Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 67 (2015) 1206 – 1211

Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

A passive, adaptive and autonomous gas gap heat switch

Srinivas Vanapalli[a,*], Bram Colijn[a], Cris Vermeer[b], Harry Holland[a], Thierry Tirolien[c], H.J.M. ter Brake[a]

[a]*University of Twente, P.O box 217, 7500 AE Enschede, The Netherlands*
[b]*SuperACT foundation, Hengelo, The Netherlands*
[c]*European Space Agency, Noordwijk, The Netherlands*

Abstract

We report on the development of a heat switch for autonomous temperature control of electronic components in a satellite. A heat switch can modulate when needed between roles of a good thermal conductor and a good thermal insulator. Electronic boxes on a satellite should be maintained within a typical optimum temperature range of 260 to 310 K. The heat sinking is usually by means of a radiator. When the operating temperature of the electronic box increases beyond 310 K, a good contact to the radiator is desired for maximum cooling. On the other hand, when the satellite is in a cold dormant state, the electronics box should be heated by the onboard batteries. In this state a weak thermal contact is desired between the electronic box and the heat sink. In the present study, we are developing a gas gap heat switch in which the sorber material is thermally anchored to the electronic box. A temperature change of the electronic box triggers the (de-)sorption of gas from the sorber material and subsequently the gas pressure in the gas gap. This paper describes the physical principles and the current status of this technology. This approach can be extended to cryogenic temperature range.

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
Keywords:
Heat switch, Gas gap, Heat transfer, micro/nanosattelite

1. Introduction

A potentially revolutionary way forward for the space sector is the development of highly capable, autonomous and configurable micro/nanosatellites. On the thermal control system point of view, it is identified that small spacecrafts will require alternative means to achieve thermal control, first because of the inherently very stringent power and mass budget requirements, but also due to the limited physical resources (small surfaces) with respect to the internal dissipation (Baturkin (2005)).

Electronic components and devices of satellites are packaged in a special container called the electronic box. The temperature of the electronic box is controlled within a desired temperature range of -10 °C to 40 °C. Cooling is

* Corresponding author. Tel.: +31-624323752.
E-mail address: s.vanapalli@utwente.nl;ask4srini@gmail.com

Peer-review under responsibility of the organizing committee of ICEC 25-ICMC 2014
doi:10.1016/j.phpro.2015.06.191

achieved by mounting the electronic box to a radiator and heating is often realized with electric heaters. Dynamic heat management system is a key enabling technology for micro/nanosatellites. Radiator panels lack the flexibility to accommodate dynamic cooling. This is because cooling rates cannot be altered, either spatially or temporally, and thus are inadequate for adaptive cooling. In the area of radiative heat transfer modulation the technologies that are being investigated are deployable radiator, variable emissivity coatings and louvers-like mechanisms (Garrison Darrin et al. (2000)). Another approach is to vary the thermal resistance between the radiator and the source of heat within the satellite with a heat switch. The desired characterestics of the heat switch are shown in the table 1.

Mechanical heat switches have not been extensively used for spacecraft thermal control applications in the past. This has been due to low performance (ON-OFF heat transfer ratio) of the switch and the large switch mass needed to conduct heat. Heat switches based on a gas gap are expected to reduce the heat switch mass by an order of magnitude compared to the current state-of-the-art heat switch technology. The thermal conductance of the gas gap heat switch can be varied continuously between a low and a high conductance state. This capability of the gas gap heat switch enables adaptive thermal design. When there is no heat flux during idle state, the heat switch is set to a very low conductance state. The electronic box temperature is maintained at the desired level without the requirement of electrical heating.

Active type: In the active type, the gas pressure in the gas gap is varied by controlling the temperature of a sorber material (Burger et al. (2002)). In the normal state the sorber material (ab)-adsorbs most of the gas leading to a low pressure in the gas gap and the corresponding low- conductance state. The thermal conductance is increased by heating the sorber material to a higher temperature leading to the release of the gas into the gas gap. The gap pressure in the gas gap can be controlled by heating the sorber material to an appropriate temperature.

Passive type: In this type, the sorber material is mounted in close thermal proximity to the component side of the heat switch. The heat switch is normally in a low thermal conductance state and isolates the component from the sink. When the component warms up, the sorber material attached close to it also warms up and releases gas leading to an increase in pressure in the gas gap. The warmer the component, the higher is the gas pressure and thus the thermal conductance. The attractiveness of this type is the autonomous behavior of the heat switch without the requirement of external control circuitry and instrumentation. Additionally, the heat switch is actuated with the thermal energy from the component and hence there is no need for external energy input.

This paper aims at exploring such an adaptive heat switch that operates fully autonomously and needs (no or) little external power or connections. Moreover, the switching ratio (on-off heat transfer ratio) would be significantly higher than the state of the art passive mechanical heat switches and being a plate, it could seamlessly be integrated to panels or electronic boxes.

Table 1. Desired characteristics of the heat switch.

Property	Value
OFF conductance,α_{off} (W/m^{2}K)	<5
ON conductance,α_{on} (W/m^{2}K)	500
ON/OFF ratio	>100
Temperature of the component,$T_{component}$ (K)	263-310
Temperature of the heat sink, T_{sink} (K)	<273
Mass of heat switch per unit frontal area, m_{switch} (kg/m^2)	8

2. Gas-gap heat switch

The heat conduction in the gas gap can be broadly classified into two regimes of heat transfer. In the continuum regime when the gap size is much larger than mean free path of the gas L, Fouriers law of heat conduction applies and the heat conductance, α, for the gas gap is

$$\alpha = \lambda_g/\delta \tag{1}$$

Where λ_g is the thermal conductivity of the gas and δ is the gap height. As the gas pressure reduces, the mean free path decreases. In the molecular regime the gas gap height is much smaller than the mean free path L, of the gas molecules.

Under these circumstances, the heat transfer between the two surfaces is said to be in the molecular regime. In this regime the heat is transported by individual molecules. This phenomenon of heat transfer is modeled by considering a temperature jump at the surface. The effect of temperature jump is to increase the length of heat transfer path by an amount that is called the temperature jump distance. Kennard (1938) gives the following equation for the temperature jump distance δ_g,

$$\delta_g = \frac{(2-\beta)}{\beta}\frac{2}{\gamma+1}\frac{\lambda_g}{\mu c_v}L \tag{2}$$

Where μ is the viscosity, c_v is the specific heat at constant volume, γ is the ratio of specific heat of gas at constant pressure and volume and L is the mean free path of the gas. The accommodation coefficient β indicates the inefficiency of energy tranfer between the solid surface and the gas molecules and depends on the quality of the surface. Equation 2 is applied to a single gas. For a mixture of gases such as air, the temperature jump distance is the mass fraction weighted sum of the temperature jump distances of the constitutent gases. Table 2 lists the properties for several gases. The values refer to atmospheric pressure and 323 K. To account for both regimes equation 1 can be modified as follows,

$$\alpha = \lambda_g/(\delta + \delta_{g1} + \delta_{g2}) \tag{3}$$

where δ_{g1} and δ_{g2} refer to the temperature jump distance at the two surfaces. In general, we can assume the accommodation coefficients for both surfaces to be the same and therefore, the temperature jump distances are the same as well.

Table 2. Properties of several gases at T=50 °C (Selden et al. (2009); Madhusudana (2014)).

Gas	γ	β (on Al)	M [g/mol]	λcontinuum [W/m.K]
Air	1.40	0.95	28.97	0.0224
Argon	1.67	0.81	39.95	0.0209
Xenon	1.66	0.86	131.3	0.0068
Hydrogen	1.41	0.40	2.02	0.163
Helium	1.66	0.53	4.003	0.159

Fig. 1 shows the calculated heat conductance as a function of gas pressure for the gases listed in table 2. Literature data is used for the accommodation coefficient of these gases on an aluminium surface (Selden et al. (2009); Madhusudana (2014)). Referring to the heat conductance requirements shown in table 1 only hydrogen and helium gas meets the ON conductance requirements. A pressure of less than 10 Pa and more than 300 Pa hydrogen gas meets the OFF and ON conductance requirement respectively. With helium gas the pressure should be less than 40 Pa and greater than 1000 Pa to satisfy the OFF and ON conductance.

3. Experimental

3.1. Test rig

The gas gap is realized with two aluminium circular plates of thickness 8 mm separated by several nylon spacers (see Fig. 2). The outer edges of the circular plates are wedge shaped to contain an O-ring. Nylon wires of diameter 160 μm are used as spacers between the two plates. Several channels of about 1mm wide are grooved on the top aluminium plate to allow flow of gas in the gas gap. A heater and a temperature sensor is mounted on the top plate to set a fixed temperature. The bottom plate houses the heat sink and a temperature sensor. The heat sink is an air cooled fin heat exchanger. Heat conductance experiments are performed with three substances namely air, helium and hydrogen gas. For each substance the pressure in the gas gap is varied between 0.01 Pa and 1 atm. At each pressure value the heat input Q_{heater} and the temperatures of the plates $T_{topplate}$,$T_{bottomplate}$ are recorded. The heat conductance is then,

$$\alpha = \frac{Q_{heater}}{A.(T_{topplate} - T_{bottomplate})} \tag{4}$$

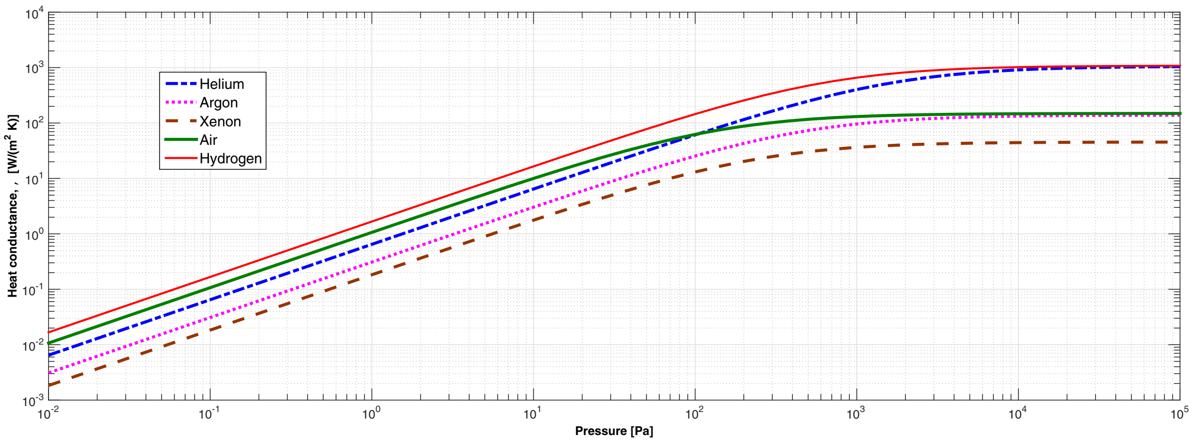

Fig. 1. Heat conductance of several gases in a gas gap of 150 μm.

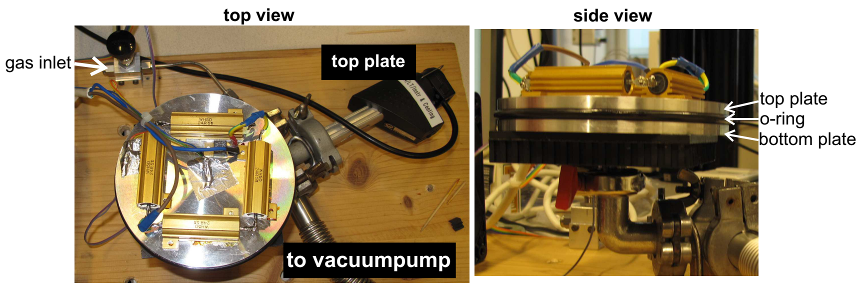

Fig. 2. Experimental setup to measure heat conductance of the gas gap.

3.2. Gap height

Fig. 3 shows the heat conductance for the three substances, namely air, helium gas and hydrogen gas. The actual gap height is estimated by considering the values of heat conductance in the continuum regime and using equation 1. The estimated height for the three substances at the corresponding pressure is given in table 3. The gap height in all the three cases is about 135 microns within an uncertainty of 10 microns. The estimated height is smaller than the nylon wire diameter, which is 160 microns. One possible explanation is the compression of the wire between the two plates due to the pressure difference between the environment and the gas gap.

Table 3. Data of several gases to calculate the gap height.

Gas	λ [W/m.K]	Experimental pressure [Pa]	Estimated height [μm]
Air	0.0276	3.0×10^3	136.0 ± 5.9
Helium	0.1666	50.0×10^3	133.4 ± 9.6
Hydrogen	0.2003	55.2×10^3	134.5 ± 8.9

3.3. OFF conductance

The OFF conductance is determined mainly by the parasitic heat leaks through the O-ring and the nylon spacers. Radiation can be neglected because the temperature difference is small. Six nylon wires each 4 cm long and 160

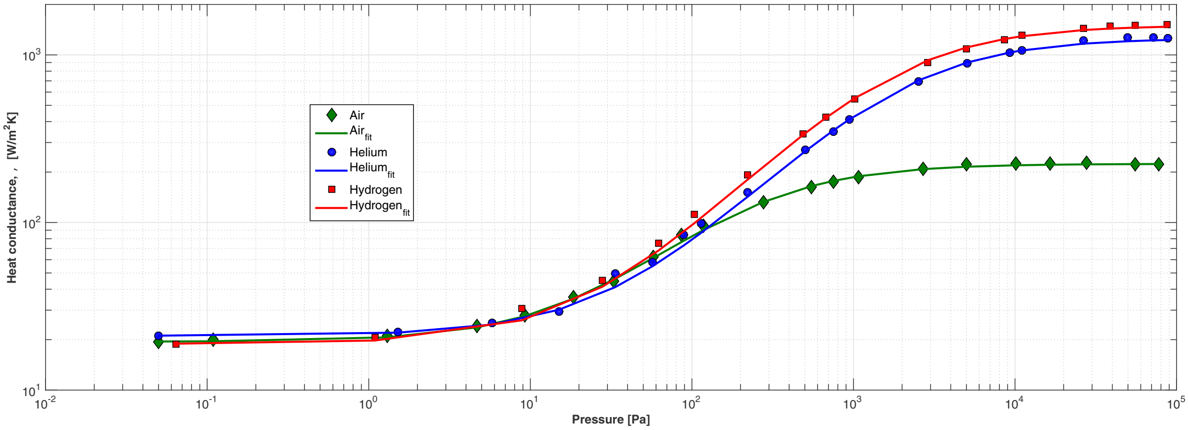

Fig. 3. Heat conductance of air, helium and hydrogen in a gas gap of 135 μm.

micron diameter are used as spacers. The heat conductance estimated through the nylon spacers is 5.1 W/m^2.K. Similarly the heat conductance of the O-ring made of veton is estimated to be 13.0 W/m^2.K. The total estimated OFF conductance is 18.1 W/m^2.K. The measured OFF conductance is about 20 W/m^2.K (see Fig. 3) which is in reasonable agreement with the estimated value.

3.4. Accommodation coefficient

The accommodation coefficient depends on the material of the surface and the working substance in the gas gap. To determine the accommodation coefficient of the aluminium surface a root mean square fit is performed with the experimental data. A build in optimizer of Matlab, Optimtool32, is used to minimize the root mean square of the difference between the experimental data and the model. It is important to note that only the gas conductance is fitted to the model, the OFF-conductance was later added to the gas contribution. The resulting accommodation coefficients are 0.87, 0.64, 0.30 for air, helium and hydrogen gas respectively. The fit of the conductance to the experimental data is shown in Fig. 3.

4. Sorber materials

Sorber materials store gas corresponding to an equilibrium pressuer and temperature. The gas can be released upon increasing the temperature of the material. In a constant volume gas-gap the released gas increases the gas pressure. This phenomena of temperature dependence of sorption of gases in material allows varying pressures and therefore varying thermal conductance between the two surfaces of the gas-gap. Hydrogen gas is readily absorbed in most metals. The thermodynamics of the absorption of hydrogen gas in metals to form metal hyride is described using pressure-composition-temperature curves. In a typical metal, the material undergoes a phase transition at a particular pressure and temperature. The equilibrium pressure and temperature of three metal hydrides namely ZrMn2Hx, LaNi5Hx and LaNi3Mn2Hx is shown in figure 4 (a). The heat conductance in a gas gap of 150 μm corresponding to the equilibrium pressure of these metal hydrides is shown in figure 4 (b). Among the chosen metal hydrides, ZrMn2Hx is the only suitable candidate for heat switch application. The ON conductance is still lower than the requirement. Further research on these materials is necessary to identify a suitable candidate sorber material.

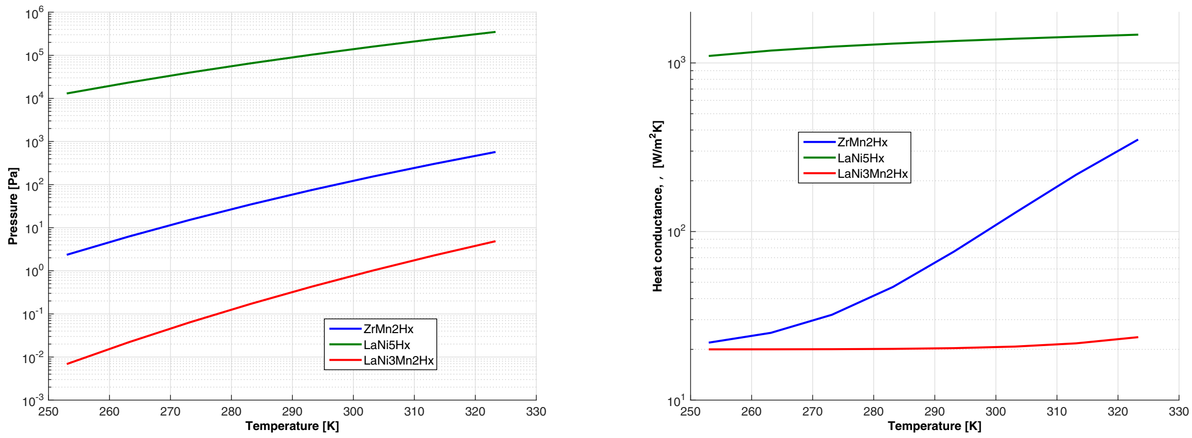

Fig. 4. (a) Equilibruim pressure and temperature of chosen metal hydrides (b) Estimated heat conductance of the gas gap for the chosen metal hydrides.

5. Discussion

Passive, adaptive and autonomous temperature control of the (sub-)components will enable miniaturization of the current satellites. One proposed approach is the development of a gas gap heat switch with the actuator, a sorber material directly in contact with the heated surface of the component. This paper shows that a gas gap of 150 μm size with hydrogen or a helium gas can meet the desired requirements of ON and OFF conductance. Among the sorber materials considered in this study, ZrMn2Hx fulfills the OFF conductance but not the ON conductance. One way to increase the ON conductance of the heat switch is to pattern the gas gap into a finned structure thereby increasing the area of heat transfer for the same frontal area. Currently modifications to the heat switch to increase the surface area and packaging is being investigated. Considerable research is needed to synthesize metal alloys as sorber materials to meet the pressure requirements of the heat switch. This concept of the passive heat switch can be extended to cryogenic temperatures. In this case the sorber material can be an activated carbon (ad-)desorbing helium gas.

Acknowledgements

Funding from the European Space Agency contract no. 4000106126/12/NL/PA for this study is gratefully appreciated.

References

Baturkin, V., 2005. Micro-satellites thermal controlconcepts and components. Acta Astronautica 56 (12), 161 – 170.

Burger, J., Holland, H., Van Egmond, H., Elwenspoek, M., Ter Brake, H., Rogalla, H., 2002. Fast gas-gap heat switch for a microcooler. In: Cryocoolers 10. Springer, pp. 565–574.

Garrison Darrin, A., Osiander, a., Champion, J., Swanson, T., Douglas, D., Grob, L., 2000. Variable emissivity through mems technology. In: Thermal and Thermomechanical Phenomena in Electronic Systems, 2000. ITHERM 2000. The Seventh Intersociety Conference on. Vol. 1. pp. –270.

Kennard, E. H., 1938. The kinetic theory of gases. with an introduction to statistical mechanics. Journal of the Society of Chemical Industry 57 (39), 901–901.

Madhusudana, C., 2014. Thermal contact conductance, 2nd Edition.

Selden, N., Gimelshein, N., Gimelshein, S., Ketsdever, A., 2009. Analysis of accommodation coefficients of noble gases on aluminum surface with an experimental/computational method. Physics of Fluids (1994-present) 21 (7), 073101.