Performance Comparison of Stirling-Type Single-Stage Pulse Tube Refrigerators of Inline and 'U' Configurations

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ABSTRACT

Pulse Tube Refrigerators (PTR) have become highly popular due to their inherent advantages like absence of moving parts at the cold end, reduced vibration, high reliability, light weight, and simple construction. There are various configurations possible in PTRs like inline, U-type, coaxial, and annular. Also, different phase-shifting mechanisms like orifice valve, double-inlet valve, inertance tube, etc. are in practice.

The present work aims to study and compare the performance of an inline and a U-type configuration of a single-stage, Stirling-type PTR developed in our laboratory, keeping the same dimensions for the pulse tube and the regenerator in both. The inline configuration reached a minimum temperature of 48.2 K, while the PTR with the U-type configuration with the same pulse tube and regenerator dimensions reached about 70 K. The U-type configuration has been further studied to understand its performance dependence on the connecting tube diameter and length. Additional investigations were carried out to study and compare the performance of these inline and U-type configurations for different operating parameters like charge pressure, frequency of operation, etc. and design parameters like length of inertance tube. The comparisons have been made with respect to cooldown time, minimum temperature reached, and cooling power.

INTRODUCTION

The Mean-Time-Between-Failure (MTBF) of tactical Stirling and commercial GM cryocoolers is generally too short for use in providing continuous cryogenic cooling for IR sensors in space satellites. To meet this need, special space-rated Stirling and Pulse Tube Refrigerators (PTR) have been developed based on long-life flexure-supported linear compressors that offer continuous operation for 5 to 10 years. PTRs have the advantage of no moving parts at the cold end, which leads to simplicity in construction, lowered manufacturing cost, reduced mechanical vibration at the cold end, and thus ultimately to high reliability.

Different configurations of PTRs for attaining minimum cold end temperatures have been tried by various researchers. The inline, U-type, annular, and coaxial are of prime importance amongst them. Different phase shifting mechanisms have also been applied to these configurations. Orifice valve, double inlet valves, and inertance tube are a few to mention [1-5].

In the 'inline' configuration, the flow losses are minimum, as there is no curved path for the flow of the working medium; hence, this configuration is often preferred where high perform-ance is desired. But, the limitation of this configuration is that the cold end is located in the middle of the assembly, which makes it difficult to access. Also, the length of the unit becomes quite large; in other words, it requires more space. On the other hand, the U-type configuration is compact in size and allows easy access to the cold tip of the PTR. But, at the same time, the performance of this configuration is hampered by the addition of the U-bend.

The objective of the present work is to compare the performance of single-stage Stirling-type PTRs in both 'inline' and 'U-type' configurations by keeping the geometrical parameters of the regenerator and pulse tube the same in both cases. These units have been developed in our laboratory. The inline unit has been developed for the liquefaction of Nitrogen, and it uses a linear-motor driven opposed-piston compressor [6]. It has also been modified into a U-type configuration. The performance, in terms of minimum cold end temperature achieved and refrigeration load that could be applied, has been compared for the two configurations for various operating parameters like charge pressure, frequency of operation, etc.

THEORETICAL MODELS

Theoretical models based on cyclic analysis have been developed to analyze the perform-ance of the single-stage inline PTR as well as the U-type configuration. Zhu and Chen [7] have presented an isothermal model for the orifice type PTR, while Atrey and Narayankhedkar [8,9] have extended the model to take into account various losses that occur in the PTR in a cyclic manner. The model has been further improved by considering the addition of an inertance tube in place of the orifice valve without loss analysis [6]. Here, the model has been further extended to a split unit, and also to take into account the addition of the U-bend between the regenerator and the pulse tube.

EXPERIMENTAL SETUP

The major components of a Stirling-type pulse tube refrigerator are a linear compressor, an aftercooler, a regenerator, a cold end heat exchanger, a pulse tube, a hot end heat exchanger, and a reservoir, along with at least one flow impedance (orifice or inertance tube), which works as a phase shifting mechanism between the dynamic pressure and the mass flow in the pulse tube.

Pulse Tube Cold Head

The pulse and the regenerator tubes are made of thin-walled Stainless Steel (SS 304) tubes. The regenerator consists of stacks of SS 304 screens of mesh size 400. The cold tip is made of a copper block that allows easy attachment of temperature sensors on its surface. The cold head is oriented in such a manner as to make it always below the warm end. The compressor used is a CFIC Model 2S132W with maximum power input of 500 W. Endevco piezo-resistive trans-ducers have been used for pressure measurement. All the warm-end heat exchangers are water-cooled. The dimensions of the various components of the PTR are given in Table 1.

Table 1. Dimensions of Components of PTR

	Length (mm)	Diameter (mm)	Thickness (mm)
Pulse Tube	80.0	12.2	0.2
Regenerator	54.0	28.0	0.2
Connecting Tube for Split Unit	150	6.25 (¼")	---
U Tube	176	2.5	---

Figure 1. Inline configuration

Figure 2. U-type configuration

RESULTS AND DISCUSSIONS

A. Cooldown Curves

Figure 3 shows a comparison of the cooldown curves for a charge pressure of 14 bar for the inline and U-type configurations. The frequency of operation was initially kept constant at 50 Hz. The power delivered by the compressor was kept constant at 250 ±5 W.

The minimum temperature reached with the inline unit was 52.5 K, while under similar conditions, the U-type configuration reached 74 K. The major temperature drop took place within 30 minutes and achieved stability within an hour in the case of the inline configuration. On the other hand, the corresponding values for the U-type configuration were about 40 min, and two hours, respectively. The additional mass in the form of the U-bend required more time for the U-type system to attain a stable temperature, and thus resulted in an increased cooldown time.

B. Refrigeration Load Curves

Figure 4 shows a comparison of experimental results for the refrigeration load achieved with both the inline and U-type configurations. The tests were carried out at the optimum frequency of operation: i.e. 54 Hz for the inline unit, and 40 Hz for the U-type configuration.

It can be seen from the figure that the refrigeration load significantly decreases as one moves from inline (6.195 W @ 80 K) to U-type configuration (0.95 W @ 80 K) for a given charge pressure (12 bar). Thus, one can draw the conclusion that the addition of a dead volume in any form (here, the U-bend) to the inline configuration deteriorates the performance of the PTR in terms of refrigeration load. This is also reflected in the minimum temperature that was possible to achieve.
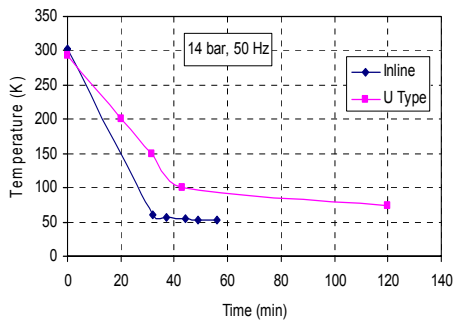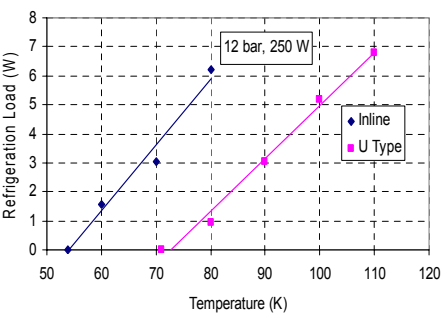

Figure 3. Comparison of cooldown curves

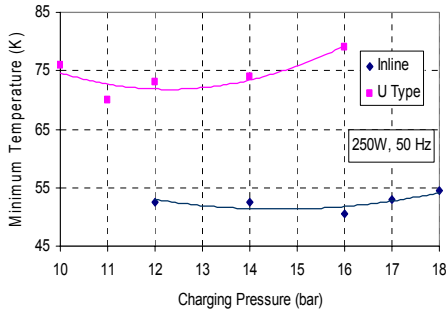**Figure 4.** Comparison of refrigeration load

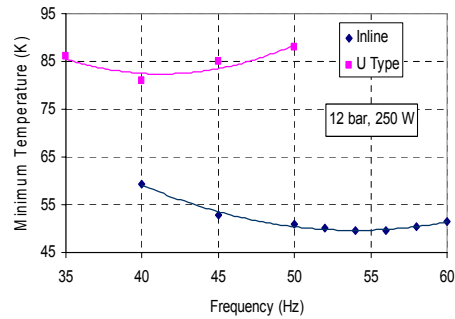**Figure 5.** Comparison of charge pressure

Figure 6. Comparison of effect of frequency of operation

C. Effect of Charge Pressure

Figure 5 shows a comparison of the effect of charge pressure on the minimum temperature for a constant compressor input power of 250 W and a frequency of 50 Hz. It can be clearly observed that the minimum temperature for the inline configuration is much lower than that with the U-type configuration for a given charge pressure (50.5 K and 79 K respectively at 16 bar). Another significant observation is that the optimum charge pressure for minimum temperature is shifted from 16 bar for the inline configuration to 11 bar for the U-type configuration.

This shift of pressure can be well understood by the fact that the losses in the system, viz. losses due to pressure drop, are minimum at 16 bar for the inline configuration, while they are minimum at 11 bar for the U-type configuration.

D. Effect of Frequency of Operation

Figure 6 shows a comparison of the effect of frequency of operation in terms of minimum temperature for a charge pressure of 12 bar for both the inline and U-type configurations.

It is observed that the minimum temperature with the inline configuration is much lower than that possible with the U-type configuration at a given charge pressure (49.6 K and 80 K respectively at 12 bar). Another important observation is that the optimum frequency of operation for the inline configuration is 54 Hz, while that for the U-type configuration is 40 Hz.

The introduction of dead volume in the form of the U-bend requires more time for the mass of the gas to pass through the system for the same amount of heat transfer, which results in a shift of the optimum frequency to the lower side.

E. Pressure Ratio

Figure 7 shows the variation in the pressure ratio as a function of the input power to the cryocooler compressor.

It can be seen from the figure that the pressure ratio for the inline configuration is 1.565, while that for the U-type configuration is 1.28 at an input power of 250 W. It can also be observed that the rate of change of pressure ratio with input power for the case of the inline configuration is much greater than that with the U-type configuration.

The addition of the U-bend in the flow passage of the gas introduces an undesired pressure drop; this reduces the peak-to-peak variation in the dynamic pressure of the system, and thus reduces the pressure ratio.
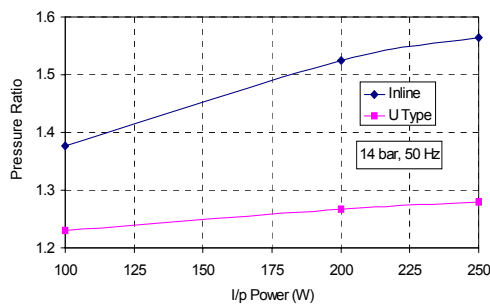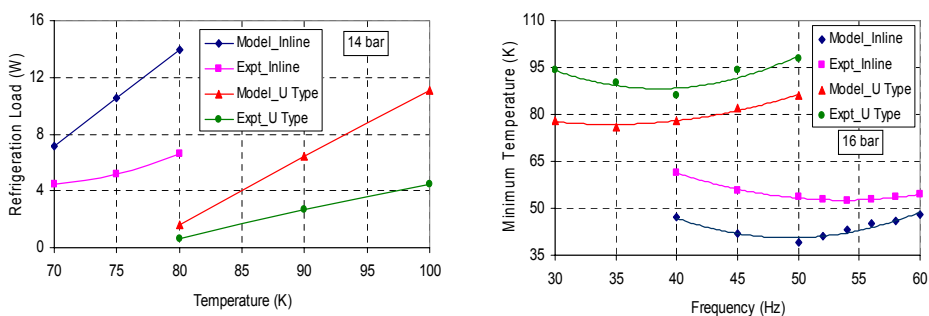
Figure 7. Comparison of pressure ratio

Figure 8. Comparison of experimental results with theoretical predictions –
(a) refrigeration load (b) frequency of operation

F. Comparison of Experimental Results with Theoretical Model Predictions

Figure 8 (a) highlights a comparison of the experimental results with model predictions. The comparison is carried out for the refrigeration load when the charge pressure is 14 bar and the frequency of operation is 50 Hz. It can be observed from the graph that the theoretical refrigeration effect is higher than that obtained experimentally. The actual analysis of the oscillating flow through a pipe for both laminar as well as turbulent regimes can not be accurately interpreted with the correlations available. These limitations are upheld by the fact that the experimental results always lag behind the corresponding theoretical values.

Figure 8 (b) shows a comparison of the experimental results with those predicted theoretically for a change in frequency of operation for a charge pressure of 16 bar. The graph shows reasonably good agreement between the results obtained experimentally and those from the theoretical prediction. The minimum temperature predicted by the model is lower than the experimentally obtained values. This can be attributed to the assumption of ideal behavior of gases (ideal thermodynamic processes and properties) and the unaccounted for losses in the model.

G. Effect of U-Tube Diameter

Figure 9 addresses one of the very important design parameters of the U-tube configuration, viz. the diameter of the U-tube.

The figure shows the effect of a change in diameter of the U-tube on the performance of the U-type configuration in terms of the minimum temperature that is possible to achieve in the PTR. The figure includes a comparison of the experimental results with the theoretical predictions; both are for the charge pressure of 16 bar.
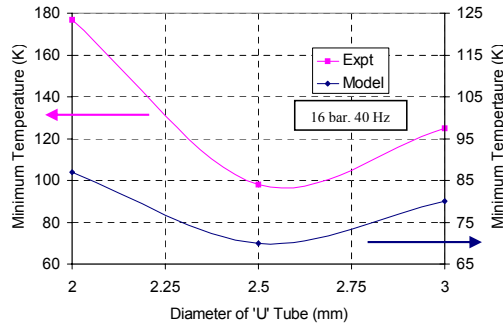
Figure 9. Effect of diameter of U-tube on minimum cold end temperature

The results show that there exists an optimum diameter of the U-tube to achieve the minimum temperature. We have found this value for our design of the U-type configuration to be 2.5 mm. The minimum temperature increases for a change in diameter on either side of the optimum one. This can be analyzed by examining the optimum mass flow rate inside the U-tube desired for the operation of the PTR. Any deviation from this value on either side results in an inappropriate value of the mass flow rate required for the optimum performance, and hence deteriorates the same. This highlights the significance of proper selection of any of the design parameters of the U-type configuration.

CONCLUSION

Experimental investigations have been carried out to examine the performance of a single-stage, Stirling-type pulse tube cryocooler. Both inline and U-type configurations have been compared, keeping the same dimensions of the pulse tube and the regenerator in both cases. The following main observations have been drawn:

1. The cooldown time for the inline configuration is less than that for the U-type configuration for the same charge pressure and constant input power to the compressor. The minimum temperature with the inline configuration is much lower than that with the U-type configuration.
2. The refrigeration load for the inline configuration is much higher than that for the U-type configuration.
3. The optimum charge pressure for the lowest cold end temperature for the inline configuration is higher than that with the U-type configuration, while the optimum frequency of operation for the lowest cold end temperature also drops as the U-bend is introduced. Similarly, the pressure ratio also lowers as we change the configuration from inline to U-type.
4. The diameter of the U-tube proves to be one of the very important parameters for proper design of the cryocooler.
5. The results of the U-configuration can approach those of the inline configuration by reducing the length of the U-tube without disturbing the 'U' profile. Thus, it can be concluded that the U-type configuration is better from a practical point-of-view, as the cold tip is made more approachable. But, at the same time, the introduction of a U-bend between the regenerator and the pulse tube results in deterioration of the performance of the PTR in terms of minimum temperature as well as refrigeration load that can be applied. Hence, one has to take into consideration the effects of all of the design and operating parameters while designing the cryocooler.

ACKNOWLEDGEMENT

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