Design of small turbo brayton cycle air refrigerator test rig

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In order to promote the development of cryocooler in China, the study of reverse turbo brayton cycle cryocooler was firstly begun in 1994 by Xi'an Jiaotong University. This paper introduces the reverse turbo brayton cycle refrigerator test rig established in 2002. The refrigerator adopts air as refrigerant medium and works in single stage, open cycle. The mechanical and thermodynamic performance of the refrigerator was tested and analyzed in this paper. The rotation speed of turbo expander has reached 230,000 rpm. The temperature in cold box can reach below 200 K and the temperature drop in the refrigerator has exceeded 80 K.

INTRODUCTION

In many fields of space application, cryocoolers are used to achieve the temperatures below liquefied nitrogen (77 K) in order to improve the performance of sensors and electronics. Mechanical cryocooler is one of the important choices to provide an environment in low temperature. In the last thirty years, for the increasing demand of infrared remote sensing and multi-object spectrometer technology, more and more efforts were put into the research of small cryocoolers used in space applications. These cryocoolers have been used in wide range of load and temperature, and continuously promote the development of space technology. Without the development of cryogenic technology, especially the development of small cryocooler, it will be difficult to use infrared equipment for detection, tracking and homing. Therefore, the research of small cryocooler used in space applications is significant to military utility and civil space technology.

Many kinds of mechanical cryocoolers used in space, such as stirling cooler, pulse tube cooler and turbo brayton cooler, have been developed. They were used in detectors of different temperature and load. To achieve the long life (10-15 years) of mechanical cryocooler, new type of cryocooler must been developed. Compared with other types, some institute such as NASA considered that the turbo brayton cryocooler matches the demands most superiority. Reverse turbo brayton cycle cryocooler, which includes high speed turbine using gas bearing system and compact heat exchanger, has many advantages such as excellent reliability, vibration free, high efficiency and long life.

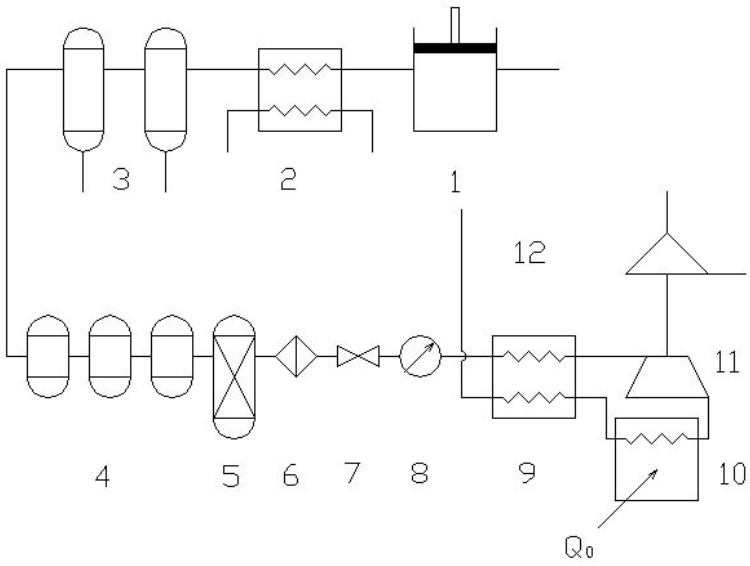
There were a lot of researches about stirling cooler and pulse tube cooler in china for many years, whereas not adequate study on turbo brayton cryocooler until now. The Institute of Cryogenic Engineering, Xi'an Jiaotong University, is one of the organizations that take the lead in the field of the reverse turbo brayton system and cryocooler in China and has got remarkable achievements. Xi'an Jiaotong University have been studied the turbo expander with gas bearing since 1970s, which was the most significant component in the reverse brayton cycle cryocooler. The research on turbo brayton cycle cryocooler for space application in China was firstly began in 1994, and the first cryocooler was built in 1995. The Institute of Cryogenic Engineering has carried on elaborate investigation in the cryogenic

technology for space application in 1998. The theoretical and experimental researches have been studied thoroughly and some key problems have been solved. In 2002, for the demand of development of prototype of the small reverse brayton cycle cryocooler used in space application, the experimental test rig of the small reverse turbo brayton cycle air refrigerator was built up.

REVERSE BRAYTON CYCLE REFRIGERATOR

This test rig of small reverse turbo brayton cycle refrigerator employs open regenerative cycle and uses the air in atmosphere temperature as its refrigerant, as shown in Fig.1. The turbo expander is the most important component of the reverse brayton cycle refrigerator, and reflects the technological level of this system. The turbo expander provides the refrigeration capability in low temperature for system, so its thermodynamic and mechanical performance are extraordinary important to the economy and reliability of this equipment. At the same time, it is the most difficult component to develop. In a word, the turbo expander is the key component in the development of small reverse brayton cycle refrigerator.

The appearance of this refrigerator is a cylinder box, which dimension is $\Phi 500 \times 600$ mm, and its compact structure makes it convenient to be moved, shown in Fig2. The perlite is filled acts as the insulate material. A piston compressor system with filter, sorption and water cooler provides the clean pressure air of 0.8 MPa. A 30 Nm^3/hr air turbo expander is adopted in this refrigerator, shown in Fig.3. A radial impeller with the diameter of 20 mm drives the rotor of the turbine, and a brake blower with a diameter of 22 mm is adopted to absorb the output power of the expander. The pressure of expander inlet is 0.35 MPa, and the outlet of turbine is atmosphere. In order to control the speed of the rotor, the flow rate is controlled through a valve. The rotor weighs about 90 g with a shaft diameter of 12 mm and a total length of 90.0 mm. The normal speed of this turbo expander is about 200,000 rpm. The turbo expander is fixed vertically on the cover of refrigerator by insulated bakelite plate to avoid cold loss, so it can be assembled easily. The compact plate fin heat exchanger is used as the regenerator to recuperate the load of the loop gas in the air refrigerator because of its high effectiveness. The cold box of the refrigerator is a cylinder which dimension is $\Phi 100 \times 180$mm. The temperature in cold box can reach 190 K and it can create 0-1 kW heat by an electric heater. The stainless steel tube in 20mm diameter and copper tube in 19mm diameter are selected as pipelines to connect each component. All the tubes are covered by foaming material to avoid cold loss.



1. Compressor
2. Water cooler
3. Oil water separator
4. Filter and sorption
5. Gas manostat
6. Accurate filter
7. Flow rate valve
8. Flow rate meter
9. Heat exchanger
10. Load
11. Turbo expander
12. Brake

Figure 1 The system schematic diagram of the small air refrigerator system

Figure 2 Reverse brayton cycle refrigerator test rig

Figure 3 Gas bearing turbo expander

THE EXPERIMENTAL STUDY

Gas bearings are adopted in this situation because the normal speed of the turbine is about 200,000 rpm. A new type of foil journal bearing, compliant foil bearing with elastic support, is used to support the rotor and the spiral grooved thrust bearing to uphold the axial load for high speed cryogenic turbo expander (Fig.3). The record of rotor vibration at a steady speed and the time base record of the rotor vibration at this speed (Fig.4) indicate that the main portion of the rotor response is synchronous (the fundamental frequency), and the amplitudes of rotor vibration are small in the running period. The rotor bearing system has best dynamic and preferable stability performance and it is clear that the operation reliability of this air refrigerator can be ensured.

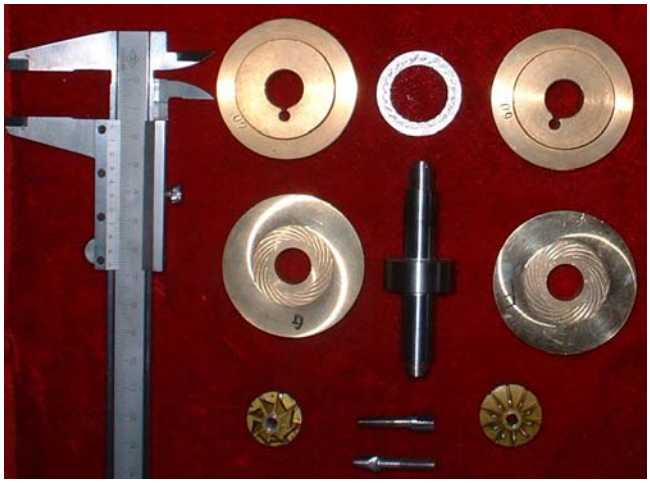


Figure 4 Rotor bearing system of turbine

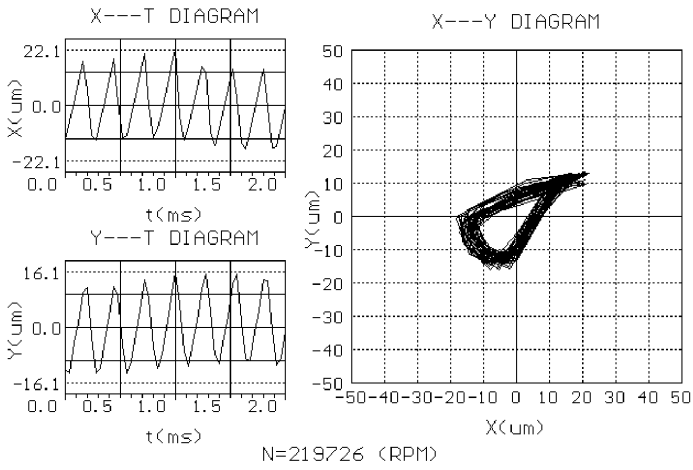


Figure 5 Time base record of rotor vibration

The thermodynamic performance of this reverse brayton cycle air refrigerator has been tested. The inlet temperature and outlet temperature falling curves of the turbo expander with the increasing of time are shown in Fig.5. The relationship between the temperature in the cryogenic box and the time was shown in the Fig.6. When the environmental temperature was 6℃ and the rotational speed of turbine maintained at 220,000 rpm, the temperature of the cryogenic box could reach -75℃ after 100 minutes and the temperature drop in turbo expander was 32℃ at this time.

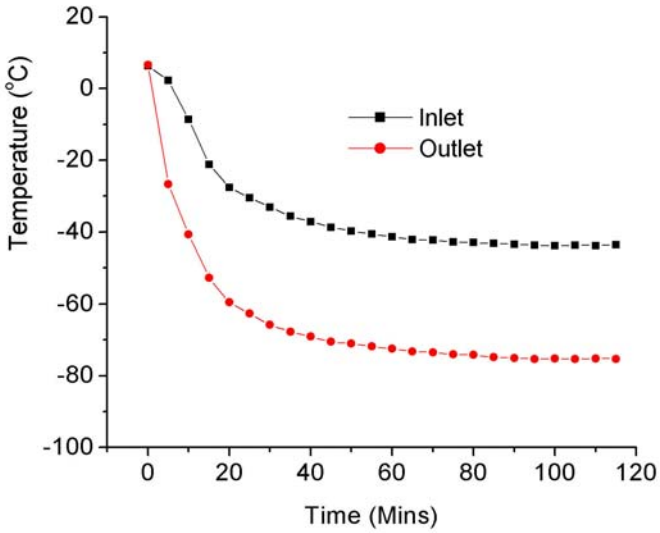


Figure 5 The inlet and outlet temperature of turbine

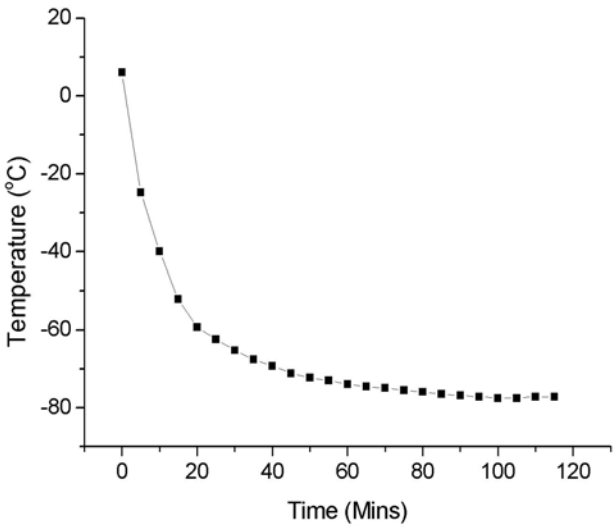


Figure 6 The temperature of the cryogenic box

CONCLUSION

It can be concluded that this air refrigerator has higher overall performance. The design of this test rig was reasonable and the refrigerator could reach -75℃ in 100 minutes, all of those achieved the design temperature and load capacity. Through the experiments on this test rig, many investigations can be done to resolve the design of compact heat exchanger, increase the efficiency of the turbo expander and the refrigerator system, improve the reliability of rotor-bearing system as well as develop the small reverse turbo brayton cryocooler. With little changes in the insulation and structure of this refrigerator and adopting He or Ne as its refrigerant medium, the test rig can also be used in the study of reverse brayton cycle cryocooler worked on the temperature of 65-80K for space application.

ACKNOWLEDGMENT

This project is supported by the National Nature Science Foundation of China (50206015). The authors also would like to thank Mr. G.J.Liu of Shuzhou Oxygen Plant Manufactory for supplying the experiment parts.

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