Development of 40-80K Linear-Compressor Driven Pulse Tube Cryocoolers


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ABSTRACT

Along with the commercialization of HTS devices in fields such as mobile communications, and the development of far infrared devices for space and military applications, there arises a strong demand for compact and reliable cryocoolers working at 40-60K. The pulse tube cryocooler driven by a linear pressure wave generator has the potential to achieve high reliability and very long lifetime because of the absence of moving parts at low temperature. The ability of this kind of pulse tube cryocooler to achieve efficiencies comparable with Stirling cryocoolers has been theoretically and practically proven. Hence, pulse tube cryocoolers appear a good choice to meet the above-mentioned requirements.

On the basis of our previous work that focused on miniature coaxial, linear-driven pulse tube cryocoolers with a few hundred milliwatts of cooling power at 80K, we are trying to develop a new series of pulse tube cryocoolers working at lower temperatures and with larger cooling powers. The goal is to provide about 200mW at 40K or 1-2W at 60K, with input power as small as possible. The pressure wave generators are being developed in our laboratory uses a moving coil linear motor supported by flexure springs. Their maximum swept volumes are 2, 4, 5, and 10 cm³. Two types of pulse tube cold head configurations, i.e. coaxial and U-shape, have been adopted to fit different applications. The present status of development for these coolers is presented in this paper.

INTRODUCTION

Cryocoolers for cooling traditional infrared devices usually work at 80K or at slightly higher temperatures. The cooling power is usually a few hundred milliwatts. With the development of far and very far infrared devices, lower temperatures such as 40K are needed for these devices to work properly. Larger focal planes also require larger cooling power.

The high temperature superconductive devices such as filters, SQUID’s, etc, are finding more and more applications. Although their superconductive transition temperature (Tc) is near the temperature of liquid nitrogen, they give more optimum performance at temperatures of 60-70K.

Based on these demands, we estimate that it is necessary to develop pulse tube cryocoolers working at 40-80K. These pulse tube cryocoolers must be compact, efficient, and reliable in order to compete with Stirling cryocoolers, and a linear driven compressor must be used. The cold head
can be either coaxial or U-shape, because each configuration has its own merits and disadvantages. We are developing both kinds of cold heads to give us more flexibility to adapt to various applications.

The cooling capacities of the linear driven pulse tube cryocoolers are as follows: 500mW/80K, 1W/80K, 200mW/60K, 1–2W/60K, 200mW/40K.

The maximum swept volumes of the linear compressors being developed are: 2cm³ (single piston), 4cm³ (dual piston), 5cm³ (single piston), and 10cm³ (dual piston).

These coolers should be able to survive severe environment tests. The goal for their lifetime is greater than 20,000 hours.

SYSTEM DESIGN CONSIDERATIONS

The critical point to be considered for system design is the cooler efficiency, which is indicated by the coefficient of performance (COP). The cooler efficiency is the product of the compressor efficiency and the cold head efficiency. The compressor efficiency is the ratio of the output PV power to the electrical power. The cold head efficiency is the ratio of the net cooling power to the PV power input. To increase the cooler efficiency, three aspects should be carefully considered.

Firstly, the compressor should be highly efficient. This requires good design of the forces working on the piston. The friction between piston and cylinder should be eliminated by the flexure bearing support structure. The magnetic circuit losses should be reduced to the minimum. The current in the coil and the resistance of the coil should be small enough so that the heating by the Joule effect can be minimized.

Secondly, the cold head should be efficient in converting PV power to net cooling power. This converting process happens in the regenerator, with the help of the pulse tube and the orifice. The geometry of the cold head should be optimized according to theoretical calculation and practical experiences. Two goals are to be achieved at the same time. First, the PV power consumption should be minimized. This means proper regenerator flow channels with a low flow resistance and a proper phase relationship between the mass flow rate and the pressure. Secondly, the cooling power losses should be minimized. The regenerator inefficiency losses and the conduction loss along the regenerator are the principal losses. The above two points may be contradictory and a tradeoff is inevitable to achieve the best overall performance at a given working temperature.

Thirdly, good matching of the compressor and the pulse tube cold head is very important to the efficiency of the cooler. Unlike the rotary compressors, the operation of a linear driven compressor is affected by the characteristics of the cold head coupled to it. In other words, the compressor and the cold head interact with each other. The cooler should be optimized as a whole system including a model of the compressor.

Beside the efficiency, other key factors such as the lifetime, the environment test conditions, are also considered. At this stage in the development of the principle models we are mainly focused on efficiency. In the next stage, that of the development of engineering models, the focus will be on reliability.

COMPRESSOR DESIGN, FABRICATION AND CHARACTERIZATION

The compressor is designed according to the thermal design of the pulse tube cryocooler. The moving coil and the piston are supported with two flexure springs. The flexure spring is one of the key technologies for the compressor. It has been numerically analyzed using finite element models and experimentally tested long before we began to design the compressor. Its long lifetime operation has been demonstrated on a special spring test apparatus.

The components are designed so that alignment can be assured during assembly. With this method, the friction between the piston and the cylinder can be eliminated. The magnets are made of neodymium iron boron and the magnetic circuit is made of iron-cobalt alloy. The five forces working on the piston, namely, the electromagnetic force, the spring force, the pressure difference...