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# Non equilibrium lumped parameter model for Pulsating Heat Pipes: validation in normal and hyper-gravity conditions

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ABSTRACT

As relatively new and promising members of the wickless heat pipes family, Pulsating Heat Pipes, with their high effective thermal conductivity, construction simplicity, low weight, and potential high power loads may answer the present industry demand of high heat transfer capability, efficient thermal control, flexibility and low cost. Numerous are the attempts to simulate their complex thermal behavior, but none of the existing models is validated for transient operative conditions and under various gravity levels. Thus, a novel lumped parameters model able to compute the steady state as well as the transient performance of PHPs has been developed. It consists of a two-phase separated flow model applicable to a confined operating regime (slug–plug flow). A complete set of balance differential equations accounts for thermal and fluid-dynamic phenomena. The main originalities of this tool lay in the suppression of the standard assumption of saturated vapor plugs as well as in the consequent embedding of heterogeneous and homogeneous phase changes. In addition, an experimental work has been carried out with a 16 turns copper capillary PHP filled with FC-72. Therefore, the model has been validated in several operative conditions and under various gravity levels by comparison with these experimental data both in normal and hyper-gravity conditions showing very good prediction capability.

## 1. introduction

Heat transfer systems are somewhat ubiquitous: they can be found in electronic devices, energy management components, in transportation, cooling and in households in general. The demand for higher performances, efficient thermal control and low cost has pushed researchers to develop a new generation of two-phase flow systems, mainly based on the phase change of a working fluid. However, the development of reliable devices, calls for a thorough understanding of fundamental principles and their modeling. In the past decades, wickless two-phase passive systems were born to meet industrial requests: such technologies, like Pulsating Heat Pipes (PHPs), have, indeed, an extremely high potential in terms of simplicity and, consequently, low cost.

Patented by Akachi in the '90 [1–2], a PHP consists of a capillary loop with alternated heating and cooling zones evacuated and partially filled with a working fluid. Due to capillary forces, a train of vapor bubbles and liquid slugs is usually generated within the channel, although this is not the only flow pattern recognizable in an operating PHP. Indeed, in particular conditions, other possible fluidic paths characterized by separation of vapor and liquid phase can appear (e.g. annular, stratification) [3]. When heat is provided to the evaporator section, the temperature increases, liquid evaporates, vapor pressure raises and a chaotic motion (i.e. oscillation and circulation) is induced within the channel pushing the train of fluidic elements towards the condenser section. In this zone at relatively lower temperature, vapor pressure decreases, condensation occurs and heat is rejected to the external environment.

The PHP thermal–hydraulic behavior is complex and, up to now, not fully defined, since it involves intricate thermal and fluidic dynamics as well as homogeneous and heterogeneous evaporation/condensation effects at the interface between the coexisting vapor and liquid elements. In addition, there is an interplay between phase change phenomena, capillary forces and gravity which may help or damp the fluid motion. Experimental studies on PHPs operating under different acceleration loads [4–11] have

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## Nomenclature

*Latin symbols*

| | |
|---|---|
| $A$ | cross flow area [m$^2$] |
| $A_{ex}$ | external lateral area [m$^2$] |
| $A_{wf}$ | internal lateral area [m$^2$] |
| $a$ | acceleration [m s$^{-2}$] |
| $c_V$ | specific heat constant volume [J kg$^{-1}$ K$^{-1}$] |
| $d_{in}$ | diameter [m] |
| $f_\tau$ | friction coefficient [–] |
| $g$ | gravity acceleration [m s$^{-2}$] |
| $H$ | enthalpy [J] |
| $h$ | convection coefficient [W m$^{-2}$ K$^{-1}$] |
| $h_l$ | liquid specific enthalpy [J kg$^{-1}$] |
| $h_v$ | vapor specific enthalpy [J kg$^{-1}$] |
| $h_{LV}$ | latent heat of vaporization [J kg$^{-1}$] |
| $k$ | thermal conductivity [ m$^{-1}$ K$^{-1}$] |
| $L$ | length [m] |
| $L_x$ | thermal entry length [m] |
| $m$ | mass [kg] |
| $m_{LV}$ | evaporated/condensed mass [kg] |
| $N$ | number of elements [–] |
| $Nu$ | Nusselt number [–] |
| $p$ | pressure [Pa] |
| $Pr$ | Prandtl number [–] |
| $Q$ | heat power [W] |
| $q_{ex}$ | external heat flux [W m$^{-2}$] |
| $q_{wf}$ | heat flux between wall and fluid [W m$^{-2}$] |
| $R^*$ | gas constant [J kg$^{-1}$ K$^{-1}$] |
| $Ra$ | Rayleigh number [–] |
| $Re$ | Reynolds number [–] |
| $T$ | temperature [K] |
| $t$ | time [s] |
| $U$ | internal energy [J] |
| $u$ | specific internal energy [J kg$^{-1}$] |
| $V$ | volume [m$^3$] |
| $w$ | velocity [m s$^{-1}$] |
| $x$ | axial coordinates [m] |
| $y$ | axial coordinates [m] |

*Greek symbols*

| | |
|---|---|
| $\Delta t$ | time step [s] |
| $\varepsilon$ | surface roughness [m] |
| $\vartheta$ | inclination to horizontal [rad] |
| $\rho$ | density [kg/m$^3$] |
| $\sigma$ | surface tension [N m$^{-1}$] |

*Subscripts*

| | |
|---|---|
| $f$ | fluidic |
| $hom$ | homogenous phase change |
| $het$ | heterogeneous phase change |
| $l$ | liquid |
| $sat$ | saturated conditions |
| $v$ | vapor |
| $w$ | wall |
| $\infty$ | environmental |

*Acronyms*

| | |
|---|---|
| ANN | Artificial Neural Networks |
| BHM | Bottom Heated Mode |
| CFD | Computational Fluid Dynamics |
| CV | Control Volume |
| ESA | European Space Agency |
| FFT | Fast Fourier Transform |
| HTC | Heat Transfer Coefficient |
| LDC | Large Diameter Centrifuge |
| LS | Liquid Slug |
| ODE | Ordinary Differential Equations |
| PHP | Pulsating Heat Pipe |
| TC | Thermocouple |
| VP | Vapor Plug |

underlined a strong relationship between these complex phenomena and the PHP thermal response.

In the last two decades, many numerical works focused on the prediction of the actual PHP performance, but only few of them are capable of complete thermal–hydraulic simulations and even less are partially validated against experimental data ([12,13]). In addition, none of the existing models is validated for transient operations or under various gravity levels, even if hyper-gravity conditions commonly arise in several applications, from automotive to aerospace.

Since slug flow is the primary flow pattern in PHPs, most of the existing efforts have focused on it. The first analytical models developed to describe the PHP functioning were very simplified with many unrealistic assumptions. Two kinds of approaches can be usually recognized: the continuum wave propagation approach (e.g. [14,15]) which assumes pressure oscillations as fundamental to induce vapor-liquid circulation; the mass-spring-dampers approach applied to describe the motion of the liquid slug and vapor plugs as a train of linearized elements (e.g. [16,17]).

Wong et al. [18] developed the first numerical model describing an adiabatic slug flow in a capillary channel with a set of first order non linear differential equations. In the following, the non linear differential analysis, comprising or not heat transfer, became the standard way to acquire more insightful of PHPs thermal–hydraulic behavior. Most of these codes were simplified lumped parameters, one dimensional models, which assume saturated conditions and usually neglect the presence of the liquid film located between the internal tube wall and vapor plugs, even if its presence influences the performance of the device, as pointed out by Nikolayev et al. [19,20]. In 2005 Holley and Faghri [21] developed one of the most comprehensive numerical model concerning a PHP system. The 1-D lumped parameter model of a water PHP assumed, a priori, slug flow and saturated conditions. The momentum equation was solved for the liquid slugs, while the energy equation was considered for both phases and for the external wall. The model was able to account for liquid elements coalescence and new vapor formation although phase changes are not directly accounted for. Later Mameli et al. [22–24] improved Holley and Faghri model introducing the effects of the tube bends on the liquid slugs dynamic and the calculation of the two-phase heat transfer coefficient for liquid and vapor sections as function of the heating regime. Furthermore, an extended library of possible working fluid was included.

Recently attempts to model PHPs making use of Artificial Neural Networks (ANN, e.g. [25–27]) as well as Computational Fluid Dynamics (CFD, e.g. [28,29]) appear in literature. However, since the ANN approach does not include any physical model, it needs to be trained with large set of experimental data to provide results that, at the end, cannot be generalized. On the other hand, the CFD approach might achieve high modeling potential in the near future; however, up to now, such models lack of a thorough experimental validation. In addition, the CFD approach has too large