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ANALYTICAL AND NUMERICAL ANALYSIS OF THERMAL STRUCTURE

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Abstract: *Heat conductive structures were designed for the Miniaturized Heat Switch to improve its parameters which are not satisfying in the prior solution. The thermal conductivity is lower than 1.5 W·K^{-1} and weight is higher than 55.1 g. To design a new efficient heat conductive structure, it was necessary to make their analytical models to compute thermal conductivity and weight. The parameters computed analytically were verified by numerical analysis which confirmed the accuracy of the calculation. The thermal conductivity of new structures is significantly higher with the most promising concept of 2T-shape structure.*

Keywords: Flexible structure, Thermal conductivity, Space, Heat switch, Analytical thermal models.

1. Introduction

Thermal management is an integral part of each spacecraft. It is necessary to ensure the thermal regulation for internal electronics from flight computers to scientific equipment to allow them to work in suitable conditions. Thermal switches, radiators, heat conductive paths and other thermal devices described by Gilmore (2002) are generally used for the thermal regulation.

The heat conductive structure introduced in this article is designed for the use on Miniaturized Heat Switch which is a mechanical and passive thermal regulator intended for temperature control. When the temperature rises, the switch is heated and the vertical stroke of 1.7 mm is employed (see Fig. 2a)). The heat conductive structure called Copper Textile Braid (CTB) (see Fig. 1) has several issues resulting in low thermal conductivity which is 0.36 W·K^{-1}. The value is four times lower than the requirement presented in Tab. 1 (Mašek, 2021). In particular, the solder is not impregnated into the wire-braided structure and creates a connection only by a mechanical joint. Additionally, the length of each individual wire is two times higher than the component height, the heat is likely to be transmitted along the wires than across the points where the wires are in contact as mentioned in (Černoch, 2020).

Tab. 1: Current design parameters

Parameter	Current value	Requirement
Thermal conductivity	0.365 W·K^{-1}	>1.5 W·K^{-1}
CTB weight (*3-parts assembly*)	55.1 g	<55.1 g
Height	24.1 mm	24.1 mm
Stroke	1.7 mm (9 %)	1.7 mm
Specific conductivity	0.66 100·W·K^{-1}·g^{-1}	>2.72 100·W·K^{-1}·g^{-1}

Fig. 1: Current CTB structure

The article aims to present the feasible solutions of the CTB structure using different concepts.

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2. Methods

The design space presented in Fig.2a) was derived from the prior design, with three pillar holes located on the diameter, (Černoch, 2020). There are three shapes of mechanical structure design: a T-shape or a 2T-shape structure (two stairs of T shapes, Fig. 2b), a helix structure and a cylindrical structure. All can be made of aluminium, copper or a combination of both to reduce the risk of cold welding.

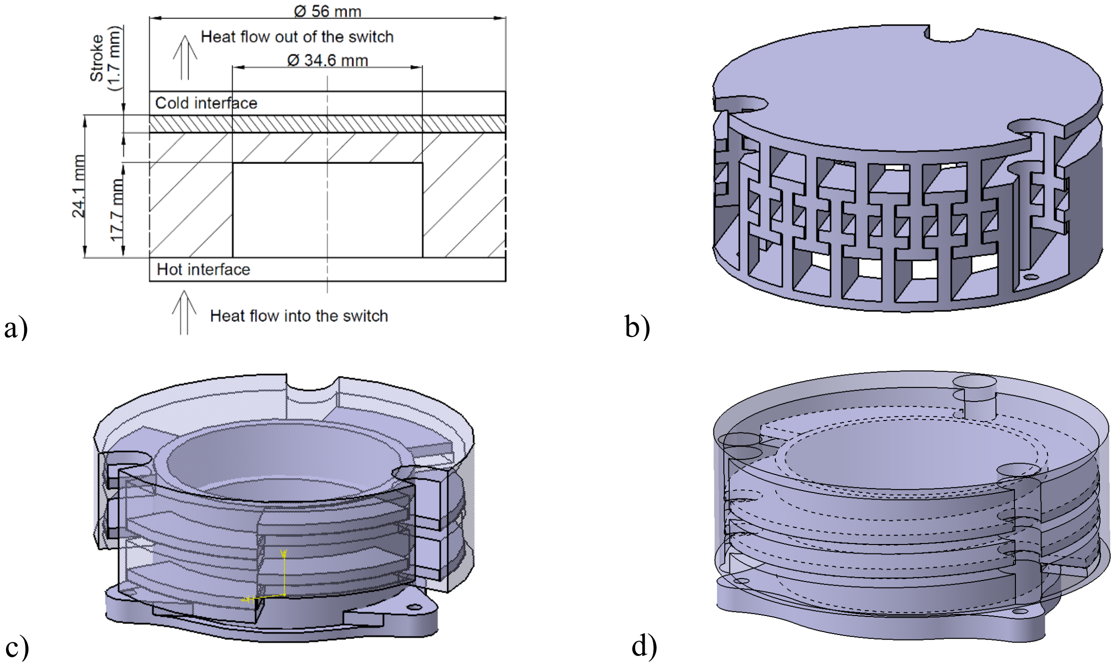

Fig. 2: a) Design space, b) 2T-shape structure c) Cylindrical structure d) Helix structure

The analytical computation of thermal conductivity is based on Fourier's law that explains the dependence of heat flux density on thermal conductance of the material λ $[W \cdot m^{-1} \cdot K^{-1}]$ and thermal gradient ∇T.

$$\vec{q} = -\lambda \cdot \nabla T \tag{1}$$

For the computation of thermal conductivity (≈ thermal resistivity), we used a basic equation with constant thermal conductance λ $[W \cdot m^{-1} \cdot K^{-1}]$ applicable for temperatures from 15°C to 25°C.

$$R = \frac{\delta}{\lambda \cdot S} \tag{2}$$

The thermal resistivity R $[K \cdot W^{-1}]$ was computed using equation (2), where δ $[m]$ is length of the heat conductive path and the S $[m^2]$ is cross-section surface of the heat conductive path.

It was possible to create a heat conductive scheme similar to Ohm's law, a combination of series-parallel resistances (Guo, 2017). Each straight geometrical section and thermal contact surface is represented by one resistor block connected by lines. Together they create the heat conductive path, as described in Fig.3. The mechanical contact between two surfaces was computed by Yovanovich's model mentioned in (Yovanovich 2005) and was modified according to study by Mateášik (2019).

The resistivity of vertical sections (R_4 R_7) in Fig.3 was divided into two routes proportionally to the thermal resistivity of each contact core. The contact core is defined by the number of resistors which presents the resistivity of contact surfaces and horizontal sections of lower and upper part, in each heat conductive path. This division was easier to apply and more flexible for dimension changes than the Y-Δ transformation due to the complicated design. Each thermal path in this structure is connected to the others (see Fig.3). The values required for thermal conductivity computations were obtained by a measurement of 3D CAD models.

The thermal analytical models of T-shape and cylindrical structures were computed from the presented scheme using basic equations for resistors in series and parallel connection. The helix structures were not computed analytically. An accurate resistivity diagram was not possible to create due to a non-discrete distribution of contact surface. It results in variable thermal conductivity on the circumference.

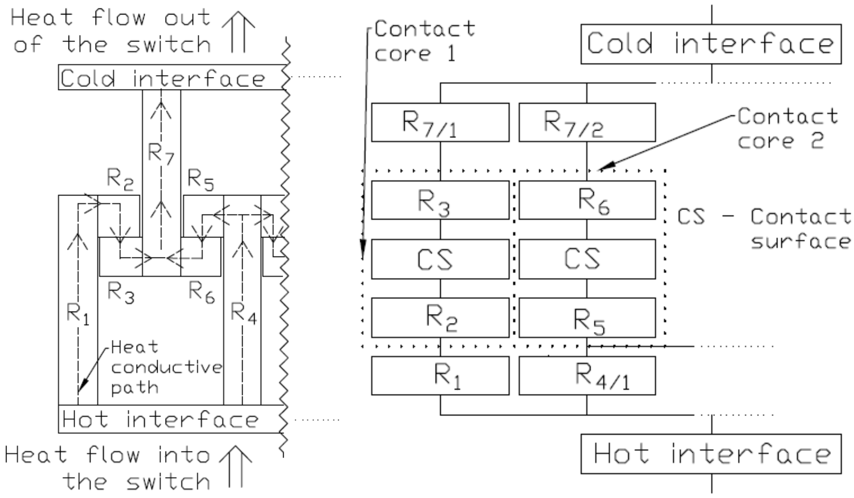

Fig. 3: Thermal resistivity diagram

Oxygen free high conductive copper and aluminium alloy are defined in Tab.2. These materials were used for the computation. The values are based on the diploma thesis by Černoch (2020). During computation, convection and radiation thermal losses were not included.

Tab. 2: Material and contact conditions

Material type	Thermal conductance λ [W·m^{-1}·K^{-1}]	Density ρ [kg·m^{-3}]	Microhardness Hc [MPa]	Contact pressure p [MPa]
Cu OFHC	394	8900	882	0.4
Alu 7075-T73	155	2810	705	

Numerical analysis was carried out by the CalculiX solver with second order tetrahedral elements (C3D10) of 1.5 mm size. For the numerical analysis, the contact thermal conductivity between surfaces was Cu/Cu = 6734 W·m^{-2}K^{-1}, Al/Al = 3328 W·m^{-2}·K^{-1} and Al/Cu = 4756 W·m^{-2}·K^{-1} at 0.4 MPa of contact pressure.

3. Results

The mechanical contact structure design was implemented by analytical computation and compared with Finite Element Analysis (FEA) for verification. The target was to compare weight and thermal conductivity of several structures according to their design. Specific conductivity (thermal conductivity divided by weight) was used to compare thermal efficiency of the designed structures. Due to the small value of this specific conductivity, it was multiplied by 100 for better orientation in results.

Tab. 3: Mechanical contact structures

No.	Structure type	Material Lower/ Upper	Wall thickness [mm] / No. of walls. [-]	Thermal conductivity [W·K^{-1}]		Specific conductivity [100·W·K^{-1}·g^{-1}]		Weight [g]
				Analytical	FEA	Analytical	FEA	
1	T-shape	Cu/Al	1.2 / T-8	1.34	1.27	1.81	1.72	73.93
2	2T-shape	Cu/Al	1.2 / 2T10	2.05	1.93	2.17	2.04	94.45
3	2T-shape	Al/Al	1.8 / 2T7	1.41	1.39	2.46	2.43	57.23
4	2T-shape	Al/Al	1.8 / 2T8	1.45	1.47	2.46	2.49	59.01
5	2T-shape	Al/Al	1.8 / 2T9	1.44	1.45	2.37	2.39	60.70
6	Cylindrical	Cu/Al	9.2/1.6 / Ce2	1.24	1.08	1.92	1.67	64.75
7	Helix	Cu/Al	Pitch: 5 Contact width: 7	-	1.83	-	1.75	104.85

The final comparison shows that the analytical and numerical analysis of 2T-structures predicts results with 1% to 5% difference (see Fig. 4). The numerical analysis confirms also the trend of specific conductivity in dependence on T-structures. The best specific conductivity values are achieved by 2T-structures. The higher differences 5% to 12% occurs in the case of structures which combines copper and aluminium components (see Fig. 5). This difference needs to be further explored.

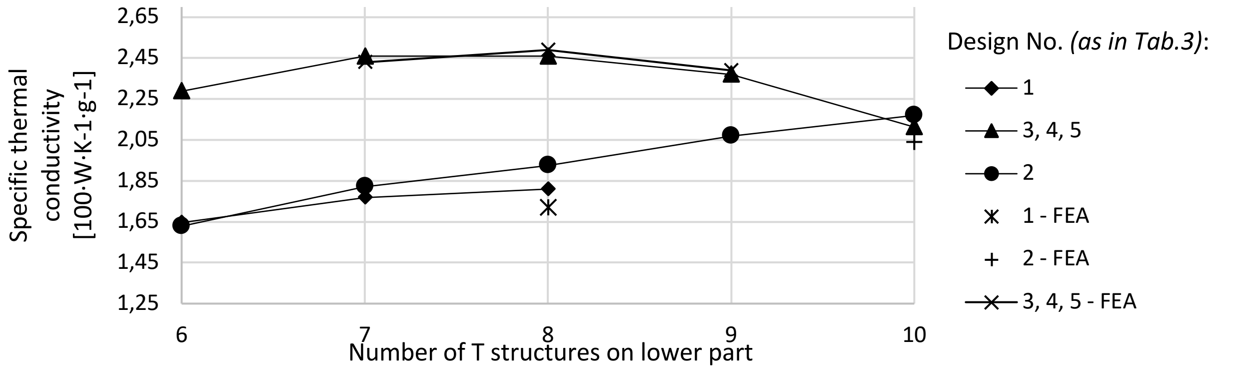

Fig. 4: Dependence of specific thermal conductivity on number of T-structures

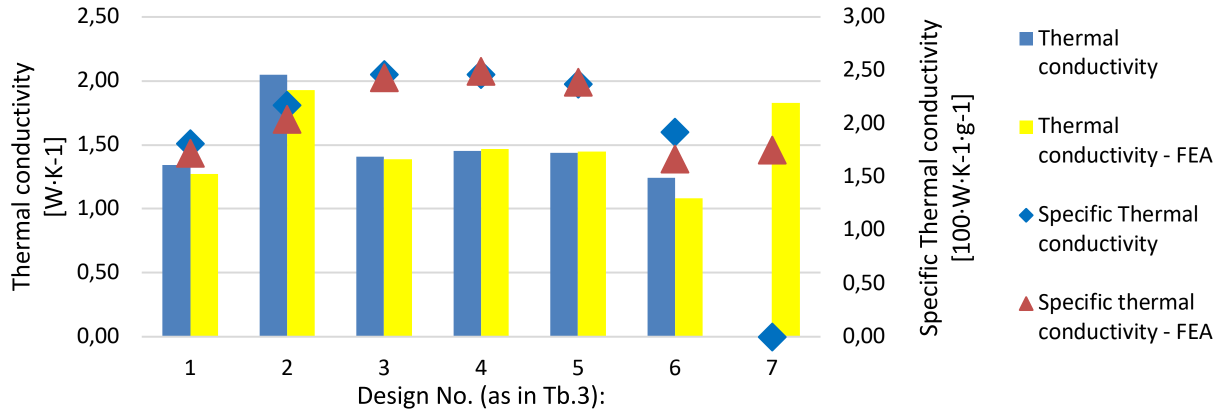

Fig. 5: Comparison of FEA and analytical computation

4. Conclusion

The confirmation of computations by numerical analysis allows us to predict and to optimize the thermal conductivity of structures. It shows that the most beneficial structure is 2T-shape structure made of aluminium. The structure achieves better specific thermal conductivity than initial design, but still does not meet the requirements by 8.5 %. The surface coating to prevent cold welding will be required for Al-Al mechanisms. The next step is a more accurate design of contact interfaces, stress and strain analyses followed by the experimental verification of manufacturability, thermal and mechanical properties.

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