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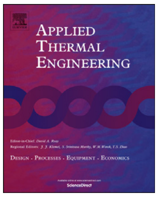

Literature review: Steady-state modelling of loop heat pipes

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HIGHLIGHTS

- This paper is a review of LHP modelling over the past 15 years.
- The physical mechanisms influencing the LHP performance are described.
- Different modelling approaches are compared.
- Few studies combine a complete LHP analysis with a precise evaporator description.

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ABSTRACT

Loop heat pipes (LHPs) are efficient and reliable heat transfer systems whose operation is based on the liquid–vapour phase-change phenomenon. They use the capillary pressure generated in a porous structure to passively circulate the fluid from a heat source to a heat sink. In this paper, an exhaustive literature review is carried out in order to investigate the existing steady-state models of LHPs. These models can be divided into three categories: numerical models of the entire system, numerical models of the evaporator and analytical models. The parameters and physical mechanisms taken into account in the different approaches are described and compared. Finally, a synthesis summarizes all the steady-state models from the literature in a comprehensive table where all the parameters having an influence on the system performance are listed. The review shows the evolution of the modelling works in the past 15 years and highlights the increasing development of 3D investigations.

1. Introduction

Loop Heat Pipes (LHPs) are efficient heat transfer devices based on the liquid–vapour phase-change phenomenon. They provide a passive heat transfer between a heat source and a heat sink, using the capillary pressure to circulate the fluid. Compared to conventional heat pipes, LHPs offer several advantages in terms of flexibility, operation against gravity and heat transport capability.

Since their first successful applications in the aerospace industry, LHPs have gained a major interest in aeronautics and terrestrial applications. As a consequence, many experimental works have been published to provide useful data to understand the physical mechanisms governing these systems in various operating conditions (against the gravity, cryogenic applications, start-up behaviour, etc.) and to optimise their design (choice of the working fluid, material of the wick, geometry of the evaporator, etc.). At the same time, many theoretical studies have been undertaken to predict accurately the behaviour of LHPs, in particular the coupled phenomena occurring in the evaporator/reservoir structure.

Several literature reviews on LHPs are already available. Ku [1] presents an extensive analysis of the operating characteristics of loop heat pipes. After explaining the operating principles and the thermohydraulics of LHPs, the authors investigate the LHP behaviour (operating temperature, temperature control, start-up, hystereses, shut-down) and the effect of the evaporator mass, the elevation, the non-condensable gases and the heat losses to the ambient on the LHP operation. Several LHP designs are also discussed.

Maydanik [2] also presents a review of developments, results of theoretical analyses and tests of LHPs. The paper mainly deals with LHP designs and applications. Various types of LHPs (large, controllable, ramified, reversible, miniature) are compared and the LHPs for both spacecraft applications and electronics cooling are presented.

An extension of these works is given by Launay et al. [3]. The authors present an exhaustive review of the parameters affecting the LHP steady-state operation. An extensive analysis of the operating limits of LHPs is also provided.

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A review from Ambirajan et al. [4] is also available in the literature. After explaining the fundamental concepts of the LHP behaviour, the authors discuss the construction details, the operating principles and the typical operating characteristics of LHPs. The paper also presents current developments in modelling of thermohydraulics and design methodologies. The review of the modelling studies is, however, far from exhaustive and needs a further analysis.

Launay and Vallée [5] present an exhaustive overview of the experimental studies published between 1998 and 2010. This review provides a database of experimental results and highlights some omissions in the published works that make the data difficult to use for further studies.

Recently, Maydanik et al. [6] presented a literature review of developments and tests of LHPs with flat evaporator designs. The authors discuss the various geometrical configurations (disk-shaped, rectangular, flat-oval) and the working fluids that may be used in each case. Then, the modelling works on flat evaporators are presented and the applications of such systems are discussed.

Wang and Yang [7] carry out a review on loop heat pipes dedicated to use in solar water heating. After analysing the working principles of LHPs and discussing the existing experimental and theoretical works, the authors further investigate the opportunities of using solar water heating systems with LHPs.

No exhaustive review on LHP steady-state modelling studies exists in the literature. This paper intends to introduce a comprehensive review of the existing theoretical works on this subject that have been published since 1999. This work should help to give a global view of the existing models in the literature and to point out their similarities and differences. It also highlights the physical mechanisms involved in LHPs that are today still not appropriately taken into account in most of the investigations.

Most of the theoretical models of LHPs can be divided into three categories: numerical models that take into account all the LHP components, numerical descriptions of the evaporator or a part of it and analytical approaches. In the following, all the detailed models have been developed using in-house code, unless otherwise stated.

2. Complete numerical LHP models

The majority of complete numerical LHP models are based on a volume element discretisation or on electrical analogies and describe the whole device as a nodal network. The links between the nodes are represented by thermal resistances or conductances and the energy balance equation is applied to each node.

The flow in the transport lines and in the condenser strongly influences the operation of loop heat pipes and various methods can be implemented to determine the pressure drops and the heat transfer coefficients, particularly in the two-phase region. However, since comprehensive theoretical studies on the characterisation of flow already exist in the literature, they will not be detailed in the present paper. The most common models to calculate the frictional pressure drops and the condensation heat transfer coefficient in a horizontal tube can be found in the extensive studies of Collier and Thome [8] and Thome [9]. For a modelling analysis of condensation flows specific to loop heat pipes, the reader may also refer to the works of Goncharov et al. [10] and Miscevic et al. [11].

Kaya et al. [12] develop a mathematical model of a loop heat pipe based on the steady-state energy balance equations at each component of the system. A cylindrical evaporator is considered. The following main assumptions are used in the development of the model:

- The heat transfer through the wick is directed only towards the radial direction.
- The compensation chamber and the evaporator core contain both liquid and vapour phases.
- The LHP reaches steady-state for a given loop condition.

The total heat load to be dissipated Q_{in} is equal to the sum of the heat rejected in the two-phase portion of the condenser (latent heat) Q_c, the parasitic heat leak Q_{hl} and the heat losses from the vapour line to the ambient Q_{vl-a}:

$$Q_{in} = Q_c + Q_{hl} + Q_{vl-a} \tag{1}$$

In the evaporator, the heat leak compensates the subcooling of the returning liquid Q_{sc} and the heat losses from the compensation chamber to the ambient Q_{cc-a}:

$$Q_{hl} = Q_{sc} + Q_{cc-a} \tag{2}$$

To calculate the heat leak, the authors only consider conduction through the wick, which can be written as:

$$Q_{hl} = \frac{2\pi\lambda_{eff}L_w}{\ln\left(D_{w,o}/D_{w,i}\right)}\Delta T_{ac,w} \tag{3}$$

where λ_{eff} is the effective thermal conductivity of the wick, L_w its length and $D_{w,i}$ and $D_{w,o}$ its inner and outer diameters, respectively. The temperature across the wick $\Delta T_{ac,w}$ is the difference between the local saturation temperatures caused by the total system pressure drops ΔP_{total}, excluding the pressure drop in the wick structure ΔP_w:

$$\Delta T_{ac,w} = \left(\frac{\partial T}{\partial P}\right)_{sat}(\Delta P_{total} - \Delta P_w) \tag{4}$$

The slope of the vapour–pressure curve $(\partial T/\partial P)_{sat}$ can be calculated using the Clausius–Clapeyron relation. The total pressure drops in the system consist of the frictional steady-state pressure drops in the vapour line ΔP_{vl}, the liquid line ΔP_{ll}, the condenser ΔP_c, a potential subcooler ΔP_{sc}, the bayonet ΔP_{bay}, the porous structure ΔP_w and the vapour grooves ΔP_{vgr}. If the LHP is not in horizontal orientation, the pressure difference associated with the gravity effects ΔP_{grav} also needs to be taken into account:

$$\Delta P_{total} = \Delta P_{vl} + \Delta P_{ll} + \Delta P_c + \Delta P_{sc} + \Delta P_{bay} + \Delta P_w + \Delta P_{vgr} + \Delta P_{grav} \tag{5}$$

The authors employ single-phase correlations to calculate all the frictional pressure drops and take into account the flow regime (laminar or turbulent) in the calculation. The relevant properties of the fluid are calculated with respect to the saturation temperature T_{sat}. Two distinct correlations are used to estimate the effective thermal conductivity of the wick. To determine heat losses to the ambient, the authors test either a natural convection hypothesis or a radiative hypothesis.

The two-phase heat removal in the condenser consists of two parts: heat rejection to the sink and heat losses to the ambient. The length of the two-phase flow portion in the condenser $L_{c,2\varphi}$ is then given by:

$$L_{c,2\varphi} = Q_c \int_{x_{in}}^{x_{out}} dx \left[(UA/L)_{c,s}\left(T_{sat} - T_{sink}\right) + (UA/L)_{c,a}(T_{sat} - T_{amb})\right]^{-1} \tag{6}$$

where $(UA/L)_{c,s}$ and $(UA/L)_{c,a}$ are the thermal conductance per unit length from the surface of the condenser to the heat sink and to the ambient, respectively and x is the thermodynamic quality of the

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