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Experimental analysis of a novel cooling system driven by liquid refrigerant pump and vapor compressor

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ABSTRACT

This study introduced a novel energy saving cooling system, i.e. a combined cycle coupled with a traditional vapor compression cycle with a pumped liquid two-phase cooling cycle. The system has two operation modes, i.e. the compression cycle mode driven by compressor and the pump cycle mode driven by refrigerant pump. A multi-purpose test bench was constructed to experimentally evaluate the performance of the integrated cycle system under various operation conditions. The effects of cycle working condition and the shift temperature between the two operation modes on the overall cycle performance were investigated in detail. It is found that the novel cycle system has a higher EER compared to the traditional compressor system when the ambient temperature is relatively low. The further experimental results and comparative annual energy saving analysis also indicated that the proper shift temperature is about −5 °C from the system EER and cooling capacity point of view.

Analyse expérimentale d'un nouveau système de refroidissement fonctionnant grâce à une pompe à frigorigène liquide et à un compresseur de vapeur

Mots clés : Centre de données ; Pompe à frigorigène liquide ; Refroidissement ; Coefficient d'efficacité énergétique ; Écart de temperature ; R22

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Nomenclature

$Q_{e,air}$	air-side cooling capacity [kW]
$Q_{e,ref}$	refrigerant-side cooling capacity [kW]
Q_{sen}	sensible cooling capacity [kW]
Q_{comp}	cooling capacity of the compression cycle mode [kW]
Q_{pump}	cooling capacity of the pump cycle mode [kW]
T	Temperature [°C]
T_a	ambient air temperature [°C]
$\dot{m}_{ref}$	refrigerant mass flow rate [$kg \cdot h^{-1}$]
$\dot{m}_{air}$	air mass flow rate [$kg \cdot h^{-1}$]
W_{evap}	evaporator fan input power [kW]
W_{cond}	condenser fan input power [kW]
W_{pump}	pump input power [kW]
W_{comp}	compressor input power [kW]
SHR	sensible heat rate [-]
$x_{e,o}$	outlet vapor quality of evaporator [-]
Δp	pressure drop [kPa]
EER	energy efficiency rate [-]
$h_{o,ref}$	refrigerant-side outlet enthalpy [$kJ \cdot kg^{-1}$]
$h_{i,ref}$	refrigerant-side inlet enthalpy [$kJ \cdot kg^{-1}$]
$h_{o,air}$	air-side outlet enthalpy [$kJ \cdot kg^{-1}$]
$h_{i,air}$	air-side inlet enthalpy [$kJ \cdot kg^{-1}$]
E	energy consumption [$kW \cdot h$]

Subscripts

ref	refrigerant
sen	sensible
comp	compressor
e	evaporator
a	ambient air
i	inlet
o	outlet
evap	evaporator
cond	condenser

1. Introduction

Data centers are computer infrastructure facilities in which a large number of enterprise servers, server communication equipment, and cooling power equipment are contained. Along with the rapid development of electronics and the advent of cloud computing, the number of data centers is increased dramatically, which requires a huge amount of electrical power for their normal operation. However, this has a noticeable impact on the energy consumption and carbon footprint due to the size and number of data centers. According to an Environmental Protection Agency (EPA) report on energy efficiency in data centers, the energy consumption of data centers in the United States was more than 100 billion kWh by 2011, which represents an annual energy cost of approximately $7.4 billion (Brown, 2008). The report emphasized that there are opportunities for data centers to improve their efficiencies - both on the facility and server sides of the data center infrastructure.

The most widely used cooling strategies in computer room air conditioners (CRAC) is refrigerated air cooling due to its high reliability, and low initial and maintenance costs. However, it has several major disadvantages. One is the by-pass air flow in the racks of servers in data centers and it cannot effectively participate in the cooling process of servers. Furthermore, the working liquid driven by a compressor has to be lifted to a higher condensing temperature to ensure the safe and stable operation of the compressor at a lower outside ambient temperature, which means a significantly amount of energy will be consumed. The poor energetic performance of traditional cooling strategies motivates thermal designers to search for green thermal solutions for higher performance servers while providing the possibility to revise the tradition cooling cycle to improve the overall performance.

Due to the performance limits of conventional cooling technologies in both military, commercial electronics and electro-optical systems, Hannemann et al. (2004) experimentally evaluated a pumped liquid multiphase cooling system (PLMC) to cool microprocessors (such as computers, telecommunications, and phased array radar systems) and Rack-based system in data centers. They emphasized the significant benefits of performance, cost, size, weight and reliability that can be provided with the PLMC solution as compared with existing active air cooling or simple liquid-loop systems. They also recommended that the PLMC can be applied to military, commercial and industrial systems due to its excellent thermal management capabilities. Chanwoo et al. (Park et al., 2007; Crepinsek and Park, 2012) presented an advanced Hybrid Two-Phase Loop (HTPL) technology which integrated active mechanical pumping with passive capillary pumping for electronics thermal management. The experimental results indicated that the hybrid loops with multi-evaporators were able to remove high heat fluxes and the total heat inputs govern the system temperature and pressures. A shortcoming of the multi-evaporators loop is that each evaporator line needs to be identical or controlled by a valve. Although there are many limitations about the traditional cooling strategies in CRAC as mentioned above, it has still attracted more attention (Mongia et al., 2006; Trutassanawin et al., 2006; Zhou et al., 2010). All studies selected lower pressure refrigerant R134a or R600a as the working fluids and mini-compressor to drive the working fluid for the small-scale refrigeration system. Active two-phase cooling system such as evaporative spray cooling (Glassman et al., 2004; Lin et al., 2006; Silk et al., 2008; Mudawar et al., 2009) has been extensively investigated over the past several years due to advantages, such as high heat flux performance and robust operation. However, it requires complex fluid control due to two-phase mixed flow and flooded boiling in the system. Ohadi et al. (2012) compared the cooling performance of electronics in data centers by using air, liquid and two-phase on-chip cooling. Advantages and disadvantages of various methods were also discussed. It was concluded that air cooling may remain a very attractive solution for locations