Cryogenics 67 (2015) 45–51

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Design and experimental investigation of a cryogenic system for environmental test applications

Lutao Yan [a,*], Hong Li [a], Yue Liu [a], Che Han [a], Tian Lu [a], Yulei Su [b]

[a] *Beijing Institute of Structure and Environment Engineering, Beijing 100076, China*
[b] *Anhui Vacree Technologies Co., Ltd, Hefei 230088, China*

ARTICLE INFO

Article history:
Received 18 August 2014
Received in revised form 13 December 2014
Accepted 24 December 2014
Available online 3 January 2015

Keywords:
Cryogenic system
Liquid helium
High cooling power
Environmental test

ABSTRACT

This paper is concerned with the design, development and performance testing of a cryogenic system for use in high cooling power instruments for ground-based environmental testing. The system provides a powerful tool for a combined environmental test that consists of high pressure and cryogenic temperatures. Typical cryogenic conditions are liquid hydrogen (LH2) and liquid oxygen (LO2), which are used in many fields. The cooling energy of liquid nitrogen (LN2) and liquid helium (LHe) is transferred to the specimen by a closed loop of helium cycle. In order to minimize the consumption of the LHe, the optimal design of heat recovery exchangers has been used in the system. The behavior of the system is discussed based on experimental data of temperature and pressure. The results show that the temperature range from room temperature to LN2 temperature can be achieved by using LN2, the pressurization process is stable and the high test pressure is maintained. Lower temperatures, below 77 K, can also be obtained with LHe cooling, the typical cooling time is 40 min from 90 K to 22 K. Stable temperatures of 22 K at the inlet of the specimen have been observed, and the system in this work can deliver to the load a cooling power of several hundred watts at a pressure of 0.58 MPa.

1. Introduction

Liquid hydrogen (LH2) and liquid oxygen (LO2) cryogenic fuels have attracted significant interest in aircraft and spacecraft areas due to its high heat of combustion, global accessibility, and clean combustion with air [1]. The structural design of storage vessels and transfer lines for LH2 and LO2 is critical to improving the performance of a flight vehicle by reducing its overall size and weight [2,3]. Environment testing such as cryogenic, pressure, vibration, static (structure and material), and combined environment for checking the environmental adaptability is essential for LH2 systems because LH2 is sensitive to many conditions in flight [4–6]. Therefore, an environment simulation test system with high accuracy proves to be very useful in analysis and optimal design of materials, tank and any connecting lines or attachments [7].

It is generally acknowledged that LH2 needs to be kept below −252 °C to minimize boiloff, and the internal tank pressure has to be maintained at a constant absolute pressure in order to maintain the hydrogen in a liquid state. If the LH2 fuel were exposed to the ambient atmosphere, the change in temperature and pressure would cause the fuel to expand and rupture the tank. Moreover, shrinkage caused by the cold environment and internal pressure may results in leakage or structural failure due to microcracking at stress levels significantly below yield stresses of the material [8]. Like for LH2, the cryogenic design of storage for LO2 should be considered.

Moreover, the thermal properties of the structure at different temperatures are definitely the main concern, and should be investigated with a cryogenic test [9,10]. This may contribute to the difference thermal stress caused by the variation in thickness. On the other hand, each vehicle has its own unique requirements of hydrogen and oxygen as propellants in order to achieve the efficiencies. However, density, flow rate and pressure drop characteristics of the cryogenic fluid will affect its ability to feed to a hydrogen engine. Therefore, comprehensive studies of the flow characteristics in the designed cryogenic structures are needed before practical applications.

Obviously, the above two factors (temperature and pressure) play an important role in storing and transferring liquid cryogenic fluids, thus consequently the environment simulation test system for the verification testing of design stress and life predictions should be designed to provide the cryogenic temperature and various pressure conditions.

Mechanical cryocoolers such as pulse tube, Gifford–McMahon, Stirling, Brayton, and JT coolers can be used as active cooling

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.cryogenics.2014.12.003
0011-2275/

sources due to their variability of cooling capacity, compact configuration and non-sensitivity for the space crucial attitude [11]. However, failure modes such as wear, leakage, fatigue and gaseous contamination may occur due to mechanical motion (piston and valve) [12,13]. During the test, unforeseen cryocooler failure will result in discontinuities of the experiment, which will inevitably lead to the low confidence level or even damage of the specimen. Moreover, the reliability and the lifetime of the test system are crucial for its application after the cooling performance can satisfy the request. LN2 can be directly used as the cooling medium to obtain the cryogenic condition, however, safety accidents may occur due to high pressure and the use of LH2 for this application.

Usually, the power levels of cryocoolers are typically limited to tens or a few watts in order to obtain high cooling capacities and fairly good efficiencies [14]. This may not satisfy the high cooling power requirement because of the heat loss of large structure and the additional mechanical environment test fixtures.

In this work, the test specimen is part of LH2 transfer line with the pressure of 0.58 MPa, and the heat loss is more than 400 W at 20 K. Due to the pressures required (nearly 6 bar), which are high pressures for normal liquid helium, and normal helium refrigerator is not applicable. Therefore, a helium system based closed cycle cryogenic cooling system is presented for providing of cryogenic temperatures (20–80 K) with designed pressure. The cryogenic system mainly comprises of two cooling stages, the liquid nitrogen (LN2) and liquid helium (LHe) are used to provide the cooling capacity, respectively. An optimal arrangement of the heat exchangers is proposed in order to minimize the consumption rate of LHe. Experiments are conducted to examine the cooling performance which includes temperatures, flow rates, and pressures.

2. Description of the system

The scheme of the cryogenic cooling system and test points are shown in Fig. 1. C1, C2, C3 and C4 are the test points at inlet/outlet of each exchanger on the circulating helium. P1 and P2 are the test points at the inlet and outlet of the compressor.

The system consists of a closed loop cycle which can be continuously operated and maintained as needed to produce the desired refrigeration. The circulating high pressure helium is driven directly by the compressor to compensate for the flow friction loss. Pure helium is used as the working gas mainly for its laboratory friendly and safe characteristics.

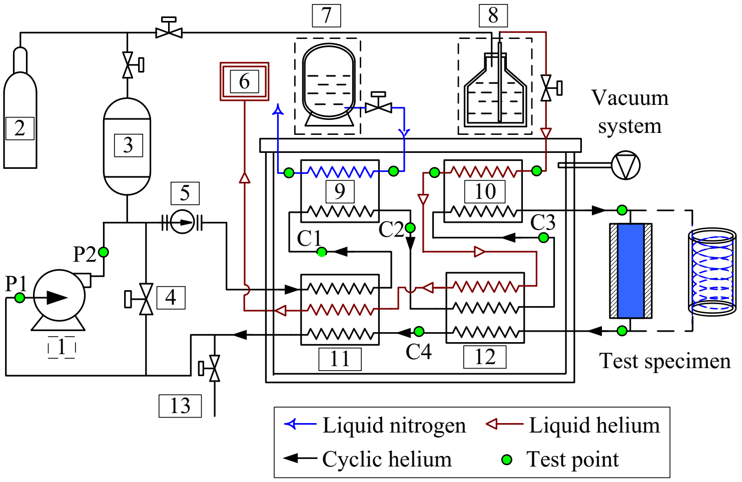
As the mass flow rate is a significant factor in determining the heat transfer coefficients, a branch valve with electromagnetic control is employed to connect the outlet and the inlet of the compressor in parallel, which is then used to regulate the mass flow rate of the circulating helium. An accumulator tank has been fabricated and assembled to provide an acceptably close approximation to constant static pressure over the full ranges of flow and pressure conditions. Beside the accumulator is a helium gas vessel, which can feed helium to the accumulator to increase the pressure to meet test requirements. Moreover, it can be used to maintain a high enough pressure in the liquid helium tank to transfer the helium to the heat exchanger.

The heat transfer process takes place in the cold box, which plays an important role in the system. Thus, a cold box with high vacuum level is designed in order to minimize heat leak into the working fluid as shown in Fig. 2. The cold box is designed to have a 1400 mm diameter and height of 2100 mm. Moreover, the test specimen is located outside the cold box and exposed in the air.

In the cold box, there are four heat exchangers, liquid nitrogen heat exchanger (HX-LN2), liquid helium heat exchanger (HX-LHe), the first level heat recover exchanger (HRX-1) and the second level heat recover exchanger (HRX-2). Here, flat plate heat exchangers are used because there are numerous advantages such as flexible, compact, low fabrication costs, small hydraulic resistance and have reduced fouling [15]. All the tubes in the cold box are made of stainless steel, because of the excellent heat conduction properties of this element. Leaks in pipelines that carry cold gas with high pressure will result in enormous heat loss and safety risk. To ensure the safety and improve the efficiency of pipeline emergency repair, helium mass spectrometer leak detector has been used for leak detection and localization.

The heat transfer process can be divided into two stages according to flow direction as shown in Fig. 1. In the first stage, the room temperature helium flows into the HX-LN2 and it is gradually cooled down by the liquid nitrogen. In the following stage, the cold working gas enters the HX-LHe to be cooled by the liquid helium. The LN2 and LHe flow in counterflow tubes in order to obtain a large temperature gradient and high heat exchange efficiency.

The cold gas out of the HX-LHe and the specimen flows into the heat recover exchanger in order to precool the circulating helium.



1 compressor, 2 helium gas vessel, 3 accumulator tank, 4 branch valve, 5 gas flowmeter, 6 Helium recovery unit , 7 LN2 tank, 8 LHe tank, 9 HX-LN2, 10 HX-LHe, 11 HRX-1,12 HRX-2, 13 exhaust valve

Fig. 1. Scheme of the cryogenic cooling system.