Single stage double-inlet pulse tube refrigerator with integral thermo-electric cooler

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The use of Thermo-electric Cooler (TEC) at the warm end heat exchanger of a pulse tube refrigerator is explored in this paper. An attempt is made to keep the warm end of regenerator at a temperature lower than room temperature using TEC. Additionally, a cam operated pressure wave generator used in this system enhances the durability compared to that of both solenoid and rotary valve based systems. When operated with an air-cooled helium compressor of 1.6 kW capacity in double-inlet mode, it gives about 7 W refrigeration at 77 K and a no load temperature of about 40 K.

INTRODUCTION

For over two decades, in the area of Pulse Tube Refrigerator (discovered by Gifford and Longsworth [1] - Basic Pulse Tube) there have been significant advancements. Due to the absence of mechanical moving component at the cold side of the system, pulse tube refrigerators find applications in semiconductor fabrication, Charge Coupled Devices for astronomical telescopes, SQUID detection for non-destructive tests and medical applications where vibration and noise levels should be very low and the system should have high reliability.

DESCRIPTION

The schematic of a Double Inlet Pulse Tube Refrigerator (DIPTR) with integral TEC is shown in figure 1. The system without the bypass valve, orifice valve and the reservoir forms the Basic Pulse Tube Refrigerator [1] in which the hot end of the pulse tube is closed. The addition of reservoir and the orifice valve converts it to Orifice Pulse Tube Refrigerator [2]. In the Double Inlet Pulse Tube Refrigerator [3], there is a bypass valve between the regenerator and the pulse tube at the room temperature end. A medium pressure (17-20 bar) helium compressor and the pressure wave generator produce the required pressure oscillations. The regenerator contains a porous matrix, which absorbs heat from the gas when it goes towards the pulse tube and gives it off when the gas flows in the opposite direction. The pulse tube is an empty tube with heat exchangers (hot end HE and cold end HE) at both the ends. In the Basic Pulse tube mode, when the system is subjected to oscillating gas flow, due to thermo-acoustic effect (acoustically driven temperature effect), open end of the pulse tube is cooled and the heat is transported to the hot end where it is rejected in the HE. In the Orifice Pulse Tube, introduction of a needle valve

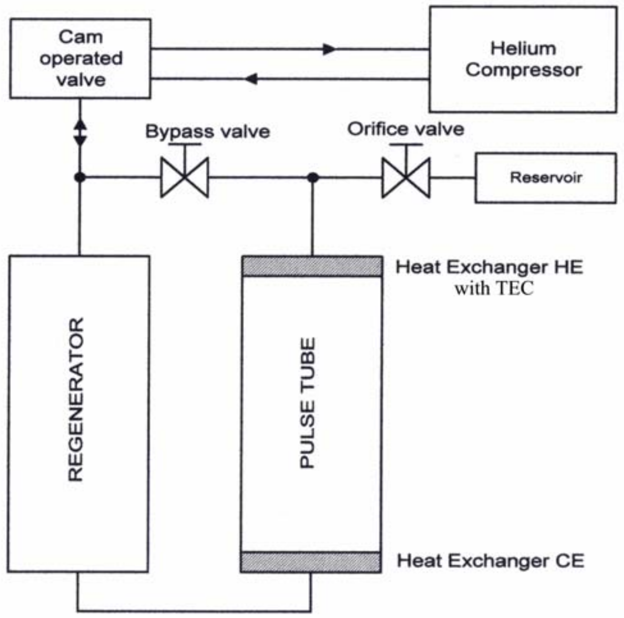

Figure 1. Schematic of DIPTR with TEC

(orifice) and a buffer volume (reservoir) enhance the performance. This arrangement creates the required phase shift between the pressure wave and the mass flow at the warm end, so that they are in phase at the cold end. Introduction of the bypass valve (Double Inlet Pulse Tube) improves the performance further by sending a part of the gas directly to the warm end of the pulse tube reducing the mass flow of the gas through the regenerator. Commercial needle valves by Hoke (1315G4B) are used for the above. The problem of non-symmetry in the flow coefficients in the forward and reverse directions is avoided by connecting a set of identical valves back to back in series. This way, the flow coefficient in the reverse direction becomes the limiting factor and the opening has to be accordingly increased.

The warm end heat exchanger consists of four numbers of Melcor make thermoelectric coolers (PT8-12-40) with suitable finned heat exchangers to dissipate the heat from the hot end of the TEC. With this arrangement, the hot end heat exchanger could be cooled to 288 K (15^{o}C) when the room temperature is 310 K while the pulse tube is being operated. This arrangement eliminates the water circulation system with or without mechanical refrigerator needed in the conventional systems. Additionally, another thermoelectric cooler kept inside the vacuum jacket is used to keep the warm end of the regenerator at 275 K. A switch mode power supply (SMPS) of 48 V and 6 A capacity is used for driving all the TECs. Each TEC module consists of 127 couples connected thermally parallel and electrically serial way. When operated with a 12 D.C. power supply, it draws 6 A current and is capable of removing around 60 W heat for zero ΔT between hot and cold faces. The maximum ΔT that could be achieved with the above power supply for Q = 0 (amount of heat that is removed from the cold face) is around 50^{o}C. The size of each module is 40 mm x 40 mm square and 3.3 mm width. Using CPU cooling fan of Pentium 4 computer, the heat from the warm end is dissipated. As 12 V D.C. is needed for operating this fan also, it is connected parallel to the TEC module. Figure 2 shows the design of the TEC setup coupled to the hot end heat exchanger of the pulse tube replacing the water circulating system.

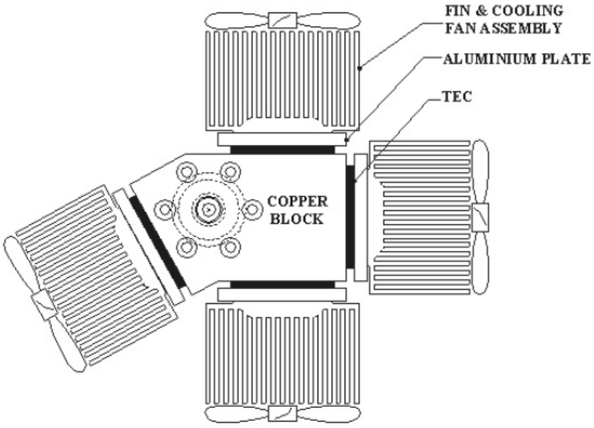

Figure 2. TEC arrangement at warm end heat exchanger

One of the critical components of the pulse tube system is the pressure wave generator. Usually a solenoid operated or a rotary valve operated pressure wave generator is used in the pulse tube systems [4]. While the solenoid operated pressure wave generator is prone to failure beyond a limited number of operations, the rotary valve system is likely to develop leaks in the sealing between the high/low pressure inlets and the outlet. For commercializing the pulse tube system, and for reliable and continuous operation for a very long period without failure, addressing the above problem and the use of TECs at warm end heat exchangers are important steps forward.

The schematic of the concept of a cam operated spring-loaded valve based pressure wave generator is shown in Figure 3. It consists of a set of spring-loaded valves coupled to the suction and discharge sides of the compressor. The outlets of both the valves are coupled together to form the common inlet to the DIPTR. A set of valve rods couples the valves to the cam mechanism. The rods are always kept under tension to avoid the leak at the valve seat. The cams can be rotated at varying speeds using a motor coupled to a variable frequency drive. Similar cam operated systems are

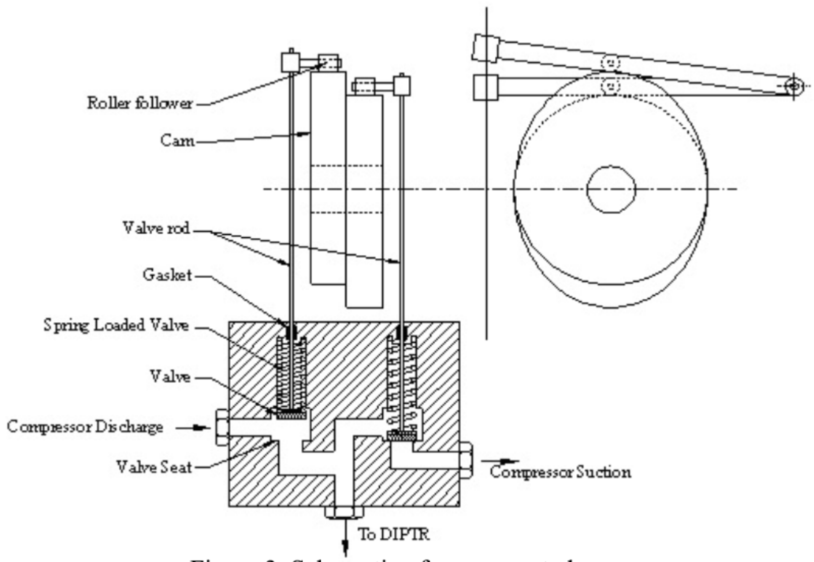

Figure 3. Schematic of cam operated pressure wave generator

employed in the expansion engine of Collin's helium liquefier for connecting high and low pressure gas streams to the expansion engine. But to our knowledge, such a system has not been employed as a pressure wave generator for pulse tube refrigerators elsewhere. Instead of developing such a system, if one has access to the cold head drive of a commercial G-M cryocooler, it can be suitably modified and used as a pressure wave generator of pulse tube refrigerator [5]. The cold head drive performs two functions in the G.M. Cryocooler.

The cold head drive converts the circular motion of the motor to reciprocal motion to move the stem up and down connecting integral regenerator-displacers of two stages. This is done in synchronization with the opening and closing of the high and low-pressure sides of the compressor by way of operating the corresponding cam operated spring-loaded valves. For the pulse tube application, as there is no mechanical displacer in the system, it is sufficient if only the pressure wave is generated by using the cam operated spring-loaded valves. Hence, the components needed for moving the integral regenerator-displacer up and down are discarded from the cold head drive in the present system and only the parts needed for generating the pressure wave are retained. The schematic of modified pressure wave generator is shown in Figure 4. The compressor discharge and suction sides are coupled to the device with the help of quick disconnect coupling (Aeroquip coupling). The common output from the device is connected to the warm end of the regenerator. As it is necessary to change the frequency of operation to maintain the pressure wave in-phase with the mass flow at the cold end of the pulse tube to get maximum refrigeration power, a variable frequency drive of approximately 750 W is used to operate the cold head drive motor. By varying the frequency of the drive, it is possible to change the operating range of pressure wave generated from 1 Hz to 10 Hz. It is also possible to vary the duty cycle of high and low-pressure profile by adjusting the cam setting.

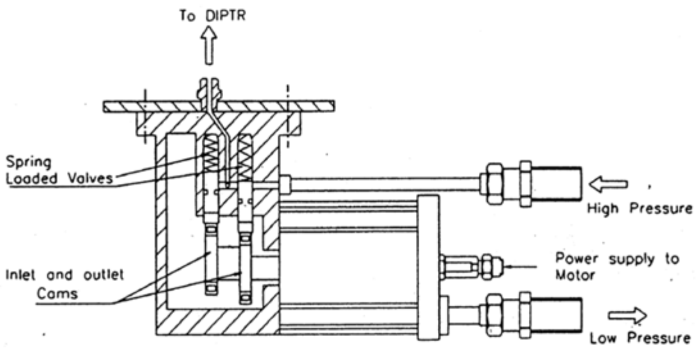

Figure 4. Schematic of modified pressure wave generator

PERFORMANCE OF THE SYSTEM

A typical cooldown characteristics of the pulse tube system using the above pressure wave generator and TECs as warm end heat exchangers is shown in figure 5. The performance is almost the same as that of the conventional water circulating system as warm end heat exchanger [6]. The temperature profile of warm end of regenerator is maintained at around 280 K with the help of TEC. The temperature of the warm end of the pulse tube is reduced in this case. The heat load curve shown in figure 6 shows that marginally higher refrigeration power could be obtained with this system compared to that of the water-cooling system showing that the

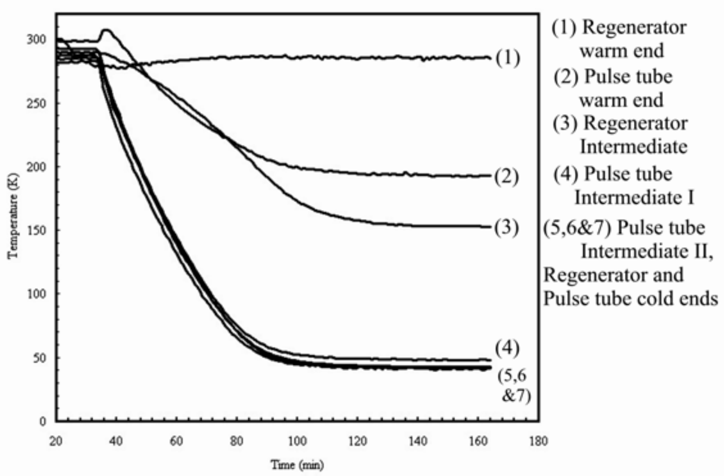

Figure 5. Typical Cooldown pattern of DIPTR with TEC at 1.5 Hz

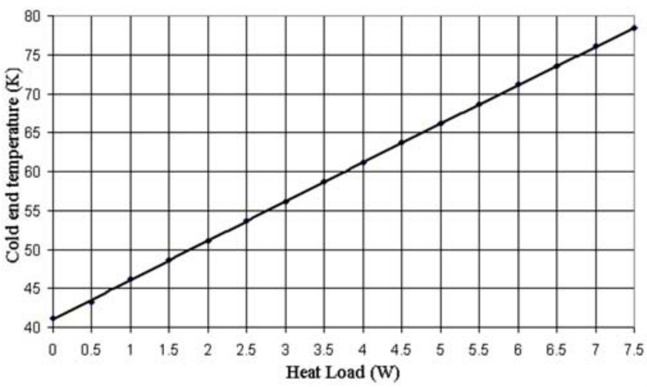

Figure 6. Heat load curve of the DIPTR wih TEC

TECs can be used to eliminate the water circulating system. Further optimization could result in better performance. The results of the cam-operated system developed by us are compared to those of a rotary valve based system [4] in Table 1.

Table 1.Comparision of the pressure data of cam operated system and the rotary valve system

Parameters	Cam operated pressure wave generator	Rotary valve based pressure wave generator [4]
$\mathbf{P_{Max}}$	17 bar	14.5 bar
$\mathbf{P_{Min}}$	9.75 bar	10 bar
$\mathbf{\Delta P}$	7.25 bar	4.5 bar
$\mathbf{P_{Max}/P_{Min}}$	1.75	1.45
$\mathbf{P_{Average}}$	13.5 bar	12 bar

From the data, it can be concluded that the performance of this system is comparable to that of a rotary valve based system. Further, from the waveform pattern shown in figure 7, we can conclude that the system presented in this paper performs as efficiently as the rotary valve based system with better durability

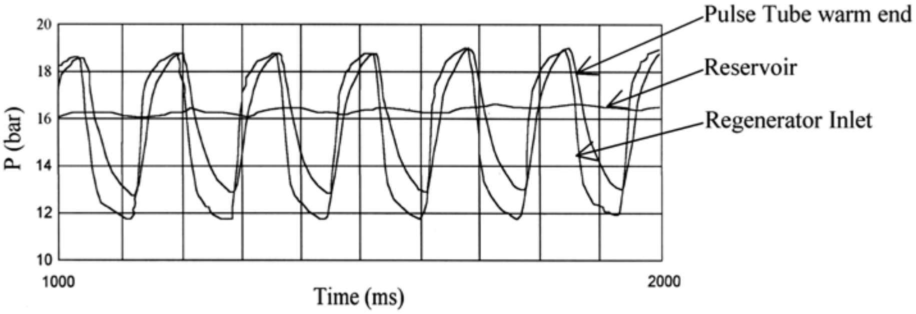

Figure 7. Pressure wave patterns at regenerator inlet, pulse tube warm end and at reservoir

CONCLUSIONS

The performances of a single stage double inlet pulse tube refrigerator operated with a cam operated pressure wave generator and thermo-electric coolers are compared with those of the conventional systems. From the data, we can conclude that the cam operated pressure wave generator performs as efficiently as the other types of the system with better reliability. The water circulation system at the hot end heat exchanger can be eliminated by the TECs without compromising on the performance. The D.C. flow due to non-symmetry of the commercial needle valves used is corrected by using a set of two identical valves back to back in series. Further optimizations in terms of cooling the regenerator warm end using the TEC are in progress. It is expected that this can result in lower no load temperature and better refrigeration capacity.

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