International Journal of Thermal Sciences 89 (2015) 372–386

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Complete analytical model of a loop heat pipe with a flat evaporator

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form
30 September 2014
Accepted 12 November 2014
Available online 24 December 2014

Keywords:
Loop heat pipe
Analytical
Modelling
Sensitivity analysis

ABSTRACT

A steady-state analytical model has been developed to determine the thermohydraulic behaviour of a loop heat pipe with a flat evaporator. Its main originality lies in the combination of energy balance equations for each component of the system with 2D analytical solutions for the temperature field in the evaporator. Based on Fourier series expansion, heat transfer in the wick as well as in the evaporator casing are accurately modelled, enabling a thorough consideration of the parasitic heat fluxes. The model is based on the thermal contact resistance between the wick and the casing, the thermal conductivity of the wick and the accommodation coefficient. This analytical method offers a simple solution that can be implemented in LHP design analysis without the need of large computational resources. A sensitivity analysis has been carried out to evaluate the influence of several parameters on the LHP behaviour. The results show that the main parameters of the model are independent. Therefore, they could be experimentally determined using an appropriate test bench with only few temperature measurements. The model has been validated with a set of experimental data from the literature. A good agreement is found between the theoretical and the experimental results.

1. Introduction

Loop Heat Pipes (LHP) are two-phase cooling systems able to passively transport high amounts of heat over distances up to several meters. Developed in the 1970's, these devices have proven their reliability in many spatial applications and are now candidates for terrestrial cooling solutions. Indeed, their specific design offers robustness and flexibility for a wide variety of practical applications [1,2].

As a consequence, many efforts have been dedicated to understand their operation in order to optimize their design. An LHP is a complex thermal system including an evaporator connected to the heat source, a condenser to dissipate the heat load and vapour and liquid lines to transport the working fluid between both components. Coupled thermo-hydraulic phenomena govern the LHP behaviour and need to be understood to enable a correct system designing. Parameters such as evaporation efficiency, heat losses to the ambient and parasitic heat flux in the evaporator as well as condensation heat transfer can be of great influence on the loop operation.

A lot of papers concerning LHP complete modelling can be found in the literature [3–6]. However, these numerical models often imply complex algorithms and large computational resources which are not always available for upstream pre-design applications. An analytical model offers the advantage to provide a solution without an excessive computing time and that can be easily implemented. Some analytical models of LHP are found in research works. Maydanik et al. [7] (cited by Launay et al. [8]) suggested a closed-form solution of an LHP analytical model establishing the energy balance in the reservoir and the pressure balance in the whole system. Furukawa [9] developed a complete analytical model of an LHP able to enhance the sizing of the system and to study the influence of many geometrical parameters on the loop operation. However, the model requires the operating temperature as input parameter. Yet in most cases, the evaporator temperature is the main expected output of an LHP model. Launay et al. [8] proposed closed-form expressions of the operating temperature of the LHP, for both the variable and the fixed conductance mode. Their model is based on energy balance equations on each system component and on thermodynamic equations. The thermal links in the reservoir are defined as equivalent thermal resistances. Their solution is a useful tool in the LHP design. However, the heat transfer in the evaporator is not accurately determined and has to be adjusted in accordance with experimental data. The purpose of the present study is to present a complete analytical model of a

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http://dx.doi.org/10.1016/j.ijthermalsci.2014.11.014
1290-0729/

Loop Heat Pipe accurately taking into account heat and mass transfer in the evaporator structure. The model is developed for a flat disk-shaped evaporator geometry. This model is based on the analytical study of Launay et al. [8]. However, the present study rests upon two 2-D analytical solutions describing the temperature field in the wick and the evaporator casing. Both solutions enable to determine parasitic heat losses through the wick and the evaporator body, the sensible heat given to the liquid flowing through the porous structure as well as the heat dissipated by evaporation at the wick–groove interface. A similar approach was implemented in the case of conventional heat pipes by Lefèvre and Lallemand [10] and later extended by Lips and Lefèvre [11]. These features, coupled with energy balances and thermodynamic relationships in the rest of the LHP, give a simple solution for the operating temperature. An iterative procedure is implemented to calculate the two-phase length in the condenser.

2. Model description

2.1. Analytical model of the LHP

The thermal state of the complete LHP can be determined using energy balance equations and thermodynamic relationships. Fig. 1 presents the operating principle of the LHP and the links between its components.

The total heat load to be dissipated by the evaporator Q_{in} is conducted through the wick or through the evaporator body so that:

$$Q_{in} = Q_w + Q_b \tag{1}$$

The wick is assumed to be fully saturated with liquid. The thermal heat flux Q_w is transversally conducted through the evaporator wall, the wall–wick interface and then divides up: a part Q_{ev} is evaporated at the wick–groove interface whereas the rest is dissipated by conduction and convection with the liquid flowing through the porous structure and with the liquid in the reservoir. Q_b is conducted longitudinally through the evaporator wall to the reservoir and a part of it, $Q_{ext,e}$, is given by convection to the ambient. Both the heat flux through the wick Q_w and the heat flux conducted through the evaporator casing Q_b are functions of the reservoir, the groove, the wick and the evaporator temperatures T_r, T_v, T_{we} and T_e. The same dependence applies for Q_{ev} and $Q_{ext,e}$:

$$Q_w = f(T_r, T_v, T_e) \tag{2}$$

$$Q_{ev} = \dot{m}_l h_{lv} = f(T_r, T_v, T_{we}) \tag{3}$$

$$Q_b = f(T_r, T_e) \tag{4}$$

$$Q_{ext,e} = f(T_r, T_e) \tag{5}$$

$Q_{ext,e}$ is also a function of T_{ext}, which is a given data of our model. As a result, the heat load Q_{in} can also be expressed as a function of these four temperatures:

$$Q_{in} = f(T_r, T_v, T_{we}, T_e) \tag{6}$$

An analytical expression of Q_{in} will be derived in subsections 2.2 and 2.3. The part of Q_w that is not dissipated by evaporation is the transversal parasitic heat flux. Part of this flux is conducted through the wick and released to the reservoir whereas the rest is dissipated by convection due to the liquid flow inside the porous structure. At the interface between the wick and the evaporator envelope, there is a temperature gap $T_e - T_{we}$ due to a contact resistance R_c defined as:

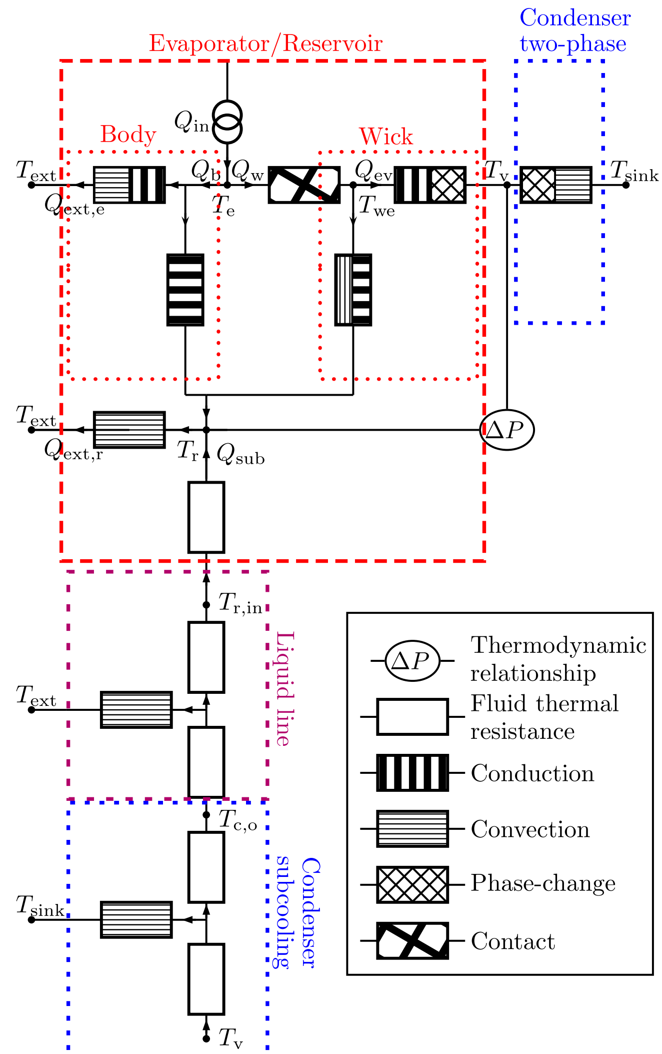

Fig. 1. LHP schematic nodal network.

$$R_c = S_c \frac{T_e - T_{we}}{Q_w} \tag{7}$$

where S_c is the contact surface between the wick and the evaporator body and T_e and T_{we} are the temperatures on the envelope side and on the wick side, respectively.

A global heat balance on the evaporator/reservoir gives the following equation:

$$Q_{in} = Q_{ev} + Q_{sen} + Q_{sub} + Q_{ext,e} + Q_{ext,r} \tag{8}$$

where Q_{sen} is the sensible heat given to the liquid, Q_{sub} is the subcooling due to the liquid entering the reservoir and $Q_{ext,r}$ is the heat flux dissipated to the ambient by the reservoir. The determination of Q_{sen} and Q_{sub} leads to:

$$Q_{sen} = \dot{m}_l c_{p,l} (T_v - T_r) \tag{9}$$

$$Q_{sub} = \dot{m}_l c_{p,l} (T_r - T_{r,in}) \tag{10}$$

where $T_{r,in}$ is the temperature of the liquid coming from the condenser and flowing back to the reservoir.

To evaluate the heat transfer given by the reservoir to the ambient, it is assumed that its surface is at a uniform temperature