

Experimental comparison of Pressure ratio in Alpha and Gamma Stirling cryocoolers with identical compression space volumes and driven simultaneously by a solitary novel compact mechanism

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Abstract. The cryocooler technology is advancing in different ways at a considerable pace to explore cooler applications in diversified field. Stirling cryocoolers are capable to satisfy the contemporary requirements of a low-capacity cooler. A compact mechanism that can drive Stirling cryocooler with larger stroke and thus enhance the cooler performance is the need of the hour. The increase in the stroke will lead to a higher volumetric efficiency. Hence, a cryocooler with larger stroke will experience higher mass flow rate of the working fluid, thereby increasing its ideal cooling capacity. The novel compact drive mechanism that fulfils this need is a promising option in this regards. It is capable of operating more than one cryocoolers of different Stirling configurations simultaneously. This arrangement makes it possible to compare different Stirling cryocoolers on the basis of pressure ratio obtained experimentally. The preliminary experimental results obtained in this regard are presented here. The initial experimentation is carried out on two Alpha Stirling units driven simultaneously by the novel compact mechanism. The pressure ratio obtained during the initial stages is 1.3538, which is enhanced to 1.417 by connecting the rear volumes of the compressor pistons to each other. The fact that annular leak across the expander pistons due to high pressure ratio affects the cryocooler performance, generates the need to separate the expansion space from bounce space. This introduces a Gamma configuration that is operated simultaneously with one of the existing Alpha units by same drive mechanism and having identical compression space volume. The results obtained for pressure ratio in both these units prove the concept that cooling capacity of Alpha configuration exceeds that of Gamma under similar operating conditions. This has been observed at 14 bar and 20 bar charge pressures during the preliminary experimentation. These results are presented in this paper. Thus, the theoretical predictions regarding pressure ratio and hence the cooling capacity of Alpha and Gamma configurations for low-capacity units are confirmed experimentally in the present work.

1.Introduction

The cryocooler applications are exploring diversified fields like space, military, civil, scientific and medical. So, the cryocooler technology is advancing in different ways to overcome existing shortcomings and fulfill contemporary market conditions. The contemporary requirement in the field of low-capacity cryocooler is of a reliable (with high reproducibility), long life cooler of lesser weight and having low power consumption. Over the period of competitive development, the Stirling cycle cryocoolers are still considered as a better option for low-capacity due to their competence in fulfilling this need. This has made it possible to employ Stirling cryocoolers in various low-capacity



applications like cooling of HTS devices, detectors like infrared sensors and computer chips. The efficient operation of a low-capacity Stirling cryocooler is supported by modifications like use of flexure bearings and linear motors, use of drives free from kinematic linkages etc. Even then, the major limitation till now has been the unavailability of a compact and efficient drive mechanism to provide larger stroke of reciprocating members. The increase in the stroke will lead to a higher volumetric efficiency. Hence, a cryocooler with larger stroke will experience higher mass flow rate of the working fluid, thereby increasing its ideal refrigeration capacity. But, the stroke of the reciprocating members and relative phase difference between them is decided by the drive mechanism. Thus, the driving mechanism certainly has a definite effect on the cryocooler performance. The novel compact drive mechanism [1] offers a concrete solution in this regards.

2. 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 and horizontal load-bearing limbs. The 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, driven by the solitary novel compact drive mechanism. The compact drive mechanism is competent enough to drive any configuration of Stirling cryocooler (based on mechanical arrangement) viz. Alpha, Beta or Gamma.

The efforts to obtain higher pressure ratio by modifying compressor and expander piston strokes using various measures are reported in literature. One such example is that of converting simple crank shaft connecting rod mechanism to slider crank mechanism. However, the criterion of compactness is not fulfilled by this mechanism. It is noticed that in Gamma Stirling cryocoolers, a variable dead volume gets created on the side of displacer opposite to expansion space and it acts as additional dead volume of the compressor. As a result, the displacer strokes are restricted to very small values (of the order of 3 mm to 5 mm for miniature units). Alpha configuration does not come across any such problem and allows for larger expander strokes leading to higher pressure ratio and consequently a better performance. As an effort to achieve this effect along with compactness, the novel compact drive mechanism is a promising alternative.

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].

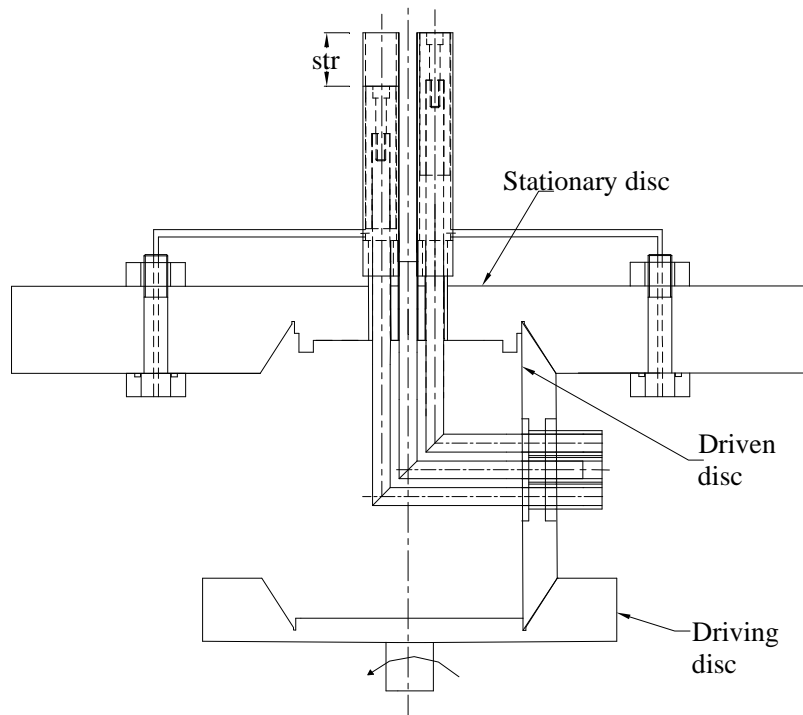


Figure 1. Schematic diagram of the actual drive mechanism with compressors of two simultaneously driven Alpha Stirling cryocoolers [2]

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].

Bapat [3] has checked the feasibility of Alpha configuration for miniature Stirling coolers, on the basis of cyclic analysis. When compared with Gamma under same operating conditions, the results computed show a superior thermodynamic performance by Alpha configuration. Therefore, Alpha or two piston arrangement is the alternative considered for present investigations. This gives an opportunity to reap the advantages of Alpha arrangement over the popularly existent Gamma and examine the achievability of theoretical facts.

3. Experimental results

The design and specifications of the cryocoolers are as given by Sant [4]. The system is manufactured and experimentation is carried on the set-up explained by Sant [4]. During the initial experimentation stage, the space below each compressor piston is connected to the bounce space (same as drive mechanism casing) by a copper capillary as shown in figure 1. It is expected that during the suction stroke of the compressor piston, the gas from this space should flow into the bounce space through the capillary. If the cross-sectional area available for flow in the connecting tube is large, then the pressure in this space will be same as bounce space pressure. Since the capillary is long, there is resistance to the flow of gas towards bounce space. The cross-sectional area of the connecting tube being just 9% more than that of the annular area between compressor piston and cylinder, possibility of annular leak

of the gas into compression space does exist. A modification is done in the experimental set-up as compared to the figure 1 to get rid of this annular leak. If the spaces below both compressor pistons are connected to each other using a connecting tube, the gas below both the pistons will move from one space to the other through this tube as a constant volume process. The minimum volume of this connecting tube should be at least equal to one compression space volume. This becomes possible because the compressor pistons are in 180° phase shift with each other and the suction stroke of one piston is accompanied by the compression stroke of the other piston. The arrangement having compressor cylinders inter-connected (below the pistons) is shown in figure 2.

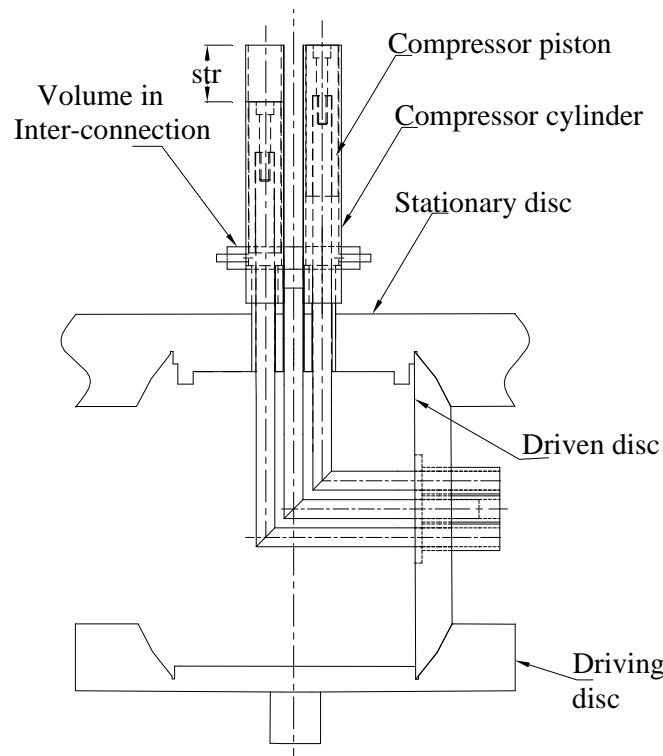


Figure 2. Compressor cylinders inter-connected below compressor pistons

Table 1. Pressure ratio after inter-connecting compressor cylinders

Charge pressure (bar)	Cryocooler frequency (Hz)	Input power (W)	Cold-tip temperature (K)		Pressure Ratio
			Cooler 1	Cooler 2	
14.0	23.92	148	292.0	290.6	1.417

During experimentation, this arrangement has provided an increase in pressure ratio from 1.3538 to 1.417 in each cryocooler [4]. This rise in pressure ratio indicates that the annular leak across compressor piston is minimized and the main reason for not attaining temperature reduction in the expansion space is the leak across the expander piston from bounce space to expansion space. During the expansion process, the pressure starts dropping, soon reaches the value same as the charge pressure and continues to drop further to the minimum pressure. Thus, during certain part of the expansion process, the pressure in the expansion cylinder is much below the bounce space pressure. A large pressure ratio, leading to large pressure difference was to provide large work of expansion resulting in large cooling capacity (assuming fixed mass of gas in the total working space). The same large pressure difference is now leading to leakage from bounce space into the expansion space due to

absence of proper sealing arrangement. The gas leaking into the expansion space is at a temperature close to atmospheric temperature and hence acts as the thermal load on expansion space. As a substantial quantity of the gas is leaking in, the entire cooling effect produced is consumed by the gas that leaks into the expansion space. This also increases the pressure in the expansion space much above the lowest pressure at which the forward stroke is expected to start which would have pushed the gas to the regenerator entry point at the lowest temperature. The excess quantity of gas, responsible for increase in pressure above the lowest pressure, gets compressed during forward stroke of the expander piston resulting in rise in expansion space temperature, to a value above the ambient temperature.

As the operating frequency of cooler increases, the time available for the gas to leak in reduces and hence the leakage per cycle reduces, leading to a slight decrease in the rise in temperature. However, as the increase in frequency leads to increase in vibration level, the cryocoolers at present can be operated only up to the maximum frequency of 24 Hz in the present system and hence further reduction in cold-tip temperature is not possible.

4. Gamma Stirling cryocooler

Since the annular leak across the expander piston is prominent, it is decided to disconnect the expansion space from the bounce space. The decision of disconnecting the expansion space of Alpha cryocooler from the bounce space led towards setting up an expansion space that is connected only with the compression space and is not directly getting connected to the bounce space, making it independent of the bounce space pressure. This scheme is executed by introducing one displacer unit of a Gamma configuration Stirling cryocooler and connecting it to one of the two compressors in the system. This forms a Gamma or split Stirling cryocooler in which small ΔP and high ΔT would exist across the displacer. A displacer unit of split Stirling cryocooler designed and developed by Gaunekar [5] is selected for this purpose. The displacer unit is connected to one of the compressors driven by novel compact mechanism during which the connecting tube of 2 mm I.D. and 200 mm length is used which is same as in original split Stirling unit [5]. The expander cylinder, from which the compressor is disconnected, is added with a dead volume (more than its swept volume) and sealed at free end. The piston corresponding to this expansion space is necessary to balance the forces on the driven disc. Henceforth, this piston-cylinder arrangement in the system is a non-contributing configuration. The reciprocating motion of the compressor piston is fixed in accordance with the drive and the compressor frequency and power are controlled by the variable frequency drive. The block diagram of modified experimental set-up is shown in figure 3.

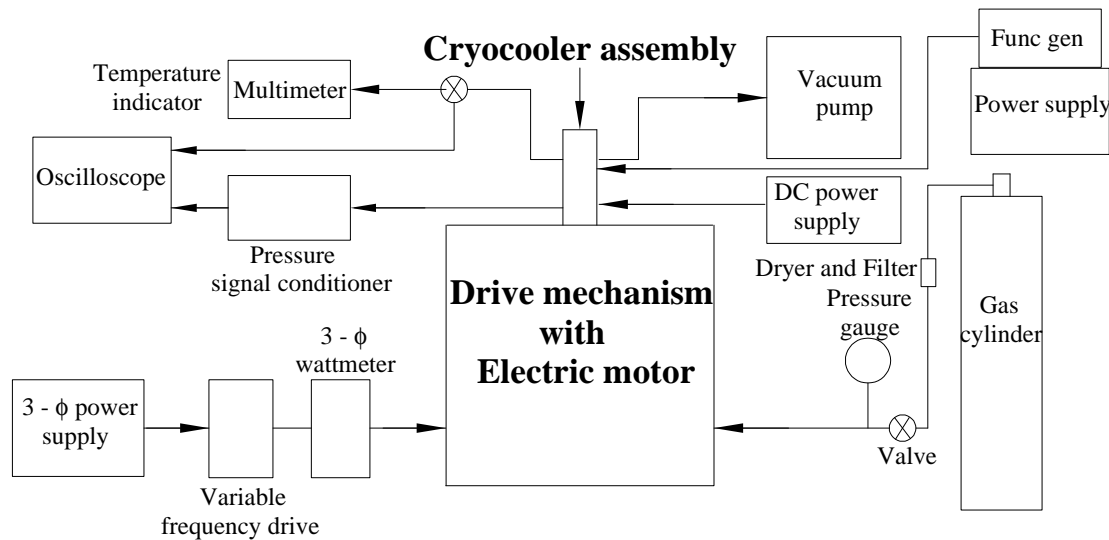


Figure 3.Block diagram of modified experimental set-up with separately powered motorised displacer

The initial test is conducted on the modified set-up charging helium at 14 bar to ensure proper working of the drive and the cryocoolers, both Alpha and Gamma. The charge pressure is not increased at this stage to avoid any operating problem. The motor frequency is maintained constant at 48 Hz. The displacer power is not increased beyond 0.5 W as it is a preliminary test carried out to check proper functioning of all components and instrumentation in the system. The electrical phase shift between displacer and compressor piston of Gamma unit is 40° . The results of Alpha and Gamma units are given in table 2. Atmospheric temperature is 302.2 K.

Table 2.Pressure ratio on modified set-up

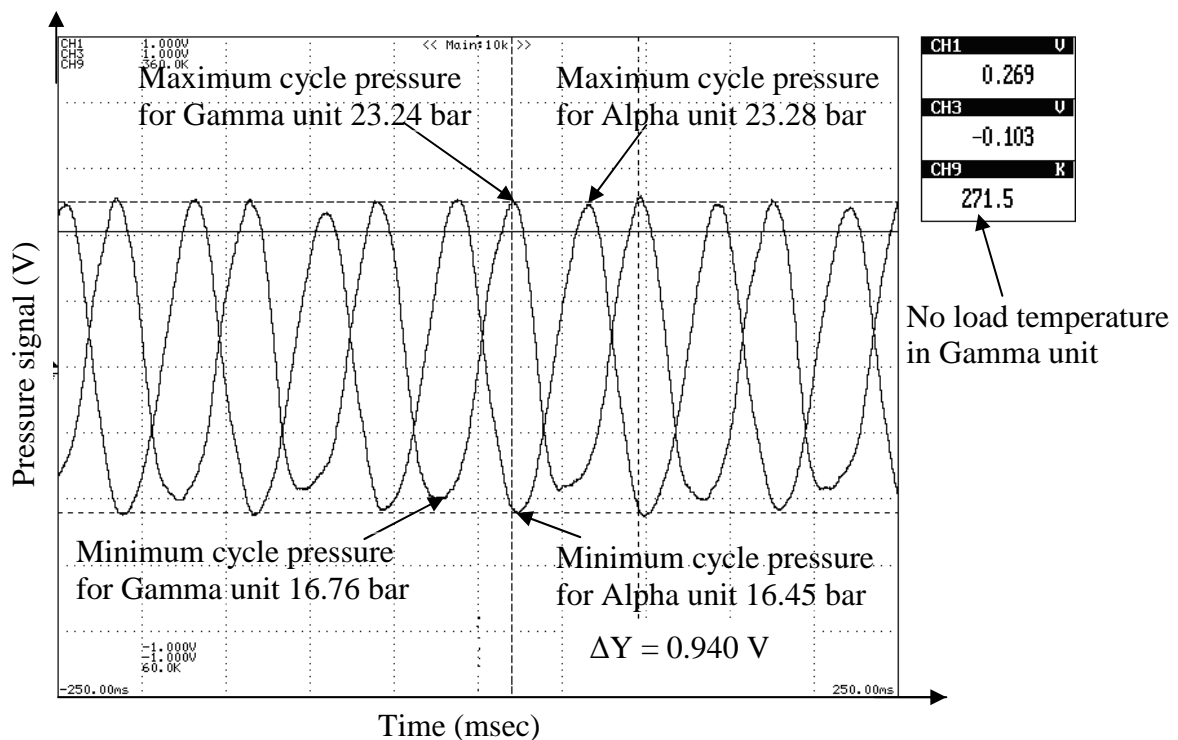
Charge pressure (bar)	Compressor frequency (Hz)	Motor power (W)	Displacer power (W)	Cold-tip temperature (K)		Pressure ratio	
				Alpha	Gamma	Alpha	Gamma
14.0	23.89	230	0.5	290.7	281.6	1.417	1.339

The cold-tip temperature achieved in Gamma unit is 281.6 K which is enough to condense the atmospheric moisture. The temperature of Alpha unit is 290.7 K which matches with the earlier result at same charge pressure. The pressure ratio achieved in Gamma unit is 1.339 and that in Alpha unit is 1.417, yet the temperature reduction in Gamma unit is more than that in Alpha unit. This is an effect of annular leak occurring over the expander piston in Alpha unit as a result of substantial pressure difference across it as compared with that across the displacer in Gamma unit which is detached from the bounce space. This preliminary result confirms the capacity of Alpha unit to provide refrigeration effect and the fact that its performance is degraded solely by annular leak.

The next test is a repetition of the previous test, but conducted at 20 bar charge pressure. The motor frequency is 48 Hz and electrical phase shift between displacer and compressor piston of Gamma unit is 88° . The results of Alpha and Gamma units are tabulated in table 3. The pressure variations are shown in figure 4. The maximum and minimum pressure values in Gamma unit are 23.24 bar and 16.76 bar while those in Alpha unit are 23.28 bar and 16.45 bar respectively. The no-load temperature achieved in Gamma unit is 271.5 K. The pressure ratio achieved in Gamma unit is 1.387 and that in Alpha unit is 1.415. Till this test, the vacuum or MLI is not used.

Table 3. Pressure ratio on modified set-up

Charge pressure (bar)	Compressor frequency (Hz)	Motor power (W)	Displacer power (W)	Cold-tip temperature (K)		Pressure ratio	
				Alpha	Gamma	Alpha	Gamma
20.0	23.95	260	0.85	287.1	271.5	1.415	1.387

**Figure 4.** Pressure variations of Alpha and Gamma units on modified set-up at 20 bar

The results of test conducted at 20 bar charge pressure are similar to those obtained at 14 bar charge pressure in terms of pressure ratio in Alpha and Gamma units. The pressure ratio in Alpha unit has not changed and that in Gamma unit has increased underlining the fact that annular leak across expander piston in Alpha unit is still affecting its performance profoundly. This actuality is clear from table 3 as well as from figure 4. However, the capacity of Alpha configuration still exceeds that of Gamma since the pressure ratio in Alpha is greater than that in Gamma.

5. Conclusions

The comparison of pressure ratio values for Alpha and Gamma units obtained at each charge pressure confirms the fact that capacity of Alpha configuration will be higher than that of Gamma, (in absence of annular leak) under same operating conditions, as predicted by Bapat [3] based on thermodynamic analysis. So, the analytical prediction made by Bapat [3] is experimentally verified during the present work.

References

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