Experimental and numerical investigation on a CO₂ loop thermosyphon for free cooling of data centers

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Abstract: Free cooling based on loop thermosyphon is an ideal method for
energy-saving of data centers. In order to promote its future application, it is
necessary to investigate the performance of utilizing environment friendly working
fluids. In this paper, an experiment based on enthalpy difference method and thermal
imaging is conducted on a CO₂ loop thermosyphon with microchannel parallel-flow
evaporator and condenser. The results show that the effect of filling ratio on CO₂ loop
thermosyphon is more significant and the optimal filling ratio is higher, compared
with R22 loop thermosyphon. Thermal image of the evaporator shows that
superheated region shrinks and then disappears with the increase of filling ratio.

Moreover, to analyze the relationship between the phenomenon and the internal flow state, a distributed-parameter model is built and validated. The simulation results show that 150% is the optimal filling ratio for no superheating or subcooling occurs along the loop. The effects of height difference and pipe length are more significant for low filling ratio. Superheating is easier to occur at the evaporator outlet when height difference is smaller or pipe length is larger, and subcooling is easier to occur at the condenser outlet when height difference or pipe length is smaller.

Key words: CO₂, thermosyphon, simulation, free cooling, data center

Nomenclature	
<i>A</i>	area (m ²)
<i>d</i>	hydraulic diameter (m)
<i>G</i>	mass flux (kg m ⁻² s ⁻¹)
<i>g</i>	gravitational acceleration (m s ⁻²)
<i>h</i>	enthalpy (kJ kg ⁻¹)
<i>m</i>	mass (kg)
<i>p</i>	pressure (Pa)
<i>Q</i>	heat transfer rate (kW)
<i>Re</i>	Reynolds number
<i>u</i>	velocity (m s ⁻¹)
<i>x</i>	vapor quality
<i>z</i>	distance in the flow direction (m)
Greek symbols	

α	void fraction
θ	angle from horizontal
λ	friction factor
ρ	density (kg m ⁻³)
Δp	pressure difference (Pa)
<i>Subscripts</i>	
act	actual
cal	calculated
fric	friction
g	gas
l	liquid
sup	supposed
<i>Abbreviations</i>	
DB	dry-bulb temperature
IT	information technology
WB	wet-bulb temperature

31 1 Introduction

32 Data centers are important auxiliary facilities of IT industry. In recent years, the
33 energy consumption of data centers is increasing rapidly and now around 1.3% of
34 total energy use of the world is consumed by data centers [1]. Data center must be
35 cooled all the year round to maintain suitable temperature for IT equipments. Cooling
36 energy consumption usually accounts over 30% of total energy use in a data center

[2,3]. It is necessary to utilize efficient **cooling** technologies to cut down this consumption.

Free cooling, which means using natural cold source to cool data centers when outdoor temperature is relatively low, is an ideal energy-saving solution. Among existing free cooling methods, free cooling based on thermosyphon has good heat transfer ability and will not disturb indoor air quality and humidity therefore it has good application potential [4].

Thermosyphon free cooling equipments are usually air cooled loop thermosyphons owing to their application demand. They transfer heat between indoor hot air and outdoor cold air, and the temperature difference and heat flux are smaller than those of common thermosyphons or heat pipes [5]. Therefore, they have their own characteristics and attract the attention of more and more researchers. The performance of different filling ratios, temperature differences and height differences are investigated experimentally [6,7]. Also, simulation models have been built to study the internal flow parameters under different working conditions and geometric parameters [8-10]. However, most of the exiting studies on thermosyphon free cooling equipments use HCFCs or HFCs as working fluids [6-10], which will be prohibited for environmental considerations. It is necessary to investigate the applicability of other environment friendly working fluids.

CO₂ is a kind of natural refrigerant and its thermophysical properties are suitable for application in this field, while only a few **studies** have been done. Tong et al. [11,12] experimentally investigated the performance of a CO₂ loop thermosyphon for

data center free cooling. The heat transfer rate of different temperatures and filling ratios was studied and compared with R22. The results showed that the heat transfer performance of CO₂ loop thermosyphon was superior to that of R22 loop thermosyphon. Also, silica parts were equipped on the connection pipes and the mixture of liquid and vapor were observed in both the riser and downcomer at high filling ratio. It was found that the heat transfer ability at a filling ratio of 100% is the highest. Considering the thermophysical features of CO₂, the performance of CO₂ loop thermosyphon is much different from those based on existing working fluids and it is necessary to investigate its performance more comprehensively to lay the foundation for its application. Meanwhile, existing studies in this field [11,12] are only experimental studies. Simulation studies are urgently needed to further investigate the relationship between the performance and internal flow state.

In this paper, an experiment based on enthalpy difference method and thermal imaging is conducted on a CO₂ loop thermosyphon for free cooling of data centers to investigate its performance and temperature distribution. Moreover, a distributed-parameter model is built to analyze the relationship between the phenomenon and the internal flow state, and the effects of some key parameters on the performance are evaluated for its optimal design. This paper will be helpful for better understanding and optimization of CO₂ loop thermosyphon for free cooling of data centers.

2 Experimental investigation

2.1 Experimental set up

In this paper, a loop thermosyphon is designed based on the cooling demand of a kind of small data center, mobile communication base station. Microchannel parallel-flow evaporator and condenser are utilized to obtain efficient and compact heat transfer, rather than the tube-fin heat exchangers used in most existing thermosyphon free cooling equipments [6-12]. The geometric parameters of the loop thermosyphon are shown in Table 1.

The schematic diagram of the experimental set up is shown in Fig. 1. The experiment is conducted in a laboratory based on enthalpy difference method. The evaporator is installed in the indoor test room. Four platinum resistance thermometers with an uncertainty of ± 0.1 °C are utilized to measure the dry-bulb temperature (DB) and wet-bulb temperature (WB) of the inlet and outlet air. The air flow rate of the evaporator is determined by a nozzle flowmeter, and the pressure difference across the nozzle is measured by a differential pressure transducer with an uncertainty of $\pm 0.5\%$. The condenser is installed in the outdoor test room and the DB and WB of the inlet air are measured. To show the performance of the loop thermosyphon in an intuitive way, an infrared thermal imager is utilized to record the temperature distribution of the evaporator. The uncertainty of the imager is $\pm 2\%$.

2.2 Experimental results

The heat transfer rate of the CO₂ loop thermosyphon when filling ratio is varied is shown in Fig. 2, and compared with using R22 as working fluid. The indoor and outdoor temperature difference is 10 °C. The filling ratio is defined as the filling liquid volume divided by the internal volume of the evaporator. It can be seen that the

effect of filling ratio on the performance of CO₂ loop thermosyphon is more significant than that of R22. The optimal filling ratio of CO₂ is around 150%, higher than R22. Meanwhile, when the filling ratio is relatively low, the heat transfer rate of CO₂ loop thermosyphon is much lower than R22. Therefore, CO₂ loop thermosyphon is suitable for larger filling ratios. As a note, the evaporator in our study is microchannel parallel-flow heat exchanger, the internal volume of which is small and even the internal volume of the connection pipes is comparable to that of the evaporator. Therefore, the optimal filling ratio is relatively high for the reason that the filling ratio is calculated as the filling liquid volume divided by the internal volume of the evaporator. The filling mass is 1.85 kg when the filling ratio of CO₂ is 150%.

The heat transfer rate of the CO₂ loop thermosyphon when temperature difference is varied is shown in Fig. 3, and compared with using R22 as working fluid. The filling ratios of CO₂ and R22 are 150% and 110%, respectively, which are optimal filling ratios. The heat transfer rates both increase almost linearly with temperature difference, and the heat transfer rate of CO₂ loop thermosyphon is larger than that of R22 loop thermosyphon. It means that using CO₂ as working fluid of thermosyphon free cooling equipments can achieve good performance.

The temperature distribution of the evaporator in different filling ratios is shown in Fig. 4 to obtain an intuitive understanding of its performance. When the filling ratio is 90%~130%, the temperature of the upper part of the evaporator is higher than the lower part. The reason is that the CO₂ in the lower part is mainly in the liquid or two-phase state and extracts considerable heat from the wall. However, the CO₂ is at

vapor state at the upper part and there is little heat transfer at this point, which explains the higher temperature. As the filling ratio increases, the vapor region shrinks and when the filling ratio reaches 140%, the vapor region nearly disappears and the temperature of the whole evaporator is relatively uniform. It can be speculated that the working fluid in the evaporator is all at two-phase state in this situation and this just explain why the heat transfer is higher in relatively large filling ratios.

3 Numerical investigation

3.1 Simulation model and validation

In order to investigate the internal flow state and its relationship with the above phenomena and further optimize the structure, a steady-state distributed-parameter model is built for the CO₂ loop thermosyphon. The model is based on the following assumptions:

- 1) The working fluid has a one-dimensional flow in the channel and all parameters are cross-section averaged;
- 2) The working fluid in different parallel microchannels has the same temperature and pressure distribution along the flow direction;
- 3) Heat losses in the riser and down comer can be neglected;
- 4) Air flow outside the flat tube is uniform.

The pressure drop for single-phase flow is calculated as:

$$\Delta p_f = \lambda \frac{\Delta y}{d} \frac{\rho u^2}{2} \quad (1)$$

where, for turbulent flow, λ is calculated by the correlation proposed by Blasius [13].

For laminar flow, λ is calculated as $64/Re$.

The pressure drop for two-phase flow is calculated as:

$$-dp = (\alpha\rho_g + (1-\alpha)\rho_l)gdz \sin \theta + G^2 d\left(\frac{(1-x)^2}{\rho_l(1-\alpha)} + \frac{x^2}{\rho_g\alpha}\right) + dp_{\text{fric}} \quad (2)$$

where, Smith model [14] is used to calculate the void fraction α . The Lockhart-Martinelli correlation [15] is used to calculate the friction pressure gradient dp_{fric} .

The other local pressure drop, including bends, sudden expansion, and sudden contraction, refer to Ref. [16].

The single-phase heat transfer rates for laminar flow and turbulent flow are calculated using Shah correlation [17] and Dittus-Boelter correlation [18], respectively. The evaporation heat transfer rate is calculated by the correlation from Kandlikar [19]. The condensation heat transfer rate is calculated using the correlation proposed by Jaster and Kosky [20]. The airside heat transfer rate is calculated by the correlation from Kim and Bullard [21].

The mass of each element is calculated as:

For single-phase flow

$$dm = \rho Adz \quad (3)$$

For two-phase flow

$$dm = (\alpha\rho_g + (1-\alpha)\rho_l)Adz \quad (4)$$

The flow chart of the simulation is shown in Fig. 5. In the simulation, the loop thermosyphon is divided into many elements along the loop. The simulation program first supposes the inlet conditions of the evaporator. Then, the heat transfer rate and pressure drop of each element are calculated. Finally, the calculated inlet conditions of

the evaporator are compared with supposed ones and corresponding changes are made until the deviations can be neglected.

The refrigerant thermodynamic properties are from the data provided by Refprop 8 [22], and the modeling code is developed based on VC6.0. The simulation is based on the same geometric and working parameters with the experiment, which are shown in Table 1. In the simulation, all the parameters remain the values in Table 1 unless they are changed to investigate the effect on the performance.

In order to verify the accuracy of the model, the calculated heat transfer rates are compared with our experimental results as shown in Fig. 6. It can be seen that the calculated values agree well with the experimental values.

3.2 Simulation results

The internal flow state of different filling ratios is firstly simulated in this section to further analyze the reason why the optimal filling ratio is 150%. The circulation flow rate, vapor quality at the evaporator outlet and vapor quality at the condenser outlet are shown in Fig. 7 (a), Fig. 7 (b) and Fig. 7 (c), respectively. The indoor and outdoor temperature difference is 10 °C. The vapor quality here is calculated as the enthalpy minus saturated liquid enthalpy and then divided by latent heat, therefore it is higher than 1.0 when the fluid is superheated and lower than 0 when the fluid is subcooled. As shown in Fig. 7 (a) ~ (c), the circulation flow rate increases with the increase of filling ratio, while the vapor quality decreases with it. When the filling ratio is relatively low, the vapor at the evaporator outlet is superheated. When the filling ratio is higher than 140%, the vapor at the evaporator outlet translates to

two-phase state, which is consistent with the thermal image shown in Fig. 4. When the filling ratio is higher than 150%, the vapor at the condenser outlet translates to subcooled state. Therefore, 150% is the optimal filling ratio since the fluid in the thermosyphon loop is all at two-phase state and the heat transfer is all phase change heat transfer.

For a more comprehensive illustration, the parameter distributions along the loop when the filling ratios are 110% and 150%, respectively, are shown in Fig. 8. The indoor and outdoor temperature difference is 10 °C. The system is divided into 80 elements along the loop. In the evaporator, the enthalpy and vapor quality increase due to the heat transfer with indoor air. The temperature rises a lot when the filling ratio is 110%, which means that superheating occurs in this situation. In the riser, the pressure decreases and the other parameters changes little for no heat transfer in this region. In the condenser, the enthalpy and vapor quality decrease and for the filling ratio of 110%, the temperature drops rapidly. In the down comer, the pressure rises mainly due to hydrostatic pressure head, which is the source of the driving force.

The effects of some geometric parameters of the loop thermosyphon are also analyzed with the simulation model to help optimize the design. The variation of performance and internal flow state with height difference are shown in Fig. 9. The filling ratios are 110% and 150%, and the indoor and outdoor temperature difference is 10 °C. The height difference here means the height difference between the top of the evaporator and the bottom of the condenser. It can be seen that the heat transfer rate and circulation flow rate increase with the increase of height difference, which is

mainly due to the increase of pressure difference caused by gravity. The effect is more significant when the filling ratio is 110%, therefore the height difference must be ensured especially when the filling ratio is low. The vapor quality at the evaporator outlet decreases with the increase of height difference. For the filling ratio of 110%, the fluid is always superheated in the outlet however for the filling ratio of 150%, the fluid translates from superheated to two-phase state with the increase of height difference. The vapor quality at the condenser outlet increases with the height difference and there is also a state change for the filling ratio of 150%.

The variation of performance and internal flow state with pipe length are shown in Fig. 10. The filling ratios are 110% and 150%, and the indoor and outdoor temperature difference is 10 °C. The pipe length refers to the length of the riser and the down comer. The heat transfer rate and the circulation flow rate decrease with the increase of pipe length, mainly due to the increase of flow resistance. The effect is more significant for the filling ratio of 110%. Superheating is easier to occur at the evaporator outlet when the pipes are longer, and subcooling is easier to occur at the condenser outlet when the pipes are shorter.

4 Conclusions

Loop thermosyphon is ideal equipment for free cooling of data centers. In order to promote its application in the future, it is necessary to investigate environment friendly working fluids to the replace traditional working fluids. In this paper, the performance of a CO₂ loop thermosyphon with microchannel parallel-flow evaporator and condenser is investigated both experimentally and numerically, and the main

results are concluded as follows:

1) The effect of filling ratio on the performance of CO₂ loop thermosyphon is more significant than that of R22. The optimal filling ratio of CO₂ is around 150%, higher than R22. The heat transfer rate of CO₂ loop thermosyphon at the optimal filling ratio increases almost linearly with temperature difference, and larger than R22.

2) According to the thermal image of the evaporator, when the filling ratio is 90%~130%, the temperature of the upper part of the evaporator is higher than the lower part, which means that the working fluid in the upper part is superheated. As the filling ratio increases, the superheated region shrinks and when the filling ratio reaches 140%, the superheated region nearly disappears and the temperature of the whole evaporator is relatively uniform.

3) A distributed-parameter model is built to further investigate its performance and internal flow state. The simulation results agree well with the heat transfer experiment and thermal image. The simulation results show that 150% is the optimal filling ratio for no superheating or subcooling occurs along the loop.

4) The heat transfer rate and circulation flow rate increase with the increase of height difference, while decrease with the increase of pipe length, and the effects are more significant for low filling ratio. Superheating is easier to occur at the evaporator outlet when height difference is smaller or pipe length is larger, and subcooling is easier to occur at the condenser outlet when height difference or pipe length is smaller.

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Figure Captions

Fig. 1. Schematic diagram of experimental set up.

Fig. 2. The heat transfer rate of CO₂ and R22 loop thermosyphon in different filling ratios.

Fig. 3. The heat transfer rate of CO₂ and R22 loop thermosyphon in different temperature differences.

Fig. 4. Thermal image of the evaporator in different filling ratios: (a) 100%; (b) 110%; (c) 120%; (d) 130%; (e) 140%; (f) 150%; (g) 160%; (h) 170%; (i) 180%.

Fig. 5. Flow chart of simulation.

Fig. 6. Comparison of experimental and calculated results: (a) filling ratio is varied when indoor and outdoor temperature difference is 10 °C; (b) indoor and outdoor temperature difference is varied when filling ratio is 150%.

Fig. 7. Variation of internal flow state with filling ratio (simulated): (a) circulation flow rate; (b) vapor quality at the evaporator outlet; (c) vapor quality at the condenser outlet.

Fig. 8. Parameter distribution along the loop (simulated): (a) enthalpy; (b) pressure; (c) temperature; (d) vapor quality.

Fig. 9. Variation of performance and internal flow state with height difference (simulated): (a) heat transfer rate; (b) circulation flow rate; (c) vapor quality at the evaporator outlet; (d) vapor quality at the condenser outlet.

Fig. 10. Variation of performance and internal flow state with riser length (simulated): (a) heat transfer rate; (b) circulation flow rate; (c) vapor quality at the evaporator outlet; (d) vapor quality at the condenser outlet.

Table Captions

Table 1. Specifications of the loop thermosyphon.

Table 1 Specifications of the loop thermosyphon

Evaporator/Condenser		Installation and working conditions	
Parameter	Value	Parameter	Value
Flat tube height (mm)	2.0	Riser length/inside diameter (m)	2.71/0.017
Flat tube width (mm)	25.4	Down comer length/inside diameter (m)	2.71/0.014
Flat tube length (mm)	710	Height difference (m)	1.0
Tube pitch (mm)	10.0	Indoor temperature (°C)	20.0
Tube number	63	Indoor relative humidity	50%
Row number	1	Air flow rate of evaporator (m ³ s ⁻¹)	0.52
		Outdoor temperature (°C)	4.0~14.0
		Air flow rate of condenser (m ³ s ⁻¹)	0.80

Fig. 1 Schematic diagram of experimental set up

Fig. 2 The heat transfer rate of CO₂ and R22 loop thermosyphon in different filling ratios

Fig. 3 The heat transfer rate of CO₂ and R22 loop thermosyphon in different temperature differences

Fig. 4 Thermal image of the evaporator in different filling ratios: (a) 100%; (b) 110%;
(c) 120%; (d) 130%; (e) 140%; (f) 150%; (g) 160%; (h)170%; (i) 180%

Fig. 5 Flow chart of simulation

Fig. 6 Comparison of experimental and calculated results: (a) filling ratio is varied when indoor and outdoor temperature difference is 10 °C; (b) indoor and outdoor temperature difference is varied when filling ratio is 150%

Fig. 7 Variation of internal flow state with filling ratio (simulated): (a) circulation flow rate; (b) vapor quality at the evaporator outlet; (c) vapor quality at the condenser outlet

(a)

(b)

Fig. 8 Parameter distribution along the loop (simulated): (a) enthalpy; (b) pressure; (c) temperature; (d) vapor quality

(a)

(b)

(c)

(d)

Fig. 9 Variation of performance and internal flow state with height difference

(simulated): (a) heat transfer rate; (b) circulation flow rate; (c) vapor quality at the evaporator outlet; (d) vapor quality at the condenser outlet

(a)

(b)

Fig. 10 Variation of performance and internal flow state with riser length (simulated):

(a) heat transfer rate; (b) circulation flow rate; (c) vapor quality at the evaporator outlet; (d) vapor quality at the condenser outlet