Postprint of Study on Operating Characteristics of a Small-Scale Liquid Nitrogen Zero Boil-Off System

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Date: 2017-11-07T00:00:00+00:00

Abstract

The small liquid nitrogen zero-boil-off system presented in this paper is primarily composed of components such as a pulse tube cryocooler, cryogenic thermosyphon, and small liquid nitrogen dewar. It can be utilized for both long-term lossless storage of cryogenic liquids and as a stable and reliable composite cryogenic cold source, featuring advantages including ultra-long lifetime, uniform and stable temperature, no-refill requirement, and isolation from vibration and electromagnetic interference. This paper briefly introduces the structural and thermal design of this small zero-boil-off system, with emphasis on preliminary analysis and experimental investigation of the system' s operational characteristics, including startup process, operational dynamics, steady-state equilibrium, and variable operating condition operation, thereby elucidating the operational principles of cryogenic liquid zero-boil-off systems.

Full Text

Operating Characteristics Study on Small Liquid Nitrogen Zero Boil-off System

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Abstract

The small-scale liquid nitrogen zero boil-off (ZBO) system primarily consists of a pulse tube cryocooler, a cryogenic thermosyphon, and a liquid nitrogen dewar. It can be utilized for both long-term lossless storage of cryogenic liquids and as a stable, reliable integrated cooling source, offering advantages such as extended lifetime, uniform and stable temperature distribution, elimination of refilling requirements, and isolation from mechanical vibration and electromagnetic interference. This paper briefly introduces the structural and thermal design of the ZBO system, with emphasis on preliminary analysis and comprehensive experimental investigation of its operating characteristics, including startup process, dynamic operation, steady-state equilibrium, and variable-load operation, thereby elucidating the operational principles of cryogenic liquid ZBO systems.

Keywords: zero boil-off system; pulse tube cryocooler; thermal design; cryogen lossless storage

Introduction

Due to their low boiling points, cryogenic liquid working fluids (such as liquid nitrogen and liquid helium) inevitably experience evaporation losses during storage. This poses significant challenges in applications where replenishment is difficult, such as remote field locations, complex spatial environments, specialized equipment, and deep space exploration missions [1-3]. Meanwhile, advancements in mechanical cryocooler technology have enabled widespread adoption due to their high efficiency, long-term operation, and convenience. However, these systems inevitably suffer from mechanical vibration, electromagnetic interference, and issues with temperature uniformity and stability. For certain specialized cooling requirements, neither immersion cooling with cryogenic liquids nor mechanical cryocoolers alone can provide satisfactory solutions. Integrating both approaches into a single zero boil-off system combines their respective advantages while circumventing their individual limitations.

A zero boil-off storage system combines a cryocooler with a dewar, utilizing active refrigeration to cool or condense the cryogenic working fluid within the dewar, thereby compensating for heat leakage and enabling long-term lossless preservation of cryogenic liquids. On one hand, ZBO systems can serve as long-term storage solutions for various cryogenic liquids, completely eliminating evaporative losses and venting requirements. Examples include large-scale zero-emission storage of liquid hydrogen and liquid helium on Earth, as well as storage of cryogenic propellants such as liquid hydrogen and liquid oxygen for long-duration space missions. On the other hand, ZBO systems can function as composite cryogenic cold sources that incorporate the benefits of both evaporative cooling from cryogenic liquid immersion and mechanical cryocoolers, achieving extended lifetime, high reliability, and uniform, stable cooling temperatures [4-5].

In this context, the Technical Institute of Physics and Chemistry, Chinese

Academy of Sciences, has developed a small-scale liquid nitrogen ZBO system. The apparatus primarily comprises a high-frequency pulse tube cryocooler, a 2.5 L liquid nitrogen dewar, and a thermosyphon, designed to investigate the performance and operational characteristics of the liquid nitrogen ZBO concept. For ground-based applications under gravity, this ZBO system employs a two-phase closed cryogenic thermosyphon (hereinafter referred to as a heat pipe) to achieve remote connection and heat transfer between the cryocooler and the dewar. This approach not only enables efficient cooling over a distance but also effectively isolates electromagnetic and mechanical vibrations. This paper presents a preliminary analysis of the system' s ZBO operating states and reports multiple experimental studies to validate the design feasibility. Additionally, the operational characteristics and patterns of the ZBO system under variable conditions were explored, laying a foundation for future practical applications.

1. Structure and Thermal Design

The schematic diagram of the liquid nitrogen ZBO apparatus is shown in Figure 1 [Figure 1: see original paper], comprising three main sections: a pulse tube cryocooler at the top, a cryogenic thermosyphon in the middle, and a ZBO dewar at the bottom. The pulse tube cryocooler serves as the cold source and includes components such as a linear compressor and a compact high-frequency pulse tube cold finger. The nitrogen-working-fluid heat pipe functions as a long-distance heat transfer component, consisting of a condenser, evaporator, and vapor-liquid lines. The dewar stores a quantity of cryogenic liquid nitrogen and is cooled accordingly, comprising the liquid nitrogen storage vessel, transfer lines, and suspension supports. All low-temperature components, including the cryocooler cold finger, heat pipe, and liquid nitrogen storage vessel, are housed within a vacuum jacket. The cold end of the cryocooler makes direct contact with the heat pipe condenser, while the heat pipe evaporator extends into the dewar storage vessel to cool or condense the liquid nitrogen or nitrogen vapor. An integrated fin structure is designed on the evaporator exterior to enhance heat transfer. The heat pipe condenser and evaporator are connected by two thin-walled stainless steel tubes approximately 1.2 m in length, forming a closed loop. The liquid nitrogen storage vessel within the dewar is suspended inside the vacuum jacket using high-strength, low-thermal-conductivity Kevlar fiber ropes. Transfer lines for liquid filling and gas venting consist of thin-walled stainless steel spiral coils approximately 0.5 m in length, significantly reducing heat leakage from solid support structures and piping.

The thermal design calculations primarily involve analyzing heat leakage from the dewar's low-temperature storage vessel, designing a heat pipe with matching heat transfer capacity, and selecting a pulse tube cryocooler with appropriate cooling power. Based on structural analysis of the dewar, three primary heat leakage paths are identified: radiation heat transfer between the multi-layer insulation-covered low-temperature storage vessel and the room-temperature vacuum jacket walls, conductive heat transfer through the liquid fill and gas vent piping, and conductive heat transfer through the Kevlar suspension supports. Using heat transfer equations and relevant material properties, these three components are calculated to be approximately 0.53 W, 0.19 W, and 0.001 W, respectively. Considering additional minor heat leakage from temperature sensor leads, the total heat leakage of the dewar' s liquid nitrogen storage vessel is approximately 0.75 W [5].

Consequently, the heat pipe must transfer at least 0.75 W in the liquid nitrogen temperature range with minimal temperature difference. To ensure reliable operation with adequate margin and accommodate potential future cooling loads, the heat pipe is designed for a heat transfer capacity of 5 W with a maximum temperature difference not exceeding 3 K. Accounting for heat leakage along the lengthy low-temperature sections of the heat pipe, a 5 W/80 K pulse tube cryocooler is selected as the matching cold source. This cryocooler delivers a maximum cooling capacity of approximately 5 W at 80 K with 120 W electrical input, with the cooling power adjustable from 0 to 5 W as the electrical input decreases, fully satisfying the cooling requirements of the ZBO system.

Figure 1: Schematic diagram of the liquid nitrogen ZBO system

2. Preliminary Analysis of Operating Patterns

A preliminary analysis of the liquid nitrogen ZBO system' s workflow is illustrated in Figure 2 [Figure 2: see original paper]. Initially, a quantity of liquid nitrogen is charged into the storage vessel (process 0-1), after which the dewar' s liquid fill and gas vent ports are sealed (state 2). Simultaneously, the pulse tube cryocooler is activated. Due to the substantial thermal capacity of the cryocooler cold end, the heat pipe itself, and its gaseous working fluid that must be cooled and liquefied, the cryocooler requires a certain period to reduce its cold end to the liquid nitrogen temperature range. During this interval, heat leakage into the dewar system causes the temperature and pressure of the liquid nitrogen in the storage vessel to gradually increase (process 2-4). When the cryocooler has cooled the entire heat pipe to liquid nitrogen temperature (state 3-4), the heat pipe starts operating normally. The nitrogen working fluid within the heat pipe is condensed into liquid in the condenser, flows to the evaporator, absorbs heat and evaporates into gas, then returns to the condenser. This cyclic process transfers heat from the dewar to the cryocooler.

During the initial phase of normal heat pipe operation, the cooling power transferred from the cryocooler exceeds the heat leakage into the dewar storage vessel, causing the temperature and pressure of the liquid nitrogen to begin decreasing (state 4). Since the cryocooler' s cooling capacity decreases with decreasing refrigeration temperature at constant electrical input, while the dewar' s heat leakage increases as the liquid nitrogen temperature drops, the rate of temperature and pressure decrease in the storage vessel gradually slows. If sufficient time is allowed, the cooling capacity will equal the heat leakage at a certain temperature, at which point the liquid nitrogen temperature and pressure remain constant, achieving long-term stable zero boil-off storage. This corresponds to stages (4) through (6) in Figure 2.

When the liquid nitrogen ZBO system is operating in steady state, changing the electrical input power to the cryocooler alters its cooling capacity, causing the ZBO system to enter a transient operating condition. The temperature and pressure of the liquid nitrogen in the storage vessel change accordingly and gradually adjust to a new equilibrium state where the dewar' s heat leakage matches the cooling capacity once again. Thus, the dewar' s ZBO operating state possesses adaptive regulation capability: when external conditions change, the system adjusts the storage temperature and pressure of the liquid nitrogen to adapt to the new environment and reach a new equilibrium. This represents the variable-load operating principle of ZBO systems. As shown in Figure 3 [Figure 3: see original paper], at time (1), reducing the cryocooler' s electrical input power (or increasing external heat leakage) causes the liquid nitrogen temperature to gradually rise until reaching a new equilibrium at time (2). Similarly, at time (3), increasing the cryocooler' s electrical input power (or decreasing external heat leakage) leads to a new equilibrium state at point (4) after a certain period.

Figure 2: Startup and operating analysis of the ZBO system
Figure 3: Variable operating characteristics of the ZBO system

3. Zero Boil-off Experimental Research

The pulse tube cryocooler, heat pipe, and dewar components were assembled into a ZBO system. PT100 platinum resistance temperature sensors were installed at the upper, middle, and lower spatial positions within the dewar storage vessel, as well as at critical locations on the heat pipe evaporator and condenser. A pressure sensor and safety valve were mounted on the storage vessel vent port. Following the experimental procedure, the system was first evacuated, after which a quantity of liquid nitrogen working fluid was charged into the storage vessel (approximately 2/3 of its capacity). The dewar' s liquid fill and vent ports were then sealed, and the pulse tube cryocooler was activated. Temperatures at various points and storage vessel pressure were monitored throughout the experiment.

The experimental results are presented in Figure 4 [Figure 4: see original paper], revealing the system' s operating states and variation patterns. At 10 minutes, liquid nitrogen began filling the dewar, causing the three temperature sensors inside the dewar storage vessel and two sensors on the heat pipe evaporator to rapidly reach approximately 77 K. After stopping the fluid charge, the temperature at the upper portion of the storage vessel gradually increased, indicating the absence of liquid nitrogen and the presence of only evaporated cold nitrogen gas, while the middle and lower temperatures remained stable at the liquid nitrogen boiling point of 77 K, confirming that the charged liquid nitrogen occupied approximately 2/3 of the storage vessel volume. The dewar was then allowed to stand for 30 minutes to achieve a relatively stable internal condition. At 60 minutes, the pulse tube cryocooler was started and the dewar transfer line ports were sealed. The heat pipe condenser temperature began to decrease gradually, while the liquid nitrogen temperature and pressure in the storage vessel increased from their initial values of 77 K and 0.1 MPa due to heat leakage. By 170 minutes, the condenser temperature reached liquid nitrogen temperature, at which point the heat pipe started operating and liquid nitrogen began flowing from the condenser outlet. The outlet temperature rapidly dropped to the liquid nitrogen temperature range, while the condenser inlet experienced a temperature rise due to the return flow of warmer nitrogen gas through the vapor line (as the pipeline temperature was higher, the cold gas stream absorbed heat from it).

For detailed observation and analysis, Figure 5 [Figure 5: see original paper] presents an enlarged view of the lower region from Figure 4, including the pressure variation inside the dewar. As the heat pipe started operating and transferred cooling power, the rate of temperature and pressure increase within the storage vessel slowed. At 200 minutes, the values peaked (temperature approximately 87 K, pressure 0.35 MPa) and began to decrease. With continued operation of the cryocooler and heat pipe, the liquid nitrogen temperature and pressure gradually declined at a progressively slower rate. By 420 minutes, the temperature and pressure stabilized at 80 K and 0.16 MPa, respectively, thereby achieving zero boil-off lossless storage of liquid nitrogen. At this point, the cryocooler' s cooling capacity was approximately 2 W, larger than the theoretical calculation, likely due to unaccounted heat leakage from low-temperature components such as the cold finger and heat pipe.

Figure 6 [Figure 6: see original paper] shows the experimental results for variable-load operation characteristics of the liquid nitrogen ZBO system. The initial process was similar to the previous experiment, with all ZBO system components starting and operating normally, reaching a stable ZBO condition after 4 hours. The cryocooler' s electrical input power was then varied to observe changes in system temperatures and pressure. At 280 minutes, the cryocooler input power was increased from 50 W to 55 W, causing the condenser and liquid nitrogen temperatures to begin decreasing and reach a new steady state within approximately 10 minutes. The liquid nitrogen temperature and pressure adjusted from the previous equilibrium state (86 K, 0.3 MPa) to a new equilibrium state (83 K, 0.24 MPa). At 360 minutes, 450 minutes, and 490 minutes, the cryocooler input power was increased to 60 W, 65 W, and 70 W, respectively. In each case, the ZBO system automatically regulated and reached a new equilibrium state within approximately 10 minutes.

Figure 4: Experimental results for the ZBO system
Figure 5: Experimental results for the ZBO system (enlarged view)
Figure 6: Variable-load operation of the ZBO system

Conclusion

A small-scale liquid nitrogen ZBO system experimental apparatus was designed and constructed, incorporating components such as a high-frequency pulse tube cryocooler, liquid nitrogen dewar, and thermosyphon. The structural parameters of this small ZBO system were introduced, and comprehensive theoretical analysis and experimental investigation of the system' s overall operating characteristics were conducted. The startup process, operational variations, steady-state equilibrium, and variable-load operation characteristics were obtained, demonstrating liquid nitrogen zero boil-off storage with remote cryocooler cooling. The research results validate the feasibility of the ZBO concept and demonstrate favorable operational performance, with the thermosyphon achieving a maximum temperature difference of approximately 2 K while transferring approximately 2 W of cooling power. The liquid nitrogen ZBO system can operate stably over extended periods and automatically regulate to reach new equilibrium states under variable conditions. These operational characteristics and patterns of the ZBO system establish a foundation for future practical applications.

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