

Hydrogen and Neon Gas-Gap Heat Switch

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ABSTRACT

Heat switches are important devices in many cryogenic setups, especially in space applications and many systems have been used to allow a good ability to make or break a thermal contact. Among them, the so-called gas gap heat switches, in which the pressure is managed thanks to a small cryopump, are known to be very reliable and simple, principally due to the nonexistence of moving parts. However, in such switches, the gas characteristics and its adsorption properties have to be taken into account to determine their functioning temperature ranges. In this article, a gas gap heat switch, with a charcoal adsorption pump, tested with neon and hydrogen as conducting gas is described. The experimental results are presented and compared with calculation from a simple thermal model. Avoiding the gas condensation, limiting the OFF conductance and reaching a viscous regime in the ON state lead to an operational temperature window for the sorption pump that depends of the amount of gas.

For neon, the minimum temperature to actuate our switch ranges from 17 K to 40 K; for hydrogen, this temperature range goes from 9.5 K up to 55 K. Such switches offer an extension to the well-studied helium gas gap heat switch which is limited to temperatures up to 15 K.

Measured values for the thermal ON conductance (74 mW/K at 20 K for neon, 110 mW/K at 11 K for H₂) compare very well with the results expected from gas conductivity properties found in literature. For neon an ON/OFF conductance ratio about 220 is obtained at 20 K, whereas, for H₂, a ratio up around 440 was measured at 11 K.

INTRODUCTION

A cryogenic heat switch is a major component in several cryogenic systems. Whenever a thermal coupling is to be turned ON and OFF, a cryogenic heat switch has an application, for instance, when a redundant cryocooler is used, both of them are connected to the sensor device through a heat switch. Among the different mechanisms for a switch to rely on, the gas gap one has the advantage of having no moving parts if actuated by a cryopump: helium gas gap heat switches (Helium Gas Gap Switch) are well studied, and broadly used in spacecraft thermal control^{1, 2}, but, due to helium adsorption properties, they can no longer be used if a 15 - 20 K cold source² is not available.

The purpose of using other gases in a similar switch aims at broadening the temperature range for their application. Recently, a neon GGHS was characterized.³ In this article, a H₂ GGHS was tested, working in a similar range as the neon one. Their results are presented and compared. Both are promising. A trade-off has to be made for particular applications.

THE SWITCH

The prototype of a gas gap heat switch (GGHS) used for these tests was previously described.³ It uses two cylindrical copper blocks (the hot and cold blocks) separated by a 100 mm gap. A thin stainless steel supporting shell (SSSS, 100 mm thickness), encloses the gas and insures rigidity to the assembly, as drawn in Figure 1 from Catarino, et al.³

The actuation of the switch relies on a 30 mg activated charcoal cryopump which pumps the gas if it is cool enough, releasing it to the gap space when heated up. This cryopump is loosely thermally-stacked to the cold block.

The total removal of gas from the gap space leads to an OFF state where the supporting shell is the only path for the heat flow when a heating power \dot{Q} is applied on the hot block. The calculation of the switch conductance for this state is thus very simple – just the cylindrical thin stainless steel shell between two isothermal blocks.

With gas in the gap, the heat conduction path may be, in a first approximation, modeled as a series association of the copper blocks and the gas in parallel with the SSSS. More details about this model are given in Catarino, et al.³ If there is enough gas in the gap to ensure a continuum (mean free path \ll gap width), the heat flow through the gap is independent of the gas pressure. In this case, the switch will reach its maximum conductance and is in the ON state.

ON-OFF RESULTS AND DISCUSSION

The prototype was characterized both with neon and hydrogen gases in the ON and OFF states. The switch was filled up at room temperature with various “charge pressures” in order to quantify the ON-OFF temperature tuning possibility as well as to probe if the continuum regime was really reached at the ON state. An operational temperature window for each GGHS is presented and discussed.

The conductance study

Adjusting the cryopump temperature to adequate temperatures (see next section), the thermal conductance was measured in the OFF and ON state by applying incremental power to the hot block, keeping the cold block at a constant temperature (20 K for neon, 11 K for hydrogen), and measuring the stabilized hot block temperature. Heating power \dot{Q} versus temperature differences ΔT between hot and cold blocks are plotted in Figure 2 (symbols). In the ON state, the data superposition for different charge pressures indicates that the continuum regime (pressure independent conductivity) was actually reached. In the OFF state, this independence indicate that the conduction through the residual gas is completely negligible compare to that of the SSSS.

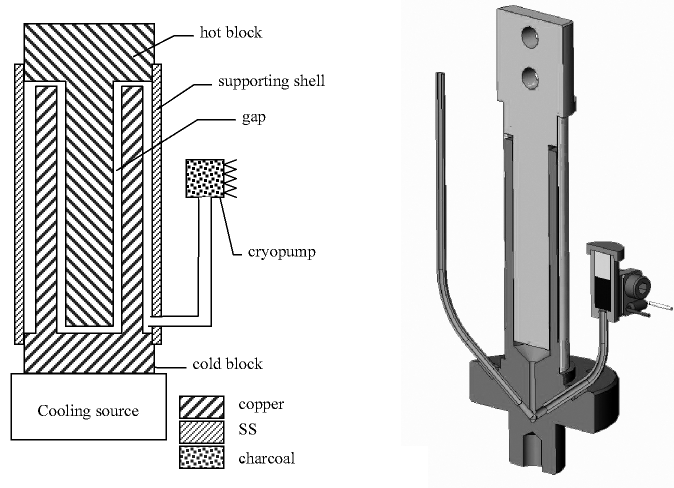


Figure 1. Schema and section draw of the GGHS prototype

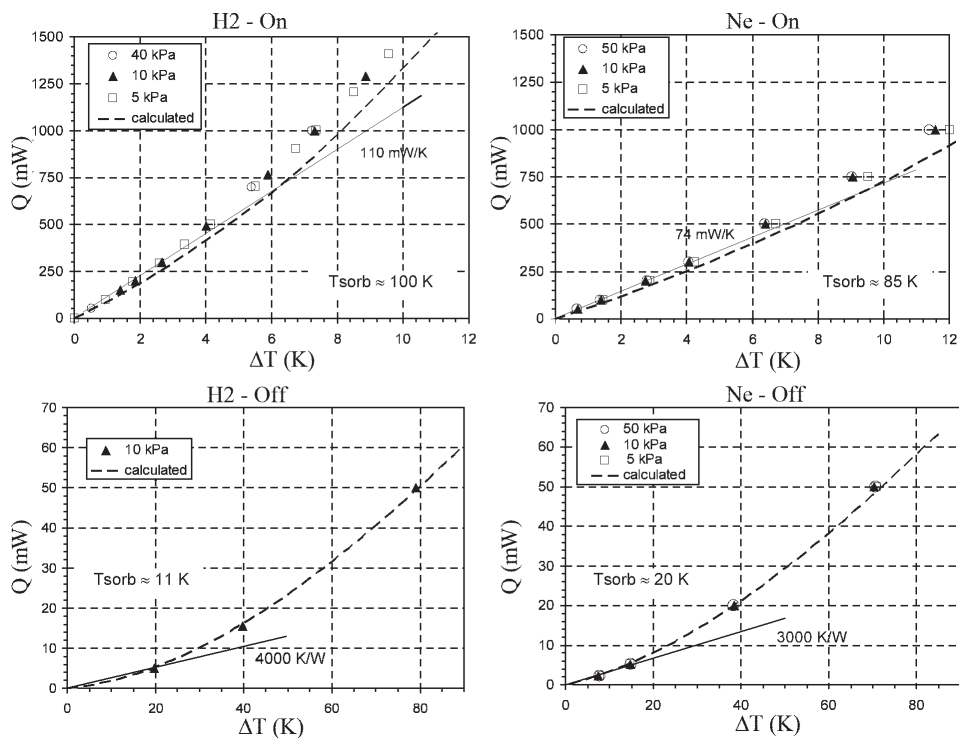


Figure 2. ON and OFF conductance curves for H_2 ($T_{\text{cold}} = 11 \text{ K}$) and Ne ($T_{\text{cold}} = 20 \text{ K}$).

Experimental data match very well with those calculated from the simple model for the heat paths in the ON and OFF states (dashed lines), where the tabulated values for conductivities of the solid materials⁴ and gases⁵ have been used. Conductance values were obtained by fitting a straight line to the small temperature differences. Measured values for the thermal ON conductance were 74 mW/K at 20 K for neon, 110 mW/K at 11 K for H_2 . An ON/OFF conductance ratio of about 220 is obtained for neon at 20 K, whereas a 440 ratio was measured for H_2 at 11 K. Let us note that the higher gas conductivity of H_2 compared to that of neon is the main origin of the better ON/OFF conductance ratio for H_2 .

The temperature window

The switching actuation between ON-OFF states depends on the amount of charcoal as well as on the amount and type of gas. Experimental results of the “conductance” $\dot{Q}/\Delta T$ as a function of the cryopump temperature (T_{orb}) are shown in Figure 3 both for hydrogen and neon for various charge pressures. Each curve is obtained for an applied power of 1 W (50 mW) for the upper (lower) parts of the curves. As expected, for a given gas, as the charge pressure increases, the desorption temperature decreases and then the ON and OFF states are both reached for lower cryopump temperatures. On the other hand, the rare gas neon is more difficult to adsorb than H_2 : the ON and OFF states are obtained for lower cryopump temperatures than for H_2 . For high cryopump temperature, i.e. the ON state, the $\dot{Q}/\Delta T$ ratio is indeed pressure independent, denoting that the viscous regime is fully established.

To quantify the OFF onset, two cryopump temperatures were defined and plotted in Figure 4 as a function of charge pressure. An experimental OFF temperature ($T_{\text{exp OFF}}$, long-dashed lines in Figure 4) is assigned to the cryopump temperature that leads to a $\dot{Q}/\Delta T$ value of 1 mW/K, corresponding roughly to twice the SSSS conductance. A calculated OFF temperature ($T_{\text{calc OFF}}$, short-dashed lines in Figure 4) uses a model based on unpublished results for the adsorption isotherms⁶ to predict a gas release corresponding to a 1% increase over the support shell’s conductance.

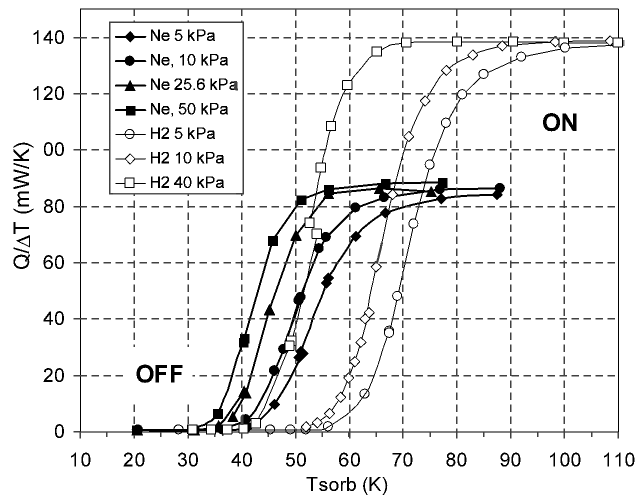


Figure 3. Hydrogen and neon's switching ON-OFF as a function of the cryopump temperature (T_{sorb}) for various charge pressure. Cold block temperature is 11 and 20 K for H_2 and Ne respectively.

This systematic experimental study has evidenced some characteristics related to the actuation of the switch summarized on Figure 4. A temperature range for the usability of the GGHS has been determined for each gas: for each gas there is a temperature window where the cryopump needs to be cooled down, in order to allow the turning OFF of a 100 mm gap switch. This window depends on the amount of gas (thus the charge pressure) and also on the charcoal amount (fixed at 30 mg in all these tests). Ensuring that the OFF conductance is essentially the SSSS conductance defines the higher limit, which is marked with two curves, for $T_{\text{exp OFF}}$ and $T_{\text{calc OFF}}$ as previously discussed. On the left of the shadowed area, the continuum regime for the ON state is no more fully established. A thermal state of the cryopump at a temperature within this window is mandatory for a switchable device with the mentioned gap width. The lower curve in Figure 4 limits the use of the GGHS due to condensation, which can be an inconvenient due to the long time expected to turn OFF or ON the

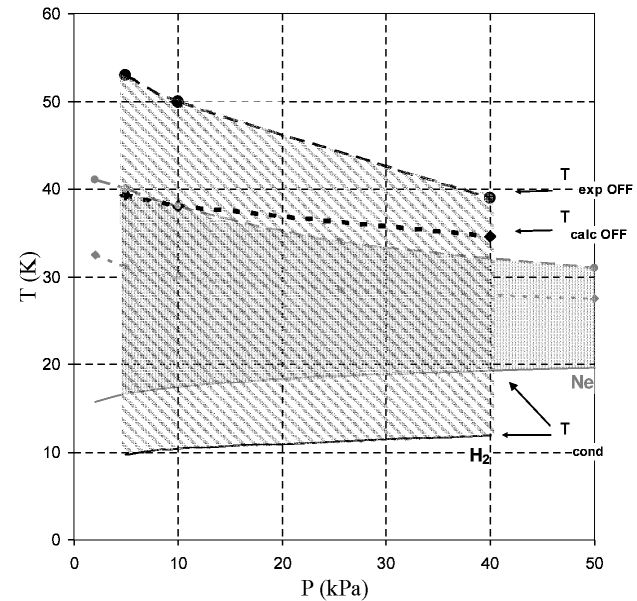


Figure 4. Hydrogen (black) and neon's (grey) switching OFF temperatures (see text) and condensation lines as a function of the charging pressure, defining the operational temperature window.

switch. For neon, the temperature to actuate our switch may range from 17 K to 40 K; for hydrogen, this temperature range goes from 9.5 K up to 55 K. This study shows that neon and hydrogen can be used in GGHS complementing the well-studied helium one whose application is limited up to about 15 K.

Another experiment, described in next section, shows that a continuum ON regime is attainable down to 9.5 K even if condensation occurs.

THE GGHS WITH CONDENSED HYDROGEN

In some cases, it could be useful to extend the low temperature range of such switches: in this section, a test with condensed hydrogen in the gap is described in order to characterize the H_2 GGHS down to 6 K.

The experimental data for $\dot{Q}/\Delta T$ in the Figure 5 (solid line) were obtained while slowly cooling (0.1 K/min) the cold block down from 20 K with 50 mW applied to the hot block. During this experiment, the cryopump was maintained at a temperature (~ 100 K) for which the switch is in its ON position (continuum regime) at least for $T > 11$ K. The charge pressure was 10 kPa corresponding to an expected condensation temperature of 10.4 K (Figure 6). Experimental data for 5, 10 and 40 kPa were found and are superimposed in Figure 6.

The experimental data are compared to calculated values using H_2 conductivity data at 0.3 kPa from the NIST Thermophysical Properties of Fluid Systems⁵ for the viscous regime (squares).

For the molecular regime, the calculated values (circles) used the Kennard relation (equation 1), upon the saturated vapor pressure data found at AVS⁷:

$$\dot{Q} = A\alpha \left(\frac{\gamma+1}{\gamma-1} \right) \left(\frac{R}{8\pi MT} \right)^{1/2} P(T_h - T_c) \quad (1)$$

where α is an accommodation factor taken as 1, $\gamma = C_p/C_v = 1.4$ for hydrogen, R is the ideal gas constant, M the molar mass, P the pressure and T is taken as the average temperature between T_c and T_h , the hot and cold block's temperature, respectively.

The fully established continuum or molecular regimes ($mfp < gap/100$ and $mfp > 100$ gap respectively) are represented in Figure 5 by using larger symbols in the plotted curves. The region

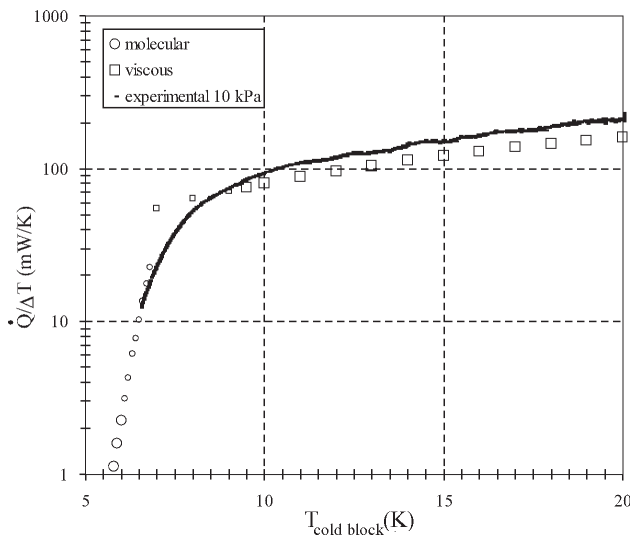


Figure 5. Hydrogen's switch $\dot{Q}/\Delta T$ ratio while cooling down the cold finger with 50 mW applied on Hot block versus Cold block temperature (solid line); calculated values for saturated pressure (open symbols) both for a viscous and a molecular regimes.

with smaller symbols would correspond to the intermediate regime. The mean free path (mfp) was calculated using Eq. 2⁸ :

$$\lambda = 3.62 \frac{\eta}{P} \sqrt{\frac{T}{M}} \quad (2)$$

where P represents the pressure, $\eta(T)$ the viscosity and M the molar mass (all in SI Units).

The calculated values in the viscous regime fit quite well the experimental values down to $\approx 9 - 10$ K. Such a fact means that, *if the continuum state is reached before condensation*, a hydrogen switch with a 100 mm gap keeps that ON state down to this temperature even if condensation occurs. The same is to say that the vapor pressure of the hydrogen is enough to ensure a $mfp < 1$ mm down to $\approx 9 - 10$ K. This way, if there is a convenient way for the condensation to occur, the lower limit for the temperature window in Figure 4 should be a straight line at ≈ 9 K. However, let us note that, at 8 K, was reduced by just a factor ≈ 2 with respect to the value in the fully established continuum regime at 10 K. For some applications, this value can still be useful.

At lower temperature, the switch toggles abruptly into the OFF state (1 mW/K corresponds to ≈ 6 K) due to the very rapid pressure decrease along the melting curve. A H_2 GGHS without cryopump was obtained. Let us note that, when comparing calculated and experimental data, for $T < 8$ K, the molecular regime (circles) seems to be reached before the limit $mfp = 100$ gap is attained (at 6 K).

In Figure 6, the circles display the evolution of the mfp during the temperature sweep of Figure 5. The horizontal dashed line in Figure 6 represents a mfp of 1 mm, one hundredth of the gap width: the gas is in the viscous regime below this line for current gap width (100 μ m). The mean free path for the ideal gas at initial pressure of 10 kPa is represented by the solid line. At 10 K, the H_2 starts to condense in the solid phase and the mfp increases rapidly due to the exponential pressure decrease along this coexistence line (short-dashed line). The analysis of Figure 6 shows that even if condensation occurs, there is still enough gas to ensure a viscous regime down to 9.5 K: at this temperature, the mfp of the vapor pressure reaches one hundredth of the gap width.

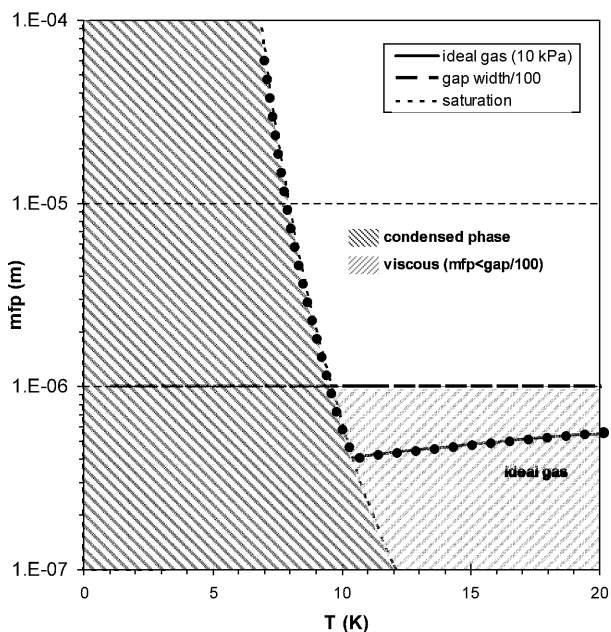


Figure 6. Mean free path in H_2 gas as a function of (cold finger) temperature. The saturation line divides the left side of the plot for the condensed H_2 (solid), right side for the gaseous phase. Horizontal line divides the lower part of the plot for a continuum regime at a 100 mm gap, and a non continuum upper part of the plot. Ideal gas line depends on the total amount of gas in the switch, i.e., the room temperature charging pressure. Independent of the total amount of gas present, on the saturation line, a viscous ON regime is attainable down to 9.5 K. Closed circles: mfp vs T during the temperature sweep of Figure 5.

Using the criteria of $mfp > 100$ gap, the molecular regime will become fully established for temperatures lower than 6 K. This is the higher limit used for the molecular curve in Figure 5 (large open circles). Actually, the comparison between experimental and calculated data below 7 K (Figure 5) shows that the limits $mfp = 100$ gap is probably over-evaluated.

CONCLUSION

Gas gap heat switch with hydrogen and neon as conducting gases and with a charcoal cryopump as the actuator were characterized: the measured and calculated conductances match very well. The higher conductivity of H_2 gas leads to a better thermal conductance in the ON state.

A temperature window was established for applicability of a GGHS both for neon and hydrogen. These gases can complement helium in a similar GGHS: H_2 can be used whenever a cold source is available at temperatures within [9.5 K, 55 K], while the range for neon is [17 K, 40 K]. The Ne GGHS is easier to be switched ON than the H_2 one, since it requires a smaller heating up of the cryopump.

The use of a GGHS with condensed H_2 was studied and discussed: if a high thermal conductance is not critical, the lower limit for its use in an ON state can be pushed down to $\gg 8$ K. It should be pointed out that we have not investigated yet the kinetic of the switch once a liquid or a solid phase is present.

Making use of results presented, a GGHS can be customized for specific requirements.

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