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

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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.

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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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Nomenclature

Roman

A_{SMV}	stepper motor valve aperture,%
$\dot{E}_d$	rate of exergy destruction due to irreversibilities within the control volume, W
$\dot{e}_{fi}$, $\dot{e}_{fe}$	inlet and outlet flow exergies, J kg^{-1}
G	transfer function of the system
h_i	MME inlet specific enthalpy, kJ kg^{-1}
HL_{MMEs}	overall heat load on the MMEs, W
$H(s)$	closed-loop transfer function
h_o	MME outlet specific enthalpy, kJ kg^{-1}
K_C	PI proportional gain
K_I	PI integral gain
K_P	static gain of the system
LPC_S	speed of main liquid pump, rpm
LPW_S	speed of water liquid pump, rpm
$\dot{m}$	mass flow rate, kg s^{-1}
$\dot{m}_i$, $\dot{m}_e$	inlet and outlet mass flow rate, kg s^{-1}
p	position of the pole in the complex plan
P	gain-scheduled parameter
P_{cond}	condensing pressure, bar
P_i	MME inlet pressure, bar
P_o	MME outlet pressure, bar
Q_{cond}	condenser heat transfer rate, W
Q_{input}	total input power applied on the pseudo-chips and post heater, W
$\dot{Q}_j$	heat transfer rate, W
T_{cond}	condensing temperature, °C
T_i	MME inlet temperature, °C
T_o	MME outlet temperature, °C
T_j	instantaneous temperature, K
T_I	integral time
T_0	dead state temperature, K
$T_{water,in}$	inlet water temperature, °C
$T_{water,out}$	outlet water temperature, °C
u	system input
UA_{cond}	condenser overall conductance, W K^{-1}
$\dot{W}_{cv}$	energy transfer rate by work, W
$\dot{W}_{input}$	pseudo chip input power, W
W_{input}	sum of input power applied on drivers and actuators, W
x_o	MMEs' outlet vapor quality (mixing point), –
y	system output
z	position of the zero in the complex plan

Greek

ΔT_{cond}	difference in temperature between outlet water flow and inlet working fluid flow in the condenser (approach temperature), °C
ΔT_{lm}	log mean temperature difference, K
η_c	cooling cycle efficiency, –
η_{hr}	heat recovery efficiency, –
ε_{cond}	condenser effectiveness, –
θ	transport delay, s
τ	time constant, s
τ_D	desired closed-loop time constant, s

Subscripts

sp	setpoint

Acronyms

CFC	chorofluorocarbons
COP	coefficient of performance
CPU	central processing unit
EEV	electric expansion valve
GWP	global warming potential
iHEx	internal heat exchanger
IGBT	insulated-gate bipolar transistor
LP	liquid pump
LPC	variable speed cycle (main) liquid pump
LPR	low pressure receiver
LPW	variable speed water (secondary fluid) liquid pump
LA	liquid accumulator
LS	liquid separator
MME	micro-evaporator
MIMO	multiple input multiple output
ODP	ozone depletion
PI	proportional integral controller
PUE	power usage effectiveness
SMV	stepper motor valve
SIMO	single input multiple output
SISO	single input single output
VC	vapor compressor
VSC	oil-free mini-compressor with variable volumetric displacement

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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