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Experimental study on the supercritical startup and heat transport capability of a neon-charged cryogenic loop heat pipe

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ABSTRACT

Neon-charged cryogenic loop heat pipe (CLHP) can realize efficient cryogenic heat transport in the temperature range of 30–40 K, and promises great application potential in the thermal control of future space infrared exploration system. In this work, extensive experimental studies on the supercritical startup and heat transport capability of a neon-charged CLHP integrated with a G-M cryocooler were carried out, where the effects of the auxiliary heat load applied to the secondary evaporator and charged pressure of the working fluid were investigated. Experimental results showed that the CLHP could successfully realize the supercritical startup with an auxiliary heat load of 1.5 W, and there existed an optimum auxiliary heat load and charged pressure of the working fluid respectively, to achieve the maximum temperature drop rate of the primary evaporator during the supercritical startup. The CLHP could reach a maximum heat transport capability of 4.5 W over a distance of 0.6 m corresponding to the optimum charged pressure of the working fluid; however, the heat transport capability decreased with the increase of the auxiliary heat load. Furthermore, the inherent mechanisms responsible for the phenomena observed in the experiments were analyzed and discussed, to provide a better understanding from the theoretical view.

1. Introduction

As a highly efficient cryogenic heat transport device, cryogenic loop heat pipe (CLHP) was first developed at the very beginning of this century, aiming at the applications in the thermal control of future space infrared exploration system, where the infrared sensors/detectors have to be maintained at 80–100 K or even lower temperatures. For instance, the NASA James Webb Space Telescope (JWST) program, to be launched in 2018, has identified the need to provide cryocooling for the telescope infrared (IR) sensors and detectors in the temperature range of 30–40 K [1,2]. Compared with conventional cryogenic heat pipes, CLHPs have the advantage of transporting a larger amount of heat over a longer distance with much enhanced anti-gravity capability. That is because in the CLHP, the micro-porous wick is only installed in the evaporator section to provide strong and robust capillary pumping, while separate liquid and vapor transport lines are employed to realize working fluid transport with much reduced flow resistance, where the entrainment phenomenon due to liquid/vapor counter flow is completely avoided [3,4]. Furthermore, unlike a conventional cryogenic heat pipe, which is generally a rigid metal tube with both ends sealed, the adoption of flexible small-diameter transport lines enables the CLHPs to secure the flexible thermal link function [5–8], which is really important for the space infrared exploration system. Because when the CLHP is to connect the infrared sensor and the cryocooler, the vibration and magnetic interference induced by the cryocooler can be effectively reduced or eliminated, to guarantee that the space infrared telescope can always be operating with high imaging quality, which is invaluable for most space exploration missions. What's more important, the CLHP makes the across-gimbal design possible for the space infrared exploration system, which can adjust its attitude independently due to the separation from the main body of the spacecraft, and under such a condition, the pointing agility of the space infrared exploration system can be enhanced significantly.

As the latest development of the heat pipe technology, CLHP has attracted the interests of many researchers recently, and CLHPs with quite different types have been proposed to meet the requirements in different application areas. In a recently published review paper [9], the CLHPs were divided into five different types mainly according to the auxiliary methods employed to help realize the supercritical startup: type A, the gravity-assisted method [10]; types B and C, the secondary evaporator method [11–16]; type D,

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Nomenclature

P_{ch}	charged pressure of the working fluid (MPa)
P_{sys}	pressure in the system (MPa)
Q_{pe}	heat load applied to the primary evaporator (W)
Q_{se}	heat load applied to the secondary evaporator (W)

Abbreviations

CC2	secondary compensation chamber
CLHP	cryogenic loop heat pipe
Con-o	outlet of the primary condenser
EV1	primary evaporator
EV1-o	outlet of the primary evaporator
EV2	secondary evaporator
EV2-o	outlet of the secondary evaporator
LL2	secondary loop line

the auxiliary loop method [17–31] and type E, the capillary pump method [32,33], and their supercritical startup processes and steady/transient operating characteristics were presented and compared in detail. In particular, the CLHP employing the auxiliary loop method to realize the supercritical startup, i.e., type D, can achieve reliable supercritical startup and stable steady-state operation with favourable heat transport capability in the space microgravity environment; at the same time, it can tolerate the parasitic heat load from the ambient surroundings with the assistance of the auxiliary loop. As a result, it promises great application potential in the thermal control of future space infrared exploration system, and it becomes the research focus in this work.

For CLHPs with type D, extensive experimental studies have been conducted so far, especially using nitrogen as the working fluid at an operating temperature range of 80–100 K, as briefly reviewed below. Hoang et al. [18–22] perhaps first designed, fabricated and tested a proof-of-concept CLHP with nitrogen and hydrogen as the working fluids, respectively. Experimental results indicated that the CLHP could successfully realize the supercritical startup and operate reliably, whose heat transport capability could reach 50 and 12.5 W × m for nitrogen and hydrogen as the working fluids, respectively. To make them viable in space applications hydrogen-charged and across-gimbal nitrogen-charged CLHPs considering weight/volume design optimization were also developed by the introduction of a swing volume. To address important issues in cryogenic integration, Bugby et al. [1,23] developed an across-gimbal CLHP with nitrogen as the working fluid with a heat transport range of 2–20 W, where the coils were designed to sustain at least 500 thousand cycles in the lifetime. Gully et al. [24] also designed and experimentally investigated a nitrogen-charged CLHP, which could achieve a maximum heat load of 19 W over a 0.5 m transport distance. To further increase the heat transport capability, Zhao et al. [25,26] designed and experimentally studied a nitrogen-charged CLHP employing a parallel condenser design to reduce the flow resistance there. Experimental results confirmed that the CLHP could operate reliably with a considerably enhanced heat transport capacity up to 41 W.

To push forward its future space applications, Bai et al. [27–30] designed a miniature nitrogen-charged CLHP, where the novel cylindrical condenser design could provide convenient interface with the cold finger of the cryocooler, and a systematic experimental study on its operating characteristics was performed. In the following, in order to enhance the operation reliability and realize a long-life operation, a CLHP-based thermal control system with redundancy design was proposed, where one CLHP was in operation, and the other was used as a backup, and the supercritical startup of CLHPs under four possible working modes were experimentally investigated [31].

To satisfy the thermal control requirements at much lower cryogenic temperature levels, i.e., <80 K, CLHPs charged with neon and operating at 30-40 K have also been developed and investigated, although relevant studies are quite few. For instance, Bugby et al. [23] designed both short and long transport length CLHPs with neon as the working fluid. Primary test results indicated that the short transport length CLHP could transport a heat load of 0.1–2.5 W over a distance of 15 cm with the thermal conductance of about 1.0 W/K. While the long transport length CLHP was able to transport a heat load of 0.1–0.8 W over a distance of 3.0 m with the thermal conductance of about 0.7 W/K. The heat transport capability of the long transport length CLHP was much smaller than that of the short transport length one, due to much increased heat transport length with significantly enhanced pressure drop in the system.

For CLHPs, when the working fluid is changed from nitrogen to neon, it may cause several issues: first, as the operating temperature of the CLHP is further reduced to 30–40 K, the parasitic heat load from the ambient surroundings becomes much severe, which is obviously adverse to the supercritical startup, matching characteristics of heat loads applied to the primary and secondary evaporators, and steady-state operation of the CLHP [27–30], and more strict insulation measures must be implemented; second, different from nitrogen with a wide operating temperature range of 80–120 K, when neon is employed as the cryogenic working fluid, because its applicable operating temperature range becomes much narrower, i.e., only 30–40 K, a careful determination of the heat loads applied to the primary and secondary evaporators and adoption of a matching cryocooler will be required to guarantee that the CLHP is always operating at the temperature range of 30–40 K; and third, comparing neon with nitrogen, the difference in the thermophysical properties such as the evaporative latent heat and surface tension will also impose an important influence on the supercritical startup and heat transport capability of the CLHP, leading to quite different thermal performance of the CLHP.

However, so far, compared with CLHPs with nitrogen as the working fluid, the investigation into the CLHPs with neon as the working fluid is quite limited and seldom reported. There is still very little knowledge on the supercritical startup, transient and steady-state operation of the CLHPs with neon as the working fluid, and sufficient theoretical and experimental studies are really needed to push forward the future space applications of this promising cryogenic heat transport device. Considering the issues mentioned above, in this work, a systematic experimental study on the CLHP with neon as the working fluid will be conducted, mainly focusing on the supercritical startup and heat transport capability. The influence of relevant parameters, i.e., the auxiliary heat load applied to the secondary evaporator and the charged pressure of the working fluid, will be explored and discussed in detail, which contributes to a better understanding on the operating characteristics of the neon-charged CLHP.

2. Experimental system

Fig. 1 schematically shows the experimental rig used in this work, which consisted of a heating system, a cryogenic cooling sys-