Design of integral Stirling cryocooler for space application

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ABSTRACT

The world is becoming more enthusiastic about exploring the space. In order to do exploration, we need to develop new technologies every single day that can help us to look far beyond our galaxy. We require devices that can help us to pinpoint far away objects in deep space precisely. We need detectors and remote sensors which can detect even a weak signal that is coming out from any celestial body from a faraway distance. For this purpose, detectors need to be made highly sensitive and accurate, that can be only possible when an instrument is operated at a cryogenic temperature. SAC-ISRO, is involved in research, development and demonstrations on the application of space technology in the field of remote sensing and satellite navigation. This includes research and development of cryocoolers that provides cryogenic temperature for detector operations. Stirling cryocoolers are used to cool down infrared detectors for many applications. We are going to design and develop integral type Stirling cryocoolers for space application detectors. It has advantages of higher efficiency compared to other cryocoolers, light weight. One of the disadvantage of Stirling cryocooler is vibration as it has two moving elements in each cylinder. It has to be reduced and to be made efficient, so that will help for large space observations for a long period of time.

NOMENCLATURE

Q_e	Ideal heat extraction the system
V_C	Maximum possible compression volume
V_c	Instantaneous compression volume
V_E	Maximum possible expansion volume
V_e	Instantaneous expansion volume
W	Work done on the cryocooler
X	Dead volume ratio
α	Phase angle between compressor and displacer
ϕ	Crank angle of the slider-crank mechanism
τ	Temperature ratio

1. INTRODUCTION

The cryocooler studied here is used for the application of cooling the Infrared Focal Planar Array (IRFPA), that is to be used in satellites. The IRFPA is a device which detects infrared region emissions from the long-distance object and does thermal imaging of the same. The object can be any planet, star or constellation, etc. As we know, the infrared emission has the longest wave length in the visible spectrum, hence in order to detect these radiations the temperature has to be brought down to the near cryogenic temperature (. i.e. below 123 K). In order to attain such low temperatures (-150 ^{0}C) in less time, cryocoolers are used. First operational cryocooler were operated on the Stirling cycle, which consist two isothermal and two constant volume processes in order to complete the cycle.

Dr. M. D. Atrey et al.[1] said in order to take first case assumptions in any cryocoolers walkers optimization charts play a vital role, the value decided should be on the basis of the cooling load including losses associated in the system and work input to the system. Mr. Manmohan Singh et al.[3] described all the losses associated in the system and shown the importance of optimization of dead volume ratio. But at first, we need to fix some design requirements such as cold tip temperature and power requirements and only then, the cooler can be designed for the needed conditions. Ruijie Li et al.[4] demonstrated in study that frictional loss is the biggest mechanical loss followed by hysteresis of the gas. Here, it has been tried to bring the temperature to the near 80 K for operational purpose. The first and foremost assumptions are demonstrated in the research paper.

2. INTEGRAL TYPE STIRLING CRYOCOOLER

2.1. System description

The detailed assembly of the system has been shown in the Figure.2.1. This cryocooler constitute of compressor, displacer, linear motor, cold tip, and, regenerator as main components in the cryocooler assembly. Absence of any of the above component will not lead to the desired result.

2.1.1. Compressor

The compressor is constituted by piston compressor which is held under the main body which acts as a compressor cylinder to the piston. Other function of the main body is to reject heat to the atmosphere that is been produced during the compression process.

2.1.2. Displacer

The displacer piston acts as a expander to the compressor end. This displacer is made of hollow cross-section and filled with the regenerator material (in our case SS304 mesh wire). The passage of gas from the compressor is provided to the main casing and this connects to the displacer end with the help passage that is made in the cold tip body. The system is driven by Brushless Direct-Current motor (BLDC) having output of around 25W.

The piston cum displacer consists of fiber epoxy cylinder stacked with SS304 wire mesh material. The fiber epoxy material doesn't let the linear conduction to occur which generates losses to the system. Dynamic seals for the clearances are used which have clearances of 10 microns in the geometry on the both compressor end and displacer end. Further, the motor winding has been kept out of Helium atmosphere with the use of thin cylinder, called the pressure membrane, for keeping the cooler operation cleaner and free from winding contamination. The metallic seals have been used for final sealing of the

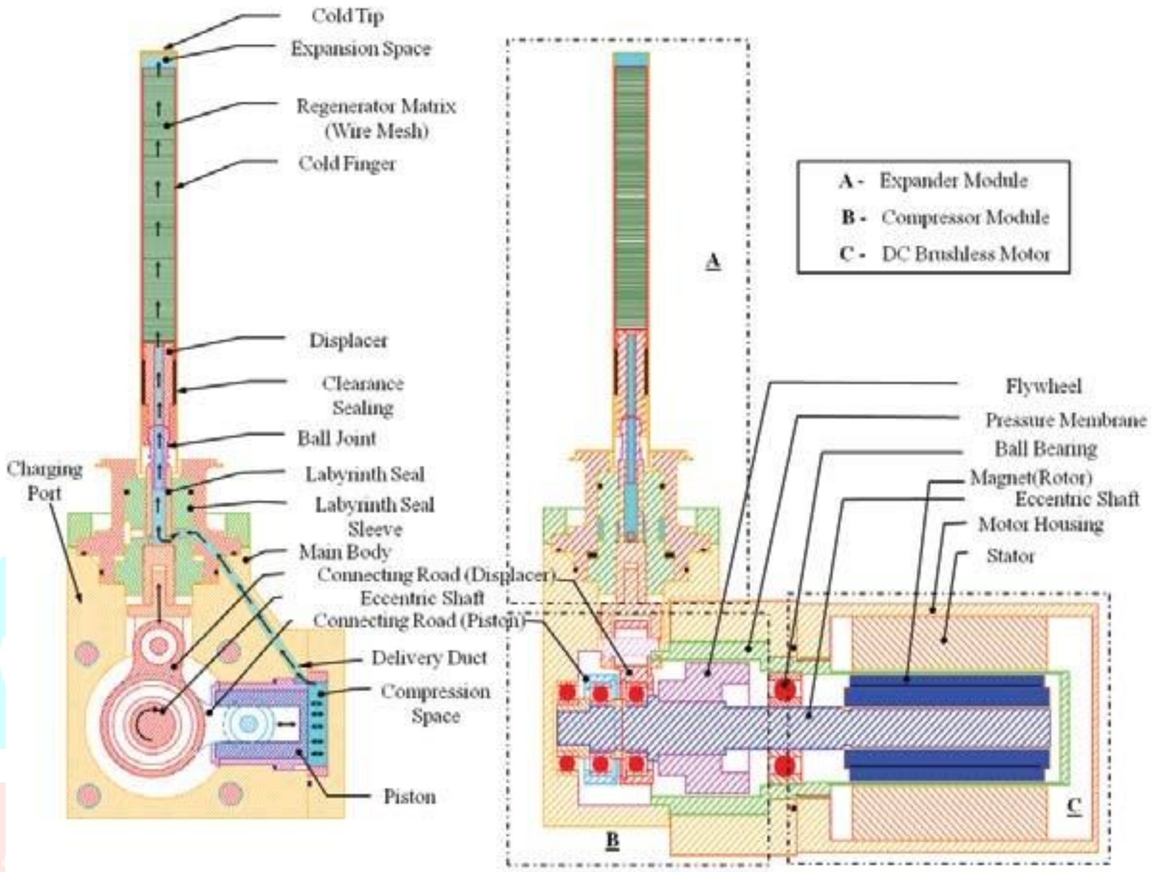

Fig.2.1. Systematic assembly view of Integral Stirling cryocooler

cooler for reducing the leak rates to minimum and more importantly for obviating the need for welding.

2.1.3. Cold tip

Cold tip is made of copper as this is the most conductive and easily available. The cold must have high thermal conductivity as this is going to be coupled directly to the cooling load (i.e. IRFPA in this case). Cold tip and the coupled load both are subject to vacuum chamber, this doesn't allow these components to get in direct contact to the atmosphere.

2.1.4. Regenerator

This is the most vital component of the cryocooler. In order to miniaturize the cryocooler, aftercooler is removed from the assembly. Hence, the net heat extraction combined from atmosphere temperature to cold tip temperature has to be brought down through regenerator. The regenerator gives its internal energy to the gas of the prior cycle and gets cooled, in next cycle the gas coming from the outside gets cooled and the regenerator gets heated up by gain internal energy from incoming gas.

2.1.5. Brushless DC motor

One of the critical technologies in the development of cryocooler is the development of an efficient brushless DC (BLDC) motor. It is the crucial component of the cryocooler system and to a large extent the performance of the system depends on this especially. when it comes to high efficiency and power savings in the battlefield, where the later is limited. The motor is equipped with advance features like standby, shut-down and cool-down indicator modes. The motor delivers a maximum power of 20 W with efficiency close to 75 per cent even at the highest of working speeds.

2.2. Thermodynamic analysis (by Schmidt's Analysis)

The thermodynamic analysis of any cryocooler for first assumptions of the dimensions of the Compressor and displacer needed for designing are obtained by Schmidt's Analysis. In general Stirling cycle comprise of the Isothermal compression at atmospheric temperature (1-2), Constant volume heat rejection to the regenerator (2-3), Isothermal expansion at cold tip temperature (3-4), and, Constant volume heat addition from the regenerator (4-1). Below shown in Figure.2.2. is the governing diagram of Stirling cycle.

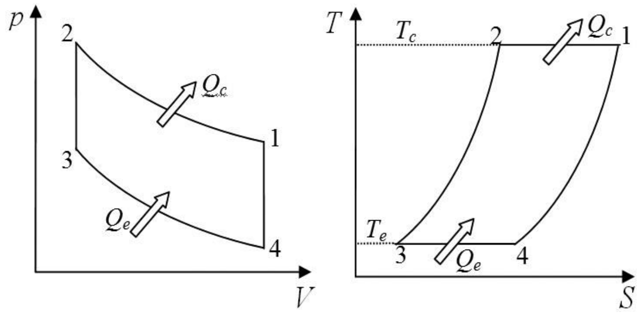

Fig.2.2. Ideal Stirling cycle: Pressure-volume diagram and temperature-entropy diagram

The assumptions of Schmidt's analysis are: -

a) Perfect isothermal compression, expansion
b) Harmonic motion of piston and displacer
c) Perfect regeneration
d) No pressure drops in the system

The governing equations in the Schmidt's analysis are: -

The instantaneous volume, V_e, of expansion space can be expressed as a function of crank angle ϕ, and expansion space swept volume, V_E , and is given by

$$Ve = \frac{1}{2}VE(1 + cos\phi)$$

If the phase lag between the piston and displacer is α, then volume variations of compression space is defined as

$$Vc = \frac{1}{2}kVE(1 + \cos(\phi - \alpha))$$

where k is the ratio of swept volumes, and is given by V_C/V_E. where V_c is compression space swept volume.

The cyclic cold production or the heat extracted from the expansion space Q_e is a function of V_E , mean charge pressure p_{mean} , intermediate parameters θ and δ, and is given as follows: -

$$QE = \int pdve = \frac{\pi pm\delta\ VE\sin\theta}{1 + \sqrt{(1 - \delta^2)}}$$

where the parameter θand δ are functions of dead volume ratio X , κ and α, and can be calculated as: -

$$\tan\theta = \frac{k\sin\alpha}{\tau + k\cos\alpha}$$

Here the term δ is the temperature ratio and is defined as T_c/T_e and

$$\delta = \frac{\sqrt{(\tau + k\cos\alpha)^2 + (k\sin\alpha)^2}}{\tau + k + 2S}$$

In above equation the term S is the reduced dead volume which is defined as

$$S = \frac{2X\tau}{1 + \tau}$$

The work done on the system, W, may be evaluated from the following

$$W = Qc - Qe = (\tau - 1).Qe$$

CONCLUSION

This paper concluded with theoretical design of the cryocooler with first case of the assumptions to be taken for the design purpose. The ideal heat extraction Q_e that we get by calculating above formulas is approximately 5W. Furthermore, the losses in the system are to be calculated and the resulting heat extraction obtained will be the actual heat extraction obtained at the cold tip of the cryocooler. The mechanical losses such as frictional flow losses, pressure drop losses, and, Hysteresis losses are predominant in the system. These needs to be optimized.

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