Effect of operating frequency and phase angle on performance of Alpha Stirling cryocooler driven by a novel compact mechanism Sant K.D. 1,2 and Bapat S.L. 1

1 Department of Mechanical Engineering, IIT Bombay, Mumbai – 400 076, India 2 Department of Mechanical Engineering, Vishwakarma Institute of Technology, Pune – 411 037, India

Poster ID - C2PoM

Amongst the mechanical cryocoolers in use, Stirling cycle cryocoolers exhibit the desirable features such as high efficiency, low specific power consumption, small size and mass and large mean time before failure. Stirling cycle cryocooler of Alpha configuration exhibits better theoretical performance as compared to Gamma. However, the theory could not be put into practice due to unavailability of compatible drive mechanism for Alpha cryocooler providing large stroke to diameter ratio. The concept of novel compact drive mechanism can be made functional to operate miniature Alpha Stirling cryocoolers. It allows the use of multi-cylinder system while converting rotary motion to reciprocating. This permits the drive mechanism to be employed for driving different configurations of Stirling cryocooler simultaneously. This drive is capable of providing large stroke to diameter ratio compared to other drive mechanisms generally in use for the purpose. A stroke to diameter ratio of three is chosen in the present work and the drive dimensions are calculated for four piston-cylinder arrangements with 90° phase difference between adjacent arrangements providing two Alpha Stirling cryocoolers working simultaneously. It has to be noted that the coolers operate at half the frequency of the motor used. As the two coolers operate at phase difference of 180°, during compression stroke of one unit, the suction stroke occurs for the other unit. Due to power output of second unit, the combined peak torque requirement falls by 26.81% below the peak torque needed when one unit is operated separately. This allows for use of a comparatively lower torque motor. The practicability of the drive ensuring smooth operation of the system is decided based on comparison between torque availability from the motor and torque requirement of the complete unit.

The second order method of cyclic (or thermodynamic) analysis provides a simple computational procedure useful for the design of Stirling cryocooler and is adopted for the present theoretical investigations. An appropriate choice of the equations to compute different losses, from available co-relations, is made in accordance with the conditions existing in the present system. The effects of operating frequency and phase angle between compressor and expander pistons are presented in this paper. The cryocooler performance enhances with increase in operating frequency. However, cryocooler operation at 24 Hz (motor operation at 48 Hz) is considered for theoretical performance prediction. The maximum net refrigeration effect as well as COP is available at phase angle of 81°. However, it is essential to fix the phase angle at 90° for both the cryocoolers for the positive functioning of drive mechanism.

NOVEL COMPACT DRIVE MECHANISM

This drive mechanism is a kinematic friction drive [1] that converts rotary motion of driving disc into reciprocating motion of pistons in their respective cylinders. It comprises of a rotary (driving) disc and a stationary disc, both having a groove at the periphery, placed parallel to each other along the same central axis. A driven disc (in form of a slice of a hemi-sphere) with axis perpendicular to that of the rotary and stationary discs rotates in the peripheral grooves of these two discs. The spherical shaped portion of the driven disc is engaged in the matching grooves of the rotary and stationary discs. The L-shaped reciprocating members comprise of vertical piston limbs are located on a pitch circle diameter such that the adjacent limbs are at an angle of 90° from each other. This positioning of the reciprocating members relieves the driven disc functioning from possible difficulties of dynamic balancing. All the piston limbs reciprocate with same stroke in their respective cylinders rigidly fitted to the stationary disc. A pair of adjacent piston-cylinder arrangements with a regenerator in between can form one Stirling cycle cryocooler of Alpha configuration. Two such cryocoolers can operate in a single ensemble, drive nechanism. The compact drive mechanism is competent enough to drive any configuration of Stirling cryocooler (based on mechanical arrangement) viz. Alpha, Beta or Gamma.

The set-up discussed here consists of two Alpha configuration Stirling cryocoolers in the same ensemble, driven by the solitary novel compact drive mechanism. The drive provides movement to four piston limbs (or rods) with two compressor pistons and two expander pistons. A mechanical phase difference of 90° is maintained by the drive mechanism between the compressor piston and the corresponding expander piston adjacent to it. The two compressor pistons move with phase difference of 180° between them. Similarly, the two expander pistons also have phase difference of 180°. The compressor pistons of larger diameter are mounted on the piston rods and move in the respective compressor cylinders. The desired mass flow rate is obtained by maintaining the compressor piston diameter more than its rod diameter. In the expander cylinders, the piston rods themselves act as the expander pistons. It means that the compression space is more than the expansion space in each cryocooler. The stroke maintained in each cylinder, either compressor or expander is same due to positioning of all the piston limbs on same pitch circle diameter. The regenerators of same size are placed between each pair of compressor and expander. The space below each compressor piston is connected to the bounce space (i.e. drive mechanism casing) through a capillary tube. The schematic of drive mechanism is as shown in Figure 1[2].

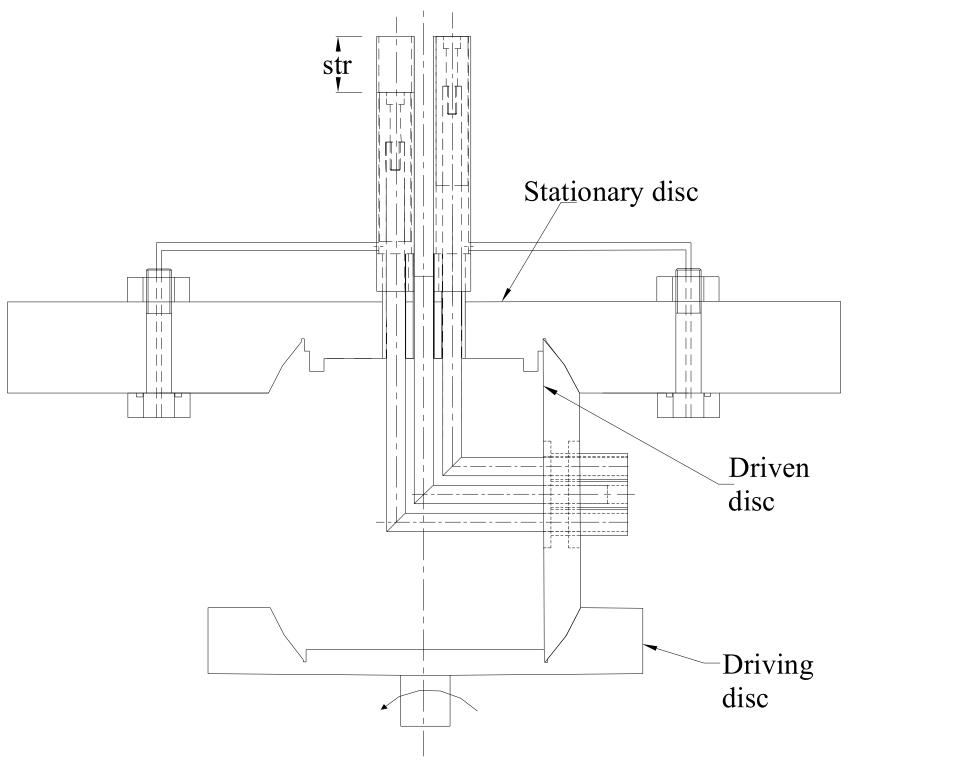


Figure 1 Schematic diagram of the actual drive mechanism with compressors of two simultaneously driven Alpha Stirling cryocoolers [2]

The maximum load on any piston in the drive is when that piston is completely inside its respective cylinder and when the maximum pressure acts on it. At this instance, the load-bearing limb is also completely inside the guide sleeve thus providing the maximum area for load bearing. The line contact between the spherical shaped power transmitting surfaces results in rolling motion and ensures low frictional loss. This can result in a high efficiency friction drive [2].

THERMODYNAMIC ANALYSIS

The second order method used for cyclic analysis of a Stirling cryocooler exhibits a pragmatic attitude with an aspect of simplified execution. These facts assist the method to confidently compete with the other methods and stand as an appropriate opportunity. Hence, second order method is used for cyclic analysis of miniature Alpha Stirling cryocooler driven by a novel compact drive mechanism during the present work. The analysis consists of calculating the ideal and net values of refrigeration effect and input power. The ideal values are modified by considering different losses to obtain the net values. The losses due to fluid friction and mechanical friction affect the input power. These losses are computed and added to the ideal input power to find the net power input to the cryocooler. The losses due to imperfect heat transfer, fluid friction and heat conduction effect. These losses are estimated and subtracted from the ideal refrigeration effect to

The cycle is assumed to start from the reference condition when the expander piston is farthest from the cold end or with maximum expansion space volume available. As the cycle initiates, the expander piston travels towards its inner dead centre. The phase shift between the expander and compressor pistons is considered as 90° with expander piston leading the compressor piston as it is actually achievable with the novel compact mechanism to be used to drive the cryocoolers. Due to this phase difference, the compressor piston is exactly midway of its stroke length when the expander piston is at its outer dead centre at the beginning of the cycle. The compressor piston moves towards its outer dead centre with the commencement of the cycle. The magnitude and direction of displacement of both the pistons over the cycle are essential to calculate the instantaneous property values at different intermediate positions (or states) during the cycle. The cycle is considered to be split into 144 intervals, each interval corresponding to 2.5° angular movement of the crank.

Thermodynamic analysis is done for cold tip temperature of 70 K. The design parameters obtained after optimization and the other geometrical parameters kept at fixed values due to mechanical strength and geometrical considerations are summarised below. The same are employed to know the effects of different parameters like frequency and phase angle on cryocooler performance.

Design parameters [4]		Other geometrical parameters [4]				
Compressor piston diameter (mm) Compressor piston stroke (mm) Expander piston diameter (mm) Expander piston stroke (mm) Compressor side connecting tube diameter (mm)	20.0 30.0 8.0	Compressor piston length (mm) Expander piston length (mm)	105.0 105.0			
Radial clearance (µm) Regenerator length (mm) Regenerator diameter(mm) Regenerator matrix mesh size		Cylinder length (mm) Cylinder thickness (mm) Compressor side connecting tube length (mm)	75.0 0.15 120.0			
(Mesh No. – wire gauge)	250 - 47					

The drive mechanism designed for mechanical safety is practical only when it can fulfill the torque requirement criterion. So, the function of a mechanically safe novel compact drive is to provide the torque required by the system. The total torque requirement includes the maximum required torque in the cycle by the system and the frictional torque consumed by the drive mechanism itself. The maximum required torque by the system is calculated from the value of maximum required input power to the system at a particular operating frequency. The torque availability is calculated from the motor power considering operating frequency of the motor and mechanical efficiency of the novel compact drive. The required torque is compared with the available torque and the designed drive is practicable only if the torque requirement is less than the available

Table 1 Effect of change in operating frequency

Stainless Steel 316

Operating frequency (Hz)	21.0	22.0	23.0	24.0	25.0
Ideal RE (W)	7.700	8.067	8.434	8.861	9.167
Total loss in RE (W)	5.206	5.367	5.534	5.732	5.885
Net RE (W)	2.494	2.700	2.900	3.129	3.282
Ideal IP (W)	36.734	38.483	40.232	42.273	43.731
Total loss in IP (W)	7.188	7.602	8.024	8.521	8.887
Net IP (W)	43.922	46.085	48.256	50.794	52.618
COP	0.0568	0.0586	0.0601	0.0616	0.0624
Refrigeration η (%)	18.659	19.247	19.748	20.245	20.496
Available torque (N-m)	2.665	2.913	3.173	3.490	3.727
Required torque (N-m)	2.982	3.091	3.170	3.342	3.445

Regenerator matrix material

CONCLUSIONS

The magnitude of vibrations in the system may not practically allow the cryocooler to operate at 25 Hz. So, an optimum operating frequency can be experimentally determined. The value of 24 Hz is considered for theoretical performance prediction.

The present system consists of four pistons placed on same pitch circle diameter forming two simultaneously operating Alpha cryocoolers. The requirement of the drive mechanism is that these pistons should be equally spaced to synchronize their reciprocation and balance the forces exerted on them during operation. This is possible only if the consecutive pistons

1. Bapat, S.L., A compact drive mechanism of a reciprocating machine, Indian Patent No. 200858, 2006. (together working as one cryocooler) are placed at an angle of 90°. These two pistons working together will make one cryocooler with a 90° phase angle between their motions. phase angle of 90° though the optimum phase angle is 81°.

Table 2 Effect of change in phase angle

Phase angle (degree)	78.0	79.0	80.0	81.0	82.0	83.0	84.0	90.0
Maximum cycle pressure (bar)	43.254	43.137	43.020	42.903	42.786	42.668	42.550	41.841
Minimum cycle pressure (bar)	9.514	9.543	9.572	9.601	9.631	9.660	9.691	9.874
Pressure ratio	4.546	4.521	4.495	4.469	4.443	4.417	4.391	4.237
Ideal RE (W)	8.616	8.651	8.683	8.713	8.740	8.765	8.786	8.861
Total loss in RE (W)	5.371	5.411	5.450	5.461	5.500	5.537	5.545	5.732
Net RE (W)	3.245	3.240	3.233	3.252	3.240	3.228	3.242	3.129
Ideal IP (W)	41.961	42.060	42.145	42.217	42.276	42.321	42.353	42.273
Total loss in IP (W)	8.286	8.317	8.346	8.376	8.400	8.420	8.441	8.521
Net IP (W)	50.247	50.377	50.491	50.593	50.676	50.741	50.794	50.794
COP	0.0646	0.0643	0.0640	0.0643	0.0639	0.0636	0.0638	0.0616
Refrigeration η (%)	21.218	21.134	21.039	21.123	21.004	20.899	20.970	20.245
Available torq. (N-m)	3.490	3.490	3.490	3.490	3.490	3.490	3.490	3.490
Required torq. (N-m)	3.394	3.393	3.391	3.389	3.386	3.383	3.379	3.342

REFERENCES

2.Sant, K.D. and Bapat, S.L., Investigations on Alpha Stirling cryocooler driven by a novel compact mechanism, 23rd National Symposium on Cryogenics (NSC – 23), N.I.T. Rourkela, 2010. Hence, allowing for the positive functioning of drive mechanism, it is essential to fix the 3.Bapat S.L., Feasibility of alpha configuration for miniature Stirling cycle coolers, Proceedings of 18th International Cryogenic Engineering Conference (ICEC-18), Mumbai, pp. 611 – 614, 2000. phase angle at 90° for both the cryocoolers. So, the present analysis considers constant 4.Sant, K. D., Investigations on twin Alpha Stirling cryocoolers drive mechanism with preliminary experimental results, Ph.D. Thesis, Department of Mechanical Engineering, I.I.T. Bombay, 2012.