Heat Management System for Long-term Continuous Observation of Electronic Instrumentation in Deep Earth

WANG Yanzhang1, 2, 3, 4, *, YANG Hongfei4, ZHANG Jie4 and SHI Jiaqing4

1 National Geophysical Exploration Equipment Engineering Research Center (Jilin University), Changchun 130026, China
2 Key Laboratory of Geophysical Exploration Equipment, Ministry of Education (Jilin University), Changchun 130026, China
3 Key Laboratory of Earth Detection Technology and Equipment, Ministry of Land and Resources (Jilin University), Changchun 130026, China
4 College of Instrumentation & Electrical Engineering, Jilin University, Changchun, 130061, China


Deep penetration into the Earth’s interior and direct monitoring of weak changes in physical fields and their cumulative processes and effects in the deep Earth can enhance the identification of deep Earth targets and deepen the degree of knowledge of the details of the deep Earth structure and deep processes (Moskvitch, 2014), which is important for promoting the development of Earth system science. To solve the above problems, long-term continuous monitoring of the deep Earth is needed—scientific logging (Fig. 1a). Continuous monitoring nodes are set up at different depths in the subsurface to obtain information on micro-change in the deep Earth and its long-term cumulative effects, and to support research on major scientific problems such as seismic and volcanic activities, environmental changes, and lithospheric tectonics caused by the cumulative effects of micro-change in the deep Earth; however, standard electronic components cannot work effectively in high-temperature and high-pressure extreme environments for a long time due to the confined space and harsh downhole environment. The current methods of probing the deep part of the Earth using deep wells are divided into follow-on logging and cable logging (Fig. 1b, c), the logging electronics of the above methods only need to stay downhole for a few hours (Soprani et al., 2016), and the electronic instrumentation inside the logging tools only withstand wellbore temperatures of more than 100°C for a few hours, yet most standard electronic components cannot withstand such a harsh environment. Several thermal management methods exist and have been successfully applied in logging instruments. Such as thermoelectric cooling (Kähler, 2014; Soprani, 2015; Weerasinghe and Hughes, 2016), adsorption cooling (Pennewitz, 2012), vapor compression cycling (Verma and Elias, 2012; Gao et al., 2019) and liquid cooling (Jakaboski, 2004; Wu et al., 2019). However, the above methods are only suitable for short-term follow-on drilling and cable logging. Standard electronic components also cannot withstand such a harsh environment, and the high temperature will lead to the degradation of the reliability of the electronic devices or even complete failure, and the electronic components cannot meet the requirements of long-term continuous observation in this environment. Therefore, we designed a heat management system for electronic instruments and equipment for long-term continuous observation in deep earth to address the above problems.

Working schematic of the thermal energy management system (Fig. 2). Firstly, the heat manager consists of a housing with black profile lines, a true hollow cavity in green, a cooling flow channel in gradient color, upper and lower end caps embedded in the outer housing, upper and lower end caps with coolant inlet and outlet respectively, and a high temperature resistant seal in the red part of the end cap. The vacuum cavity is used to protect the entire electronic apparatus and equipment, and thermal insulation plugs are placed at the two edges of the system to minimize the heat transfer from the surrounding high temperature to the electronic module. The coolant in the cooling water channel carries away the heat leakage from the outside environment and most of the heat dissipated by the internal electronics. Finally, the heat manager is installed downhole and the power system transfers the coolant to the manager inlet and transports the fluid, already carrying heat, through the lower outlet to the heat exchange station for heat transfer cooling and recycling.

A device was designed to verify the effectiveness of the heat management system based on the downhole environment (Fig. 3). Firstly, the thermal insulation performance of the vacuum cavity was explored, when the external environment was 150°C and different power
electronic devices were installed inside the manager for comparison, and the results showed that the time at temperatures below 100°C were all longer than without the vacuum layer, 2.2 h, 0.85 h and 0.6 h, respectively (Fig. 4). Secondly, the temperature control performance of the heat manager system was verified. Under the experiment conducted for 30 days, the results showed that as the temperature gradient increased, the temperature of the instrument installation area also increased, but under five temperature gradients (corresponding to five different depths) we designed the heat manager system to control the instrument installation area below 50°C for a long time, so the heat management system we designed meets the temperature requirements for long-term monitoring of electronic instruments under different depths of wells (Fig. 5; experimental conditions are shown in Table 1). Finally, in order to solve the problem that some electronic instruments (such as seismographs) cannot work effectively in a vibrating environment, we designed an experiment to cool down the instrument installation area in a high temperature condition, and the results showed that the time required to control the temperature of the instrument installation area to below 25°C is 20 min when the temperature gradient is 70°C and 90°C, and 40 min when the temperature gradient is 150°C. The cooling time (40 min) meets the demand for long-term monitoring of some of the above instruments (Fig. 6; experimental conditions are shown in Table 2).

Therefore, the proposed thermal management method meets the demand for long-term continuous observation of electronic instruments and equipment in deep earth.
Table 1 Initial conditions of temperature control experiments of the manager system at different temperature gradients

<table>
<thead>
<tr>
<th>Temperature gradient (℃)</th>
<th>Initial coolant temperature (℃)</th>
<th>Electronic heat source (W)</th>
<th>Experiment duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70, 90, 110, 130, 150</td>
<td>18</td>
<td>10</td>
<td>≥120</td>
</tr>
</tbody>
</table>

Table 2 Initial conditions of the management system cooling experiment

<table>
<thead>
<tr>
<th>Temperature gradient (℃)</th>
<th>Initial coolant temperature (℃)</th>
<th>Electronic heat source (W)</th>
<th>Initial temperature of the instrument installation area (℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70, 90, 110, 130, 150</td>
<td>18</td>
<td>10</td>
<td>60, 75, 90, 110, 115</td>
</tr>
</tbody>
</table>

Fig. 5. Heat management system five kinds of temperature gradient control experiment.

Fig. 6. Heat management system cooling experiment.

Key words: deep earth exploration, scientific logging, high-temperature harsh environments, heat management, recirculation cooling

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References

About the first and corresponding author
WANG Yanzhang received his B.S. degree from Jilin University in 2002, M.S. degree from Jilin University in 2005, and Ph.D. degree from Jilin University in 2010. His main research interests are laser and quantum effect based spinless relaxation atomic magnetometer, special environment atomic magnetometer, nonlinear random resonance fluxgate magnetometer, satellite-based and ground-based vector induction magnetometer, deep well electric and magnetic detection instrument development, intelligent geomagnetic signal processing, etc.