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Research Paper

# Passive thermal management system for downhole electronics in harsh thermal environments

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## HIGHLIGHTS

- A passive thermal management system is proposed for downhole electronics.
- Electronics temperature can be maintained within 125 °C for six-hour operating time.
- The result shows potential application for the logging tool in oil and gas industry.

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## ABSTRACT

The performance and reliability of downhole electronics will degrade in high temperature environments. Various active cooling techniques have been proposed for thermal management of such systems. However, these techniques require additional power input, cooling liquids and other moving components which complicate the system. This study presents a passive Thermal Management System (TMS) for downhole electronics. The TMS includes a vacuum flask, Phase Change Material (PCM) and heat pipes. The thermal characteristics of the TMS is evaluated experimentally. The results show that the system maintains equipment temperatures below 125 °C for a six-hour operating period in a 200 °C downhole environment, which will effectively protect the downhole electronics.



## 1. Introduction

Due to the increasing demand for hydrocarbon resources, deeper and hotter wells are being explored worldwide. The oil and gas industries use a logging tool to detect the downhole viscosity, pressure and temperature, with required operating times of 4–6 h [1–4]. However, standard electronic components and sensors cannot effectively function for such long periods due to the harsh downhole environments. In general, the temperature and pressure in a downhole environment exceed 200 °C and 135 MPa, such that standard electronics quickly exceed their design temperatures (125 °C) [5,6]. Ongoing operation in such environments can degrade the detection performance as well as cause severe accidents. While the use of electronic components that can effectively operate at high temperatures would solve the temperature problem. However, the current options require expensive Silicon-On-Insulator (SOI) designs and die-attach materials [7–9].

A Thermal Management System (TMS) for the downhole electronics is currently more cost-effective and reliable than developing specialized electronic components. However, the harsh downhole conditions and the complex well logging structures have impeded the implementation of current TMS designs. Fig. 1 shows a well logging schematic. The logging tool burrows into the High-Temperature and High-Pressure (HTHP) muds that are thousands of meters deep. Hence, unlike conventional electronics [10–12], a downhole system needs to be hermetically sealed and protected from high pressures. Furthermore, the electronic components inside the system must be shielded from the corrosive downhole fluids. Various active cooling techniques have been proposed for thermal management, including thermoelectric cooling [5], vapor compression refrigeration [13], sorption cooling [14], convection cooling cycles [15], refrigerant circulation cooling [16] and thermoacoustic refrigeration [17]. These cooling techniques dissipate excess heat from the electronics into the surrounding downhole fluids. However, they generally require extra power, cooling liquids and other moving components, which further complicate the system.

In addition to active solutions, passive cooling technics have also been developed. Parrott et al. [18] proposed a passive cooling system that combined a Dewar flask with a heat sink. However, the overall thermal resistance between the electronics and the heat

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**Nomenclature**

| | |
|---|---|
| $q$ | heat transfer rate [mW] |
| $T$ | temperature [°C] |
| $V_T$ | temperature rise rate [°C/s] |
| $P$ | heating power [W] |
| $m$ | mass [kg] |
| $m_{PCM}$ | mass of the PCM [kg] |
| $c_p$ | specific heat capacity [J/(kg·°C)] |
| $Q_s$ | sensible heat [J] |
| $Q_L$ | latent heat [J] |
| $T_0$ | initial temperature [°C] |
| $T_e$ | final temperature [°C] |
| $\rho$ | density [kg/m$^3$] |
| $L$ | latent heat of the PCM [kJ/kg] |
| $u$ | velocities in the x direction [m/s] |
| $v$ | velocities in the y direction [m/s] |
| $H$ | specific enthalpy [J/kg] |
| $S$ | heat generation rate [W/m$^3$] |

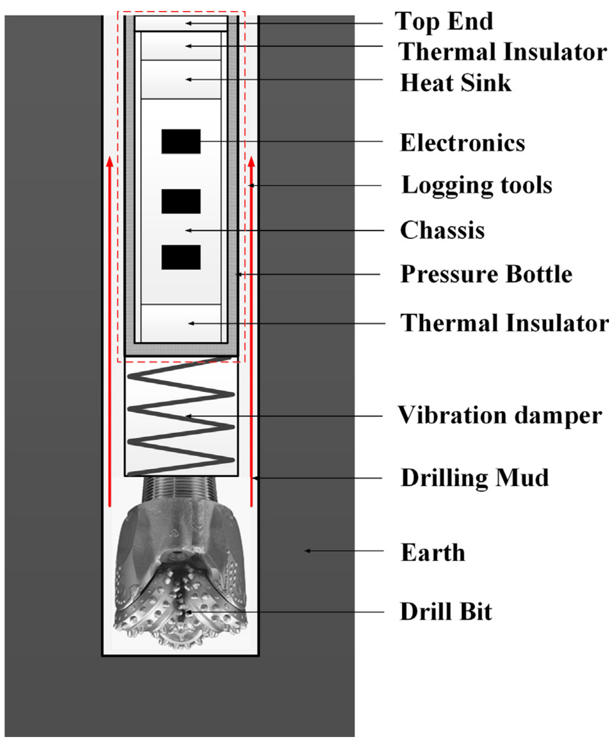


**Fig. 1.** Well logging schematic.

sink was quite large, resulting in a high temperature difference and a reduced reliability period for the electronic components. Jakaboski et al. [19] developed a closed coolant flow loop to provide a thermal path between the electronic components and the heat sink. However, the coolant pump and fluid expansion compensator complicated the system.

This paper describes a passive TMS inspired by existing downhole electronics thermal management systems. A vacuum flask was employed to insulate the electronic components from the harsh external environment. The internal heat generation must also be transferred out of the components and stored elsewhere. Phase Change Materials (PCM) are viable thermal storage materials due to their significant latent heat capacity [20–24]. The TMS developed here used eutectic salts as the PCM. Heat pipes were used to provide an efficient heat transfer path from the electronic components to the PCM to reduce the temperature difference between them and, thereby, extend the viable operating time.

This study describes a passive TMS that uses a vacuum flask, a PCM and a heat pipe. The thermal characteristics of the present system is evaluated by experiments with a finite-element analysis for further validation.

## 2. Experimental setup

An experimental setup was designed to simulate practical operating conditions. Fig. 2(a) shows a schematic of the experimental setup. An oven created a high temperature environment with temperatures from 5 to 300 °C, with an accuracy of ±1 °C. To insure uniform heating, two Teflon blocks were used to prevent direct contact between the logging tools and the oven. K-type thermocouples detected the electronic component temperatures to evaluate the TMS characteristics.

Fig. 2(b) shows a schematic of the original logging tool, which was comprised of a pressure bottle, electronic components, chassis, heat sink and adiabatic plug. Two resistance heaters (40 × 40 × 3 mm) were used as the electronic components. Thermal grease (FL-658) was used as the Thermal Interface Material (TIM) to attach the heaters onto the chassis. The grease thermal conductivity was approximately 3 W/(m·K). Fig. 2(c) shows a schematic of the logging tool with the TMS having a vacuum flask, heat pipes and the PCM.

The vacuum flask was made of titanium alloy, which could maintain a pressure of 1000 MPa. The flask was built of two concentric stainless steel tubes that were permanently cold-welded at both ends. The annular space between the tubes was evacuated at high temperature, providing an excellent barrier to heat transfer via conduction or convection. Both ends of the flask were sealed to reduce heat gain from the environment. The vacuum flask was 900 mm in length with inner and outer diameters of 73 and 90 mm.

The round heat pipe was made of copper with a length of 250 mm and a diameter of 5 mm. Water was used as the working fluid inside the pipe. The TMS had five heat pipes to connect the chassis to the PCM.

The PCM provided thermal storage for the electronic components and any heat gain into the vacuum flask. The low melting point and high latent heat of the PCM kept the electronic temperatures below their maximum temperature for a longer period. Therefore, the PCM selection is critical for the TMS characteristics. Eutectic salts, organic paraffin and eutectic metal alloys are common PCMs with high latent heats and low melting points. The PCM properties were evaluated to improve the system design.

Differential Scanning Calorimeter (DSC) tests were conducted to obtain the thermal properties and phase transition characteristics of the PCM, with a temperature rise rate of 5 °C/min. Fig. 3 shows the typical DSC curves. The PCM have different melting temperatures and different heat transfer rates with the latent heats calculated from the DSC test curves as:

$$L = \frac{\int_{Onset}^{End} q dT}{V_T m} \tag{1}$$

where $q$ is the heat transfer rate, $T$ is the temperature, $V_T$ is the temperature rise rate, and $m$ is the sample mass. *Onset* represents the