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Experimental investigation of a dual compensation chamber loop heat pipe

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ABSTRACT

This work performs a fundamental study of a Dual Compensation Chamber Loop Heat Pipe (DCCLHP) through partial visualization of the flow phenomenon inside its compensation chambers and the condenser. Both startup and steady-state performance of the DCCLHP and the influence of initial vapor–liquid distribution, startup heat load, heat sink temperature and relative orientations on the performance of the DCCLHP are studied. The result shows a typical 'V' curve operation temperature at heat loads over 50 W at the steady-state, and reveals some unique phenomena during the startup of the DCCLHP such as bubble generation in the liquid core, reverse flow, fluctuated flow and liquid re-distribution between the compensation chambers and the external loop, which are caused mainly by the radial heat leak from the evaporator. Some unstable phenomena during the startup, steady-state operation and unloading period of the DCCLHP are also revealed in this study including temperature fluctuations, temperature hysteresis and transient penetration of vapor.

1. Introduction

Loop heat pipes (LHPs) are effective two-phase heat transfer devices that utilize the evaporation and condensation of a working fluid to transfer heat, and the capillary forces developed in fine porous wicks to circulate the fluid [1]. Their high pumping capability and good heat transfer performance have been traditionally utilized to address the thermal-management problems of spacecraft, and were successfully applied in many space tasks [2,3]. More recently, their applications have been extended to terrestrial surroundings such as in electronics cooling systems and thermal-management systems for aircrafts and submarines [4–6]. Their long distance heat transport capability and flexibility in design could offer many advantages compared with traditional heat pipes.

A conventional LHP consists of an evaporator, a condenser, a compensation chamber (CC), and vapor and liquid transport lines. One major problem affecting the performance of a LHP is the relative orientation limit, i.e. different gravitational height between the evaporator, compensation chamber and condenser will result in different initial liquid–vapor distributions, which will affect the startup and subsequent steady-state operation of the LHP significantly [7,8]. To address this problem and also improve the performance of LHPs, Dual-Compensation Chamber Loop Heat Pipes (DCCLHP), which has two CCs on both ends of the evaporator, have been developed [9]. Only limited studies on DCCLHP have been performed and some in-consistent results have been reported. For instance, Gerhart and Gluck [10] designed a DCCLHP and claimed that it could operate successfully terrestrially when the evaporator and CCs were at different positions, which however contrasted significantly to the results from the observations from Gluck et al. [11]. A systematic investigation of the startup and steady-state performance of DCCLHPs at different relative orientations between the evaporator and CCs under gravitational surroundings was conducted by Lin et al. [9] and Bai et al. [12]. It showed that the introduction of a second CC can avoid the most difficult startup situation encountered by conventional LHPs, and the DCCLHP can start and operate normally for a startup heat load higher than 50 W. For smaller heat loads, some unique phenomena were observed during the startup period [12]. Compared with conventional LHPs with a single CC, both theoretical research and experimental results of DCCLHPs are insufficient at moment.

A few studies have been conducted on the visualization of LHP with a single compensation chamber that provided useful insight into the mechanisms. For example, Ogushi et al. [13] achieved a partial visualization of the liquid core of the evaporator and the liquid/vapor line. Salient natural convection phenomena were observed at the outlet of the liquid bayonet for heat loads over 400 W. Suhla et al. [14] investigated the steady-state performance of a flat LHP at horizontal and vertical positions with partial visualization on the evaporator and liquid/vapor line. A number of interesting phenomena were observed such as the formation of vapor and nucleate boiling in the evaporator, local dryout of the wick and pressure fluctuations in the condensation chamber. However no visualization work has yet conducted on DCCLHPs.

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This work will investigate fundamentally the operation of a DCCLHP through transient temperature measurement and partial visualization of the flow phenomena inside its compensation chambers and condenser. Both transient and steady-state performance of the DCCLHP will be studied under terrestrial conditions, and a parametric study of the influence of the heat sink temperature, start-up heat load and the relative orientation will be conducted.

2. Experimental setup

The DCCLHP designed for the experiment is schematically shown in Fig. 1. It consists of an evaporator, a condenser, two compensation chambers, and vapor and liquid transport lines. The vapor transport line connects the vapor grooves and the condenser inlet, and the liquid transport line connects the bayonet and the condenser outlet. The working principal of a DCCLHP is similar to that of LHPs, which is detailed by Maydanik et al. [15,16]. In brief, liquid is vaporized in the vapor grooves when LHPs start to work. The menisci formed in the evaporator wick develop capillary pressure to push the vapor through the vapor transport line to the condenser where fluid condenses and heat is rejected. The condensed liquid is pushed back through the liquid transport line, generally through a bayonet, to the evaporator core and two compensation chambers. For convenience, the compensation chamber without the bayonet inside is defined as CC1 and the other one is called CC2.

The DCCLHP used in the experiment is an ammonia-stainless steel type having a nickel wick with designed maximum capillary pressure of 90 kPa. Ammonia of purity higher than 99.999% is charged into the heat pipe under ambient temperature and a system pressure of ~5 Pa. The charging ratio is controlled at 77.8%. Fig. 2 shows the system setup with amplified views of two CCs and the condenser, and Table 1 summarizes the geometric parameters of each component. Transparent windows are installed on the CCs and partly on the condenser to achieve the visualization. The bayonet is extended to the middle point of the evaporator core so that it could push gas or vapor bubbles out of the evaporator core at any orientation. No secondary wick is constructed between the evaporator core and CCs in this experiment as the evaporator core can always be flooded by liquid for terrestrial experiments thanks to the employment of two CCs. The vapor and liquid transport lines, and condenser line are all stainless steel smooth-walled tubes. Before the experiment, the whole system is vacuum tested

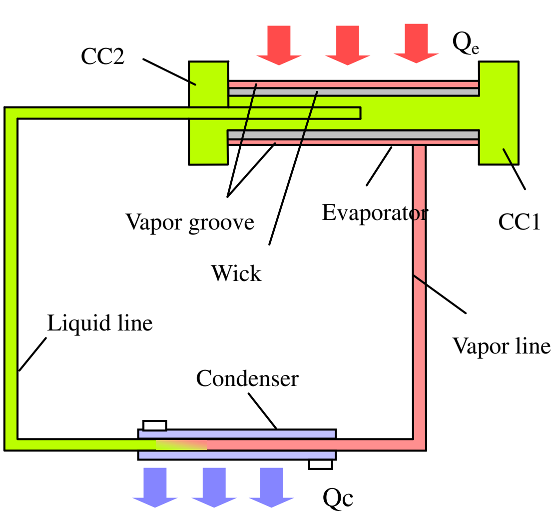
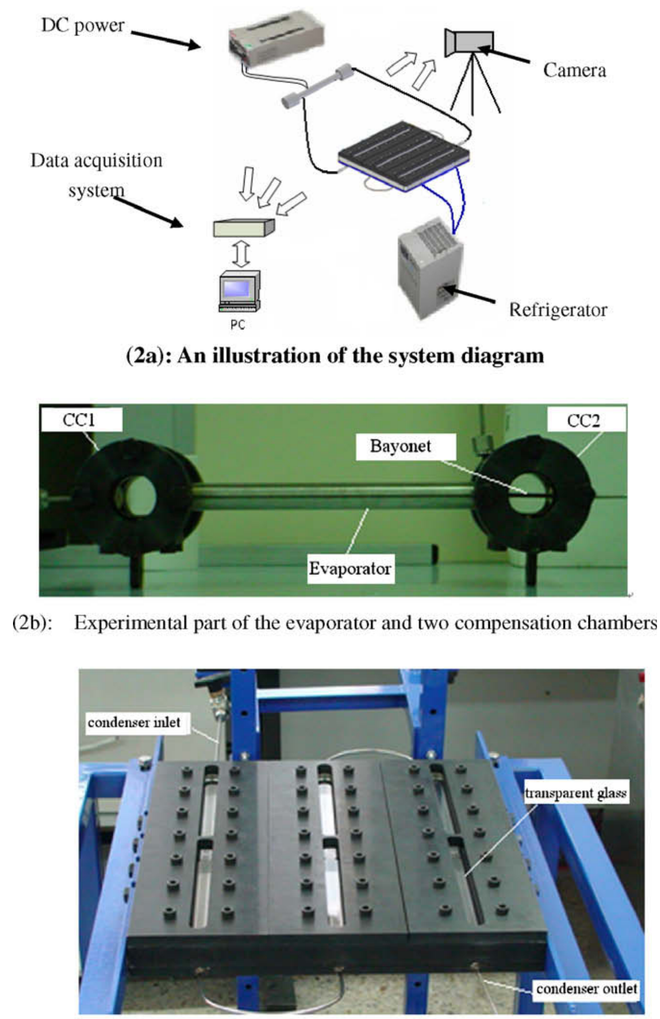


Fig. 1. A schematic illustration of a dual compensation chamber loop heat pipe.



(2a): An illustration of the system diagram

(2b): Experimental part of the evaporator and two compensation chambers

(2c): Experimental part of the condenser

Fig. 2. The experimental system.

Table 1
Geometric parameters of the experimental DCCLHP.

Components	Dimensions
o.d./i.d. × length of evaporator/mm	Φ18/16 × 190
o.d./i.d. × length of vapor line/mm	Φ3/2 × 2500
o.d./i.d. × length of liquid line/mm	Φ3/2 × 2500
Height/width × length of Condenser/mm	2.5/2.5 × 1800
Volume of CC/ml	24.7 × 2
Working fluid inventory/g	50
Maximum radius of Wick/μm	1.1
Porosity of Wick	55%
Permeability of Wick/m^2	>5 × 10^{-14}
o.d./i.d. × length of Wick/mm	16/6 × 160
Number × height × width of vapor grooves/mm	6×1 × 1

to check any leakage and the system capillary pressure is tested that fully satisfies the design requirement.

Beside the components, the experimental system includes a heater, a heat sink, a CCD camera and a data acquisition system (DAQ). In the experiments, heat load to the evaporator is provided by a thin-film electric resistance heater, which is attached directly to the evaporator symmetrically and adjusted by a DC power supply with variable input voltages. The thermal mass of the film electric resistance heater is designed to be small to supply uniform