CFD MODELLING OF THERMAL MANAGEMENT IN DOWNHOLE TOOLS

Thomas P Hughes*, Rohitha Weerasinghe

Faculty of Environment and Technology, University of the West of England,
Coldharbour Lane, Bristol, BS16 1QY, UK
*Corresponding author: tom.hughes@uwe.ac.uk

Abstract

Investigation of oil and gas fields using vertical seismic profiling subjects the equipment used to extreme temperatures and pressures. As wells become deeper and higher temperature, the need for effective thermal management in instrumentation and the demands placed on the downhole tool system increases.

One approach to reduce the temperature of sensitive electronics is to use a thermoelectric cooler to reduce the temperature of the electronics within the tools. This work uses computational fluid dynamics to model the temperature profile in a downhole tool when fitted with a commercially available thermoelectric cooling module and a custom made module. High temperature properties of the module are estimated from simple laboratory experiments and applied to the computational model to map the temperature field of the system. The simulation data is compared to experimental hot oil bath testing data and found to be in close agreement.

1 INTRODUCTION

1.1 Seismic Investigation

Seismic surveys are a critical element in the search for oil and gas providing useful data to those involved in exploration and production. 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.

Seismic surveys may be broadly defined as *"surface seismic"* and *"borehole seismic"* also known as *"Vertical Seismic Profiling"* (VSP). In a surface seismic study usually both the source and the receivers (*"geophones"*; sensitive ground velocity sensors) are located at the surface and the reflected waves are analysed. 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. The borehole seismic data recorded 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. An additional application for borehole seismic logging tools is the monitoring of hydraulic fracturing ("fracking") sites.

Instrumentation used in borehole seismic investigations needs to be extremely sensitive in order to capture the microseismic 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 well being surveyed this maybe include pressures of up to 30 000psi (2068 bar), temperatures of greater than 200°C (Baird et al., 1998) and often in environments with high concentrations of H_2S. In the case of a VSP survey the job may be completed in less than a day, but a fracture monitoring application may see the tools running continuously for several years, requiring effective thermal management to ensure reliability and continuity of data.

1.2 Electronics cooling in Downhole Tools

Whilst electronics manufacturers are continually pushing to increase the service temperatures of their products, 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. Various strategies have been deployed to achieve this especially over the last 30 years including vacuum (Dewar) insulation, eutectic alloys which extend the time available downhole (Bennett and Sherman, 1983) and various active cooling technologies (Bennett, 1986, 1988). 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.

Many of the active cooling techniques considered in the literature 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, or at the least exceedingly challenging to implement. This study looks at the thermal performance of a commercially available borehole seismic logging tool and

correlates the temperatures observed in experimental testing with those predicted by a numerical model.

2 METHODOLOGY

2.1 Numerical modelling of Thermoelectric cooler

Thermoelectric devices utilise the Seebeck effect to produce a differential temperature, and thus function as a heat pump when a voltage is applied across the unit. The temperature difference across the unit is proportional to the voltage drop across the device according to the Seebeck coefficient (α). 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:

$$Q_C = 2N[IT_C - \frac{I^2}{2G} - (T_H - T_C)G]$$ (1)

Unfortunately, often the only data available to the design engineer is that given in the manufacturer's data sheet. This usually takes the form of the properties of the system as a whole, usually specified at one or two hot side temperatures and thus to model the device numerically it is necessary to manipulate the data to derive linear equations for the resistance, Seebeck coefficient and conductance. Luo (2008) presents simplified equations which can be rearranged to give heat transfer across the module, as shown by Bons (2014):

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

$$Q_H = \kappa T_C - (\alpha I - \kappa)T_H + \frac{I^2 R}{2}$$ (3)

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

The resistance of the unit can be taken from the data sheet for the given temperature values. The values for the Seebeck coefficient and conductance can be inferred from the values calculated.

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

$$(T_H - T_C)_{max} = \frac{\alpha^2 T_C^2}{2R\kappa} \therefore$$ (6)

$$\kappa = \frac{\alpha^2(T_H - \Delta T_{max})^2}{2R\Delta T_{max}}$$ (7)

Two further parameters are useful when describing the performance of thermoelectric devices; the coefficient of performance (Z) and a dimensionless figure of merit (zT). The coefficient of performance is a simple measure of the overall efficiency of the unit, the

figure of merit describes the conversion efficiency of the system:

$$z = \frac{Q_C}{Q_H} \tag{8}$$

$$zT = \frac{\alpha^2 R T}{\kappa R} \tag{9}$$

These values can then be used to fit a linear equation for the Seebeck coefficient, conductance and resistance as a function of temperature.

The values for α, κ and R were used in the CFD package Star CCM+ to provide heat flux boundary conditions for the Thermoelectric Cooler (TEC) region of the numerical model as a function of the mean temperature of the device. Two TEC modules were considered in the analysis; a commercially available Bismuth Telluride (BiTe) module and the second a custom hybrid unit. The parameters for each device were extracted from the data sheet in order to define the linear equations that describe their behaviour at room temperature.

As this is a linear approximation (interpolated between the temperatures specified in the data sheet) a further complication arises when modelling the system at elevated temperature. The thermal conductance, electrical resistivity and Seebeck coefficient for the thermoelectric modules vary with temperature, each material having a differing characteristics. LaLonde et al. (2011) shows the variation in zT for a range of n-type and p-type semiconductor materials at elevated mean temperature. In order to derive the linear equations that define the performance of the TECs at elevated temperature it is necessary to re-evaluate the data sheet values for these temperatures. In the case of the BiTe module, it is possible to use the manufacturers analytical design tool, Aztec (Scillasoft, 2014) to find these values at the system temperature. For the second module these data were not available, and an alternative approach was found.

The values for α and κ are derived from R, Q_{max} and ΔT_{max} (see eqs. 5 and 7). 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. Finding experimental values for Q_{max} and ΔT_{max} requires test equipment that was not available, and thus an estimate had to be made of these values at elevated temperature.

LaLonde et al. (2011) 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. An estimate of the cooling (based on the insulation in the system) and the input power were used to find z and the result normalised relative to the performance seen at $T_{hot} = 50°$C, the data sheet value (see figure 1). This scaled was then used to estimate Q_{max} and ΔT_{max} and used to compute revised coefficients for the linear equations used in the model, using the methodology outlined above.
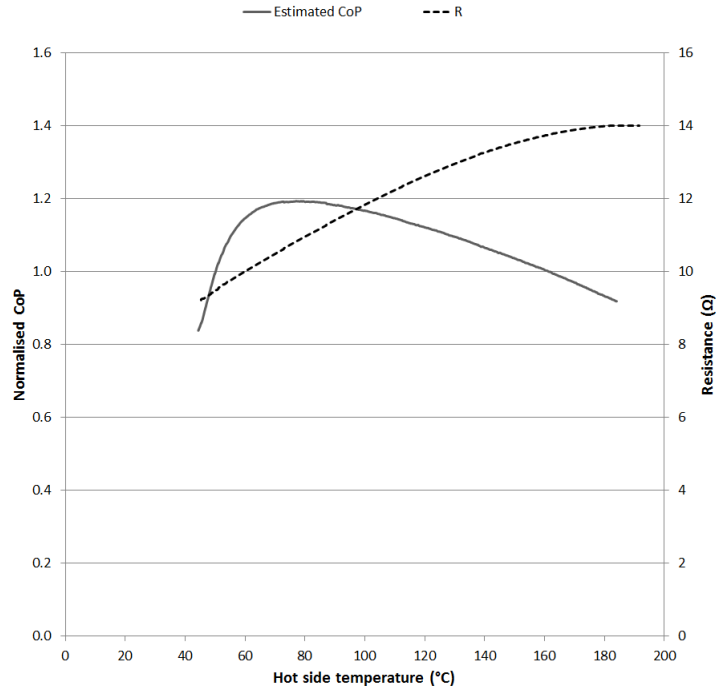
Figure 1: Experimental measurement of the resistance of the hybrid TEC unit at a T_{hot} of between 50°C and 190°C and estimated coefficient of performance, normalised to the performance at $T_{hot} = 50$°C

.

2.2 CFD Model of downhole tool

The tool modelled was loaned for the purposes of the study 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 and active cooling is provided by a Thermoelectric Cooler (TEC) module (Peltier device).

The model is a three dimensional representation of the downhole tool. 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 that 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 PCB is used.

The model takes advantage of the symmetry of the tool; a representation of one half of the system is modelled, cut down the central axis of symmetry. 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 low conductivity ($1 \times 10^{-6} \mathrm{Wm}^{-1}\mathrm{K}^{-1}$). 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.

2.3 Experimental Validation

To validate the numerical results, experimental testing of the system was conducted. As it was not practical to deploy the tool in a well at elevated temperature a pumped hot oil bath was used. 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.

3 RESULTS

The data from the experimental testing was used to validate the model using the input parameters provided by the manufacturer of the BiTe unit, at the 160°C external fluid temperature. 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. Table 1 shows the temperatures recorded for each TEC module in the CFD simulations and experimental testing.

Table 1: Summary of mean temperatures and cooling observed in experimental testing and CFD models at steady state

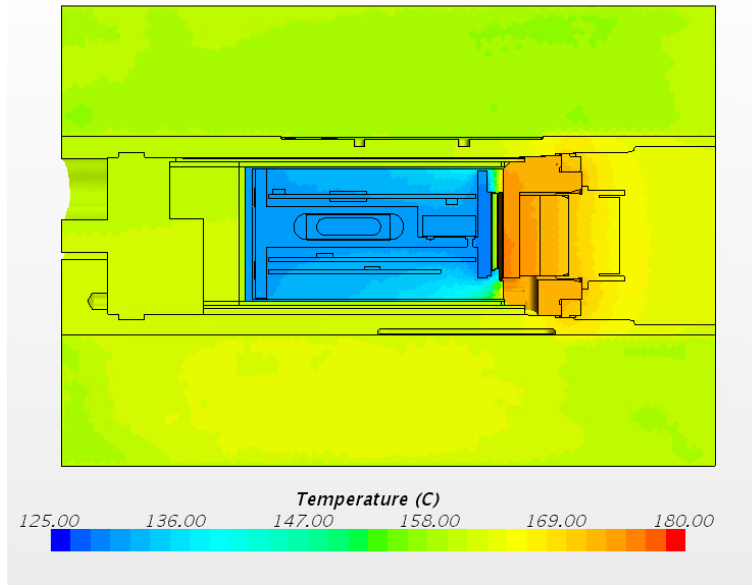|	Expt. BiTe	CFD BiTe	Expt hybrid	CFD hybrid
Fluid temp (°C)	161.06	160.00	160.37	160.00
Flask temp (°C)	134.82	133.77	127.57	126.40
Cooling (°C)	26.2	26.2	32.8	33.6
Voltage (V)	12.5	11.6	16.5	20.67

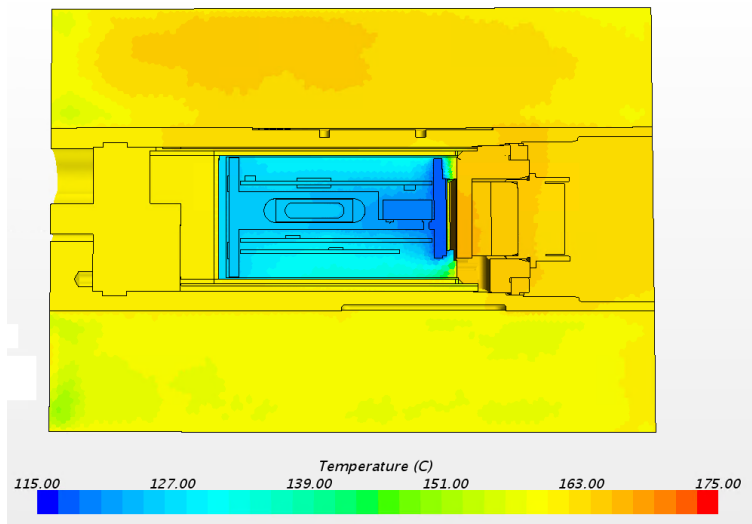Figure 2: Temperature profile of the tool, with commercially available module

Figure 3: Temperature profile of the tool, with the custom hybrid module

Figures 2 and 3 show the temperature profile of the tools in steady state. The numerical model is able to show the difference in performance between the modules; the hybrid module predicts greater cooling than the BiTe module, and the mean temperatures recorded at the electronic region of the model are within one degree Celsius of those seen experimentally. The voltage predictions of the tool show less agreement, particularly in the case of the hybrid module. This is likely to be a result of the estimation of α at elevated temperature.

4   CONCLUSIONS AND FURTHER WORK

The purpose of the study was to investigate the feasibility of using the CFD simulation to virtually prototype differing thermoelectric coolers used in the thermal management of downhole tools, using the information in the data sheet and a simple experimental

techniques to characterise the units at elevated temperature. It has been shown that the first-order linear approximation method provides a steady-state solution that is comparable with experimental data, where resistance of the unit at elevated temperatures can be found from a simple laboratory experiment and the values for Q_{max} and ΔT_{max} can be estimated based on values reported in the literature.

Analytical prediction of the performance of thermoelectric coolers at elevated temperature remains a challenge to the design engineer when the composition of the modules is unknown, and further work will focus on developing a simple method for deriving higher order equations to model the performance of the units across a range of temperatures with minimal empirical data.

Acknowledgements

References

T Baird, T Fields, R Drummond, D Mathison, B Langseth, A Martin, and L Silipgno. High-pressure, high-temperature well logging, perforation and testing. Technical report, Schlumberger, 1998.

G.A. Bennett. Active cooling for downhole instrumentation: design criteria and conceptual design summary. *Office of Scientific and Technical Information, U.S. Dept. of Energy,*, May 1986. doi: 10.2172/5507005.

G.A. Bennett. Active cooling for downhole instrumentation: Preliminary analysis and system selection. *Office of Scientific and Technical Information, U.S. Dept. of Energy,*, Mar 1988. doi: 10.2172/5360643.

G.A. Bennett and G.R. Sherman. Analysis and thermal-design improvements of downhole tools for use in hot-dry wells. *Office of Scientific and Technical Information, U.S. Dept. of Energy,*, Feb 1983. doi: 10.2172/6491119.

R Bons. Efficiently simulating thermoelectric devices and heat pipes. Online., Accessed May 2015, April 2014.

Aaron D. LaLonde, Yanzhong Pei, Heng Wang, and G. Jeffrey Snyder. Lead telluride alloy thermoelectrics. *Materials Today*, 14(11):526 – 532, 2011. ISSN 1369-7021.

Zhaoxia Luo. A simple method to estimate the physical characteristics of a thermoelectric cooler from vendor datasheets. *Electronics Cooling Magazine*, August 2008.

Scillasoft. Aztec. Computer program, 2014. URL `http://www.lairdtech.com/support/learning-center/product-selection-tools/aztec-software-download`. Version 4.0.7.