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ACTIVE COOLING AND THERMAL MANAGEMENT OF A DOWNHOLE TOOL ELECTRONICS SECTION

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ABSTRACT

High Temperature (HT) wellbores represent one of today's biggest challenges for the oil and gas industry. The majority of well intervention wireline tools contain temperature sensitive electronics that are not able to withstand the high temperatures of HT wellbores (> 150 °C), for an extended period of time. This work presents the design and construction of an actively cooled laboratory prototype, which is able to operate at temperatures which are higher than the temperature limit of the electronics. A different concept of heat management, compared to prior works, is presented: the design combines active and passive cooling techniques, aiming at an efficient thermal management, preserving the tool compactness and avoiding the use of moving parts. Thermoelectric coolers were used to transfer the dissipated heat from the temperature-sensitive electronics to the external environment. Thermal contact resistances were minimized and thermally insulating foam protected the refrigerated microenvironment from the hot surroundings.

1. INTRODUCTION

Sandeep *et al.*(2003) defined well interventions as remedial operations that are performed on producing wells, with the intention of restoring or increasing production. Well interventions may be necessary because of flow restrictions, sand production, mechanical failure, changes in reservoir characteristics, or to access additional reservoir areas. Typical downhole applications that are performed during the interventions include monitoring of the well conditions, as well as installations (e.g. of valves or pipes), drilling of new well branches, cleaning, and repairing. Different downhole tools can be employed to carry out the mentioned operations and several intervention techniques can be adopted in order to deliver the tools down the wellbore.

The *electric wireline* intervention technique involves running and pulling tools and equipment into and out of the well, by the use of a continuous length, small diameter solid or braided wire mounted on a powered reel at the surface. This cable is an electric conductor and delivers the feed power to the downhole tools from the surface; every wireline tool has, therefore, a section that contains electronic components and circuits that remotely control the tool, transform the feed power or store logging data. The enclosed electronics dictate one of the main limits of the electric wireline technique, which is represented by the exposure of the downhole tools to high temperatures. High Temperature wells, where the temperature ranges from 150 °C to 200 °C, represent one of today's biggest challenges for wireline interventions, since most of the currently employed electronics are rated for lower temperatures. Active cooling systems are a possible solution to the electronics overheating, as they would maintain the critical components at a temperature below the external environment. This type of solution has been investigated in several works in the literature, which faced different integration constraints, cooling loads, operating temperatures and adopted different cooling technologies.

Bennett (1988) performed a theoretical analysis of the suitable cooling technologies for a downhole application, defining respectively an acoustic cycle, a two-stage vapor compression cycle and a reverse Brayton cycle as the best options. Flores (1996) performed a similar analysis and implemented his results into a once-through vapor compression cooler for a downhole exploration tool. Jakaboski (2004) first carried out a review of the prior works and patents and then studied the integration of a phase change material tank into a downhole tool string, in order to maintain the electronics at a lower temperature than the borehole. Sinha and Joshi (2011) investigated, instead, the use of thermoelectric devices for thermal management of downhole electronics, reporting the test results of a lab-prototype. Pennewitz *et al.* (2012) evaluated the feasibility of sorption cooling for downhole electronics in the geothermal sector.

Some common features among the mentioned works are the employment of Dewar flasks for thermal insulation of the cooled electronics from the external environment, the use of convective fluids and heat exchangers, and the necessity of adding to the tool string a section containing the cooling system. This work aims at presenting the design and the implementation of a different heat management concept, which involves both active and passive cooling, aims at preserving the original compactness of the tool and does not require the use of a Dewar flask.

2. APPROACH AND METHOD

The desired active cooling and thermal management systems have to satisfy certain design criteria:

- Absorb the cooling load and keep the temperature of the high temperature-sensitive electronics below 175 °C.
- Provide cooling for an unlimited time period.
- Be able to operate in up to 200 °C borehole temperatures.
- Fit a cylindrical housing with an inner diameter of 60 mm.
- Require less than 1 kW of feed power.
- Preserve the original length of the tool (no additional sections).
- Minimize the thermal resistances between different materials.

Electronic components of an existing downhole tool were considered for the implementation of the cooling system and of the thermal management. The main components of the section are a metallic cylindrical housing, with an inner diameter of 60 mm, a metallic chassis, on top of which the electronic components are mounted and then inserted into the housing. The electronic components can be distinguished between high temperature-sensitive (HTS) and high temperature-non-sensitive (HTNS). The HTS components were mounted on a printed circuit board (PCB) and were estimated to dissipate 1 W at maximum load; HTNS components were mounted directly on the chassis and were expected to dissipate 18 W at maximum load.

The main cooling techniques were screened and their suitability to the application evaluated according to the design criteria listed above. The result of the feasibility study is summarized in Table 1.

Table 1. Feasibility study summary. *fair/poor,**marginal, ***good, ****very good, / not available.

Technology	Efficiency	Packaging	Cost	Feasibility
Vapor compression cycle	****	***	**	**
Thermoelectric (Peltier) cooling	*	****	****	***
Reverse Brayton cycle	*	**	**	**
Magnetic cooling	***	*	*	*
Liquid Nitrogen/Phase Change materials	/	***	**	***

The thermoelectric cooling technique was chosen to be implemented as it is very compact, cheap, and does not have any moving parts. It is less efficient than competing technologies, though, and might generate some heat rejection issues, as discussed in the next sections.

Figure 1 shows the thermal management principle that was implemented in the experimental setup.

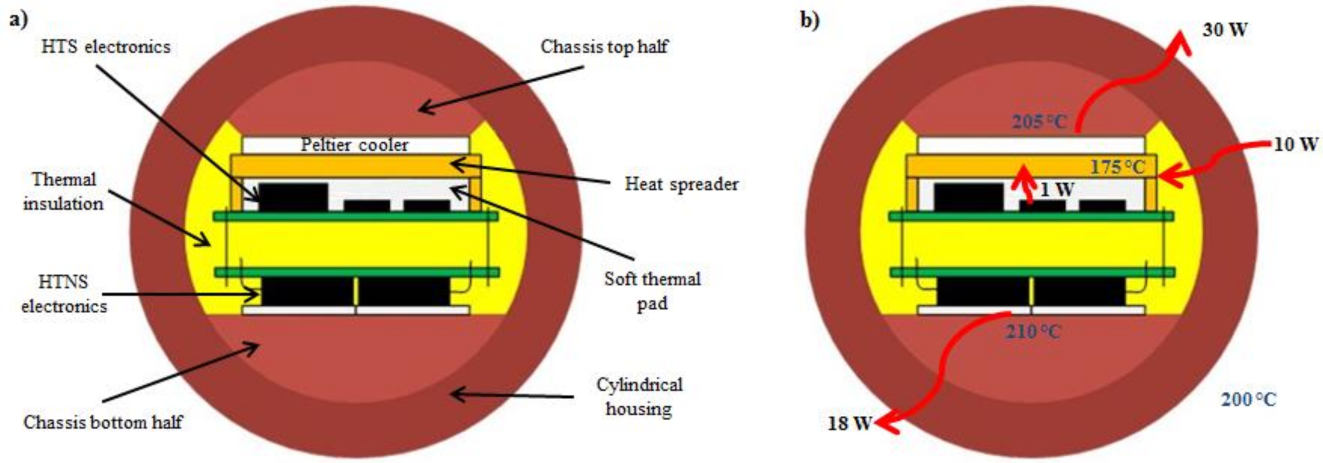

Figure 1. Illustration of the thermal management principle for the actively cooled electronic unit. A representation of the cross section of the tool shows the main components (a) and the design parameters that characterize the system (b).

The HTNS electronics are mounted on the bottom half of the chassis, so the dissipated power can be passively rejected to the surroundings, through the chassis itself and through the tool housing. Some electric wires connect the HTNS components to the high temperature-sensitive ones, which are soldered on a printed circuit board and thermally coupled with the cold plate of the thermoelectric cooler (TEC). The interface between the HTS components and the cold plate is composed of a soft thermally conducting silicone pad and a metallic heat spreader. The hot plate of the cooler is, instead, attached to the top half of the chassis. Both the top and the bottom halves of the chassis are in tight contact with the cylindrical housing, so the thermal resistance is minimized. The housing outer surface is in contact with the external fluid in the borehole and experiences forced convection. The remaining volume of the unit is filled with thermal insulating foam. No Dewar flask is employed, so the generated heat can be rejected directly through the housing and the original length of the tool is maintained.

This design aims at a maximum operating well temperature of 200 °C, a maximum cooler hot plate temperature of 205-210 °C, a maximum HTS electronics temperature of 175 °C and a maximum HTNS electronics temperature of 210 °C. From a first approach estimation, the heat fluxes that characterize the system are 18 W dissipated by the passively cooled components, 1 W dissipated by the HTS components, 10 W of heat conduction through the housing and 30 W rejected by the cooler hot plate (assuming a TEC coefficient of performance equal to 0.5).

3. IMPLEMENTATION OF THE EXPERIMENTAL SETUP

The previously described system was implemented in an experimental setup. The two halves of the chassis were manufactured; both the HTS and the HTNS electronics were simulated by resistive components and respectively installed on the bottom chassis and on the printed circuit board; two high temperature thermoelectric coolers were assembled between the top chassis and the metallic heat spreader. Thermally insulating polyimide foam was used to insulate the cooled electronics from the hot surroundings. The temperatures of the main components were monitored by thermocouples.

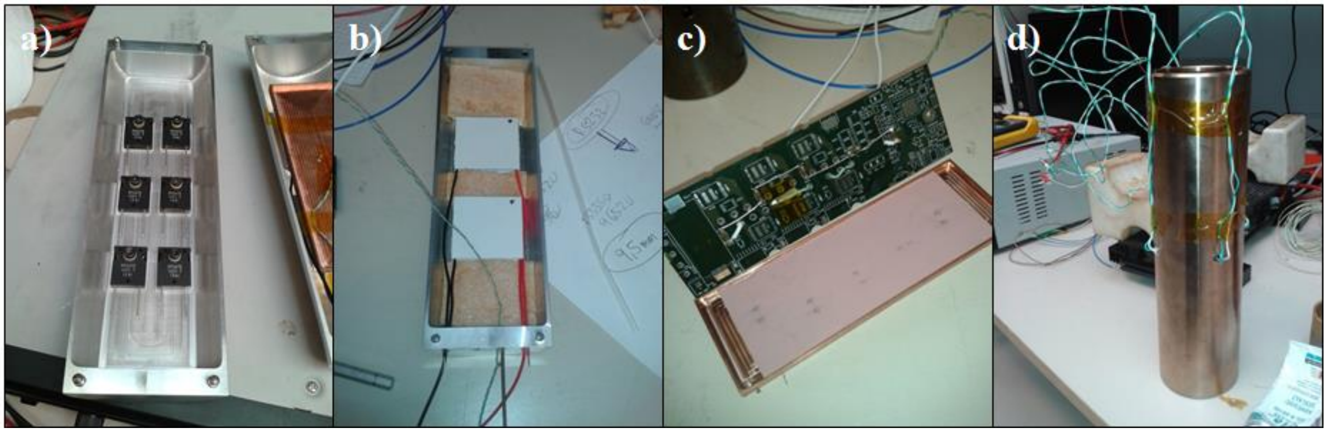

Figure 2. Implementation of the experimental setup. Bottom half of the chassis with the HTNS electronics (a), top half of the chassis with two HT thermoelectric coolers and thermal insulating foam (b), HTS electronics installed on a printed circuit board with heat spreader and soft thermal pad (c), cylindrical housing with welded thermocouple wires (d).

Three different assembly techniques have been investigated for testing the thermal interface between the hot and cold plates of the cooler and, respectively, the top chassis and the heat spreader. The performance of the system was evaluated as proportional to the temperature difference (ΔT_{cooler}) the cooler could maintain, at steady state, between the HTS electronics and the cooler hot plate. The three assembly techniques comprise the use of:

- thermal conductive epoxy;
- adhesive soft thin thermal pads;
- a screw system with thermal grease (clamping method).

The clamping method proved to be the best performing technique as can be seen in Figure 3(a). The coolers were spread with thermal grease on the plates and then "clamped" between the heat spreader and the top chassis, with two plastic screws. On the other side, epoxy guaranteed a good thermal connection, but caused a degradation of the cooler when cycled at high temperature; the adhesive thermal pad absorbed the stresses due to the thermal expansion, but did not perform well from a thermal standpoint. Several candidate coolers from different manufacturers and in different sizes were also tested in the setup, in order to obtain the best performance of the system. The criterion for the choice of the cooler type is the same used for the choice of the assembling technique. *Coolers #1* and *#3* proved to be the best performing in our system, as can be notice in Figure 3(b).

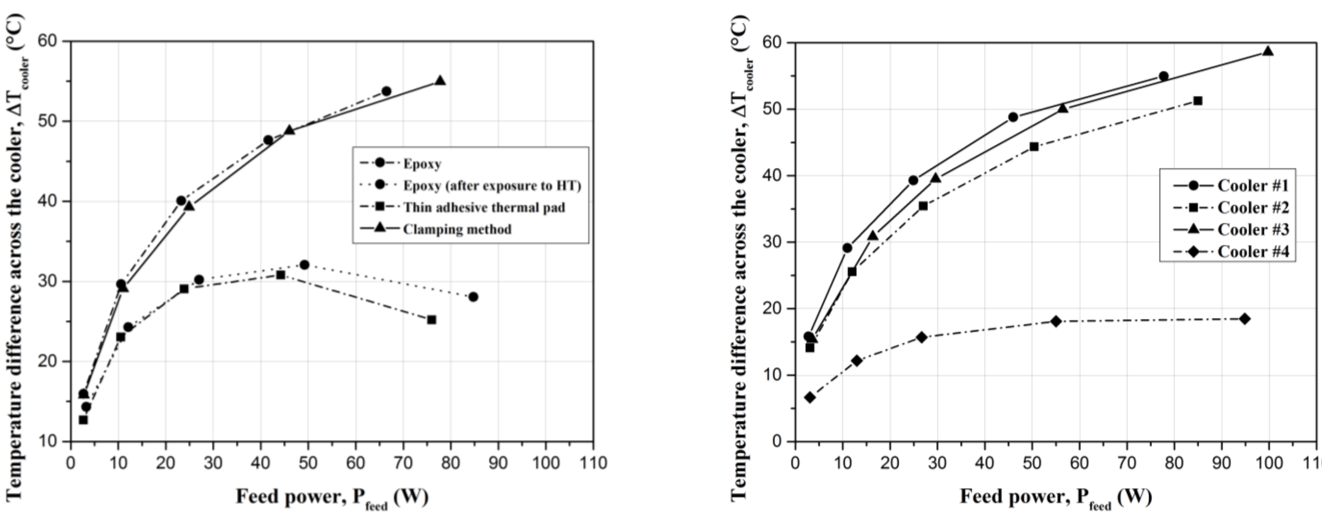

Figure 3. Temperature span across the cooler ΔT_{cooler} vs coolers feed power. Test of the different assembling techniques (left) and of the different cooler types and sizes (right). Tests were carried out at room temperature.

The main components of the system and their dimensions are listed in Table 2.

Table 2. List of the main components with their dimensions.

Component	Dimension
Metallic housing	O.D. = 80 mm I.D. = 60 mm Length = 300 mm
Top chassis	O.D. = ˜ 60 mm Length = 200 mm
Bottom chassis	O.D. = ˜ 60 mm Length = 200 mm
Heat spreader	120 mm x 41 mm x 3 mm
Soft thermal pad	115 mm x 40 mm x 2 mm
Peltier cooler	*#1* : 30 mm x 30 mm x 3.6 mm / *#3* : 40 mm x 40 mm x 3.9 mm

4. TEST RESULTS

Based on the setup test, it was decided to use two *Cooler #1* assembled with thermal grease with a clamp. The coolers were installed between the top chassis and the heat spreader with the clamping method. The two halves of the chassis were coupled and inserted into the housing. Power supplies were used to feed the test electronics and the coolers. A ventilated furnace was used in order to reproduce a dry borehole environment and characterize the performance of the system at different temperatures 25 °C, 100 °C, 150 °C and 170 °C. Three main parameters were considered to evaluate the performance of the system at steady state, and were evaluated at different operating conditions and temperatures:

$$\Delta T_{cooler} = T_{HotPlate} - T_{PCB} \quad \textbf{(1)}$$

$$\Delta T_{HotPlate} = T_{HotPlate} - T_{ext} \quad \textbf{(2)}$$

$$\Delta T_{PCB} = T_{PCB} - T_{ext} \quad \textbf{(3)}$$

Where:
$T_{HotPlate}$ is the temperature of the cooler hot plate [°C], T_{PCB} is the temperature of the HTS electronics on the PCB and T_{ext} is the oven temperature. ΔT_{cooler} (Eq. 1) proves the capability of the system to maintain the electronics to a lower temperature than the hot plate. A low $\Delta T_{HotPlate}$ (Eq. 2) is an indicator of a good heat rejection to the external environment. ΔT_{PCB} (Eq. 3) is usually negative; a low value of ΔT_{PCB} is an indicator of a good insulation and a good overall system performance, as the HTS electronics is cooled far below the oven temperature.

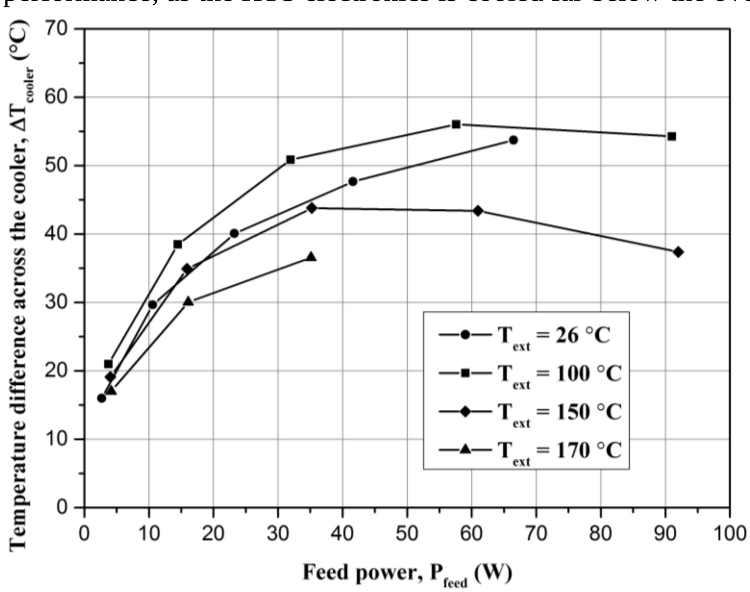

Figure 4. Temperature span across the cooler ΔT_{cooler} vs. cooler feed power, at different oven temperatures.

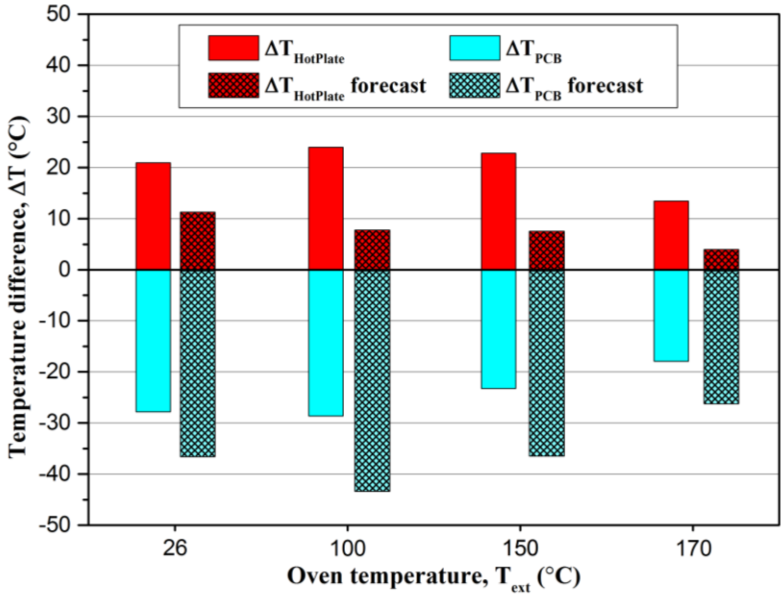

Figure 5. Representation of $\Delta T_{HotPlate}$ (red bar) and ΔT_{PCB} (blue bar), at the operating conditions that minimized the HTS electronics temperature, at different oven temperatures T_{ext}. The tests were carried out in air in a ventilated furnace, where the convective heat transfer coefficient along the housing surface was estimated ˜ 30 W/(m^{2}K). The system behavior was also forecast for an external convective coefficient of 100 W/(m^{2}K) and represented with dashed bars.

The performance of the system strongly depends on the operating temperature, as can be noticed in Figure 4. The largest temperature span between the PCB and the coolers' hot plate is obtained around 100 °C oven temperature. Bismuth Telluride, the semiconductor material generating the thermoelectric cooling effect, has in fact a peak of its thermoelectric properties (i.e. figure of merit) around 100 °C. Above 100 °C the performance of the system decreases again and the HTS electronics temperature increases (see Figure 5). At T_{ext} = 100 °C the HTS electronics is maintained 28 °C below ambient; while at T_{ext} = 170 °C it is only 18 °C colder than ambient. With an increased outside convection coefficient (100 W/(m^{2}K)) the HTS electronics would be cooled 43°C and 26°C below ambient, for T_{ext} respectively equal to 100 °C and 170 °C.

Tests results also revealed that the power dissipated by the HTNS electronics significantly increases the temperature of the chassis and of the coolers' hot plate; if the coolers' hot side temperature rises, the temperature of the cold plate and of the HTS components subsequently increases; that is because the temperature span the coolers are able to maintain between the plates (ΔT_{cooler}) remains approximately constant (at a given feed power). In other words, an increase in the coolers hot side temperature "shifts" the temperature difference between the plates upwards, towards hotter temperatures.

Therefore, reducing the hot plate temperature could be an effective way to improve the cooling of the HTS electronics and to keep the coolers far below their maximum operating temperature. That could be done by reducing the power dissipated by the passively cooled components or by improving the heat rejection to the external environment, which is mainly driven by convection in the wellbore and cannot be controlled in a downhole environment.

4.1 Implementation of the real tool electronics

The original downhole tool electronics were then reviewed and optimized; the main components were replaced with more efficient ones so the dissipated power from the HTNS electronics was reduced to one fourth of the original value, around 5 W. The same heat management principles were applied to the new setup, which aimed at actively cooling the new, optimized, electronics. Only one *Cooler #3* was used in the new setup, which preserved the same main components and dimensions of the previous setup. The tool was then tested in a larger furnace at the temperatures 100 °C, 125 °C, 150 °C and 180 °C.

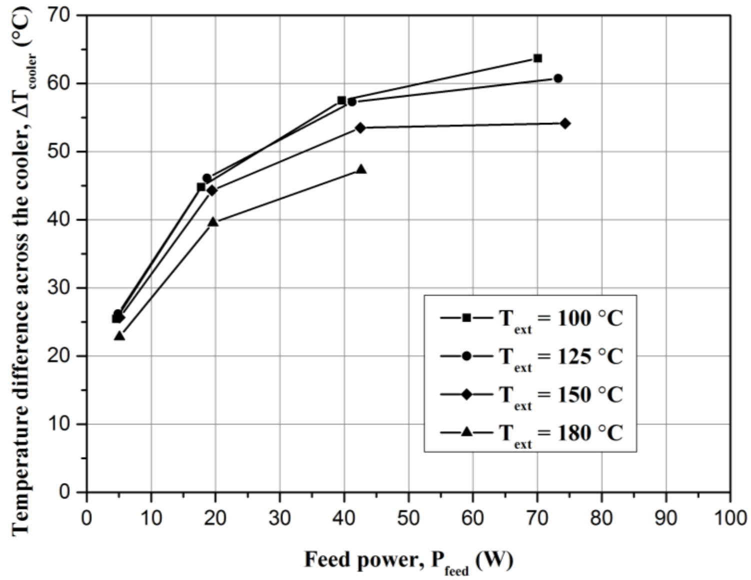

Figure 6. Temperature span across the cooler ΔT_{cooler} vs. cooler feed power at different oven temperatures.

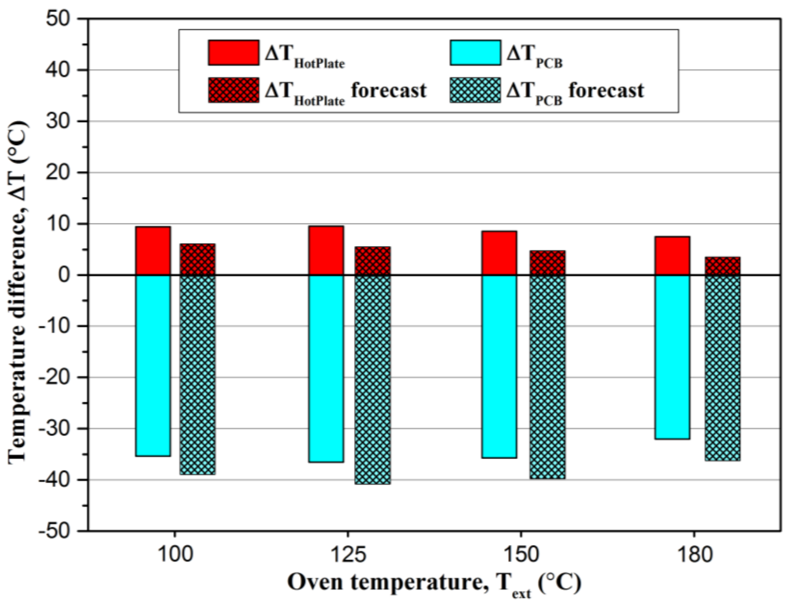

Figure 7. Representation of $\Delta T_{HotPlate}$ (red bar) and ΔT_{PCB} (blue bar), at the operating conditions that minimized the HTS electronics temperature, at different oven temperatures T_{ext}. The tests were carried out in a ventilated furnace, where the convective heat transfer coefficient along the housing surface was estimated ˜ 45 W/(m^{2}K). The system behavior was also forecast for an external convective coefficient of 100 W/(m^{2}K) and represented with dashed bars.

The capability of the cooling system of maintaining a temperature differential between the HTS electronics and the coolers hot plate is enhanced by the use of one *Cooler #3*; Figure 6 shows in fact higher values of ΔT_{cooler}, compared to Figure 4, at a given feed power and oven temperature. Figure 7 shows, instead, how the system performance is improved by the increased efficiency of the HTNS electronics. The cooler hot plate temperature is significantly lower compared to the previous setup; consequently the HTS electronics are maintained at a lower temperature: 35 °C and 32 °C colder than the oven temperatures 100 °C and 180 °C. The dependence of the system performance on the external convection is also reduced since the heat that needs to be rejected is lower. The difference between measured temperatures differences and those forecast with an external convective coefficient of 100 W/(m^{2}K) is much lower than seen in Fig. 5 and is only 3 – 4 °C of cooling in this case.

5. CONCLUSIONS

This work presented the design and implementation of an active cooling system into a downhole tool electronics section. Thermoelectric coolers were chosen among the possible cooling technologies in order to fulfill the main design criteria. The tool length and compactness were preserved, no Dewar flasks were used, no moving parts were introduced and the thermal resistances were minimized.

The thermal management principle was first demonstrated with resistors to simulate the actual electronics. The most suitable assembly technique and types of thermoelectric coolers for the application were investigated and successively applied, and the system was tested at different oven temperatures. The test results proved the heat rejection to the external environment can be a critical design parameter.

The real tool electronics were reviewed and improved in efficiency; the new optimized electronics were then implemented in a new actively cooled setup, with the same features of the previous one. The new test results showed a significant enhancement in performance, thanks to an improvement in the heat rejection mechanism, and are encouraging for operations in a 200 °C environment. A better management of the thermal expansion issues and a further development of the new electronics will improve the performance of the system. More tests, at higher temperatures, will be carried out.

The setup was tested for 60 hours at high temperature (between 150 ºC and 200 ºC) and a stable and constant cooling performance was delivered within the design criteria. After the 60 hours at high temperature, a degradation of the cooler was noticed, so the temperature span between the TEC plates was reduced by ~2 ºC. This result is promising if we consider well interventions on wireline rarely require more than 24 continuous hours downhole; furthermore the cheap price of commercial HT thermoelectric coolers allows a frequent replacement of the degraded parts, when deemed necessary. The degradation of the cooling system can be evaluated by measuring anomalous temperature differentials across the cooler and by measuring the AC electric resistance of the thermoelectric module, which would increase as the performance decreases.

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