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Research Paper

Two-phase flow pattern based theoretical study of loop heat pipes

Chih-Yuan Weng, Tzong-Shyng Leu *

Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 70101, Taiwan

HIGHLIGHTS

- A new two-phase flow pattern based theoretical modeling is proposed for LHP.
- The proposed LHP model is for condensation tube diameter design ranging from 1 to 5 mm.
- MAPE of LHP compensation chamber temperature shows only 2.00% in FCM operation mode.
- More detailed characteristics within LHP can be obtained by the proposed model.

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ABSTRACT

Loop heat pipes (LHPs) are passive heat transport devices using capillary structures to circulate the working fluid. In this study, several theoretical models based on conservation equations in the system are used to evaluate the characteristics of LHPs. In addition, while computing the characteristics of two-phase flow within LHP, the progression of the flow regimes in the condensing tube is specially considered by adopting proper two-phase flow pattern map. In this study, the comparison between the experimental and theoretical results of new proposed model achieves the smallest mean absolute percentage error (MAPE) of 2.00% in the fixed conductance modes among all existing models. It has been shown that the characteristics of LHP can be better predicted by using new proposed model with consideration of the surface-tension influence on two-phase flow pattern map within condensation tube diameter ranging from 1 mm to 5 mm.

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1. Introduction

The technology of loop heat pipes (LHPs), first employed in spacecraft [1], was developed in the 1970s. Over the past decade, LHPs have been extensively investigated both experimentally and numerically. The visualization of the LHP has been explored by several researchers. Cimbala et al. [2,3] first studied the flow visualization of an LHP by neutron radiography and radioscopy. Via neutron radioscopic images, slug flow and the vapor/liquid interface were observed. Others [4–6] have studied the visualization of fluid-flow and phase-change phenomena by using transparent materials such as glass, plastic tubes or plexi-glass. A variety of flow patterns, including bubbly, slug, wavy flow and annular, were observed according to different tube sizes. These results demonstrated that different flow patterns exist in LHPs.

Additionally, steady-state models of the LHP have been developed by numerical methods and verified with experimental results. Kaya and Hoang [7] developed a mathematical model based on the energy conservation equations of the loop. Their model used two-phase multiplier method to calculate the pressure drop and heat transfer coefficient of the condenser. Based on Kaya and Hoang's model, numerous studies have since been dedicated to improving the steady-state models of LHPs. Chuang [3,8] enhanced the steady-state model with the gravity-assisted model to analyze the non-horizontal operating performance. Calculations of the two-phase characteristics were obtained by the two-phase multiplier method. Further refinement of the LHP models was conducted by Bai et al. [9], for which working-fluid inventory in the compensation chamber was computed. Their model was based on annular-flow convective condensation to estimate the performance of condenser. Recently, Lin et al. [10] developed a model that considers the effect of the pore-size distribution in wick structure. The two-phase multiplier method was adopted to calculate the characteristics of the condenser.

Nevertheless, the entire flow map of two-phase flow in a condensation tube included four types of flow patterns [11], namely wavy and stratified flow, intermittent flow (slug and plug), annular flow, and bubble flow. Through fundamental studies, two-phase flow regime maps have been developed to predict the distinctions between flow patterns [12–14]. The Taitel and Dukler's [13] flow map is based on the theoretical analysis of the flow-transition mechanism, and is the most widely adopted by investigators studying

* Corresponding author. Tel.: +886 6 2757575 ext. 63638; fax: +886 6 2389940.
E-mail address: tsleu@mail.ncku.edu.tw (T.-S. Leu).

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the phenomenological maps of two-phase flow. Moreover, the Taitel and Dukler's flow map shows good agreement with large diameter tubes ($D_h > 10$ mm) but poor flow-regime predictions of small tubes ($D_h < 10$ mm) [15–17]. To improve the Taitel and Dukler flow map, Tabatabai and Faghri [18] proposed a flow-regime map that takes into account the influence of surface tension for small condensation tubes ranging from 1 to 5 mm. Cavallini et al. [19] and Thome et al. [20,21] developed multiple-flow regime models to compute the heat transfer coefficients and pressure drops during the condensation process by the experimental data of refrigerants for 3–21 mm tube diameter. In addition, based on numerous models and experimental databanks for condensing two-phase flow regimes, Mishkinis and Ochterbeck [22] selected several methods of heat transfer coefficient and pressure drop by comparing with experiments and Taitel and Dukler's flow regime map to calculate the condensation performances within the 6 mm tube. Furthermore, Adoni et al. [23] presented a model adopting Thome's condensing correlations to study the performance of an LHP, but the condensing section results were not discussed in depth.

From the above studies, the operating characteristics and phenomena of LHPs can be analyzed by steady-state model. However, most of the current existing physical models adopted two-phase multiplier method to estimate two-phase pressure drop and heat transfer within an LHP. In this paper, a new mathematical model of an LHP is proposed that accounts for the two-phase flow patterns inside the condenser. Results of the LHP are also compared with Chuang's experimental data [3]. Finally, the two-phase flow patterns inside the condenser of an LHP can be predicted by using new proposed model.

2. Mathematics of the loop heat pipe

A steady-state model is developed to predict the operation condition of an LHP based on mass, momentum and energy conservation. The assumptions of the proposed model are as follows:

1. The mass and heat transfer through the wick occur only in the radial direction.
2. The LHP transfers heat by natural convection to the ambient air. The evaporator and the vapor line are assumed to be insulated to prevent any heat exchange.
3. The roughness of the pipes and the minor effects of bends, fittings and valves are neglected.
4. Based on the steady-state LHP model of Kaya and Hoang [7], the filling mass of working fluid is not considered in the current paper, too.

In the following subsections, the conservation equations are developed for all control volumes within an LHP system. The schematic of the LHP model is divided into four control volumes to analyze the energy balance, as shown in Fig. 1.

2.1. Mass conservation of an LHP

The conservation of mass in each control volume can be written as:

$$\sum_i (\dot{m}_i)_{in} = \sum_i (\dot{m}_i)_{out} \quad (1)$$

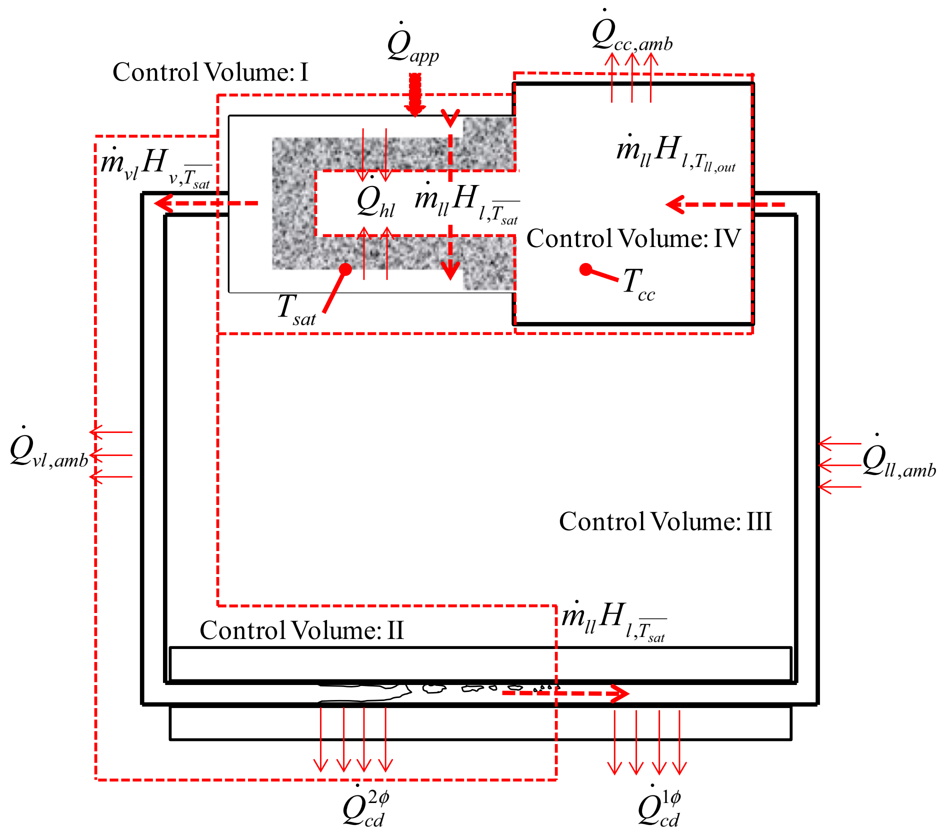

Fig. 1. Schematic of the LHP with control volumes.

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