Experimental Investigations on 20 K Stirling-Type Two-Stage Pulse Tube Cryocooler with Inline Configuration

M.V. Tendolkar [1,2], K.G. Narayankhedkar [2], M.D. Atrey [1]

[1] Indian Institute of Tech. Bombay, Powai, Mumbai-400076, India
[2] Veermata Jijabai Tech. Institute, Matunga, Mumbai-400019, India

ABSTRACT

Multistaging in a Stirling-type Pulse Tube Refrigerator (PTR) is employed to reach the temperature range of 20 K and below. Various configurations of two-stage PTRs can be used, where the former stage provides precooling for the next stage. There are several candidate two-stage configurations, each with advantages and limitations. These include: inline, 'U' type, coaxial, and combinations of these. In addition to the above, the configuration can be of integral or split type, depending if the compressor is directly attached to the pulse tube assembly or is remote.

The present work describes experimental investigations carried out on an integral-configuration Stirling-type two-stage PTR with inline pulse tubes for both stages. This pulse tube configuration is thermodynamically advantageous as it involves the least dead space and flow resistance. Inertance tubes are used as the phase shift mechanism for both stages. The second-stage alone has an added double-inlet valve along with the inertance tube. A linear compressor is used to provide the PV power to the PTR and is maintained at 350 W. The investigations are carried out for different operating conditions.

INTRODUCTION

The development of low temperature cryocoolers has been initiated to fulfill the need for low temperatures in several space missions. These requirements include the cooling of electronic devices such as infrared sensors, or the precooling of Joule-Thomson refrigerators. Under the given constraints on the cryocoolers for space applications in terms of reliability, lifetime, and generated vibration, pulse tube cryocoolers with no moving parts at the cold end are an attractive technology to satisfy the same.

Multistaging is used to achieve such low levels of temperatures, where the former stage serves as a precooling stage for the next one. The two stages can be coupled in two different ways. The gas-coupled design contains the same gas in both the stages with the same pressure and the same frequency. On the other hand, a thermally-coupled design can have two different gases, different pressures and frequencies, and different compressors for each stage. Yang and Thummes [1] have reported a minimum temperature of 20.02 K for the input power of 200 W using a Leybold Polar SC7 compressor. The design is of the gas-coupled type. Nguyen et al. [2]

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have developed a thermally-coupled design. The minimum temperature reported is 20 K at the second stage with 600 W input power, while Yan et al [3] reported a minimum temperature of 14.2 K with 400 W input power. Thummes et al [4] have reported a minimum temperature of 13.7 K in their recent work for a thermally coupled design. However, the compressor employed is of 10 kW class and uses 4.6 kW to reach the no load temperature. In addition, the second stage regenerator is filled with lead spheres of 100 micron size. Recently, Yang et al [5] have reported a minimum temperature of 12.96 K at the second stage with thermally coupled stages. A power of 200 W is given to both the stages with two separate compressors. The second stage regenerator consists of SS screens of # 400 and 500 mesh along with a certain height of lead-coated SS screens. This configuration is employed with a double inlet valve only at the second stage. The charge pressures and the operating frequencies are also different in each stage. It may be noted that the configurations of the above mentioned two-stage PTRs are of 'U' type, while the charging pressure is around 20-22 bar.

In our laboratory at IIT Bombay, both experimental and theoretical work related to different geometrical configurations with different phase shifting mechanisms has been carried out. A single-stage PTR of inline configuration with both orifice and inertance tube has been developed [6,7]. The work has then been extended from inline to the 'U' type configuration. Based on a comparison of the performance of the two configurations [8], and additional work, it has been concluded that the inline configuration is better than the 'U' type; it offers 20% higher refrigeration as compared to the 'U' type configuration. The flow losses are minimum in the case of the inline configuration due to the absence of curved flow channels and minimum dead volume. On the other hand, for the inline configuration, the cold end lacks accessibility, as it is located in the middle of the assembly. This results in an increased height of the unit, demanding more space. The main drawback of the 'U' type configuration is the performance deterioration due to increased dead volume, and more importantly, it is normally a split configuration. The coaxial configuration is compact in size, but involves complex fabrication issues in addition to increased pressure drop. In view of this, the present work is aimed at the development of a two-stage PTR with inline and integral configuration focused on providing temperatures near 20 K.

In this work, we describe our experimental investigations on the two-stage Stirling-type integral PTR with inline configuration using a linear compressor. The experimental investigations have been carried out to analyze the effects of various design and operating parameters like charging pressure, operating frequency, double inlet valve opening, etc. on the minimum temperature for the configuration developed.

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The theoretical model, based on cyclic analysis [9], is used to design and analyze the performance of the two-stage PTR. Zhu and Chen [10] presented an isothermal model for an orifice type PTR; while Atrey and Narayankhedkar [9,11] extended the model to take into account various losses in a cyclic manner. The model is further modified to consider the inertance tube in place of the orifice valve [7]. It is then extended for a single-stage 'U' type configuration. The theoretical and experimental performance with respect to various design and operating parameters for both inline and 'U' type configurations is compared [8]. It is also extended for the single-stage coaxial design [12]. The model is then further extended to design a two-stage pulse tube cryocooler with inline, integral arrangement. The phase shifting mechanism employed for the two-stage PTR is different for each stage. For the first stage, an inertance tube is used, while for the second stage, a combination of inertance tube and double inlet valve is used. This configuration is shown in Figure 1.

The design is carried out to reach 20 K at the second stage while the first stage is at around 87 K. The charge pressure is kept at 20 bar. The pulse tubes and the regenerators are made of thin walled Stainless Steel (SS 304) tubes. The regenerators consist of stacks of SS 304 screens of mesh size 400 and 500 for the first and second stages, respectively. The optimised dimensions of various components of the PTR are given in Table 1.

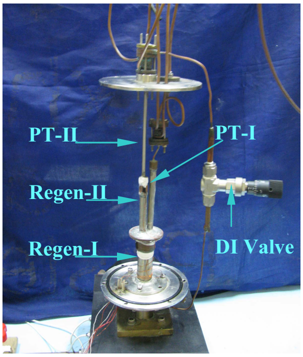

Figure 1. Two-stage configuration

Table 1. Dimensions of Components of Two-Stage PTR

	Pulse Tube		Regenerator	
	I-Stage	II-Stage	I-Stage	II-Stage
Length	90	120	55	60
Diameter	9	4	20	9
Thickness	0.2	0.15	0.2	0.2

* All dimensions in mm.

EXPERIMENTAL SETUP

The pulse tube cold ends are made up of copper caps on which the temperature sensors are mounted, and they are kept below the hot ends of the pulse tubes to avoid the adverse effects of natural convection inside the pulse tubes. The compressor used is a CFIC Model 2S132W with maximum electrical input power of 350 W. The hot end heat exchangers and the aftercooler are water-cooled. The double inlet valve incorporated is Swagelok Inc. make (Model SS-4MG-MH). ENDEVCO Piezo-resistive transducers are used for pressure measurement, while silicon diodes are used for temperature measurement. The experimental setup is shown in Figure 2.

RESULTS AND DISCUSSIONS

For the present two-stage PTR configuration, experimental investigations have been carried out to optimize the operating parameters. The helium charge pressure has been varied in the range of 18-22 bar, while the frequency of operation has been varied in the range of 66-74 Hz. Similarly, the setting for the double inlet valve (number of turns) has also been optimized.

Cooldown Curve

Figure 3 shows the cooldown curve obtained with the two-stage PTR. The optimized values of charge pressure and operating frequency were found at 20 bar and 70 Hz, respectively. The minimum temperatures were 95.92 K and 23.5 K for first and second stages, respectively.

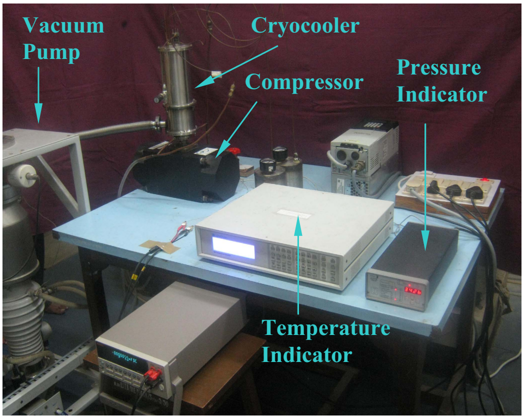

Figure 2. Experimental setup

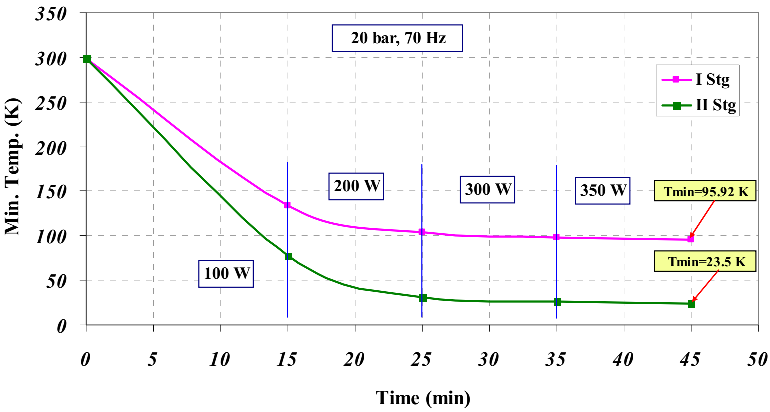

Figure 3. Cooldown curve

It can be observed from the cooldown curve that the major temperature drop takes place within 25 min and achieves stability within 45 min. The input power is supplied gradually so as to avoid any damage to the pistons. Initially, the gas is allowed to cool into the cryogenic range using a nominal input power of 100 W, and then the power is increased gradually in steps of 100 W, until finally 350 W of power is applied.

Charging Pressure

Figure 4 shows the effect of variation in the helium charging pressure with respect to the minimum temperature at the second stage. The frequency of operation is kept constant at 70 Hz and the charging pressure is varied from 18-22 bar. The electrical input power is also maintained at 350 W for the experimentation. The experimental investigations were carried out at the optimum settings of the double inlet valve.

It is clear from the figure that there exists an optimum value of the charging pressure with respect to the minimum temperature of the second stage, although the change in lowest temperature in not significant. The optimum value of the pressure is due to an integrated effect of dead volume in the system and the pressure drop losses in the cooler with respect to the compressor used in the present case.

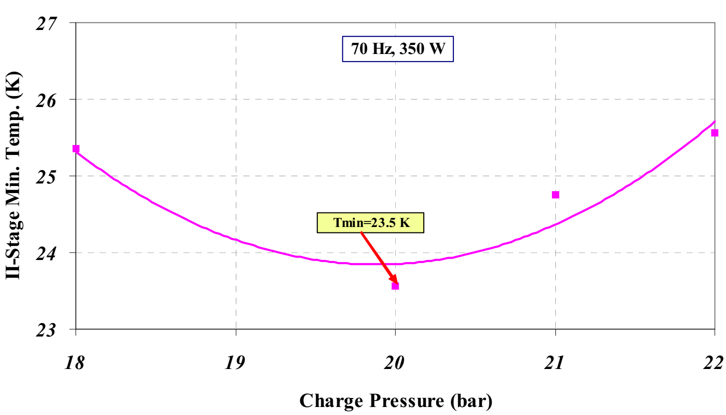

Figure 4. Effect of charge pressure

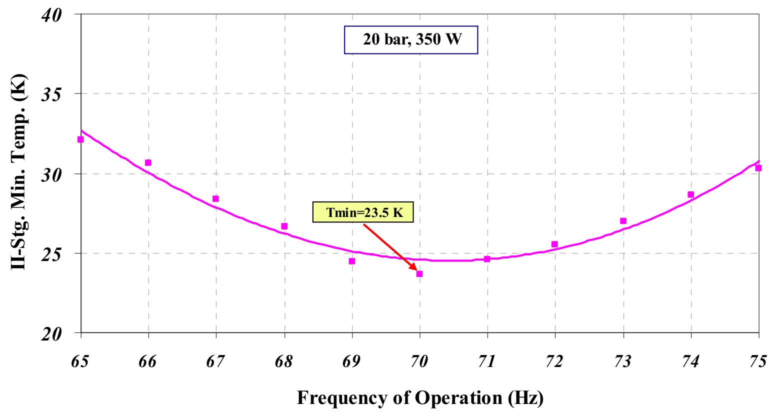

Figure 5. Effect of frequency of operation.

Frequency of Operation

The two major losses associated with the regenerator, viz. pressure drop losses and the losses due to regenerator inefficiency, are mainly governed by the frequency of operation. Frequency, therefore, is one of the major parameters to be optimized for minimum temperature to be achieved. The optimization is carried out for the available compressor.

Figure 5 shows the effect of variation in the frequency of operation with respect to the minimum temperature at the second stage. Along similar lines as the effect of charging pressure, it can be clearly observed from the figure that there exists an optimum value of the frequency of operation with respect to the minimum temperature at the second stage. At this value, the resonant frequency for the system results in the minimum losses inside the cryocooler.

Double Inlet Valve Setting

As explained earlier, the phase shift mechanisms implemented in the present PTR unit are of two types. For the first stage, only an inertance tube is employed. However, for the second stage, a combination of inertance tube and double inlet valve is incorporated. The similar arrangement of double inlet valve for the first stage resulted in poorer performance in this case. With the double inlet valve at the second stage only, a portion of the gas is made to bifurcate from the compressor, bypass the first as well as second stage completely, and is allowed to mix with the main stream at the second-stage hot end.

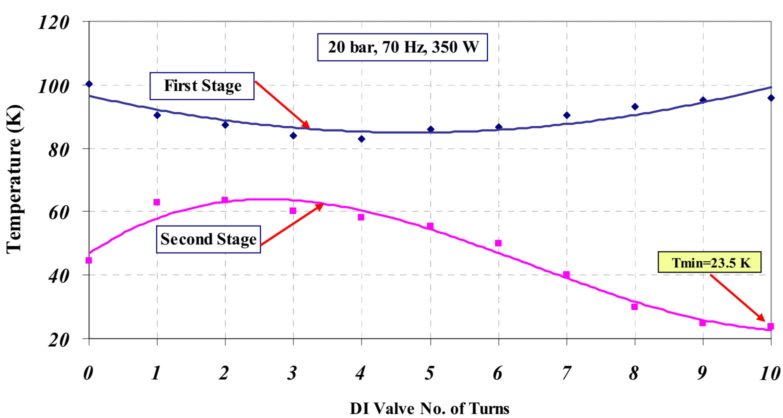

Figure 6. Effect of no. of turns of DI valve.

The effect of the number of turns of opening of the second-stage double inlet valve is presented in Figure 6. The second stage temperature recorded is 37.75 K when the valve is closed. It is interesting to observe that the temperature initially increased rapidly up to the range of 60 K until 3 turns of the valve were achieved. The temperature then reduced with further opening of the valve. The corresponding variation in the first stage temperature is small.

ANALYSIS OF RESULTS

The objective of the present work has been to design and develop a two stage pulse tube cryocooler for 20 K. The experimental investigations have yielded the minimum temperature of 23.5 K. The following investigations may be carried out to further reduce the temperature.

1. The dead volume associated with the whole system needs to be minimized. The resonant frequency should be optimized to get the highest pressure ratio for minimum power input.
2. The second stage cold end heat exchanger is in close proximity of the first stage pulse tube hot end heat exchanger. This may result in radiative losses. Also, any physical contact between MLI wrappings between the two parts needs attention.
3. The first stage pulse tube hot end heat exchanger is inside the vacuum chamber. The temperature of the water flowing through the same needs to be monitored for desired pulse tube action.

CONCLUSIONS

Experimental investigations have been carried out on a two-stage, Stirling-type pulse tube cryocooler with inline configuration. The following are the major conclusions of the work:

1. The PTR reached a minimum temperature of 23.5 K at the second stage with 20 bar charging pressure and 70 Hz operating frequency. The electrical input power was maintained at 350 W.
2. The double inlet valve for the second stage only, proved beneficial to reach the lowest temperature. The trial use of a double inlet valve for the first stage resulted in deterioration of the performance, and was not implemented.
3. The performance of the PTR can be further improved with different means as discussed in the above section.

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