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Active flow control for cold-start performance enhancement of a pump-assisted, capillary-driven, two-phase cooling loop

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ABSTRACT

This paper discusses active flow control schemes for the cold-start performance enhancement of a pump-assisted, capillary-driven, two-phase cooling loop. A Proportional-Integral (PI) control algorithm was used to regulate the boiling condition (from pool boiling to thin-film boiling) in the evaporator and back pressure in the system during cold-start at low heat input. The active flow control improved the thermal resistance at low heat inputs by 50% compared to the baseline case using constant flow rate, while realizing a total pumping power savings of 56%. Temperature overshoot and its associated large temperature fluctuations occurring at cold-start were also investigated. A separate PI control algorithm was used to mitigate temperature overshoot and achieve a more stable start-up with smaller temperature fluctuations. A constant evaporator surface temperature of 60 °C with a variation of ±8 °C during start-up was accomplished. Evaporator thermal resistances as low as 0.10 cm^2-K/W were also observed.

1. Introduction

Excess power dissipation of electronic components in current and future space-based applications has increased the demand for highly efficient compact cooling systems capable of removing larger heat fluxes. In the past, the thermal demands of these systems have been met by capillary-driven, two-phase heat transport devices, such as heat pipes, capillary pumped loops (CPLs), and loop heat pipes (LHPs) [1]. But these devices may not meet the thermal demands of future space missions. Thermal loads driven by the demand for increased data acquisition capability and direct energy weapon systems, such as advanced radar systems for military applications, and increasing heat transport distances driven by larger, multi-mission, spacecraft are projected to outstrip the heat transport capabilities of passive capillary-driven devices [2–4]. Hybrid (pump-assisted and capillary-driven) two-phase cooling loops (HTPLs) [5–7] have been developed that can effectively raise the performance threshold of which passive systems are subject to.

The capillary pumping that makes passive thermal control devices effective in delivering working fluid to the heated surface also defines their performance limitation due to the limited capillary pressure head that can be developed. The maximum capillary pressure head, ΔP_c, that can be developed in a capillary-driven device is given by

$$(\Delta P_c)_{\max} = (P_v - P_l)_{\max} = \frac{2\sigma}{r_p} \tag{1}$$

where σ is the surface tension of the working fluid and r_p is the pore radius. The maximum capillary pumping pressure sets the limit for the total pressure drop that can be sustained in the system. The total pressure drop consists of the liquid (ΔP_l), vapor (ΔP_v), and gravitational (ΔP_g) pressure drops [8]. As such, this limits the effective length of the cooling system and the maximum heat load that can be applied. For an HTPL, the total pressure head is determined by the sum of the maximum capillary pressure head developed in the evaporator wick and the pressure head of the mechanical pump. As a result, the pressure head limit for an HTPL can be increased indefinitely by a proper selection of the mechanical pump.

The most important issues in the operation of the HTPL are those associated with cold-start. The HTPL suffers from many of the inherent problems also found in CPLs and LHPs (i.e. wick flooding, delayed startup, and temperature overshoot) [9–11]. For-the loop to reach start-up and prevent continuous flooding of the evaporator, the pressure inside the vapor chamber must be greater than the pressure in the liquid chamber ($P_v > P_l$). Furthermore, the vapor pressure must be high enough so that is can expunge most of the

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Nomenclature

A	area [m^2]
c	specific heat [J/kg-K]
e	error
K	gain
k	thermal conductivity [W/m-K]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [Pa]
Q	heat input [W]
R	thermal resistance [m^2-K/W]
r	radius [m]
T	Temperature [°C]
t	time [s]
U	uncertainty
X	measured variable
Y	calculated variable

Greek letters

Δ	difference
σ	surface tension [N/m]

Subscripts

c	capillary or chiller
e	evaporator or excess
g	gravity
h	heater
i	index
l	liquid
p	pore or proportional
s	surface
v	vapor

liquid from the vapor lines. For an HTPL, liquid pressure is a direct function of the pressure head generated by the mechanical pump; therefore, start-up is also a function of the pressure head developed by the mechanical pump.

Researchers have applied diverse methods to help mitigate issues during start-up and dynamic operation, but few researchers have examined the potential of active control schemes in two-phase cooling loops. Ambrose et al. experimentally investigated the performance of a pump-assisted, capillary-driven, loop heat pipe, where the system's pressure was controlled using regulating valves and orifices [12]. Active control using regulating valves and orifices is unrealistic for thermal control in spacecraft applications because such a system would add a significant amount of weight and complexity, thereby increasing the overall cost and reducing the overall reliability of the system. Wang et al. experimentally investigated the geometric parameters of an evaporator and their effect on start-up performance [13]. They found that start-up was a function of evaporator construction and that an increase in the thickness of the porous structure separating the liquid and vapor phases resulted in reduced heat leakage and improved start-up at lower heat inputs.

A mechanically pumped two-phase cooling loop developed for the temperature control of the AMS-O2 silicon tracker, a cosmic particle detector onboard the international space station, was reported on by Zhang et al. [3]. Thermoelectric modules and resistance heaters were used to vary the (saturation) pressure of the loop and control the (saturation) temperature using a PI control algorithm. They concluded that dryout in the evaporators could be suppressed by using a higher pump flow rate. Using the active flow control algorithm they developed, they were able to achieve temperature homogeneity and stability along the evaporator tubes with a temperature variation of ±0.5 °C.

Dong et al. proposed the use of fuzzy incremental control logic of an LHP for space cooling applications utilizing a variable emittance radiator adjusted by a MEMS louver [14]. They developed a mathematical model for the dynamic analysis and control of steady-state, transient, and start-up operation. Their numerical analysis found that the temperature overshoot and steady state error could be improved by approximately 50% when compared to a traditional PID controller.

Previous works have extensively studied various operational conditions of an HTPL [5–7]. These works used a constant pump speed (constant DC power supply) and relied exclusively on capillary-pumping to autonomously regulate the liquid supply to the boiling surface in the evaporator under variable heat inputs. Passive regulation of liquid flow rate is only effective once start-up has been achieved and a stable meniscus has been created in the wick structure. Furthermore, the use of constant pump speeds promotes the aforementioned problems associated with the cold-start of the HTPL and also represents a wasteful use of pumping power at low heat inputs [11].

This paper experimentally investigates and characterizes the thermal performance of an HTPL with active flow control for cold-start improvement. The main objective of the active flow control was to improve the inherent cold-start problems of HTPLs, specifically by achieving the following:

i. Lower the thermal resistance at low heat inputs during cold-start operation.
ii. Minimize temperature overshoot and achieve a more stable, constant temperature, start-up.
iii. Minimize pumping power consumption.

2. Experimental setup

To experimentally investigate the effect of active flow control on cold start performance, an experimental setup using an HTPL was constructed. Fig. 1 illustrates the experimental configuration of the HTPL. The system consists of a reservoir/condenser, a mechanical pump and a unique arterial evaporator. A liquid bypass line was used between the pump and evaporator to achieve lower flow rates and avoid pump stall. Sub-cooled liquid (distilled water) is mechanically pumped from the reservoir into the liquid chamber located inside the evaporator. Only a small fraction of liquid passes through the porous membrane via capillary action and enters the vapor chamber, the rest of the liquid (termed *excess liquid*) returns to the reservoir via the liquid return line. Capillary pumping pulls the liquid through the porous posts and saturates the porous media located on the surface of the heater block where it evaporates. The vapor exits the evaporator and returns to the reservoir via the vapor return line. An external chilling loop is used to condense the vapor inside the reservoir. A copper heater block is used to simulate a high heat flux electronics package that requires cooling. Heat is provided to the heater block by four cartridge heaters.

The system is monitored using a data acquisition system (Keithley, 2701) and an Excel add-in provided by Keithley. Ten T-type thermocouples (T1–T10) are used to monitor the temperature at relevant locations throughout the loop. Two micro-turbine flow meters (McMillan, 104) are used to monitor the flow rate entering, F1, and leaving, F2, the liquid chamber. A rotameter (Blue White Industries, F-450) is used to monitor the flow rate of the chilling fluid at F3. The liquid inlet and outlet pressure, P1 and P2, are