DEVELOPMENT OF A COOLING SYSTEM FOR GEOTHERMAL BOREHOLE PROBES

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ABSTRACT
The high potential of geothermal energy in quantity and availability can be a great option, facing the huge problem of growing energy use linked with the climatic problems. Therefore it is necessary to reduce costs and risks for the use of geothermal energy sources. Because most of the problems have to do with insufficient knowledge about the conditions in the earth crust, the key to take root of geothermal energy is widespread research. The cooling system allows the use of all needed devices in deep boreholes without strict time or temperature limitations and so promotes the achieving of comprehensive information. Developing the purpose-built components among conducting experiments about the thermodynamic processes, a prototype is provided step by step.

INTRODUCTION
Borehole temperature in Germany normally don’t exceed 200°C but there do exist geothermal locations with much higher temperatures. There are intentions to use the heat of magma chambers [IPGT, 2012]. Because only few electronic components and special seal materials withstand temperatures around 200°C, logging in this boreholes is already a serious problem. Therefore it would be a great advance to introduce an active cooling system for logging devices with unlimited operating time.

THE SYSTEM
The cooling system shall make it possible to use various measurement devices with standard electronics for long time periods, in boreholes with temperatures up to several hundred degrees Celsius. Therefore the concept consists of two central fields. The first one is the insulation to reduce the heat input from outside. The 2nd field of the concept is a thermodynamic cycle process to limit the temperature inside the cool room (Figure 1).

Insulation
A MLI (Multi Layer Insulation) and a vacuum-insulation inside the wall of the refrigeration room housing minimize heat radiation and heat conduction at ones. First experiments showed that the heating-up of the refrigeration room is slowed down significantly with a vacuum of less than 0.5 E-4 mbar (Figure 2).

For the corresponding experiment, a heating jacket was used to heat the cool room from outside. The temperature profiles inside were logged during different runs, with or without vacuum and compared afterwards. The results show clearly that the vacuum insulation works, though there are still some technical problems with its stability.
Active cooling

The heat which gets through the insulations and the heat produced by the electronic components themselves have to be dissipated to guarantee that a maximum temperature of 70°C won’t be exceeded. This prevents damage to the components by overheating. Realizing this cycle the devices and appending electronics can be used without time limitations, like it would exist using only PCM (Phase Change Material) cooling. The process consists of four important sub-processes, which have to be carried out by purpose-built components.

The process

The special ambient conditions in the boreholes evoke a special process conduct (see Table 1 and Figure 3). This means usual refrigerants are not usable. Searches for compounds with fitting evaporation temperatures and pressures indicated acetone, 1,1-dichlorethane and ethyl-formate as possible refrigerants for 200°C environments. In the moment acetone is preferred, because it’s the best known and available substance of the mentioned fluids. Figure 3 shows the predicted process with acetone in a borehole with 200°C ambient temperature [REPROP Database, 2011].

Table 1: sub-processes

<table>
<thead>
<tr>
<th>diagram</th>
<th>conditions</th>
<th>sub process</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 - 1</td>
<td>56.5°C</td>
<td>isothermal evaporation</td>
</tr>
<tr>
<td></td>
<td>1 bar</td>
<td></td>
</tr>
<tr>
<td>1 - 2</td>
<td>gaseous</td>
<td>polytropic compression</td>
</tr>
<tr>
<td>2 - 2*</td>
<td>isobar</td>
<td>sensible heat loss</td>
</tr>
<tr>
<td>2* - 3*</td>
<td>220°C</td>
<td>isothermal condensation</td>
</tr>
<tr>
<td></td>
<td>40 bar</td>
<td></td>
</tr>
<tr>
<td>3* - 3</td>
<td>isobar</td>
<td>sensible heat loss</td>
</tr>
<tr>
<td>3 - 4</td>
<td></td>
<td>isenthalpic expansion</td>
</tr>
</tbody>
</table>

For hotter surroundings it is possible to use a 2nd stage with a 2nd refrigerant, whose intermediate cool room serves as the surrounding for the first stage condenser.

Figure 2: Influence of vacuum insulation

Figure 3: acetone cooling process
Following an analogical structure as in stage one, the 2nd refrigerant evaporates in the intermediate cool room, becomes compressed gaseous and condenses above the ambient temperature of the borehole. The whole system can be imagined as a refrigerator inside a house with air conditioner, but with very different temperatures. An example for the 2nd stage with dodecane is pictured in Figure 4.

Figure 4: 2nd stage: dodecane

The maximum cooling capacity can be calculated as follows (1) [VDI 2006].

\[
\frac{dQ}{dt} = \dot{m} \cdot T_1 \cdot (s_1 - s_4) \\
\approx \dot{m} \cdot \left[ \frac{dp}{dT} \cdot T_1 \cdot x \cdot (v'' - v') \right] \tag{1}
\]

With

- \(dQ\): heat differential
- \(dp\): Pressure differential
- \(dT\): Temperature differential
- \(dt\): time differential
- \(\dot{m}\): mass flow
- \(T\): temperature
- \(s\): entropy
- \(x\): percentage of liquid phase
- \(v''\): specific volume superheated
- \(v'\): specific volume sub cooled

The prototype currently used for the experiments, was engineered with the aim to achieve maximum surface for heat conduction under the constraint of available space in the cool room (Figure 5).

Figure 5: evaporator

The extreme process and environment conditions, corrosive surrounding media and aggressive refrigerants pose a big challenge for the engineering of the cooling system components. Besides, the probe has to be designed compactly. To be usable in most of the boreholes, the outer diameter should not exceed 170mm. Because the evaporator has to fit into the cool room, this means the actual diameter’s maximum is 110mm. In future probe designs, diameters of 129mm will be allowed for the evaporator. It has to mentioned, that the components which has to be cooled have to fit in the cool room as well.

The condenser is in preparation for Technical Control Board (TÜV), because it needs a technical approval for inside pressures of over 40 bar. The throttle and the compressor are in the construction design phase. The assembly of a big compressor for the usage in laboratory experiments is running. The condenser can take more space as the evaporator placed outside, but has direct contact with the borehole environment. It has to resist the high temperatures and pressures and still perform a sufficient heat transfer. Materials which are usable for this purpose, like nickel-base alloys, are expensive and difficult-to-machine. To reach a big surface for heat conduction the design is based on a small tube structure (Figure 6).

Figure 6: condenser engineering model

Problems

The installation space, operating temperatures and pressures can be summarized as inner problems for the cooling system. As outer problems, the ambient temperatures, pressures and corrosive media have to be mentioned. A big issue for the system which occurs inside and outside the system, even though with different parameters, is the heat conduction. Talking about insulation some possibilities to minimize the heat conduction were described.
In contrast to this, the condensation and evaporation process require good heat conduction performances. In formula (2) the most important influencing variables can be recognized [WSÜ 2008]. The heat transfer coefficients \( \alpha_i \) depend on involved materials and fluids and like the temperature gradient \( \Delta T \), also on constant process parameters. Hence they are only partly modifiable and the surface \( A \) has to be focused to increase the transferable heat flow \( \frac{dQ}{dt} \).

\[
\frac{dQ}{dt} = \left( \sum_{i=1}^{n} \alpha_i \right)^{-1} \ast A \ast \Delta T \quad (2)
\]

Because there are many heat transfer steps (Figure 7), the heat conduction issue is very complex. It is nearly impossible to implement simulations which can deliver reliable prognoses, without trustable validation by several experiments.

![Figure 7: heat transfer steps](image)

That is why experiments are a central task during the development of the cooling system for the validation of the constructed component prototypes and the prognosticated process behavior.

**EXPERIMENTS**

**Evaporation and heat transfer**

**Outer heat source**

Following the process structure, the first sub-process to investigate is the evaporation. Using acetone as refrigerant and a prototype of the refrigeration room housing (with integrated MLI and vacuum insulation of \(< 0.5 \text{ E-4 mbar}\)) the cooling and heat transfer capacity was tested. The latest evaporator version (Figure 5) was utilized as a heat exchanger inside.

The casing was heated up from outside with a heating jacket at over 200°C (Figure 8).

![Figure 8: cool room casing with heating jacket](image)

The evaporator was filled with 700 ml of liquid acetone at atmospheric pressure. With thermocouples inserted in the casing and the evaporator, the temperature-time curves were plotted (Figure 9).

![Figure 9: temperature profile, outer heat source](image)

The profile shows a temperature plateau at 56, 5°C for about 200 minutes, which indicates the evaporation phase. With formula (1) and the substance properties of acetone, the cooling capacity was estimated (Table 2). The result was about 22 watt, which is equivalent with the heat flow from outside through the insulation. The temperature curves of the air and acetone don’t differ much. The temperature inside the insulation layers of ceramic wool at the casing bottom and cover runs at a significant higher level, because there is no MLI and vacuum insulation in axial direction.

**Table 2: substance properties of acetone**

<table>
<thead>
<tr>
<th>m</th>
<th>time</th>
<th>( s_1 )</th>
<th>( s_4 )</th>
<th>( T_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[kg]</td>
<td>[s]</td>
<td>[kJ/kgK]</td>
<td>[kJ/kgK]</td>
<td>[K]</td>
</tr>
<tr>
<td>524 E-3</td>
<td>12 E3</td>
<td>1,525</td>
<td>-5 E-4</td>
<td>329,5</td>
</tr>
</tbody>
</table>

refrigerating capacity [W] 21,95
**Outer and inner heat sources**

In the next step a board with resistors was installed additionally, to simulate the loads in the cool room. A part of them was admitted with output of 20 watt, the rest stood dead (Figure 10). So in total (with heating jacket outside) there was a heat input of about 40 watt inside the casing.

![Figure 10: thermocouples and resistors](image)

The temperature profiles were logged with the same quantity of acetone (700ml) as before (Figure 11).

![Figure 11: temperatures, inner and outer heat source](image)

The problem which occurred is that the resistors heat up to fast in comparison with the acetone. That is why the plateau is reached when the temperatures are above 70°C. For the electronics in the later probe this would mean damage which has to be prevented. The results show that the heat conduction from the loads to the refrigerant has to be optimized. A Simulation showed that forced convection of the inner air would improve the problematic heat transfer (Figure 12).

![Figure 12: simulation of temperature profiles](image)

In a first test a fan was used to move the air inside the cool room (Figure 12).

As result the temperature gradient between refrigerant and resistors is smaller and the resistors heat up slower. But the temperature profiles logged deviate notable from the simulation prognosis and the improvement of the heat transfer is weaker as expected and not sufficient for later application.

**Optimization**

A new evaporator design shall make the problematic heat transfer more direct. Besides it can perform a higher refrigeration capacity and offers more installation surface for loads (Figure 14).
Accordingly the other components, like condenser and compressor, have to be tested under realistic conditions in the laboratory. Based on the experiments, they can be optimized in a 2nd iteration step. Following this structure it is possible to approximate an optimal cooling cycle and to realize a solid construction simultaneously. The end of this described operating sequence will be an operational prototype, which can be varied and rapid adjusted.

**PROSPECTS**

**Next steps**

There is still a lot of work to do, realizing a complete prototype of the borehole cooling system. After testing the evaporation phase firstly, there have to follow more experiments to optimize this sub-process. The next step to do is the installation of experiments for the missing sub-processes condensation, compression and expansion and to combine them to form the whole cooling cycle in the laboratory, which shall be realized within this year. Therefore the component prototypes for compressor, throttle and condenser are in preparation.

**Open questions**

Besides the concrete steps for the development of a prototype of the cooling systems, questions about field operation and special applications has to be answered. The engineering of components like the compressor and the implementation of experiments are expensive and time-consuming.

Even if a usable machine will stay at the end of this project, it is still a research project which first and foremost aims at scientific findings and is shareware oriented. That simplifies some engineering exercises, relieving them from economic factors, but at the other hand brings difficulties for the financing. For further development and a better performance, it could be reasonable to find partners for technical parts, as well as for questions about application. A vision for a possible version of the borehole cooling system already exists (Figure 15).

**WEBSITE**

http://geothermiewiki.iai.kit.edu/index.php
REFERENCES


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