Development of a reliable and simple pressure wave generator for pulse tube refrigerators

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The pressure wave generator is a critical component of a pulse tube refrigerator. Conventionally either a solenoid operated electromagnetic valve or a rotary valve driven by a hermetically sealed motor is used for this. In this article, we present a novel pressure wave generator design based on cam operated valves for use with pulse tube refrigerators. This, when coupled with an inverter drive (variable frequency drive), forms a versatile pressure wave generator in the range between 1 and 10 Hz. In a single stage double inlet pulse tube using this type of pressure wave generator, refrigeration power of about 6 W at 77 K and a no load temperature of about 42 K were obtained. The above results are comparable to those obtained with pulse tube systems based on other two types of pressure wave generators. While the rotary valve based pressure wave generator is prone to developing leaks at the rotating seal, the solenoid valve based system cannot be operated continuously due to coil failure. The cam operated valve based pressure wave generator overcomes the above shortfalls of rotary valve and solenoid valve type pressure generators and is well suited for continuous operation of the refrigerator.

I. INTRODUCTION

For over two decades in the area of pulse tube refrigerator (the basic pulse tube discovered by Gifford and Longworth¹) there have been significant advancements. Due to the absence of a mechanical moving component at the cold side of the system, pulse tube refrigerators find applications in semiconductor fabrication, charge coupled devices for astronomical telescopes, super conducting quantum interference device (SQUID) detection for nondestructive tests, and medical applications where vibration and noise should be very low and the system should have high reliability. A schematic of a double inlet pulse tube refrigerator (DIPTR) is shown in Fig. 1. The system without a bypass valve, orifice valve, and reservoir forms a basic pulse tube in which the hot end of the pulse tube is closed. The addition of a reservoir and orifice valve converts it into an orifice pulse tube.² In the double inlet pulse tube,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 pressure wave required. 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 (HEs) (hot end HE and cold end HE) at both the ends. In basic pulse tube mode, when the system is subjected to oscillating gas flow, due to a thermoacoustic effect (an acoustically driven temperature effect), the open end of the pulse tube is cooled and heat is transported to the hot end where it is rejected in the HE. In the orifice pulse tube intro-

duction of a needle valve (orifice) and a buffer volume (reservoir) enhance 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 part of the gas directly to the warm end of the pulse tube, thus reducing mass flow of the gas through the regenerator. One of the critical components of the pulse tube is the pressure wave generator. Usually a solenoid operated or a rotary valve operated pressure wave generator is used in pulse tube

FIG. 1. Schematic of the double inlet pulse tube refrigerator.

FIG. 5. Cool down profile of the double inlet pulse tube refrigerator.

Fig. 3. The compressor discharge and suction sides are coupled to the device with the help of quick disconnect coupling (Aeroquip coupling). Common output from the device is connected to the warm end of the regenerator. Since 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 to 10 Hz. It is also possible to vary the duty cycle of high- and low-pressure profiles by adjusting the cam setting. For a set of parameters such as openings of the orifice and double inlet valves, dimensions of the components, etc., it is necessary to find the optimum frequency of operation to get the maximum refrigeration capacity. Similarly, by keeping the duty cycle at different values, the system can be fine-tuned. Figure 4 shows the pressure wave patterns at the inlet to the regenerator, pulse tube warm end, and at the buffer volume of the pulse tube. Due to the cam operated valves, the suction and discharge sides are alternatively connected to the common outlet instantaneously. Hence, the wave form is close to that of a square wave at the regenerator inlet. The pressure amplitude is maximum at this point since it represents the total mass flow into the system. At pulse tube hot end, it is slightly less than that at the regenerator due to the drop in pressure in the regenerator. In the buffer, it is very close to the mean value as the gas is allowed into the buffer through a high impedance orifice valve. The phase of the oscillating pressure wave is adjusted with the help of the orifice and double inlet valves such that it is in phase with the mass flow at the cold end.

The results of the cam operated system developed by us are compared to those of a rotary valve based system⁴ in Table I. From the data, it can be concluded that the performance of this system is comparable to that of a rotary valve based system.

Typical cool down characteristics of the pulse tube system using the above pressure wave generator are shown in Fig. 5. The temperature data from seven locations in the pulse tube system are monitored. It can be observed from Fig. 5 that the cold end of the pulse tube and regenerator reaches a steady state value of about 42 K in approximately about 1 h. The temperature increase per watt of heat load is about 8 K and the refrigeration power at 77 K is about 6 W. The system has been in operation for the past three years, with each test run exceeding continuous operation for five days. There has been no failure of the pressure wave generator during the tests up to now. From the results, it can be concluded that the cam operated pressure wave generator performs very well and has the added advantages of better durability and reliability.

ACKNOWLEDGMENT

The authors acknowledge financial support by the Indian Institute of Science–ISRO Space Technology Cell for this work as a project under STC.

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