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Effect of component layout on the operation of a miniature 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 and terrestrial applications. Due to the complexity of its structure, the startup and operation of CLHPs might be influenced by the relative position of different components; however, little work has been done on this aspect. In this work, a miniature CLHP with nitrogen as the working fluid employing an auxiliary loop to assist the supercritical startup was developed. The effect of the layout of the secondary loop line and the gas reservoir on the startup and operation of the CLHP was experimentally investigated. The experimental results show that the relative position of these components can affect both the startup and steady-state operation of the CLHP. The heat transport capacity of the CLHP can be increased considerably when the secondary loop line is connected to the middle or top of the primary compensation chamber.

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 forces 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 system [4–6] and thermal-management system of aircraft [7,8]. Their 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), so called ambient loop heat pipes (ALHPs), and the working fluids are typically ammonia, water and acetone. However, for low temperature application fields such as in the space exploration system where the space infrared sensors/detectors have to be maintained at 80–100 K or even lower temperature and in the cooling of superconductor, ALHPs cannot be used, and LHPs operating in the low temperature range, i.e. cryogenic loop heat pipes (CLHPs), have to be developed. For the space exploration system, inheriting the advantages such as long distance flexible heat transport from ALHPs, CLHPs can realize the separation of the infrared optical instruments from the cryocoolers and achieve effective long distance cryogenic heat transport between them. By using such a CLHP, the pointing agility of the optical instruments can be improved considerably, and the vibration induced by the cryocoolers can be isolated, which can provide jitter-free observations of the space telescope.

Recently, quite a few experimental studies of CLHPs have been conducted, which are briefly reviewed here. Pereira et al. [9] designed and experimentally investigated a CLHP with different working fluids, which employs 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. 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 reliably start up in multiple tests and operated with the heat load applied to the main evaporator from 0.5 W to 9 W with zero power on the secondary evaporator. Mo et al. [13–15] designed and experimentally investigated a nitrogen-charged CLHP, which 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. James et al. [16] developed a CLHP for passive optical bench cooling applications. Ethane was selected as the working fluid to

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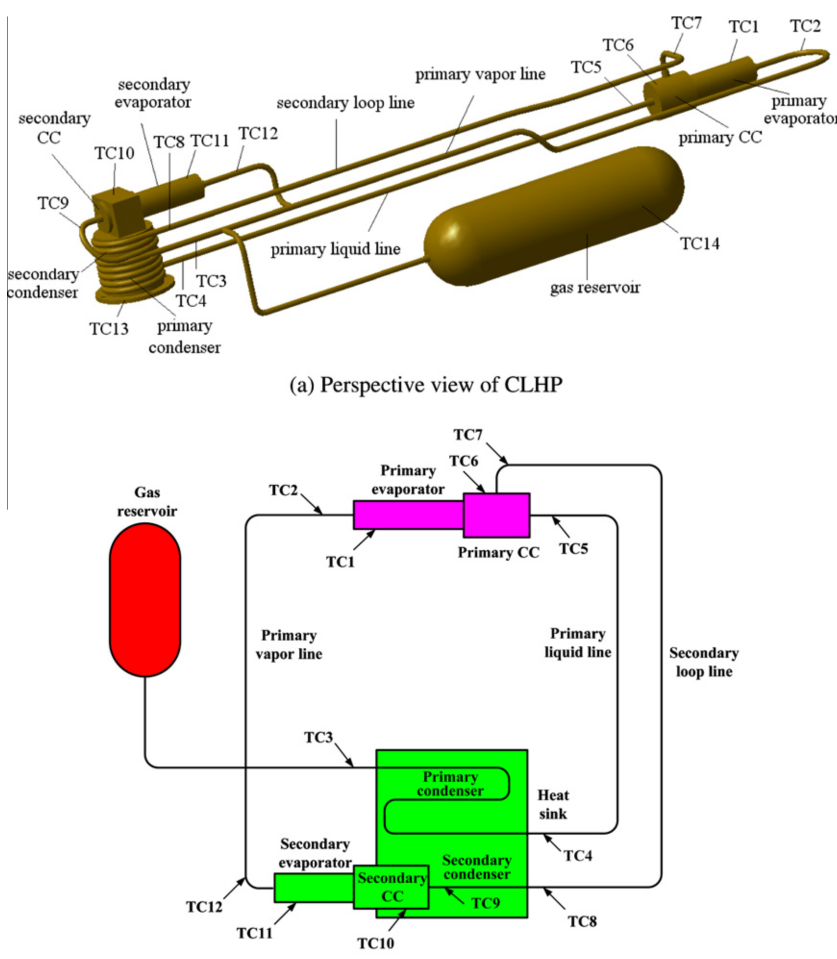
provide an operating temperature range of 215–218 K. The experimental results clearly demonstrated the capability of the CLHP, i.e. it could start up reliably from a supercritical temperature of 62 °C (335 K) to achieve a normal operating temperature of −58 °C (215 K) by switching on the secondary evaporator. With a heat load of 5 W applied to the secondary evaporator, the CLHP can achieve a 50 W heat transport capability at −58 °C (215 K). Hoang et al. [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 parallel condenser, which could greatly reduce the flow resistance and increase the cooling capability of the condenser. Experiments showed that the CLHP could operate reliably with a high heat transfer capacity up to 41 W and a limited temperature difference 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. Bai et al. [22] designed a miniature CLHP with nitrogen as the working fluid, and the supercritical startup capability and matching characteristics of the heat loads applied to the primary and secondary evaporators were experimentally investigated. In addition, the heat transport capacity and thermal resistance variation of the CLHP were also studied. Of particular note that all CLHPs introduced in Refs. [16–22] 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. Although quite a few experimental studies have been conducted on CLHPs mainly focusing on the supercritical startup characteristics and heat transport capability, little work has been done on the influence of component layout such as the connecting points of the secondary loop line and the gas reservoir on the CLHP performance, and further study is needed to get a better understanding to the operation of CLHP. Aiming at future space applications, a miniature CLHP with nitrogen as the working fluid, which employed an auxiliary loop to realize the supercritical startup, was designed and experimentally investigated in this paper. The experiments were mainly focused on the effect of component layout



(a) Perspective view of CLHP

(b) Sketch of CLHP

Fig. 1. Schematic of the CLHP and thermocouple locations.