Development of the 0.5W/80K Co-axial and U-shaped Pulse Tube Cryocoolers

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In order to meet the requirements of different applications, two types of cold heads, i.e. co-axial and U-shape, are being developed for the 0.5W/80K class pulse tube refrigerator in the Cryogenic Laboratory of the Chinese Academy of Sciences (CL/CAS). Linear compressors with flexure springs are being developed for driving the pulse tube cold head. The first prototype compressor with a maximum swept volume of 2cm^3 has reached efficiencies higher than 80%, while further improvements are being made. The prototype linear compressor was coupled with the co-axial cold heads. The prototype co-axial PTR reaches the lowest temperature of 64K, and has cooling power of 0.4W at 80K.

INTRODUCTION

Small infrared sensors usually need half Watt of cooling power at 80K. They are integrated in Dewars with cryocoolers. According to the applications, two types of Dewar are generally used. The first one is the standard Dewars developed for coupling with the Stirling cryocooler cold fingers, of which the diameters are fixed (usually a few millimeters). The second type of Dewar is just a vacuum insulated chamber, in which the cold head of cryocooler and the infrared sensor are connected with sapphire etc., and there is no limit on the dimension of the cold head. For the first type, the cold head must be designed to be able to fit into the Dewar, while for the second type the Dewars are designed specially for the cold head.

With its significant progress in recent years [1,2,3], pulse tube refrigerator (PTR) becomes a competitive alternative cooler compared with the traditional Stirling cooler. The CL/CAS has been developing co-axial 0.5W/80K pulse tube cryocoolers since 1995 [4]. The coaxial cold head configuration has the merit of compactness, which makes it the exclusive choice in some cases such as the cooling of infrared sensors with existing Dewars. However, the co-axial configuration is the most difficult to realize. Its efficiency may be relatively low due to the following factors: 1) significant turbulent flow losses at the cold end; 2) possible by-pass of gas along the inner and outer boundaries of the regenerator screens; 3) mismatch of axial temperature distributions of regenerator and pulse tube; 4) inaptitude for effective heat dissipation at the hot end. For the applications where the geometry of the cold head is not strictly imposed and where the efficiency is very much concerned, for example, the cooling of some infrared and HTS sensors in space, the U-shape configuration may be a better choice. So we are also developing U-shaped pulse tube cold heads.

COMPRESSOR DEVELOPMENT

The compressor is the main source of unreliability for the pulse tube refrigerator, because it is the only moving parts in the whole cooler system. To achieve high reliability and long lifetime required by the infrared sensors, linear driven compressors with flexure springs are being developed. The main technical development objective is to eliminate friction between the piston and cylinder. The flexure springs of the compressor have been first checked by using the finite element method and they have been practically demonstrated to operate at full stroke and 50Hz for long time without failure. With the reliable spring, the next step is to design the compressor so that the alignment of central axis would be assured mechanically. After all parts of the compressor are well fabricated, cleaned and baked out, the assembly process is carried out in such a way that it is quantitatively controllable. With the above design concept, we are successful in eliminating piston/cylinder friction with good gap sealing simultaneously. Figure 1 is the prototype of the linear compressor with a swept volume of $2cm^3$.

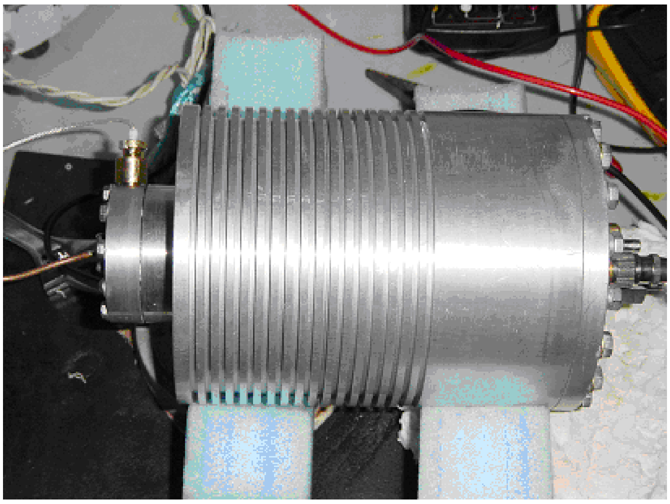


Figure 1 Prototype of the linear compressor

Another important aspect of the compressor is the efficiency in converting electrical power into P-V power. This efficiency depends on the design of the compressor using a theoretical model taking into account the vectors of the forces working on the piston. It is also affected by the structure and the materials used for the magnetic circuit. The resistance of the moving coil should be small in order to minimize the Joule heat loss. The magnetic field intensity of the magnet should be high. Figure 2 is the magnetic field intensity distribution along the magnet. The magnetic field intensity has a highest value of 1.17 Tesla in the compressor.

The first prototype compressor developed is a single piston compressor with maximum swept volume of $2cm^3$. Its efficiency can reach higher than 80% under the best operation conditions. This compressor is used to drive the coaxial and U-shape pulse tube cold heads. At the same time, its parameters are being adjusted so that better matching of compressor and cold head can be achieved.

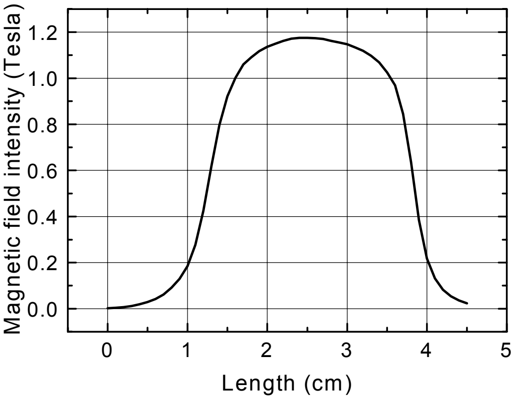


Figure 2 The magnetic field intensity distribution

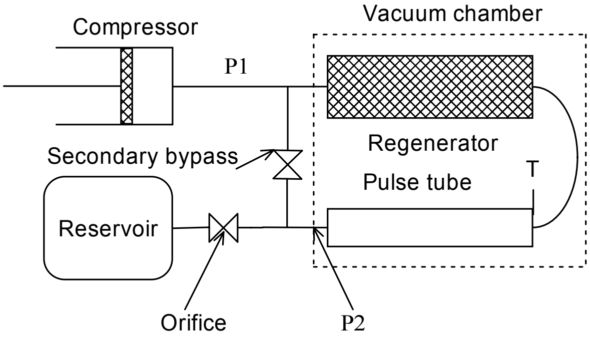
COLD HEAD DESIGN

There are two geometrical arrangements of a pulse tube and a regenerator in PTR developed in CL/CAS. Those are the co-axial and the U-shaped configuration. The most attractive merit of the co-axial PTR is its compactness. It can adopt the existing Dewars for Stirling cryocoolers. To improve the efficiency of the co-axial PTR, flow straighteners, heat exchanger at the hot end, the arrangement of the pulse tube and the regenerator tube are carefully designed to minimize the losses in the PTR. On the other hand, the U-shaped PTR is easier to fabricate, and has a strong structure for supporting side forces induce by launching or vibration. For space applications where the Dewars are specially designed, the U-shaped PTR is a good choice. In order to meet different application requirements, the coaxial and the U-shaped cold heads are being developed in parallel.

For a certain compressor, dimensional optimization of the pulse tube and regenerator is the most important issue. At first, calculation surveys based on a numerical simulation method [5,6,7] are carried out. The prototype PTR is fabricated according to the simulative result. However, it is very difficult to predict precisely the performance of the PTR. The testing result of this cooler diverges from the calculated result. Therefore, the dimensional optimization is carried out by experiments by taking into account the calculated dimensions.

After the dimensions of the pulse tube and regenerator are determined, phase shifter at the hot end of the pulse tube cryocooler plays an important role in the performance of the cooler. Inertance tubes, symmetric spray nozzles and asymmetric spray nozzles have been investigated in our laboratory. It is found that asymmetric spray nozzles as the phase shifter are appropriate for the miniature PTR.

Presently, as the first development phase, co-axial cold heads for coupling with the 2cm^3 compressor has been fabricated and tested. U-shaped cold heads for the same compressors are in fabrication and the detail will be given in another paper.



T: type T thermocouple, P1-P2: pressure transducers

Figure 3 Experimental setup

TESTING OF COOLERS

Experimental apparatus

The experimental setup is shown in Figure 3, which consists of a PTR, a vacuum system and a measuring system. The pulse tube cryocooler is arranged either in “U” shaped or in co-axial. The compressor is of a linear type with a swept volume of 2.0cm^3. The vacuum environment is maintained by a turbomolecular pump system. Temperature is measured at the cold end of the pulse tube with a copper-constantan thermocouple (Type T). Dynamic pressures are measured by small quartz pressure transducers (Kistler, type 601A) at the inlet of the regenerator and the hot end of the pulse tube. The pressure voltage signs are amplified by charge amplifiers (Kistler, type 5011) and collected by computer.

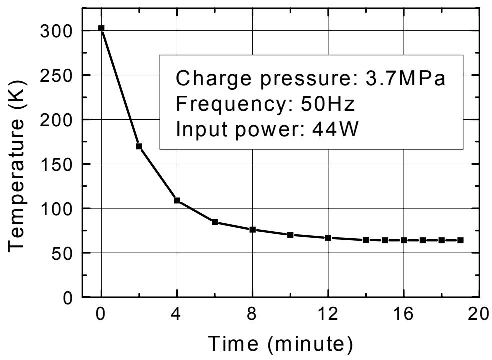


Figure 4 Cool down curve

Test results

A typical cooling down procedure of the PTR is shown in Figure 4. The cooler can reach the lowest temperature of 64K within 20 minutes. In the experiment, the symmetric spray nozzle and the asymmetric spray nozzle are used as the orifice and the double inlet, respectively. The experiments are carried out under the charge pressure of 3.7MPa and operating frequency of 50 Hz.

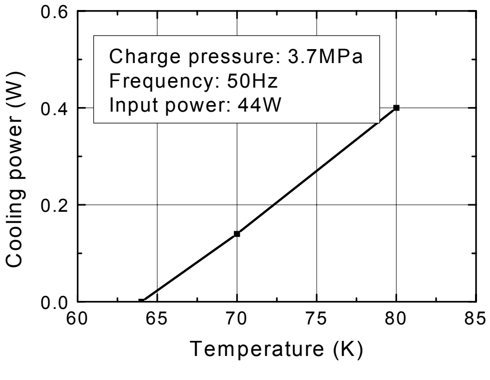


Figure 5 Cooling power vs. temperature

Figure 5 shows the relationship between the cooling temperature and cooling power. The cooler reaches the no-load temperature of 64K; has the cooling power of 0.4W at 80K with input power of 44W. This result is slightly inferior to the expected result of 0.5W at 80K. It is still necessary to optimize the geometric size. Future work will be carried out in the optimum designing of the PTR and the matching of the compressor with the cooler.

CONCLUSION

In the Cryogenic Laboratory of the Chinese Academy of Sciences, linear compressors with flexure springs are being developed for driving the pulse tube cold head. The first prototype compressor with a maximum swept volume of 2cm^3 has reached efficiencies higher than 80%; further improvements are currently carried out. The prototype linear compressor is coupled with the co-axial cold heads. The prototype co-axial PTR reaches the lowest temperature of 64K, and has cooling power of 0.4W at 80K.

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