Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

Experimental evaluation of a controlled hybrid two-phase multi-microchannel cooling and heat recovery system driven by liquid pump and vapor compressor

Duan Wu, Jackson Braz Marcinichen, John Richard Thome*

Laboratory of Heat and Mass Transfer (LTCM), Faculty of Engineering (STI), École Polytechnique Fédérale de Lausanne (EPFL), Station 9, CH-1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 6 August 2012
Received in revised form
6 November 2012
Accepted 8 November 2012
Available online 23 November 2012

Keywords:
Data center
Chip
Cooling
Heat recovery
Two-phase flow
Controller

ABSTRACT

The energy use in data centers is on an accelerating rise due to both demand and technological limitations. Today, the most widely used cooling strategy for data centers is refrigerated air-cooling. Unfortunately, air-cooling presents phenomenally low efficiencies. Therefore green computing paradigms are needed to improve energy efficiency by several orders of magnitude and allow a continued chip scaling for tackling the energy crisis in future-generation data centers. A promising solution would be implementing direct on-chip two-phase cooling technology, which not only improves the heat removal efficiency but also permits the reuse of waste heat since the two-phase coolant can cool CPUs effectively at 60 °C. In the present work a specific cooling cycle using micro-evaporation technology has been experimentally evaluated considering different aspects such as cooling cycle and energy recovery efficiencies and controllability. In resume, this novel cycle shows strong competence in energy usage, heat recovery and controllability towards green data center.

Evaluation expérimentale d’un système hybride et régulé de refroidissement diphasique à microcanaux et de récupération de chaleur entraîné par une pompe et un compresseur de vapeur

Mots clés : centre de données ; puce ; refroidissement ; récupération de chaleur ; écoulement diphasique ; régulateur

* *Corresponding author.* Tel.: +41 21 693 5894; fax: +41 21 693 5960.
E-mail address: jackson.marcinichen@epfl.ch (J.B. Marcinichen).
0140-7007/$ – see front matter © 2012 Elsevier Ltd and IIR. All rights reserved.
http://dx.doi.org/10.1016/j.ijrefrig.2012.11.011

Nomenclature

Roman

A_{SMV}	stepper motor valve aperture [%]
C	transfer function of the controller or empirically adjusted parameter
COP	coefficient of performance [–]
G	transfer function of the system
h	specific enthalpy [kJ kg^{-1}]
H	closed-loop transfer function
HL_{MMEs}	overall heat load on the MMEs [W]
K_C	PI proportional gain
K_I	PI integral gain
K_P	static gain of the system
$\dot{m}$	working fluid mass flow rate [kg s^{-1}]
p	position of the pole in the complex plan
P	pressure [bar] or scheduling parameter
Q	heat transfer rate [W]
Q_{input}	total input power applied on pseudo-chips and post heater [W]
T	temperature [°C]
T_I	PI integral time
u	system input
UA	overall conductance [W K^{-1}]
W_{input}	total input power applied on drivers and actuators [W]
$\dot{W}_{input}$	total input power of the two pseudo-chips [W]
W_{vsc}	compressor input power
x_o	outlet vapor quality [–]
y	system output
z	position of the pole in the complex plan

Greek

ΔT	temperature difference [°C]
ε_{cond}	condenser's effectiveness [–]
η_c	cooling cycle efficiency [–]
η_{hr}	heat recovery efficiency [–]
θ	transport delay, s
τ	time constant, s
τ_D	desired closed-loop time constant, s

Subscripts

cond	condenser
i	inlet junction of the two MMEs
o	outlet junction of the two MMEs
s	speed
sp	set point

Acronyms

CHF	critical heat flux [W cm^{-2}]
CPU	central processing unit
EEV	electric expansion valve
iHEx	internal heat exchanger
LA	liquid accumulator
LPC	liquid pump of cooling loop
LPW	liquid pump of water loop
LS	liquid separator
MIMO	multiple input multiple output
MME	multi-microchannel evaporator
SIMO	single input multiple output
SISO	single input single output
SMV	stepper motor valve
VSC	oil-free mini-compressor

1. Introduction

The energy consumption of data centers in the US was estimated to be about 80 billion kWh by 2010, which represents an annual energy cost of approximately $5.9 billion and 2% of total electricity use (EPA, 2007; Joshi and Kumar, 2012, Koomey, 2011). With the US having an annual increase of total electrical generation of approximately only 1.5% combined with the current growth rate of electrical energy by data centers being between 10% and 20% per annum (driven now even more by smart phones), data centers potentially will use all of the electrical energy produced by 2030 (Utsler, 2010) if current growth rates continue! With air cooling of the servers in data centers accounting for most of the non-IT energy usage (up to 45% of the total energy consumption (Joshi and Kumar, 2012, Koomey, 2007)), this is the logical energy user that needs to be earmarked to reduce its wasteful use.

Nowadays, the most widely used cooling strategy is refrigerated air cooling of the data centers' numerous servers. When using this solution, nevertheless, 40% or more of the refrigerated air flow can by-pass the racks of servers in data centers all together (Joshi and Kumar, 2012, Marcinichen et al., 2010) while also "cooling" thousands of servers that are not even in operation. This massive waste of energy motivates the search for a new "green" cooling solution for the future generation of higher performance servers that use much less energy for their cooling. One promising solution is the application of on-chip two-phase cooling to dissipate the high heat flux densities of server CPU's. The most promising working fluids for these applications appear to be conventional refrigerants, for instance HFC134a, as opposed to low pressure dielectric coolants (such as FC-72) or water-cooling.

Hannemann et al. (2004) proposed and experimentally evaluated a pumped liquid multiphase cooling system (PLMC) to cool microprocessors and microcontrollers of high-end devices such as computers, telecommunications switches, high-energy laser arrays and high-power radars. They emphasized the significant benefits of reduced pumping energy consumption, size and weight that were provided with the PLMC solution.

Mongia et al. (2006) designed and built a small-scale refrigeration system applicable to a notebook computer, which included a mini-compressor, a microchannel condenser, a microchannel evaporator and a capillary tube as the throttling device. COP's on the order of 3.7 were obtained, comparable with those obtained in modern household refrigerators.