

Experimental Investigation of Single-Stage Inline Stirling-Type Pulse Tube Refrigerator

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ABSTRACT

The salient features of a Stirling-type Pulse Tube Refrigerator (PTR) are its compactness, low vibration, high frequency of operation, and longevity. The flow in the pulse tube is complex because of its oscillatory nature. The flow pattern plays an important role in the performance of the pulse tube. Various design parameters like dimensions of the pulse tube, the regenerator, and operating parameters like pressure and frequency affect pulse tube performance. The cold end heat exchanger forms the most important component of the PTR, as the cooling effect is distributed from this component. This paper evaluates the experimental performance of a PTR for different configurations of the cold end heat exchanger in terms of cool down curve, lowest temperature reached, and cooling power at 80 K. The performance of the PTR is studied using a stack of coarse copper meshes in the cold heat exchanger. A similar investigation is carried out by replacing the meshes with a tapered finned copper block in order to get better heat transfer at the cold end. The results show a substantial improvement in the performance of the PTR. It is also found that the optimum frequency gets affected by such changes. In another system, the study is extended to investigate the effect of tapering the cold end heat exchanger using coarse copper meshes. The included taper angle is varied, and its effect on the performance of the PTR is studied.

INTRODUCTION

Stirling-type Pulse Tube Refrigerators (PTRs) have the advantage of the absence of cold moving parts, better vibration characteristics, and high frequency of operation. Due to the above advantages they are used in space, medical, and other fundamental-research fields. Variations in configuration and operating frequency can be used to classify PTRs into different types: namely, orifice PTR, double-inlet PTR, and inertance-tube PTR (ITPTR). The ITPTR, a relatively new invention, involves replacing the previous orifice and double-inlet phase shifting devices with a small-diameter tube known as the inertance tube.^{1,2} In a single-stage Stirling-type PTR, the lowest temperature achieved is 34.5 K using a 10 kW linear compressor.³

The pressure variation in the Stirling-type PTR is sinusoidal in nature, which induces oscillatory flow in the PTR. Oscillatory flow makes the analysis of the PTR complicated. The

flow pattern in the PTR is governed also by geometrical parameters like the dimension of the regenerator, pulse tube, dead volumes in different components, and operating parameters like charge pressure and frequency.

The heat exchangers are vital components of the PTR, as their effectiveness highly influences the performance of the PTR. The cold end heat exchanger is the most important, as the cooling load is transferred from this part. This could be enhanced by ensuring proper heat transfer between the working gas and the outer component of the cold end heat exchanger.

In this paper, the performance of the PTR is evaluated for two different configurations of the cold end heat exchanger.

HEAT EXCHANGER CONFIGURATION

The heat exchangers used in PTRs should have features like low pressure drop, better heat transfer, and minimum dead volume. The above features are contradicting to each other. Therefore, an optimum configuration has to be achieved.

The heat exchangers considered in the PTR have two parts. The outer part is made up of a solid copper block having a tapered hole, and the inner part consists of stacks of coarse copper meshes of 100 mesh size through which the gas passes. The stack of meshes is press-fitted with the outer component to ensure proper contact. Another configuration is to use a slotted copper block press-fitted against the outer copper part. Both of these configurations for the cold end heat exchanger are shown in Figure 1. The arrangement having the stack of meshes has the advantage of low pressure drop, but dead volume is large. At the same time, in the solid block arrangement, pressure drop will be large, but the dead volume is small. Two other possible arrangements are to vacuum braze the meshes or solid block to the outer copper part. All four possible configurations are given as:

Configuration-I: A stack of 125 coarse copper screens press-fitted

Configuration-II: A tapered solid block having 12 slots of thickness 0.4 mm and depth of 4 mm along the periphery press-fitted

Configuration-III: Meshes vacuum brazed with the outer copper part

Configuration-IV: Slotted block vacuum brazed to the outer copper part

The first two configurations of the cold end heat exchanger are considered here. The cold end heat exchanger is tapered in structure as it joins the regenerator and the pulse tube, as shown in Figure 1. The paper also describes the effect of the taper angle on PTR performance.

EXPERIMENTAL SET UP

A schematic of the ITPTR on which the experiments were carried out is shown in Figure 2. The dimensions of the system are listed in Table 1. A moving-coil type linear compressor of swept volume 30cc was used as the pressure-wave generator. An experimentally optimized inertance tube of internal diameter 2.3 mm and length 2m was used for experimentation.

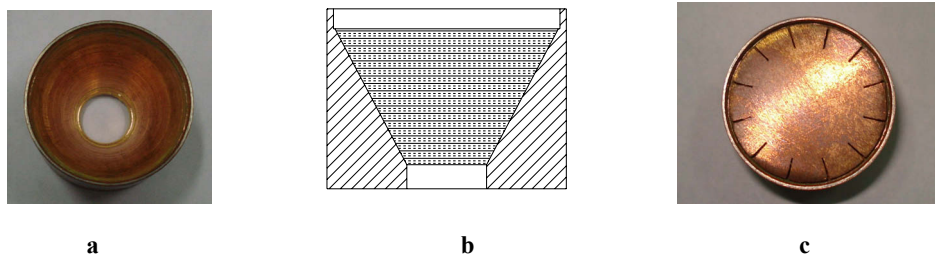


Figure 1. a) Outer part of the cold end heat exchanger; b) Schematic of Configuration-I, c. Configuration-II

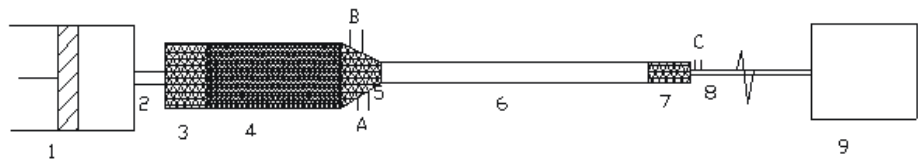


Figure 2. Schematic diagram of the PTR used in the experiments: 1.Compressor 2.Connecting tube 3.Aftercooler 4. Regenerator 5.Cold-end heat exchanger 6.Pulse tube 7.Hot-end heat exchanger 8.Inertance tube 9.Reservoir; A-Temperature sensor, B-Heater, C-Pressure Sensor

Table 1. Dimensions of the PTR unit

	Diameter(mm)	Length(mm)	Thickness(mm)
Regenerator	28	65	0.2
Pulse Tube	9.6	130	0.15

In the cold end Heat exchanger, a Lakeshore PT100 sensor is mounted for measuring the temperature. Also, a heater is provided to apply the load in the system. A piezoresistive pressure sensor is mounted near the hot end before the entry to the inertance tube to monitor the pressure variation and to obtain the pressure ratio.

RESULTS AND DISCUSSION

Experiments were carried out with both of the configurations for different pressures, frequencies, and maximum power input of 180 W. The experiment was started with an input power of 100 W until the temperature reached 123 K. Then, the power was increased to 180 W until the lowest temperature was achieved. After attaining the minimum temperature, the frequency was varied to find out the optimum frequency of operation.

Cooldown curves for both configurations for operation at a charge pressure of 16 bar are shown in Figure 3. The minimum temperature achieved for the configuration-I (with stack of copper mesh) was 80 K, whereas the minimum temperature for configuration-II (with the solid copper block having slots) was 70 K.

In the case of the solid block, gas takes a peripheral path near the wall of the outer copper part that enhances the heat transfer from the gas to the outer copper component. Also the thermal contact is improved by solid-to-solid contact of the unslotted surface of the solid block and the outer copper part. The Reynolds number increases, as the flow passage is very small through the

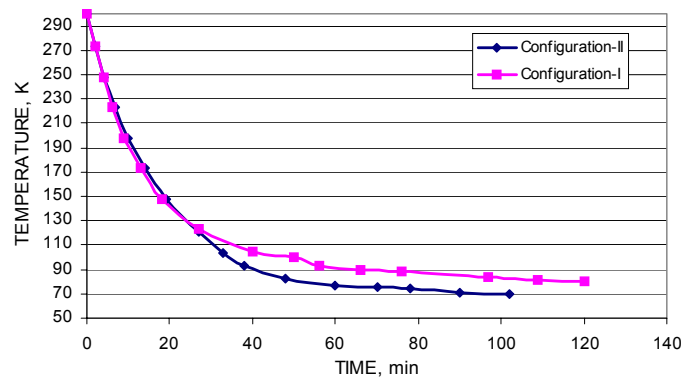


Figure 3. Cooldown curve for both configurations of cold end heat exchangers

slots, which increase the turbulence effect resulting in heat transfer enhancement. The initial cooldown time is almost the same for both of the configurations; however, after reaching around 120 K, the cooldown rate for configuration-I slows down.

Figure 4 shows the cooling load at different temperatures for an input power of 180 watts. In configuration-II, the minimum temperature is lower compared to configuration-I. That leads to improvement in the cooling load in configuration-II.

Effect of Frequency

The effect of operating frequency can be observed from Figure 5. From both curves, it can be seen that there exists an optimum frequency at which the lowest temperature is achieved. However, the optimum frequency is different for the two configurations. The optimum frequency for configuration-I is 37 Hz, while for configuration-II it is 42 Hz.

The difference in the optimum frequency can be attributed to the fact that the dead volume in the cold end heat exchanger is reduced in case of Configuration-II. In Configuration-I, the dead volume in the cold end heat exchanger is 4048 mm³, where as in Configuration-II, the dead volume is 422 mm³.

Effect of Taper Angle

Figure 6 shows the cooldown curves for the two different taper angles included in the cold end heat exchanger.

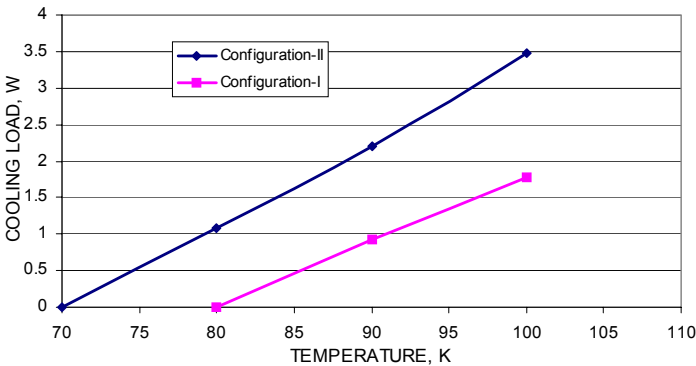


Figure 4. Cooling load at different temperatures for configurations I and II

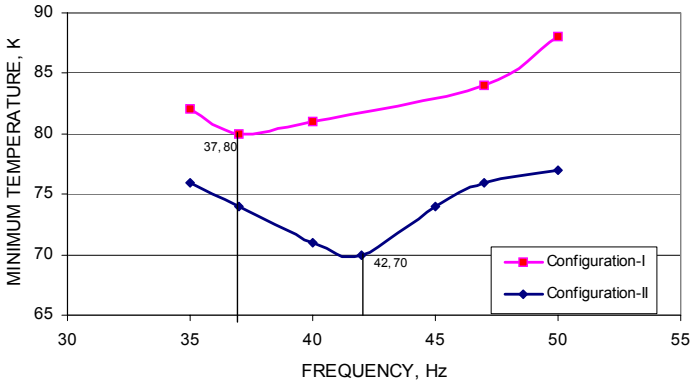


Figure 5. Effect on minimum temperature of various frequencies of operation

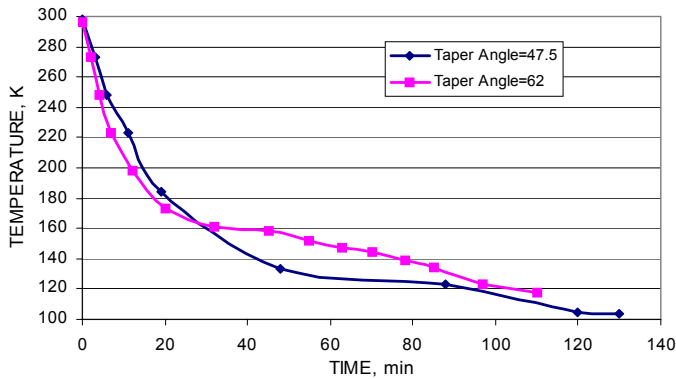


Figure 6. Cooldown curve for two different taper angles included in the cold end HX

The effect of the taper angle included in the cold end heat exchanger was also studied in a different setup. This involved use of a single-stage integral Stirling-type PTR having a regenerator diameter of 35 mm, and a pulse tube diameter of 17 mm with tube thickness of 0.2 mm. In these tests, it was observed that, as the taper angle is reduced, the flow pattern changes significantly, which leads to improvement in the performance of the PTR. The minimum temperatures attained were 118 K in the case of a taper angle of 62 deg, and 104 K for a taper angle of 47 deg; these were for operation at 25 Hz, a charge pressure of 16 bar, and 150 watts of input power.

CONCLUSION

The replacement of the coarse copper mesh by a slotted solid block improves the performance of the PTR by means of improved heat transfer from the gas to the copper outer part of the heat exchanger. The dead volume in the cold end heat exchanger is a sensitive parameter; change in the dead volume shifts the optimum operating frequency. The included taper angle in the cold end heat exchanger is also an important parameter that governs the flow pattern, which in turn affects the performance of the PTR.

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