Experimental Study and Energy Saving Analysis of CO2 Thermosyphon for Data Center Free Cooling (Postprint)

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Abstract

Data center natural cooling technology has been increasingly recognized 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 indicate that, compared to R22, 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 demonstrating higher heat transfer capacity than R22. When the filling ratio or indoor-outdoor temperature difference is relatively small, a dry-out zone exists in the upper region of the evaporator, which gradually diminishes as the filling ratio or temperature difference increases. Energy-saving effect analysis results demonstrate that replacing R22 with CO2 working fluid can substantially increase the annual thermosyphon natural cooling duration for data centers.

Full Text

Experimental Investigation and Energy-Saving Analysis of a CO2 Thermosyphon for Free Cooling of Data Centers

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Abstract

Free cooling technology for data centers has gained increasing attention as an effective energy-saving approach for data center thermal management. Natural cooling systems based on thermosyphons exhibit excellent heat transfer performance under small temperature differences, making them promising for practical applications. This paper investigates the performance and energy-saving potential of a thermosyphon using CO2 as the working fluid for data center free cooling, with comparative analysis against R22.

Experimental results demonstrate that the performance of CO2 thermosyphons is more significantly influenced by filling ratio compared to R22 systems. The optimal filling ratio for CO2 is approximately 150%, which is higher than that for R22. Under optimal filling ratio conditions, the heat transfer rates of both CO2 and R22 thermosyphons increase with indoor-outdoor temperature difference, with CO2 systems achieving higher heat transfer rates than R22. When the filling ratio or temperature difference is small, a dryout region exists in the upper portion of the evaporator, which gradually disappears as the filling ratio or temperature difference increases. Energy-saving analysis reveals that substituting CO2 for R22 can substantially increase the annual thermosyphon free cooling duration for data centers.

Keywords: Data center; Free cooling; Thermosyphon; CO2

1. Introduction

With the rapid development of the information industry, both the number of data centers and their energy consumption have grown dramatically. Currently, global data center energy consumption accounts for 1.1–1.5% of total worldwide energy usage [**?**]. Within the energy consumption profile of data centers, cooling systems represent over 30% of the total [**?**, **?**]. Consequently, reducing cooling energy consumption has become an imperative for data center energy conservation and emission reduction, driving rapid advancement in related energy-efficient cooling technologies.

Traditional data center cooling relies on compressor-driven refrigeration throughout the year, consuming substantial electrical energy. For most regions in China, outdoor temperatures remain below indoor levels for considerable portions of the year. Utilizing these natural low-temperature sources for data center cooling can significantly reduce compressor energy consumption—a technique known as free cooling. Natural cooling technology based on thermosyphons has attracted widespread attention due to the excellent heat transfer performance of phase-change processes and its non-disruptive impact on indoor air quality and humidity environments. Numerous researchers have conducted experimental and simulation studies on thermosyphon performance under various structural configurations, operating conditions, and filling ratios [?]. Additionally, investigations have examined the annual energy consumption characteristics of thermosyphon heat exchangers and the influence of building envelope structures and setpoint temperatures [?, ?].

However, most existing research has employed fluorocarbon refrigerants [?]. These working fluids are being phased out due to environmental concerns, making the investigation of environmentally friendly alternatives essential for the future development and application of thermosyphon-based free cooling. CO2, as an environmentally benign working fluid with favorable thermodynamic properties, represents a suitable replacement for fluorocarbons in this application. Current research on CO2 thermosyphons remains limited. Tong et al. [?, ?] experimentally studied CO2 thermosyphon performance, demonstrating that CO2 systems achieve higher heat transfer rates than R22 and that the optimal filling ratio is 100% based on evaporator internal volume. Given the limited research findings in this field and the fact that previous studies utilized finned-tube heat exchangers, further investigation of CO2 thermosyphon performance—particularly under different heat exchanger configurations—is necessary to explore its temperature distribution and circulation characteristics.

This study focuses on a CO2 thermosyphon employing microchannel parallel-flow evaporators and condensers, examining its performance under various filling ratios and operating conditions while analyzing energy-saving effects in comparison with R22. To investigate circulation characteristics, infrared thermography 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 utilizing microchannel parallel-flow heat exchangers.

2. Experimental Setup

Experiments were conducted on a separated CO2 thermosyphon equipped with microchannel parallel-flow evaporators and condensers. Testing was performed using an enthalpy difference laboratory, with the experimental apparatus shown in [Figure 1: see original paper]. The evaporator was installed on the indoor side, while the condenser was placed outdoors, maintaining a 1.0 m height difference to sustain working fluid circulation. A FLIR T610 thermal imaging camera was used to record temperature distributions on the thermosyphon evaporator.

The structural parameters of the thermosyphon and experimental conditions are presented in . Both evaporators and condensers employed microchannel parallel-flow heat exchangers, with riser and downcomer tubes constructed from standard air-conditioning copper tubing.

2.1 Heat Transfer Analysis

Performance comparisons between CO_2 and R22 thermosyphons at various filling ratios are illustrated in [Figure 2: see original paper], with the indoor-outdoor temperature difference maintained at 10°C. The results show that heat transfer rates for both CO_2 and R22 systems initially increase then decrease with rising filling ratio. The optimal filling ratio for CO_2 is approximately 150%. Below this optimal value, the heat transfer rate of CO_2 thermosyphons declines significantly, while above it, the rate remains relatively stable. For R22, the optimal filling ratio is approximately 110%, with relatively modest variations in heat transfer rate when deviating from this optimum. These findings indicate that CO_2 thermosyphons are better suited for higher filling ratios compared to R22 systems and exhibit more pronounced performance degradation under insufficient charging conditions, which should be avoided.

Comparative performance under various indoor-outdoor temperature differences is shown in [Figure 3: see original paper], with CO_2 and R22 filling ratios set at their optimal values of 150% and 110%, respectively. Both working fluids demonstrate nearly linear increases in heat transfer rate with increasing temperature difference, with CO_2 thermosyphons achieving significantly higher rates than R22 under identical temperature differences. This confirms the suitability of CO_2 as a replacement working fluid for data center free cooling applications.

2.2 Thermal Imaging Analysis

To further investigate temperature distribution and circulation characteristics, infrared thermography was performed on the CO_2 thermosyphon under different filling ratios and temperature differences. [Figure 4: see original paper] presents evaporator thermal images at a 10°C temperature difference across various filling ratios. At lower filling ratios, the upper portion of the evaporator appears red (light-colored), indicating elevated wall temperatures compared to the lower section. This occurs because working fluid evaporates completely at a certain point during upward flow, leaving the upper region filled with vapor and preventing effective evaporator wall cooling. As filling ratio increases, the dryout region progressively diminishes and completely disappears at approximately 150% filling ratio, explaining the optimal filling ratio identified above.

Thermal images at different temperature differences with a 150% filling ratio are shown in [Figure 5: see original paper]. At small temperature differences, a dryout region exists in the evaporator upper section but gradually vanishes as the temperature difference increases. This phenomenon arises from insufficient circulation driving force and low mass flow rates under small temperature differences, causing complete evaporation of the working fluid shortly after heating begins. The presence of dryout regions contributes to reduced heat transfer performance at small temperature differences.

2.3 Energy-Saving Analysis

The experimental results demonstrate that CO2 thermosyphons offer superior heat transfer performance compared to conventional R22 systems. To evaluate the energy-saving potential, this section analyzes and compares the annual free cooling performance.

Based on the experimental results from [Figure 3: see original paper], correlations were developed for the cooling capacity of CO2 and R22 thermosyphons as functions of indoor-outdoor temperature difference:

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

$$Q_{R22} = 0.0017\Delta T^2 + 0.2717\Delta T - 1.1709 \quad (2)$$

where Q_{CO2} and Q_{R22} represent the cooling capacity of CO2 and R22 thermosyphons (kW), respectively, and ΔT denotes the indoor-outdoor temperature difference (°C).

For a modular data center with 4 kW IT equipment heat load and an indoor setpoint temperature of 27°C, the annual free cooling duration is defined as the total time when the thermosyphon cooling capacity exceeds the equipment heat load. Using meteorological data for Harbin, Beijing, Shanghai, and Guangzhou [?], the calculated annual free cooling durations for CO2 and R22 thermosyphons are presented in [Figure 6: see original paper]. The results show that CO2 working fluid significantly increases annual thermosyphon free cooling time, with more pronounced improvements in southern China compared to northern regions.

3. Conclusions

Thermosyphon-based natural cooling represents an ideal method for energy-efficient data center thermal management. This study investigated the performance and energy-saving effects of a separated thermosyphon with microchannel parallel-flow evaporators and condensers using CO2 as the working fluid, with comparative analysis against R22. The main conclusions are:

(1) The optimal filling ratios for CO2 and R22 are approximately 150% and 110%, respectively. Compared to R22, CO2 is better suited for higher filling ratios. CO2 thermosyphons exhibit significant performance degradation when operating below the optimal filling ratio. The cooling capacity of both working fluids increases with indoor-outdoor temperature difference, with CO2 achieving higher heat transfer rates than R22 under identical conditions.

(2) At low filling ratios, a dryout region exists in the evaporator upper section, which gradually diminishes and completely disappears at approximately

150% filling ratio. Similarly, at small temperature differences, a dryout region appears but vanishes as the temperature difference increases.

(3) Substituting CO2 for R22 can substantially increase annual thermosyphon free cooling duration for data centers, with more significant improvements observed in southern China compared to northern regions.

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Note: Figure translations are in progress. See original paper for figures.