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Design and Development of Mechanical System of Stirling Cryocooler for Space Application

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Abstract: A reliable cryocooler is one of the basic and foremost requirements for successful operation of Infrared Sensor used for Space applications. Technological complexity and requirement of long duration fail-safe operation of the cryocooler demands robust design, fabrication and assembly with tolerances. The theoretical investigations in the design of Stirling cycle cryocooler will be reported and the issues related to the design aspects will discuss in sufficient details. The Balance within reciprocating parts was always been a concern of designers. Any unbalance within a cooler can result in component fatigue and failure, excessive vibration and noise. So, it is a need of mechanical system which can perform efficiently with elimination of mechanical losses including vibration and wear losses. The components that affect the balance of the cryocooler will identify and different design aspects within each component that affect the balance will be explored. Design using CAD software and further weight optimization and size by changing design parameter and by selection of material which is applicable for space application. The Calculations that were used to calculate static and dynamic balance of the system and how these affect the design of our cryocooler will investigate. 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.

Keywords: Cryocooler design, balancing, Mechanical System, Space application, Cooling Load Capacity, IR Sensors, Piston – Displacer Arrangement

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.

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$\delta = \frac{A}{B}$

$\theta = \tan^{-1}\left[\frac{k \sin\alpha}{\tau + k\cos\alpha}\right]$.

$k = \frac{V_C}{V_E}$, 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

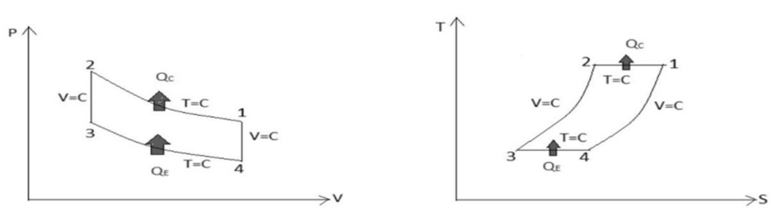

Figure 1 P-V and T-S diagram of Stirling Cycle

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.

The Stirling Cycle alternately compresses and expands a fixed quantity of helium in a closed cycle. The compression takes place at room temperature to facilitate the discharge of heat caused by compression, whereas the expansion is performed at the cryogenic temperature required by the application

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) There are no temperature gradients in the heat exchangers.
7) The cylinder wall, and piston, temperatures are constant.
8) There is perfect mixing of the cylinder contents.
9) The temperature of the working fluid in the ancillary spaces is constant.
10) The speed of the machine is constant.
11) Steady state conditions are established.

A. *Basic Equations*

1) Volume of expansion space

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

2) Volume of compression space

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

3) Instantaneous pressure

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

4) Mean cycle pressure

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

5) 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:

$Q_E = 1\ W$

$T_E = 80\ K$

$T_C = 300\ K$

Assumed Data:

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

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

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

$$T_D = \frac{T_E + T_C}{2} = \frac{80 + 300}{2}$$
$$= 190$$

$$S = \frac{(2X\tau)}{(\tau+1)} = \frac{2(3)(3.75)}{(3.75+1)}$$
$$= 4.736$$

$$A = \sqrt{(\tau^2 + 2\tau k \cos\alpha + k^2)}$$
$$= \sqrt{(3.75)^2 + 2(3.75)(3.5)\cos 90° + 3.5^2)}$$
$$= 5.1295$$

$$B = (\tau + k + 2S)$$
$$= (3.75) + (3.5) + 2(4.736)$$
$$= 16.722$$

$$\delta = \frac{A}{B} = \frac{5.1295}{16.722} = 0.3067$$

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

For p_{min}, $\emptyset = \theta$

$$p_{min} = \frac{3.5}{16.722[(0.30675)\cos(0°) + 1]}$$
$$= 16\ bar$$

For p_{max}, $\emptyset = (\theta + \pi)$

$$p_{min} = \frac{3.5}{16.722[(0.30675)\cos(\pi) + 1]}$$

$$= 30.19\ bar$$

$$p_{mean} = p_{max}\sqrt{\frac{1-\delta}{1+\delta}}$$
$$= 30.19\sqrt{\frac{1-(0.30675)}{1+(0.30675)}}$$
$$= 22\ bar$$

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

$$V_E = \frac{Q_E\left[1+\sqrt{1-\delta^2}\right]}{\pi\,p_{mean}\,\delta\sin\theta} = \frac{(1)\left[1+\sqrt{1-(0.30675)^2}\right]}{\pi(22)(0.30675)\sin 90°}$$
$$= 92.06\ mm^3$$

Now, $V_E = 92.06$

$$\frac{\pi}{4}d^2(l) = 92.06$$
$$\frac{\pi}{4}d^2(2) = 92.06$$ (As decided, $l = 2$)

Hence, Displacer diameter, $d = 7.65\ mm$

$$k = \frac{V_C}{V_E}$$

So, $V_C = k(V_E)$

$$= 3.5(92.06)$$
$$= 322.21\ mm^3$$

Now, $V_C = 322.21$

$$\frac{\pi}{4}D^2(l) = 322.21$$
$$\frac{\pi}{4}D^2(2) = 322.21$$ (As decided, $l = 2$)

Hence, Piston diameter, $D = 14.32\ mm$

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.

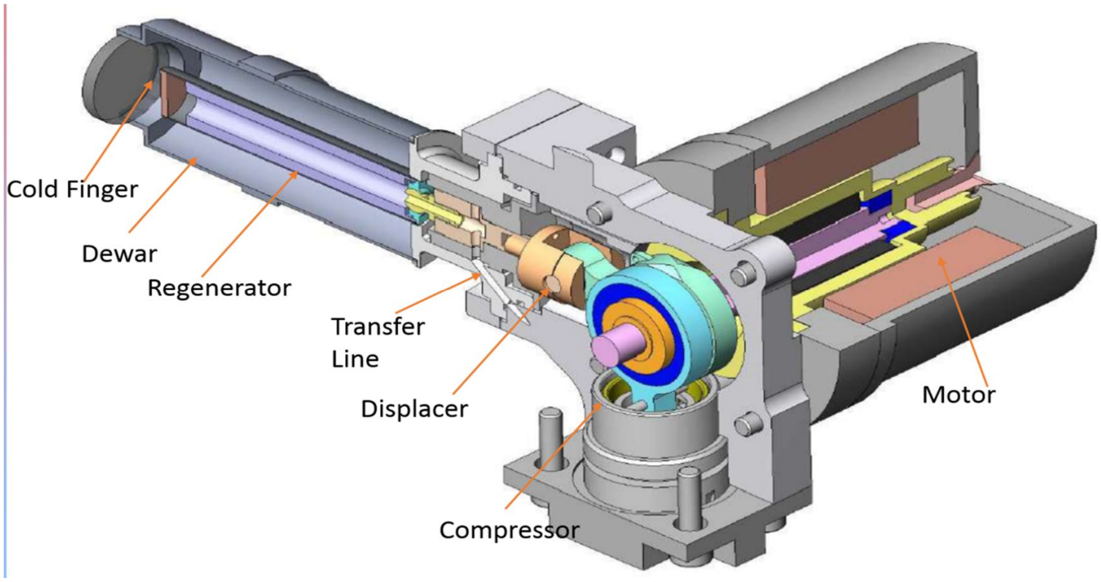

Figure 2 Model of Cryocooler

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

After Fabricating Components, Cryocooler assembly prepared. A Whole setup prepared for practical experiment at our practical lab. The results are shown below.

Sr. No.	1	2	3	4	5
Speed(RPM)	1800	2400	2400	3000	3000
Voltage(V)	24	24	24	24	24
Current (A)	0.2	0.3	0.35	0.5	0.8
Time (PM)	12 – 12:10	12:10 – 12:20	12:20 – 12:28	12:28 – 12:35	12:35 – 12:45
Vacuum Pressure (mbar)	$3.4 * 10^{-3}$	$3.4 * 10^{-3}$	$3.4 * 10^{-3}$	$3.4 * 10^{-3}$	$3.4 * 10^{-3}$
Resistance	96	92	87.3	82	79.6
Temp (˙c)	-10	-20	-33	-45	-52

Experimental Result shows that Cryocooler was able to achieve -52 ˙C (221K), Which is good but not still satisfactory. In order to achieve temp. as low to 80 K there are some problems which are discussed below :

1) We were able to generate vacuum Pressure in range of 10^{-3} mbar, for 80 K the pressure needs to be 10^{-6} mbar. Which is not reached because of unavailability of turbo molecular pump.
2) As per the theoretical Calculation helium pressure needs to be 25 bar but we have reached upto 10 to 13 bar due to problem with purging valve.

So, After performing experiment it is found that design is satisfactory. There are some issue with experimental setup which further needs to be improved. Once it's done Cryocooler is capable enough to achieve 80K temperature.

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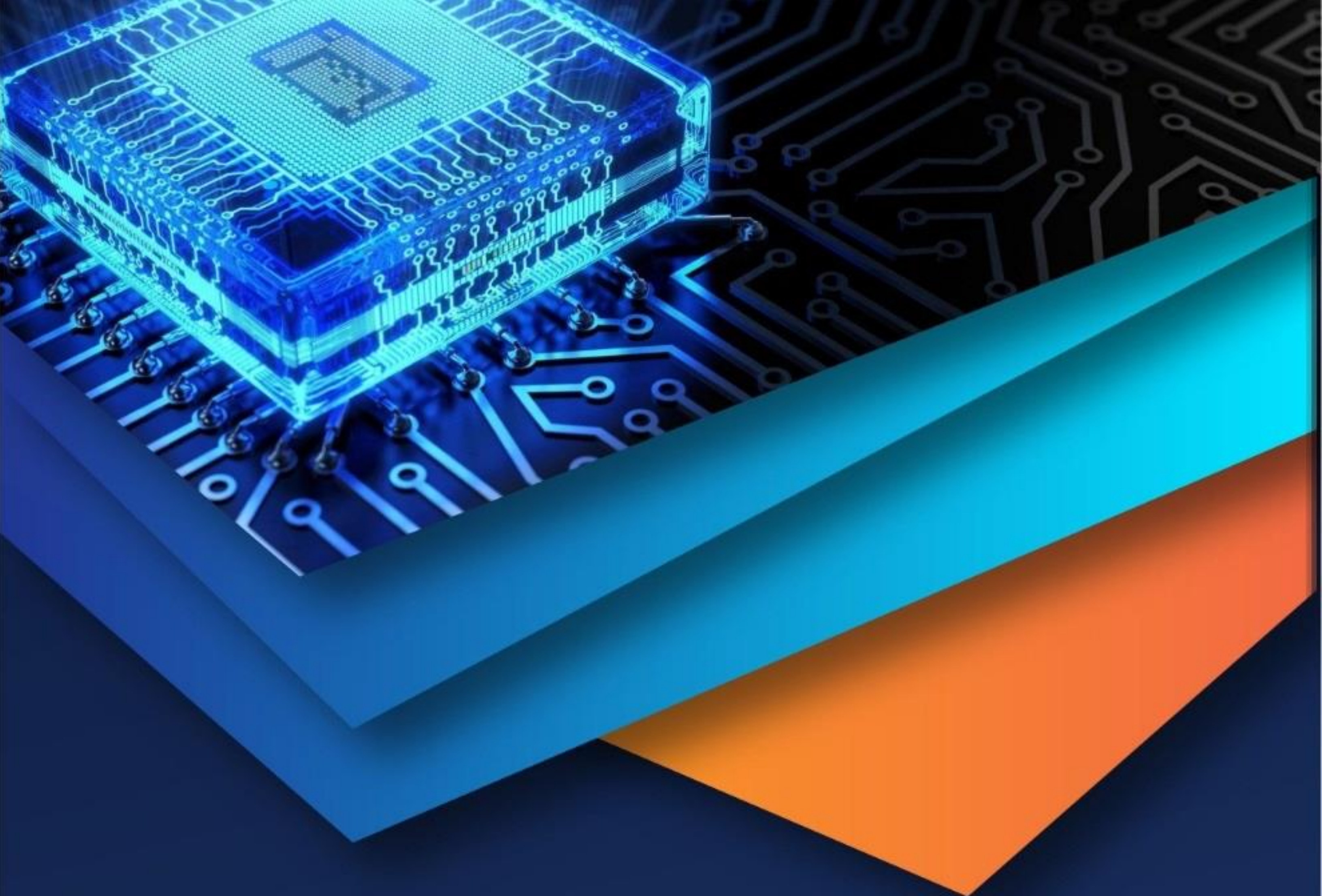

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