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# Dynamic flow control and performance comparison of different concepts of two-phase on-chip cooling cycles



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Jackson Braz Marcinichen<sup>a,\*</sup>, Duan Wu<sup>a</sup>, Stephan Paredes<sup>b</sup>, John R. Thome<sup>a</sup>, Bruno Michel<sup>b</sup>

<sup>a</sup> Laboratory of Heat and Mass Transfer (LTCM), École Polytechnique Fédérale de Lausanne (EPFL), Switzerland
<sup>b</sup> IBM Research GmbH, Zurich Research Laboratory, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland

## HIGHLIGHTS

• Experimentally evaluated a hybrid on-chip two-phase cooling cycle.

• Steady-state and transient operation of two parallel pseudo-chips.

• Control strategies evaluated by reference tracking and disturbance rejection tests.

• Energetic and exergetic comparison with two other cooling cycles.

#### ARTICLE INFO

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# ABSTRACT

A hybrid on-chip two-phase cooling cycle specifically designed to cool server boards with chips of high performance computers was experimentally evaluated considering steady-state and transient operation of two parallel pseudo-chips and auxiliary electronics mimicking a real server board. Control strategies were developed and evaluated by reference tracking and disturbance rejection tests considering several setpoints of controlled variables. The hybrid cycle, operating with a common refrigerant R134a as the working fluid, was energetically and exergetically compared with two other cooling cycles experimentally evaluated in a previous study, one driven by an oil-free gear pump and another by an oil-free mini-compressor. The results showed that, for a specific steady state condition and heat load, respectively 28.9%, 51.9% and 62.5% of the energy out of the pump, compressor and hybrid cycles were associated with heat losses. The differences observed between the three cycles were justified firstly due to the concept of the cycles, i.e. cycles with the compressor showed as expected lower thermal performance than that with pump since its appeal is for energy recovery (benefitting from a higher condensing temperature) and secondly due to the irreversibilities observed in drivers, condenser and piping (thermal insulation). In summary, the three cycles proved to be efficient, simple and reliable concepts to cool server boards (CPUs, DIMMs etc.), showing high thermal performance and potential for heat recovery when compared with traditional air-cooling systems in current use in data centers. It can also be said that the pump cycle showed the best results in terms of energy and exergy, with the cooling and heat recovery performances reaching a maximum of about 5 and 1.8 times higher than the other cycles (worth noting that the focus in the present study was two-phase flow control and proof-of-concept of different cooling loops, meaning that no "optimal" system design was attempted and the differences above can be reduced).

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\* Corresponding author. Tel.: +41 21 693 5894; fax: +41 21 693 5960. *E-mail address: jackson.marcinichen@epfl.ch* (J.B. Marcinichen).



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# Nomenclature

$A_{SMV}$ stepper motor valve aperture,% $A_{Tord}$ difference in temperature between outlet water flow and inlet working fluid flow in the condenser (approach temperature), °C $E_d$ inlet and outlet flow exergies, $ kg^{-1}$ $\Delta T_{lm}$ log mean temperature difference, K temperature difference, - $R_{lm}$ $k_p, b_p$ inlet and outlet flow exergies, $ kg^{-1}$ $\Delta T_{lm}$ log mean temperature difference, K temperature difference, K $k_p$ MKE indet specific enthalpy, $k kg^{-1}$ $R_{lm}$ heat recovery efficiency, - $R_{lm}$ $k_{lm}$ MKE outlet specific enthalpy, $k kg^{-1}$ $R_{lm}$ heat recovery efficiency, - $R_{lm}$ $K_r$ Pl proportional gain $r_D$ desired closed-loop time constant, s $K_r$ Pl integral gain $K_p$ static gain of the systemSubscripts $PC_S$ speed of mater liquid pump, rpm $Sp$ setpoint $m$ mass flow rate, $kg s^{-1}$ $R_{construction}$ $R_{construction}$ $p$ position of the pole in the complex planCOPcoefficient of performance $P_p$ MKE indet pressure, barCVPglobal warming potential $R_{out}$ condensing pressure, barEVVglobal warming potential $P_n$ MKE indet temperature, °CLPNLPN $Q_{out}$ condensing temperature, °CLPNLPN $Q_{out}$ condensing temperature, °CLPNLPN $R_{out}$ condensing temperature, °CLPNLPN $R_{out}$ fulle temperature, °CLPN $Q_{out}$ <th>Roman</th> <th></th> <th>Greek</th> <th></th>	Roman		Greek		
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$ \begin{array}{cccc} & \mbox{transfer function of the system} & \eta_c & \mbox{coling cycle efficiency,} \\ h_L MMete \\ het Mete specific enthalpy, kJ kg^{-1} & \eta_{tr} & heat recovery efficiency, \\ \eta_{tr} & heat recovery efficiences, \\ 0 & \mbox{transport delay, s} \\ \eta_c & \mbox{transport delay delay} \\ \eta_c & \mbox{transport delay, s} \\ \eta_c & \mbox{transport delay}$	ė <sub>fi</sub> , ė <sub>fe</sub>	inlet and outlet flow exergies, J $kg^{-1}$	$\Delta T_{lm}$	log mean temperature difference, K	
$h_1$ MME inlet specific enthalpy, kJ kg <sup>-1</sup> $\eta_{hrr}$ heat recovery efficiency, - $H_{LMMEs}$ overall heat load on the MMEs, W $k_{cond}$ condenser effectiveness, - $H_{s}$ closed-loop transfer function $\theta$ transport delay, s $h_b$ MME outlet specific enthalpy, kJ kg <sup>-1</sup> rtime constant, s $K_{C}$ PI proportional gain $T_{D}$ desired closed-loop time constant, s $K_{C}$ PI proportional gain $T_{D}$ desired closed-loop time constant, s $K_{C}$ PI proportional gain $Subscripts$ $FC_{S}$ speed of main liquid pump, rpm $Sp$ $m$ mass flow rate, kg s <sup>-1</sup> $CPC$ chorofluorocarbons $p$ position of the pole in the complex planCOP $p$ condensing pressure, barCPC $P_{rond}$ condensing pressure, barEEV $P_{rond}$ condensing pressure, barEEV $Q_{ond}$ condensing pressure, barGWP $Q_{input}$ total input power applied on the pseudo-chips and post heater, WIHEx $Q_{input}$ total input power applied on the pseudo-chips and post heater, WLPR $Q_{input}$ total input power applied on the pseudo-chips and post heater, wCLP $I_{int}$ instantaneous temperature, "CLA $I_{int}$ instantaneous temperature, "CLA $I_{int}$ instantaneous temperature, "CLA $I_{int}$ inter temperature, "CLA $I_{int}$ inter temperature, "CLA $I_{int}$	Ġ	transfer function of the system	$\eta_c$	cooling cycle efficiency, –	
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$h_0^+$ MME outlet specific enthalpy, kJ kg^{-1} $\tau$ time constant, s $K_C$ PJ proportional gain $\tau_D$ desired closed-loop time constant, s $K_P$ Integral gain $\tau_D$ desired closed-loop time constant, s $K_P$ speed of main liquid pump, rpm $sp$ setpoint $PW_S$ speed of water liquid pump, rpm $sp$ setpoint $in$ , $m$ inle than outlet mass flow rate, kg s <sup>-1</sup> $CFC$ chorofluorocarbons $p$ gain-scheduled parameterCPUcentral processing unit $P_{ond}$ condensing pressure, barEEVelectric expansion valve $P_1$ MME inlet pressure, barEUVelectric expansion valve $P_0$ condenser heat transfer rate, WGWPglobal warming potential $Q_{ond}$ condenser heat transfer rate, WLPCvariable speed cycle (main) liquid pump $Q_1$ heat transfer rate, WLPKvariable speed cycle (main) liquid pump $Q_1$ instantaneous temperature, °CLAliquid separator $T_1$ instantaneous temperature, °CLSliquid separator $T_1$ integral timeMIMOmultiple input multiple output $T_0$ dead state temperature, °CPIproportional integral controller $T_{water,M}$ updet temperature, °CPIproportional integral controller $T_{water,M}$ updet temperature, °CPIproportional integral controller $T_{water,M}$ updet temperature, °CPIproportional integral controller $T_{wate$	H(s)	closed-loop transfer function	θ	transport delay, s	
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$ \begin{array}{cccc} & \text{MME outlet pressure, bar} & \text{GWP} & \text{global Warming potential} \\ & \text{Gond} & \text{condenser heat transfer rate, W} & \text{IHEx} & \text{internal heat exchanger} \\ & \text{Insulated-gate bipolar transistor} \\ & \text{heater, W} & \text{IPC} & \text{variable speed cycle (main) liquid pump} \\ & \text{heater, W} & \text{IPC} & \text{variable speed cycle (main) liquid pump} \\ & \text{heater, W} & \text{IPC} & \text{variable speed cycle (main) liquid pump} \\ & \text{figure from the pressure receiver} \\ & \text{for the transfer rate, W} & \text{IPC} & \text{variable speed water (secondary fluid) liquid pump} \\ & \text{figure from the transfer rate, W} & \text{IPC} & \text{variable speed water (secondary fluid) liquid pump} \\ & \text{figure from the transfer rate, W} & \text{IPR} & \text{low pressure receiver} \\ & \text{for the transfer rate, C} & \text{IA} & \text{liquid accumulator} \\ & \text{Integral time} & \text{MME outlet temperature, °C} & \text{IS} & \text{liquid separator} \\ & \text{figure from the transfer rate, K} & \text{MME} & \text{micro-evaporator} \\ & \text{figure from the twater temperature, K} & \text{ODP} & \text{ozone depletion} \\ & \text{fwater, in} & \text{inter water temperature, °C} & \text{PI} & \text{proportional integral controller} \\ & \text{fwater, in} & \text{inter water temperature, °C} & \text{PI} & \text{proportional integral controller} \\ & \text{fwater, out} & \text{system input} & \text{system input} & \text{sum of input power, W} & \text{SISO} & \text{single input multiple output} \\ & \text{W}_{input} & \text{sum of input power, W} & \text{SISO} & \text{single input single output} \\ & \text{w}_{input} & \text{sum of input power, applied on drivers and actuators, W} \\ & x_o & \text{MMEs' outlet vapor quality (mixing point), -} \\ & y & \text{system output} \\ & z & \text{position of the zero in the complex plan} \\ & z & \text{position of the zero in the complex plan} \\ \end{array}$	P;	MME inlet pressure, bar	EEV	electric expansion valve	
$\begin{array}{llllllllllllllllllllllllllllllllllll$	Pa	MME outlet pressure, bar	GWP	global warming potential	
Cond $Q_{input}$ total input power applied on the pseudo-chips and post heater, WICB1insulated-gate bipolar transistor $Q_{input}$ total input power applied on the pseudo-chips and post heater, WLPliquid pump $Q_j$ heat transfer rate, WLPCvariable speed cycle (main) liquid pump $T_{cond}$ condensing temperature, °CLPWvariable speed water (secondary fluid) liquid pump $T_i$ MME inlet temperature, °CLAliquid accumulator $T_o$ MME outlet temperature, °CLSliquid pump unultiple output $T_0$ dead state temperature, KMMEmicro-evaporator $T_i$ instantaneous temperature, °CPIproportional integral controller $T_{water,in}$ inlet water temperature, °CPIproportional integral controller $T_{water,in}$ inputcondenser overall conductance, W K^{-1}SIMOsingle input multiple output $W_{cv}$ energy transfer rate by work, WSISOsingle input miltiple output $W_{input}$ pseudo chip input power, WVCvapor compressor $W_{input}$ system outputVCvapor compressor with variable volumetric dis- placement $z$ position of the zero in the complex planplan	0 0 cond	condenser heat transfer rate. W	IHEX	internal heat exchanger	
CamputFor the problem of the pockado campo and postLPInquid pump $\dot{Q}_j$ heater, WLPRlow pressure receiver $T_{cond}$ condensing temperature, °CLPRlow pressure receiver $T_i$ MME inlet temperature, °CLPWvariable speed water (secondary fluid) liquid pump $T_i$ MME outlet temperature, °CLAliquid accumulator $T_i$ instantaneous temperature, °CLSliquid separator $T_i$ instantaneous temperature, KMMEmicro-evaporator $T_i$ integral timeMIMOmultiple input multiple output $0$ dead state temperature, °CPI $T_{water,out}$ outlet water temperature, °CPI $vatter,out$ outlet water temperature, °CPI $u$ system inputSMV $W_{cv}$ energy transfer rate by work, WSISO $W_{input}$ pseudo chip input power, WSISO $W_{input}$ pseudo chip input power, WVC $v_{a}$ MMEs' outlet vapor quality (mixing point), -VSC $y$ system outputvapor quality (mixing point), -VSC $y$ system outputpacino of the zero in the complex planvapor compressor	Q:	total input power applied on the pseudo-chips and post	IGBI	insulated-gate bipolar transistor	
$Q_j$ heat transfer rate, WLPCvariable speed cycle (main) liquid pump $C_{cond}$ condensing temperature, °CLPRlow pressure receiver $T_i$ MME inlet temperature, °CLPWvariable speed water (secondary fluid) liquid pump $T_i$ MME outlet temperature, °CLAliquid accumulator $T_o$ MME outlet temperature, °CLSliquid separator $T_j$ instantaneous temperature, KMMEmicro-evaporator $T_i$ integral timeMIMOmultiple input multiple output $T_0$ dead state temperature, °CPIproportional integral controller $T_{water,ini}$ inlet water temperature, °CPIproportional integral controller $T_{water,out}$ outlet water temperature, °CPIEpower usage effectiveness $u$ system inputSiMOsingle input multiple output $W_{cv}$ energy transfer rate by work, WSiSOsingle input multiple output $\dot{W}_{cv}$ pseudo chip input power, WVCvapor compressor $w_{input}$ pseudo chip input power, WVCvapor compressor $w_{input}$ system outputysystem output $z$ position of the zero in the complex planplacement	<b>C</b> anput	heater W	LP	liquid pump	
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TenderContention of the zero in the complex planCLPWvariable speed water (secondary fluid) liquid pump $I_i$ MME inlet temperature, °CLAliquid accumulator $I_o$ MME outlet temperature, °CLSliquid separator $I_1$ integral timeMMEmicro-evaporator $I_0$ dead state temperature, KMMEmicro-evaporator $I_1$ integral timeMIMOmultiple input multiple output $I_0$ dead state temperature, °CPIproportional integral controller $I_{water,out}$ outlet water temperature, °CPIproportional integral controller $I_{water,out}$ outlet water temperature, °CPUEpower usage effectiveness $u$ system inputSMVstepper motor valve $UA_{cond}$ condenser overall conductance, W K <sup>-1</sup> SINOsingle input multiple output $W_{input}$ pseudo chip input power, WSISOsingle input single output $V_{input}$ sum of input power applied on drivers and actuators, WVCvapor compressor $x_o$ MMEs' outlet vapor quality (mixing point), -ysystem output $z$ position of the zero in the complex planplacement	Сј Т	condensing temperature °C	LPR	low pressure receiver	
International	Т.	MMF inlet temperature °C	LPW	variable speed water (secondary fluid) liquid pump	
$T_0$ Initial outlet temperature, CLSliquid separator $T_j$ instantaneous temperature, KMMEmicro-evaporator $T_1$ integral timeMIMOmultiple input multiple output $T_0$ dead state temperature, KODPozone depletion $T_{water,int}$ inlet water temperature, °CPIproportional integral controller $T_{water,out}$ outlet water temperature, °CPUEpower usage effectiveness $u$ system inputSMVstepper motor valve $UA_{cond}$ condenser overall conductance, W K <sup>-1</sup> SIMOsingle input multiple output $\dot{W}_{cv}$ energy transfer rate by work, WSISOsingle input single output $\dot{W}_{input}$ sum of input power, WVCvapor compressor $W_{input}$ sum of input power applied on drivers and actuators, WVSCoil-free mini-compressor with variable volumetric displacement $y$ system outputposition of the zero in the complex planplacement		MME nucle temperature °C	LA	liquid accumulator	
If instantaneous temperature, RMMEmicro-evaporator $T_1$ integral timeMIMOmultiple input multiple output $T_0$ dead state temperature, KODPozone depletion $T_{water,in}$ inlet water temperature, °CPIproportional integral controller $w_{water,out}$ outlet water temperature, °CPUEpower usage effectiveness $u$ system inputSMVstepper motor valve $UA_{cond}$ condenser overall conductance, W K <sup>-1</sup> SIMOsingle input multiple output $\dot{W}_{cv}$ energy transfer rate by work, WSISOsingle input single output $\dot{W}_{input}$ pseudo chip input power, WVCvapor compressor $W_{input}$ sum of input power applied on drivers and actuators, WVSCoil-free mini-compressor with variable volumetric dis- placement $y$ system outputposition of the zero in the complex planplacement	Т <sub>0</sub> Т.	instantaneous temperature, K	LS	liquid separator	
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$T_0$ dead state temperature, $R$ ODPozone depletion $T_{water,in}$ inlet water temperature, $C$ PIproportional integral controller $T_{water,out}$ outlet water temperature, $C$ PUEpower usage effectiveness $u$ system inputSMVstepper motor valve $UA_{cond}$ condenser overall conductance, $W K^{-1}$ SIMOsingle input multiple output $\dot{W}_{cv}$ energy transfer rate by work, $W$ SISOsingle input single output $\dot{W}_{input}$ pseudo chip input power, $W$ VCvapor compressor $W_{input}$ sum of input power applied on drivers and actuators, $W$ VSCoil-free mini-compressor with variable volumetric dis- placement $y$ system outputposition of the zero in the complex planplacement	1] Т.	dead state temperature K	MIMO	multiple input multiple output	
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$OricondContentist overall conductance, withSIMOsingle input multiple output\dot{W}_{cv}energy transfer rate by work, WSIMOsingle input multiple output\dot{W}_{input}pseudo chip input power, WSISOsingle input single output\dot{W}_{input}sum of input power applied on drivers and actuators, WVCvapor compressorW_{input}system outputVCvapor compressorysystem outputvisiting point), -placementzposition of the zero in the complex planvisiting point$	μ ΠΔ.	condenser overall conductance $WK^{-1}$	SMV	stepper motor valve	
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x <sub>0</sub> initial output years quarty (mixing point), -placementysystem outputzposition of the zero in the complex plan	v v input v	MMEs' outlet vapor quality (mixing point)	VSC	oil-free mini-compressor with variable volumetric dis-	
<i>z</i> position of the zero in the complex plan	Λ <sub>0</sub>	system output		placement	
	у 7	position of the zero in the complex plan			
	۷	position of the zero in the complex plan			

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### 1. Introduction

The worldwide refrigeration advances can be characterized by three important milestones in the history: (i) the production and commercialization of ice in the 19th century, (ii) the artificial cold production through refrigeration systems by absorption and by vapor mechanical compression using methyl ether and ammonia as refrigerant (second half of the 19th century), and (iii) the "boom" in development with the introduction of the refrigerants CFCs (chlorofluorocarbons) in 1930.

Nowadays, thanks to all scientific and technological development of the last two centuries, the refrigeration has spreading into many different domains (electronic, automotive, military, etc.). Consequently, the need for environmentally friendly cooling Download English Version:

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