosen depends on the properties of the fluids. Shell and tube and plate heat exchangers are most commonly used for geothermal plants; the plate exchangers (PHE) being mainly used for small scale systems due to their compactness (Franco & Vaccaro, 2017). The PHEs used are either brazed or gasketed ones although newer types of PHE designs such as the Semi-welded Plate Heat Exchanger are becoming more popular in difficult environments.

The condensing heat exchanger is also of great importance because the efficiency of the cycle is in part governed by its ability to cool down the working fluid efficiently. It is not in contact with geothermal fluid and does therefore not generally experience corrosion and scaling like the evaporating heat exchanger. Consequently, the design of this component is relatively independent of the chemical composition of the primary fluid and does not have to be adapted to the geothermal area in the same way as for instance an evaporator.

4.2 Usage

Organic Rankine Cycle systems are used in various ways to generate electricity from heat. Waste heat recovery, geothermal power production and solar power production commonly use ORCs to make electricity (Tchanche, et al., 2011). ORCs are used in various ways within the geothermal industry. They are used in geothermal power plants to generate electricity from fluids that have already passed through a main steam turbine. This allows the power plant to extract even more power from its resources before it is re-injected into the ground or used for other purposes. This is the case in Svartsengi power plant, where a secondary ORC cycle is used to further extract power from the geothermal fluid's heat (Þórólfsson, 2005). ORCs are often used in Enhanced Geothermal Systems (EGS) where the temperatures are not high enough to warrant a steam cycle. The geothermal power plant in Soultz-sous-Forêts is a good example of an EGS using an ORC system for power production. The plant in Soultz-sous-Forêts was the first of its kind in France and produces 1,7 MW of electricity (Dezayes, et al., 2005; Portier, et al., 2018). Other examples in Europe include Altheim and Bad Blumau ORC plants in Austria which produce 350 kW and 180 kW of electricity, respectively (Bertani, 2007) and the 17,5 MW Velika Ciglena power plant in Croatia (Turboden, 2018).

A great potential for power generation lies in the many low temperature geothermal boreholes spread around Iceland. These wells are mostly used for direct use and most are in private ownership of farmers and landowners. The leftover hot fluid for many of these wells is simply disposed of as the energy coming from the well is enough to fulfil the needs of house-heating for the owners of said wells. Using ORC technology these wells could be used both for direct use and electricity generation, making the people inhabiting nearby farms and houses even more self-sufficient than today. This development has already begun in Iceland. In 2018 a project was launched to generate electricity using ORC technology in Flúðir, Iceland. The 45 l/s, 116 °C geothermal fluid at Flúðir will be used to generate up to 600 kW of electricity before being directly used for space heating (Hreiðarsson, 2018).

Another potential lies in the numerous mature oil wells in Europe. In 2017, the French government decided to ban all oil production in the country by the year 2040 (Chailleux, et al., 2018). This has forced oil companies in France to look to other horizons for the future of their business. Most, if not all, oil wells in France are mature and most of the fluid extracted from them is hot water. Until now, most of the water has been separated from the oil and re-injected into the ground to keep pressure in the wells. This is about to change. The MEET project, funded by H2020 Europe, seeks to bring French oil companies into the future by demonstrating the possibilities of ORC electrical power production using the hot water by-produced in the oil wells. Thus, oil and geothermal energy will be co-produced until 2040 when the legislation will force the operators of the oil wells to completely shift into geothermal power and heat production. This possibility, of using old oil wells in Europe for geothermal purposes has been previously suggested and explored, both in Poland and Lithuania (Barbacki, 2000; Puronas, 2002).

4.3 Material selection for heat exchangers

Material selection is important as the proper material can increase efficiency, decrease costs and increase safety of projects. Choosing the most appropriate material can be challenging as wells even within the same geothermal area can be quite different; some experiencing corrosion problems while others do not. ORCs are built up of multiple components but since the heat exchangers are generally the only component in the cycle to come into contact with geothermal fluid they are the focus of material selection with regard to the geothermal field.

The material used for heat exchangers is therefore highly dependent on the properties of the fluid on site. Heat exchangers are not only used in ORC cycles but also in geothermal power plants. This is common for geothermal power plants in Iceland as use low enthalpy separated fluid for heating of freshwater intended for district heating.

Although ORCs are generally not used for high temperature systems their components can experience numerous problems. Heat exchangers for geothermal environments are frequently made from stainless steel but harsher environments can require use of high-grade stainless steel or titanium alloys. The choice of material can also be limited by the design of the heat exchanger. The MEET project looks into the applicability of materials within these different categories for heat exchangers in low and high temperature areas. Another option is to use coatings to protect the heat exchanger components (Sugama, 2007) and finding such solutions is among the challenges being addressed in the Geo-Coat and GeoHex projects.

4.4 Corrosion and scaling problems

The presence of various dissolved chemicals in the geothermal fluid make it necessary to anticipate potential problems the heat exchangers that are in contact with this fluid can face and take preventive measures. This is mostly done through selection of a material for the heat exchanger which is able to resist the corrosive environment it is subjected to. The main factors that affect corrosion, hydrogen embrittlement (HE) and sulfide stress cracking (SSC) are; acidity (pH) and chloride concentration of the liquid; the concentration of dissolved non-condensable gases in geothermal steam; and temperature of the geothermal well.

Corrosive chemicals generally found in geothermal fluids are species such as oxygen, carbon dioxide, species of hydrogen sulphide, ammonia, chloride and sulphate (Conover, et al., 1979). The most commonly reported issue for heat exchangers is scaling. Scaling build-up prevents proper heat transfer and can lead to clogging. The presence of scaling can lead to crevice corrosion and pitting that can eventually cause leaking. A study done through the Geo-Coat project on problems encountered by geothermal power plant operators this was also considered one of the biggest issues. In addition to this, erosion was reported as an issue that can lead to leaking (Haraldsdóttir, 2018). It is therefore important to use adequately hard, corrosion resistant material that preferably minimizes scaling build-up.

4.4 Materials

The most commonly used material in geothermal environment is carbon steel and stainless steel (Sanada, et al., 1995; Sanada, et al., 2000). Stainless steel is more expensive and thus it is used in smaller quantities than carbon. Stainless steel is an excellent corrosion resistant material. This is due to its high chromium content, 11,5% or higher. Stainless steel is especially resistant to uniform corrosion but the presence of chloride can increase the effect of localized corrosion in the material, allowing for further corrosion damages to the inner surface of the steel. 316L stainless steel is the most commonly used material for geothermal heat exchangers (Kristmannsdóttir, et al., 2003) but this is dependant on the fluid composition. At the Krafla and Þeistareykir site both 316L and 254SMO are used for heat exchangers (Arnarson, 2015). The 254 SMO material is also used for heat exchangers at Hellisheiði (Hallgrímsdóttir, et al., 2012). Super duplex stainless steel can be used and an example of that is the use of 2507 super duplex steel for shell and tube heat exchangers in the Rittershoffen project, a deep EGS well project in France (Ravier, et al., 2016).

Titanium alloys are light metals but are also very strong. Titanium is very corrosion resistant to many chemical environments such as solutions of chlorine (Cl), especially in lower temperature geothermal brine environments (Pye, Holligan, Cron, & Love, 1989; Thomas, 2003). Titanium and its alloys are relatively expensive and therefore not commonly used. Titanium tubes have been used for heat exchangers for instance at Hellisheiði (Hallgrímsdóttir, et al., 2012).

4.5 Material testing

It is important to choose material that is adequate for each site based on results from tests. These tests can include testing in similar environments to those under consideration or in-situ tests which give a better understanding of the effects in that particular environment.

Apart from the temperature difference, low and high temperature areas generally have their different qualities. In Iceland, the high temperature systems tend to be acidic while the low temperature areas are alkaline with low amounts of dissolved species. The high temperature system at Reykjanes and the low temperature system at Grásteinn are good examples of the difference between HTGR and LTGT.

The Reykjanes system has temperatures above 250°C and is acidic with particularly high amounts chloride, which is understandable due to the origin of the geothermal fluid. The temperature of the Grásteinn II area is around 100°C and the dissolved species in accordance with what is expected from wells in the area. The amount of silica is greater at Reykjanes than at Grásteinn which is also to be expected (Villarroel Camacho, 2017). The underground water in the area surrounding Grásteinn II is mostly alkaline, with a pH ranging from 6,9 to 9,8 (Sigurðsson, 1996; Korneliúsdóttir & Kristmannsdóttir, 2010).

This difference is likely to result in different material choices for each site as they encounter different chemicals and overengineering would cause unnecessary cost. In-situ tests are being performed to determine the behavior of materials in these environments to allow for appropriate materials selection for heat exchangers. This information will then be used to create heat exchangers for ORC systems that will subsequently be tested in similar environments.

4. CONCLUSIONS

There is great potential for increasing the use of ORC cycles for power production in Iceland, Europe and the world. ORCs are applicable for both low and high temperature resources as they can be used to tap into a previously unused low temperature resources and compliment established systems by increasing cascading use and therefore the efficiency utilization of the resource. ORCs might also be a good solution for further utilization of previously drilled oil wells as there can be water present in the formations at high enough temperatures to allow for ORC power generation. This potential is being investigated and is one of the focus points of the MEET project.

A crucial step to making ORCs more cost effective, and therefore a more viable option, is designing the ORC based on the environment it will be operating in. This includes choosing appropriate materials for the heat exchangers in the system, which are the main components that come into contact with the geothermal fluid. Such contact has led to heat exchangers experiencing corrosion, erosion and scaling during operation. Appropriate material selection can therefore reduce operation cost as it should lead to less down time and less need for fixing and replacing damaged components.

Various materials are viable for heat exchangers in geothermal fluids. However, to prevent unnecessarily high CAPEX the material should preferably be designed for the environment instead of using expensive materials that can withstand the harshest environments. This therefore shows the necessity of choosing different materials based on the environment. Using coatings in conjunction with inexpensive carbon steel bulk material is a potential option to reduce the CAPEX which is being explored in the Geo-Coat and GeoHex projects. Different materials including stainless steels and titanium, the most common materials for this purpose, are being tested as potential heat exchanger materials in MEET for different locations and the results are to be used in actual ORC test unit connected at Grásteinn II and Reykjanes. The results from these tests will give insight into requirements needed in those, and similar areas, and allow for better tuning of the ORCs based on the environment.

The wide distribution of low and medium temperature areas in the world offer great potential for electricity production through the use of affordable Organic Rankine Cycles, tailored to each environment. This can lead to great changes within the electrical market as an increase in the number of small operators in the grid can potentially make areas more self-sufficient and hopefully reduce the overall carbon footprint of electrical production.

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