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Design and Development of a Novel Knudsen Compressor as a Part of a Joule-Thomson Cryocooler

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Abstract. This paper presents the design and development of a novel Knudsen compressor, with no moving parts, as a part of a Joule-Thomson cryocooler. The compressor works by using the Knudsen diffusion principle and includes a combination of graphene-based layers and Knudsen membranes in a particular fashion to pressurize the fluid. The Knudsen membrane for this application was selected by testing several commercially available materials. Prototypes of single stage and a multistage compressors are presented together with experimental evaluations. Insights on a Tube-in-Tube heat exchanger, as another part a the Joule-Thomson cryocooler, intended to integrate with the Knudsen compressor, are also presented.

1. Introduction

Thermal management is a critical part of spacecraft design and performance. Generally, every piece of equipment has a specific temperature range which is appropriate for its working condition. A spacecraft contains components/systems that are required to be significantly cooled, down to cryo temperatures (below -150 °C). These components are often critical for the mission such as optical subsystem in an observatory spacecraft. For example, a telescope detector is required to be kept at cryogenic temperature to detect very faint IR waves from long distance [1]. A cryogenic cooler is a type of thermal management system that maintains cryogenic temperature at a desired location. Conventional cryogenic systems are generally large and heavy, mostly because of its compressor (a small and low mass compressor replacing the conventional one are always welcomed). A Knudsen compressor can be one such replacement for a Joule-Thomson cryocooler. The Knudsen compressor developed at APR Technologies is small, lightweight, reliable and consumes less power than the conventional cryo compressor [2]. Since this compressor does not involve any moving parts, it does not introduce vibrations or wear and tear, which reduces its potential risk of failure compared to compressors with moving parts.

2. Joule-Thomson Cryocooler

Cryogenics have shown tremendous progress in the last 25 years [2, 3]. A cryocooling cycle, in general, is compared to the reversed Carnot cycle because its highest efficiency involves isentropic (constant entropy) processes. It is a virtual cycle because, in actual cases, the isentropic (ideal) processes are not possible as the entropy of the universe (*i.e.* system + surroundings) always increases. In the basic principle behind the reversed Carnot cycle, the heat is absorbed from the

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cold storage and transferred to the hot by applying work into the system. It is the exact opposite of the fundamental heat engine [2, 3, 4, 5]. The schematic of a Joule-Thomson (JT) cryocooler [2] is analogous to an actual refrigeration system consisting of a compressor, a heat exchanger, an expansion valve and a reservoir. The difference between a JT cryocooler with that of other refrigeration system is the throttling/expansion process that takes place in the JT valve. This expansion process is maintained at constant enthalpy unlike in other expansion valves. The cold output of the JT cryocooler is achieved by the fluid after going through several phases namely, compression, pre-cooling, heat exchange and expansion. The cumulative performance of each of the components in the system adds up to determine the efficiency of the entire cryocooler system.



Figure 1. Schematic of a Joule Thomson cryocooler. Blue colour indicates the cold flow and the green indicates the hot flow. The cryo device is kept inside the thermally isolated volume, at the coldest end of the nozzle.

The Joule-Thomson cooling cycle is based on the principle of expanding a pressurized gas through a special valve called the Joule-Thomson expansion valve, where throttling or fluid expansion takes place. Figure 1 represents a simple schematic of a JT cooler. The incoming gas is compressed while maintaining the same inlet and outlet temperatures. The pressurized gas is fed into series of components namely, pre-cooler to bring down the gas to room temperature, heat exchanger where the gas further cooled down and finally to the JT valve where the cooled pressurized gas is expanded maintaining the enthalpy constant (JT effect). The cycle is complete when the gas collects the heat from the targeted device. The JT effect can be seen only in nonideal gases. All the known gases are non-ideal, which implies the choice of the working fluid for the cryocooler is quite wide. However, the choice is narrowed by the inversion temperature property of the fluid which determines the energy required for it to achieve a positive JT effect (cooling effect) and cooling power.

3. Knudsen Compressor Overview

A Knudsen compressor compresses the gas using Knudsen diffusion. Knudsen compression takes place when a temperature gradient is imposed across a porous and low thermal conductivity transpiration membrane. The Knudsen membrane is selected based on the operating pressure and the mean free molecular path of the working fluid. To have a Knudsen diffusion, the pore size in the Knudsen membrane should be comparable (not larger than 10 times [6]) to the mean free molecular path of the gas flowing through it. Knudsen diffusion occurs when the molecules collides with the walls of the membrane rather than colliding with each other. The movement of molecules from the region with lower temperature to that of the higher temperature due to Knudsen diffusion is called thermal transpiration. The molecules get warmer as they reach the hot end and this is coordinated with the pressure increase that is proportional to the square root of the temperature. The governing equation of this flow is given as $P_H/P_C = (T_H/T_C)^{1/2}$. A higher pressure at the inlet of the JT valve leads directly to a lower temperature at the valve outlet [6]. Therefore, the compressor indirectly determines the capability of the cooling system.

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Figure 2. Temperature and pressure profile across a single stage of a compressor. Capillary and connector section refers to the Knudsen and insulation membrane respectively.



Figure 3. Temperature and pressure profile in a multistage compressor

The pressure inside a Knudsen membrane is built up due to the flow restriction of the gas molecules. Variation of the temperature, from low to high, across the membrane facilitates the thermal transpiration and the rise in temperature is reflected as a pressure rise as shown in Figure 2 [6, 7]. The Knudsen compressors that APR Technologies has designed consists of one Knudsen membrane per stage, surrounded by hot/cold Graphene-based Films(GbF) and thermally insulated to the next stage by membranes, as shown in Figure 3. The Knudsen membrane is cooled and heated with the help of GbF at its leading and trailing surfaces respectively. Copper rails (not shown) support these layers mechanically and is used as thermal busses to transport heat in and out of the GbF layers.

4. Design Procedure

A study carried out previously at APR technologies derived a targeted requirement for the JT cryocooler. This serves as an input to the design of the system level parts. The compressor should have an output of 10 bar for the correct function of other components of the JT-cryocooler as mentioned below. The cooling power of the cryocooler is required to dissipate 40 mW and maintain the cryo temperature below 150 K [7].

- Gas mixture: Nitrogen / hydrocarbon / (possibly noble gas)
- Pressure ratio: 1:10
- Heat load: 40 mW
- Heat exchanger efficiency: 95%
- Gas flow rate at normal conditions: 100-200 ml/min

The following compressor design and results will help to estimate the number of stages required to satisfy the compressor output pressure requirements.

4.1. Single-stage Compressor

A single stage compressor was designed as a technology demonstrator and for selecting the right Knudsen membrane. A schematic diagram of the single stage Knudsen compressor is shown in Figure 4, where the single Knudsen membrane is fitted into an Aluminium casing. Heat is applied with the help of Kanthal wire at one end and the other end is cooled with cold-water current inside copper tubes. The working gas used for this compressor is N_2 which has a positive JT coefficient at normal temperatures.



Figure 4. Various parts of a single stage Knudsen compressor



A suitable sealant was employed at vulnerable points to avoid leakage. The test setup of the single stage Knudsen compressor with the sensing elements can be seen in Figure 5. The hoses are connected to the gaseous source at the end. Flow control valves are equipped in the setup for letting in the gas and to test the compressor.

4.2. Multi-stage Compressor

Multiple Knudsen stages are required to realize a high-pressure ratio of the compressor. As the working fluid passes the Knudsen stages, the pressure is increased in tandem with the temperature. This implies that the temperature of the media needs to be lowered between the stages in order to have continuous flow. The design of multi-stage compressor is therefore different from the single stage compressor described above. The changes include the lighter plastic casing, the rectangular shape of the Knudsen membrane and the improved heating and cooling of the gas using porous sheets of graphene based films attached to copper heating/cooling blocks. These changes are made to easily increase the number of stages as required. As indicated in Figure 6, the stages are separated by a free flow and thermally insulating membrane (A). The stages themsels consist of a cooling GbF on the leading face (B), a Knudsen diffusion membrane (C) and a heating GbF on the trailing face (D). The multistage design uses a perforated GbF to facilitate loss-free gas flow. This is distinguished from the previously described single stage design, where a circumferential Aluminium contact serves as a thermal contact. To share a common cold and hot region, the GbF and other layers are bonded into a copper slabs. A multistage design involves stacking of layers in the order B-C-D[-A-B-C-D]_n

A – Insulating layer

B – Cold Graphene C- Porous Knudsen layer

D – Hot Graphene

outflow

Figure 6. Multi-stage Knudsen compressor design.

Single stage



Figure 7. CAD model of the multistage Figure 8. Assembled multistage compressor. compressor casing.

A four-stage and a three-stage Knudsen compressors were designed and fabricated. Figure 6 shows an eight stage cascade Knudsen compressor. The variation of pressure and temperature across the layers of the multistage Knudsen compressor is illustrated in Figure 3. At the end of every stage, there is a pressure rise and slight pressure drop before it enters the next stage. This drop-in pressure is due to the conversion of pressure energy into flow energy. The harmonic temperature variation across the layers corresponds to the compressor pressure accumulation.

4.3. Compressor Assembly and Test Setup

Inflow

Cold copper metal.

A viable casing for a four-stage compressor with proper support to hold everything together at the right position was 3D printed. The material used for 3D printing was ABS plastic. The CAD model of the final casing design is shown in Figure 7. The compressor core layers are bonded to the copper with the help of thermally conductive adhesive. It is then bonded to the compressor case to make the compressor leak proof. Copper on the top and bottom surface of the compressor are used for thermal contact for heating and cooling. The assembled compressor can be seen in Figure 8. The test setup for the compressor includes a cooling plate connected to the bottom of the compressor, a heater connected at its top surface, hoses connected to the source gas, sensing electronics connected to a computer and power supplies. Figure 9 shows the

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compressor mounted between the cooling plate and PCB heater. The laboratory test setup of the compressor, the sensing elements and data acquisition system can be seen in Figure 10.



Figure 9. Compressor mounted on a cooling plate.



Figure 10. Laboratory test setup of a multistage compressor.

5. Compressor Testing

5.1. Thermal Testing

To achieve thermal transpiration, the Knudsen membrane is cooled and heated at its leading and trailing surfaces respectively. The temperature profile of the compressor core is simulated in a finite element tool (NASTRAN/PATRAN). Figure 11 shows the temperature profile of the simulated model using the boundary conditions of 353 K at the hot GbF and 273 K at the cold GbF. For reference, the measured core temperatures were 76°C (349 K) and 10°C (283 K) in hot and cold end, respectively.



Figure 11. Multi stage thermal simulation: Temperature



Figure 12. Multi stage thermal observation using IR camera.

The temperature measurement by the IR camera is dependent on the emissivity of the observed materials that is preset in the camera. Since the observed materials are of different kinds and with different emissivity values for the current observation, the emissivity set in the camera is 0.86. Therefore, the temperature measured in the camera should only be seen only as a relative measurement. Thermal tests were carried out with the selected insulating layer, shown in Figure 12, in addition to only using an air gap for insulation, shown in Figure 13. An air gap can be considered as an interesting insulation layer as it reduces the complexity in the fabrication process as well as the weight. However, the thermogram does not show sharp temperature gradients which questions its usage as insulating "material" in this application.

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Figure 13. Multi stage thermal observation using IR camera (with air gap).



Figure 14. Bubbles leaked through the bulk material when the compressor was immersed in water and pressurized gas was passed into the inlet.

5.2. Buble Leak Test

The single stage compressor was leak tight and showed a leak rate of 10^{-2} mbarL/s which is nearly impossible to spot in the bubble leak test. The four-stage compressor enclosure was initially thought to be completely sealed after assembly. However, bubble leak testing by passing slightly pressurized gas across the compressor while it was immersed in water revealed this was not the case. Bubbles appeared around the compressor as shown in Figure 14. After several iterations of gluing over leaking areas it was concluded that the gas was leaking through the compressor enclosures bulk material (ABS plastic).

5.3. Performance Test

The single stage compressor produced very different pressure gradients for the various materials tested for the Knudsen compressor application. The performance of different membrane material is listed in Table 1. The most interesting material, Knudsen membrane, produced a pressure difference of 2100 Pa when subjected to a cold and hot temperature of 13°C and 99.9°C respectively. Due to the large amount of heating and cooling applied in the test setup most of the materials were observed to achieve a satisfactory temperature difference. The achievable pressure difference was however modest for all the material except two. The Knudsen membrane* showed the highest-pressure difference and the PMMA sheet the second highest pressure difference of only 150 Pa. PMMA was limited by the ability to surpass the gas. According to Bernoulli's principle when the flow rate increases, the pressure of the flow decreases. Due to this inverse proportionality of the flow rate and the pressure build up, the flow is stopped when PMMA sheet reaches the maximum pressure. Having the system at different pressure levels, it was inferred that the maximum compression was limited by leaks in the system.

The multi stage design allows for very simple variation in the number of connected steps. Three and four stage compressors were designed and fabricated. Initially the heater, the cooler, electronics and power supplies were turned on until the pressure of the compressor was stabilized. The data from the sensing elements were recorded and plotted in real time. Thermal transpiration was demonstrated over a period by varying the applied temperatures in the four-stage compressor. However, the temperature on the hot side of the compressor eventually melted the Knudsen membrane which in turn caused internal gas leaks that limited our success with the first multi stage compressor.

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Material	$T_{cold}(^{\circ})\mathbf{C}$	$T_{hot}(^{\circ})\mathbf{C}$	$\Delta T(^{\circ})\mathbf{C}$	$P_{max}(diff, Pa)$	flow (ml/min)
PI 0.02 μm	28	100.3	72.3	13	0.00
PI 0.2 μm	27.3	100.4	73.1	2.75	0.22
PI 1 μm	28.6	99.9	71.3	1.5	0.41
PMMA sheet	14.3	80.5	66.2	< 150	0.00
Silica aerogel	12	81.7	69.7	4	0.99
Open (ABS net)	12.2	82.6	70.4	0	0.00
Knudsen	13	99.9	86.9	2100	1.2
membrane*					
Thermal Wrap TM	11.6	79.4	67.8	< 1	0.14
Spaceloft TM	11.6	79.9	68.3	< 1	1.8

 Table 1.
 Summary of performance characteristics for different membrane materials.

 Temperatures are in Celsius [7]

* Material used is confidential

The three-stage compressor was therefore maintained very carefully at 349 K and 283 K at the hot and the cold end respectively. The three-stage compressor achieved a pressure difference of 290 Pa. This is far less than the single stage compressor and we believe this was due to leaks in the compressor casings bulk material. However, when the temperature is varied, the pressure also changed in accordance to it, which indicates that the compressor is functional and behave more as expected.

6. Heat exchanger and JT valve combination

After the design and development of the Knudsen compressor, the next logical step is to integrate it with the other part of the JT cooling cycle, i.e. the heat exchanger and JT valve. Depending on the pressure ratio and the temperature required at the cold end, these parts may vary in dimension and specifications. However, with a holistic view, they were conceptually designed and tested.



Figure 15. Heat exchanger and JT valve combination.

As a next step, a Tube-in-Tube heat exchanger with a length in the order of a few tenths of

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centimeters was designed and fabricated. The dimensions of the Tube-in-Tube heat exchanger were updated in system iterations to meet the JT cryocooler requirements and are kept confidential. While tested for short duration of less than an hour, with pressurized CO_2 , the heat exchanger achieved a 7.5°C temperature decrease for a 5 bar CO_2 pressure. Figure 15 shows the miniature Tube-in-Tube heat exchanger that was developed and tested in the laboratory at APR Technologies. The test was conducted with the CO_2 gas and a prominent temperature was obtained at the cold end of the heat exchanger. A JT valve and thermally isolated volume are being developed to integrate a complete JT-cryocooler system

7. Results and Conclusions

The two key factors to increase the pressure ratio of the Knudsen compressor are the number of stages and the temperature difference across the Knudsen membrane. The number of stages of the compressor is limited by the weight as well as the complexity in fabrication. The temperature difference is also limited by the properties of the Knudsen membrane to take up the hot/cold temperatures without deformations. Three Knudsen compressors (Single stage, three stage and four stage compressors) were developed at APR Technologies and their performance were recorded. In all the three compressors, the GbF reached 90% of the applied hot/cold temperatures at the Knudsen membrane. Additionally, pressure gradients achieved by two of the compressors were recorded. The single stage compressor showed a good pressure difference of 2100 Pa while the three-stage compressor produced a pressure difference of only 290 Pa. The drastic pressure loss in the three-stage compressor was due to bulk gas leakage in the 3D printed ABS plastic case that was implemented for weight reduction and ease of manufacturing and assembly. The four-stage compressor developed a gross leak due to multiple thermal transpiration tests conducted on it, which prevented pressure measurements. The stage pressure ratio for each of the compressor were computed to 1:1.1. To achieve the JT cryocooler requirement of 1:10 pressure ratio, it is expected to have at least a 24-stage compressors. However, with design improvements we believe it is possible to reach the specified compression ration with far fewer stages. The Knudsen compressors developed at APR Technologies are light weight, do not contain any moving parts and consumes minimal power. For example, the four-stage compressor that was developed weighs less than 150 grams and consumes 12 Watts power to induce the thermal energy needed for its operation.

8. Future Work

First and the foremost, the compressor enclosure is to be replaced with non-leaking bulk material. This bulk material shall be molded plastic or a lightweight metal that can withstand the operating pressure range. Temperature limitation at the hot end to avoid melting of the Knudsen membrane is also foreseen. Further, the compressor will be integrated to the other company made parts of the cryocooler system. The fully developed cryocooler is expected to undergo normal space qualification tests including radiation, thermal cycling and vibration. Optimization is required to be done essentially in the functionality, cost, reliability, weight, lifetime and power requirements of the system.

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