Theoretical Study and CFD Analysis of a Single Stage Gm Type Double Inlet Pulse Tube Refrigerator (DIPTR)

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Abstract— a pulse tube cryocooler is a refrigeration machine that reaches cryogenic temperatures with small refrigeration capacity. The objective of the present work describes the theoretical study and CFD analysis of a single stage GM type double inlet pulse tube refrigerator. And Heat loss calculation of pulse tube. Pulse tube refrigerator has the advantages of long life and low vibration over the conventional cryocoolers, such as GM and Stirling coolers because of the absence of moving parts in low temperature. This project deals with study and computational fluid flow analysis (CFD) of a GM type double inlet pulse tube refrigerator (DIPTR), operating under a variety of thermal boundary conditions. A commercial computational fluid dynamics (CFD) software package, ANSYS is used to model the oscillating flow inside a pulse tube refrigerator.

Key words: GM type PTR, Pulse tube, DI valve

I. Introduction

Cryocooler is a refrigeration machine with refrigeration temperature below 123K and with a small refrigeration capacity. Pulse Tube works without mechanical displacer. Gas works as a displacer. There is no need for a mechanical drive for the displacer. Vibration is less as compared to Stirling and Gifford McMahon Cryocoolers. The piston moves down to compress the gas (helium) in the pulse tube. Compressed gas is at a higher pressure than the average in the reservoir , it flows through the orifice into the reservoir and exchanges heat with the ambient through the heat exchanger at the warm end of the pulse tube. The flow stops when the pressure in the pulse tube is reduced to the average pressure. The piston moves up and expands the gas adiabatically in the pulse tube. This cold, low-pressure gas in the pulse tube is forced toward the cold end by the gas flow from the reservoir into the pulse tube through the orifice.

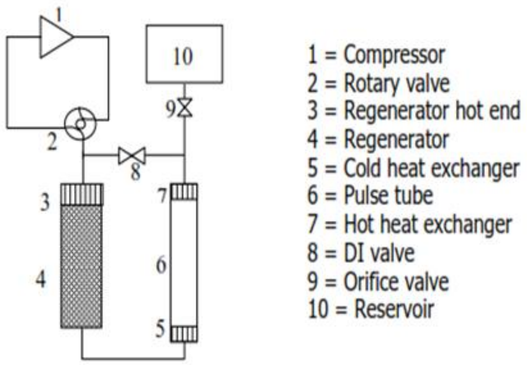

Fig. 1: Typical pictures of Pulse tube.

In G-M type PTR pressure distribution system limits its working frequency. Generally rotary valve is used as pressure distribution system. Therefore, a G–M-type pulse tube refrigerator usually works at low frequencies (1Hz-5Hz) with large oscillating amplitudes to yield lower temperature compared to Stirling model.

II. Components of GM type (DIPTR).

A. Components

1) Compressor:

The main function of the compressor is to supply gas pressurization and depressurization in the closed chamber. Electrical power is applied to the compressor where this electrical work is converted into the mechanical energy associated with sinusoidal pressure waves, resulting in gas motion. In an ideal compressor, the electrical power provided to the compressor must be equal to $f\oint Pdv$ where the integration is performed over an entire cycle, P is the compressor pressure, and f is the compressor frequency. In an actual system, however, the above-mentioned power (the Pdv power) is always less than the actual measured electrical power due to the associated irreversibilities.

2) Aftercooler:

The function of the ideal after cooler is to extract all the heat that is generated in the compressor volume during the gas compression and dispose to environment. This minimizes the warm end temperature so that the regenerator can work more efficiently and supply low temperature working fluid to the system. Typically, these types of heat exchangers are assembled using copper wire mesh screens that are directly in contact with the housing wall.

3) Regenerator:

The regenerator is the most important component in pulse tube refrigerator. Its function is to absorb the heat from the incoming gas during the forward stroke, and deliver that heat back to the gas during the return stroke. Ideally, PTC regenerators with no pressure drop and a heat exchanger effectiveness of 100% are desired, in order to achieve the maximum enthalpy flow in the pulse tube. The performances of the real regenerators are of course far from ideal. Stainless steel wire screens are usually selected as the regenerator packing material, since they offer higher heat transfer areas, low pressure drop, high heat capacity, and low

4) Cold Heat Exchanger (Chx):

CHX can be best viewed as the equivalent of the evaporator in the vapour compression refrigeration cycle. This is where the refrigeration load is absorbed by the system. This is the junction of the regenerator and pulse tube. Copper wire mesh screens are used to exchange heat with the housing wall, and thereby receive the applied heat load.

5) Pulse Tube:

The pulse tube is the most critical component of the whole refrigerating system. The main objective of the pulse tube is to carry the heat from the cold end to the warm end by an enthalpy flow. By imposing a correct phase difference between pressure and mass flow in the pulse tube by phase shifting mechanisms, heat load is carried away from the CHX to the HHX. Physically, the pulse tube is simply a hollow cylindrical tube made up of stainless steel with an optimum thickness to enhance the surface heat pumping.

6) Hot Heat Exchanger (Hhx):

Hot end exchanger is where the gas rejects heat of compression in every periodic cycle of operation. Upon receiving the enthalpy flow from the pulse tube, the heat load at a higher temperature is rejected to the environment. Usually, air cooling or water cooling system is used to take away the heat from the hot end exchanger.

7) Orifice Valve:

The role of either the inertance tube or the orifice valve is to appropriately adjust the phase difference between the mass flow rate and the pressure. By controlling the orifice diameter or the inertance tube diameter and length, the desired phase relationship can be obtained. In general, the orifice valve is a needle valve, and the inertance tube is an open cylindrical stainless tube. In comparison with the aforementioned pulse tube, the inertance tube is much longer, and its diameter is much smaller.

8) Rotary valve:

The rotary valve is one of the critical components of a GM type pulse tube refrigerator. It is used to switch high and low pressure from a helium compressor to the pulse tube system. The high and low pressure of helium compressor are connected to the rotary valve through the quick disconnect couplings. The rotary valve has a rulon part which is made to rotate with the help of a synchronous motor against an aluminium block with predefined passages connecting the high and low pressures from the helium compressor. The rotational frequency of the synchronous motor is controlled using an inverter drive. The rotary valve has been designed to produce pressure wave in the frequency range from 1Hz to 3Hz.

9) Double Inlet Orifice:

In the double inlet pulse tube refrigerator the hot end of the pulse tube is connected with the hot end of the regenerator by a tube with an orifice. In this case the gas can move in and out of the pulse tube not only via regenerator, but also via the 2nd orifice. That explains the name double inlet. Since the gas can enter the pulse tube from the hot end via the double inlet, bypassing the regenerator, the cooling power of the PTR reduces as it depends on the amount of the gas, passing the cold heat exchanger of the pulse tube. In addition, the pressure drop over the double inlet orifice is the source of the irreversible entropy production, which leads to losses. However, both the disadvantages are overcome by the fact, that the double inlet reduces the entropy production in the regenerator. As a result the overall performance of the system improves significantly.

10) Surge Volume:

The surge volume can be viewed as a closed buffer reservoir of sufficient volume, volume of which is typically 10 times larger than the volume of the pulse tube, to allow for small pressure variations resulting from the oscillating mass flow. The pressure in the buffer is practically constant and the close to the average pressure in the Pulse tube. The combination of the orifice and the buffer provides a phase difference between the flow of the gas in the tube and the pressure. This is required because any pressure oscillation in phase with the surge volume inlet mass flow serves to retard the phase shift and the mass flow amplitude, which reduces performance.

B. Selection of Regenerator Material:

The regenerator materials and geometries generally fall into three groups, based on the temperature range over which they are most commonly used. A representation of regenerator materials used at different temperature range is shown in fig.2.

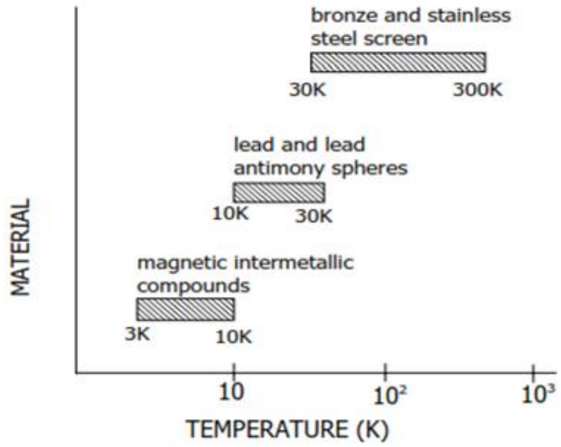

Fig. 2: Temperature range for commonly used regenerator materials in cryogenic refrigerators. [4]

The first groups are the woven screen materials-such as stainless steel, bronze, and copper which are easy to weave into the screen geometry. These materials are used over the temperature range from 30K to 300K, where they provide the following advantages:

- Low pressure drop
- High heat transfer area
- Low axial conductivity
- High heat capacity

At temperature below 30K screens lose their advantages and exhibit the following disadvantages:

- High void volume
- Low heat capacity

In the range between 10K and 30K lead and lead antimony spheres are used because of their higher heat capacity than any of the screen materials. In addition to the higher specific heat, spheres provide two advantages in this temperature range

- Low void volume related to low porosity
- Low pressure drop reflecting the decrease in the fluid viscosity

C. Diptr Refrigerator Analysis Methods:

1) Surface Heat Pumping Theory:

Gifford and Longsworth [1] proposed a surface heat pumping theory to explain the performance of the basic pulse tube refrigerator after they have constructed a prototype of BPTR.

2) Enthalpy Flow Analysis [5]:

The PTR's heat absorption and rejection occur at the cold heat exchanger (CHX) and the two hot heat exchangers; (an after cooler (AFTC) and a hot end heat exchanger (HHX)). Clearly, HHX is equivalent to a condenser in a conventional vapor compression cycle, and CHX is equivalent to an evaporator. During the PTR operation, most of the heat generated due to compression is rejected through the after cooler.

3) Phasor Analysis:

Phasor analysis is one of such methods which have been proposed by Radebaugh [3]. Phasor analysis is based on the following assumptions for phasor analysis.

- Adiabatic behaviour of gas in the pulse tube
- Pressure is constant throughout the pulse tube and amplitude of dynamic pressure is small Compared to average pressure
- Sinusoidal variation of pressure and temperature with no phase difference between them.

D. Thermodynamic Non-Symmetry Effect:

The thermodynamic non symmetry effect, which is responsible for the production of refrigeration power is qualitatively described and demonstrated for the idealized case.

1) Idealized pulse tube:

Liang [2] proposed the so-called thermodynamic non symmetry effect in the orifice pulse tube. By tracing a thermodynamic cycle of the fluid parcel flowing from the cold end of the regenerator to the pulse tube and then flowing back to the regenerator, he found that the fluid gas parcel is undergoing a temperature decrease during this cycle, which he called the thermodynamic non symmetry effect. Based on this model, Liang [2] extended the theory of surface heat pumping to all type of pulse tube refrigerators. He proposed that the surface heat pump theory prevailed only in the thermal boundary layer. In order to explain non symmetry effect, the regenerator and the cold and hot end heat exchangers are assumed to be perfect. For simplicity, the working fluid is regarded as an ideal gas, and gas flow in the pulse tube is assumed to be adiabatic inviscid flow, with no length-wise mixing or heat conduction.

III. CONCLUSIONS

The current work deals with the theoretical study and CFD analysis of GM type double inlet PTR. In context to the study it can be concluded that from the review that the DI valve is helpful to increase the performance of the GM PTR and also helps to get low temperature by providing proper phase shift.

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REFERENCES

[1] Gifford, W.E. and Longworth, R.C. Pulse tube refrigeration, Trans ASME B J Engg. Industry 86(1964), pp.264-267.
[2] Liang, J., Ravex, A. and Rolland, P., Study on pulse tube refrigeration Part1: Thermodynamic nonsymmetry effect .Cryogenics, 36(1996), pp. 87-93.
[3] Radebaugh, Ray. Development of the pulse tube refrigerator as an efficient and reliable cryocooler, Proc. Institution of Refrigeration (London) 1999-2000.
[4] Robbert AA. Cryogenic regenerative heat exchangers. New York; Plenum Press; 1997.
[5] Storch, P.J. and Radebaugh, R. Development and experimental test of an analytical model of the orifice pulse tube refrigerator, Advances in cryogenic engineering 3(1988), pp.851-859.

