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A compact thermal heat switch for cryogenic space applications operating near 100 K

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ABSTRACT

A thermal heat switch has been developed intended for cryogenic space applications operating around 100 K. The switch was designed to separate two pulse tube cold heads that cool a common focal plane array. Two cold heads are used for redundancy reasons, while the switch is used to reduce the thermal heat loss of the stand-by cold head, thus limiting the required input power, weight and dimensions of the cooler assembly. After initial evaluation of possible switching technologies, a construction based on the difference in the linear thermal expansion coefficients (CTE) of different materials was chosen. A simple design is proposed based on thermoplastics which have one of the highest CTE known permitting a relative large gap width in the open state. Furthermore, the switch requires no power neither during normal operation nor for switching. This enhances reliability and allows for a simple mechanical design. After a single switch was successfully built, a second double-switch configuration was designed and tested. The long term performance of the chosen thermoplastic (ultra-high molecular weight polyethylene) under cryogenic load is also analysed.

1. Introduction

In space technology, redundancy concepts are often used to minimise the impact of a single failure. For applications requiring cryocoolers this can be done in several ways [1]. Nowadays cryocoolers for space applications in the 77 K range are of the pulse-tube type combined with a flexure bearing compressor. Possible sources of failure in such a configuration are the control electronics and the compressor (e.g. coils, spring breakage, seals), and the pulse-tube cold head (e.g. gas leakage). Additionally, the cold head can suffer from a long term gas contamination by outgassing components in the compressor or cold head itself.

As part of a research project studying various redundancy concepts for satellite operations, a heat switch was developed including two cold heads (CH1 and CH2) mounted on a single focal plane array detector (FPA, see Fig. 1). The heat switch thermally connects an active cold head to the FPA while increasing the thermal contact resistance ϑ to a second cold head in stand-by mode, thus reducing the heat load of the stand-by system to the active cold head. In case of a failure of the active cold head, the stand-by cryocooler is turned on and the heat switch thermally disconnects the malfunctioning system while thermally connecting the now active redundant cryocooler. The switching is done automatically without need for external control or power.

There exist various kinds of heat switches for space applications, each having their own advantages and disadvantages. Most common are heat switches of the Gas-Gap and CTE-based (CTE: linear thermal coefficient of expansion) type [2–4], but also some designs based on other physical effects are known [5,6]. In Gas-Gap switches the pressure of a gas in a small gap is controlled. This can be done e.g. by use of adsorbers or valves connected to gas reservoirs. The presence/absence of the gas in the small gap (typically $\ll 100\ \mu m$) enables/disables a thermal contact. The use of adsorbers is preferred for space applications as it enables passive switching. The design is somehow complicated because it involves the choice of a proper combination of gas sort, filling pressure, and adsorption material for a given temperature range. Especially for relatively high temperatures this can be challenging [7]. On the other side, this switch type does not contain any moving parts which may fail during the lifetime, e.g. because of wear or mechanical breakage.

The CTE-based switches rely on the thermal expansion of one or more components. In the most common mode of operation, a small gap separates two solids one of which has a high CTE compared to the other one. When the temperature decreases the high CTE material "shrinks" and closes the gap between the two solids. Below a certain "switching temperature", the gap is fully closed, thus providing a heat conduction path. Further decrease in temperature

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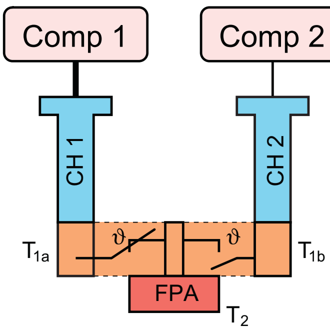

Fig. 1. Schematic of the cold head assembly including heat switch and FPA.

increases the contact pressure and therefore lowers the thermal contact resistance. While the CTE-based switch is less complex compared to the gas-gap variant, it shares with it the disadvantage of requiring a relatively small gap in the order of several micrometers. However, by using thermoplastics with a high CTE, such as ultra-high molecular weight polyethylene (UHMW-PE), in order to circumvent the requirement of tiny gaps, the CTE-based switch becomes superior compared to other designs with respect to the required temperature range and standards for space applications. The aim of this work was to provide a proof of concept; so properties like minimum weight, high stability, and device integration, which are required for space applications, had a minor priority.

2. Thermal heat switch concept

Based on the design considerations outlined in the previous section, a CTE-based switch was chosen. Because the switch also needs to serve as a support for the FPA, the contact areas that are connected to the cold head and FPA must not move upon switching. As another requirement, the switch should exhibit an on-state thermal conductivity of more than 1 W/K at an operating temperature between 80 and 100 K and an off-state conductivity of less than 1 mW/K.

In many switches, the high-CTE component itself also acts as a thermal conductor. Unfortunately, high thermal conductivity materials, such as metals, exhibit a rather small CTE leading to a small gap sizes which require careful manufacturing and increase the risk of failure. Thermoplastics on the other hand, have a relatively high CTE compared to metals but a low thermal conductivity. This leads to a design where a thermoplastic is used as the switching element only, bringing two metals with high thermal conductivity into contact. Fig. 2 shows the CTE between 80 K and 300 K of some metals and thermoplastics; the data for metals were taken from the NIST database [8]. While most metals exhibit a CTE of 10–20 $\times$ 10^{-6}/K, polytetrafluoroethylene (PTFE) for example has an order of magnitude higher CTE compared to copper at room temperature, but as for all polymers this strongly depends on the composition. PTFE shows two solid–solid phase transitions near room temperature with a maximum CTE of more than 500 $\times$ 10^{-6}/K [9]. Our measurements using liquid nitrogen revealed that ultra-high-molecular-weight polyethylene (UHMW-PE) has an even higher thermal contraction than PTFE between room temperature and 77 K, though we could not find any CTE data for UHMW-PE at cryogenic temperatures. So we initially based our calculations on the HDPE (high-density polyethylene) CTE data from [10].

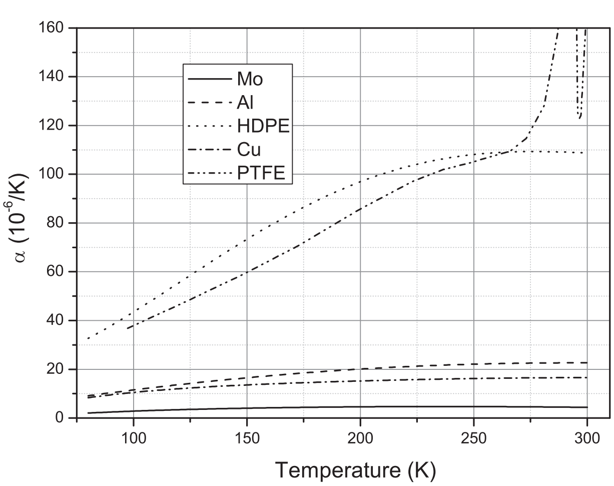

Fig. 2. Coefficient of thermal expansion (CTE) versus temperature for Copper, Aluminium, Molybdaenum and PTFE. Data for metals were taken from the NIST database [8], except for HDPE which was taken from Hartwig [10] and PTFE which was taken from [9].

When designing a CTE-based switch, one important parameter is the gap width, which depends on the CTE material and the desired switching temperature. One has to take into account, that the standy-by cold head will cool down because of the finite off-state conductance. In our case, an off-state conductance of 1 mW/K would cool the stand-by cold head down to about 220 K. This means, that the switch needs to change state below this temperature. Otherwise the switch would also close on the stand-by side producing a thermal short. On the other hand, a high on-state switching temperature is desired to achieve a high contact pressure and thus a low thermal resistance. For HDPE, a CTE of

$$\alpha(T) = 28.9 - 0.6338 * T + 0.01178 * T^2 - 4.51254 * 10^{-5} * T^3 + 5.28582 * 10^{-8} * T^4$$

as extracted from the graph in Appendix 4A of [10] was used for calculations. The contraction in radial direction of the cylindrical switch (see Fig. 3(b)) is calculated by

$$\Delta r = R_0 \int_{Tw}^{Tc} \alpha(T)\, dT,$$

where T_c is the switching temperature and T_w is the warm temperature at which the gap size is measured. R_0 is the inner radius of the UHMW-PE cylinder at room temperature. The copper shaft and jaws also shrink, but their shrinking was ignored in the initial gap calculations, since it is about an order of magnitude less than that of the UHMW-PE. Based on the considerations above, a gap width of 80 μm at room temperature T_w was chosen. The remaining 50 μm which the UHMW-PE would additionally shrink from T_c = 200 K to the detector operating temperature of 100 K, if there will be no shaft, are turned into increased contact pressure. During the initial testing, the gap was adjusted several times to account for the higher CTE of UHMW-PE and the thermal expansion of the copper shaft and jaws.

Two switches were built: a single switch connected to a single cold head and heat load, which was used for initial testing. Later on, a second switch was built which has a T-form to connect two cold heads to a single load located in the middle of the switch. Fig. 3(a) shows the sectional drawing and Fig. 3(b) shows a 3D-model of the single, cylindrical switch design. The part connected to the heat load (detector side) consists of an inner shaft made of a solid copper cylinder (10 mm diameter) with a flange on one end. The part connected to the cold head (PE-side) consists of a copper flange with four integrated copper jaws that are separated from the inner cylinder by the gap. A non-enforced hollow UHMW-PE (virgin Tivar®1000 from Quadrant PHS GmbH, Vreden, Germany) cylinder is put around the jaws to act as the high-CTE element. The two copper parts are hold together by four thin