Thermal Management of Downhole Measuring Tools Using Thermoelectric Cooling; A Numerical and Experimental Investigation

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ABSTRACT

Vertical seismic profiling (VSP) is a common geophysical technology used in oil and gas investigation in deep wells. VSP provides high resolution and dependable results but is subjected to high temperatures and harsh well environments. As these wells become deeper and hotter, the need for effective thermal management in the instrumentation becomes paramount in keeping the electronics of the measuring tool within allowable working temperatures. A highly effective and a novel technique used to cool the circuitry inside equipment is thermoelectric (Peltier) cooling. A Peltier device in a deep well measuring tool works as a heat pump. As the well is a closed environment, the understanding of the thermal behaviour inside is important in designing the tools. Thermal modelling is used for this study, but accurate modelling of the Peltier device is crucial in predicting the thermal behaviour and subsequent thermal management of the tool. Present paper is based on numerical simulations using computation fluid dynamics and experimental analysis of the thermal behaviour inside an industry standard deep well measuring tool. Present modelling results are based on two mathematical models to predict the thermal behaviour of the Peltier device. An advanced second order approximation that has been based on experimental data used to model the Peltier device is capable of producing accurate thermal predictions. Experimental validation of the model is based on measurements and is presented here. Predictions agree closely with the measurements and the model can be used as a computational tool reducing cost and time in measurements.

INTRODUCTION

More than 76 % of the world's primary energy today is supplied by fossil fuels [1]. Oil and gas are still of primary importance to future societies as we have not yet perfected the technology surrounding alternative fuels. Seismic surveys are a critical element of the search for oil and gas exploration. In a seismic survey, the propagation of elastic waves through the rock gives an indication of the sub surface distribution of different rock types and thus the probability of finding a viable source of hydrocarbons. The seismic source varies depending on the application but may be dynamite, an air gun, or a vibrating plate to produce waves at a range of frequencies. In a surface seismic study usually both the source and the receivers are located at the surface and the reflected waves are analysed. These sensitive ground velocity sensors are called geophones. In a Vertical Seismic Profiling borehole investigation the receivers are located within the borehole and the source is usually located at the surface or, less frequently, downhole. Borehole seismic data can provide calibrated, high resolution data that can be used alone, or in conjunction with surface seismic data in order to make exploration decisions and thus is a valuable technique for well characterisation. Another important and fast growing application for borehole seismic logging tools is the monitoring of hydraulic fracturing (fracking) sites.

NOMENCLATURE

COP	[%]	Coefficient of performance
G	[-]	Ratio of length to area
I	[A]	Current
N	[-]	Number of junctions
Q	[J]	Heat transfer
R	[m^{2}K/W]	Thermal resistance
T	[K]	Temperature
V	[V]	Voltage
x	[m]	Cartesian axis direction
Special characters		
α	[V/K]	Seebeck Coefficient
Δ	[-]	Difference
κ	[S]	Conductance
Subscripts		
C		Cold
H		Hot
max		Maximum
min		Minimum

Instrumentation used in borehole seismic investigations needs to be extremely sensitive in order to capture the micro-seismic waves at the receiver and large volumes of data must be sent back to the surface-in the case of continuous monitoring surveys this must be in near real time. This process requires sensitive and sophisticated electronics to be exposed to extremely hostile environments; depending on the wellbeing surveyed this may be pressures of up to 30,000psi (2000 bar or 206 MPa), temperatures of greater than 200 °C [3] and often in environments with high concentrations of H_2S. In downhole measuring the time taken can be from a single day to a few months depending on application and location.

The Problem: Cooling of the Downhole Tooling

Many devices are not able to survive at the temperatures encountered in a borehole and thus it is necessary to provide a degree of cooling to the electronics within downhole tools. The electronics manufacturers are continually pushing to increase the service temperatures of their products. Various strategies have been deployed to achieve this over the last 30 years including vacuum (Dewar) insulation, eutectic alloys which extend the time available downhole [2] and various active cooling technologies [3]. Unlike in conventional electronics cooling applications, the need for the system to be hermetically sealed and withstand high pressures prevents the use of forced air cooling. In addition to shielding the electronics from the heat of the borehole fluid, a further challenge is in dissipating the heat produced by the electronics themselves. Various active cooling techniques have been evaluated in the past. Many of these use refrigerant recirculation techniques which when employed in a "logging whilst drilling" scenario can be very effective but in a VSP application the noise generated by the system makes this impractical.

The present study stemmed from this cooling requirement but the major motivation was to improve the thermal characteristics of the tooling. The practical approach to this is to study the thermal behaviour inside the tooling and improve the cooling path of the sensitive electronic circuitry inside the tool.

METHODOLOGY

The approach of solving the cooling problem in the tools was tackled using a numerical method of the heat transfer within the tool. It was found that the critical part of the modelling problem lies within the modelling of the thermoelectric module that is used to solid state cool the device. Two physics model to model the thermoelectric cooling has been used and the performance of these models are compared with measurements in the present article. The borehole tooling used in this study was supplied by Avalon Sciences Ltd that is being used in measuring. It comprises a steel pressure barrel which houses the geophones, a mechanism to operate an arm which clamps the tool to the wall of the borehole and a module containing the digital electronics which perform the signal processing function. These electronics are housed within a vacuum insulated vessel and active cooling is provided by a Thermoelectric Cooler (TEC) module. Figure 1 shows such a GSR (Geochain Slim Receiver) tool.

The Mathematical Model

The mathematical model is based on the Seebeck effect; essentially cooling [6, 8]. A model is devised to represent the cooling effect due to the current supplied. The differential temperature across the thermoelectric device is due to the Seebeck effect. The temperature difference across the unit is proportional to the voltage drop across the device according to the Seebeck coefficient α [7].

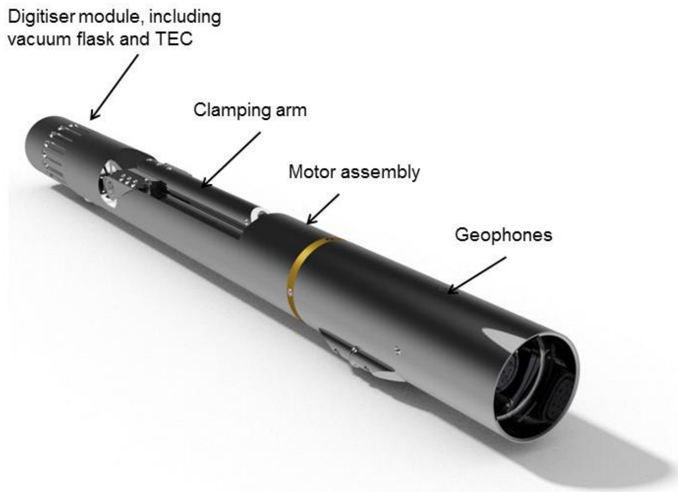


Figure 1 A picture of the GSR tool housing the electronic module and TEC.

The total heat pumped by the device can be found from the number (N) of junctions (pairs of N-type and P-type semi-conductors), the ratio of the length to area of these junctions (G) and the thermal conductance of the unit (κ) for a given temperature distribution of the hot (T_H) and cold (T_C) faces, as a function of the supplied current [4];

$$\dot{Q}_C = 2N\left[\alpha I T_C - \left(\frac{I^2}{2G}\right) - \kappa(T_H - T_C)G\right] \tag{1}$$

However, these equations can be simplified to obtain the linear resistance Seebeck co-efficient and conductance. These equations can be written after Luo and Bons [8] as

$$Q_C = -\kappa T_H + (\alpha I + \kappa)T_C - \frac{I^2 R}{2} \tag{2}$$

$$\dot{Q}_H = \kappa T_C - (\alpha I - \kappa)T_H + \frac{I^2 R}{2} \tag{3}$$

$$V = \alpha(T_H - T_C) + IR \tag{4}$$

The resistance of the unit is available from manufacturer data (validated by manufacturer measurements). This helps derive the Seebeck co-efficient and the conductance [10].

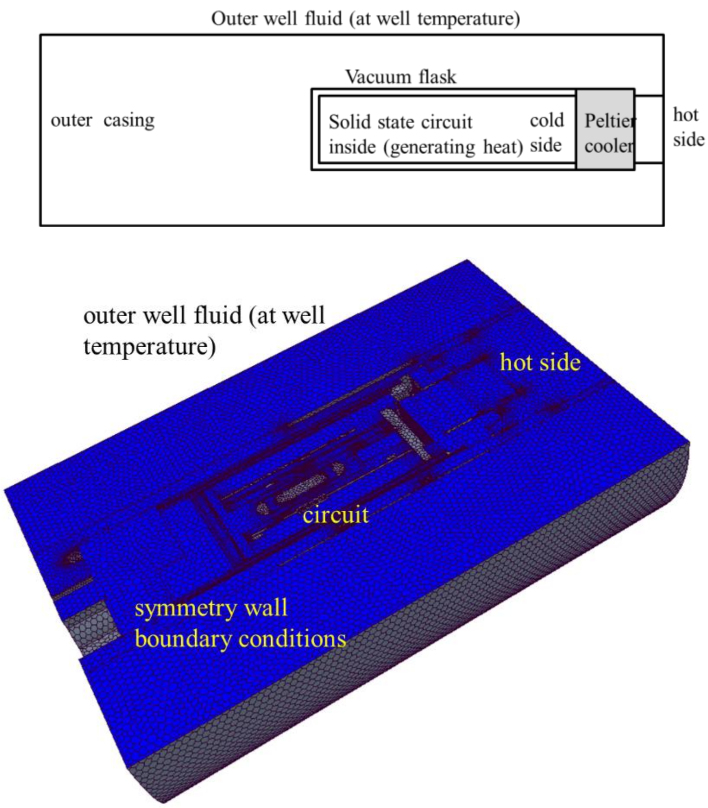
$$\alpha = \sqrt{\frac{2RQ_{\max}}{T_H^2}} \tag{5}$$

$$\kappa = \frac{\alpha^2 (T_H - \Delta T_{\max})^2}{2R\Delta T_{\max}} \tag{6}$$

Coefficient of performance (Z) and figure of merit (zT) are also very useful in determining performance of thermoelectric devices [6, 12].

The Problem in Modelling Space

The mathematical model above can be used in a simulation tool if the temperature and heat flux to be solved for the region. The values defined above can be used to obtain the Seeback coefficient, conductance and resistance as a function of temperature [11, 12]. The values of α, κ (derived using equations 5 and 6 above) and *R* (obtained from the manufacturer data) were used in a commercially available CFD package Star CCM+ to provide heat flux boundary conditions for the thermoelectric cooling model (TEC). Temperature boundary conditions were set for the hot side of the tool. The above system of six equations would be solved to obtain the heat flux and the temperature field. A simplified version of the boundaries defined is given in figure 2.



. **Figure 2** Basic configuration of the tool showing boundaries and computational mesh

In the simulation model in figure 2 above the well temperature is set to 160 °C, 180 °C and 225 °C, respectively for two simulations.

Initial validation of the TECs were done using a linear interpolation and a curve fitting technique. Two test modules were considered in the analysis, one Bismuth Telluride (HT2) and the other custom hybrid bi-Te doped with lead (TESH127). In order to derive the linear equations for resistance and Seebeck co-efficiencts , data from the manufacturers were used. These values were verified with in house testing of the data. The so developed TEC model was valid in the tested temperature range. At elevated temperatures however, the performance could vary as the thermal conductance, electrical resistivity and Seebeck coefficient for the thermoelectric modules vary with temperature, each material having differing characteristics. In order to derive the linear equations that define the performance of the TECs at elevated temperature it is necessary to re-evaluate the manufacturer data values for these temperatures. In the case of the Laird module, it is possible to use the manufacturers analytical design tool, Aztec (Scillasoft, 2014) to find these values at the system temperature. When such data are not available, an alternative approach has to be followed. The resistance of the unit at a range of mean temperatures was measured in a laboratory oven and a digital multi meter to record to voltage drop across the unit at a fixed current. From these data, a linear equation for the resistance could be derived. In the absence of direct experimental data and extrapolation technique based on measurements and curve fitting was used to find values of *zT*. [7, 9] plots values for *zT* at temperature for a range of materials. If the composition of the module was known, values could be estimated from these curves. In the absence of these values, the data from the experimental oven testing was used to approximate *zT* with temperature. A copper heat sink was used to dissipate heat from the hot side, and the cold side was fixed to an insulated mass. Thermocouples were used to measure the hot and cold side temperatures.

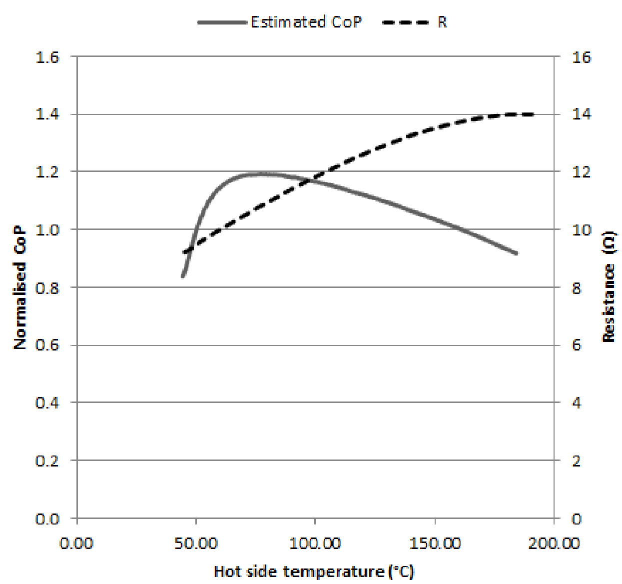


Figure 3 Experimental measurements of the hybrid TEC unit

An estimate of the cooling and the input power were used to find *z* and the result normalised relative to the performance seen at T_H = 50 °C, the data sheet value. This scale was then used to estimate $Q_{\max}$ and $\Delta T_{\max}$ and used to compute revised coefficients for the linear equations used in the model, using the above methodology.

COMPUTATIONAL MODEL

The temperature performance has been predicted using derived linear equations [6]. Table 1 shows the values available from manufacturer data. These values are used in the CFD numerical tool in order to simulate the thermal performance. The thermoelectric cooling performance was initially tested with a

CFD cooling model of the Peltier device alone. Tests were carried out to characterize the TEC performance. The heat flux and cold side temperatures were measured at different hot side temperatures, viz: 160 °C, 180 °C and 225 °C. The modules are fitted into an oven test rig, this comprises a copper heatsink and a vacuum flask. The system was placed in the oven at 160 °C, 180 °C and 225 °C and the time to heat the slug observed Figure 3 shows the temperature results of the TEC module using a linear interpolation technique. It shows that the predicted COP values are coherent with the measured and are able to predict the TEC performance satisfactorily. The tool modelled used for the purposes of the study was supplied by Avalon Sciences Ltd. It comprises a steel pressure barrel which houses the geophones, a mechanism to operate an arm which clamps the tool to the wall of the borehole and a module containing the digital electronics which perform the signal processing function. These electronics are housed within a vacuum insulated vessel. Active cooling is provided by a Thermoelectric Cooler (TEC) module similar to one that has been modelled above.

The numerical model is a three dimensional representation of the downhole tool similar to one that is commercially manufactured. To expedite the simulation, the regions adjacent to the digital electronics module are excluded from the model as there is no active components in this region and thus have no impact on the cooling of the electronics. To fully resolve all of the electronic components housed within the module would incur a high computational cost to accurately resolve the geometry and thus a simplified representation of the printed circuit board is used. This simplification does not hinder the performance analysis of heat transfer.

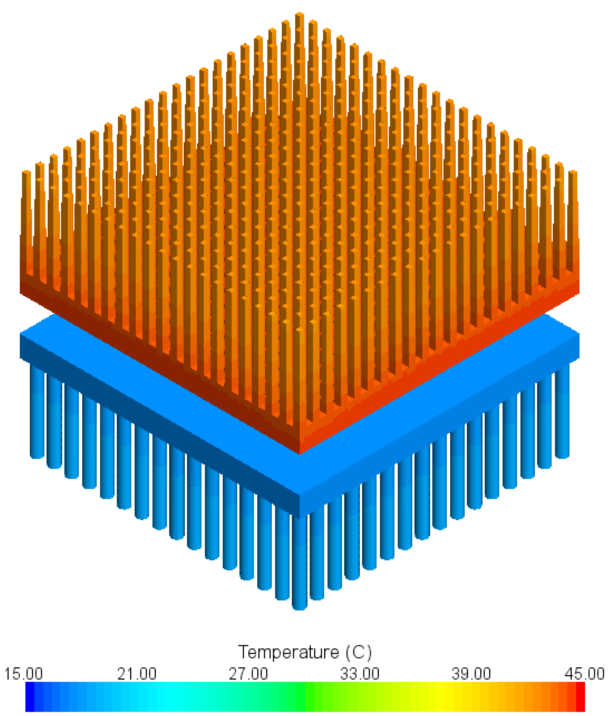


Figure 4 Thermoelectric cooling in the TEC using liner interpolation

The model takes advantage of the symmetry of the tool; only one half of the system is modelled, cut down the central axis of symmetry. (See figure 2) Planar symmetry conditions are applied to the cut faces. The external region of the model, representing the well fluid, has a fixed temperature boundary condition on the far face, representing the large thermal capacity of the borehole fluid. The fluid is modelled in the laminar regime, with convection driven by gravity in the direction that the tool is oriented in the well. The well fluid is modelled as water. The solid regions of the tool were modelled with appropriate material properties, sourced from the manufacturers' data sheet. The vacuum region of the flask is modelled as a gas with a conductivity of $1x10^{-6}Wm^{-1}K^{-1}$.
Surface to surface radiation is modelled, with the air in the spaces using the participating media model. To expedite the simulation, the whole model was initialised at the borehole temperature, and the electronic packaging region allowed to cool under the action of the TEC. Given that the tools spend many hours, if not months, in well conditions, a steady state model was run requiring around 4000 iterations to converge to a solution.

RESULTS AND VALIDATION

The main aim of the tool thermally is to isolate the hot fluid from the electronic circuitry and pump the heat generated out of the flask. Table 2 shows the fluid temperatures and flask temperatures with the cooling effect at a temperature difference.

A pumped hot oil bath was used to emulate the well fluid at elevated temperature and pressure. It is intended to take measurements in a well, but the controlled conditions in the laboratory represent the conditions down the hole. The limit of the fluid in the open system was 160 °C. The tool was submersed in the fluid which was then heated. Once the system has reached steady state the temperature, as reported by a sensor embedded within the on-board electronics, was recorded. With the data from the experimental results at 160 °C external temperature the model was validated. The temperatures seen in the model are equivalent to those seen in the experimental testing. The model was then replicated with the derived parameters for the hybrid module, and the temperature field computed.

Figures 4 and 5 show the temperature profiles obtained with the computational simulation. The temperature profiles show that the cooling effect of the hybrid model is about 5 degrees better than that of the standard TEC based one. This is evident from the bright red colours in the heat sink side.

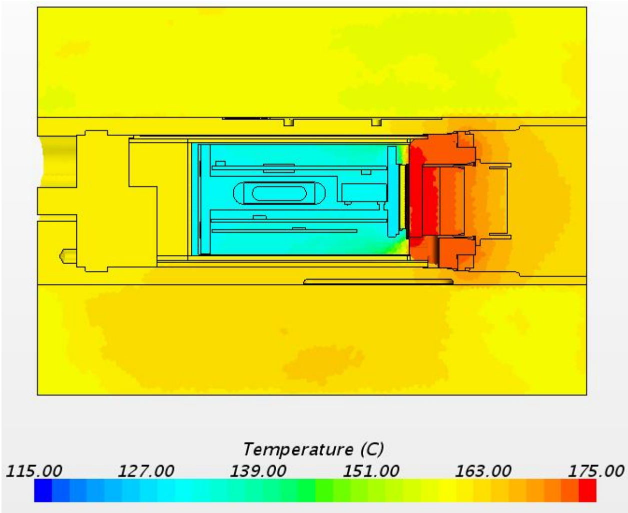


Figure 5 Temperature profile of the tool with the standard TEC module (HT2)

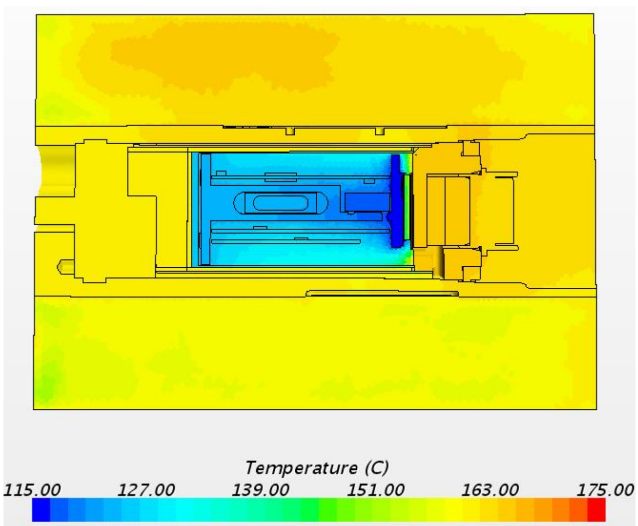


Figure 6 Temperature profile of the tool with the hybrid TEC module (TESH 127)

The results are in line with the results that were obtained with the simulation of the thermoelectric cooling device. The increased cooling effect is evident in the darker blue colour near the TEC of Figure 6 thank Figure 5. The hybrid TEC also results in an even distribution of the higher temperature in the heat sink that is evident from the more even colour distribution in Figure 6.
The area just adjacent to the TEC unit shows a good cooling effect with a temperature abound high 180 °C s in the hybrid model and in the standard model mid 190 °C. This few degrees is significant in the performance as it defines whether it leads to exceeding the threshold or not. The experimental results and the simulations show very good agreement as shown in table 1.

Table 1: Summary of mean temperatures and cooling observed in experimental testing and simulation

	Fluid Temp. (°C)	Flask Temp. (°C)	Cooling (°C)	Voltage (V)
Experiment HT2	161.06	134.82	26.20	12.5
CFD HT2	160.00	133.77	26.20	11.6
Experiment TESH 127	160.37	127.57	32.80	16.5
CFD TESH 127	160.00	126.40	33.60	20.67

CONCLUSION

The main aim of the simulation work was to evaluate the performance of the downhole tool with two types of TEC cooling modules and then use the model as a base model in evaluating performance of similar tools. The numerical model was able to show the difference in performance of the two modules. The temperatures recorded in the electronic region of the module shows good agreement with the experimental values. However, the agreement on the voltage predictions is less impressive. This is, most likely due to the estimation of the α value.

The first order linear approximation method gives realistic values for the TEC properties at elevated temperatures. This is more true for Q and T. It is yet to be confirmed how accurate it is for α. A non-linear approximation method based on experimental values is under development at the moment and it could be more accurate at higher temperatures. Initial investigations have shown that the relationship is better explained with second and third order terms. This should give better predictions at elevated temperatures. However with current capabilities and available knowledgebase, the numerical model has been able to predict the thermal behaviour of the downhole measuring tool accurately. Further, the performance of the hybrid TEC has shown improved performance over the conventional TEC. This has already shown to give huge benefits in design changes in tool geometry and TEC sizing. Accurate model prediction have also resulted in better meeting of customer demands of the tool users. Further measurements, and with a more advanced prediction model, the numerical models are expected to give accurate models that will eliminate the use of testing, enabling the tool manufacturers to validate their designs without prior extensive testing.

Acknowledgements
The authors would like to thank Avalon Sciences Ltd for the continual support for the project given as the industry partner.
The research work was funded by the knowledge transfer partnership grant No KTP009448 of Innovate UK.

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