Applied Thermal Engineering 110 (2017) 481–494

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Two-phase mini-thermosyphon electronics cooling: Dynamic modeling, experimental validation and application to 2U servers

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HIGHLIGHTS

- Novel dynamic modeling of a microchannel-based thermosyphon is presented/validated.
- A geometry is proposed/simulated for the retrofitting of a commercial 2U-server.
- Both stable and unstable solutions are found for the steady-state.
- A riser diameter increase of 30% led up to 60% increase in flow rate.
- The flow self-redistributes into the highest heat load CPU during parallel cooling.

ARTICLE INFO

Article history:
Received 13 May 2016
Revised 6 July 2016
Accepted 28 August 2016
Available online 30 August 2016

Keywords:
2U server
Cooling
Flow boiling
Thermosyphon
Microchannels
Dynamic modeling

ABSTRACT

Gravity-driven cooling systems employing microchannel flow boiling can become a scalable and viable long term solution for the cooling of datacenter servers. In order to design this emerging type of cooling system, a new dynamic simulation tool using interconnected PDEs is described in the first part of the present paper followed by the validation of the modeling for both steady and dynamic regimes using a first-of-a-kind 15 cm-height thermosyphon test bench. A corrected error of 0.4 K was found for 7 different steady-state mean chip temperatures and heat load disturbances were predicted with the same 2-stage process presented here as the experimental results. The code was then used to predict the behavior of a mini-thermosyphon that would fit within the height of a 2U server. Multiple steady-state solutions were found with both stable and unstable operating states. A sensitivity study demonstrated that a 30% increase in the riser internal diameter led to 10–60% increase in the mass flow rate depending on the heat flux. Then, simulations with unbalanced heat loads showed that the flow gets self-redistributed into the CPU with the highest heat load, e.g. 1.7 times larger flow rate for a heat flux 3 times larger. Finally, heat load and water coolant flow rate disturbances were also simulated and discussed.

1. Introduction

1.1. Two-phase cooling system background

The paradigm shift from performance-driven to efficient computing is creating a demand for more innovative and efficient cooling concepts to minimize power consumption and cooling costs for ownership of data centers. Indeed, the power consumption dedicated to cooling in a datacenter can represent up to 45% [1] of the overall power consumption due to the necessity of CRAC units and fans to cool, dry and circulate the air used as coolant. While air-cooling is far from being obsolete, novel cooling technologies are emerging, among which single- and two-phase liquid cooling seems the most appealing. Single-phase water-cooled systems at the chip level are simple and demonstrate efficient heat transfer characteristics, allowing increased computational and power density. The Aquasar project [2] and the first commercialized "hot-water" cooled supercomputer, SuperMUC [3], were proofs of this emergent technology. As for two-phase cooling systems, additional benefits such as higher heat transfer coefficients, lower power consumption, constant coolant temperature, and dielectric nature of the coolant, to cite a few [4] makes this type of cooling concept even more appealing.

The trend for these new cooling technologies is to bring the coolant closer to the heat source in order to eliminate/minimize thermal resistances. When the heat sink is located directly on top of the heat source, it is referred as "on-chip" cooling. Two-phase on-chip cooling combines the small footprint area and large heat exchange surface of microchannels together with

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.198
1359-4311/

Nomenclature

A	flow cross sectional area, m^2
C_h	channel height, m
C_w	channel width, m
cp	specific heat capacity, $J\,kg^{-1}\,K^{-1}$
D_i	internal diameter, m
F_w	fin width, m
g	gravity, $m\,s^{-2}$
H, h	thermosyphon height, m AND enthalpy, $J\,kg^{-1}$
k_{Cu}	copper thermal conductivity, $W\,m^{-1}\,K^{-1}$
K_{fd}	gain for flow distribution, $kg\,s^{-2}\,Pa^{-1}$
K_{thermo}	gain for thermosyphon flow rate control, $kg\,s^{-1}\,Pa^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L_{ex}	widthwise exchanged length in condenser, m
L_{ME}	length of evaporator, m
M	mass of refrigerant, kg
$\dot{m}$	mass flow rate, $kg\,h^{-1}$
N_c	channel number in evaporator, –
P	pressure, Pa
P_{heat}	heated perimeter, m
Q	heat load, W
q	heat flux, $W\,cm^{-2}$
T, t	temperature, K AND time, s
th	thickness, m
U	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
u	velocity, $m\,s^{-1}$
V	volume, m^3
W_{ME}	width of evaporator, m
x	vapor quality, –
y	from chip to fluid direction, m
z	flow wise direction, m

Greek symbols

α	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
ΔP	pressure difference, Pa
ε	void fraction, –
η_f	fin efficiency, –
μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
Φ	diameter, m
ρ	mass density, $kg\,m^{-3}$
θ	orientation angle, rad

Subscripts

amb	ambient
base	related to the base of the evaporator package
branch	one of the two branches of the loop
cond	related to condenser
down	related to downcomer
dr	driving
evap	related to evaporator
fl	fluid
fr	friction
ftp	footprint level
l	liquid
lv	two-phase (liquid-vapor)
mom	momentum
p	related to package
pipe	related to piping
plate	related to double-finned plate of micro-condenser
ref	refrigerant, i.e. working fluid
riser	related to riser
sec	secondary coolant in condenser
sys	system
tot	total
ts	thermosyphon
v	vapor
w	wall

Acronyms

2U	measurement unit for server (=8.89 cm)
CPU	Central Processing Unit
CRAC	Computer Room Air Conditioning unit
FDR	Friction Dominant Regime
FR	Filling Ratio
GDR	Gravity Dominant Regime
LA	Liquid Accumulator
LSODE	Livermore Solver of Ordinary Differential Equations
MC	Micro-Condenser
ME	Micro-Evaporator
TDP	Thermal Design Power

the extremely high heat transfer performance of evaporating flow. Additionally, since the coolant can be at a higher working temperature due to the lower thermal resistance, heat recovery can become a profitable free source of thermal energy, to be redistributed for example to a District Heating Network or used for boiler feed water preheating in a power plant [5].

The ultimate cooling solution is to deploy efficient passive two-phase cooling systems, i.e. devices which rely on gravity and the resulting buoyancy to drive the two-phase refrigerant flow into the heat sink. Such a system is called a closed-loop two-phase thermosyphon and operates thanks to a difference of height and density, resulting in a driving potential that yields much higher flow and thus heat dissipation rates than capillary flow in heat pipes. A thermosyphon eliminates the need, cost, vibrations, and volume of a mechanical driver, such as a pump or a compressor, thus increasing the reliability of the system while decreasing its power consumption. It is understood, however, that some air cooling will still be required to cool the low power components in the server (memories, converters, power supplies, etc.), potentially about 10–20% of the total [6]. Hence, enhancement of the thermal performance, drastic reduction in power consumption, feasibility of energy reuse and inherent passive nature of the two-phase thermosyphon cooling system offer a wide range of solutions to thermal designers.

1.2. Two-phase thermosyphon principles and review

A schematic of a thermosyphon is given in Fig. 1. Such a system is composed of five main components: (i) the evaporator, which is where the heat is exchanged between the heat source and the evaporating fluid, (ii) the riser, in which the two-phase fluid flows upward, (iii) the condenser, which is where the fluid condenses by exchanging heat with a secondary coolant, (iv) the accumulator which has the role of self-adjusting the active mass of refrigerant (refer to Section 2.4) and (v) the downcomer, in which the single-phase liquid fluid flows downward.

The flow in the thermosyphon is due to a driving potential (ΔP_{dr}), which depends on the difference of height between the evaporator and the condenser, the gravity, and the difference of density between the riser (two-phase, low density) and the downcomer (single-phase, high density). In order to have an operating thermosyphon, this driving potential (see Eq. (1)) needs to overcome the mass flow rate dependent frictional (ΔP_{fr}) and momentum (ΔP_{mom}) pressure drop within the system. Thus by