A Review of Pulse Tube Refrigerator

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***Abstract*—Pulse tube is a cryocooler which is capable to achieve very low temperature in a single stage and further low temperature by using two stages. Unlike ordinary refrigeration cycles which utilize the vapor compression cycle, a PTR implements the oscillatory compression and expansion of gas within a closed volume to achieve the desired refrigeration. This paper describes about pulse tube refrigerator and review of experimental, analytical and CFD work carried out on pulse tube refrigerator.**

Keywords*— *Pulse tube refrigerato; Basic pulse tube refrigerator; Orifice pulse tube refrigerator; Double inlet pulse tube refrigerator; Inertance tube pulse tube refrigerator

I. INTRODUCTION

Cryocoolers are small refrigerators that can reach cryogenic temperatures and provide refrigeration in the temperature range 10 K to 120 K. Pulse tube cooler is one kind of cryocooler. The use of pulse tube has been propelled by many requirements of modern day applications such as adequate refrigeration at specified temperature with low power input, long lifetime, reliable and maintenance free operation with minimum vibration and noise, compactness, and lightweight.

II. APPLICATION OF PULSE TUBE REFRIGERATOR

- Liquefaction of gases such as nitrogen, oxygen, hydrogen, helium, natural gas
- SQUID magnetometers
- Cooling of super-conducting magnets
- Cooling of infrared sensors for missile guidance
- Cryo vacuum pumps
- Cryosurgery
- Cooling of high temperature superconductors and semiconductors
- Gamma ray sensors for monitoring nuclear activity
- Preservation of biological materials, blood, biological specimens etc.

III. HISTORY

The first pulse tube refrigerator was discovered accidently at Syracuse University by Gifford and Longsworth in the 1960s as they were developing the Gifford McMahon [1] refrigerator. They observed that when there was a pressure oscillation inside the pipe, the closed end of a pipe became very hot, whereas the open end near the compressor was cool. After further studies and modify the dimensions, they were able to achieve a low temperature of 124 K at one end when the closed end, in the atmosphere was cooled with water. In their setup they used a Gifford-McMahon compressor in the system, but there was no orifice or any other separate reservoir. There was a small reservoir associated with the heat exchanger at the warm end of the pulse tube. Pulse tube diameters were about 20 to 25 mm and operating frequencies were about 1 Hz. This pulse tube refrigerator without an orifice is now referred to as the basic pulse tube refrigerator.

Gifford et al. discovered basic pulse tube refrigerator they got 150 K in a one stage cooler and 120 K in a two stage. After a few years the refrigerator had reached 120 K in single stage and 85 K in double stage.

Dr. J. Wheatley at the DOE's Los Alamos National Laboratory took interest in this kind of technology: thermo-acoustic engines and coolers. These are a class of inherently irreversible machines that operate at acoustic resonance (Pulse Tubes operate at frequencies well below resonance). These devices have low efficiency. The coolers were driven by a simple loudspeaker; while the engines had no moving parts except working fluid.

In 1981, after hearing a talk by Dr. Wheatley (16th International Conference on Low temperature Physics), Dr. P. Kittel of NASA's Ames Research Centre recognized the potential for space applications of a cooler with a single moving part. The main advantages are greater reliability and lower cost compared to the Stirling cooler and an order of magnitude lower mass, lower cost, and longer life than the current state of the art coolers: stored cryogens. Another advantage is that there are no cold moving parts which enhances life time and removes vibration causing components from the cold head.

In 1982, Dr. Kittel in partnership with Dr. R. Radebaugh of NIST started developing Pulse Tubes. The first breakthrough came the next year. At the 1983 Cryogenic Engineering Conference, Dr. E. Mikulin (Moscow Bauman State Technical University, Russia, formerly the Moscow High Technical School, USSR) showed that the efficiency could be increased by inserting an orifice and reservoir at the hot end. This increased the phase shift between the pressure and mass flow oscillations. This observation led to the Orifice Pulse Tube which has become the standard implementation. Single stage Orifice Pulse Tubes have reached temperatures below 30 K (various workers, late 1980's); while a 3-stage device built by Prof. Matsubara at Nihon University in Japan has reached 3.6 K (15th International Cryogenic Engineering Conference, 1994).

By the late 1980's, a good theoretical understanding had been developed at NIST (NASA funded). This was 1-D thermodynamic model based on Enthalpy flow. During this time, technology transfer from the NIST/NASA team was well under way with a number of companies. The biggest industrial effort was at TRW. They started in 1987 with a development contract from NASA Ames and with substantial in-house funding. TRW built a number of Pulse Tubes, including the first one to works below 10 K. In 1994 TRW delivered its first Pulse Tube built under contract to the Air Force's Phillips Laboratory. The success of this cooler (1 watt at 35 K with 200 watts of input power) lead to TRW being selected to build a Pulse Tube for the AIRS instruments for the EOS program. This is a 1.5 watts at 55 K cooler with an input power of less than 100 watts; an efficiency comparable to Stirling coolers.

Meanwhile; Dr. G. Swift at Los Alamos with DoE funds had continued developing the thermo-acoustic compressor. The compressor was coupled to a Pulse Tube developed by Dr. R. Radebaugh at NIST. This produced a cooler with no moving parts (4th Interagency Meeting on Cryocoolers, 1990). The cooler reached 90 K and produced 5 watts of cooling at 120 K with an input thermal power of 3 kilowatts. Not very efficient, but tremendous potential for reliability!

By the late 1980's many laboratories around the world had started Pulse Tube development. The principal groups are located in China, Japan, France and Germany. Many different configurations and specifications have been investigated. One of the most active is the group lead by Prof. Matsubara (Nihon University, Japan). They were the first to develop the moving plug or hot piston Pulse Tube. This added a second moving component and increases the efficiency. The most important development has been the discovery of the double inlet Pulse Tube by Dr. Zh of Xi'an Jiaotong University, China (13th International Cryogenic Engineering Conference, 1990). This technique was further refined into the multiple by-pass Pulse Tube by Dr. Zhou of the Academia Sinica, China (7th International Cryocooler Conference, 1992). In 1994, the first commercially available Pulse Tube was announced in Japan by Iwatani as a replacement for the cold head of a Gifford-McMahon cooler. (Gifford-McMahon coolers are a low cost variation of a Stirling cooler. They are the most common type of cryogenic refrigerator sold industrially.)

The quality of the analytic models has also improved over the years. NASA Ames has been developing a 2-D model that incorporates both thermodynamics and hydrodynamics. This model has shown that there are secondary flows in the system thatearlier 1-D models had ignored. The existence of these secondary flows has been confirmed by flow measurements made at NASA Ames (8th International Cryocooler Conference, 1994). Current work at Ames also includes the fabrication of a 4-stage Pulse Tube based on the multiple by-pass approach.

A number of American manufactures are also interested in replacing Gifford-McMahon coolers with Pulse Tubes; although, none of the major industrial manufactures are close to making this change. When they make this change, the new coolers will be lower cost, lower vibration, and more reliable. Most of the non-aerospace work on Pulse Tubes has been in small companies working with SBIR contracts.[2][3]

IV. PRINCIPLE OF WORKING

Pulse tube refrigerator works on the principle of surface heat pumping which is shown in fig. 1

1. Process 1-2 adiabatic compression

Because of the pressure difference gas which compressed in the compressor it works as a piston and compress the gas in the pulse tube and this process increase the temperature of the gas.

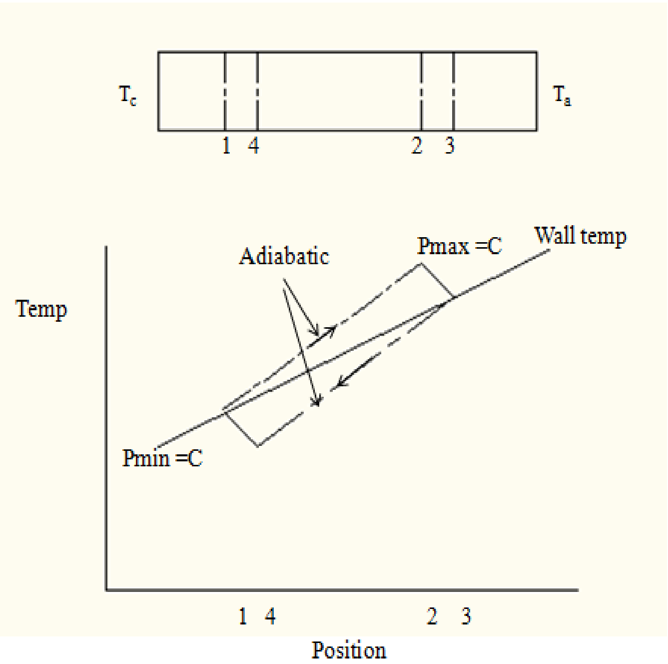

Fig 1. Principal of pulse tube refrigerator

2. Process 2-3 constant high pressure cooling

In process 1-2 gas temperature increased compare to the wall temperature hence in this process gas is being cooled by the heat exchanger and temperature becomes T_a, which produces the refrigeration effect during the expansion process.

3. Process 1-2 adiabatic expansion

In process 3-4 piston moves up and produces pressure difference in the system therefore it produce adiabatic expansion of the gas with the drop in temperature to the wall temperature thus it produce the cooling effect during the low pressure, gas which leaves the pulse tube during this process it also colder than heat exchanger, which provides cooling for thermal load at T_c in the heat exchanger.

4. Process 4-1 Constant low pressure heating

In this process the gas which was expanded is warmed at constant low pressure by cooling the wall and providing the refrigerating effect in the heat exchanger.

V. TYPES OF PULSE TUBE REFRIGERATOR

A. Basic Pulse Tube Refrigerator
B. Orifice Pulse Tube Refrigerator
C. Double Inlet Pulse Tube Refrigerator
D. Inertance Tube Pulse Tube Refrigerator

A. Basic Pulse Tube Refrigerator

It is the first pulse tube which was built in 1963 by Gifford and Longsworth. [1] Its basic components are regenerator, pulse tube, pressure wave generator, and two heat exchangers as shown in Fig. 2.

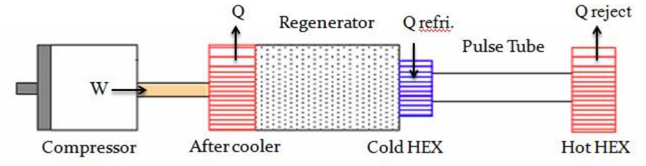

Fig 2. Schematic diagram of Basic Pulse Tube Refrigerator (BPTR)

The pulse tube is a simple tube which has one open end and one closed end. The closed end is the hot end which capped with a heat exchanger that cools it to the ambient temperature with the help of water. The open end which is cold end is connected to the regenerator which is a second heat exchanger. The regenerator is a periodic flow heat exchanger which absorbs heat from gas pumped into the pulse tube pre-cooling it, and stores the heat for half a cycle then transfers it back to outgoing cold gas in the second half of the cycle cooling the regenerator. The interior of the regenerator tube is filled with either packed spheres or stacked fine mesh screens to increase its heat capacity. A piston, compressor or similar pressure wave generator is attached to the warm end of the regenerator and provides the pressure oscillations that provide the refrigeration. Generally Helium is used as the working gas due to its monotonic ideal gas properties and low condensation temperature. In systems with a base temperature below 2K the 3He isotope is used. Record low temperatures achieved with this basic pulse tube design are 124K with a single stage and 79K using two stages.

B. Orifice Pulse Tube Refrigerator

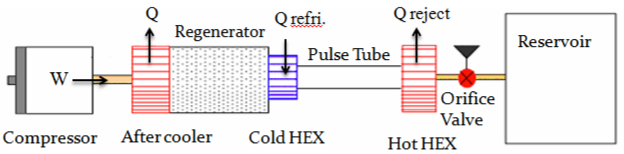

Fig 3. Schematic diagram of orifice pulse tube refrigerator (OPTR)

Mikulin et. al was the modified in basic pulse tube refrigerator and added a small orifice valve at the warm end of the pulse tube in 1984, An orifice is just a needle valve or throttle valve to regulate flow. Their new design had a base temperature of 105K [4]. And Radebaugh et. al further improved the design, by arranging the orifice outside the heat exchanger and added a reservoir after the orifice. The reservoir is large enough to be maintained at nearly constant intermediate pressure during experiment. This design reached a temperature of 60K [5]. This new design is responsible for increase in efficiency. It is due to addition of small orifice causes improve in phase between velocity and temperature as a result more enthalpy flow near hot heat exchanger. Such types of refrigerator are known as Orifice Type Pulse Tube Refrigerator (OPTR) which is shown in figure 3.
The disadvantage of the orifice pulse tube is that a large amount of compressed gas which produces no actual refrigeration, it has to flow through the regenerator. This reduced the refrigeration power per unit of compressed mass and hence increases the regenerator loss. The increase in mass flow rate in the regenerator reduces the effectiveness of the regenerator, and increase the pressure loss. Both of these effects reduced performance of OPTR.

C. Double Inlet Pulse Tube Refrigerator

Small amount of the gas that flows through the regenerator does external work. The efficiency of the pulse tube refrigerator can be increased by maximizing the refrigeration power per unit mass flow. The extra gas, even though it provides no refrigeration power, but it must be cooled by the regenerator which increases the heat transfer load but does not work and therefore limits refrigeration.

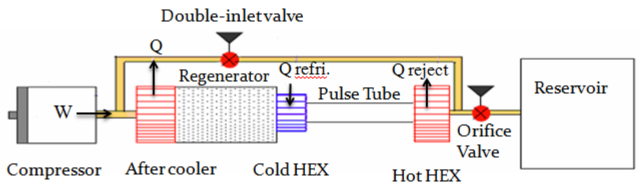

Fig. 4 Schematic diagram of double inlet pulse tube refrigerator (DIPTR)

Zhu, Wu and Chen addressed this problem by adding a direct connection, or secondary orifice, between the warm end of the regenerator and the warm end of the pulse tube [6]. This is known as double inlet pulse tube refrigerator (Fig. 4).

The secondary orifice is designed as it allow about 10% of the gas, which does not contribute to refrigeration, to travel directly from the pressure oscillator to the warm end of the pulse tube, bypassing the regenerator pulse tube arrangement. This direct flow compresses and expands the warm working gas in the pulse tube, and reduces the amount of gas that needs to be pre-cooled by the regenerator. The extra gas flow also regulates the phase angle between the pressure and mass flow in the system.

D. Inertance Tube Pulse Tube Refrigerator

The fourth and the most recently invented PTR is inertance tube pulse tube refrigerator shown in Fig. 5. In this type of PTR the orifice valve is replaced by a long inertance tube having very small internal diameter and adds reactive impedance to the system.

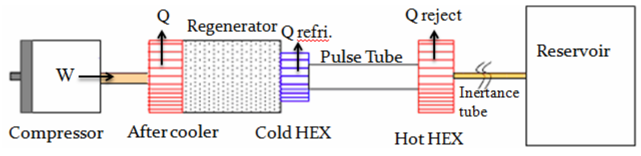

Fig.5 Schematic diagram of inertance tube pulse tube refrigerator (IPTR)

The implementation of this inductance generates an advantageous phase shift in pulse tube and produces an improved enthalpy flow. Studies show that use of the inertance tube is significantly beneficial for large-scale pulse tubes operating at higher frequencies.

VI. RECENT DEVELOPMENT IN PULSE TUBE REFRIGERATOR

1. Experimental work

L. M. Qiu et al. [7] worked on pulse tube refrigerator by changing regenerative material $GdAlO_3$. They found that the cooling power and coefficient of performance of two stage pulse tube cooler below 4K has been increase gradually by using the newly developed ceramic magnetic regenerative material $GdAlO_3$. Cooling power of 200mW at 3.13 K, and 400mW at 3.70 K have been achieved with a compressor input power about 4.8 kW. Result shows that the cooling power near 3.0 K increased by 150% compared to that same pulse tube cooler employing only conventional $HoCu_2$ and ErNi regenerator material because of their volumetric specific heat difference.

M.Y. Xu, et al. [8] worked on pulse tube refrigerator below 2 K. before they worked on 3He other pulse tube refrigerators operating at the liquid helium temperature range use 4He as the working fluid. However, the lambda transition of 4He is a barrier for reaching temperatures below 2 K. Theoretical analysis in this paper shows that, using 3He, the temperature limit is below 2 K, and the efficiency of a 4 K pulse tube refrigerator can be improved significantly. A three stage pulse tube refrigerator is constructed. A compressor with input power of 4 kW and a rotary valve are used to generate the pressure oscillations. With 4He, a minimum average temperature of 2.19 K was reached. Replacing 4He by 3He, at the same valve settings and operating parameters, the minimum average temperature goes down to 1.87 K and the cooling power at 4.2 K is enhanced about 60%. After fine tuning of the valves, a minimum average temperature of 1.78 K was obtained. This is the lowest temperature achieved by mechanical refrigerators.

K. Wang et al. [9] are worked on pulse tube refrigerator with 'L' type pulse tube and two orifice valves they conclude that in L type pulse tube big wall thickness affect the lowest temperature of the system and they reach at the lowest temperature of 72 K at 2.5 Hz frequency.

There is a shuttle loss occurred in pulse tube this loss can be reduced by inside coating of Teflon material in the pulse tube this experimentally observed by Taekyung Ki and sangkwon jeong [10]. They found that When Stycast 2850 FT material is used as the coating material, the no-load temperature they obtain from 38.4 K to 34.9 K and the cooling capacity is improved by 0.4W.

K. R. Parikh, G. Patel, M. C. Barot [11], worked on wire mesh material of the regenerator. They use S.S. wire mesh for basic pulse tube refrigerator and conclude that S.S. 150 mesh size produce batter cooling as compare to S.S. 200, 300 and 350.

2. Analytical work

Neveu et al. [12] developed both dynamic and ideal models for better understanding of the energy and entropy flows occurring in the pulse tube coolers. Their ideal modeling is sufficient to quantify the maximum performance, which could be reached, but dynamic modeling is required modification in design.

M. Azadi et. al. [13] worked on two dimensional compressible oscillating flows in the tube section of a pulse tube refrigerator system model; it is based on the successive approximation method. The effects of frequency of operation and taper angle on the temperature distribution, time-averaged enthalpy flow, and heat transfer behavior during a cycle are investigated. By increasing the frequency it leads to a higher heat transfer rate in the pulse tube. The enthalpy flow, as the cooling performance representative of the pulse tube, reaches maximum for an optimum convergent taper angle. After studied the temperature distribution and heat transfer process along the axial direction, and the phase behavior of the heat transfer coefficient, it is shown that, moving from the cold to the hot end of the pulse tube, the temperature variation domain and heat transfer rate decrease.

The influence of the double inlet valve on the cooling effect and characteristics of inertance tubes are numerically studied and then an experimental setup is built to verify the numerical results. From this results, J.Y. Hu et. al.[14] conclude that the inertance tube cannot provide the optimum impedance for small cooling powered pulse tube because of turbulence in flow. In those cases, the double-inlet valve can assist better impedance and further improve the cooling performance. On the other hand, the inertance tube can provide the optimum impedance for large cooling powered pulse tube refrigerators.

Pressure drop in the regenerator is one of the effective parameter as the pressure drop increase with increase in L/D ration of the regenerator, cooling effect will decrease. A. D. Badgujar and M. D. Atrey [15] conclude that increase in L/D ratio 1.93 to 9 will decrease cooling effect 6.1 W to 1.7 W. Their theoretical results are verified with experimental data.

3. CFD work

Regenerator is the important part of the PTR. S.K. Rout et al. [16] did numerical study with the help of CFD on single stage coaxial and inline inertance type pulse tube refrigerator.

To find out the best regenerator material porosity, They set operating frequency for all case is 34 Hz, pulse tube diameter 5mm and length is 125mm for changing porosity of material 0.5 to 0.9. After analysis they conclude that porosity value of regenerator 0.6 at which it gives a better cooling.

Phase difference in mass flow rate and pressure in Inertance tube type refrigerator can affect on refrigeration effect pravin mane et. al. [17] did numerical analysis of oscillation flow in cfd software of inline Inertance tube refrigerator they use helium as working medium and frequency 12Hz. For regenerator stainless steel wire mesh and for heat exchangers copper wire meshes are used. By varying phase angle, they get lowest temperature 132 K at phase angle 40 degree. The mass flow rate is lagging the pressure wave.

By changing the valve opening conditions in DIPTR for different boundary conditions variation in refrigerating effect analyzed by banjare et. al. [18] they did three different simulations are analyzed. First they assumed an adiabatic cold end heat exchanger; another assumed a known cooling load, and the last assumed a pre-specified temperature of cold end heat exchanger. After analysis they found that by opening double inlet valve 20% and orifice valve 30% offers a better potential for higher performance and efficiency compared with other values of valve openings. They also compare the experimental data and CFD simulation they get better cooling.

CONCLUSION

- Regenerative material $GdAlO_3$ can be use to achieve less than 5K temperature for 2 stage pulse tube refrigerator.
- Cooling effect can be increase by replacing 3He with 4He as a working gas
- Wall thickness of pulse tube affect the cooling effect
- Coating inside the pulse tube also gives better refrigeration effect.
- 150 mesh sizes of wires in regenerator gives better cooling.
- Pressure drop in the pulse tube is inversely proposal to cooling effect.

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