Energy 98 (2016) 15–25

Contents lists available at ScienceDirect

Energy

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

Simulation study on the operating characteristics of the heat pipe for combined evaporative cooling of computer room air-conditioning system

Zongwei Han [a], [*], Yanqing Zhang [a], Xin Meng [a], Qiankun Liu [a], Weiliang Li [a], Yu Han [b], Yanhong Zhang [b]

[a] School of Materials & Metallurgy, Northeastern University, Shenyang 110819, PR China
[b] Xinjiang Solar Technology Development Company, Urumqi 830011, PR China

ARTICLE INFO

Article history:
Received 24 May 2015
Received in revised form
31 December 2015
Accepted 7 January 2016
Available online 2 February 2016

Keywords:
Simulation study
Evaporative cooling
Separate type heat pipe
Mathematical model
Energy saving

ABSTRACT

In order to improve the energy efficiency of air conditioning systems in computer rooms, this paper proposed a new concept of integrating evaporative cooling air-conditioning system with heat pipes. Based on a computer room in Shenyang, China, a mathematical model was built to perform transient simulations of the new system. The annual dynamical performance of the new system was then compared with a typical conventional computer room air-conditioning system. The result showed that the new integrated air-conditioning system had better energy efficiency, i.e. 31.31% reduction in energy consumption and 29.49% increase in COP (coefficient of performance), due to the adoption of evaporative condenser and the separate type heat pipe technology. Further study also revealed that the incorporated heat pipes enabled a 36.88% of decrease in the operation duration of the vapor compressor, and a 53.86% of reduction for the activation times of the compressor, which could lead to a longer lifespan of the compressor. The new integrated evaporative cooling air-conditioning system was also tested in different climate regions. It showed that the energy saving of the new system was greatly affected by climate, and it had the best effect in cold and dry regions like Shenyang with up to 31.31% energy saving. In some warm and humid climate regions like Guangzhou, the energy saving could be achieved up to 13.66%.

1. Introduction

As the Internet is becoming more accessible to the public, the demands for more and bigger data centers are growing rapidly. Bigger data centers mean more heat generated from the equipment. Therefore, when the outdoor temperature is lower than the indoor temperature of the data centers, even in winter, air-conditioning systems are still required to keep the indoor temperature within a desired range. This also leads to a huge increase in energy consumption for air-conditioning systems in data rooms. A typical data center energy consumption breakdown, according to the national laboratory of Lawrence Berkeley, shows that IT equipment, air-conditioning equipment, power and lighting equipment accounted for about 44%,38% and 18% respectively, so air-conditioning system is the major energy consumer after IT equipment [1]. According to statistics, the total power consumption of data centers as of 2011 in China was 700 billion kWh, accounted for 1.5% of the national total electricity consumption. Therefore it is essential to take energy saving measures on computer room air conditioners.

In recent years, various new methods have been tested to reduce the energy consumption of air conditioning systems in computer rooms, among which are the optimization of indoor airflow patterns as well as the utilization of natural cold source in air-conditioning systems. However, the optimization of indoor airflow patterns [2–6] are restricted by many geometry factors of a room itself, and this limits its application in real cases. The utilization of natural cold source in air-conditioning systems can be further divided into two types, namely the direct and the indirect types. A system with direct use of natural cold source [7,8] is simple and its initial investment and the maintenance costs are relatively low, but it is difficult to control the humidity and cleanliness levels within a desired range. To address the above-mentioned problems,

---

[*] Corresponding author. Tel.: +86 024 83686994; fax: +86 024 83672218.
E-mail address: hanzongwei_neu@163.com (Z. Han).

http://dx.doi.org/10.1016/j.energy.2016.01.009
0360-5442/© 2016 Elsevier Ltd. All rights reserved.

some systems adopt indirect methods to use the natural cold source, such as the utilization of high efficient heat exchangers and refrigeration medium cycle [9–13]. However this scheme still needs two independent devices, requires high initial cost, more complex installation and maintenance, and occupies extra space. And the lacking of research on controlling two devices coordinately may affect the whole energy saving, even compromise the safety of the cooling process in the room. In order to make the device more compact and address the above-mentioned problems, a separate type heat pipe technology is applied to the air-conditioning system in the computer room. Dan–dan Zhu [14] proposes SHP (separate heat pipe) heat exchanger using in telecommunication base stations, uses a simulation method to estimate the operating performance, examines the applicability of the system, and results show that if evaporative-cooling is used for the outdoor units, SHP can run more hours and have a higher energy-saving potential in dry climate regions. M. Ahmadzadehtalatapeh and Y.H.Yau [15–17] analyze theoretically the performance of separate heat pipe heat exchangers in air conditioning system, apply it in a hospital ward to improve the air quality and reduce energy consumption, simulate the annual operation performance of the system and the existing system. Based on the comparison, the system with the added eight-row heat pipe heat exchangers has better performance and it could provide the temperature and relative humidity of approximately 23 °C and 51.1% in the ward space. Okazaki [18], Lee [19,20] use both simulation and experimental methods to analyze the performance of the separate type heat pipe with vapor compression air-conditioning system. They conclude that the indoor and outdoor temperatures, refrigerant charge, and the height difference of heat exchangers are the most impactful factors to the combined air-conditioning system. Han L J et al. [21] develop and use the heat pipe and vapor compression air-conditioning system in many base stations to make a long-term pilot application, and results show that 30–45% energy saved than normal air-conditioning system in the same condition.

Hence, the energy saving, efficiency and reliability of the separate type heat pipe with vapor compression air-conditioning system are better than those conventional ones, and it promises a good application prospect. However, on the basis of the above systems, which use air cooling condenser, it is difficult to further improve the performance of the system. In order to enhance the utilization of natural cooling source, an evaporative cooling air-cooled condenser is included in the separate type heat pipe with a vapor compression air-conditioning system. The performance of this novel evaporative cooling combined air-conditioning system will be studied in this paper. The mathematical model of the system will be established, and the simulation will be performed to predict the performance of the system.

2. The operation principle of evaporative cooling combined air-conditioning system

Evaporative cooling combined air-conditioning system consists of evaporative condenser, wind cold evaporator, compressor, expansion valve, spray pump, electromagnetic valve and so on, which can realize three operation modes:(1) Air-cooled heat pipe heat transfer mode; (2) Evaporative cooling heat pipe heat transfer mode; (3) Evaporative cooling vapor compression refrigeration mode. The schematic diagram of the evaporative cooling combined air-conditioning system at different operation modes is showed in Fig. 1.

Compared with the conventional air-conditioning system, a heat pipe branch is added to the vapor compression refrigeration cycle in the combined air-conditioning system, The system is able to switch among 3 modes, namely the heat pipe heat transfer Mode 1 and 2, as well as the vapor compression refrigeration Mode 3, through a three-way valve and a solenoid valve. When the system is operating under Mode 1 as shown in Fig. 1 (a), the compressor and the throttle device are bypassed by the three-way valve and the solenoid valve, the condenser and the evaporator are then connected directly through the gas pipe and the liquid pipe. The refrigerant is evaporated due to the heat absorbed, and the evaporated refrigerant rises to the condenser due to the pressure difference and density difference. In the condenser, the evaporated refrigerant is then condensed and released heat, and eventually turns into liquid form. Because of the gravity, the liquid refrigerant flows back to the evaporator to complete the entire cycle of the heat pipe. During this process, the indoor heat is transferred to the outdoor environment. The working principle of Mode 2 is basically as same as Mode 1, only except that the spray pump is operating and the air-cooled condenser becomes the evaporative condenser as shown in Fig. 1 (b). Under the Mode 3, the working principle of the combined air-conditioning system is basically as same as the traditional air-conditioning system. The only difference is the use of evaporative condenser instead of the air-cooled condenser.

3. Mathematical model of evaporative cooling combined air-conditioning system

To examine the annual operating characteristics of the system, the mathematical models of main components in the system are established.

3.1. Mathematical model of evaporative condenser

The heat transfer process in evaporative condenser (as shown in Fig. 2) is complex. To simplify the mathematical model, the following assumptions are made: 1) Refrigerant flows as one-dimensional along the axial in pipes; 2) Refrigerant flow distribution is uniform; 3) Refrigerant flows as homogeneous flow; 4) Exothermic heat of refrigerant is converted to water's vaporization latent heat to the air; 5) Ignore air heat exchange with the surrounding environment; 6) Ignore the influence of refrigerant's pressure drop. Based on the above assumptions, the evaporative condenser's distribution parameter model is established.

The heat transfer process of evaporative condenser can be expressed as follows:

1. Flow heat exchange equations of refrigerant in the pipe

$$\mathrm{d}Q_c = m_r(h_{ro} - h_{ri}) \tag{1}$$

$$\mathrm{d}Q_c = \alpha_c \mathrm{d}A_i(t_{rm} - t_w) \tag{2}$$

Where, $\mathrm{d}Q_c$ is heat transfer rate of infinitesimal section, W; α_c is heat transfer coefficient of refrigerant, W/(m^2 °C); $\mathrm{d}A_i$ is inner surface area of pipe, m^2; t_w is temperature of tube wall, °C; t_{rm} is average temperature of refrigerant, $t_{rm} = (t_{ri} + t_{ro})/2$, °C; m_r is mass flow of refrigerant, kg/s; h_{ri},h_{ro} is import and export enthalpy of refrigerant of infinitesimal section, J/kg.

For single-phase region and two-phase region, the heat transfer coefficient of refrigerant $\alpha c'$ and $\alpha c''$ are calculated by Dittus-Boeler [22] heat correlation and Shah [23] heat correlation respectively:

$$\alpha_c' = \frac{\lambda_r \cdot Nu_i}{d_i} \tag{3}$$