

Cooling System for Borehole Tools

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ABSTRACT

The cooling systems engineered at the IAI provide a cooling service for different borehole tools in different environments. A system for short operations, which uses a container with PCM-(Phase Change Material) and custom designed heat-pipes can protect standard electronics in hot environments for several hours from overheating. Since borehole tools sometimes need more time for operations, a lot of effort is put into the development of an active cooling system as well. This “active” cooling system, based on the principle of refrigerators, is developed especially for the use in geothermal wells. The components are specifically designed for borehole operations, respecting small dimensions, corrosion resistant materials, economical and reliable handling. The thermodynamic cycle process performed by the cooling machine allows down-hole operations without time-limitations using standard electronics and can be adapted to different borehole conditions.

1. INTRODUCTION

Borehole investigation tools which provide sensors, monitoring, data transmission, control tasks and others, have all in common, that they contain a large number of electronic components. Although there are some high-temperature electronics, they are strongly limited concerning the application range and the maximum operation temperature. Beyond the point of 200°C they are extremely rare, since they are nearly pushing the physical limit. In many cases the time periods for the use at high temperatures are restricted. Moreover it has to be pointed out, that these high temperature electronic components are very costly [Bauer 2010].

There are a lot of boreholes with temperatures which exceed 200°C clearly and therefore stay inaccessible for investigation (or other) tools, containing electronics, without any cooling system even in case of using “high temperature electronics”. Examples for such boreholes or borehole fields can be found all over the world.

- Coso Volcanic Field, Inyo County, California, max. temperature ~340°C [Wohletz 1992]
- Kizildere Plant, Denizli Province, Southwest Turkey, max. temperature ~240°C [Serpen 2005]
- ASAL Field, Djibouti, Iceland, max. temperature ~330°C [Khairah 1989]
- Bietigheim Plant, Baden-Württemberg, Germany, max. temperature ~220°C
- Lohmen Plant, Mecklenburg-Vorpommern, Germany, max. temperature ~200°C [GtV 2013]
- Soultz Plant, Elsaß, France, max. temperature 200°C [BINE 2014]

These are only few of many more examples to show, that hot boreholes exist, which are actually used for energy production. How deep it has to be drilled, naturally depends strongly to the region. In Southwest Germany i.e. to reach temperatures about 200°C, the boreholes have depths of 5,000 m and more. This brings additional difficulties for the machines with it, namely the high surrounding pressures of up to 600bar (depending on the exact depth), long distances for data transmission and so on.

The trend in Europe goes to deeper and hotter boreholes to maximize the production to improve the economic efficiency [BFE 2006], which means that that more of these deep wells will be used in the future. Geothermal Energy shall become an important part of part of the future energy supply that is why a lot of effort has to be put into the research and development of geothermal technologies.

At the same time, the demand for borehole data is growing. A widespread borehole research is needed for both: the geothermal research and the geothermal energy production, to generate appropriate results. Since in some cases the geologist are dependent on over 30 year old borehole data, collected by the oil-industry as a byproduct to substantiate their investigations ([Birner 2013] and others), while others which don't have any direct down-hole data are limited to computer modelling, a need for investigation tools is evident. Of course these tools have to be accessible for those who need them.

Borehole tools have to be reliable, custom designed for various purposes and in a way affordable for scientific and industrial players in the geothermal field, who often face financing bottlenecks. A project which has tasked itself with realizing exactly this attributes is called ZWERG, which means dwarf in german. Dwarfs, "..., workers in deep mines, could be used to disclose..." the "secrets" in the reservoirs [Isele 2013]. This metaphoric shall clarify which vision stands behind this development efforts. Basic components for nearly every type of borehole tools, repeated elements, are the housing with its 'special requirements for materials, sensors for measurements, monitoring systems, data transmission concepts and cooling systems for parts which are sensitive-to-heat. ZWERG tries to develop a platform or "tool-kit" for the modular construction of borehole probes using "blueprints" or standardized elements to quickly engineer different affordable tools for different applications.

This paper will concentrate on the issue of cooling systems usable in borehole probes and slightly touch the material topic, because it is closely connected to the component design for cooling systems.

2. WAYS OF COOLING IN BOREHOLE TOOLS

There are two different approaches for the cooling inside borehole tools, which are both conducted at the Institute of Applied Computer Science IAI, at Karlsruhe Institute of Technology. The first approach which is technically simpler is the PCM cooling for short operations. Secondly an active cooling system, a cooling machine for borehole tools, is developed for operations without time limit. An important factor is the outer insulation which won't be described in detail but only mentioned as PTFE, MLI and vacuum insulations.

2.1 PCM Cooling

The short-time-cooling is realized by using a PCM (Phase Change Material) which receives heat from the cooled area of a probe – practically the installation surface for the electronic parts – by conducting a thermodynamic transformation to another phase. During this phase change, from solid to liquid or liquid to vapor the material consumes energy in form of heat while holding the temperature constant. This latent heat can be used as cooling capacity. The temperatures which can be hold for the time of cooling as well as the time of cooling itself depend on the substance properties of the used PCM. The melting temperature (if using the phase change from solid to liquid) or the boiling temperature (if using the phase change from liquid to vapor) at certain pressure leads to the reachable cooling temperature. Of course there has to be a temperature gradient between the cooled parts and the PCM so heat flow is possible. The resulting cooling temperature is the sum of phase melting (boiling) temperature and this gradient. To realize a low cooling temperature, besides the choice of PCM it is therefore important to realize a small gradient. This is made by installing heat-pipes between cooled surfaces and PCM-container as sketched in figure 1.

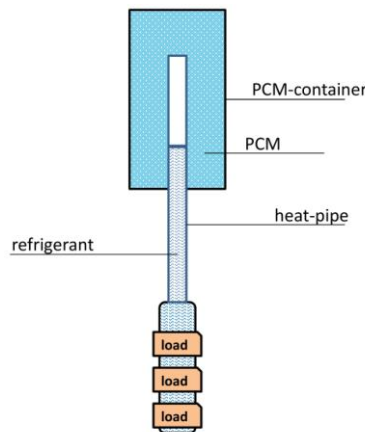


Figure 1: Basic diagram of PCM-Heat-pipe cooling

Heat-pipes are closed pipes of metal containing a refrigerant. When heated up the refrigerant starts moving caused by convection and later evaporating inside the pipe. It pulsates between vapor and liquid phase while carrying the heat from one end to the other. When condensing at the end in contact with the cool PCM it transfers the heat to it. At the other end heat from the cooled surfaces is transferred to the heat-pipe refrigerant. The described process is many times faster than normal heat conduction through metals. As equation 1 shows: with a better heat transfer coefficient α , the temperature gradient ΔT can be hold low for the same heat-flow dq/dt through an existing heat-transfer surface A .

$$\frac{dq}{dt} = \alpha \cdot A \cdot \Delta T \tag{1}$$

To fully exploit the PCM, this value should be higher than the possible cooling capacity linked to it. The actual cooling capacity cc depends on the evaporating (melting) enthalpy Δh at the phase change temperature T_c and mass flow dm/dt of the state changing mass percentage (plus the sensible heat transferred while heating up from start-temperature T_0 to limit temperature T_l with heat capacity cp). The total mass m gives the cooling time with an assumed heat input P .

$$cc = \frac{dm}{dt} \cdot \underbrace{[\Delta h + cp \cdot (Tl - T0)]}_c \tag{2}$$

$$t_{cooling} = \frac{m \cdot C}{P} \tag{3}$$

At the IAI different PCM refrigerant combinations are tested. Figure 2 is the picture of a heat pipe of copper with acetone as refrigerant and water (ice) as PCM. An example estimation for this combination is listed in table 1 with the evaporation temperature of acetone Te and maximal cooled surface temperature Tm [VDI 2006].



Figure 2: Picture of Heat-pipe prototype connected with PCM-container

Table 1: Example of estimated PCM-system values (ice)

α [W/m^2-K]	cp [$kJ/kg-K$]	Δh [kJ/kg]	Tc [$^{\circ}C$]	$T0$ [$^{\circ}C$]	Te [$^{\circ}C$]	Tl [$^{\circ}C$]
777	4.18	333.5	0	20	56.5	45
Tm [$^{\circ}C$]	ΔT [K]	dm/dt [kg/s]	m [kg]	A [m^2]	P [W]	
70	13.5	4.5e-4	11.5	0.02	186	
dq/dt [W]	cc [W]	t [s]	t [min]	t [h]		
209.79	197.1	27080	451	7.5		

This means, that in the described combination, the temperature of critical components can be hold under 70 °C for 7.5 hours with a total heat-input of 186W. It has to be pointed out, that a significant part of the heat-input comes from outside through the insulation, so the effective cooling capacity for electronics is reduced.

In experiments the functionality of the water-acetone combination has been proofed. The refrigerant pulsation can be seen clearly in figure 3, too. For this experiment a test heat-pipe is mounted in an insulated cabinet. Power resistors produce the heat input. The PCM container is filled with ~450g ice, the heat-pipe with ~120ml acetone.

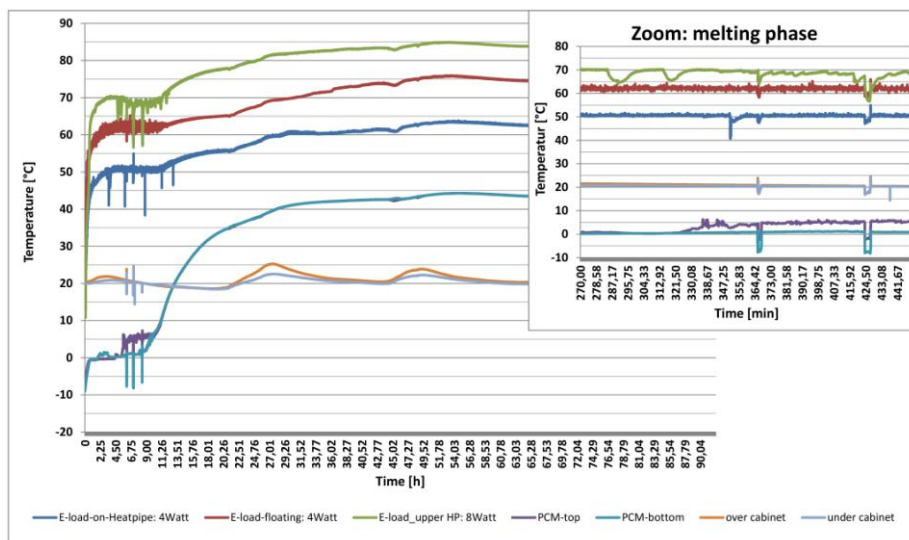


Figure 3: Experimental data of heat-pipe test

2.2 Borehole tool cooling machine

The borehole cooling machine consists basically of four components: evaporator, compressor, condenser and throttle (expansion valve) – corresponding to the main sub processes: evaporation, compression, condensation and expansion. This construction and the realized thermodynamic cycle process are an old, well known principle used in almost every home refrigerator or air conditioner. The process can be described with the ideal Carnot process, consisting of two isotherms and two isentropic transformations as heat-pump process with reversed exploit and expense. This ideal process leads to a maximal theoretical efficiency, which is usually named COP (coefficient of performance) in case of heat-pumps. The real process is changed by the influence of polytropic changes (with generation of entropy) and pressure drops. For the borehole tool cooling in hot environments (i.e. 200°C) the process has to be strongly modified and an appropriate refrigerant has to be used. The established substances for “normal” cooling machines are suitable for temperature levels around surface ambient temperatures and therefore unfit for the borehole cooling machine.

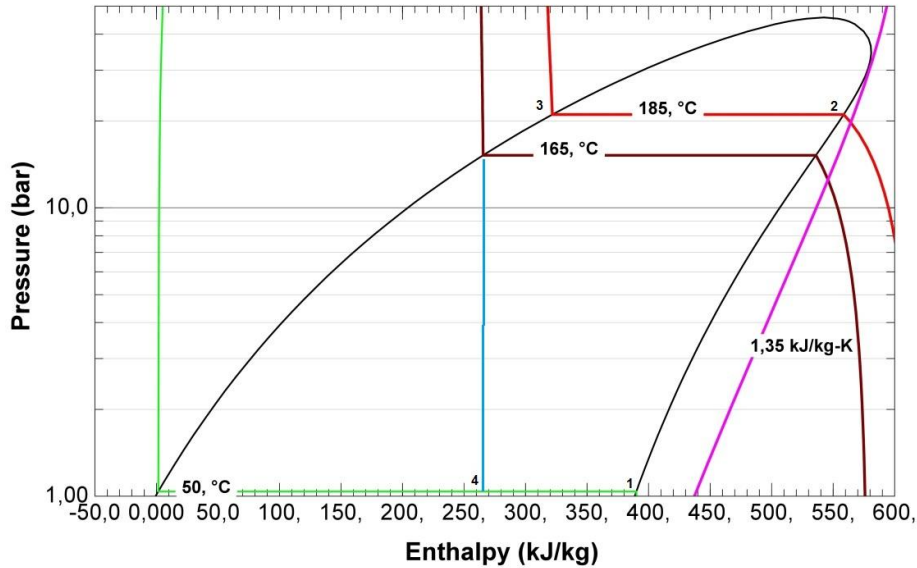


Figure 4: log p-h plot of borehole cooling (incl. sub cooling) cycle with cyclopentane [REF 9.1]

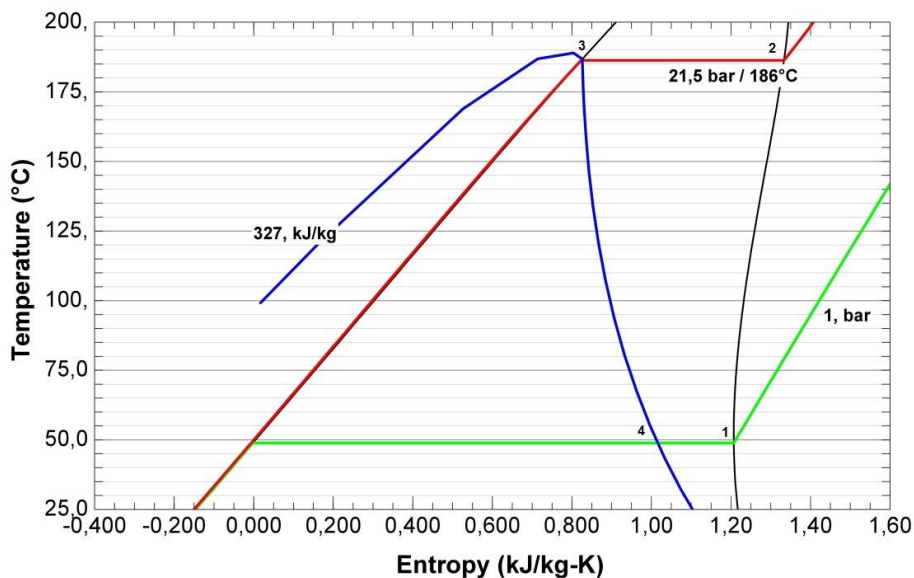


Figure 5: T –s plot of borehole cooling cycle with cyclopentane

Figure 4-5 demonstrate an exemplary proceeding with cyclopentane as refrigerant and a borehole temperature of approximately 165°C. The cyclopentane evaporates at normal pressure at the temperature 50°C. Assuming a probably temperature gradient of 15 K between the cooled surface and the evaporator, electronic temperature could be hold constant at 65°C. The evaporated substance is compressed gaseous at the pressure 21.5 bar, at which it condensates at 186°C. Thereby heat is transferred from the pressurized substance to borehole surrounding (under a temperature gradient of 21K). The condensed refrigerant passes the throttle, an expansion valve or orifice using the Joule-Thomson-effect or a capillary where the pressure is reduced via pipe friction. This sub process is estimated as isenthalpic change, thus the substance reenters the evaporator in the two-phase region. Because of this circumstance the usable evaporation heat is reduced – the cooling capacity is smaller, compared with the ideal (Carnot). In the logarithmic p (pressure) – h (enthalpy) plot, the heats can be read off directly as lengths between the process points. It can be seen,

in Figure 5, that less than 17% of the evaporation-line is passed ($\sim 0.2 \text{ kJ/kg-K} \sim 64 \text{ kJ/kg}$), when the condensate is not sub cooled. This percentage depends on the used refrigerant. Like displayed in figure 6, the usable cooling enthalpy of acetone is significantly higher ($\sim 33\% \sim 0.5 \text{ kJ/kg-K} \sim 164 \text{ kJ/kg}$).

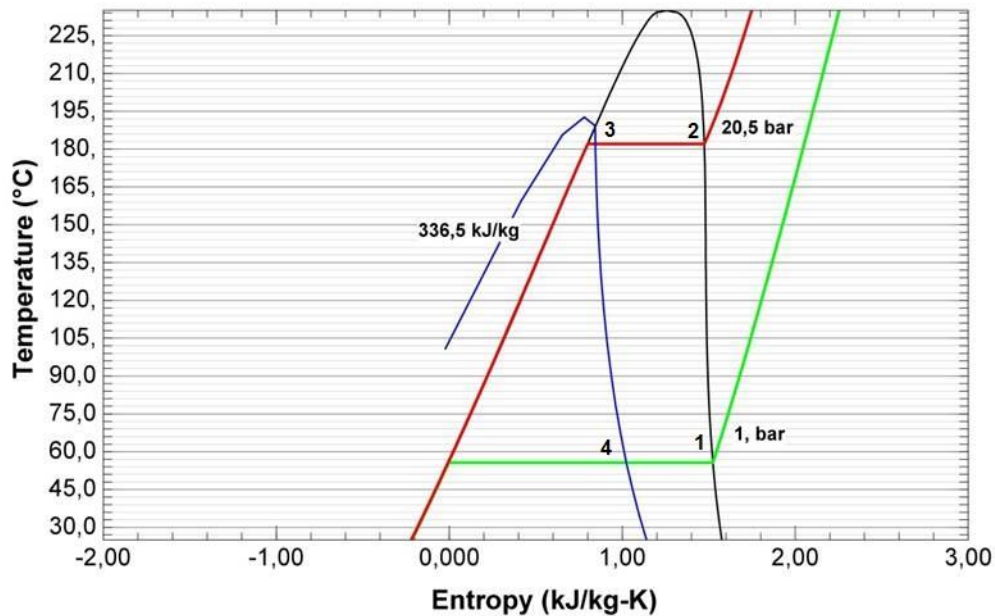


Figure 6: T-s plot of borehole cooling cycle with acetone

The important substance values can be read off the diagram. With equation (4-6), the enthalpies h_{1-4} and the assumed mass-flow dm/dt , the heat output during condensation dQ_2/dt , the evaporation heat dQ_1/dt and the compression work dW/dt can be calculated [Bockhorn 2008].

$$\frac{dQ_2}{dt} = - \frac{dm}{dt} \cdot (h_3 - h_2) \quad (4)$$

$$\frac{dQ_1}{dt} = \frac{dm}{dt} \cdot (h_1 - h_4) \quad (5)$$

$$\frac{dW}{dt} = \frac{dQ_2}{dt} - \frac{dQ_1}{dt} = \frac{dm}{dt} \cdot (h_3 + h_4 - h_2 - h_1) \quad (6)$$

The evaporation heat dQ_1/dt is similar to the cooling capacity realized by the process. The so calculated compression work is an ideal value, assuming the compression as isentropic transformation. As mentioned, a polytropic change is a more realistic assumption (equation 7), producing a higher compression work value. This is important, since the compression work is the external power input for the cooling machine.

$$\frac{dW_{poly.}}{dt} = \frac{dm}{dt} \cdot R \cdot T_1 \cdot \frac{n}{n-1} \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] \quad (7)$$

After Clausius-Clapeyron with the individual gas constant R , the compressor input temperature T_1 , the polytropic coefficient n and the pressure p_1, p_2 at the compressor in-/output. Table 2 shows the exemplary process values for a mass-flow of 2 kg/h and different refrigerants, as well as the ideal and polytropic compression work and the interesting cooling capacity [Bockhorn 2008].

Table 2: Calculated process values for alternative refrigerants

substance	dm/dt [kg/h]	R [J/kg-K]	Tl [°C]	n	$p2$ [bar]	$p1$ [bar]	<i>ideal</i> compression work [W]	<i>poly.</i> compression work [W]	<i>heat</i> output [W]	<i>cooling</i> capacity [W]
acetone	2	143.34	56,4	1.2	21,5	1	74.642	105.06	166.562	96.64
cyclopentane	2	118.55	50	1.185	20	1	101.82	81.25	137.82	36
R113	2	44.37	50	1.185	22	1	32.226	31.63	41.09	8.864
R365mf	2	56.15	40	1.183	29	1	22.31	43.14	32.77	10.46
1,1- dichlorethane	2	84.01	57,3	1.15	17	1	-	52.84	-	57.15

3. MATERIAL QUESTIONS

Like mentioned in the introduction, the material issue is not the central part of this paper. But it is an important factor for the engineering task of designing borehole-cooling-systems and there have to be mentioned some important things about it.

The housing material has to be noncorrosive, with high strength at high temperatures and promise a minimum of machinability so the requested form can be realized with manageable effort. A broadly research in this direction led to a short list of super-alloys based on nickel or silicon carbide. For further considerations the material field is restricted to nickel-based alloys like the Inconel or Hastelloy groups. The preferred material for the probe-housing and components in direct contact with the borehole environment at this moment is Inconel 718 (2.4668) because of the high tensile strength and corrosion resistance and the similarities to commonly used Inconel forms (600, 625 etc.) which simplify the handling.

If the PCM solution, called short-time-cooling in section 2, is used the material problem is limited to the housing for the whole probe. The explicit cooling-system components are located completely inside the probe. For the heat-pipes and the PCM-cartridge, materials with high thermal conductivities and heat capacities, like copper are well suited. The formability of Copper is another argument for its use in this case.

In case of the borehole tool cooling machine, the unlimited-cooling, a direct contact to the surrounding must be made, to transfer the heat from inside the probe to the borehole. This is realized by the outer heat exchanger, the condenser which of course has to be located outside. This means it has to stand the high pressures and temperatures as well as the corrosive thermal waters. Because the super-alloys named before are expensive and only available in limited forms respectively have a limited machinability as counter-balance to the high strength. Thus it is advisable to use geometrically simple designs with few different part sizes to find an optimum between functionality and effort. Figure 16 (left) shows the attempt to follow these rules designing a condenser for the borehole-cooling-system using a combination of big and small pipes.

Both systems contain necessarily seals and gaskets. The important difficulty here is the resistance (and impermeability) against the respective refrigerant combined with high temperatures arising in specific areas, like the compressor output of the cooling machine. In case of acetone as refrigerant PTFE can be used, but it is not completely impermeable. Additionally it is not usable at temperatures far above 200°C. FFKM seals are highly resistant against acetone and the most chemicals substances. It can be used at temperatures up to 350°C and more in special configurations. The only disadvantage is their high prize.

More details about the material questions will be given in a paper (and presentation) about a currently running BMU- (german Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit – Ministry for the Environment, Nature Conservation and Nuclear Safety) project, called GeoKam [Spatafora 2014].

4. BOREHOLE COOLING MACHINE

4.1 Adaption of process to borehole environment

The process of the cooling cycle, conducted by the borehole cooling machine is adjustable to different environments. This is limited by the used refrigerant and mostly controlled by the reached pressure (and temperature). Figure 7 shows the process of acetone with one evaporation level, but two different condensation levels, since the requested evaporation temperature for the cooling of electronics is always the same (below 70°C). If used in a borehole surrounding with temperature 165°C, the refrigerant is compressed at approximate 20.5 bars, 180°C condensation temperature. This guarantees a sufficient temperature gradient to transfer the heat from refrigerant to borehole fluid. In the second case of 200°C surrounding temperature, a pressure of 40 bars and a condensation temperature of 220°C have to be reached.

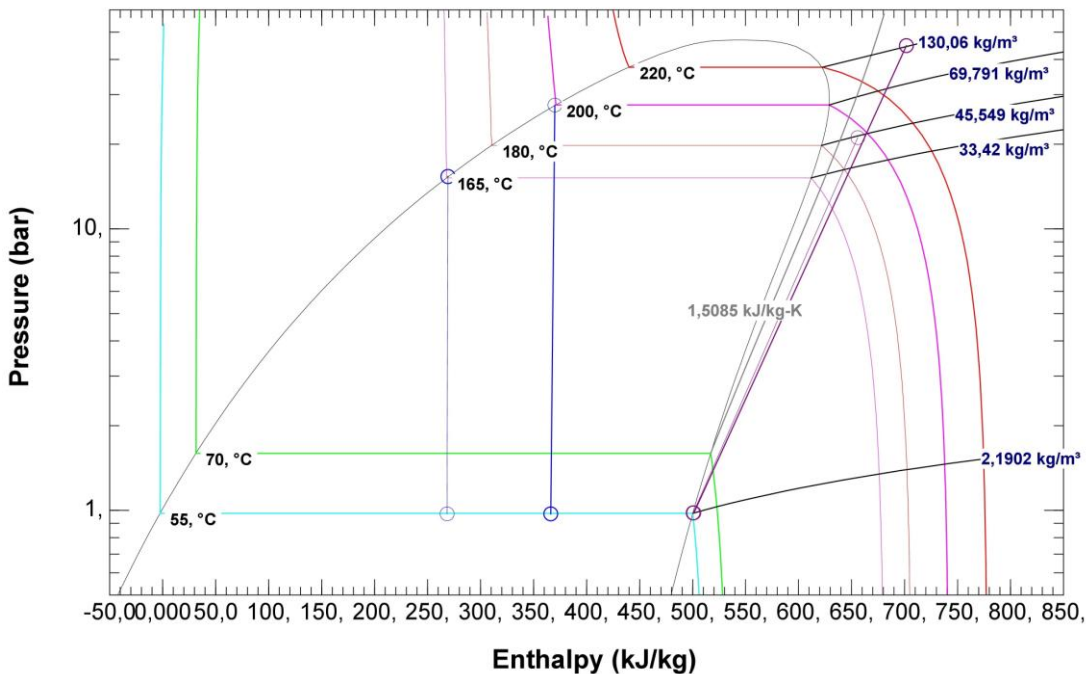


Figure 7: Borehole adjusted cooling process (incl. sub-cooling), log p-h diagram

This means of course a higher energy request for the cooling machine, because the compression work is slightly increased. Using equation (7) for the second case with a compressor output temperature of ~230°C, the compression work is ~114W. The cooling capacity is reduced in case of higher surrounding temperature because starting from a higher condensate temperature, the isenthalpic expansion leads to a smaller liquid refrigerant percentage (re. Figure 4 - 6).

If the borehole temperature strongly exceeds 200°C, the acetone cycle cannot realize the heat transfer to environment anymore. For this situation a second stage would be the adequate solution. A second refrigerant, conducting a second process would act as surrounding for stage 1, while the low temperature level (evaporation) of stage 2 corresponds to the high level (condensation) of stage 1. Cycle 2 realizes the heat transfer to the surrounding at a higher temperature. In Figure 8 such a process using water as refrigerant is shown for an exemplary borehole with a temperature between 350-360°C.

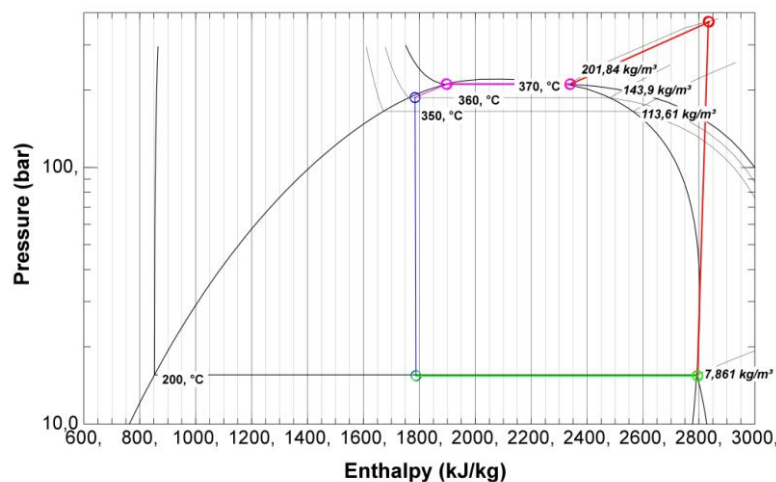


Figure 8: 2nd stage cooling process with water

As we can see, the evaporation passes at ~17 bars and 200°C, the condensation at 370°C and over 200 bars. It is clear that such a process would be really challenging for the engineering of the system components and its' energy supply, but it is a promising concept for the cooling of investigation-tools in very hot boreholes in the future. It seems to be obvious to use water in a one-step system to cool the electronics but this is not practical. To hold the electronic temperature below 70°C the water has to evaporate with sufficient gradient below i.e. at 55°C, thus the pressure has to be reduced under atmospheric conditions –in this case ~0.18bars. This also means that the compressor must realize a compression from 0.18 to 200 bars for the described borehole example, which corresponds to a pressure ratio of 1,111.1. The suggested 2-stage-solution is expected to be technically clearly less expensive.

4.2 Construction of a test stand for the borehole cooling machine

An important step for the development of the borehole cooling machine is the realization of the process in a laboratory version, where the sub processes, components and refrigerants can be tested. The claim for this test stand is to simulate the borehole environment as realistic as possible. This is difficult in many aspects, namely to produce the high pressures of many hundred bars, the temperatures and the chemical composition of the borehole fluids for the artificial component environment. Therefore this high claim is being approached in small steps, starting with realizing the environment temperatures and the approximate geometrical arrangement of the components. The components itself are engineered in the way they would be usable in an actual borehole tool, as far as it is possible for cost and organization reasons.

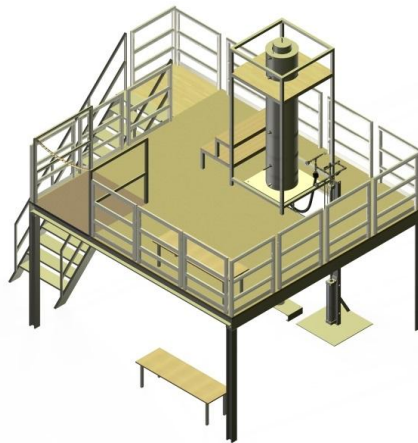


Figure 9: 3D Modell of the experimental cooling process

The 3D Modell implies the vertical arrangement, with evaporator housing and compressor on the ground, condenser above in the borehole environment and throttle component between them (in the air). The condenser is installed inside a deep fry (Figure 10) which simulates the environment temperatures and a liquid environment which is important for the testing of the heat transfer. The environment consists of oil, because there is no solution for the pressure generation and a realistic chemical borehole fluid composition provided, so far. The other components are heated up using controlled electrical heater-bands.



Figure 10: Photo of the special deep fryer inside the condenser is mounted

To receive as much data as possible, a widespread measurement structure for the analog system is planned (Figure 11). Thermocouples and pressure sensors are redundantly placed at every important position in optical and digital interface-versions. Mass-flow detection will also be integrated in the cycle. The low pressure and high pressure levels are separated through a laboratory platform. Additionally there is a pipe construction for the component connections and energy supply.

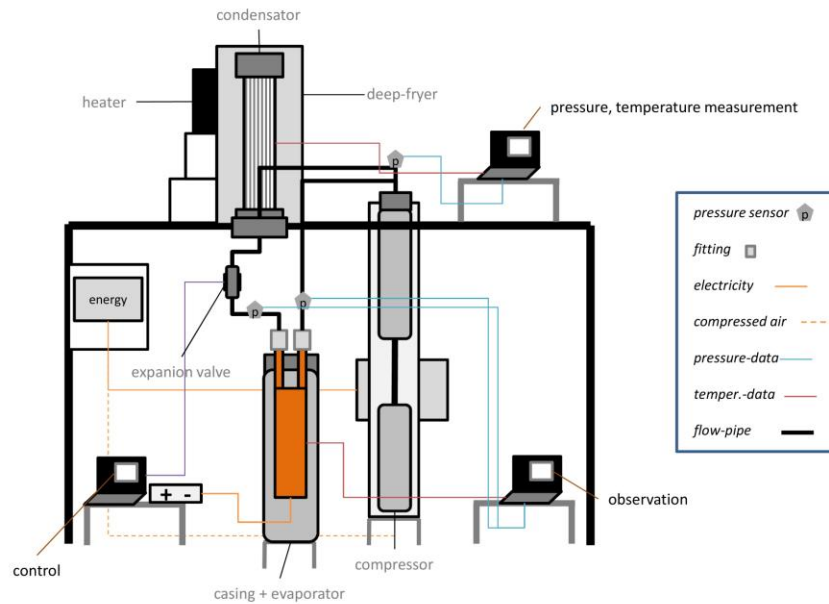


Figure 11: Scheme of the experimental cycle with important measurement devices

As compressor, a single staged compressor with pneumatic engine is used. It uses compressed air from the energy supply to compress the refrigerant with a piston. Figure 12 shows the test stand in the mounting phase, with the compressor piercing through the floor of the platform. The 2nd Version of the evaporator which will be used in this cycle can be seen in Figure 13, with axial Teflon-insulation, mounted electrical loads and thermocouples. At the upper floor a framework construction for the positioning of the deep fry with its pump is placed over the gateway for the compressor. In the left, the computers for data acquisition and controller for the heater-bands are visible.



Figure 12: Photo of the test stand while mounting the components

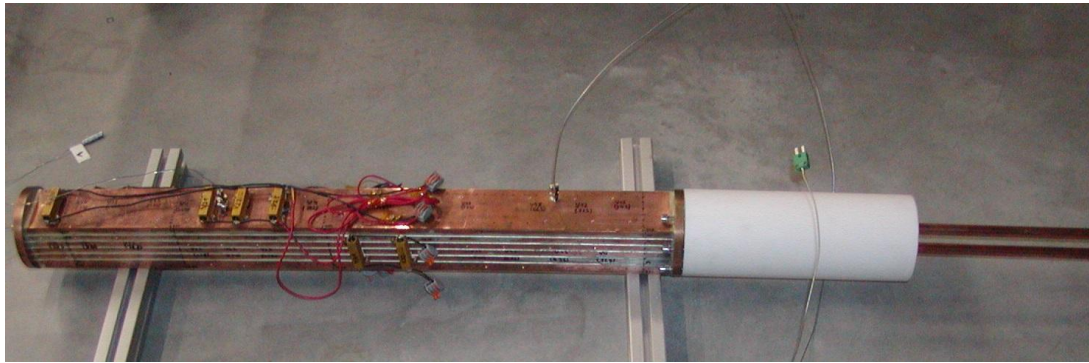


Figure 13: New evaporator version of copper; loads, thermocouples and bottom insulation mounted

While the evaporator has already the shape and the material structure suitable for borehole probes for 8 ½ inch wells, which means it enters the housing prototype with 170mm outer diameter [Holbein 2013], the used compressor is only a laboratory version. The dimensions are not proper for a compact tool. A recently completed research work done at the IAI demonstrated that a double stage piston-compressor could be designed fitting into the required housing [Armbruster 2013]. The compressor should be driven electrically. Therefore a Maxon-motor for high temperature operations was designated [Bauer 2013] as engine.

4.3 Experimental work and Simulation

To theoretical investigate the important sub processes and the refrigerants behavior; simulations are important to better understand the experimental results. Examples for interesting processes which are of central meaning for the functionality of the cooling system are the two heat transfers conducted by condenser and evaporator. Thus a focus is laid on the simulation of these. In Figure 14 some simulation results for the heating-up- and evaporation-phase, based on data from experiments with a previous evaporator version are displayed. The especially written simulation programs have to be adjusted to the data of the new evaporator tests in the next step.

The evaporator heat transfer is important for the cooling. It has to function good enough to surely protect the sensitive electronics from overheating. A trustworthy evaporator and process design can only be achieved with sufficient test and simulation experience.

Another simulation program shows the heat transfer between condenser and environment. This process is also evident for the cooling cycle because an inadequate heat transfer to the surrounding causes a process stop and lack of cool liquid refrigerant in the evaporator, thus the functionality would be disabled.

For the condenser heat transfer experimental data is not yet available. That’s why only the substance properties are based on measurements and the intrinsic simulation is purely theoretical. The diagram (Figure 15) shows the temperature profiles of the gaseous and condensed acetone and the pipe wall (Inconel 718) in different depths.

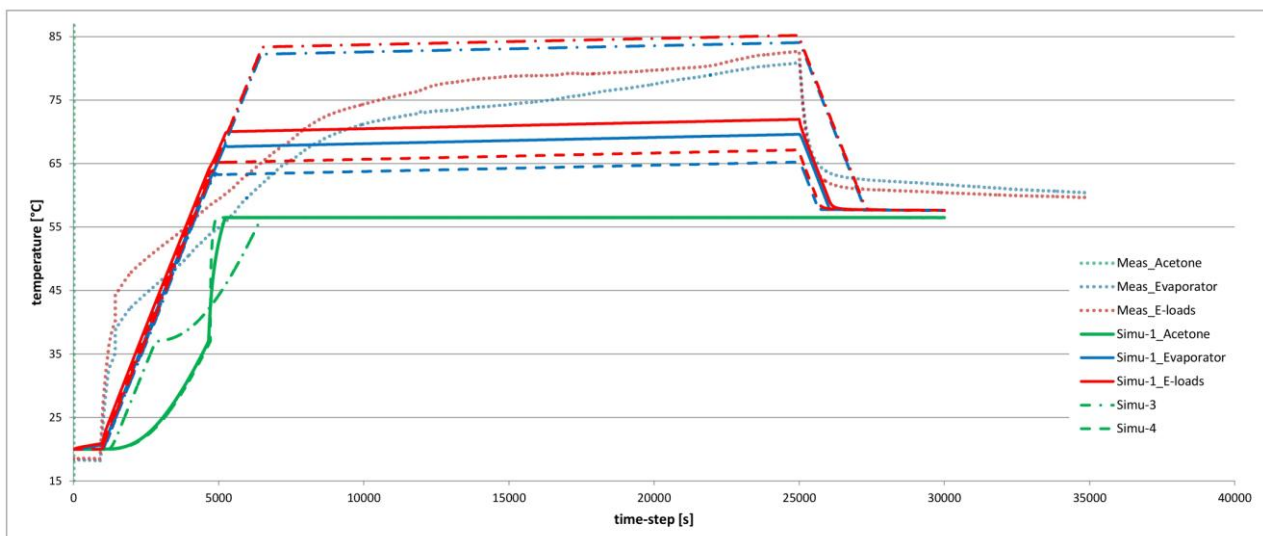


Figure 14: Comparison of Measurement Data (Meas) and Simulation results (Simu) for the evaporator heat transfer

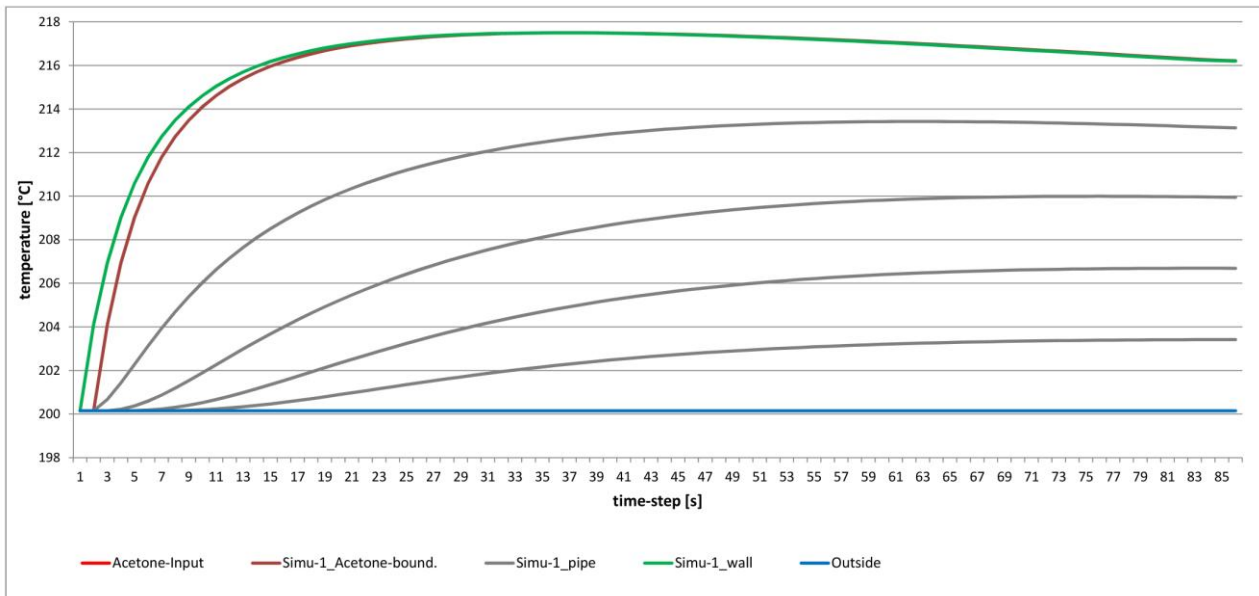


Figure 15: Simulation results for the condenser heat transfer

5. OUTLINES

The statements in this paper should show that the development of a functional borehole cooling system is progressing, although a lot of work is missing to complete this project. In the near future the experimental cycle will be completed. Afterwards a lot of experimental and engineering work to design a borehole suitable system will follow.

The commitment of a project-request at the BMU in Germany is expected soon. We are confident that in cooperation with our project partners and an adequate financial and substantial support, the borehole-cooling-system project will be successful and give rise to a useful borehole machine.

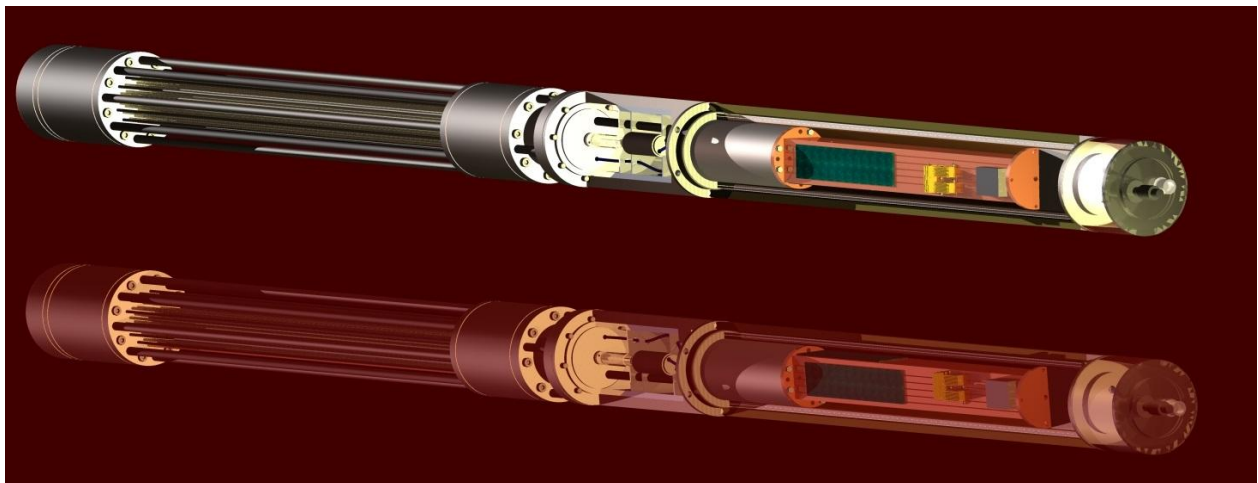


Figure 16: Picture of the borehole probe cooling system

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