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DESCRIPTION OF A HIGH-EFFICIENCY FLOATING-PISTON EXPANDER FOR A MINIATURE CRYOCOOLER

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ABSTRACT

A cryogenic expander employing low-temperature helium is under development. This expander employs a floating piston operating between a warm variable volume and a cold variable volume to expand the working fluid. The piston's position is dynamically regulated through an active control routine that actuates electromechanical valves. These valves control helium flow in and out of the variable volumes. Throttling through the warm-end valves regulates the piston's velocity. The cold-end valves, operating at cryogenic temperatures, are of novel design to achieve system miniaturization and high efficiency at range of operating points.

INTRODUCTION

A floating piston reciprocating expander is being developed at the MIT Cryogenic Engineering Laboratory and at Advanced Mechanical Technology, Inc. This work is a continuation of previous research by Jones and Smith [1,2]. The basic concept is described in a US Patent [3]. Three of these expanders will be incorporated into a three-stage modular Collins-cycle cryocooler that is being designed to achieve one Watt of cooling at 10 Kelvin.

As shown in Figure 1, the expander consists of a cold expansion volume that is cycled by the motion of the floating piston. The working fluid is high-pressure helium, which enters the variable cold volume through a cold electromechanical inlet valve, v_{in}. This valve operates at the expander inlet's cryogenic temperature. The floating piston travels within a cylinder extracting work from the helium in the cold volume by compressing gas in a room-temperature warm volume. The expanded helium leaves the cold volume through a cold electromechanical exhaust valve, v_{ex}. The outlet valve operates at the expander outlet's cryogenic temperature. The motion of the floating piston is controlled by the flow of room-temperature helium into and out of the warm volume through valves v_1, v_2 and v_3.

The warm end contains three electro-mechanical valves (v_1, v_2 and v_3) that control the timing and rate of flow of the room-temperature helium into and out of the warm volume. Through throttling action, the warm valves determine the velocity of the floating piston. Minimum throttling occurs through the cold valves (v_{in} and v_{ex}). As a result of the slow throttling processes in the warm valves, the pressures in the warm and cold volumes are nearly the same throughout the cycle. Since the pressure difference across the floating piston is small, the need for piston rings is eliminated and the clearance seal between the piston and the cylinder wall provides adequate sealing.

The cold end inlet and outlet valves are of novel electro-mechanical design. These valves are timed to open when the pressure difference across the valve is small and the piston is at an extreme position. This measure avoids impact between the piston and the cylinder heads at the end of the piston travel. A pulse of electrical current is applied to open the cold valves. This signal is shaped to minimize the electrical and mechanical dissipation in the valve. A high current is applied to initially open the valve and a much smaller current is then used to hold the valve open. The cold valves are held closed by the gas pressure difference across the valve ports and by a permanent magnet acting as a valve spring.

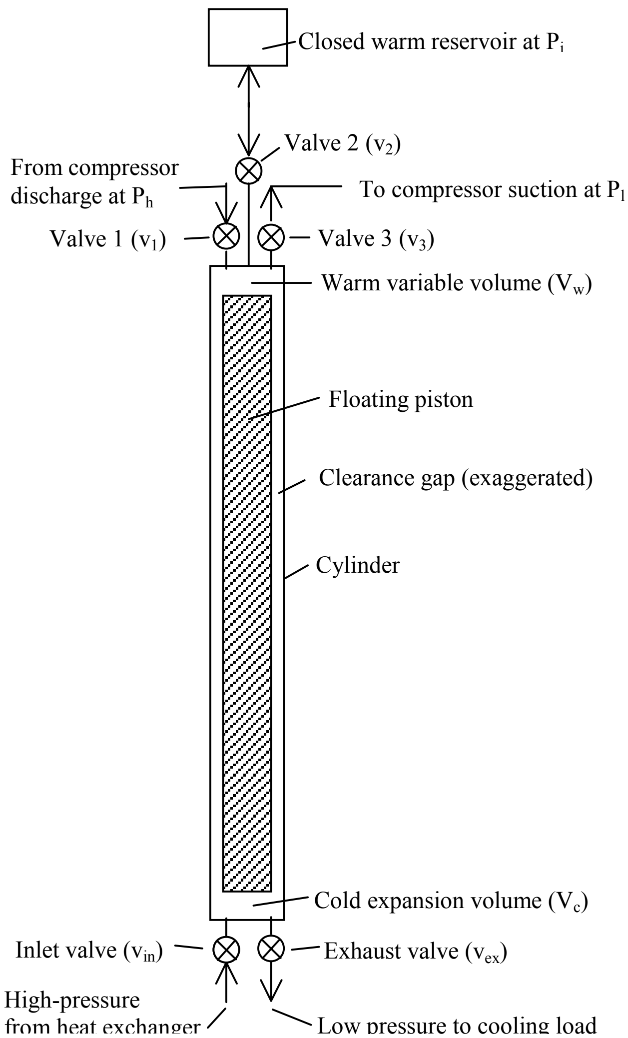

Figure 1. Schematic diagram of the floating piston expander

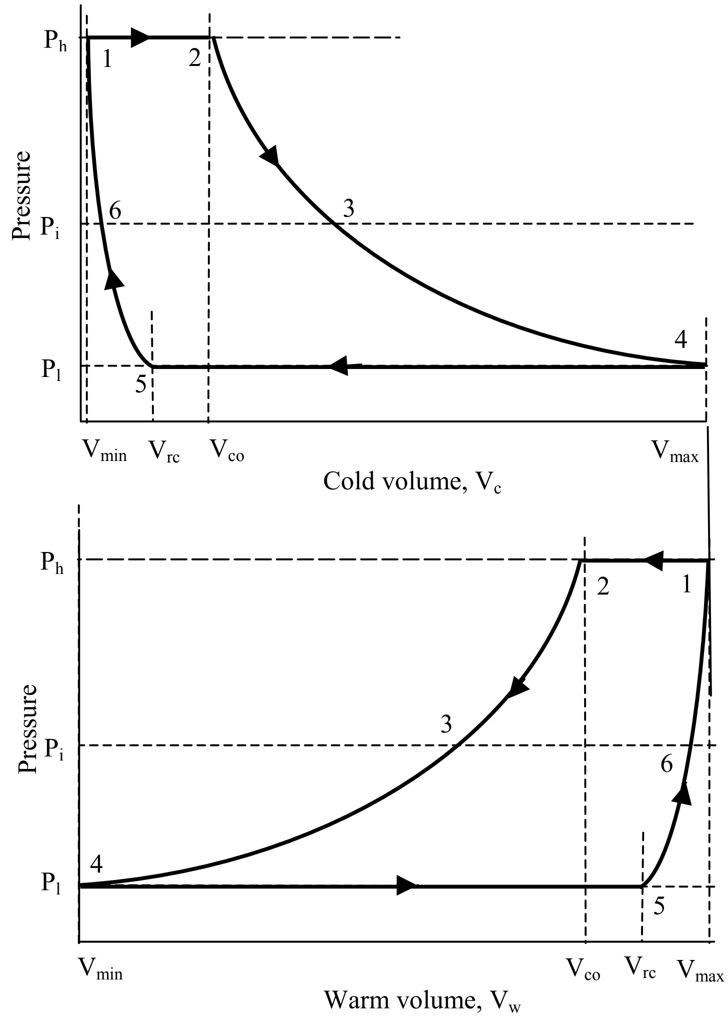

Figure 2. Ideal pressure-volume diagrams for the cryocooler cycle

Both the cold and warm valves are controlled by a digital data acquisition and control board in a PC. The PC board monitors the warm-volume pressure and piston position. A LabView program actively controls the opening and closing of each valve so that the expansion of the helium in the cold volume approximates a reversible adiabatic process as shown in Figure 2. The cold end expansion process is expected to achive an adiabatic efficiency of 75 percent, based on extensive experience with mechanically operated expanders operating under similar conditions.

Conventional cryocoolers of the G-M type and of the pulse tube type suffer significant losses associated with the pressure cycling of the thermal regenerator. This loss becomes even more significant at temperature of 10K and below because of the limited heat capacity of regenerator packing materials. Conventional cryocoolers are limited to practical pressure ratios of 3 or smaller by these losses. In contrast the floating piston expander allows cryocoolers to utilize pressure ratios of 15 and the utilization of constant pressure heat exchangers.

NOMENCLATURE

- v_1 Warm-end inlet valve connecting the compressor discharge to the warm volume
- v_2 Warm-end two-way valve connecting the warm volume to the intermediate pressure reservoir
- v_3 Warm-end outlet valve connecting the compressor suction to the warm volume
- v_{in} Cold-end inlet valve connecting high pressure pre-cooled helium to the cold volume
- v_{ex} Cold-end exhaust valve connecting expanded helium to the cooling load
- V_c Cold-end volume
- V_w Warm-end volume
- V_{co} Cold-end cut-off volume
- V_{rc} Cold-end recompression volume
- P_I Intermediate pressure of the warm intermediate pressure reservoir
- P_h High pressure of the compressor discharge
- P_l Low pressure of the compressor inlet

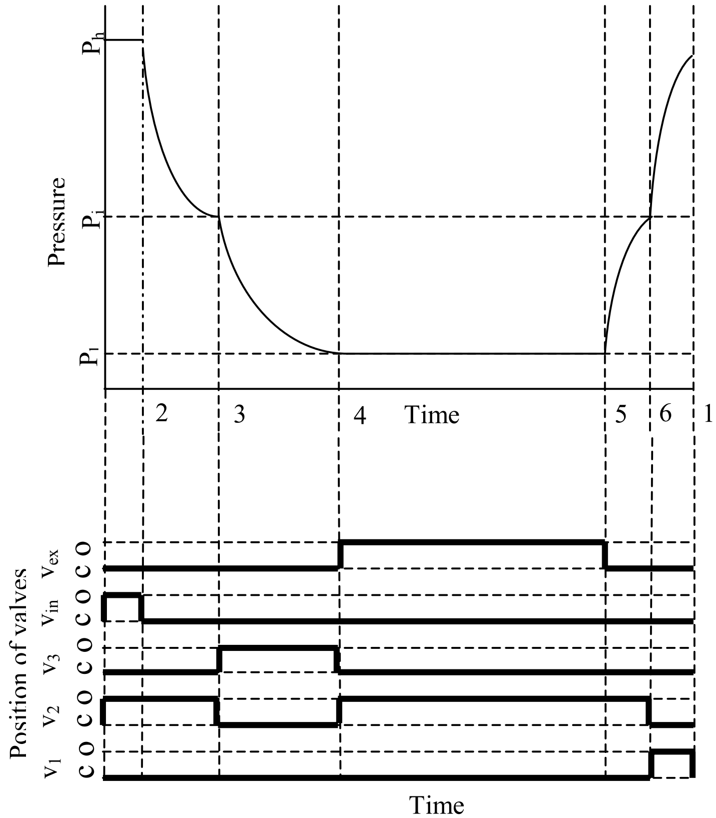

Figure 3. Pressure and valve actions versus time for each expander cycle process

EXPANDER CYCLE

In steady state operation as shown in Figure 3, the cycle of the expander starts with the piston in the position where the cold volume, V_c is a minimum and the pressure is at the compressor discharge pressure, P_h. The piston is floating so that the pressure in the warm volume, V_w, is the same as in the cold volume, V_c. The two cold valves, v_{in} and v_{ex}, and the three warm valves, v_1, v_2 and v_3 are all closed.

Process 1 - 2

The cycle begins when the inlet valve, v_{in}, is opened. There is no flow since the pressures are equal across the inlet valve. As soon as the inlet valve is open, v_2 is opened allowing helium to flow from the warm volume, V_w, into a reservoir at an intermediate pressure, P_i. The flow through v_2 is throttled so that the rate of flow of helium from V_w is controlled. As the helium flows out of V_w, the floating piston moves, shrinking the warm volume, while cold helium flows into V_c keeping the pressure constant at the compressor discharge pressure, P_h. When the cold volume has reached a predetermined cut off volume, V_{co} the inlet valve is closed. The cut off volume, V_{co} is selected so that the piston comes to a stop as it reaches the warm end of the cylinder at the end of process 4-5.

Process 2 - 3

With v_{in} closed and helium still flowing from V_w into the warm reservoir at P_i, the pressure in V_w decreases. The pressure in V_c tracks the pressure in V_w since the floating piston is free to move toward the warm volume. The pressure continues to fall until the pressure in the cylinder is essentially at the intermediate pressure P_i.

Process 3 - 4

When the pressure reaches P_i valve v_2 closes and valve v_3 opens. Helium flows from V_w through the throttle of v_3 to the compressor-suction pressure, P_l. The piston continues to shrink V_w as gas flows out of the warm volume. The pressure in the cylinder decreases to P_l or nearly to P_l.

Process 4 - 5

When the piston reaches the warm end, valve v_3 closes and cold exhaust valve, v_{ex} opens. The piston does not move significantly since the cylinder pressure is essentially P_l. After v_{ex} opens, valve v_2 opens allowing helium from the P_i reservoir to flow into V_w through the throttling action of v_2. As the helium flows into V_w the piston moves shrinking the cold volume, V_c. Expanded, cold helium flows out through the exhaust valve, v_{ex}. This cold helium flows to the cooling load. The helium is then returned to the cold end of the recuperative heat exchanger (not shown). The piston continues to move into the cold volume until V_c has reached the recompression volume V_{rc}. The helium trapped in V_c is for recompression. V_{rc} is selected so that the gas trapped in the cold volume is compressed to P_h at the end of process 6 - 1.

Process 5 - 6

When the cold volume reaches V_{rc}, the next process of the cycle begins. The exhaust valve, v_{ex} closes and helium continues to flow into V_w from the intermediate pressure reservoir. With v_{ex} closed the flow into V_w increases the cylinder pressure until the pressure is essentially at P_i. The helium confined within V_c is recompressed from P_l to P_i.

Process 6 - 1

When the recompression pressure reaches P_i, valve v_2 closes and then valve v_1 opens. Helium is throttled from P_h through v_1 into the warm volume, V_w. The pressure in the cylinder increases to P_h or nearly to P_h. The helium trapped in V_c is recompressed to P_h. When the pressure reaches P_h, valve v_1 closes and the expander is back to the initial condition for the next cycle.

EXPANDER COLD VALVES

The two primary motivations for utilizing low-temperature electromagnetic actuators for the cold end valves are: (1) to create a compact design and (2) to provide dynamic control of the expander cycle. Electromagnetic actuators do not require bulky room temperature actuating cams, mechanisms and long actuating rods that drive conventional cold mechanical valves. The control program can easily modify the timing of the electric currents actuating the valves so that the expander cycle can be modified during operation. The timing of mechanically operated valves is fixed. The work on the electromagnetic actuators is a continuation of research by Ceridon and Smith [4, 5].

As shown in Figure 4, the valve design is similar to the multi-ported check valves found in conventional reciprocating gas compressors. The inlet valve disk and solenoid yoke are located outside of the cylinder head plate. The exhaust valve disk and solenoid yoke are placed around the cylinder at the cylinder head plate. For both the inlet and exhaust valves,

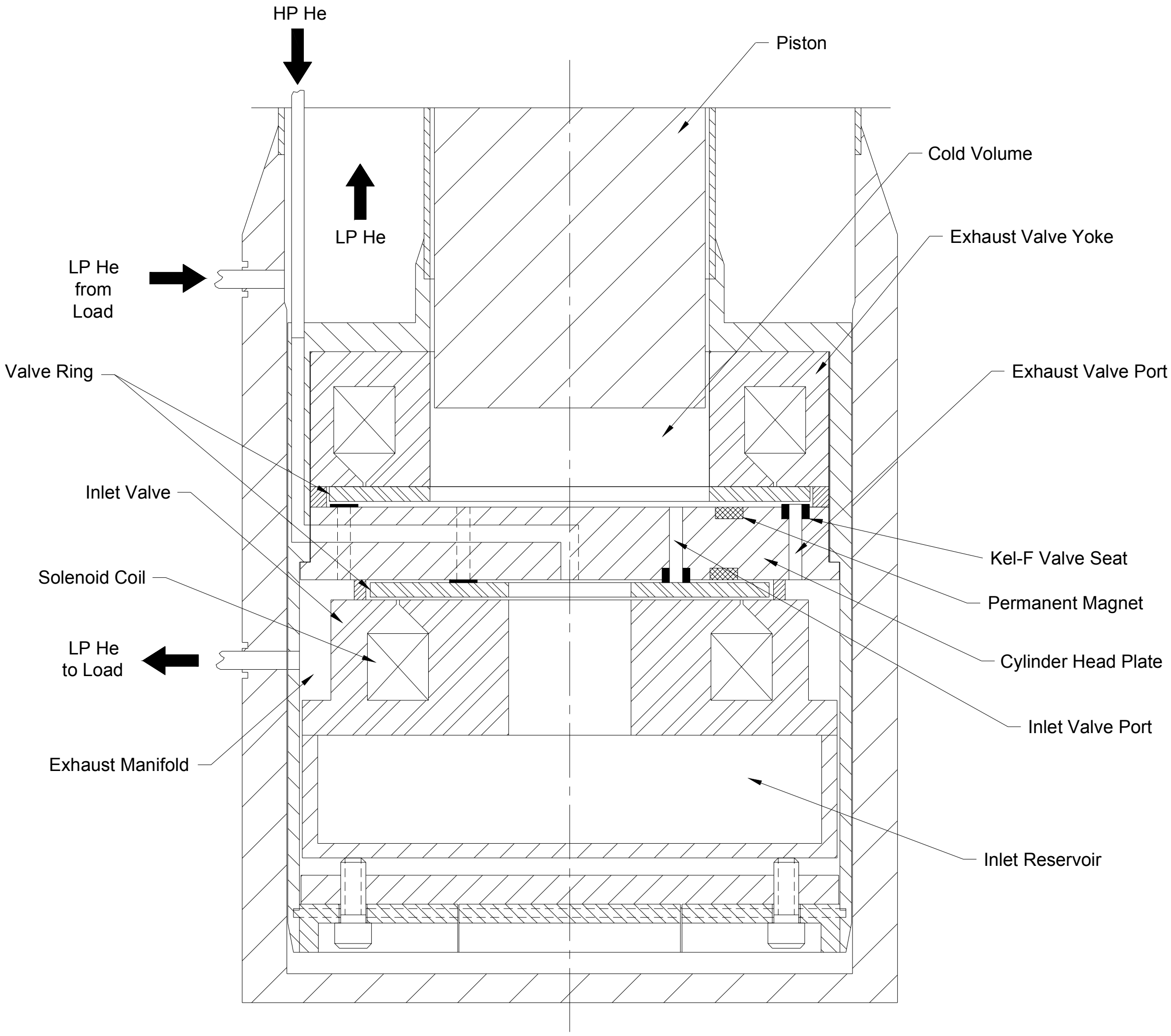

Figure 4. Schematic cross section of the expander cold end showing the annular valves

action is by the motion of a valve ring relative to a valve plate, which is also the cylinder head of the expander. When against the plate, the valve ring is held against the valve seats by the gas pressure difference across the valve ports and by permanent magnets acting as a valve spring. The valve is opened by a magnetic field that pulls the valve disk away from the plate. The valve port area of each valve consists of eight small-diameter holes through the plate equally spaced on a circle. As in compressor valves, multiple ports with small dimensions provide a small valve lift for the required flow area. The small lift allows an optimum magnetic design for a quick opening and closing valve with minimum impact stress.

The axisymetric magnetic configuration of the valves is shown in Figure 4. A toroidal yoke of ferromagnetic stainless steel surrounds a ring coil of copper wire. The valve ring of ferromagnetic stainless steel is separated from the flat face of the yoke by a small air gap that decreases as the valve ring moves to open the valve. When current flows in the coil, magnetic field flows through the yoke, across the air gap, through the valve disk and back to the yoke creating closed flux lines around the coil. The magnetic field crossing the air gap causes an attractive force between the valve yoke and the valve ring. This attractive force is sufficient to lift the valve ring off of the non-magnetic cylinder head plate against the gas pressure difference across the valve. A large flux path area and a small air gap thickness give a large force for a given number of ampere-turns in the coil. When the current is turned off the attractive force between the yoke and the ring is zero. The ring is pulled back to the cylinder head plate by permanent magnets mounted in the plate and by the pressure difference generated as the gas flow is interrupted.

The valves are designed for long life and bubble tight sealing when closed. Non- metallic valve seats of PolyChloroTriFluoroEthylene PCTFE, "Kel-F," plastic are used to avoid cold welding and galling in the cryogenic helium environment. The seats are crimped into recesses in the valve plate. For tight sealing the valve ring and the valve seat faces are accurately surface-ground flat and polished to a mirror finish. The contact pressure between the valve ring and the seats is high so that there is some elastic deformation of the valve seats to accommodate small inaccuracies in the sealing surfaces.

The inlet valve is a valve-in-head design so that the only clearance volume is the volume within the inlet valve ports through the cylinder head plate. On the other hand, the exhaust valve is a L-head design that requires radial gas flow from the cylinder to the valve ports. The clearance volume of this design is the area of the valve disk times the valve stroke. There is no clearance volume associated with the iron yoke or the ring coil since these components are fully potted with epoxy. The exhaust valve ports through the cylinder head plate do not contribute to the cylinder clearance volume.

The circuits that supply current to the valve actuator coils are designed to minimize the ohmic heating in the cold valve coils. A high current is supplied just long enough to crack the valve open. As the valve opens any pressure differential across the valve decreases rapidly and the force from the permanent magnets also decreases rapidly. This process allows a lower current to complete the valve opening and a much smaller current to hold the valve open. The low hold-open current is the result of the small air gap in the magnetic flux path when the valve is open. With a small air gap, a given current produces a much higher magnetic force between the valve ring and the yoke. The ohmic losses in the ring coil are much lower when the coil is at 10 K than when it is at room temperature because the resistance of copper is at least 1/30 of its room temperature resistance and can easily be as low as 1/80 for extra-high-purity copper.

A expander is being designed and constructed to demonstrate the floating piston concept. The piston diameter is 25.4 mm (1 inch) and the stroke is 25.4 mm (1 inch). The working fluid is helium with a high pressure of 1.5 MPa and a low pressure of 0.10 MPa. The inlet temperature for the cold expander is 10 K. The operating frequency is 1 Hz. The valve port diameter for each of the eight valve ports in each of the two cold valves is 1 mm (0.040 inch) and the valve ring lift is .025 mm (0.010 inch)

ACKNOWLEDGMENTS

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