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Investigation on thermal behaviours of a methane charged cryogenic loop heat pipe

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ABSTRACT

As a highly efficient cryogenic heat transfer device, cryogenic loop heat pipe (CLHP) promises great application potential in the thermal control of future space infrared detection system. In this work, a CLHP using methane as working fluid operating at 100–190 K was developed, and its thermal performance including the supercritical startup, heat transport capacity under different heat sink, power cycling characteristics, temperature hysteresis phenomenon and thermal resistance variation, was experimentally investigated. Experimental results showed that the CLHP could successfully realize the supercritical startup under various auxiliary heat loads applied to secondary evaporator, reach a various heat transfer capacity under different heat sink temperature over a 0.6 m distance, and manifest good response characteristics to the cycle of heat load applied to the primary evaporator. The temperature hysteresis phenomenon was detected and thermal resistance of the CLHP varied with increasing heat load applied to the primary evaporator, but not the same with that in heat load reverse motion.

1. Introduction

As a highly effective two-phase heat transfer technique, heat pipe can transport several orders of magnitude greater heat loads than that of highly conductive solids such as copper bar. Among all types of heat pipes, loop heat pipe(LHP) have the advantage of being able to provide reliable thermal control function over long distance and the ability to operate against gravity, which has been successfully employed in a wide sphere of application both terrestrial based [1–3] as well as space applications [4].

Cryogenic loop heat pipe(CLHP) developed from LHP focuses on the thermal cooling and control demand in low temperature, which could guarantee the infrared sensors and superconductive magnetic materials at a certain temperature range. The usual measures are using cryogenic liquid or mechanical cryocooler, but both of the two methods have some disadvantages such as liquid evaporating leakage, mechanical vibrations and space limitation. Meanwhile, these problems lead to lower efficiency or other energy problems, which are becoming more and more serious. CLHP could solve these problems to a certain extent by cooling down the sensors and magnetic materials directly or indirectly. It could separate vibrations and keep an outstanding temperature consistency and could be used widely for superconducting magnet and electronic devices for harvesting energy.

From the time CLHP was put forward and test in ground surroundings, CLHPs have attracted many researchers all over the world, and extensive experimental studies have been conducted almost through all of the low temperature range such as propane for the operating temperature range of 200–240 K, oxygen for 90–140 K, nitrogen for 80–110 K, neon for 30–40 K and hydrogen for 20–30 K, and helium as low as 2–4 K. Bai et al. [5] presented a review of cryogenic loop heat pipes, which highlighted the key issues for designing CLHP in terrestrial and space application together with five different types in its development. And from the working temperature range, the literature could be classified as follows.

In the relatively high temperature range, Pereira et al. [6] constructed and experimentally investigated a CLHP using gravity to assist the startup process and liquid saturation for evaporator wick, whose heat transport capacity could reach 20 W and 30 W with

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argon(90–150 K) and propane(200–240 K) as the working fluid respectively. Yun et al. [7] firstly reported the experimental test of an auxiliary loop CLHP with ethane as the working fluid, whose operating temperature range was 215 K–218 K. All the transport lines were plated with gold to minimize parasitic heat leak so that it could achieve a heat transport capability of 50 W with auxiliary heat load of 5 W applied to the secondary evaporator. The CLHP using auxiliary method to accomplish supercritical startup process is the most potential type, which has an additional auxiliary loop composed of a secondary evaporator(EV2), secondary compensation chamber(CC2), secondary condenser(Con2) and secondary loop line(LL2) in addition to the gas reservoir.

The researches of nitrogen CLHP operating in 80 K–100 K range has been published the most. Mo et al. [8,9] designed and experimentally investigated a nitrogen-charged CLHP with an additional secondary evaporator within condenser line path to assist the supercritical startup process. The secondary evaporator was a traditional grooved heat pipe and was attached directly to the cryogenic heat sink simulated by LN2 copper plate together with condenser lines. Hoang et al. firstly developed a proof-of-concept CLHP with nitrogen and hydrogen as the working fluids. Hoang and O'Connell [10] designed, fabricated and tested a nitrogen-charged CLHP, which could realize the supercritical startup process and operate at the temperature range of 80–100 K. The CLHP displayed a good performance in power cycling characteristics, heat transport capacity and could reach a transport limit of 5Wwith a transport distance of 4.3 m. Gully et al. [11,12] designed and experimentally investigated a nitrogen-charged CLHP. Experimental results were analyzed and discussed both in the supercritical startup and in steady state conditions, and a maximum heat transport capacity of 19Wwith a limited temperature difference (5 K) over a large distance (0.5 m). In order to enlarge the heat transfer capacity of CLHP, Zhao et al. [13,14]introduced a parallel condenser adopted to reduce the flow resistance in the condenser and increase its cooling capability. Experimental results confirmed that the nitrogen CLHP could achieve a significantly enhanced heat transport capacity up to 41 W and a limited temperature difference of 6 K across a 0.48 m transport distance. Bai et al. [15–17] designed and experimentally investigated a miniature nitrogen CLHP, where the thermal performance such as supercritical startup, effects of component layout and charging pressure were studied extensively. And testing results showed that the miniature CLHP using LN2 as heat sink could realize supercritical startup and steady state operating test.

To solve the problems of flexible thermal link for future cryogenic integration, Bugby et al. [18,19]developed three CLHPs: an across-gimbal CLHP, a short transport length miniaturized CLHP and a long transport length miniaturized CLHP. The across-gimbal CLHP was designed with nitrogen as the working fluid with a heat transport capacity of 20 W, in which the coils were designed to sustain at least 500 thousand cycles in the lifetime. In Refs. [20,21] D. Bugby introduced six advanced cryogenic thermal management devices/subsystems developed by Swales Aerospace for ground/space-based applications of interest to NASA, DoD and some of them were designed with redundancy for thermal control in actual space application. In the redundancy design process, R.G. Ross [22] presented an analysis of the reliability advantages and disadvantages of a variety of cryocooler redundancy options, and determined a double cryocooler together with double cryogenic switches scheme based on their total reliability, mass, and power impact at the cryogenic system level. In order to enhance the operation reliability and realize a long-life operation, Guo et al. [23] also designed and tested a redundancy system of two nitrogen charged CLHPs operating at 80 K–100 K for space application, which had four working modes.

In the temperature range below 80 K, Khrustalev et al. [24,25] experimentally investigated a CLHP using oxygen as working fluid for flexible thermal linking with cryocoolers. The CLHP owned an additional secondary evaporator, secondary CC and secondary condenser in addition to the gas reservoir to accelerate supercritical startup process and could sustain at 75 K and 100 K when the shroud temperature was maintained at 170 K and 290 K, respectively. However, the researches in oxygen CLHP has been reported fewer than that of nitrogen CLHP.

While temperature went deeper, in Refs. [18,19] Bugby et al. developed another two CLHPs: a short transport length miniaturized CLHP and a long transport length miniaturized CLHP. Both of them utilized neon as the working fluid operating in 30 K–40 K, and the short one was as small as an adult hand while the long one was 250 cm. Guo et al. [26–28] designed and experimentally investigated the supercritical startup characteristics and heat transfer capability of a neon CLHP working at 35 K, and the effect of auxiliary heat load and charging pressure was discussed detailly. Hoang [29] experimentally studied a hydrogen-charged CLHP operating at the temperature range of 20–30 K, which could obtain a maximum heat transport capability of 5 W over 2.5 m. In order to be conducted for future space applications, the CLHP was optimized to minimize its mass and volume and optimized testing results were published in Ref. [30].

From the literature review of CLHP working between 20 K and 250 K, there was a most vacancy in 150 K temperature range and only a couple of papers have mentioned the related research. While the CLHP operates in 150 K temperature range between 100 K and 200 K, there exist four kinds of working fluid available to choose from as shown in Fig. 1. The Dunbar Number that is calculated according to Eq. (1) by surface tension, density, latent heat and viscosity coefficient represents the thermal-physical properties potential to be working fluid.

$$Du = \frac{\sigma \rho_v h_{fg}}{\mu_v} \tag{1}$$

where h_{fg} and σ are the evaporative latent heat and surface tension of the working fluid, respectively; ρ_v and μ_v are the density and viscosity coefficient of the vapor working fluid, respectively.

From Fig. 1 the argon CLHP could operate between 90 K and 150 K but get the best performance at 120 K and the krypton CLHP could operate between 120 K and 200 K getting the best performance at 165 K. Similarly, the ethane CLHP could work through a

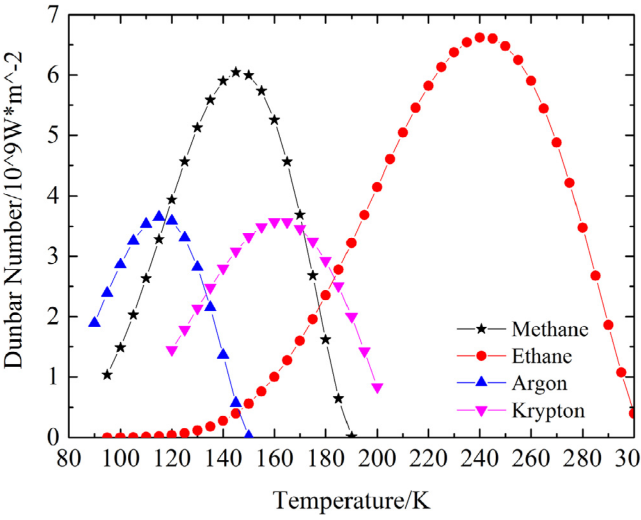

Fig. 1. Variation of Dunbar Parameter of working fluid between 100 K and 300 K.