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Research Paper

On-line thermal regulation of a capillary pumped loop via state feedback control using a low order model

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HIGHLIGHTS

- Evaporator temperature regulation of a capillary pumped loop is proposed.
- Reduced models are built via Modal Identification Method from in situ measurements.
- The model-based control is achieved through a state feedback loop.
- The study is conducted for two types of disturbance: a smooth one and a sharp one.
- Results show the disturbance rejection for the sine signal.

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ABSTRACT

This study focuses on the regulation of a two-phase capillary pumped loop. The aim is to adjust the temperature and therefore the pressure in the reservoir in real time in order to reject the disturbance which occurs in the evaporator due to high-power cycles of electronic equipment. Regulation is achieved through a state feedback approach, which appeared to be very efficient for other fields of application. A very fast model of the thermal behavior of the loop is required. Low order models are elaborated via the Modal Identification Method. This model, built from in situ measurements, is valid around a nominal operating point where we can consider the behavior of the loop linear. A Kálmán filter is introduced in order to estimate the state of the system in real time. Two types of disturbance are considered: a slow and a fast one, in order to simulate a real power cycle. Results show that the control of the evaporator temperatures, adjusting the reservoir temperature, is quite satisfying when the disturbance variations are smooth in time. In this case, the objective, which is to limit the temperature variations at the evaporator, in order to avoid deterioration of the high-power electronics, is reached.

1. Introduction

Capillary Pumped Loops (CPLs) are highly efficient devices in regard to heat transfers, particularly in electronic and high-dissipation electronic cooling [1]. Two fundamental aspects must be highlighted:

- the heat transfer is induced by the latent heat of the working fluid and not by sensible heat as in conventional cooling circuits. The evacuated heat flux is increased by two orders of magnitude in comparison with a classical heat exchanger for a given mass flow rate;
- the CPL is an autonomous passive system: no external intervention (pump for example) is required for displacing the working fluid.

CPLs include an evaporator in which a porous wick is incorporated [2], a condenser and a reservoir. The condenser is a heat exchanger dedicated to vapor condensation and liquid subcooling. In the evaporator, when heat power is applied, the fluid motion is induced by capillary forces that arise in the menisci dispersed in the porous wick, where evaporation occurs. This porous medium is a key component of the loop.

The reservoir is a crucial part of the loop as it compensates for liquid volume fluctuations during operation and sets the temperatures of the cycle to an equilibrium state. Due to their separate two-phase reservoir, capillary pumped loops can easily be regulated with a heater. That requires a supply of energy, but allows

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Nomenclature

C_P	specific heat, J kg^{-1} °C^{-1}
F	state matrix
G	global input matrix
G_A	input matrix for actuator
G_D	input matrix for disturbance
h_{lv}	latent heat of vaporization, J kg^{-1}
H	global output matrix
K_f	gain matrix of Kálmán filter
n	LOM order i.e. size of vector δX
N_t	number of time samples
p	dimension of global input vector
q	dimension of global output vector
t	time, s
Δt	time step, s
T	temperature, °C
δP	power variation, W
δT	temperature deviation, °C
δU	global input vector
δX	state vector
$\widehat{\delta X}$	estimate of δX
δY	global output vector
δZ	output vector for controlled points
w_m	temperature measurement noise, °C

Greek symbols

α	ratio between standard deviations of measurement and disturbance noises
$\boldsymbol{\Theta}$	macro-matrix linking output to actuator deviations in the control problem
σ_D	standard deviation of disturbance noise, W
σ_{id}	mean quadratic discrepancy for LOM identification, °C
σ_m	standard deviation of measurement noise, °C
σ_{val}	mean quadratic discrepancy for LOM validation, °C
σ_Z	mean quadratic discrepancy between desired and obtained temperatures, °C
$\boldsymbol{\Psi}$	macro-matrix linking output to state deviations in the control problem

Subscripts

aver	average
evap	evaporator
nom	nominal configuration
res	reservoir
z	relative to controlled points

Superscripts

m	measured
T	transposition sign

Abbreviations

CPL	Capillary Pumped Loop
LOM	Low Order Model
MIM	Modal Identification Method
MPC	Model Predictive Control

precise temperature control and ensures the stability of the evaporator temperature whatever the heat load, rendering CPL performances easy to predict [1,3]. Another relevant factor is the effect of gravity: in a CPL, the positioning of the reservoir relatively to the evaporator is important: Joung et al. [4] have conducted an experimental investigation on a CPL with a reservoir located above the evaporator, thereby resorting to gravitational forces to permanently ensure the supply of liquid to the porous wick.

Based on these considerations, a capillary pumped loop was specifically designed in 2006 by Euro Heat Pipe, in order to meet the requirements of high-power electronics cooling for transportation applications (rail, automobiles, aviation). More precisely, the capillary pumped loop operated under the gravity field and had to extract extremely high heat power values (up to 5000 W for a single evaporator) under particularly harsh transient conditions. The *capillary pumped loop for integrated power* (CPLIP, or CPLTA for *capillary pumped loop for terrestrial application*) has already been studied by Lossouarn in his PhD thesis [5], along with Ayel et al. with the same experimental device [6] and Lachassagne et al., using a similar but better instrumented loop [7] and a steady-state modeling of this system [8]. Recently, Dupont et al. [9] presented an advanced version of this device, installed on a train as a demonstrator, comprising four evaporators and tested with methanol transferring a total heat power of 27.7 kW. The present CPLIP, described in the following section, is composed of an evaporator, a cylindrical reservoir in which the liquid returning into the evaporator flows through the lower part, and a condenser (Fig. 1).

Finally, a special feature of the present CPLIP is that the liquid flows through the reservoir before entering the evaporator: the reservoir can thus be better thermally controlled by means of a heater driven, for instance, by a PID regulator: it is constantly partially cooled by liquid when functioning, which leaves open the possibility for the reservoir temperature to exceed the set-point without making this irreversible. This ensures thermal stability in the reservoir and, therefore, in the overall loop. It is that specific feature that will be utilized in the context of this study, by acting on the control of reservoir temperature in order to actively regulate evaporator wall temperature, i.e. the electronic hot source temperature.

Thermal control of two-phase loops CPL (or LHP, Loop Heat Pipes) is an actual problem to be solved, as regulation of such devices is not a trivial task. In 2013, Goncharov et al. [10] reviewed more than twenty years of research and applications about methods of thermal control of loop heat pipes for space applications. The main methods are: heat input to the liquid line or, more efficiently, to the reservoir (or compensation chamber); creation of a heat exchange between liquid and vapor lines; application of cooling thermoelectric modules on the compensation chamber. This is performed by using an adapted control algorithm. Generally these methods, using external thermal action on loop elements, have no effect on the reliability of the LHP itself. More recently, Mishkinis et al. [11] presented experimental results of an efficient regulated "advanced control heat transfer loop" (ACHTL) with several evaporators and including a remote two-phase compensation chamber (RCC): each evaporator of the loop is attached to a liquid monophasic compensation chamber for stability and liquid supply, and the RCC is thermally controlled in such a way that its temperature is always above that of any attached compensation chambers. Through this design, the authors managed to guarantee stable and unfailing operation of the system, as well as precise temperature control of heat sources by improving the algorithm of control. Dupont et al. [12] also proposed the use of the introduction of a suitable amount of non-condensable gases in the separate reservoir of CPL for fully passive temperature control by pressure stabilization. This method, though not very accurate, proved to be efficient and reliable over time.