

# Design of a moving magnet-type free piston Stirling cryocooler for futuristic space application

Archana B Suresh<sup>1\*</sup> and Biju T. Kuzhiveli<sup>1</sup>

<sup>1</sup>Center for Advanced Studies in Cryogenics (CASC), National Institute of Technology Calicut-673601, India

\*E-mail: archana\_p200097me@nitc.ac.in

**Abstract.** The utilization of free piston Stirling cryocoolers is becoming more widespread in space technology, particularly for the purpose of cooling infrared sensors used in satellites and other space-related equipment. This study focused on the design and optimization of a miniature integral type free piston Stirling cryocooler using SAGE 12 software. The design features an electromagnetically driven resonating mechanism with a clearance seal setup to ensure optimum COP and minimal system vibration. The engineered integral type free piston Stirling cryocooler can produce a cooling effect of 1.58 W with a COP of 0.0424 at 80 K. A comprehensive evaluation of the designed cryocooler was conducted to evaluate the influence of different design characteristics and operational parameters. Subsequently, a moving magnet-type linear motor necessary for the cryocooler was designed using Ansys Maxwell software. In the final phase of the study, the original cryocooler design was modified by replacing the single mesh regenerator with a multi-mesh regenerator. The optimal combination of the multi-mesh regenerator to enhance the system performance was determined.

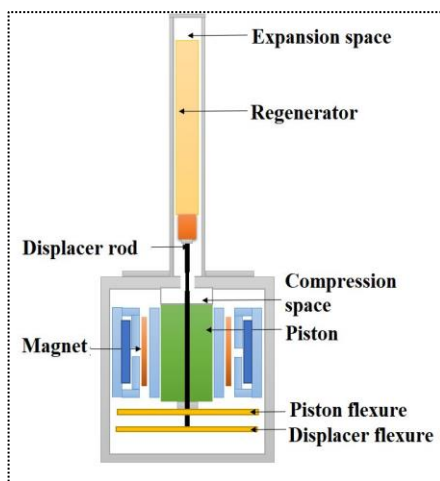
## 1. Introduction

The mercury telluride (HgCdTe) infrared sensors used in space applications require continuous cooling in the range of 35 K - 80 K to enhance the signal-to-noise ratio and mitigate thermal noise. Stirling cryocoolers offer a viable solution for achieving this objective. The Stirling cooler was first introduced in 1950's for air liquefaction by the Philips company in Netherlands [1]. Compactness and reliability are two of the primary factors taken into account for cryocoolers used for space applications [1]. A free piston Stirling cryocooler, equipped with a linear drive mechanism, adequately satisfies these essential criteria. In the free piston Stirling cryocooler, a linear motor is used to drive the power piston [2]. The utilization of direct linear drive offers several benefits, such as improved dynamic performance and increased reliability due to eliminating the rotary-to-linear motion conversion mechanism. Stirling cryocoolers are regenerative types of cryocoolers that work according to the reversed Stirling cycle and it has superior Carnot efficiency at liquid nitrogen temperature compared to other cryocoolers. In this study, an integral type free piston Stirling cryocooler with a moving magnet linear motor is initially designed by using the SAGE 12 software. In the second part of the study, a moving magnet linear motor for the cryocooler was designed using Ansys Maxwell. In the final part of the study, the designed cryocooler was modified by replacing the single mesh regenerator with a multi-mesh regenerator.

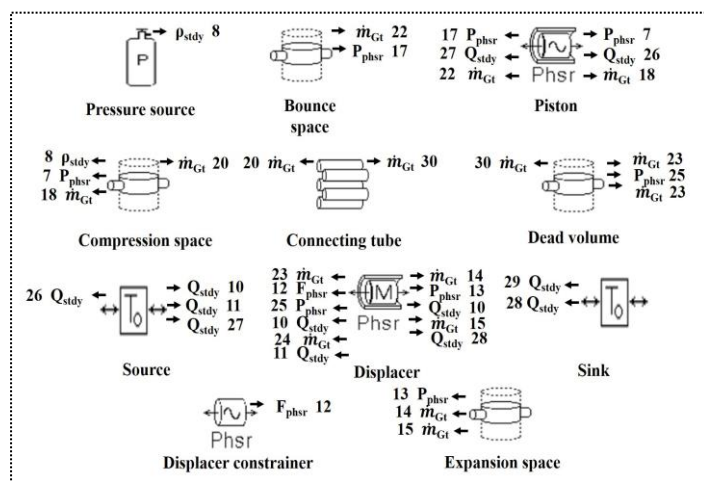


## 2. Numerical modelling of integral type free piston Stirling cryocooler

This study's main objective is to design an integral type free piston Stirling cryocooler featuring a moving magnet linear motor through the utilization of SAGE 12 software. SAGE is a third-order design software tool employed for the analysis, design, and optimization of various engineering models representing a spring mass damper system. The schematic representation of the integral type cryocooler is depicted in Figure 1, comprising components like piston, linear motor, displacer containing the regenerator material, compression volume, expansion volume, and buffer volume. Figure 2 illustrates the SAGE model of the integral type cryocooler. Each component given in the sage model contains sub-models inside it. Each cell inside the system communicates with each other via the established heat and mass paths [3].



**Figure 1.** Schematic of integral type free piston Stirling cryocooler.



**Figure 2.** Sage model of integral type free piston Stirling cryocooler.

**Table :1** Geometric parameters.

Geometric parameters	Values
Piston Diameter	16 mm
Displacer diameter	8.8 mm
Displacer length	52 mm
Displacer clearance	25 μm
Regenerator diameter	8.6 mm
Regenerator material	SS304
Regenerator mesh no	200
Porosity	0.6909
Compression Space volume	3.17 cm <sup>3</sup>
Expansion Space volume	2.87 cm <sup>3</sup>
<b>Operating parameters</b>	<b>Values</b>
Frequency	50 Hz
Charge pressure	16 bar
Piston amplitude	8 mm
Displacer amplitude	3 mm
Displacer phase angle	45
Cold tip temperature	80 K

**Table :2** SAGE simulation results.

Parameters	Values
Net PV work in the compression space	37.35 W
Gross refrigeration effect	8.14 W
<b>Losses</b>	
Displacer shuttle loss	2.62 W
Heat pump loss in displacer clearance	0.0089 W
Conduction loss	0.903 W
Regenerator thermal loss	3.03 W
Total losses	6.56 W
Cooling effect	1.58 W
COP	0.0424
Ideal COP	0.3637
Relative Carnot COP	11.16 %
Linear motor force	30.05 N

The fundamental governing equations of the SAGE software are given below.

Continuity:  $\frac{\partial \rho}{\partial t} + \frac{\partial \rho u A}{\partial x} = 0$  (1)

Momentum:  $\frac{\partial \rho u A}{\partial t} + \frac{\partial u \rho u A}{\partial x} + \frac{\partial \rho}{\partial x} A - F = 0$  (2)

Energy:  $\frac{\partial \rho u e A}{\partial t} + P \frac{\partial A}{\partial t} + \frac{\partial}{\partial x} (u p e A + u P A + q) - Q_w = 0$  (3)

The cooling capacity of the system is determined by subtracting the losses incurred by the system from the gross refrigeration effect.

$Q_c = Q_{Gross} - \Sigma Q_{losses}$  (4)

$W_{net} = WPV_{compressor} + WPV_{displacer}$  (5)

The main losses associated with the system are displacer shuttle loss, heat pump loss in the displacer clearance, regenerator thermal loss, and conduction loss. The geometric and operating parameters used for designing the integral type free piston Stirling cryocooler are given in Table 1. The working fluid used here is helium gas. The SAGE simulation results are provided in Table 2. It shows that the designed cryocooler is capable of producing a cooling effect of 1.58 W with a COP of 0.0424.

2.1 Sensitivity analysis of the designed cryocooler

In this section sensitivity analysis of the designed cryocooler is carried out to find out the effect of various operating and geometric parameters on the COP and cooling effect produced. Figure 3 illustrates the changes in frequency on the cooling effect and COP of the system. In a Stirling cryocooler, frequency plays a crucial role in determining the mechanical resonance state and phase adjustment of the displacer, while also impacting thermal and viscous penetration depths. As frequency rises, the cooling effect of the system increases proportionally, and the COP initially rises to an optimal point before gradually declining. Figure 4 depicts the relationship between the cooling effect and COP on the phase difference between the piston and displacer. It indicates that the optimal phase angle for achieving maximum cooling effect and COP is at 85°. Figure 5 shows the P-V diagram of the compression space and expansion space of the cryocooler. Figure 6 shows the effect of piston seal thickness on the COP, input PV work, and the various AE losses. In SAGE,

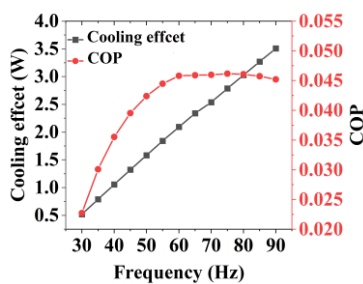


Figure 3. Effect of frequency on cooling effect and COP.

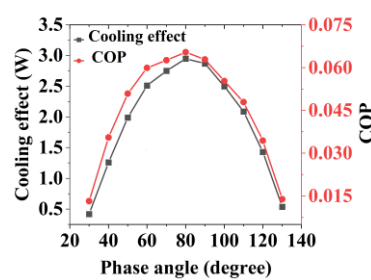


Figure 4. Effect of phase angle on cooling effect and COP.

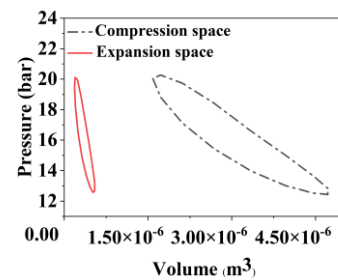
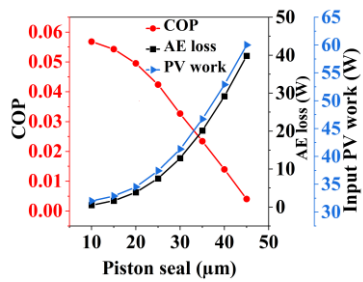


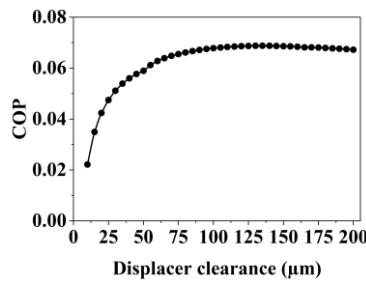
Figure 5. P-V diagram.

AE losses represent various exergy losses associated with individual components and it includes, losses due to flow friction, axial heat flow, and surface heat flow. From the figure, it can be seen that when the piston seal thickness increases the COP of the system continuously decreases and losses associated with the piston seal as well as the input PV work to the system increases. Figure 7 shows the variation of the cooling effect with the clearance between the displacer and the cryocylinder. Initially, the cooling effect produced by the system increases up to 120 μm and then

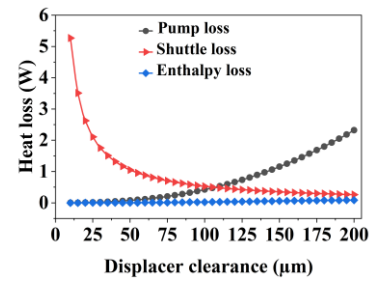
decreases. This is due to the cumulative effect of heat shuttle loss as well as the heat pump loss in the clearance. Figure 8 represents the variation of heat pump loss, shuttle loss, and the enthalpy loss that occurs at the displacer clearance. When clearance thickness increases the shuttle loss decreases whereas the heat pump loss associated with the system increases. Figure 9 illustrates how the cooling effect and the COP of the designed cryocooler changes with



**Figure 6.** Effect of piston seal on COP input work and AE loss.

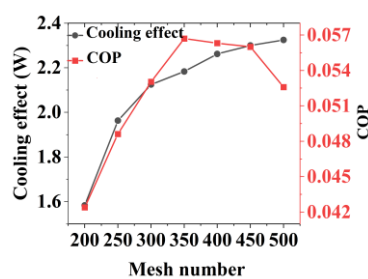


**Figure 7.** Effect of displacer clearance on COP.

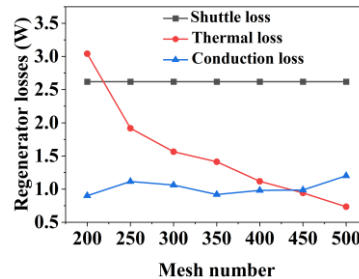


**Figure 8.** Displacer clearance vs heat loss.

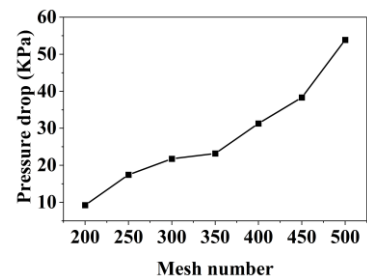
the regenerator mesh number. Regenerators made up of SS304 wire screen mesh with different mesh numbers and wire diameters were used here for conducting the analysis. It was found that the integral type regenerator achieves a higher COP with #350 mesh regenerator. Figures 10 shows the variation in regenerator heat losses due to an increase in the regenerator mesh number. As the regenerator mesh number increases, the thermal loss decreases, mainly due to the reduction in hydraulic diameter and Reynolds number. The shuttle loss remains consistent despite the increase in regenerator mesh number. The cryocooler experience least conduction loss with the #350 wire mesh regenerator. Figure 11 illustrates how the pressure drop in the



**Figure 9.** Effect of mesh number on cooling effect and COP.



**Figure 10.** Regenerator losses vs mesh number.



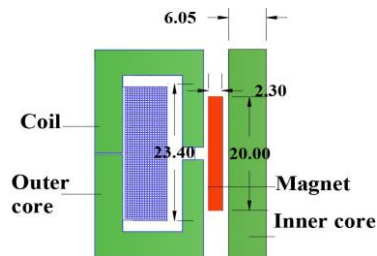
**Figure 11.** Regenerator pressure drop vs mesh number.

regenerator changes with an increase in mesh number. It is clear that as the regenerator mesh number rises, the associated pressure drop in the system also increases.

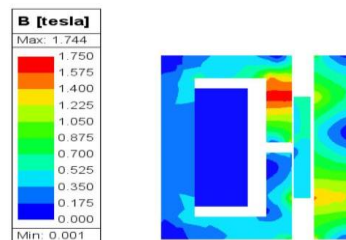
### 3. Design of moving magnet-type linear motor

In this section, a linear motor for the integral type Stirling cryocooler is designed. The chosen linear motor for the free piston Stirling cryocooler is of the moving magnet type. In this configuration, the permanent magnet is integrated with the moving component, while the coil remains stationary. Various input parameters necessary for the design of linear motors were

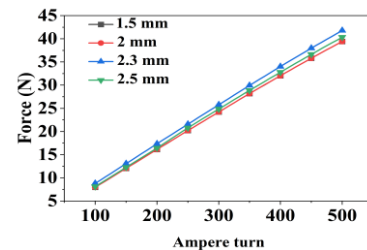
extracted from the SAGE 12 software. The force required to drive the linear motor was obtained from SAGE and is 30.05 N. For the design and optimisation of the linear motor Ansys Maxwell



**Figure 12.** Schematic of moving magnet linear motor.



**Figure 13.** Magnetic field distribution.



**Figure 14.** Linear motor force vs ampere turn.

software was used. Figure 12 shows the schematic of the linear motor. From the electromagnetic analysis it was found that a moving magnetic type linear motor with radially energized permanent magnet (NdFe35) of 2.3 mm thickness and 370 ampere turns for coil (copper) windings can produce a force of 30.05 N. The magnetic field distribution of the linear motor is given in Figure 13 and linear motor force vs ampere-turns for different thicknesses of permanent magnet is given in Figure 14.

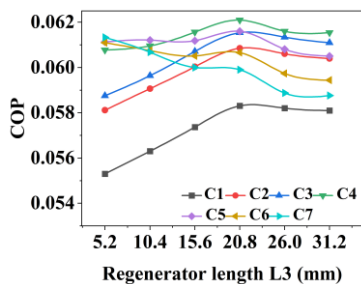
#### 4. Modelling of Stirling cryocooler with multi-mesh regenerator

In a Stirling cryocooler, the regenerator serves as an intermediate between the hot and cold working fluid, playing a crucial role in reaching the low temperature at the cold end. The efficiency of the Stirling cryocooler largely depends on how effective its regenerator is. Nowadays, wire screen mesh regenerators outperform other regenerators in most cryocoolers. Factors like the size of the wire screen mesh, which is the number of openings per inch, and porosity significantly influence the cryocooler's performance. In this section, the initially designed integral cryocooler was modified by replacing the single mesh regenerator with a multi-mesh regenerator. The regenerator material used here is SS304 wire screen mesh. The multi-mesh regenerator of the integral type cryocooler was modelled and analysed by using SAGE 12 software. The multi-mesh regenerator comprises three distinct regions (L1, L2, and L3), each of which contains wire screen meshes with different mesh numbers. The total length of the regenerator remains constant (52 mm) and different combinations of regenerator mesh numbers and porosities were examined to optimize the multi-mesh configuration for enhanced system performance. A total of seven distinct combinations of multi-mesh regenerators were evaluated, with varying lengths to identify the most effective configuration that maximizes the COP of the cryocooler. In all the combinations, mesh number #200 was placed at the hot side of the regenerator due to its high porosity. Each multi-mesh combination was further analysed for six different length variations, with L3 values ranging from 1% to 60% of the total regenerator length, while maintaining constant L1 and L2 values. Figure 15 shows the variation in COP for different multi-mesh regenerators, characterized by different length combinations for the L3 section. By considering all the multi-mesh combinations, it can be inferred that the maximum COP is achieved when the L3 value is 15.6 mm. Figure 16 shows the COP of the various multi-mesh regenerators for optimum length. The results indicate that the multi-mesh regenerator with case no 4 (#200#350#400) yields a maximum COP of 0.0621. The COP value of case no 4 is 8.71% higher than #350 single mesh case. In the

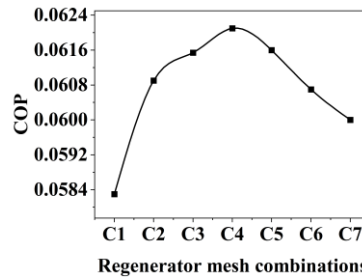
optimized multi-mesh configuration, the regenerator matrix is structured in such a way that the coarser regenerator matrix with a higher porosity value is positioned at the L1 section, followed by a material with lower porosity at the middle section L2, and finally, a finer mesh with the lowest porosity value is placed at the exit section L3. This specific arrangement serves to decrease the overall pressure drop experienced within the system, as illustrated in Figure 17.

**Table :3** Properties of different wire mesh and the various combinations of multi-mesh regenerator.

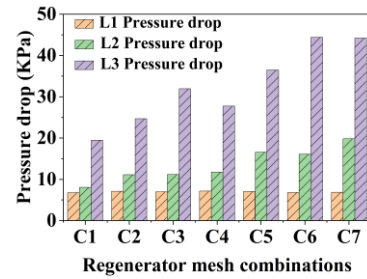
Mesh number	Wire diameter(m)	Porosity	Case no.	Combinations of multi-mesh
#200	5.0e-05	0.6909	C1	#200#250#300
#250	5.0e-05	0.6136	C2	#200#300#350
#300	4.0e-05	0.6291	C3	#200#300#400
#350	3.0e-05	0.6755	C4	#200#350#400
#400	2.8e-05	0.6539	C5	#200#400#450
#450	2.5e-05	0.6523	C6	#200#400#500
#500	2.5e-05	0.6136	C7	#200#450#500



**Figure 15.** COP of multi-mesh regenerator.



**Figure 16.** COP of multi-mesh regenerator for optimum length.



**Figure 17.** Regenerator pressure drop.

### Conclusion

An integral type free piston Stirling cryocooler that produces 1.58 W of cooling effect with a COP of 0.0424 was designed by SAGE 12 software. A moving magnet-type linear motor required for the integral cryocooler was designed with ANSYS Maxwell and the thickness of permanent magnet and number of coil winding of the linear motor were optimised as 2.3 mm and 370 respectively. The integral cryocooler was then improved by replacing the single mesh regenerator with a multi-mesh regenerator. Through parametric analysis, it was found that the optimal mesh numbers for the single mesh and multi-mesh regenerators were #350 and #200#350#400, respectively. The performance of the integral type Stirling cryocooler with optimized multi-mesh regenerator is 8.71% higher than that of the optimized single mesh regenerator.

### References

[1] R. Li and L. Grosu, "Parameter effect analysis for a Stirling cryocooler," *International Journal of Refrigeration*, 80, 2017 pp. 92-105.

[2] K. H. Jang, H. S. Kim, and S. H. Lee, "Numerical analysis of free-piston Stirling cooler systems for improving cooling performance," *Case Studies in Thermal Engineering*, 37, 2022, pp.1-10.

[3] D. Gedeon, "For Solving and Optimizing Engineering Models Sage User's Guide Stirling, Pulse-Tube and Low-T Cooler Model Classes," 2021.