Ross-Stirling Spacecraft Refrigerator

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Abstract

A SPACECRAFT refrigerator was investigated capable of providing cooling for low-temperature storage of food and biological samples in the temperature range of −20 to 0°C with cooling capacity in the range of 1-2 kW, operating for long periods with great reliability. The system operated on the Stirling refrigeration cycle, a closed thermodynamic regenerative cycle in which the gaseous working fluid experiences repeated compression and expansion at different temperature levels, using the spacecraft life-support gases as the working fluid.

A prototype spacecraft Stirling refrigerator was designed, built, and tested with air as the working fluid. The system performance was satisfactory, generally meeting the preceding specified requirements. There is a wide range of additional potential applications of the prototype refrigerator in submarines, tanks, aircraft, and emergency shelters. Should Freon refrigerants eventually be banned because of the environmental impact (ozone destruction in the upper atmosphere), applications may extend as alternative refrigeration systems to commercial, automobile, train, and bus air conditioning and refrigeration systems.

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Introduction

Innovative approaches to the development of refrigeration systems for spacecraft were solicited by NASA. A refrigerator was required with the capability to achieve up to 2 kW of cooling in the temperature range of −20 to 0°C. Possibilities for head rejection at higher temperatures were also of interest. The higher temperatures are not specified, but were thought to be in the range of 40 to 90°C.

Stirling Refrigerator

A Stirling refrigerator using the normal spacecraft atmosphere as the working fluid was proposed to obviate concern about the spacecraft atmosphere pollution by leakage of refrigerant from the refrigerator.

A Stirling refrigerator operates on a closed thermodynamic regenerative cycle in which the gaseous working fluid experiences cyclic compression and expansion at different temperature levels so that there is a net conversion of heat to work or vice versa. The system may operate also as a prime mover, converting heat to work, and as a refrigerator or as a heat pump absorbing heat at a low temperature and rejecting it at a higher temperature. When operating as a refrigerator or heat pump, an input of work to drive the system is required. The detail technology of Stirling machines has been well summarized.[1]

Stirling refrigerators have several advantages over more conventional vapor compression refrigerators using an organic (Freon) working fluid. One important advantage is that the working fluid can be the same gas mixture as the life-support system provided in the spacecraft. Leakage of working fluid from the refrigerator, therefore, presents no hazards to the crew, for it is the same provided for their life support. This virtually eliminates problems of fluid sealing. Leaks can be tolerated and replenishment simply drawn from the spacecraft environment and compressed in a miniature compressor associated with the refrigerator.

The inventory of fluids onboard is reduced, relieving housekeeping and logistical pressures. Moreover, as the working fluid does not experience a phase change, there is no problem of fluid management in handling liquids and vapors.

In a Stirling refrigerator, the pressure and temperature levels for the working fluid can be independently chosen. They are not inimically related as in a vapor compression machine where the pressure of condensing vapor or evaporating liquid is the saturation pressure corresponding to the temperature at which these phase change processes occur. In a Stirling refrigerator, the pressure can be increased to raise the cooling ca-

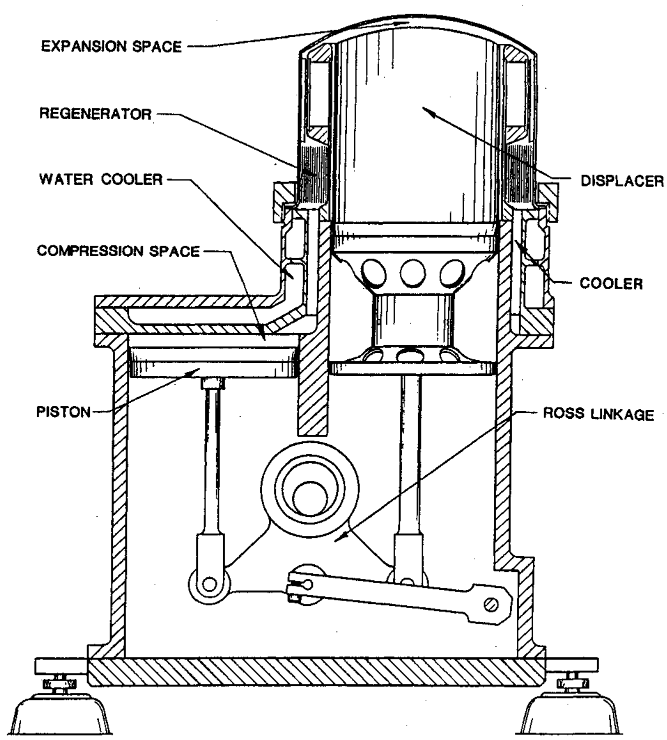

Fig. 1 Cross-section diagram of prototype Ross-Stirling spacecraft refrigerator.

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pacity, while maintaining the same temperature regimes can be adjusted to compensate for changes in the operating temperatures as required. There is no chance the working fluid will become overheated and decompose/carbonize as the heavy organic (Freon) working fluids—large, pregnant molecules of molecular weight 100 or more—are prone to do. In a Stirling refrigerator, there is no upper limit of temperature although, of course, the necessary work input increases in direct proportion to increases in heat-rejection temperature.

At present, Stirling refrigerators are not widely used for refrigeration near ambient temperatures. Vapor-compression machines are overwhelmingly used. Stirling refrigerators are less efficient than vapor compression machines at near ambient temperatures, but the absence of use is, primarily, one of cost and familiarity rather than any fundamental defect. At much lower temperatures (in the cryogenic range of 6–120 K) Stirling refrigerators are the system of choice for miniature cryocoolers used for infrared night vision and missile guidance systems and many other electronic applications.[2]

The technology for Stirling engine design, operation, and use is well developed and established with no apparent fundamental problems awaiting solution.

Ross-Stirling Refrigeration

Figure 1 shows the general arrangement of the two-piston, parallel-cylinder Stirling engines used for the spacecraft refrigerator described here. This machine incorporates a new simplified Ross linkage invented by A. Ross.[3] This gives the pistons a close approximation to the required phasing, a nearly sinusoidal motion, and is virutally a straight-line linkage, and so there are no significant piston side forces. This latter feature is very important from the aspect of long, maintenance-free life.

The machine shown operates as a refrigerator, absorbing power input to produce a low temperature in the expansion space and rejecting heat from the compression space/cooler to the coolant.

Computer Simulation

Computer simulation of the Ross-Stirling refrigerator was carried out using the suite of analytical and simulation programs described by Weiss and Fauvel.[4]

The machine simulated was a Ross-Stirling refrigerator similar to that shown in Fig. 1 with a single set of reciprocating elements rather than the twin opposed system anticipated for eventual use.

It was assumed that the cylinder diameters were equal, 7.62 cm (3 in.), and the linkage geometry was selected to result in a piston stroke of 2.5 cm (1 in.). The engine speed was 16 Hz (1000 rpm), the mean pressure 1 MPa of air. Numerous other data required by the program were assumed on the basis of experience. The computer simulation studies were limited to parametric investigation around a given arbitrary design, and were primarily directed to assess the effect of variations in the temperature of the cold expansion space in the range of -20 to 0°C.

For the conditions assumed of mean pressure $=10$ bar, swept volume $=122.5$ cm^3, frequency 16.6 Hz, and expansion space temperature of 273 K, the computer predicted refrigeration capacity as 750 W at 0°C.

Proof-of-Principle Prototype Ross-Stirling Refrigerator

A proof-of-principle prototype two-cylinder single-engine Ross-Stirling refrigerator as shown in Fig. 1 was designed following the computer-based simulation studies described above.

For precise control and variation of the refrigerator load, a mineral-insulated copper-sheathed electric-resistive heater was tightly wound and secured to the upper end of the expansion (cold) cylinder.

Twin chromel/alumel thermocouples were brazed to the cylinder head, diametrically opposite each other, and then the cylinder head was enclosed entirely in thermal insulation.

The refrigerator was driven by a 120 V 3/4 hp squirrel-cage ac motor operating at 1760 rpm. Cone pulleys and belt-drive coupling the motor and refrigerator were used to permit variable-speed operation of the refrigerator.

A water-cooling circuit was connected to the refrigerator with facilities to remove the mass rate of flow and the inlet and outlet temperatures.

Provision was made for the refrigerator to be pressurized with air from the laboratory compressed air line. The mean pressure of air in the working space was measured.

Instrumentation was provided to measure power input to the motor and to the cylinder head resistance heater.

Test Procedure

Testing of the prototype was limited to two series: 1) cool-down time characteristics as a function of speed and pressure, and 2) refrigeration capacity and power consumption as a function of speed and pressure.

The first series of tests, the refrigerator cool-down time characteristics, was carried out by starting the engine from an isothermal condition at room temperature, but charged to the specified mean cycle pressure. The machine was operated at constant speed, and the cylinder head temperatures were noted at 3-min intervals for a total 15-min period. These tests were carried out at a mean pressure of 2.5 bar, for engine speeds of 8, 16, and 24 Hz.

A second series of tests were carried out in which measurements were made of the power input to the drive motor and to the cylinder-head resistive heater so as to maintain equilibrium operation at a prescribed cylinder-head temperature, mean working space pressure, and engine speed observations were noted for cylinder heat temperatures in the range of -20 to 0°C, for a mean cylinder pressure of 2.5 bar, and engine speeds of 8, 16, and 24 Hz.

Throughout the limited test program, the unit operated satisfactorily and, generally, in accord with the performance anticipated from the computer simulation studies.

Conclusion

A proof-of-principle Ross-Stirling prototype spacecraft refrigerator has been designed, manufactured, and tested. The observed performance was sufficiently encouraging to justify continued effort to optimize the design and introduce refinements to improve life, reduce maintenance, and facilitate manufacture.

Acknowledgments

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