Studies on an improved indigenous pressure wave generator and its testing with a pulse tube cooler

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Abstract.
Earlier version of an indigenously developed pressure wave generator could not develop the necessary pressure ratio to satisfactorily operate a pulse tube cooler, largely due to high blow by losses in the piston cylinder seal gap and due to a few design deficiencies. Effect of different parameters like seal gap, piston diameter, piston stroke, moving mass and the piston back volume on the performance is studied analytically. Modifications were done to the PWG based on analysis and the performance is experimentally measured. A significant improvement in PWG performance is seen as a result of the modifications. The improved PWG is tested with the same pulse tube cooler but with different inertance tube configurations. A no load temperature of 130 K is achieved with an inertance tube configuration designed using Sage software. The delivered PV power is estimated to be 28.4 W which can produce a refrigeration of about 1 W at 80 K.

Keywords: Pressure Wave Generator, Pulse tube cooler, Inertance
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INTRODUCTION

Aerospace applications like infrared detectors etc. require highly reliable and vibration free cooling systems. Pulse tube cryocoolers can meet these requirements and hence are finding increasing application. A research and development program was initiated at the Indian Institute of Science, Bangalore to develop expertise in the design, fabrication and testing of high frequency pulse tube coolers (PTC) including the Pressure Wave Generator (PWG).

A moving magnet linear motor PWG with 2 cm^3 swept volume and dual opposed piston configuration supported by spiral flexure bearings was designed and developed indigenously [1]. This PWG was utilized to drive a PTC and a no load temperature of 180 K was obtained when the design target was 80 K [2]. A study was taken up to analyze the reasons for the low performance which involved analyzing both the PWG and the pulse tube cooler. This paper describes the progress that has been achieved.

METHODOLOGY FOR IMPROVING THE PRESSURE WAVE GENERATOR

Pressure wave generator is of critical importance for an efficient operation of the pulse tube cooler. It should be able to generate a sufficiently high pressure amplitude and displace optimum mass flow required for producing the refrigeration. The pressure amplitude can be related to different parameters of the PWG and the PTC [3] as

$$p_1 = \left[(2\pi f_{res})^2 m - \frac{A^2 P_{mean}\gamma}{V_{back}} - k_{mech} \right] \frac{x_1}{A} \tag{1}$$

where p_1 is the pressure amplitude in the compression space, f_{res} the resonance frequency of the combined PWG-PTC system, m total moving mass, A area of the piston, V_{back} volume at the back of the piston in a single motor, P_{mean} is the mean filling pressure, k_{mech} mechanical spring stiffness, x_1 amplitude of piston stroke.

It is evident from equation (1) that for a given f_{res} the pressure amplitude p_1 can be increased by increasing the stroke, decreasing the area of the piston, and increasing the moving mass and back volume. This also implies that there is an optimal combination of these parameters to obtain a certain cooling wattage. There is an additional advantage of reducing the piston diameter. A force balance on the piston when it is at the top of the compression stroke gives

$$p_1 A = BiL \tag{2}$$

where B is the magnetic flux density, i is the current flowing through the motor coil and L is the effective length of the motor coil. From equation (2), as the piston area is reduced the current required to produce the same pressure amplitude decreases. This is a significant advantage when the BL value of the motor is not very high.

Other factors that affect the performance of the PWG are the mechanical losses consisting of pressure loss and flow loss. The former is due to the seal blow by where as the latter is due to the viscous resistance in the internal flow passages of the PWG [4]. Jacob et. al. studied the effect of seal gap on the losses and found that there is an optimal seal gap that minimizes the losses [5]. The optimal seal gap (δ) was arrived at by using the equation

$$\delta = \sqrt{\frac{2L\mu v}{\Delta P}} \tag{3}$$

where L is the length of the seal, ΔP is the pressure drop across the seal and v is the velocity of the gas and μ is the viscosity of the gas. A seal gap of 10 μm was suggested as practical compared to the calculated optimal value of 1 μm due to fabrication and assembly constraints. Hence modifications were made to the pressure wave generator which are listed in Table 1.

TABLE 1. List of modifications made to the PWG.

Component	Initial	Modified
Piston diameter (*mm*)	18	15
Maximum piston stroke (*mm*)	±2	±2.8
Seal gap (μm)	≈21	≈10
moving mass (*g*)	153	171
Total effective back volume (cm^3)	20	40

EXPERIMENTAL VALIDATION OF THE PWG IMPROVEMENTS

The PWG was assembled after making the modifications and was tested to experimentally ascertain the effect of the changes. Figure 1 shows the pressure amplitude in the compression space in the blanked off condition before and after the modifications. A maximum pressure ratio of 1.33 was achieved as against 1.17 obtained prior to modifications. This is a significant improvement and is expected to raise the performance of pulse tube cooler. At a particular total stroke, defined as the combined stroke of two motors, the pressure amplitudes developed after modifications are less than the initial values. A total stroke of 2 mm, corresponding to a maximum stroke of ±1 mm per motor, was only feasible before modifications because of very high current requirement to drive the PWG.

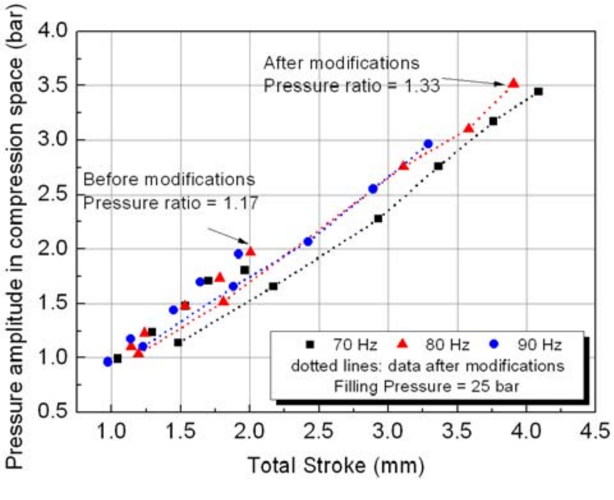

FIGURE 1. Pressure amplitude developed by the PWG in blanked off condition at different values of total stroke in comparison with data before modifications.

Figure 2 shows the variation of the total stroke with the total current supplied to the PWG before and after the modifications. The changes effected to the PWG have resulted in a higher stroke to be produced for the same current input in agreement with equation 2. Thus significant advantage is achieved by reducing the diameter of the pistons.

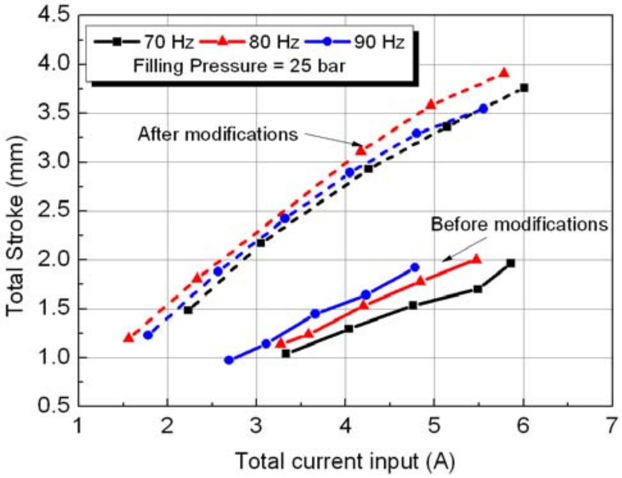

FIGURE 2. Variation of total stroke with total current supplied to the PWG before and after the modifications.

The mechanical losses were also measured after the modifications. Figure 3 shows the pressure loss after modifications in comparison with the loss prior to the modifications. It can be seen that the pressure loss is significantly reduced in the experimental range of frequencies. Figure 4 shows similar measurements of the flow loss. At 70 Hz, flow loss is lower after modifications. At 80 Hz, the flow loss is increased. This is because the resonance frequency of the system is close to 70 Hz, thus resulting low input current and hence low I^2R losses.

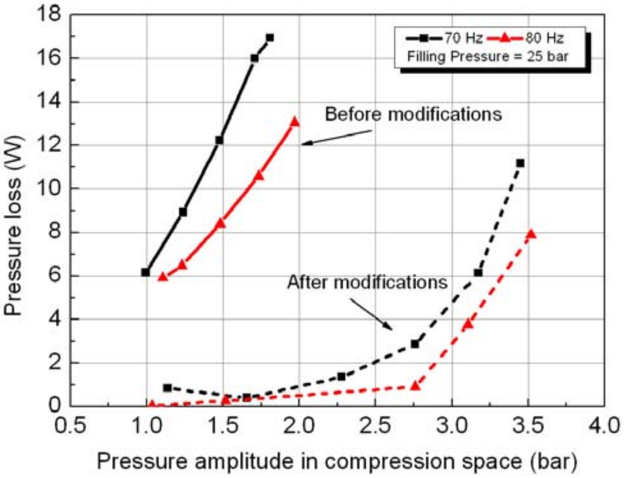

FIGURE 3. Pressure loss after modifications to the PWG in comparison with the loss before.

TESTING THE IMPROVED PWG WITH A PULSE TUBE COOLER

After validating the improvements, the PWG was tested with a pulse tube cooler. The cooler used in the earlier work [2] was tested to ascertain the effect of PWG improvements in terms of cooling performance. Table 2 gives the dimensions of the major components of the cooler. This cooler had achieved a no load temperature of 180 K before the modifications. Also keeping in view the possibility of non optimal inertance, different inertance configurations

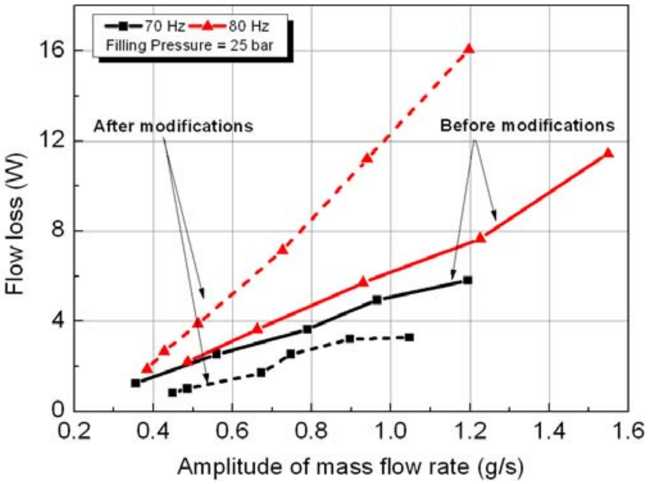

FIGURE 4. Flow loss after modifications to the PWG in comparison with the loss before.

TABLE 2. Dimensions of the pulse tube cooler used to test the PWG.

Component	Inner Diameter (mm)	Length (mm)
Regenerator	12.0	40
Pulse tube	6.0	30
First inertance tube	1.1	1236
Second inertance tube	1.4	2400

were tested which are listed in Table 3. The inertance configuration IC1 was designed using transmission line model before the modifications to the PWG were done, where as IC2 was selected off the shelf from an earlier experimental system. The inertance configuration IC3 was arrived at by using the optimization routine of the Sage software [6].

TABLE 3. Inertance configurations that were used to test the PWG.

Inertance	Component	Inner Diameter (mm)	Length (mm)
Configuration IC1	First inertance tube	1.1	1236
	Second inertance tube	1.4	2400
Configuration IC2	First inertance tube	2.0	865
	Second inertance tube	4.0	2354
Configuration IC3	First inertance tube	2.0	2184
	Second inertance tube	3.0	1664

The cooler was assembled and Mylar multilayer insulation was used to reduce radiation. A vacuum jacket enclosed the cooler and was continuously pumped to a vacuum of $5E-3$ torr. The cooler was filled with helium gas to a pressure of 25 bar.

Experimental observations

Table 4 lists the important parameters during the testing of different inertance configurations. For almost the same total stroke, the total current and input power is the least with IC1, followed by IC3 and IC2. This shows the significant effect the inertance configuration has on the power required to drive the cryocooler. The pressure amplitude in the compression space is the highest in IC2 followed by IC3 and IC1. This could be due to the higher impedance of the

TABLE 4. Important parameters during testing of each inertance configuration.

Parameter	IC1	IC2	IC3
Filling Pressure (bar)	25	25	25
Operating frequency (Hz)	69	70	70
Total Stroke (mm)	4.77	4.50	4.77
Input Power (W)	22.8	63.2	35.7
Total current (A)	2.49	5.28	3.42
Compressor pressure amplitude (bar)	1.48	2.13	1.69
Hot heat exchanger pressure amplitude (bar)	1.48	1.2	1.34
No load temperature at cold heat exchanger (K)	217	229	130

cooler in IC2. A no load temperature of 130 K was achieved with IC3 as compared to 217, 219 K achieved with IC1 and IC2 respectively. Figure 5 shows the cool down curve that was achieved with IC3.

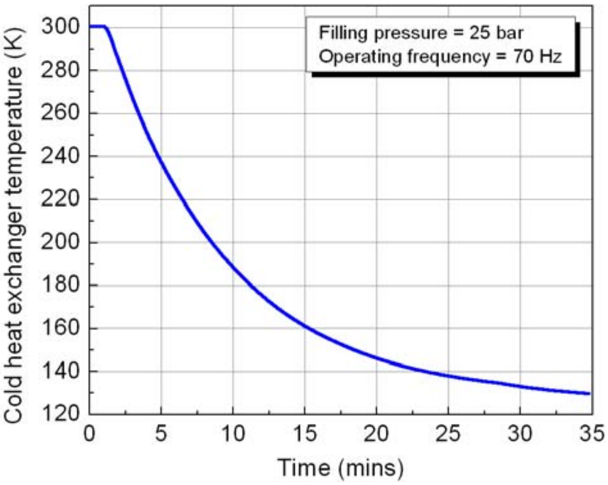

FIGURE 5. Cool down curve achieved with inertance configuration IC3.

The PV power that is delivered to the cooler was estimated as shown in Table 5. A PV power of 28.44 W is being delivered to the cooler by the PWG which is sufficient to produce a refrigeration of 1 W at 80 K [7]. The cooler components like the regenerator etc. need to be further optimized.

TABLE 5. Estimate of the PV power delivered to the pulse tube cooler with inertance configuration IC3

	Watts
Input power (a)	35.70
Copper losses (b)	5.85
Shaft Power (a) - (b)	29.85
Pressure loss (c)	0.40
Flow loss (d)	1.01
PV power delivered to the cooler (a) - (b) - (c) - (d)	28.44

CONCLUSIONS

Efforts to improve the pressure wave generator resulted in significant improvements in terms of high pressure amplitude, low input current and low mechanical losses. Initial experimental program aimed at improving the pulse tube cooler performance by designing an appropriate inertance. A no load temperature of 130 K was achieved using the inertance configuration designed using Sage software. The PV power delivered to the pulse tube cooler was estimated and found to be sufficient to a refrigeration of 1W at 80 K. Inspite of this the cooler performance was not as expected, the reasons for which are under investigation.

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REFERENCES

1. S. Jacob, V. Ramanarayanan, R. Karunanithi, C. Damu, G. Jagadish, M. Achanur, R. Manjunatha, R. Prabhu, J. Kranthi Kumar, A. Gour, and A. Gaunekar, “Development of Moving Magnet Linear Motor Pressure Wave Generator for Pulse Tube Refrigerator,” in *Cryocoolers 16*, ICC Press, 2008, pp. 361–369.
2. S. Jacob, V. Ramanarayanan, R. Karunanithi, C. Damu, G. Jagadish, M. Achanur, R. Manjunatha, R. Prabhu, J. Kranthi Kumar, A. Gour, and A. Gaunekar, “Development and Testing of Linear Motor Compressor Driven Miniature Pulse Tube Cooler,” in *Advances in Cryogenic Engineering*, AIP, 2010, vol. 51, pp. 185–190.
3. J. A. Corey, and J. Martin, Matching an acoustic driver to an acoustic load in an acoustic resonant system, patent 6604363 (2002).
4. P. Bradley, M. Lewis, R. Radebaugh, Z. Gan, and J. Kephart, “Evaluation of Total Pressure Oscillator Losses,” in *Cryocoolers 14*, ICC Press, 2007, pp. 353–359.
5. S. Jacob, R. Karunanithi, J. Kranthi Kumar, C. Damu, M. Achanur, G. Jagadish, and A. Gour, “Evaluation of mechanical losses in a linear motor pressure wave generator,” AIP, 2012, vol. 1434, pp. 1226–1233.
6. D. Gedeon, *Sage users guide*, Gedeon Associates, Athens, Ohio, USA, 2009.
7. J. Ross, R.G., D. Johnson, A. Metzger, V. Kotsubo, B. Evtimov, J. Olson, T. Nast, and R. Rawlings, “Gamma-Ray Pulse Tube Cooler Development and Testing,” in *Cryocoolers 11*, Springer US, 2002, pp. 155–162.