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Determination of charged pressure of working fluid and its effect on the operation of a miniature CLHP

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ABSTRACT

In this paper, a miniature cryogenic loop heat pipe (CLHP) with nitrogen as the working fluid was designed, and the principle and calculation method to determine the charged pressure of working fluid were proposed and experimentally validated. Meanwhile, the effect of reduced charged pressure of working fluid on the operation of the CLHP such as the supercritical startup, matching characteristics of heat loads applied to the primary and secondary evaporators and heat transport capacity was experimentally investigated. Experimental results reveal that with an appropriate charged pressure of working fluid, the CLHP can reliably realize the supercritical startup, the primary evaporator can operate independently when the heat load applied to the primary evaporator is larger than a certain threshold value, and it achieves a heat transport capacity of 12 W. The effect of reduced charged pressure of working fluid on the supercritical startup and heat transport capacity of the CLHP is not salient. However, it has significant effect on the matching characteristics of heat loads applied to the primary and secondary evaporators, and the secondary evaporator must be kept in operation to assist the normal operation of the primary evaporator even though the heat load applied to the primary evaporator is comparatively large.

1. Introduction

Cryogenic loop heat pipes (CLHPs) are effective and efficient two-phase heat transfer devices that utilize the evaporation and condensation of a cryogenic working fluid to transfer the heat, and the capillary forces developed in fine porous wicks to circulate the working fluid. As an advanced low temperature heat transport device, it inherits the advantage of long distance flexible heat transport from ambient loop heat pipes (ALHPs) [1–3], and can be employed in many space and terrestrial applications, i.e. in the space infrared exploration system where the space infrared sensors/detectors have to be maintained at 80–100 K or even lower temperature, CLHPs can realize the separation of the infrared optical instruments from the cryocoolers while maintaining effective long distance cryogenic heat transport between them. The advantages of the application of CLHPs are evident: first, the pointing agility of the optical instruments can be improved considerably; secondly, the vibration and electromagnetic interference induced by the cryocoolers can be isolated from the optical instruments, which can provide jitter-free observations of the space telescope at a target and that may prove invaluable for most space missions [4–6].

The research and development of CLHPs began at the beginning of this century, and various CLHPs with different structures have been developed to solve the supercritical startup problem, which are briefly reviewed here. Pereira et al. [7] designed and experimentally investigated a CLHP that employed the gravity to realize the temperature drop and liquid saturation of the evaporator wick, and the structure is just like that of ALHPs. 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. [8] and Khrustalev [9,10] experimentally investigated an oxygen-charged CLHP which employed a secondary evaporator to realize the temperature drop and liquid saturation of the primary evaporator wick, and the CLHP had an additional secondary evaporator compared to ALHPs. The CLHP can operate at the temperature range of 65–140 K, and the experimental results showed that the CLHP could reliably start up and operate with the heat load applied to the primary evaporator from 0.5 W to 9 W with zero power on the secondary evaporator. The CLHP could transport 9 W with the main evaporator elevated versus the condenser by 5 cm. Mo and Liang [11,13] and Mo et al. [12] designed and experimentally investigated a nitrogen-charged CLHP which also employed a secondary evaporator to realize the

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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. Note that, the structure of the secondary evaporator in Refs. [8–10] is just like that of the primary evaporator, while the structure of the secondary evaporator in Refs. [11–13] is like a traditional grooved heat pipe.

James et al. [14] developed a CLHP for passive optical bench cooling applications and conducted the tests in a thermal vacuum chamber. 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 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 and O'Connell [4] 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. Hoang and O'Connell [5] experimentally investigated a hydrogen-charged CLHP, 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. [6]. To increase the heat transport capacity, Zhao et al. [15] experimentally investigated a nitrogen-charged CLHP with parallel condenser, which could greatly reduce the flow resistance and increase the cooling capability of the condenser. 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. [16] designed and experimentally investigated a nitrogen-charged CLHP. Experimental results were analyzed and discussed both in the transient phase of cooling from room temperature and 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. Bai et al. [17–19] designed and experimentally investigated a miniature CLHP with nitrogen as the working fluid. The supercritical startup characteristics and the matching characteristics of heat loads applied to the primary and secondary evaporators as well as the heat transport capacity were investigated experimentally, and quite a few important conclusions such as the component layout effect have been drawn. Of particular note that all CLHPs introduced in Refs. [4–6,14–19] employed an auxiliary loop to realize the large temperature drop of the primary evaporator during the supercritical startup process.

In conclusion, extensive experimental investigation has been conducted on CLHPs, which contributes to a better understanding of the working principle and operating characteristics of this device, such as the supercritical startup characteristics, power cycling characteristics, heat transport limit and the effects of working fluid, gravity and component layout, etc. However, there are still some aspects on CLHPs that requires further study to put this new device into future space applications. An example is the determination of charged pressure of working fluid and its effect on the operation of CLHPs. An appropriate charged pressure of working fluid can guarantee the normal operation of CLHPs and help it achieve the best performance. At the same time, it is necessary to investigate the effect of reduced charged pressure of working fluid on the operation of CLHPs, because during long time operation in practical application, the slight leakage of working fluid is generally unavoidable, and it is important to assess this effect on the performance of CLHPs.

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 main focus for this study is the determination of charged pressure of working fluid and its effect on the supercritical startup, matching characteristics of heat loads applied to the primary and secondary evaporators and the heat transport capacity of the CLHP. The experimental results are presented and analyzed in detail.

2. Determination of charged pressure of working fluid

2.1. Principle and calculation method

Fig. 1 shows the schematic of a CLHP that employs an auxiliary loop to realize the supercritical startup. An ALHP consists of an evaporator, a condenser, a compensation chamber (CC) and vapor and liquid transport lines. Compared with ALHPs, the CLHP has an additional gas reservoir with relatively large volume and an auxiliary loop composed of a secondary evaporator, a secondary condenser, a secondary CC and secondary loop line. Detailed introduction of the supercritical startup process of a CLHP that employs an auxiliary loop to realize the supercritical startup was presented in Ref. [20], which is not repeated here.

In the design of CLHPs, the appropriate determination of charged pressure of working fluid is very important, and it should be conducted simultaneously with the gas reservoir volume after the structure and size of the other components of the CLHP are determined. The principle for the determination of charged pressure of working fluid is to guarantee that sufficient working fluid exists in the CLHP, at the same time, the pressure in the CLHP when the cooling of the secondary evaporator is completed during the supercritical startup process should be sufficiently lower than the critical pressure of the working fluid to guarantee successful startup of the secondary evaporator, which is a key factor affecting successful supercritical startup. In addition, the pressure in the CLHP when the CLHP is idle i.e. the charged pressure of working fluid should not be too high for safety purpose, and the gas reservoir volume should not be too large for weight/volume saving purpose.

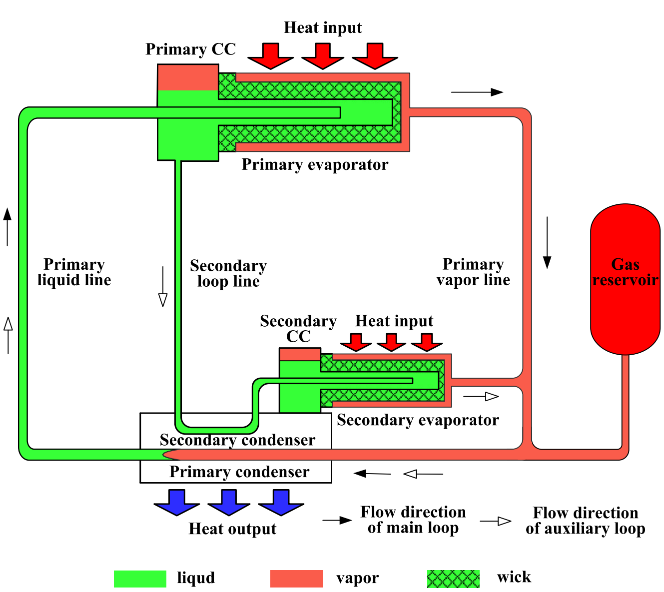

Fig. 1. Schematic of a CLHP that employs an auxiliary loop.