Experimental and Analytical Performance of Gas Gap Cryogenic Thermal Switch using N_2 gas

Mr. Khalid Siddiqui[1] Mr. Bhavesh parekh[2]
[1]M. E. Mechanical (Cryogenic) Engineering [2]M. Tech. Production Engineering,
[1,2]Shankersinh Vaghela Bapu Institute of Technology, Vasan, Gandhinagar

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 are known to be very reliable and simple due to the nonexistence of moving parts. The ON (conducting) state of the switch are obtained by varying the gas pressure and OFF (insulating) are obtained by creating vacuum in gap. In this paper, the gas gap cryogenic thermal switch is fabricated and tested using LN2 storage vessel. The thermal characteristics (Conductance in the ON and OFF state) of a ‘‘Gas Gap Heat Switch’’ are obtained experimentally and analytically using nitrogen as exchange gas. It is concluded that for both ON and OFF state, thermal conductance increases as heat load increases.

Key words: Thermal Conductivity; Gas Gap; Thermal switch.

I. INTRODUCTION

The cryogenic thermal switch is a device that enables the thermal link between two components to be turned on or off. The cryogenic thermal switch (CTSW), which is one of the key technologies for thermal integration, is used to couple redundant cryocoolers to cryogenic devices in order to minimize the parasitic heat load from the off-cryocoolers. The CTSW works on the principle of differential thermal expansion.

With the development of infrared surveillance technology, cryogenic systems on future spacecraft will require a variety of advanced integration components to meet their performance goals such as long-life, high-reliability and high-efficiency. There are two key steps to achieve high reliability, one is to use a high performance cryocooler and the other is to incorporate a redundant cryocooler to protect against individual cryocooler failure. The parasitic heat leak from the redundant, nonoperating cryocooler increases the cooling requirements of the operating cry cooler. As a result, the inactivate cry cooler needs to be thermally isolated from the cryogenic element while the active cooler needs to be thermally connected to the system. The capability to thermally isolate can be accomplished by a cryogenic thermal switch (CTSW). The other use of CTSWs is to reduce the initial cool-down time with multiple crycoolers working in a double harness configuration.

II. EXPERIMENTAL SETUP

The schematic of the experimental set-up is as shown in the Fiure1. The experimental set-up objective is to measure the total thermal resistance as a function of temperature of a prototype of the heat switch. It consists basically of a vacuum chamber, a cold plate, a nitrogen cylinder, a thin circular electric heater and heat switch. The cold plate consists of a hollow cylinder filled with liquid nitrogen.

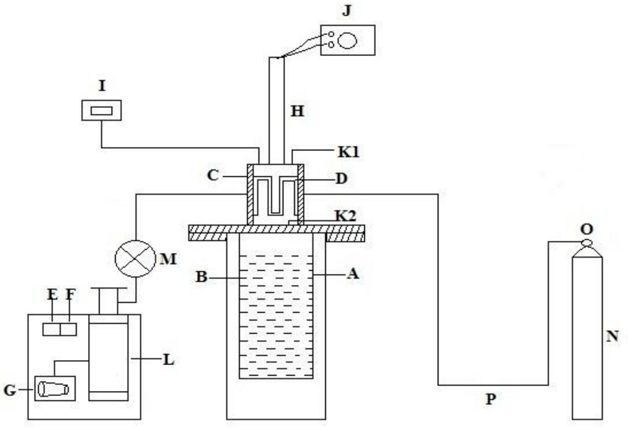

Fig. 1: Experimental set up

Legends:

A. Liquid Nitrogen Reservoir
B. Liquid Nitrogen
C. Thermal Switch
D. Gas Gap
E. Pirani Gauge
F. Paining Gauge
G. Rotary pump
H. Heater
I. Temperature Indicator
J. Voltage Regulator
K. Temperature sensor
L. Diffusion pump
M. Vacuum valve
N. Gaseous Nitrogen Cylinder
O. Regulator
P. Pressure pipe

The prototype of the heat switch was made of Stainless Steel 304 (supporting shell) and copper (hot and cold block) in which supporting shell is used to maintain gap between hot and cold block. It is placed between the cold plate and the electric heater. MLI insulation covers the liquid nitrogen container in order to minimize thermal radiation losses to the radiation shield as well as to reduce liquid nitrogen boil-off rate. The radiation shield consists of an aluminum foil placed over the cold plate. During the experiment, the radiation shield reaches the cold plate temperature and absorbs all radiation coming from the external environment. A Gaseous Nitrogen cylinder connected to one side of heat switch is used to supply the nitrogen gas to the system while on the other side, a vacuum pump is connected to maintain at a pressure of 10-4 mbar in heat switch. A heater is provided at the top of the heat switch to increase the temperature of hot block. A number of temperature sensors have been located at critical positions of the heat switch in the set-up. All electronic sensors are connected to the data acquisition system, which helps to digitally monitor data. The photograph of Experimental set up is shown in Figure2.

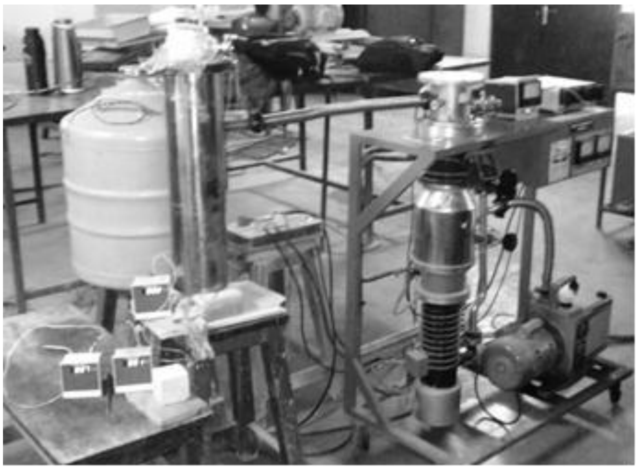

Fig. 2: Photograph of Experimental Set up

III. RESULTS AND DISCUSSION

A. *Introduction*

In experimental work, the thermal switch was filled up with nitrogen gas at room temperature with different charge pressures. Heat supply was given to the hot block by electric heater while the cold block temperature was maintained constant at 148 K (-125°C) with the help of LN2. The conductance/resistance for ON and OFF states were calculated by observing the temperature difference between hot and cold plate by varying the heat supply from 2 W to 9 W. The experimental results for ON and OFF state are shown in Table1 and Table2 respectively.

B. *Experimental results*

Charge Pressure (kPa)	Cold block temp T_{COLD} (K)	Incremental Power Q (W)	Hot Block temp T_{HOT} (K)	Temp Difference $\Delta T = T_{HOT} - T_{COLD}$ (K)	ON Conductance $U_{ON} = Q / \Delta T$ (mW/K)
20	148	2	286	138	14.49
		3	288	140	21.42
		4	289	141	28.36
		5	290	142	35.21
		6	292	144	41.66
		7	294	146	47.94
		8	295	147	54.42
		9	297	149	60.40
30	148	2	281	133	15.03
		3	282	134	22.38
		4	283	135	29.62
		5	285	137	36.49
		6	286	138	43.47
		7	288	140	50.00
		8	289	141	56.73
		9	290	142	63.38
50	148	2	278	130	15.38
		3	280	132	22.72
		4	282	134	29.85
		5	283	135	37.03
		6	285	137	43.79
		7	286	138	50.72
		8	287	139	57.55
		9	289	141	63.82
70	148	2	278	130	15.38
		3	279	131	22.90
		4	280	132	30.30
		5	282	134	37.31
		6	284	136	44.11
		7	285	137	51.09
		8	287	139	57.55
		9	288	140	64.28

Table. 1: Experimental results for ‘ON’ State

Charge Pressure (mbar)	Cold block temp T_{COLD} (K)	Incremental Power Q (W)	Hot Block temp T_{HOT} (K)	Temp Difference $\Delta T = T_{HOT} - T_{COLD}$ (K)	OFF Conductance $U_{OFF} = Q / \Delta T$ (mW/K)
0.5	148	2	310	162	12.34
		3	311	163	18.40
		4	313	165	24.24
		5	314	166	30.12
		6	315	167	35.92
		7	316	168	41.66
		8	317	169	47.33
		9	318	170	52.94

Table. 2: Experimental results for ‘OFF’ State

1) Comparisons of thermal conductance Vs heat load in ON and OFF state:

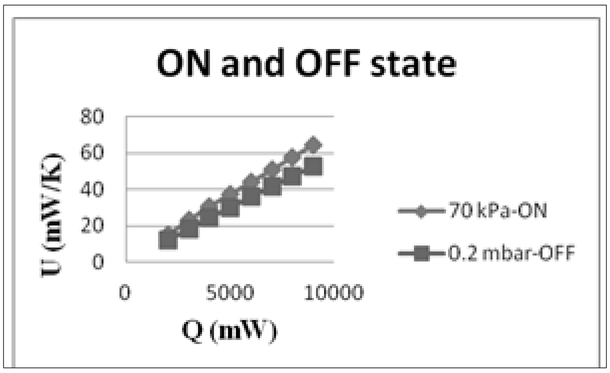

Fig. 3: Thermal conductance U Vs. heat load Q for ON and OFF state

Figure3 shows the graph of thermal conductance ‘U’ Vs heat load ‘Q’ for ON and OFF state. It can be seen from Figure3 that thermal conductance is maximum in ON state as compared to OFF state. It is found that as thermal conductance is higher, continuum regime is reached i.e. thermal switch is in ON state while as thermal conductance is lower, vacuum is created i.e. thermal switch is in OFF state

2) Comparisons of temperature difference ΔT Vs heat load Q for ON and OFF state:

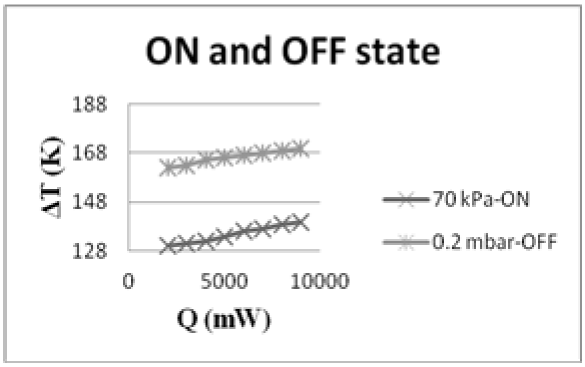

Fig. 4: Graph of temperature difference ΔT Vs. heat load Q for ON and OFF state

Figure4 shows the graph of temperature difference 'ΔT' Vs heat load 'Q' for ON and OFF state. It can be seen from Figure4 that for 70 kPa, the temperature difference is small which in turn increases thermal conductance in ON state. On the other hand, for 0.2 mbar the temperature difference is larger as compared to ON state which decreases thermal conductance in OFF state.

C. Theoretical Results and Calculations:

1) Thermal Conductance in ON state:

In the ON state, the heat flow Q through thermal switch is given by:

$$Q = U\ A\ \Delta Tm$$

Where,

$\Delta Tm = (T1 – T2) / \ln (T1/T2)$

U = thermal conductance of switch (W/K)

A = area of hot block + area of cold block + gas gap area

= 0.178 + 0.374 + 0.048 = 0.6 m2

T1 and T2 = outside and inside temperature of thermal switch respectively (K)

So, Thermal conductance in ON state, UON = Q / A ΔTm

Cold block temp T_{COLD} (K)	Incremental Power Q (mW)	Hot Block temp T_{HOT} (K)	Mean Temp Difference ΔT_m (K)	ON Conductance U_{ON} = Q / A ΔT_m (mW/K)
148	2000	314	220.69	15.10
	3000	316	221.48	22.57
	4000	317	221.87	30.04
	5000	319	222.66	37.42
	6000	321	223.44	44.75
	7000	323	224.23	52.02
	8000	325	225.01	59.25
	9000	329	226.57	66.20

Table. 3: Theoretical calculation of thermal conductance in ON state

2) Thermal Conductance in OFF state**:**

Cold block temp T_{COLD} (K)	Incremental Power Q (mW)	Hot Block temp T_{HOT} (K)	Temp Difference ΔT $=T_{HOT}-T_{COLD}$ (K)	ON Conductance U_{ON} = Q / ΔT (mW/K)
148	2000	314	166	12.04
	3000	316	168	17.85
	4000	317	169	23.66
	5000	319	171	29.23
	6000	321	173	34.68
	7000	323	175	40.00
	8000	325	177	45.19
	9000	329	181	49.72

Table. 4: Theoretical calculation of thermal conductance in OFF state

D. Comparison Of Experimental Results With Theoretical One

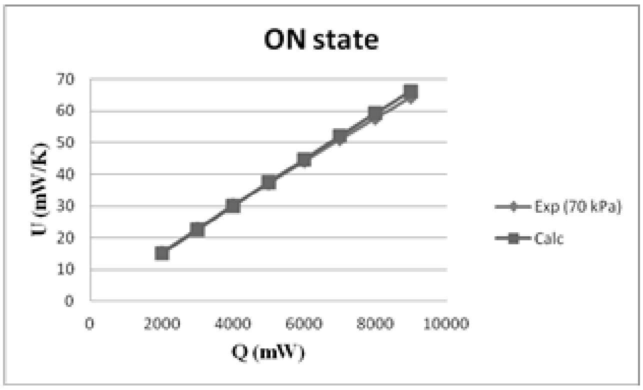

Fig. 5: Graph of thermal conductance Vs. heat load in ON state

Figure5 and Figure6 show comparisons of experimental thermal conductance with theoretical one for ON and OFF state respectively. The theoretical thermal conductance in ON and OFF state are calculated as above. It can be seen from Figure5 and 6 that the experimental data match very well with the calculated results. It can be seen from Figure3 that at higher heat load, slight variation occurs. An experimental result is higher than calculated one at high heat load.

	ON Conductance				
Incremental Power Q (mW)	Experimental ON Conductance $U_{ON} = Q / A\ \Delta T_m$ (mW/K)				Theoretical ON Conductance U_{ON} = Q / A ΔT_m (mW/K)
	20 kPa	30 kPa	50 kPa	70 kPa	
2000	14.49	15.03	15.38	15.38	15.10
3000	21.42	22.38	22.72	22.90	22.57
4000	28.36	29.62	29.85	30.30	30.04
5000	35.21	36.49	37.03	37.31	37.42
6000	41.66	43.47	43.79	44.11	44.75
7000	47.94	50.00	50.72	51.09	52.02
8000	54.42	56.73	57.55	57.55	59.25
9000	60.40	63.38	63.82	64.28	66.20

Table. 5: Comparisons of experimental results with theoretical readings for ON state

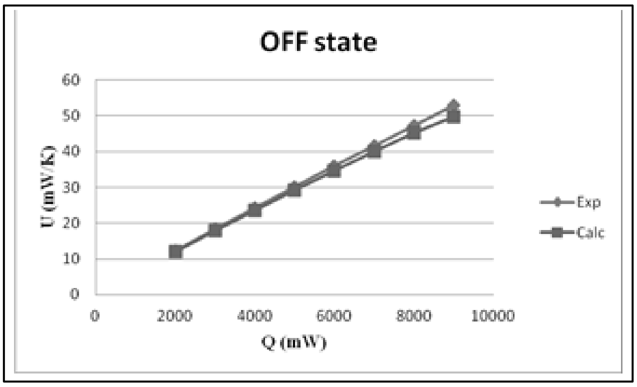

Fig. 6: Graph of thermal conductance vs heat load in OFF state

IV. CONCLUSION

It is concluded that there is no significant difference found in temperature level. The thermal conductance vs heat load was determined for various charge pressure i.e. 20 kPa, 30 kPa, 50 kPa and 70 kPa. It was found that for 50 kPa and 70 kPa, variation in thermal conductance is negligible. The experimental thermal characteristics in the ON and OFF states were found in good agreement with calculated data. ON conductance characteristics are mainly determined by the gas properties and the gap geometry.

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