Energy and Buildings 154 (2017) 560–568

Contents lists available at ScienceDirect

Energy and Buildings

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

Experimental investigation of an integrated cooling system driven by both liquid refrigerant pump and vapor compressor

Jiankai Dong[a,*], Yana Lin[a], Shiming Deng[b], Chao Shen[a,*], Zhuo Zhang[c]

[a] School of Municipal and Environmental Engineering, Harbin Institute of Technology, Harbin, China
[b] Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong Special Administrative Region
[c] China Railway Siyuan Survey and Design Group CO., LTD., China

ARTICLE INFO

Article history:
Received 17 July 2017
Received in revised form 13 August 2017
Accepted 16 August 2017
Available online 24 August 2017

Keywords:
Integrated cooling system
Pumped refrigerant two-phase cycle
Vapor compression cycle
Liquid refrigerant pump
Feasibility analysis

ABSTRACT

The energy consumption of air conditioning system accounts for a significant proportion of the total energy consumed in data center. To reduce the energy consumption of the cooling system, an integrated system, which combines pumped refrigerant two-phase cycle (PRTC) with vapor compression cycle (VCC), is proposed in this paper. The impacts of input frequency and outdoor air temperature on the performances of PRTC, and that of the outdoor air temperature on the performances of VCC have been investigated. It was found that PRTC had higher EER than VCC, but its cooling capacity was limited by outdoor air temperature. In PRTC, the designed cooling capacity of 2500 W could be obtained when the outdoor air temperature was −3.0 °C. In addition, 80% and 50% of the designed cooling capacity can be obtained at ambient temperatures 3.2 °C and 12.0 °C, respectively. Besides, the feasibility of the system in different climate zones in China was demonstrated by analysis of the climate data in Harbin, Beijing, Wuhan, Guangzhou and Guiyang, respectively. Results indicated the proposed system had high feasibility in Harbin and Beijing. The results of this paper can provide valuable insights into the cooling system driven by both liquid refrigerant pump (LRP) and vapor compressor, targeting at reducing the cooling energy consumption and maximizing the economic efficiency of the cooling system in data center.

1. Introduction

The rapid development of Information Technology (IT) industry has resulted in a significant increase of data centers [1]. To ensure the reliable operation of the equipment in the data center, it's necessary to apply the cooling system [2]. In 2011, the energy consumption of data center was more than 100 billion kWh in US [3]. Among these, the energy consumed in cooling system accounted for 30% [4], which means that proper optimization in cooling system would make a vital contribution to energy saving. Vapor compression cooling system, as a conventional cooling system, has been widely applied in the data center no matter what the outdoor air temperature is. However, there is a considerable amount of free cooling energy that could be used when the outdoor air temperature is low. It's no doubt that using free cooling technology can decrease energy consumption effectively.

From the open literature available, several investigations in terms of direct fresh-air cooling were conducted [2,4–9]. Bulut [2] carried out an investigation on the performance characteristics of the cooling system in Istanbul. It can be concluded that the temperatures of indoor supplied air and outdoor ambient air affected the amount of the energy saving in the cooling system. According to their research, free cooling technology was not an optimum choice in the period from June to August when outdoor air temperature was equal to or slightly lower than the supply air temperature. Ham [4] simulated the performances of three types of air-side economizers, including direct air-side economizer with ultrasonic humidifier, indirect air-side economizer with heat pipe and indirect air-side economizer with indirect evaporative cooler, under different supply air temperatures and heat exchanger effectiveness in South Korea. The results demonstrated that the optimum supply air temperature was within 18–23 °C. Lee [5] used a dynamic building energy simulation program to examine the potential energy savings of the air-side free cooling technology with differential enthalpy control used in data centers in 17 climate zones. The study showed that the energy saving of free cooling technology decreased by 2.8–8.5% with 2 °C decline of indoor temperature. Endo [6] experimentally investigated a cooling system introducing fresh air directly for a data center located in Tokyo under different climate conditions. The results indicated that the energy

* Corresponding authors.
E-mail addresses: djkheb@163.com (J. Dong), chaoshen@hit.edu.cn (C. Shen).

http://dx.doi.org/10.1016/j.enbuild.2017.08.038
0378-7788/

Nomenclature

c_p	Specific heat, kJ/(kg K)
h	Enthalpy, kJ/kg
m	Mass flow rate of the fluid, kg/s
Q	Cooling capacity(W)
T	Temperature (°C)
$\dot{V}$	Volumetric flow rate, m^3/s
W	Power (W)

Subscripts

a	Air
com	Compressor
con	Condenser
eva	Evaporator
f	Fan
in	Inlet of indoor coil
out	Outlet of indoor coil
PRTC	Pumped refrigerant two-phase cycle
LRP	Liquid refrigerant pump
VCC	Vapor compression cycle

Abbreviations

EER	Energy efficiency ratio
IT	Information technology
LRP	Liquid refrigerant pump
PEM	Proton exchange membrane
TPTL	Two-phase thermosyphon loop

Greek symbols

ρ	Fluid density (kg/m^3)

consumption of the cooling system was 20.8% less than that of a conventional air conditioning system. According to the meteorological data of the past sixteen years in Islamabad, Pakistan, Hassan [7] carried out an investigation on the potential application for free cooling technology. The results showed that significant energy savings through free cooling can be achieved during the months of December, January, and February. Siriwardana [8] made an investigation on using air-side economizers to introduce outside air based on analyzing the hourly temperature and humidity data over past 12 years in Australia, and determined that the outside air cooling energy could be used for 5500 h per year in Tasmania and Southern Australian cities, such as Melbourne and Adelaide. Liu [9] concluded that full fresh air ventilation can save 40% of the air conditioning energy conservation and make power usage effectiveness (PUE) lower than 1.4. However, most of these investigations mentioned above actually focused on the energy saving in direct fresh-air cooling, while some focused on air-side economizers to analyze optimum supply air temperature to evaluate the potential usage of direct fresh-air cooling. Although the direct fresh-air cooling system could achieve enormous energy conservation, the utilization of direct fresh-air cooling was limited due to its performance fluctuation, which was resulted from the uncontrollability of outdoor air. Besides, the indoor air quality was badly affected if the outdoor air was supplied directly without purification treatment. Furthermore, heating the supplied air was necessary to avoid fogging or dewing when the outdoor air temperature was low, which caused an increase in the initial cost of direct fresh-air cooling system.

Therefore, indirect fresh-air cooling attracts more and more attention because of its relatively high cooling capacity and controllability. The studies on indirect fresh-air cooling were mainly divided into natural cooling and mechanical cooling. There were some researchers concentrating on the study of natural cooling. Zhang [10] established a visual experimental setup to investigate the performances of a two-phase thermosiphon loop (TPTL), in terms of the variation of temperature difference, liquid charge, height difference, and circulation flow resistance, etc. The results showed that larger height difference was not always advantageous to the performance of TPTL. Garrity [11] developed a flow boiling micro-channel cooling plate which can be easily inserted into the stack of a proton exchange membrane (PEM) fuel cell for thermal control. Furthermore, some researchers paid special attention to heat pipe. Jouhara [12] studied the thermal management based on heat pipe. The results revealed that 75% of potential energy saving can be achieved. Ding [13] made a conclusion that the total entransy dissipation of the heat pipe system was 48.3% lower than that of a traditional air conditioning system by analyzing the heat transfer process.

On the other hand, some researchers showed their interest in mechanical cooling. Choi [14] investigated an integrated system designed for telecommunication equipment rooms. It can be seen that the optimum outdoor air temperature was 8.3 °C, which was the control parameter to convert the cycle using ethylene glycol as refrigerant into VCC. Considering the driving force into the indirect free cooling technology, some researchers showed a significant concern for applying pump into cooling system. Hannemann[15] applied pump into liquid multiphase cooling system. According to this study, the mass flow rate, size of condenser and power consumed by the pump in water-circulating single-phase cooling system were 4.6 times, 2 times and 10 times as those in liquid multiphase cooling system, respectively. Marcinichen [16] carried out a further investigation on the thermal performances of refrigerated cooling of microprocessors with micro-evaporation. The results suggested that the energy consumption of vapor compression cooling system was far higher than that of pump-driven cooling system. Yan [17] introduced a novel energy saving cooling system combining traditional VCC with pumped liquid two-phase cooling cycle, and evaluated the system performance under various operation conditions. The results showed that the proper shift temperature between these two operations was about −5 °C according to the system EER and cooling capacity. Ma [18] proposed a novel integrated cooling system of vapor compression and pump-driven two-phase loop for energy saving in data centers. And the results showed that the maximum cooling EER of the integrated system reached up to 29.71, and the proper shift temperature of the system using 3 HP compressor and 1 HP compressor was 5 °C and 15 °C, respectively.

As mentioned previously, a considerable amount of literature related to free cooling technology has been carried out. Some focused on direct fresh-air cooling, while other paid attention to indirect fresh-air cooling. Among the studies for the indirect fresh-air cooling, the integrated system, combining vapor compression cooling with pump-driven two-phase cooling, has obvious energy saving, controllability, and can be used in both micro-channel evaporator and data centers to effectively use the natural cooling energy and reduce the energy consumption. Although Yan [17] and Ma [18] introduced the integrated systems combining vapor compression with pump-driven two-phase cooling cycle, both did not indicate the correspondence of LRP and compressor for generating certain cooling capacity. Simultaneously, the used LRP in these two experiments were both constant frequency. However, the cooling capacity of the LRP varied obviously with the change of outdoor air temperature under fixed condenser and evaporator. And thus, changing the input frequency into the LRP according to the variation of outdoor environment would improve its cooling performance. In this paper, an integrated system driven by vapor compressor and LRP is firstly developed. Then the operation performances of the system are experimentally evaluated under two operation cycles. This is followed by presenting the experimental results and detailed