Journal of Mines, Metals and Fuels, *73(9): 2881-2886; 2025. DOI: 10.18311/jmmf/2025/49839*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Performance Study of Single-Stage and Two-Stage Pulse Tube Refrigerator Using Adiabatic Model

M. N. Thejaswini[1*], U. Bhavana[1], A. S. Bindhu[1] and S. Kasthurirengan[2]

[1]*Department of Mechanical Engineering, JSS Science and Technological University, Mysuru - 570006, Karnataka, India, thejaswinimn@jssstuniv.in*

[2]*Centre for Cryogenic Technology, Indian Institute of Science, Bangalore - 560012, Karnataka, India*

Abstract

The capability of Pulse Tube includes reaching and maintaining a cryogenic temperature. The present work is a numerical simulation of both Single-stage and Two-stage Pulse Tube, which is carried out to optimise the different parameters of Pulse Tube, hence optimising its performance. A better version of single-stage PTR is 2-stage PTR; it is preferred to obtain the lowest temperatures possible. Special regenerator materials are needed to reach a temperature close to 4 K. The adiabatic model of single-stage and 2 stage pulse tube is developed in Matlab and is simulated with known dimensions. The cooling power and pressure variation at different parts of the pulse tube are predicted by the Analysis. To obtain the precise results, the parameters of the pulse tube are adjusted.

Major Findings: *Adiabatic modelling and laboratory experiments are employed to examine and enhance single-stage and two-stage Pulse Tube Refrigerators (PTRs). Temperature swings are smaller in the one-stage PTR, whereas the two-stage can operate at a no-load temperature of 3.3 K rather than the 40 K of the one-stage. The outcomes of experiments match the theories, but adding in predicted losses gives better estimations.*

Keywords: *Adiabatic Model, Pulse Tube Refrigerator, Refrigeration Power*

1.0 Introduction

Cryogenics began when scientists found that permanent gases could be liquefied at extremely low temperatures in the nineteenth century. Cryogenics is a combination of two Greek words: cryos, which means "cold," and genic, which means "to generate." Cryogenics is the science of creating and using "cold" fluids. Cryogenics is used in a variety of fields, including cryobiology, cryosurgery, cryonics, cryoelectronics, cryotronics, and so on. Cryocoolers are being developed quickly because the demand for cryogenic temperatures in various fields of research and technology is greater than before. Cryocoolers are refrigerating machines that use the compression and expansion of permanent gases. Electronics, space communication, military, medical, high-vacuum manufacturing, high-energy physics, and other fields require refrigeration at such low temperatures.

The majority of applications call for a cryocooler with high efficiency, dependability, extended lifetime, low cost, and minimal interference with the chilled object. Since the moving parts are present in the cold zone, meeting all of these requirements is difficult. Many of these needs are met by a novel cryocooler design known as the Pulse Tube Refrigerator (PTR). PTRs with the absence of moving parts in cold areas have higher reliability, better temperature stability, lower manufacturing costs, and vibration-free operation. Pulse tube refrigerators have a bright future because of these properties.

Cryocoolers come in a variety of shapes and sizes. Pulse Tube Cryocoolers, GM Cryocoolers, JT Cryocoolers,

**Author for correspondence*

Stirling-type Cryocoolers, and so on are examples. Cryocoolers used in different applications must be low-cost, low-maintenance, and have high reliability and efficiency. Because the moving part is in the cryocooler's cold zone, it's difficult for me to meet all of the above conditions. Gifford discovered the Pulse Tube Cryocooler in the 1950s. It outperforms other cryocoolers in the cold zone since there are no moving parts. It is simple to construct and offers a high level of operating reliability and longevity.

Due to the oscillating flow inside the pulse tube, as well as the accompanying complex thermodynamic and heat transfer processes, the functioning of the pulse tube was initially unknown. The degree of understanding expanded with time; improvements and better designs yielded a great deal in terms of increased efficiencies. It has now proven to be one of the most capable cryocoolers in the known dimension.

In 1961, Gifford came up with the idea of PTR as a new method for obtaining low temperatures. Although the study on PT began in 1962, the first publication[1] documenting the development was published in 1964. The pressurisation and depressurisation of a volume confined at its periphery caused temperature disparities on its surface. However, the geometry of the volume and the operational situation both influence this effect. When you pressurise and depressurise a particular volume, heat energy is transferred both inside and outside the volume. To construct a refrigerator, heat transmission can be combined with heat exchangers and regenerators.

Zhu *et al.*,[2] discovered the DPTR in 1990 at X'ian Jiaotong University in China, which adds better efficiency over the OPTR. The results of the investigation show that DPTR outperforms OPTR. The mass flow rate into the regenerator in the OPTR is demonstrated to be quite high. By putting a needle valve between the compressor and the PT warm-end, the pressure is decreased. This valve reduces the regenerator mass flow, increasing the cooling power per unit mass flow rate via the regenerator. The experimental and theoretical findings support DPTR's superior performance over OPTR.

Chao Wang *et al.*,[3] established a numerical modeling technique for OPTRs in 1991. This model is utilised to measure refrigeration power, compressor work, mass flow rate, pressure, compressor work, and gas temperature in the cold and warm zones by varying factors such as temperature, orifice openings, and DI and Crank angle. In 1992, C Wang *et al.*,[4] applied the numerical analysis described above to DIPTR. They may be able to attain a high level of agreement between experimental and theoretical results.

PTR's 1D model was simulated by I.A. Lyulina *et al.*,[5]. The research presents a new numerical model for PTRs that is based on oscillatory heat and mass flow. The model calculates refrigeration power, average enthalpy flow, and temperature distribution by solving equations of energy, momentum, and mass.

C Wang *et al.*,[6] developed modified OPTR in 1993. In their research, they employed the crankcase of a Helium compressor as a reservoir. Modified OPTR, or MOPTR, was the name given to this setup. The reverse phase of the pressure wave in the crank case can be employed to generate the proper phase angle between mass flow and pressure at the cold end, according to a numerical simulation. MOPTR had a greater cooling capacity than OPTR.

DIPTR was studied experimentally by Cai *et al.*,[7]. They discovered that the DI impedance and the orifice impedance matched, resulting in maximum cooling power. The orifice was discovered to lessen the phase shift between pressure and gas flow, although its minimum value is 480 rather than 00.

Zhu *et al.*,[8] created another model in 1994. The PT is believed to be divided into three pieces. 1. Cold zone, via which fluid flows into and out of the regenerator and into the PT 2. The heated end's hot zone, from which fluid flows into the orifice. 3. The midzone, where the fluid is inside PT and is compressed and expanded adiabatically. The displacer of a Stirling cooler is equivalent to the aforementioned. When compared to nodal analysis, the results of this model showed that the cooling power and input power were 20 per cent less.

An article on the theoretical model of the PTR system was published in 2006 by P. K Das, S.K. Sarangi and P.C. Roy[9]. The majority of the writers looked at analytical models of PTRs that used symmetric pulse tube pressure variations during suction and compression, such as trapezoidal or sinusoidal behaviour. In their analysis, the variation in stroke volume with time was considered to be sinusoidal. They calculated compressor, PT, and reservoir pressure variations, as well as mass flow behaviour at various sites. The phase relationships between the cold zone mass flow rates and the pulse tube pressure have been used to compare the different types of PTRs, such as BPTR, OPTR, and DIPTR.

Shafi *et al.,*[10] provide an adiabatic gas flow numerical model in two-stage PTR for predicting detailed PT performances. In their research, they discovered pressure changes at the reservoir, compressor, and PT. Their model's projected cooling powers matched the measured values of experiments very well.

E I Mikulin *et al.,*[11] worked on overall improvement of pulse tube refrigerators especially in low temperature processes through varying the design configuration of a pulse tube refrigerator which involves the use of a gas distributor and receiver as a way of increasing the speed and efficiency of cooling relative to use of conventional systems. The authors tested two versions, a simplified pulse tube suitable to moderate cooling, and an advanced cryogenic version in which a regenerator is inserted to attain even colder temperatures. Valve mechanics and gas flows mechanics are also studied and utilized to discuss the mechanisms behind the cooling.

Liang J *et al.,*[12] experiments to find the relation between regenerative volume and pulse tube volume and OPTR's lowest temperature. C.Wang *et al.,*[13] revealed that DIPTR can obtain more refrigeration power with less P-V work than a traditional orifice refrigerator.

Gawali *et al.,*[14] IPTR model suggested system is unique because it relies on two compressors running at 180 degrees with just one tube on the high and the other on the low side to create the pressure wave. The jet switches direction approximately every 180 crank angle rotations.

Rout. A, K *et al.,*[15] suggested that two compressors are connected in such a way that one is on the high-pressure side and the other on the low-pressure side, running at exactly opposite times to produce the pressure wave. After every 180-degree turn of the crank, the flow is reversed.

2.0 Materials and Methods

2.1 Numerical Analysis using Adiabatic Model

Pierre Neveu *et al.* created the proposed model for a single-stage PTR, and it is now being used for a two-stage PTR. Liang *et al.*,[12] first simulated a single-stage PTR using the thermodynamic behaviour of gas in an adiabatic flow. During compression and expansion, pressure oscillations in the form of trapezoidal waveforms were utilised in their study. The volume variation of the compressor was considered sinusoidal. In addition, the effect of the void volumes of various components was taken into account in their model. The following are the assumptions.

1. Axial heat conduction is ignored.
2. The regenerative material is incompressible and has uniform porosity.
3. The regenerator and heat exchangers in the cold and hot zones are ideal.
4. Pressure drops in different components are neglected.

We got an optimisation of various parameters by altering the size of individual sections and comparing the pressure variation and cooling power of both single-stage and two-stage PTRs using Numerical Analysis and different empirical equations. Figures 1(a) and (b) depict a single stage and a double stage, respectively.

3.0 Results and Discussion

3.1 General performance of PTR

In both single-stage and two-stage pulse tube refrigerators, the usual behaviour of the PTR system is discussed regarding the pressure variation of the Reservoir, Compressor, and Pulse Tube.

Pressure fluctuations in the compressor, pulse tube, and reservoir as a function of time are plotted in Figures 2(a) and 2(b) for single-stage and two-stage PTR, respectively. A certain number of cycles of these pressures can be seen depending on the frequency of oscillations. When the reservoir volume is raised in both circumstances, the compressor pressure amplitude is found to be higher than that of the pulse tube, and the reservoir pressure variations are relatively minor compared to those of the compressor.

When compared to single-stage PTR, the amplitude of pressure variation in the pulse tube, reservoir, and compressor of two-stage PTR is quite high.

3.2 Comparisons of Cooling Power

Our laboratory has designed and produced single and double-stage PTRs. The cooling powers generated in the cold zone were measured as follows: A low-wattage heater has been installed in the cold zone. The pulse tube system is initially allowed to cool to no-load temperature. The heater positioned in the cold zone is then given a known quantity of voltage. This allows current to flow inversely proportional to resistance

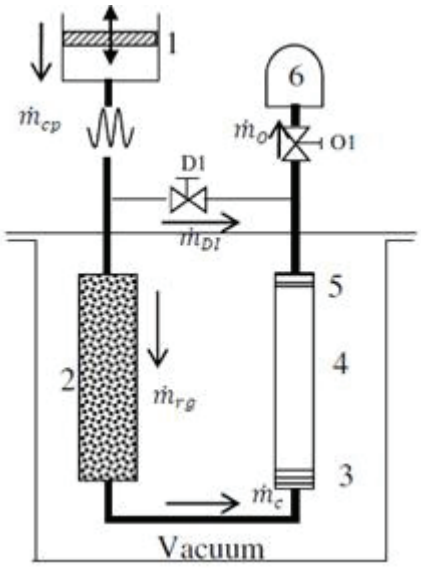


Figure 1(a). Schematic of single-stage PTR.

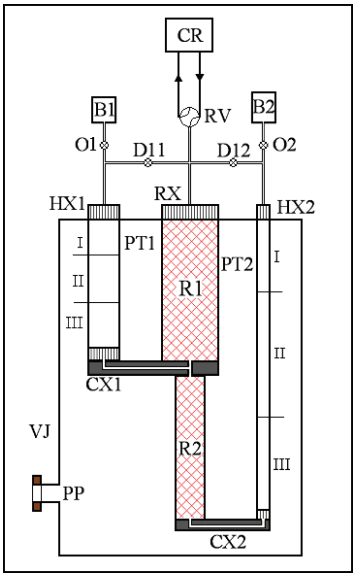
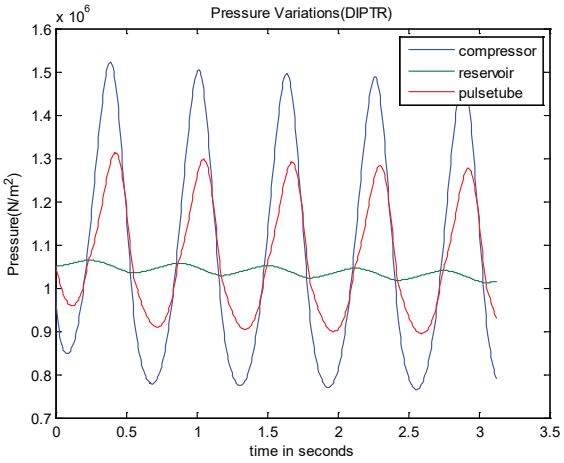
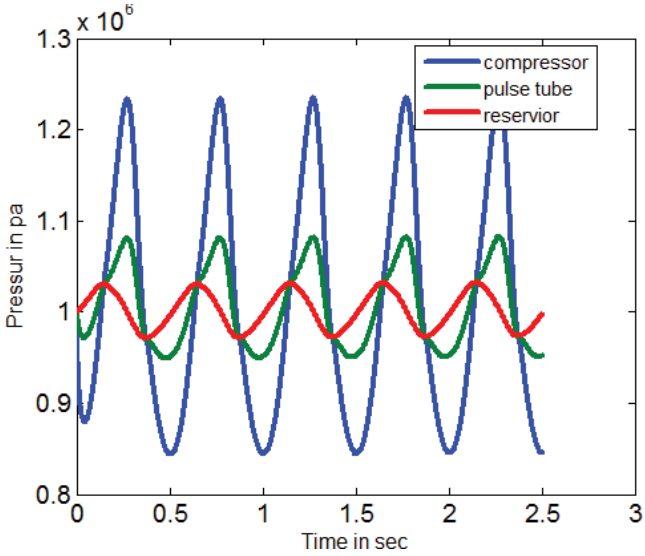


Figure 1(b). Schematic of a 2-stage PTR.



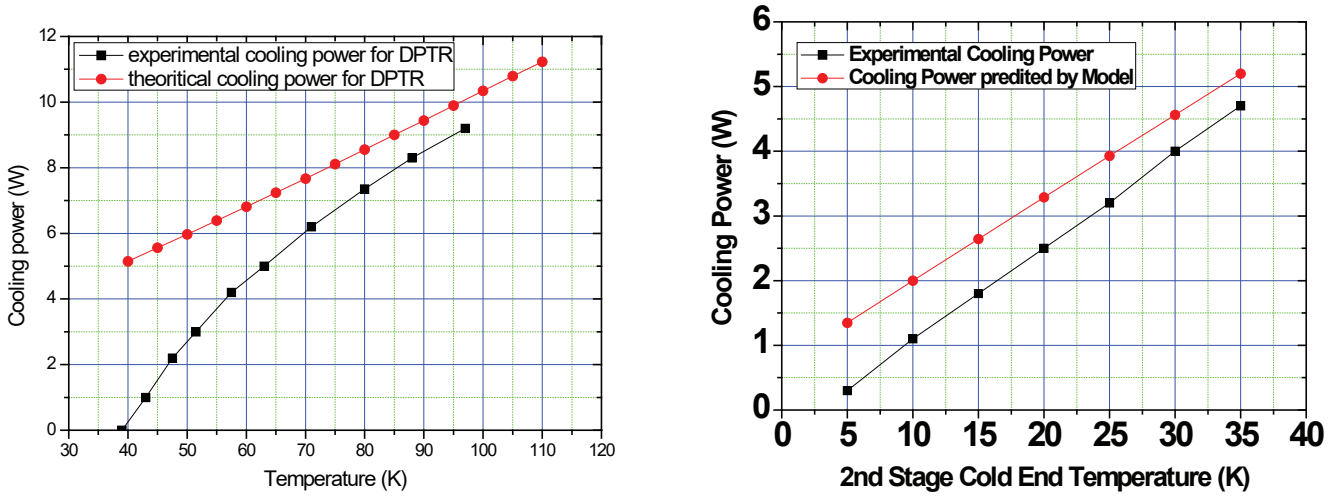
(a)



(b)

Figure 2. Pressure variation of **(a)** Single stage PTR and **(b)** 2-stage PTR.

through the heater wire. The product of the current and applied voltage equals the heat load applied by the heater. The steady-state temperatures reached in the cold zone are calculated for various heat loads applied to the cold zone. The cooling power produced by a cryocooler can be calculated by plotting the applied heat load as a function of the cold zone temperature. The cooling powers obtained experimentally can be compared to those predicted by a computer model based on adiabatic flow. Figure 3(a) and (b) depict such a comparison (b). In both cases, the experimental and theoretical cooling powers show a reasonable degree of agreement. Generally, the experimental values are lower when compared theoretical values. Importance is to be given to experimental values as it addresses the various losses. There will be a fairly good agreement between experimental data and theoretical predictions if losses are taken into account.



(a) **(b)**

Figure 3. Comparison of experimental data and theoretical predictions of the cooling power of both **(a)** Single stage PTR and **(b)** 2-stage PTR.

When comparing the cooling power of single and two-stage PTRs, it is obvious that the cooling power achieved by the two-stage PTR is higher in both experimental and numerical analyses than that of the single-stage PTR.

4.0 Conclusion

In this paper, an adiabatic modelling was used to perform a numerical analysis of a single and two-stage PTR, as well as experimental studies on both. To optimise the PTR, the above analysis was used. The outcomes are outlined in the following paragraphs.

Single-stage PTR has a smaller amplitude of pressure variation in the compressor, pulse tube, and reservoir than two-stage PTR.

The development of a PTR that provides a no-load temperature of 3.3K and 40K, respectively, in the Double stage and Single stage PTR.

Both PTRs experimentally measured cooling power is found to be in reasonable agreement with the adiabatic model's theoretical predictions. However, in order to obtain correct estimates of performance, a more complete analysis incorporating losses is required.

8.0 References

1. Gifford WE, Longsworth RC. Pulse tube refrigeration. Trans ASME J Eng Ind. 1964; 86:264-7. https://doi.org/10.1115/1.3670530
2. Zhu SW, Wu PY, Chen ZQ. Double inlet pulse tube refrigerator: an important improvement. Cryogenics. 1990; 30(6):514-20. https://doi.org/10.1016/0011-2275(90)90051-D
3. Wang C, Wu PY, Chen ZQ. Numerical modelling of an orifice pulse tube refrigerator. Cryogenics. 1992; 33(5):522-8. https://doi.org/10.1016/0011-2275(92)90310-7
4. Wang C, Wu PY, Chen ZQ. Numerical analysis of a double inlet pulse tube refrigerator. Cryogenics. 1993; 33(5):526-30. https://doi.org/10.1016/0011-2275(93)90249-N
5. Lyulina IA, Mattheij RMM, Tijsseling AS, de Waele ATAM. Numerical simulation of pulse-tube refrigerators: 1D model. Eindhoven: Eindhoven University of Technology; 2002.
6. Wang C, Wu P, Chen Z. Modified OPTR without a reservoir. Cryogenics. 1994; 34(3):191-6. https://doi.org/10.1016/0011-2275(94)90049-3
7. Cai JH, Zhou Y, Wang J, Zhu WX. Experimental analysis of the double inlet principle in a pulse tube refrigerator. Cryogenics. 1993; 33(6):522-7. https://doi.org/10.1016/0011-2275(93)90248-M
8. Wang C, Thummes G, Heiden C. A two-stage pulse tube cooler operating below 4 K. Cryogenics. 1997; 37(3):159-64. https://doi.org/10.1016/S0011-2275(96)00112-9
9. Roy PC, Das PK, Sarangi SK. A simplified theoretical model of a pulse tube refrigeration system. In: Proceedings of the 3rd BSME-ASME International Conference on Thermal Engineering; 2006 Dec 20-22; Dhaka, Bangladesh; 2006.

10. Shafi KA, Rasheed KKA, George JM, *et al*. An adiabatic model for a two-stage double-inlet pulse tube refrigerator. Proc Inst Mech Eng C J Mech Eng Sci. 2008; 222(10):1977-86. https://doi.org/10.1243/09544062JMES775
11. Mikulin EI, Tarasov AA, Shkrebyonock MP. Low temperature expansion pulse tube. In: Advances in cryogenic engineering. New York: Plenum Press; 1984; 629-37. https://doi.org/10.1007/978-1-4613-9865-3_72
12. Liang J, Zhou Y, Zhu W. Development of a single-stage pulse tube refrigerator capable of reaching 49 K. Cryogenics. 1990; 30(1):49-51. https://doi.org/10.1016/0011-2275(90)90114-R
13. Zhu SW, Wu PY, Chen ZQ. Double inlet pulse tube refrigerators: an important improvement. Cryogenics. 1990; 30(6):524-7. https://doi.org/10.1016/0011-2275(90)90051-D
14. Gawali BS, Narayankhedkar KG. Performance evaluation of the pulse tube refrigerator. AIP Conf Proc. 2006; 823:11-8. https://doi.org/10.1063/1.2202395
15. Rout AK, Behura AK, Dalai S, Sahoo RK. Numerical analysis of a modified type pulse tube refrigerator. Energy Procedia. 2017; 109:456-62. https://doi.org/10.1016/j.egypro.2017.03.067