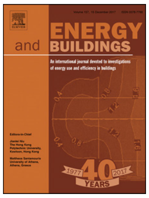
Energy & Buildings 169 (2018) 295–304

Contents lists available at ScienceDirect

Energy & Buildings

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



# Energy-saving analysis of a case data center with a pump-driven loop heat pipe system in different climate regions in China

Feng Zhou[a,b,*], Cuicui Li[a], Wanpeng Zhu[a], Jing Zhou[a], Guoyuan Ma[a,b], Zhongliang Liu[a,b]

[a] *College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China*
[b] *The Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education of China, China*

ARTICLE INFO

*Article history:*
Received 8 December 2017
Revised 6 February 2018
Accepted 30 March 2018
Available online 5 April 2018

*Keywords:*
Data center
Free cooling
PLHP
Energy saving ratio
Payback period

ABSTRACT

It is important to cool data centers for improving IT equipment reliability through indoor temperature control. The air conditioning energy consumption is almost 38% of the total energy consumption. Free cooling in cool days is a promising technology for energy conservation. A pump-driven loop heat pipe (PLHP) system for free cooling was developed and installed in a data center project, which has a high energy efficiency ratio (EER) compared to air conditioners. The running performance of the PLHP system in the case project was tested and studied. The fitting rule of EER and outdoor temperature was obtained. The hourly energy savings and payback periods of the PLHP system for different cities of different climate regions in China were analyzed basing on the fitting formula compared to air conditioners. A national distribution map was developed to show the annual energy saving ratio in China. Results show that the PLHP system provides remarkable energy savings and the indoor temperature is remained at 18°C to 25°C. About 74.2% of Chinese cities lie in regions suitable for applications, and the annual energy saving ratio is over 30%. The average payback period for most cities in China is about 3.9 years.

## 1. Introduction

The information exchanging and handling needs are getting huge with rapid development of information technology (IT), especially cloud computing and big data. The world market for data centers has been 32.79 billion $ till 2014 and the growth rate was 15.3% [1]. In the last 20 years, the heat flux of a server increased by almost 20 times [2]. The number and scale of data centers keep increasing, and power consumption continues to grow. The world power consumption for data centers in 2010 took 1.1% to 1.5% of the total global power consumption, and increased by 56% compared to 2005 [3]. In China there were over 400,000 data centers until 2014, and the annual power consumption took over 1.5% of total social power consumption [4]. The total power consumption of data centers in China was over 83 billion kWh in 2014, which only was 36.4 billion kWh in 2009 [5]. The cooling power consumption in a data center occupies 38% of total power consumption, which is only less than power consumption of IT devices (44%) [6,7]. Therefore, it is very important to reduce the cooling power consumption for energy saving and emission reduction of data centers.

Among present cooling strategies for data centers, air-side free cooling devices [8–11] (known in North America as economizer [12]) were applied in over 10% data centers [13], except intelligent variable frequency controls, air distribution optimization [14–16], operation management, building envelope, renewable and sustainable energy utilization [17], and energy storage [18]. For air-side free cooling, the direct cooling system could save more energy and would cost less to implement compared with an indirect cooling system under same conditions [19]. However, in most developing countries, the outdoor air cannot meet the environment requirements of data centers due to dust, humidity, and acid gas once the direct free cooling system is used [20–21]. The indirect heat pipe free cooling system (split loop heat pipe) that can isolate indoor and outdoor air effectively and ensure the temperature and cleanliness requirements was proposed. Bai et al. [22] tested the steady-state operation performance of a loop heat pipe assisted with gravity, and obtained two running modes (gravity driven mode, capillary force and gravity driven mode) for different heat loads. The cooling efficiency of the split loop heat pipe was obviously higher than mechanical refrigeration for cooling data centers [23,24]. Han et al. [25] and Lee et al. [26] developed an integrated system combining the split heat pipe and mechanical refrigeration, which could save by 30% to 45% power consumption under same

---

*Abbreviations:* AC, air conditioner; EER, energy efficiency ratio; PLHP, pump-driven loop heat pipe.

[*] Corresponding author at: College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

*E-mail address:* zhoufeng@bjut.edu.cn (F. Zhou).

https://doi.org/10.1016/j.enbuild.2018.03.081
0378-7788/

## Nomenclature

| | |
|---|---|
| $A$ | facing heat exchanging area of evaporator, $m^2$ |
| $A_1$ | power consumption of air conditioner with rated power after the transformation, kWh |
| $A_2$ | power consumption of air conditioner with tested power after the transformation, kWh |
| $C_1$ | power consumption of air conditioner with rated power before the transformation, kWh |
| $C_2$ | power consumption of air conditioner with tested power before the transformation, kWh |
| $c$ | air specific heat capacity, kJ/(kg °C) |
| $d$ | air vent diameter of evaporator outlet, m |
| $ES$ | annual electricity savings, kWh |
| $H$ | the hour number |
| $I$ | the initial investment, RMB |
| $n$ | number of air vents in front side |
| $P$ | operating power of the PLHP system, kW |
| $Q_0$ | cooling capacity or heat load, kW |
| $\eta$ | annual energy-saving ratio |
| $t_{mi}$ | average temperature of evaporator inlet, °C |
| $t_{mo}$ | average temperature of evaporator outlet, °C |
| $t_o$ | outdoor air temperature, °C |
| $v$ | facing air velocity, m/s |
| W | power consumption of PLHP system, kWh |
| $Y$ | payback period, year |
| *Greek symbol* | |
| $\alpha$ | the commercial electricity price, RMB/kWh |
| $\triangle t$ | inlet and outlet air temperature difference of evaporator, °C |
| $\rho$ | air density, $kg/m^3$ |

conditions compared to conventional air conditioner. Zhang et al. [27–29] proposed an integrated system of mechanical refrigeration and thermosyphon for free cooling using a triple working fluids heat exchanger, and the annual energy saving ratio was 5.4% to 47.3% when the indoor air temperature was 27 °C. Wang et al. [30] took plate heat exchanger place of the triple working fluids heat exchanger. The power usage efficiency (PUE) of the data center in Beijing or Harbin decreased by 0.3. However, for split loop heat pipe the condenser must be higher than the evaporator, and the height difference has to exceed some point for sufficient driving force, which brings limitations for installation. Moreover, for split loop heat pipe the driving force is gravity and Buoyancy force from fluid vaporization, which is not much. The split loop heat pipe would fail to work due to increasing flow resistances when the pipelines are complex or very long. Part of the condenser may be useless due to the small kinetic energy of working fluid and the circulation performance gets worse.

In order to solve the above problems of split loop heat pipe, a pump-driven loop heat pipe (PLHP) was proposed for free cooling in data centers [31]. In such system the high efficiency phase-change heat exchanging of heat pipe was combined with the powerful driving force of mechanical pump. The low boiling-point working fluid was charged for anti-freezing. Liu et al. [32] designed a $CO_2$ two-phase thermal control system with mechanical pump under micro-gravity conditions. These studies showed that the cooling loop exhibited excellent performances and flexibility of structures. However, the structure and heat transfer mechanism were quite different from those in the ground compared with the space microgravity environment. Bubble pump [33] and steam turbine [34] as the driving pump were studied, but the driving force was still not enough. Yan et al. [35], Udagawa et al. [36] and our group [37–38] investigated the PLHP system for data center free cooling experimentally and achieved considerable energy savings.

However, the thermal performance of the data center is significantly affected by locations or climatic conditions [39,40], and the energy efficiency ratio (EER) of a PLHP system depends on the outdoor air temperature [38,41]. The cities lying in different climate regions own different weather data, especially in outdoor air temperature. So, the energy savings using a PLHP system in a data center for different cities will be different. How much are the energy savings for different cities and climate regions? Whether the PLHP system is suitable for a city or not? These questions can be answered if the energy savings in different cities with a PLHP system are simulated and illustrated.

In this paper, the software DeST-c was adopted for building energy consumption simulation, which was developed by Tsinghua University [42]. It can be used to simulate and analyze the building energy consumption and HVAC system design. In DeST-c software, the Meteorological Data Producer for HVAC analysis (Medpha) model of hourly climatic data in a whole year was built up based on the actual tested data from 194 meteorologic stations for about 50 years through random algorithm [42]. The real time daily weather basic data includes outdoor air temperature, humidity, solar radiation intensity, wind speed and direction, sunshine hours, and atmospheric pressure. In Medpha model, the typical meteorologic years for high and low temperature, maximum and minimum solar radiation intensity were picked up. Then the hourly weather data, including air temperature, humidity, direct and diffuse solar radiation intensity, wind speed and direction, and sky background radiation temperature, was simulated according to the daily variation rules of weather parameters [42]. Then the weather data in typical meteorologic year was adopted as basic data for annual simulation in DeST-c software. An hourly energy consumption simulation model of a case data center with a PLHP system was set up, and the hourly energy consumption in a whole year basing on fitting EER formula from a case project was summed up as the annual energy consumption. In the simulation model, the annual energy consumptions of different cities in China were obtained according to different yearly climatic data. The energy savings using a PLHP system in a case data center were calculated. The national energy saving distribution map is given for different climate regions in China, which is very useful to the PLHP energy saving evaluation and project application.

## 2. Energy consumption case model

### 2.1. Case data center model

As shown in Fig. 1, the simulation model is developed based on a typical data center for data exchanging and storage in Beijing, which lies in 9th floor of a 12-storey building. The building envelope is made of reinforced concrete. The area of the data center is about 40 $m^2$ and the story height is 2.3 m. There are 14 IT cabinets with total 28 kW rating power and one UPS with 40 kVA rated capacity. IT devices in a data center work continuously for 8760 hours a year. The actual load ratio of IT cabinets is only 40%. The air conditioners (AC) with 12 kW rating cooling capacity were installed. Two double-layer glass windows lie in the north of the data center and both windows cover 7.2 $m^2$. For this case project, a PLHP system with 12 kW rating cooling capacity was developed and used to cool the case data center using ambient energy. The working time of the air conditioner is reduced and the cooling energy consumption decreases. At steady state, IT cabinets provides little thermal storage and there is negligible energy loss through the electromagnetic wave. Thus, the heat load of each IT cabinet is approximately equal to its input power. The energy from the input power is mainly dissipated by air convection and surface radiation,