Design of Stirling Cryocooler for Space Application of 1 W At 80K

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Abstract— The world is becoming more enthusiastic about exploring the space. Researchers all over the world are developing new technologies every single day that can help us to look far beyond our galaxy. We require devices which can help us to look faraway objects in deep space precisely. We require detectors which can detect even a weak signal that is coming out from any celestial body from a faraway distance. For that, detectors must be highly sensitive and that is only possible when an instrument operates at a very low temperature, below 50 K. Space based companies are involved in research, development and demonstrations of applications of space technology in the field of remote sensing and satellite navigation. This includes research and development activities that require high sensitive detectors which need cryocooler at its heart for the best outcome from the detectors. Stirling cryocoolers are now used for cooling infrared detectors for many space applications. This paper deals with design of Stirling cryocooler for space application of 1 W at 80 K. It has the advantages of highest efficiency over the other types of cryocooler, light weight. One of the disadvantage of Stirling cryocooler is vibration as it has two moving elements in each cylinder. This can be reduced with the help of selection of motor used for operation and hence efficient cryocooler can be made that will be helpful for large space observations for a longer period of time.

Key words: Cryocooler, Stirling cycle, Regenerator

I. Nomenclature

BLDC = Brush Less DC motor
A = a factor $\sqrt{(\tau^2 + 2\tau k \cos\alpha + k^2)}$
B = a constant $(\tau + k + 2S)$
K = constant
M = total mass of working fluid
N = machine speed
p = instantaneous cycle pressure
p_{max} = maximum cycle pressure
p_{min} = minimum cycle pressure
p_{mean} = mean cycle pressure
R = characteristic gas constant of the working fluid
$S = \frac{(2X\tau)}{(\tau+1)}$
T_C = temperature of the working fluid in the compression space,
T_D= temperature of the working fluid in the dead space.
T_E= temperature of the working fluid in the expansion space.
V_C= swept volume in compression space.
V_E= swept volume in expansion space.
V_D = total internal volume of heat exchangers, volume of regenerator, and associated ports and ducts.
$V_T = (V_C + V_E)$ Total volume
$X = \frac{V_D}{V_E}$ Dead volume ratio
α = angle by which volume variations in the expansion space lead those in the compression space.
$\delta = \frac{A}{B}$
$\theta = \tan^{-1}\left[\frac{k\sin\alpha}{\tau + k\cos\alpha}\right]$.
$k = \frac{V_C}{V_E}$, swept volume ratio
$\tau = \frac{T_C}{T_E}$, temperature ratio.
$\emptyset$ = crank angle.

II. Introduction

Stirling cryocoolers are widely used in applications like space exploration, earth observation, gas industries, medicines (MRI), IR cameras and superconducting magnets. This paper deals with the application of cryocooler for space exploration and earth observations. The sensitive of sensors depends upon the temperature at which the instrument is working. It also depends upon the surrounding temperature. The sensitivity can be improved effectively if the instrument is operated at cryogenic temperature. If the instrument is operated at cryogenic temperature than the signal to noise ratio will be more and much more accurate data can be obtained. The thermal sensors can be used for receiving a weak signal coming out from deep space objects. It can also be used for measuring the temperature of faraway objects in astronomy and astrophysics. Stirling cryocooler is most widely used cooler for above mentioned objectives. Stirling cryocooler can be of different types according to internal mechanism used. Mainly there are two variants of it namely Integral crank driven stirling cryocooler [1] and Split cryocooler. Another variant is of Pulse tube type namely Stirling type pulse tube cryocooler.

Integral type stirling cryocooler is used because of its smaller and compact configuration yet giving highest efficiency [2, 3]. Earlier rubbing seals were used in this type of cooler but with the advancement in technology, dynamic clearance seals have replaced them giving the same life as the other types i.e. linear motor driven stirling cryocooler. Split type of configuration is used when the space is not a constraint and the displacer should be operated vibration free and kept separated from moving parts. Stirling type pulse tube cryocooler has also started emerging as a new variant in which the compression space and expansion space are operated at a difference frequency. Vibration is almost obsolete in expansion space. Pulse tube cryocooler has an adverse effect of orientation. The performance depends on the type of configuration.

Amongst all variants of stirling cryocooler, integral crank driven is the best suitable in space application where the heat lifted is small, compact design, longer life, high efficient and less vibration due to use of BLDC motor.

III. STIRLING CYCLE

Stirling cryocooler works on Stirling cycle. Below fig. (1) Show the P-V diagram of stirling cycle.[11]

The processes of stirling cycle are as follows.

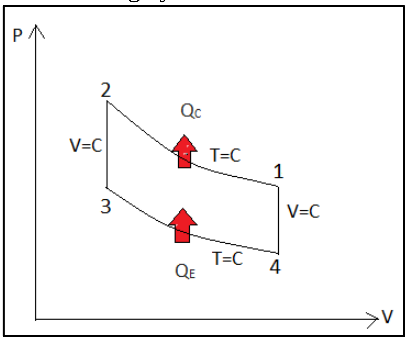

Fig. 1: P-V diagram of stirling cryocooler

Process (1-2)	Isothermal compression; heat transfer from the working fluid to the external sink at ambient temperature, T_C
Process (2-3)	Constant volume ; heat transfer from the working fluid to the regenerator matrix
Process (3-4)	Isothermal Expansion; heat transfer to the working fluid from an external source at the refrigerating temperature
Process (4-1)	Constant volume; heat transfer to the working fluid from the regenerator matrix.

Table 1:

The coefficient of performance of the Stirling cycle is the same as for the Carnot cycle.

COP = $\frac{T_E}{T_C - T_E}$ Below.

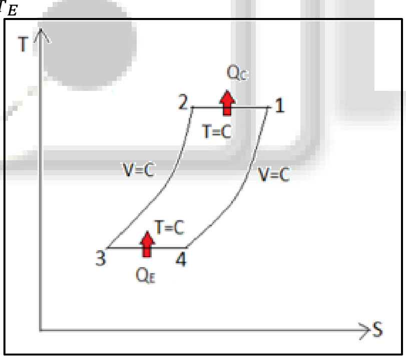

Fig. 2: Shows the P-V diagram of stirling cycle

The performance and cooling capacity of the stirling cycle cooler depend on various parameters including the dead volume ratio, swept volume ratio, the phase angle and temperature ratio.

IV. DESIGN STEPS

Before going into the actual design procedure, there are certain assumptions based on Schmidt analysis. [5, 11]

Principal assumptions of the Schmidt cycle are:

1) The regenerative process is perfect.
2) The instantaneous pressure is the same throughout the system.
3) The working fluid obeys the characteristic gas equation, $pV = RT$.
4) There is no leakage, and the mass of the working fluid remains constant.
5) The volume variations in the working space occur sinusoidally.
6) The speed of the machine is constant.
7) Steady state conditions are established.

A. Basic Equations

Volume of expansion space:

$$V_e = \frac{1}{2} V_E (1 + \cos \emptyset) \qquad (1)$$

Volume of compression space:

$$V_c = \frac{1}{2} V_C [1 + \cos(\emptyset - \alpha)] \qquad (2)$$

Instantaneous pressure:

$$p = \frac{k}{B[\delta \cos(\emptyset - \theta) + 1]} \qquad (3)$$

Mean cycle pressure:

$$p_{mean} = p_{max} \sqrt{\frac{1-\delta}{1+\delta}} \qquad (4)$$

Heat transferred and work done:

Since the processes of expansion and compression take place isothermally, the heat transferred will be equal to the work done.

Expansion Space:

$$Q_E = \frac{V_E \, \pi \, p_{mean} \delta \, \sin \theta}{1 + \sqrt{(1 - \delta^2)}} \qquad (5)$$

Compression Space:

$$Q_C = \frac{V_E \, \pi \, k \, p_{mean} \delta \, \sin(\theta - \alpha)}{1 + \sqrt{(1 - \delta^2)}} \qquad (6)$$

B. Sample Calculation

Given Data:

Assumed Data:

$$Q_E = 1\ W$$

Dead volume ratio, $X = \frac{V_D}{V_E} = 3$

$$T_E = 80\ K$$

Swept volume ratio, $k = \frac{V_C}{V_E} = 3.5$

$$T_C = 300\ K$$

Temperature ratio, $\tau = \frac{T_C}{T_E} = 3.75$

With the help of above data and equations from (1) to (6), for the given heat load condition and required temperature, piston and displacer diameter can be found out. Based on that Design of compressor side piston assembly including piston, piston pin, cylinder and displacer side assembly can be done.

C. Regenerator Losses

There are certain losses which are encountered in this cryocooler. The losses can be divided into following two type of categories:[8,9]

Losses that consumes fraction of the input power available for refrigeration like joule heating in coil windings and irreversible compressions etc.

Losses that consume part of a refrigeration directly and related to expander side.

The net refrigeration available at cold end can be given as follows.

$Q_{Net} = Q_e - (Q_{ief} + Q_{\Delta Pf} + Q_{rt} + Q_{cmg} + Q_{shtl} + Q_{dewar})$ (7)

Where, Q_{Net} = Actual net refrigeration available for cooling, Q_e = Maximum refrigeration available in ideal Stirling cycle, Q_{ief} = Loss due to thermal ineffectiveness of regenerator, $Q_{\Delta Pf}$ = Loss due to frictional pressure drop, Q_{rt} = Conduction loss, Q_{cmg} = Longitudinal conduction loss of regenerator matrix, Q_{shtl} = Shuttle heat transfer loss, Q_{dewar} = Dewar loss.[1]

With the help of above equations, various parameters were found out. The 3-D model of Stirling cryocooler was made in CREO 2.0 and structural analysis of various components were done to make sure that it works effectively at required pressure and temperature condition.
Below Figure (2) shows the view of stirling cryocooler and figure (3) and (4) shows its cross section views.

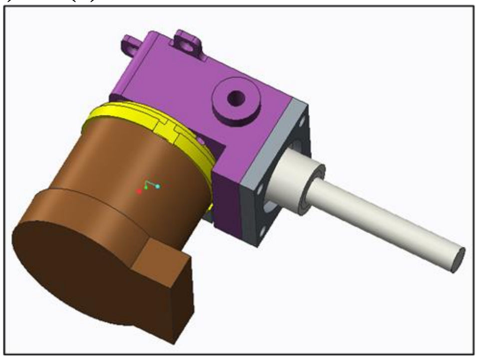

Fig. 3: Stirling cryocooler

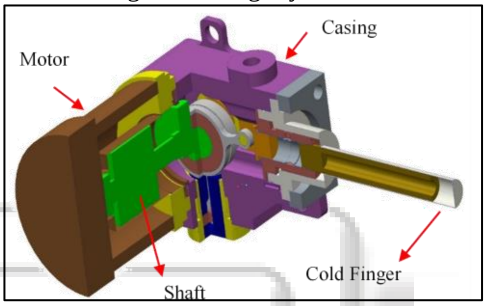

Fig. 4:

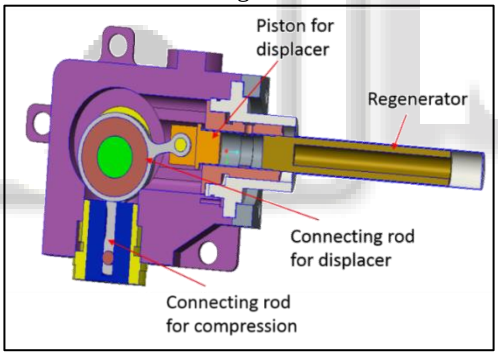

Fig. 5: Cross section of Stirling cryocooler

V. Conclusion

This research paper shows the design steps for developing integral type stirling cryocooler for space application of 1W at 80K. Thermodynamic cycle and analysis of stirling cycle has been presented in this paper. There are two ways to design a stirling cryocooler, (a) By using Ideal stirling cycle and (b) By using Schmitz analysis. The various losses that affects the coefficient of performance of system have also been mentioned in this paper. It also shows the various regenerator losses and only the important loss which affect the most to the performance of the system.

References

[1] Manmohan Singh, Mukesh Sadana, Sunil Sachdev, and Gaurav Pratap. "Development of Miniature Stirling Cryocooler Technology for Infrared Focal Plane Array." Defense science journal, Vol. 63, No. 6, November 2013, PP. 571-580.
[2] Lele M. M., Bapat S.L and Narayankhedkar K G. "Design and development of Stirling cycle cryocooler". Conference Paper IIT Bombay 2005.
[3] Xiaotao Wang, Wei Dai, Jian Zhu, Shuai Chen, Haibing Li, Ercang Luo. "Design of two stage high capacity Stirling cryocooler operating below 30K." Physics Procedia 67 (2015) 518-523.
[4] Lionel Duband "Space cryocooler development" Physics Procedia 67 (2015) 1-10.
[5] Stuart Watson "Design and development of a high power Stirling cryocooler" 15th European Space Mechanism and Tribology Symposium-2013.
[6] M.D. Atrey, S.L. Bapat and K.G. Narayankhedkar. "Optimization of design parameters of Stirling cycle machine" Cryogenics 1993 Vol. 33, No 10.
[7] S.J. Park, Y.J. Hong a, H.B. Kim a, D.Y. Koh a, J.H. Kim b, B.K. Yu b, K.B. Lee "The effect of operating parameters in the Stirling cryocooler" Cryogenics 42 (2002) 419-425.
[8] M. D. Atrey and C. Heiden "Performance evaluation of an optimized two stage, free displacer plastic Stirling cryocooler with gap regenerator". Cryogenics 36 (1996) 47-52.
[9] M. D. Atrey, S L Bapat, K.G. Narayankhedkar. "Influence of regenerator matrix and working fluid on optimization of design parameters of Stirling cryocooloers." Cryogenics 1994 Volume 34 ICEC Supplement.
[10] Chih Wu, "Analysis of an endoreversible Stirling cryocooler", Energy conservation and management Volume. 34, 1992.
[11] Graham Walker, Cryocoolers, and Part: 1 Fundamentals, Plenum press, 1983, 1st Edition, ISBN: 0-306-40715-9, pp 95-140.
[12] Graham Walker, Cryocoolers, and Part: 2 Applications, Plenum press, 1983, 1st Edition, ISBN: 0-306-41219-5, pp 59-100.