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Operational performance of a cryogenic loop heat pipe with insufficient working fluid inventory

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Abstract

A cryogenic loop heat pipe (CLHP) has been developed for future aerospace applications at the Technical Institute of Physics and Chemistry (TIPC). It has been demonstrated that this CLHP, when placed horizontally, can operate in liquid-nitrogen temperature range and have a heat transfer capability of up to 12 W with proper working fluid inventory. This paper presents some particular characteristics of the CLHP when the compensation chamber is half-filled with liquid-phase working fluid before startup. The device has been tested at different orientations using nitrogen as the working fluid in order to compare its thermal behavior, specially related to the heat transfer capability, the operation temperature and the thermal resistance, as well as to investigate its operational characteristics under power level as low as 1 W. Tests were performed for the CLHP at horizontal position and with the liquid line 3.4 and 6.4 cm below the vapor line, respectively. The experimental results show the operationability of the CLHP tested at three orientations and tests with the liquid line 6.4 cm below the vapor line show lower operation temperatures and higher heat transfer capability.

Keywords: Cryogenics; Heat pipe; Heat transfer; Experiment

Performance de fonctionnement d'un caloduc cryogénique à charge partielle de fluide actif

Mots clés : Cryogénie ; Caloduc ; Transfert de chaleur ; Expérimentation

1. Introduction

The loop heat pipes (LHPs) can transport several orders of heat load than traditional single-phase techniques and offer efficient design solutions for the thermal management problems of spacecraft [1]. Thus the LHPs have gained acceptance as the primary thermal control systems by many spacecraft manufacturers. Terrestrial applications such as electronics cooling are also emerging. A detailed analysis of

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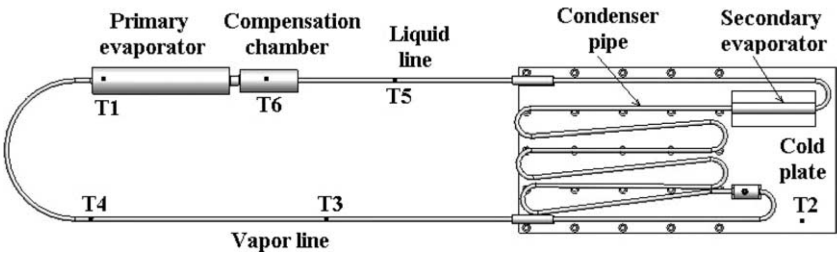

Fig. 1. The configuration of the CLHP.

the LHP working principles can be found in Maidanik et al. [2]. Furthermore, with the development of cryocooler technology and cryocooler-based applications such as those for space exploration, it is required to use cryocoolers to cool the optical instruments operating at a temperature range below 100 K and ambient loop heat pipe which operation temperature is around 273 K such as ammonia LHP will not meet this requirement. For the above mentioned reasons, it becomes necessary to develop the cryogenic LHP which can operate at liquid-nitrogen temperature range or even lower cryogenic temperature range to provide effective thermal link and vibration isolation between the cooling sources and their components to be cooled. Some loop heat pipes used for cryogenic applications can be found in [4–7].

It is well known that the typical trend of steady-state operation temperature (i.e. the compensation chamber temperature) of an ambient LHP as a function of heat load is U-shaped [3]. In other words, the operation temperature first decreases as the heat load increases causing an increase on the mass flow rate and thus a returning of more subcooled liquid to the capillary evaporator until it reaches a minimum value. Then it will increase almost linearly as the heat load increases and more of the condenser tubing is filled with vapor, which decreases the subcooling of the returned condensate. In the last case, when the condenser is fully utilized and the liquid displaced is completely located in the compensation chamber, the LHP will operate at constant conductance. Although a cryogenic LHP must have a pressure reduction reservoir with large volume involved in its configuration, its thermal behavior can be similar to that of the ambient LHP when the working fluid inventory only can fill half of the compensation chamber before the startup, which have been found in the experimental tests of the CLHP studied in this work.

In this paper, the working fluid inventory is defined as optimum if with its further increase the heat transfer capability of the CLHP will be weakened. Therefore, the working fluid inventory is insufficient when it is much less than the optimal value, which means that the compensation chamber is half-filled with liquid before startup for the specific design of the CLHP studied in this work. Based on the experiments which are not shown in this paper, the CLHP can have a much higher heat transfer capability (12 W under horizontal orientation) when the working fluid inventory is proper. But when using it in some applications in which high heat transfer capability is not so important, the CLHP is allowed to operate under insufficient working fluid inventory to get lower operating temperatures. Furthermore, when the working fluid inventory is insufficient, some particular phenomenon will occur, such as temperature oscillation. So it is necessary to study the operational performance of the CLHP under insufficient working fluid inventory.

2. Configuration and test system of the cryogenic LHP

Basically, the cryogenic LHP used in this work has the configuration presented by Fig. 1. The CLHP consists of a primary evaporator with an integral compensation chamber, a condenser, a secondary evaporator, two transportation lines and a pressure reduction reservoir. The serpentine condenser is made of a long copper pipe with the length of 1.2 m and the outer diameter of 3 mm. This configuration has two transport lines for vapor phase and liquid phase, respectively. These lines are stainless steel thin-walled pipes with the inner diameter of 2 mm, and the heat transfer distance between the heat source and sink is about 200 mm. The secondary evaporator is actually a short pipe with axial grooves on its internal surface, which is involved in this design to prepare for the development of this cryogenic loop heat pipe in aerospace applications. The pressure reduction reservoir is placed out of the vacuum vessel and connected to the condenser through a long pipe with the inner diameter of 1.5 mm. Some configuration parameters are listed in Table 1.

Table 1
Some parameters of the cryogenic LHP with nitrogen as working fluid

Primary wick	Stainless steel	Vapor line OD	3 mm
Wick pore size	8–12 μm	Liquid line length	170 mm
Wick permeability	$>5\times10^{-14}$ m^2	Liquid line OD	3 mm
Primary evaporator OD	20 mm	Condenser line OD	3 mm
Vapor line length	470 mm	Condenser line length	1200 mm