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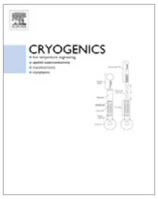

Experimental study of a nitrogen-charged cryogenic loop heat pipe

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ABSTRACT

Cryogenic loop heat pipes (CLHPs) are effective and efficient cryogenic heat transport devices suitable for many space applications. In this work, a miniature cryogenic loop heat pipe (CLHP) with nitrogen as the working fluid was designed and experimentally investigated. An auxiliary loop was employed to assist the supercritical startup of the primary evaporator. The operational characteristics of the CLHP and the matching characteristics of heat loads applied to the primary and secondary evaporators were investigated experimentally. The results show that the CLHP can achieve reliably the supercritical startup when the heat load applied to the secondary evaporator is no less than 3 W; when the heat load applied to the primary evaporator is no less than 2.5 W, the primary evaporator can operate independently, otherwise a proper selection of the heat load applied to the secondary evaporator should be considered to overcome the parasitic heat load from the ambient. The CLHP is working at the variable conductance mode and can achieve smooth operational transition subject to a large step change of the heat load applied to the primary evaporator.

1. Introduction

As an effective and efficient two-phase heat transfer device, loop heat pipe (LHP) utilizes the evaporation and condensation of a working fluid to transfer heat, and the capillary force developed in fine porous wicks to circulate the working fluid [1]. Their high pumping capability and excellent heat transport performance have been traditionally utilized to address the thermal control problems of spacecraft, and successfully applied in many space missions [2,3]. Recently, its application has been extended to terrestrial surroundings such as in electronics cooling [4–6] and thermal-management system of aircraft [7,8]. Their relative long distance heat transport capability and flexibility in design could offer many advantages compared with traditional heat pipes, especially under the situation of antigravity operation.

Currently, most LHPs investigated or in use are operating at the ambient temperature range (0–60 °C), i.e. so-called the ambient loop heat pipes (ALHPs), and the working fluids charged are typically ammonia, water and acetone, etc. However, for the low temperature applications, such as in a space exploration system where the space infrared sensors/detectors have to be maintained at 80–100 K or even lower temperature, ALHPs are not applicable. It is necessary to develop LHPs operating in the low temperature range, i.e. cryogenic loop heat pipes (CLHPs). Inheriting the advantage of long distance and flexible heat transport features of ALHPs, CLHPs can realize the separation of the infrared optical instruments from the cryocoolers with effective long distance cryogenic heat transport between them. The advantages of the application of CLHPs onto space optical instrument are evident: first, the pointing agility of the optical instruments can be improved considerably; secondly, the vibration induced by the cryocoolers can be isolated from the optical instruments, which can provide jitter-free observations of the space telescope at a target that may prove invaluable for most space missions.

Since 2000, many investigations have been performed on the design and functional study of CLHPs, which are briefly reviewed here. Pereira et al. [9] designed and investigated experimentally a CLHP with different working fluids, which utilized the gravity to realize the temperature drop and liquid saturation of the evaporator wick. The CLHP was able to transfer up to 20 W when filled with argon, 25 W when filled with krypton and 30 W when filled with propane in a gravity assisted orientation. The limitation of heat transfer in each case was only due to the limited cooling power of the cryocooler used to perform the tests. Khrustalev et al. [10–12] experimentally investigated an oxygen-charged CLHP, which employed a secondary evaporator to realize the temperature drop and liquid saturation of the primary evaporator wick. The CLHP can operate at the temperature range of 65–140 K, and the experimental results showed that the CLHP could startup and operate reliably when the heat load applied to the main evaporator varied from 0.5 W to 9 W with zero power on

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the secondary evaporator. The maximum 9 W could be obtained under anti-gravity condition, i.e. with the main evaporator elevated 5 cm above the condenser. Mo et al. [13–15] designed and experimentally investigated a nitrogen-charged CLHP, which also employed a secondary evaporator to realize the temperature drop and liquid saturation of the primary evaporator wick, and the effects of gravity, volume of the gas reservoir, effective pore diameter of the wick and different working fluids on the operating performance of the CLHP were reported. It is worth noted that the structure of the secondary evaporator in Refs. [10–12] is similar to that of the primary evaporator, while the structure of the secondary evaporator in Refs. [13–15] is like a traditional grooved heat pipe. James et al. [16] developed a CLHP and conducted the tests in a thermal vacuum chamber for passive optical bench cooling applications. Ethane was selected as the working fluid to provide an operating temperature range of 215–218 K. The experimental results clearly demonstrated the capability of the CLHP, i.e. it could startup reliably from a supercritical temperature of 335 K to achieve a normal operating temperature of 215 K by switching on the secondary evaporator. With a heat load of 5 W applied to the secondary evaporator, the CLHP could achieve a 50 W heat transport capability at 215 K. Hoang and O'Connell [17] developed a nitrogen-charged CLHP, which could realize the supercritical startup and operate at the temperature range of 80–110 K. The CLHP showed good performance in power cycling and long duration low heat load tests, and its maximum heat transport capability was found to be 5 W with a transport distance of 4.3 m. In Ref. [18], a hydrogen-charged CLHP was experimentally investigated, which could realize the supercritical startup and operated at the temperature range of 20–30 K. A maximum heat transport capability of 5 W with a transport distance of 2.5 m was obtained. An optimization of the CLHP to minimize its mass and volume was conducted for future space applications, and further results were reported in Ref. [19]. To increase the heat transport capacity, Zhao et al. [20] experimentally investigated a nitrogen-charged CLHP with a parallel condenser, which could greatly reduce the flow resistance and increase the cooling capability of the condenser. The results showed that the CLHP could operate reliably for a maximum heat load of 41 W with a small temperature drop of 6 K across a 0.48 m transport distance. Gully et al. [21] designed and experimentally investigated a prototype of CLHP working around 80 K with nitrogen as the working fluid. Experimental results were analyzed and discussed both in the transient phase of cooling from room temperature and in stationary conditions. The effects of transferred power, filling pressure and radiation heat load for two basic configurations of cold reservoir of the secondary circuit were studied in stationary conditions, and a maximum cold power of 19 W with a corresponding limited temperature difference of 5 K was achieved across a 0.5 m distance. Of particular note that all CLHPs introduced in Refs. [16–21] employed an auxiliary loop to realize the large temperature drop of the primary evaporator during the supercritical startup process.

Above short review shows that CLHPs are effective and efficient cryogenic heat transport devices developed in recent years, and the study is just at the beginning mainly focusing on experimental aspects. Within these studies, experimental investigation on its working principles and operating characteristics are still inadequate. Furthermore, to push CLHP into space applications, besides each component should be optimized to reduce its volume and weight, appropriate design of the structure of the evaporator casing and the condenser is also required to satisfy the interface requirements between the CLHP and the heat source (infrared sensors/detectors) and heat sink (cryocoolers). Aiming at future space applications, a miniature CLHP with nitrogen as the working fluid, which employed an auxiliary loop to realize the temperature drop of the primary evaporator during the supercritical startup, was designed and experimentally investigated in this paper. The outer diameters of the evaporator and the transport line were 13 mm and 2 mm respectively, and the cylindrical condenser design can provide convenient interface with the cold finger of the cryocooler, making the CLHP with considerable application potential. The experiments were mainly focused on the supercritical startup capability and matching characteristics of the heat loads applied to the primary and secondary evaporators, and its heat transport capacity and thermal resistance variation were also tested. The experimental results are presented and analyzed in detail in this paper.

2. Experimental setup

Fig. 1 shows the schematic of the CLHP designed in this work, and Table 1 gives the basic parameters of the CLHP, where CC represents the compensation chamber and OD and ID represent the outer and inner diameters respectively. As shown in Fig. 1, because the CLHP employs an auxiliary loop to realize the supercritical startup, the system is composed of a main loop and an auxiliary loop apart from the gas reservoir. The main loop includes a primary evaporator, a primary CC, a primary condenser and the primary vapor and liquid lines, and the auxiliary loop consists of a secondary evaporator, a secondary CC, a secondary condenser and the secondary loop line. The gas reservoir with a comparatively large volume is utilized to reduce the system pressure at ambient state, and it is connected with the inlet of the primary condenser. All the components of the CLHP were made of stainless steel except that the primary and secondary evaporator wicks were made of sintered nickel powder. The CLHP was operating at the temperature range of 80–120 K, and nitrogen whose purity was greater than 99.9995% was used as the working fluid.

In the experiments, heat loads applied to the primary and secondary evaporators were provided by two thin-film electric resistance heaters, and they were attached directly to the casings of the primary and secondary evaporators symmetrically. The heat load can be adjusted from 0 W to 30 W by altering the DC power output voltage imposed on the heaters. The primary and secondary condenser lines were coiled and soldered onto a solid cylindrical cold block (see Fig. 1) to reduce the contact thermal resistance. The cryogenic heat sink was simulated by liquid nitrogen circulating through another hollow cylindrical cold block (see Fig. 2), and the two cylindrical cold blocks were connected tightly through the end faces. For practical application, the hollow cylindrical cold block would be replaced by the cryocooler. To reduce the parasitic heat loss from the ambient, the CLHP was placed in a thermal-vacuum chamber, and all the components except the gas reservoir were covered with multilayer insulation materials. Note that, the pressure in the thermal vacuum chamber can be maintained at below 2×10^{-2} Pa, and the parasitic heat loss by convective heat transfer becomes negligible in the experiments. Type T thermal couples (TCs) were used to monitor the temperature variations of the characteristic points along the loop, the measuring uncertainties of the thermal couples are ±1.0 K by calibration, and the TC locations are shown in Fig. 1. To reduce the influence of gravity, the primary evaporator and the primary condenser were placed in a horizontal plane in the experiments.

3. Experimental results and analysis

3.1. Supercritical startup

3.1.1. Temperature variations of characteristic points along the loop

Fig. 3 shows the temperature variations of the characteristic points along the loop during the supercritical startup process. In