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Development and testing of a passive check valve for cryogenic applications

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ABSTRACT

Several cryogenic technologies use check valves, such as the Cold Cycle Dilution Refrigerator (CCDR) and the Hybrid Pulse-Tube/Reverse-Brayton Cryocooler. This paper details the development of a reed-style passive check valve with a PTFE seat for cryogenic applications. The experimental results of tests on the valve using helium gas at temperatures from 293 K down to 5.2 K, verify a scaling argument based on fundamental fluid dynamics that allows results from 78 K to be used in predicting valve performance at much lower temperatures. The scaling argument is then applied to a test conducted at the normal boiling point of Nitrogen to examine the results of improved fabrication methods.

1. Introduction

The following paper covers the development of a cryogenic check valve employing a passive, reed-style sealing technique. Experimental results of tests at temperatures ranging from 293 K down to 5.2 K, reveal that a scaling argument based on fundamental fluid dynamics can be used to predict valve performance at different states. The scaling argument is subsequently applied in further development of the valve.

Interest in this cryogenic valve was initially motivated by the requirements of a continuous Cold Cycle Dilution Refrigerator (CCDR). The CCDR is a sub-Kelvin refrigeration system for space based applications, such as Infrared and X-ray astrophysics missions. A continuous refrigerator capable of cooling to temperatures below 100 mK, it is based on concepts developed by Miller and Brisson [1] and makes use of a novel thermal magnetic pump currently under development by Miller [2]. The pump takes advantage of the fountain effect in ^{4}He to produce reciprocating flow of a ^{3}He–^{4}He mixture, which is rectified by means of a series of check valves. Requirements for the valve are summarized in Table 1, and are based on an in-depth analysis of the CCDR refrigeration cycle [3].

However, as is shown in later sections, the process of reed and seat preparation necessary to meet these specifications makes this specific design difficult to implement in the CCDR, and some investigation into actively actuated valves will be required. The information presented, however, does advance the understanding of reed type check valves operating at cryogenic temperatures. The scaling argument presented also serves to provide the tools to quickly and affordably test valves with a similar geometry and materials, including active designs. For further information see [4].

1.1. Previous work

Previous work on passive, reed style check valves has been reported by Veenstra et al. [5]. They designed, fabricated and tested a very low leakage stainless steel seated, gold coated, reed type valve for application in a sorption compressor. The sealing rate was found to be as low as 6 μg/s with a sealing pressure of 10 bar. However the pressures involved in their system were orders of magnitude higher than the range involved in the CCDR.

Work done by Nellis and Maddocks on a brass seated reed valve for a hybrid Pulse Tube/ Reverse Brayton (PT/RB) cryocooler provided the basis for the design of the check valve presented in this paper. The PT/RB had both higher pressures and lower flow rates than the CCDR [6].

2. Valve design

This valve is designed to take advantage of our experience with Kel-F seated manually-actuated valves, as well as experience with passive metal seated reed valves. The basic principle of a Kel-F seated valve is to apply a manual preload at room temperature

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Table 1
Check valve requirements for the CCDR.

Requirement	Symbol	Value
Working fluid		^{3}He–^{4}He mixture (~6% ^{3}He molar concentration)
Operating temperature	T_{valve}	1.8 K
Sealing pressure difference	ΔP_s	10–20 kPa
Forward flow pressure drop (1% of sealing ΔP_s)	ΔP_{ff}	100–200 Pa
Forward flow rate	$\dot{m}_{ff}$	3.94–9.20 mg/s
Leakage rate (1% of forward flow)	$\dot{m}_S$	39.4–92.0 μg/s

and maintain the preload as the valve cools down. At approximately 100 K the Kel-F goes through a phase transformation that "freezes" the sealing surface into the shape of the corresponding steel boss. The preload is released at low temperatures (below 100 K) and very little force is required to reseal the valve since the two surfaces match [1]. The work in this paper applies the same principle to a passive reed valve using pressure as a preload. Polytetrafluoroethylene (PTFE) is chosen as the seat material for the valve because it undergoes a transition similar to what occurs in Kel-F at approximately 170 K, but it is slightly softer than Kel-F at room temperature [7]. A preload pressure difference is applied across the reed at room temperature and maintained while the valve cools below 170 K, after which, in principle, the preload can be released and the valve will continue to seal, since the PTFE will not relax back to its original shape until it is warmed up.

The valve body is fabricated in two sections that bolt together. A hermetic seal is accomplished by use of an indium o-ring. The PTFE seat is epoxied in place; PTFE is notoriously difficult to wet with epoxy so the seat is treated with FluoroEtch to create a bondable carbonaceous layer, with care taken to avoid etching any of the sealing surface in contact with the reed. The reed is then installed and the body assembled. A schematic of the valve is shown in Fig. 1. After completion of the first few tests it became evident that frozen particulates were a problem, so a filter was added to the design consisting of screens punched out of a stainless steel weave. These filters can block particles larger than 10 μm in diameter.

3. Test facilities

To fully characterize the check valve, two test facilities are employed: a cryocooler facility and a liquid nitrogen facility. The primary purpose of each is to characterize the leakage flow rate of pure ^{4}He gas, i.e., the mass flow rate through the closed valve

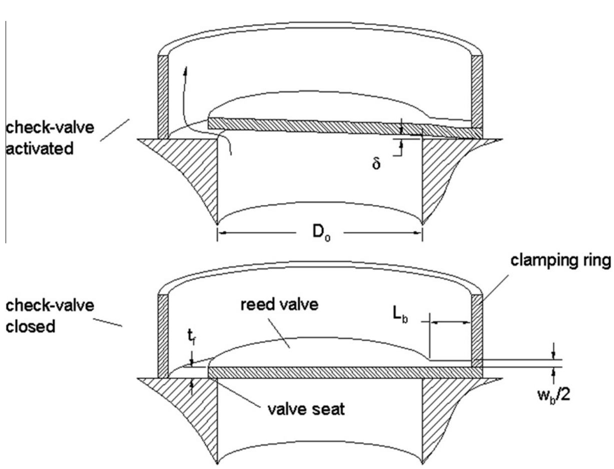

Fig. 1. Schematic representation of check valve design.

with a back pressure applied. The liquid nitrogen test facility also has the capability to test the mass flow and associated pressure drop with flow moving in the forward, or open, direction. The cryocooler facility provides a continuous profile of the leakage mass flow rate for temperatures from 293 K down to approximately 6 K. The liquid nitrogen test facility allows for quick and cost effective testing of various valve iterations.

3.1. Cryocooler test facility

The cryocooler providing a platform for mass flow rate measurements with a variable temperature is a Cryomech PT-410. The PT-410 has a cooling power on the 1st stage of 35 Watts at 45 K and on the 2nd stage of 1 Watt at 4.2 K. A full discussion of the PT-410 cryocooler and temperature sensor calibration can be found in Reference 2 [8]. Since the cooling power of each stage is dependent on the heat load applied, the heat exchangers for each platform are designed with additional length such that the ^{4}He gas flowing through always exits at the given stage's temperature. Between parasitic heat leak and the actual load of the gas, the 2nd stage temperature remains above the critical point of ^{4}He and thus the working fluid is in the gas phase for the entire test. Given the small flow rates involved, the flow loop is open, with the inlet of ^{4}He supplied from a bottle and the outlet venting to atmosphere. Plumbing and valve location also allow the flow to run in both the forward and reverse directions (open and closed) to verify that no blockages are present in the test giving a false positive reading on valve sealing. For instrumentation, the cryocooler test facility has Cernox temperature sensors mounted on the 1st and second stages, as well as the valve itself. The Cernox sensors are calibrated with an accuracy of ±.025 K in the temperature range of .1 to 77 K and ±.153 K from 77 to 300 K. Pressure taps are located before and after the valve to find the pressure drop across the valve. Endevco 8510B-500 pressure transducers are used to measure the gauge pressure and, with a known atmospheric pressure, the absolute pressure from each of the taps. To measure higher flow rates two Omega FMA1700/1800 flow meters with ranges of 0–500 standard mL/min (0–2 mg/s ^{4}He) and 0–2 standard L/min (0–8 mg/s ^{4}He) are upstream of the valve. These have accuracies of .005 mg/s ^{4}He and .021 mg/s ^{4}He respectively. A second volume accumulation type flow meter is used for very small flow rates. Essentially, it consists of a graduated cylinder upended in a larger beaker filled with water. The outlet of the valve flow loop is piped into the graduated cylinder, displacing the water. The volume accumulated was measured in mL increments and the resolution of this device is only limited by the time waited for a volume to accumulate (e.g., waiting 30 minutes for .5 mL to accumulate results in a helium mass flow rate of .09 μg/s).

3.2. Liquid nitrogen test facility

The liquid nitrogen test facility is used to conduct timely and cost-effective experiments on various valve iterations. The facility consists of a valve mounted between two heat exchangers, all of which is submersed in liquid Nitrogen. Operation consists of installing the valve, applying the required preload/preparation steps, and slowly lowering the facility into liquid nitrogen. The valve and heat exchangers are considered to be isothermal after nucleate boiling has collapsed (implying that the material is approximately at the saturation temperature of the surrounding nitrogen). The heat exchangers are coils of copper tubing designed such that the helium gas reaching the valve in both the forward and reverse directions is at the temperature of the surrounding nitrogen. The facility is configured to allow helium flow in both the forward and reverse directions, and is instrumented to measure the pressure drop in both directions. The same endevco