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Postprint: Experimental Study and Energy Analysis of CO2 Thermosyphons for Data Center Free Cooling

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Abstract

Natural cooling technology for data center rooms is gaining increasing attention as an effective energy-saving cooling method for data centers. Natural cooling devices based on thermosyphons exhibit excellent heat transfer performance under small temperature differences and possess promising application prospects. This paper presents experimental and energy-saving effect analysis studies on thermosyphons for data center natural cooling using CO2 as the working fluid, with comparisons made to R22. Experimental results demonstrate that, compared to R22 as the working fluid, the performance of CO2 thermosyphons is more significantly influenced by the filling ratio. The optimal filling ratio is 150%, which is higher than that of R22. Under optimal filling ratio conditions, the heat transfer capacity of both CO2 and R22 thermosyphons increases with increasing indoor-outdoor temperature difference, with CO2 thermosyphons exhibiting higher heat transfer capacity than R22. When the filling ratio or indoor-outdoor temperature difference is small, a dry-out zone exists in the upper portion of the evaporator, which gradually disappears as the filling ratio or temperature difference increases. Energy-saving effect analysis results indicate that adopting CO2 as the working fluid to replace R22 can significantly enhance the annual thermosyphon natural cooling time for data centers.

Full Text

Introduction

With the rapid development of the information industry, the number and energy consumption of data centers have grown dramatically. Currently, global data center energy consumption accounts for 1.1-1.5% of total worldwide energy consumption [1]. Among the components of data center energy consumption, cooling systems account for over 30% [2,3]. Therefore, reducing cooling energy consumption has become an essential requirement for data center energy conservation, and relevant energy-saving cooling technologies have developed rapidly.

Traditional data center rooms rely on compressor work throughout the year to obtain cooling sources, consuming substantial electrical energy. For most regions in China, outdoor temperatures are below indoor temperatures for a considerable portion of the year. Utilizing natural low-temperature cold sources from the environment to cool data centers during these periods can save compressor energy consumption. This technology is called free cooling. Thermosyphon-based free cooling technology, as a heat transfer device, offers excellent phase-change heat transfer performance without compromising indoor air quality or humidity conditions, making it a promising free cooling method. In recent years, thermosyphon-based free cooling has attracted widespread attention, with many scholars conducting experimental and simulation studies on the performance of thermosyphons for free cooling under different structural configurations, operating conditions, and filling ratios [4-8]. Additionally, research has been conducted on the annual energy consumption characteristics of thermosyphon heat exchangers, as well as the influence of building envelope structures and set temperatures [9,10].

However, most current research uses Freon as the working fluid [4-10]. This type of working fluid is being phased out due to environmental considerations, making it imperative to investigate the performance under environmentally friendly working fluids for the future development and application of thermosyphon free cooling. CO2, as an environmentally friendly working fluid with favorable thermodynamic properties, is suitable as a replacement for Freon in this field. Currently, research on CO2 thermosyphons remains very limited. Tong et al. [11,12] experimentally studied the performance of CO2 thermosyphons, demonstrating that the heat transfer rate under CO2 charge is higher compared to R22, with an optimal filling ratio of 100% based on evaporator internal volume. Given the limited research findings in this area and the fact that heat exchangers in these studies have been finned-tube types, it is necessary to investigate the performance of CO2 thermosyphons, particularly under different heat exchanger configurations, and to explore their temperature and circulation flow characteristics.

This study focuses on a CO2 thermosyphon with microchannel parallel-flow evaporators and condensers, investigating its performance and energy-saving effects under different filling ratios and operating conditions, and comparing it with R22 charging. To explore its circulation flow characteristics, infrared thermal imaging was employed to analyze the temperature distribution of the CO2 thermosyphon. The research findings provide guidance for the design and application of CO2 thermosyphons, particularly those employing microchannel parallel-flow heat exchangers.

Experimental Setup

The experiments were conducted on a CO2 separated thermosyphon with microchannel parallel-flow evaporators and condensers. An enthalpy difference laboratory was used for testing, with the experimental facility shown in [Figure 1: see original paper]. The evaporator was placed on the indoor side, while the condenser was placed on the outdoor side, maintaining a 1.0 m height difference to sustain working fluid circulation. A FLIR T610 thermal imaging camera was used to record the temperature distribution of the thermosyphon evaporator.

The structural parameters of the thermosyphon and experimental operating conditions are presented in . Both evaporators and condensers employed microchannel parallel-flow heat exchangers, while the riser and downcomer used copper pipes for air conditioning applications.

Heat Transfer Analysis

The performance comparison between CO2-charged and R22-charged thermosyphons under different filling ratios is shown in [Figure 2: see original paper], with the indoor-outdoor temperature difference maintained at 10°C. As evident, the heat transfer rate of both CO2 and R22 thermosyphons initially increases and then decreases with increasing filling ratio. The optimal filling ratio for CO2 is approximately 150%, higher than that for R22. Under conditions below the optimal filling ratio, the heat transfer rate of the CO2 thermosyphon decreases significantly, while above the optimal filling ratio, the heat transfer rate shows minimal variation. For R22, the optimal filling ratio is approximately 110%, with relatively small variations in heat transfer rate when deviating from this optimum, either higher or lower. This indicates that CO2 thermosyphons are more suitable for larger working fluid filling ratios compared to R22 thermosyphons, with heat transfer rates being more significantly affected under low filling ratio conditions. Insufficient charging should be avoided.

The performance comparison between CO2-charged and R22-charged thermosyphons under different indoor-outdoor temperature differences is illustrated in [Figure 3: see original paper]. In the experiments, the filling ratios for CO2 and R22 were 150% and 110%, respectively, representing their optimal values. As shown in [Figure 3: see original paper], the heat transfer rate of thermosyphons charged with both working fluids increases nearly linearly with increasing indoor-outdoor temperature difference. At the same temperature difference, the CO2 thermosyphon demonstrates significantly higher heat transfer rates compared to R22. This confirms that CO2 is suitable as an alternative working fluid for thermosyphon-based free cooling in data centers.

Thermal Imaging Analysis

To further investigate the temperature distribution and circulation flow characteristics of the CO2 thermosyphon, infrared thermal imaging analysis was conducted under different filling ratios and temperature differences. [Figure 4: see original paper] presents thermal images of the evaporator at different filling ratios with an indoor-outdoor temperature difference of 10°C. At lower filling ratios, the upper portion of the evaporator appears red (light-colored) in the thermal images, indicating higher wall temperatures than the lower section. This occurs because dryout occurs at a certain location as the working fluid flows upward through the evaporator, leaving the upper region filled with vapor-phase working fluid that cannot effectively cool the evaporator wall, resulting in elevated temperatures. As the filling ratio increases, the dryout region gradually diminishes and completely disappears at a filling ratio of approximately 150%. This explains why the optimal filling ratio is 150% as discussed above.

[Figure 5: see original paper] shows thermal images of the evaporator at different indoor-outdoor temperature differences with a filling ratio of 150%. When the temperature difference is small, a dryout region exists in the upper portion of the evaporator, but this region gradually disappears as the temperature difference increases. This is because at small temperature differences, the system has insufficient circulation driving force and low circulation flow rate, causing the working fluid to evaporate completely soon after being heated in the evaporator. The presence of the dryout region is thus one reason for the lower heat transfer rates observed at small temperature differences.

Energy-Saving Analysis

The experimental results demonstrate that CO2 as a working fluid for thermosyphon-based free cooling offers better heat transfer performance than the conventional R22 working fluid. To investigate the energy-saving prospects of CO2 thermosyphons, this section analyzes their energy-saving effects in comparison with R22.

The relationship between cooling capacity and indoor-outdoor temperature difference for both CO2 and R22 thermosyphons was fitted using the experimental results from [Figure 3: see original paper]:

$$Q_{CO2} = -0.0020\Delta T^2 + 0.3695\Delta T - 0.8538 \quad (1)$$
$$Q_{R22} = 0.0017\Delta T^2 + 0.2717\Delta T - 1.1709 \quad (2)$$

where Q_{CO2} and Q_{R22} are the cooling capacities of thermosyphons using CO2 and R22 as working fluids, respectively, in kW; and ΔT is the indoor-outdoor temperature difference in °C.

For a modular data center with an information equipment heat load of 4 kW and an indoor ambient temperature set at 27°C, the annual free cooling time using thermosyphon-based free cooling equipment is defined as the total time when the thermosyphon cooling capacity exceeds the equipment heat load. Combining weather data for four cities—Harbin, Beijing, Shanghai, and Guangzhou [13], the calculated annual free cooling times for thermosyphons using CO2 and R22 as working fluids are shown in [Figure 6: see original paper]. The results demonstrate that using CO2 as the working fluid can significantly increase the annual thermosyphon free cooling time for data centers. Moreover, the improvement in free cooling time is more pronounced in southern China compared to northern regions.

Conclusions

Thermosyphon-based free cooling technology represents an ideal method for energy-efficient cooling of data centers. This study investigated the system performance and energy-saving effects of a separated thermosyphon using CO2 as the working fluid with microchannel parallel-flow evaporators and condensers, comparing it with R22. The main conclusions are as follows:

(1) The optimal filling ratios for CO2 and R22 are approximately 150% and 110%, respectively. Compared to R22, CO2 is more suitable for larger working fluid filling ratios. The heat transfer rate of CO2 thermosyphons decreases significantly under filling ratios below the optimum. The cooling capacity of thermosyphons charged with both working fluids increases with indoor-outdoor temperature difference, with CO2 thermosyphons demonstrating greater heat transfer rates than R22 at the same temperature difference.

(2) At lower filling ratios, a dryout region exists in the upper portion of the evaporator, which gradually diminishes as the filling ratio increases and completely disappears at a filling ratio of approximately 150%. When the indoor-outdoor temperature difference is small, a dryout region also exists in the upper evaporator section, but it gradually disappears as the temperature difference increases.

(3) Substituting CO2 for R22 can significantly increase the annual thermosyphon free cooling time for data centers. The improvement in free cooling time is more significant in southern China than in northern regions.

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