Development of a J-T Micro Compressor

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Abstract. Lockheed Martin has developed and tested a space-quality compressor capable of delivering closed-loop gas flow with a high pressure ratio, suitable for driving a Joule-Thomson cold head. The compressor is based on a traditional “Oxford style” dual-opposed piston compressor with linear drive motors and flexure-bearing clearance-seal technology for high reliability and long life. This J-T compressor retains the approximate size, weight, and cost of the ultra-compact, 200 gram Lockheed Martin Pulse Tube Micro Compressor, despite the addition of a flow-rectifying system to convert the AC pressure wave into a steady flow.

1. Background and Motivation
In 2013 Lockheed Martin introduced a very compact and lightweight Pulse Tube Cryocooler [1], the Micro Cryocooler (figure 1). A major part of this development was the design of the Micro Compressor (figure 2) which, at 90 mm long, weighs less than 200 grams. This makes it small enough, for example, to fit in a single CubeSat unit. However this miniaturized compressor retains our space-quality architecture and technology to assure long life and high reliability. This design was conceived not only to be small and light, but also amenable to low cost and high volume production. Both the component parts fabrication and the assembly processes are based on established mass production-type processes.

Figure 1. Lockheed Martin Micro Cryocooler
Figure 2. Micro Compressor
With the establishment of the pressure-pulse Micro Compressor as a baseline mechanism, there was interest from various sources to adapt this technology to produce a constant, DC flow of compressed gas while still maintaining the advantages of the clearance-seal, flexure-bearing motor modules (figure 3) of the baseline mechanism. To this end, the addition of a pulse-rectifying mechanism to the output of the compressor was pursued and resulted in the development of the J-T Micro Compressor.

![Micro Compressor Motor Module](image)

**Figure 3.** Micro Compressor Motor Module

### 2. Rectifying Scheme

The center Hub of the Micro Compressor serves to mount two individual Motor Modules and to combine and port the pressure pulse from the pistons. In order to achieve a high DC pressure ratio for the J-T system, it was necessary to implement a two-stage pump, separating the compression spaces of the two pistons, and using a pair of check valves for each (figure 4). An intermediate reservoir volume connects the two stages and buffers the pumping action.

![Schematic of 2-stage pump](image)

**Figure 4.** Schematic of 2-stage pump
3. Check Valve Development
The heart of a flow rectifying mechanism is a one-way valve, or check valve. Ideally such a valve will allow uninhibited flow in the forward direction while blocking it in the reverse direction.

3.1. Valve Design
A mechanically simple implementation of an effective check valve is the classic flapper valve: a flat flexible flap cover positioned over a ported orifice plate (figure 5), the “diving board” valve. The only moving element is the thin flexible flap that is alternatively pushed closed over the port, or blown away from it by the alternating flows. In this way it is passively self-actuating.

![Figure 5. Flat flapper check valve](image)

For this application, our valve had to be not only mechanically simple for reliability, but also extremely small to fit into the compressor where it could be positioned close to the compression space to minimize any dead volumes. One of the major challenges of working at this small scale is that components must be conceived within the confines of a plausible manufacturing process to be viable and cost effective. The solution was a circular-shaped valve assembly with a double-reverse flexing flap, the Micro Check Valve (figure 6).

![Figure 6. Micro Check Valve](image)
The reverse-bending flap design compresses the size of the flexing element to fit within a smaller dimension while still having the effective bending length necessary to keep stresses low (figure 7).

![Figure 7. Reverse bend flap length](image)

In addition, the reverse bend counters the progressively steeper bending angle of the straight flap to affect a more uniform opening at the port orifice (figure 8). This improves the flow in the open condition.

![Figure 8. Reverse bend flap angle](image)

FEM analysis of the flap stresses insured that the operational flexing stress stayed well below the fatigue limit of the material and the resulting deflections produced the desired geometry in the open condition (figure 9).

![Figure 9. Reverse bend flap analysis](image)
3.2. **Valve Construction**

The Micro Check Valve is comprised of three parts: the round Base with a ported orifice, the reverse-bending Flap, and a protective Cover. The Cover serves to protect the Flap and limit its flex excursions to prevent overstressing. It also forms the top half of the clamping bars which securely anchor the root of the Flap. The Base is relieved to form the bottom half of the clamping bars and to provide clearance for Flap bending. The remaining unrelieved circular ring forms the valve seat (figure 10). This geometry precludes any wedging action at the flap root which can trap debris and inhibit complete valve closure.

![Figure 10. Micro Check Valve cross section](image)

The entire valve assembly fits in a 5 mm diameter bore and is less than 1 mm thick (figure 11).

![Figure 11. Prototype Check Valve](image)
3.3. Valve Performance
Prototype valves were successfully manufactured using chemical milling and tested in a DC flow environment to measure static flow characteristics and pressure capabilities. This testing demonstrated a forward to reverse DC flow ratio of 200 to 1 (figure 12) and a back pressure survival capability of at least 250 psi (differential pressure).

![Figure 12. Micro Check Valve flow tests show 200 to 1 forward to reverse ratio.](image)

4. Rectifying Hub Integration
The Micro Check Valves were incorporated into the compressor with a goal of minimizing dead volumes in order to maximize output. The resulting design manages to retain a single-piece Hub with the addition of four radial bores and simple drilled internal passages (figure 13). Each bore is fitted with a check valve, located at the bottom near the piston head, adding minimal dead volume to the compression space. One bore becomes the input reservoir and another the output reservoir. The two remaining bores are connected internally by cross-drilling to form the intermediate reservoir volume. Smaller cross bores link the in/out valve sets while intersecting their compression spaces. Retaining clips are used to keep each valve seated against an O-ring seal at the bottom of the bore.

![Figure 13. Cross sections of 4-valve Hub](image)
With this compact arrangement the overall size of the J-T Hub has been kept the same as the Hub for the Pulse Tube Compressor. Thus the rectifying system was added without an increase in the size or weight of the Compressor. A prototype hub was readily fabricated using conventional NC machining techniques (figure 14).

For long-life applications, the two intermediate bores are capped and welded closed for hermetic sealing. Removable caps can be used for run-in cycles or shorter-duration applications. The other two bores are adapted to connect to the input and output lines using hermetic metallic seals.

5. Compressor System
To complete the J-T compressor system this Rectifying Hub is mated to two standard motor modules (figure 15) featuring clearance seals and flexure bearings. In this case, the modules are equipped with smaller diameter pistons than the Pulse Tube modules in order to produce the higher pressure ratios needed for J-T operations. However, the established processes for assembly, alignment, and welding of the motor modules are the same as those for the Pulse Tube Compressor. Commonality of the majority of parts and tooling ensure that the low cost and known reliability are maintained.
6. Performance Testing

System testing was done with a simple instrumented flow loop, since no specific cold head or circulation requirements were yet established. To characterize performance, the flow loop measured input and output pressures as well as mass flow of the gas. Argon was used as the baseline gas for testing.

The goal of this development was a 3 to 1 pressure ratio, which is a minimum needed for J-T cooler operation. This goal was nearly achieved—although at minimal flow—in the very first operation of the compressor. Subsequent refinements of the valve through improved finish of the sealing surfaces produced flow rates up to nearly 1 SLPM (Standard Liters per Minute) at that pressure (figure 16). Testing was done at an operating frequency of 110Hz, and system efficiency proved to be insensitive to small variations in speed (figure 17).

![Figure 16. Flow at 3 to 1 pressure](image)

![Figure 17. Drive frequency variation](image)

Higher flow rates, such as needed for lower-pressure circulation systems, can be achieved with this same compressor by using larger piston sizes in the motor modules and opening up the port hole in the check valve base. For maximum flow at low pressure, the Hub could be reconfigured into a single stage pump. This would have a common compression space for the two pistons so they operate in parallel, instead of in series, and use a single set of large-ported check valves.

7. Summary

A J-T Micro Compressor was designed, built, and tested to demonstrate the technology. The size, weight, and manufacturing costs of this J-T Compressor are essentially the same as our Pulse Tube Micro Compressor. And since it uses many of the same parts and processes, it can be readily adapted to the same high-volume, low cost manufacturing.

The development of the Micro Check Valve is covered in US Patent Application US2014/0216064 A1 and International Patent Application WO 2013043883 A1. The Rectifying Hub is covered in US Patent Application US2014/0013776 A1.

Although the obvious use, and indeed the title of this paper, points to J-T cryocooler systems, it is not limited to that application. Other uses for this compressor include long-life low power pumping of circulating systems, such as ambient or cryogenic remote cooling loops.

References

[1] Olson J R, Champagne P, Roth E, Nast T, Saito E, Loung V, Kenton A C and Dobbins C L, 2013 Advances in Cryogenic Engineering 59, 357-364