**Simulation on the performance and free cooling potential of the
thermosyphon mode in an integrated system of mechanical
refrigeration and thermosyphon**

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Abstract: Free cooling based on thermosyphon is a promising technology for energy-saving in data centers. Integrated system of mechanical refrigeration and thermosyphon does not need auxiliary refrigeration system, therefore it is an ideal way of free cooling based on thermosyphon. To study its free cooling performance and potential, it is built that a distributed-parameter model of the thermosyphon mode in an integrated system of mechanical refrigeration and thermosyphon and validated by experimental data. The simulation results show that the cooling capacity and circulation flow rate increase with the increase of height difference mainly due to

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21 higher driving force of gravity, while the increase is little when the height difference
 22 is higher than 0.5 m. The cooling capacity and circulation flow rate decrease with the
 23 increase of connection pipe length due to higher flow resistance, therefore the
 24 connection pipe should be as short as possible. The cooling capacity increases rapidly
 25 with the temperature difference and reaches 5.3 kW when the temperature difference
 26 is 15 °C, with an EER of 14.3. Also with the performance model and weather data of
 27 China, annual free cooling potential in China and corresponding energy-saving and
 28 economic benefits are analyzed. For the studied cities in China except those in the hot
 29 summer & warm winter zone, the free cooling percentages are approximately
 30 30%~70%, the annual energy-saving rates are 16%~49% and the payback period is
 31 1.7~4.3 years. Therefore, free cooling based on integrated system of mechanical
 32 refrigeration and thermosyphon has great application potential for energy-saving of
 33 data centers.

34 **Key words:** simulation, data center, thermosyphon, free cooling, energy-saving

Nomenclature	
A	area (m^2)
B	benefit (RMB)
e	electricity price (RMB kWh^{-1})
G	mass flow rate (kg s^{-1})
h	enthalpy (kJ kg^{-1})
I	investment (RMB)
k	heat transfer coefficient ($\text{kW m}^{-2} \text{°C}^{-1}$)

M	filling quantity (kg)
n	total number of free cooling numbers
P	payback period (year)
p	pressure (Pa)
Q	heat transfer rate (kW)
T	temperature (°C)

Greek symbols

Δp	pressure drop (Pa)
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Subscripts

act	actual
c	capacity
cal	calculated
cr	critical
d	dissipation
g	ground
i	indoor
l	load
o	outdoor
r	roof
sup	supposed
w	wall

Abbreviations

CRAC	computer room air conditioner
EER	energy efficiency ratio
ESQ	energy-saving quantity
ESR	energy-saving rate
FCP	free cooling percentage
ISMT	integrated system of mechanical refrigeration and thermosyphon
TAC	traditional air conditioner
THE	three-fluid heat exchanger

1 Introduction

With the rapid development of data centers, increasing energy consumption of them has become a topic of wide concern. Data centers include all the buildings, facilities, and rooms that contain data servers, telecommunication equipment, cooling equipment and power equipment [1]. Nowadays, the energy consumption of data centers accounts for 1.1–1.5% of the world's total electricity usage [2], and industry predictions suggest that the annual increase in data center power demand can be as high as 15–20% [3].

In a typical data center, 30%-50% of the total energy is consumed by cooling system [4-5], much higher than other auxiliary equipments. Currently, most cooling systems of data centers are CRAC units with floor plenums. In this configuration, recirculation air flow and bypass air flow often exist in data centers, which lead to a poor indoor thermal environment. Moreover, CRAC units utilize mechanical cooling

all the year round, without free cooling function in cold seasons [6]. As a result, traditional cooling systems are low in energy efficiency. Utilizing effective methods to cut down the consumption is essential.

Several solutions have been proposed by researchers to improve cooling efficiency, including air flow prediction and optimization methods [7-11], rack cooling solutions [12-14], absorption refrigeration utilizing waste heat in data centers [15-17] and so on. In these solutions, a solution called free cooling attracts more and more attention, which means using natural cold source to cool data centers when the outside climate is cool enough. Existing free cooling methods can be divided to different categories: airside free cooling [18], waterside free cooling [19] and free cooling based on thermosyphon [20-22].

Airside free cooling means drawing the outside air directly inside or utilizing the cooler outside air indirectly by air to air heat exchangers. Free cooling by air to air heat exchangers takes much space and investment therefore the application is limited. By contrast, drawing air directly inside is more feasible and its energy-saving potential in various regions across the world has been investigated by researchers, including America [23,24], Europe [24], Australia [24,25] and Korea [26]. These studies showed that airside free cooling has good energy-saving potential in most of the above regions. However, ventilation may introduce disturbance to the indoor air quality [6]. Especially in countries with poor air quality such as China, its applicability remains in doubt and the reliability risk is difficult to forecast. Waterside free cooling means utilizing natural cold source through a cooling water infrastructure.

This kind of system has been developed by many air conditioning manufacturers and used in large and medium data centers, and its energy-saving potential is widely demonstrated [27]. Free cooling based on thermosyphon is a new technology, which does not affect the indoor air quality and can utilize outdoor cooling source more efficiently than waterside free cooling for the heat transfer ability under small temperature difference of thermosyphon [6,28].

As thermosyphon can only work in cool seasons, mechanical refrigeration systems have to be equipped for hot seasons. To avoid two sets of equipment, integrated system of mechanical refrigeration and thermosyphon (ISMT) is an ideal solution and several designs have been proposed [29-32]. Zhang et al. proposed a new type ISMT, which overcomes the short comings of the former design and achieves high energy efficiency [33].

Thermosyphon mode is the most important working mode and determines the application potential of ISMT. Its performance and energy-saving contribution are worthy of investigation. Until now, most recent studies in this field are experimental studies [29-33] while few simulation studies have been conducted [34,35]. Also, the exiting simulation studies only focus on the design [34] or energy consumption in several certain areas [35]. Its application method and potential is not clear, which limits its application. Considering the effectiveness of simulation for refrigeration systems [36,37] , there is a lack of comprehensive simulation study in this field, especially on application method and potential.

In this paper, a simulation model of the thermosyphon mode in the ISMT

proposed by Zhang et al. [33] is built and validated by experimental data. The effects of some geometric parameters in practical applications and indoor and outdoor temperature differences are simulated. With this performance model and weather data of China, annual thermosyphon free cooling potential in 31 cities across China and corresponding energy-saving and economic benefits are analyzed. The results are also summarized for using in other regions of the world. This paper offers a simulation method for thermosyphon mode of ISMT and meaningful data for application. It is hoped that this study will attract more attentions to ISMTs and free cooling based on thermosyphon.

2 Performance model and analysis

2.1 Performance model

The performance model is built based on the ISMT proposed by the authors, as shown in Fig. 1 [33]. The system consists of two circulation loops: a refrigeration loop and a thermosyphon loop. A three-fluid heat exchanger (THE) is used to connect the two loops, which has three flow channels for the fluid of refrigeration loop, the fluid of thermosyphon loop and outdoor air respectively. This system has three working modes. It works in refrigeration mode in hot weather, the fan of the three-fluid heat exchanger stops and the compressor starts to cool the thermosyphon working fluid. Dual mode in mild weather, all fans and the compressor work to utilize both natural cold source and mechanical cold source. Thermosyphon mode in cold weather, only the fans of three-fluid heat exchanger and evaporator work to cool the data center using natural cold air. The performance of thermosyphon mode is the key

parameter and determines the free cooling potential of the system. Therefore in this paper, the performance model of the thermosyphon mode is built to investigate free cooling performance and potential.

The detailed geometric parameters of the evaporator and the three-fluid heat exchanger can be looked up in Ref. [33]. The geometric parameters of the connection pipes and the inlet conditions of the thermosyphon loop used for simulation are shown in Table 1. It is worth noting that in this study the indoor temperature is set at 24.0 °C according to a Chinese standard [38]. Some values will be changed in the following sections to study their effect on the performance and the rest ones keep the value in Table 1.

The numerical model is developed with distributed-parameter method. The flow chart of simulation is shown in Fig. 2. The thermosyphon loop is divided into 100 elements and heat transfer and pressure drop are calculated for each element. The internal flow parameters of the thermosyphon loop are unknown therefore three iterations are needed to achieve the conservation of momentum, energy and mass respectively. The calculated filling quantity is the sum of the fluid mass of all elements. The evaporation heat transfer coefficient is calculated according to the correlation proposed by Kandlikar [39]. The correlation proposed by Jaster and Kosky [40] is used to calculate the condensation heat transfer coefficient. Single-phase heat transfer coefficient for turbulent flow is calculated by Dittus-Boelter Equation [41]. Single-phase heat transfer coefficient for laminar flow is calculated in the method recommended in Ref. [42]. The airside heat transfer coefficient for tube-fin heat

exchanger is calculated using the equation recommended in Ref. [43], and that for parallel flow heat exchanger is calculated by the equation proposed by Kim and Bullard [44]. The friction loss of two-phase flow is calculated by Lockhart-Martinelli Equation [45]. The friction loss of single-phase flow is calculated by Blasius Equation [46]. The refrigerant thermodynamic properties are from the data provided by Refprop 8 [47], and the modeling code is developed based on VC6.0.

In order to verify the accuracy of the model, the calculated heat transfer rate and system pressure are compared to our experimental results of the ISMT as shown in Fig. 3. The calculated values agree well with the experimental ones with deviations of $\pm 6\%$.

2.2 Performance analysis

Some geometric parameters that affect the performance of the thermosyphon need to be investigated to achieve a better performance in practical application. The height difference between the bottom of THE and the top of indoor evaporator is an important parameter for installation. The performance varied with the height difference when the connection pipe length is fixed is shown in Fig. 4. The indoor and outdoor temperature difference is fixed at 30 °C. As seen in Fig. 4, the cooling capacity and circulation flow rate increase with the increase of height difference, mainly due to higher driving force of gravity. However, the increase is little when the height difference is higher than 0.5 m. Considering both of the performance and convenience of installation, the height difference is fixed at 1.0 m.

The connection pipe length also affects the performance and is often changed

according to the structure of data centers in practical application. Therefore, its effect needs to be evaluated. The performance varied with the riser length when the height difference is fixed at 1.0 m is shown in Fig. 5. It is worth noting that when the riser length increases, the down comer length is assumed to increase with the same increment and the indoor and outdoor temperature difference is fixed at 30 °C. As seen in Fig. 5, the cooling capacity and circulation flow rate decrease with the increase of connection pipe length, due to higher flow resistance brought by longer pipe. Therefore the connection pipe should be as short as possible in practical application, and it is assumed to be 2.0 m and 2.76 m for the riser and down comer, respectively.

With the above determined parameters, the performance under different indoor and outdoor temperature differences can be obtained. The cooling capacity, input power and EER varied with the indoor and outdoor temperature difference are shown in Fig. 6. The cooling capacity increases rapidly with the temperature difference. It reaches 5.3 kW when the temperature difference is 15 °C, and 10.7 kW when it is 30 °C. The relationship between cooling capacity, indoor temperature and outdoor temperature can be fitted as:

$$Q_c = a(T_i - T_o) + b \quad (1)$$

where T_i and T_o are the indoor and outdoor temperature respectively, °C; a and b are the fitting coefficients, a=0.3611, b=-0.1318 in this study.

The fans are the only consumers in thermosyphon mode, so that the input power remains unchanged (0.37 kW). Therefore, the EER increases with the temperature

difference and it is 14.3 when the temperature difference is 15 °C, much higher than traditional CRACs.

3 Free cooling potential

With the performance calculated above, the free cooling potential of application in data centers is further investigated in this section. The physical model of the data center is based on a typical telecommunication base station, a common kind of small data center. The specifications of it are shown in Table 2.

The cooling load of the data center can be calculated as:

$$Q_l = Q_d - (k_w A_w + k_r A_r + k_g A_g)(T_i - T_o) \quad (2)$$

where k_w , k_r , k_g are the overall heat transfer coefficient of the wall, roof and ground respectively, $\text{kW m}^{-2} \text{°C}^{-1}$; A_w , A_r , A_g are the area of the wall, roof and ground respectively, m^2 .

If the cooling load is lower than the cooling capacity, the data center can be cooled by free cooling. Therefore, the critical outdoor temperature T_{cr} for free cooling is obtained by making Eq. (1) equal to Eq. (2) and the result is 12.5 °C in this study.

When the outdoor temperature is lower than this value, thermosyphon mode can work and only the fans consume energy.

Free cooling percentage (FCP) is calculated as:

$$\text{FCP} = n/8760 \quad (3)$$

where, n is the total number of free cooling hours in one year.

For contrastive calculation of energy consumption, the performance model of a traditional air conditioner (TAC) with rated cooling capacity of 5.10 kW and rated

input power of 1.77 kW is built in the method from a national standard [48]. The annual energy-saving quantity (ESQ) are calculated as the sum of energy-saving quantity in each free cooling hour:

$$ESQ = \sum_{i=1}^n (Q_i / EER_{TAC} - Q_i / EER_{ISMT}) \quad (4)$$

The annual energy-saving rate (ESR) is then calculated as ESQ divided by the annual energy consumption of TAC:

$$ESR = ESQ / \sum_{i=1}^{8760} (Q_i / EER_{TAC}) \quad (5)$$

The static payback period is calculated as:

$$P = I / B \quad (6)$$

where, I is the extra investment of the ISMT compared with TAC, 5000 RMB; B is the benefit of a year, which is calculated as:

$$B = ESQ \times e \quad (7)$$

where, e is the electricity price, set to 0.8 RMB (kWh)⁻¹.

The above procedure is summarized in Fig. 7, which is a general procedure for evaluating the applicability in a certain region. The results are calculated based on weather data of 31 cities, which are the capitals of all the 31 provinces in China mainland. The weather data are obtained from weather monitoring stations of different cities in China from 1971 to 2003 [49]. The annual free cooling time, free cooling percentage, energy-saving quantity, energy-saving rate, annual benefit and payback period are listed in Table 3. The free cooling potential of five representative cities of them is further illustrated in Fig. 8 ~ Fig. 12 in two display modes: hourly

and total.

As seen in Table 3, the cities with the highest thermosyphon free cooling potential are Sining and Lhasa with free cooling percentages of more than 65%, which are in the plateau of West China. Although their latitude is lower than some of the other cities, their outdoor air temperature remains low in a longer period through the year due to the plateau climate therefore the free cooling time is longer. As an example, the free cooling potential of Sining is shown in Fig. 8. The cities in the severe cold zone except Sining rank after Sining and Lhasa and all have more than 4800 h of thermosyphon free cooling time, and the free cooling percentages are higher than 55%. These cities lie in higher latitudes and the outdoor temperature is very low in winter, which is very suitable for thermosyphon cooling, an example is Harbin as shown in Fig. 9. The potential ESR of the above cities is higher than 35%, and the payback period is less than 2.2 years.

For cities in the cold zone except Lhasa, the thermosyphon free cooling potential is from around 3600 to 4800 h and the percentages are between 40% and 55%, which are sufficient for free cooling. An example is Beijing as shown in Fig. 10. For these cities, the ESR of utilizing free cooling based on thermosyphon is 24%~37% and the payback period is 2.2~2.9 years. Cities in the hot summer & cold winter zone and mild zone have free cooling time of around 2500 h to 3500 h and percentages of around 30% to 40%, which is considerable for application. Although these cities have hot summer, there is still enough time of low temperature, example city is Shanghai as shown in Fig. 11. ESR of cities in the hot summer & cold winter zone and mild zone

is 16%~24%, and the payback period is 3.0~4.3 years.

For cities in South China in the hot summer & warm winter zone, the free cooling percentages are less than 20% and the application potential is limited. In these cities, even in winter the time applicable for free cooling based on thermosyphon is not enough, an example is Guangzhou as shown in Fig. 12. The ESR is also small and less than 10%. Therefore, free cooling based on thermosyphon is limited for application in this zone, while can be considered on a case by case basis.

For regions in China, the applicability of free cooling based on thermosyphon can be found in Table 3. For regions in other countries with similar latitude and climate, the applicability can be inferred generally based on the above results, which are summarized in Table 4 for a quick overview. As shown in Table 4, the ESR and payback period can be speculated based on the indoor setting temperature of a data center and outdoor temperature data. In the world, China lies in the mid latitudes of the northern hemisphere. Considering the vast territory and different climate types of China, it can be speculated that in most regions at middle and high latitudes of the world, free cooling based on thermosyphon is applicable for energy-saving of data centers.

4 Conclusions

Free cooling based on thermosyphon is a promising technology to utilize free cooling source in data centers for its superior heat transfer ability and no disturbance of indoor environment. In this paper, a distributed-parameter model of the thermosyphon mode in an ISMT is built and validated by experimental data. The

performances of thermosyphon free cooling of different geometric parameters and indoor and outdoor temperature differences are simulated. Combined with the specifications of a typical telecommunication base station and weather data from monitoring stations across China, the thermosyphon free cooling potential, corresponding energy-saving and payback period are investigated. The main results are concluded as follows:

(1) The cooling capacity and circulation flow rate increase with the increase of height difference mainly due to higher driving force of gravity, while the increase is little when the height difference is higher than 0.5 m. The cooling capacity and circulation flow rate decrease with the increase of connection pipe length due to higher flow resistance, therefore the connection pipe should be as short as possible. The cooling capacity increases rapidly with the temperature difference, and it reaches 5.3 kW when the temperature difference is 15 °C. The EER also increases with the temperature difference and it reaches 14.3 when the temperature difference is 15 °C, much higher than traditional CRACs.

(2) Cities in the plateau of West China like Sining and Lhasa have the highest free cooling potential of more than 65% of the total time though the year, which is mainly due to the long time of low temperature of plateau climate. For cities in the severe cold zone, the free cooling percentages are higher than 55%. The outdoor temperature in these cities is very low in winter, which is very suitable for free cooling based on thermosyphon. For other cities except those in the hot summer & warm winter zone, the free cooling percentages are approximately higher than 30%. For the above cities,

the energy-saving rate is 16% ~49% and the payback period is 1.7~4.3 years, for a telecommunication base station with heat dissipation of 4.5 kW. Only for the cities in the hot summer & warm winter zone in South China, the free cooling percentages are lower than 20%. Therefore for most cities in China except cities in hot summer & warm winter zone, free cooling based on thermosyphon has great application potential for energy-saving of data centers.

(3) Considering the vast territory and different climate types of China, it can be speculated that in most regions at middle and high latitudes of the world, free cooling based on thermosyphon is applicable for energy-saving of data centers.

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Figure Captions

Fig. 1. Schematic diagram of the ISMT [33].

Fig. 2. Flow chart of **performance** simulation.

Fig. 3. Comparison of calculated and experimental values of cooling capacity and internal pressure.

Fig. 4. Cooling capacity and circulation flow rate varied with height difference when temperature difference is 30 °C, riser length and down comer length are 2.0 m and 2.76 m, respectively.

Fig. 5. Cooling capacity and circulation flow rate varied with connection pipe length when temperature difference is 30 °C and height difference is 1.0 m.

Fig. 6. Performance varied with indoor and outdoor temperature difference when height difference is 1.0 m, riser length and down comer length are 2.0 m and 2.76 m, respectively.

Fig. 7. Flow chart of free cooling potential simulation.

Fig. 8. Free cooling potential of Sining (severe cold, 36.72N).

Fig. 9. Free cooling potential of Harbin (severe cold, 45.75N).

Fig. 10. Free cooling potential of Beijing (cold, 39.80N).

Fig. 11. Free cooling potential of Shanghai (hot summer & cold winter, 31.40N).

Fig.12. Free cooling potential of Guangzhou (hot summer & warm winter, 23.17N).

Table Captions

Table 1. Geometric parameters and working conditions.

Table 2. Specifications of the telecommunication base station for modeling.

Table 3. Free cooling potential, energy-savings and payback period.

Table 4. Summary of applicability in different climates.

Table 1 Geometric parameters and working conditions.

Parameter	Value
Riser length/inside diameter (m)	2.0/0.017
Down comer length/inside diameter (m)	2.76/0.014
Height difference (m)	1.0
Indoor temperature (°C)	24.0
Indoor relative humidity	50%
Air flow rate of evaporator (m ³ s ⁻¹)	0.75
Outdoor temperature (°C)	-6.0~19.0
Outdoor relative humidity	50%
Air flow rate of three-fluid heat exchanger (m ³ s ⁻¹)	1.114
Filling quantity of thermosyphon loop (kg)	3.80
Working fluid	R22

Table 2 Specifications of the telecommunication base station for modeling.

Parameter	value
Total heat dissipation Q_d (kW)	4.5
Indoor temperature setting T_i ($^{\circ}\text{C}$)	24.0
Dimensions (m)	3.75 (length) $\times$ 2.8 (width) $\times$ 2.9 (height)
Wall	sandwich panel, heat transfer coefficient $k_w=0.848 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$
Roof	heat transfer coefficient $k_r=0.819 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$
Ground	heat transfer coefficient $k_g=0.295 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$

Table 3 Free cooling potential, energy-savings and payback period.

City	Latitude	Longitude	Climate zone	Annual free cooling time (h) / percentage	Annual energy-saving amount (kWh) / rate	Annual benefit (RMB) / Payback period (year)
Harbin	45.75N	126.77E	Severe cold	5390/61.5%	3064/41.9%	2451/2.04
Changchun	43.90N	125.22E	Severe cold	5307/60.6%	3060/41.2%	2448/2.04
Urumchi	43.78N	87.65E	Severe cold	5088/58.1%	2962/38.3%	2369/2.11
Shenyang	41.73N	123.45E	Severe cold	4849/55.4%	2838/36.2%	2270/2.20
Hohhot	40.82N	111.68E	Severe cold	5272/60.2%	3080/40.8%	2464/2.03
Beijing	39.80N	116.47E	Cold	4146/47.3%	2469/29.4%	1976/2.53
Tianjin	39.08N	117.07E	Cold	3992/45.6%	2383/28.3%	1906/2.62
Yinchuan	38.48N	106.22E	Cold	4875/55.7%	2891/36.8%	2312/2.16

Shijiazhuang	38.03N	114.42E	Cold	3883/44.3%	2322/27.1%	1858/2.69
Taiyuan	37.78N	112.55E	Cold	4587/52.4%	2730/34.1%	2184/2.29
Sining	36.72N	101.75E	Severe cold	6054/69.1%	3564/48.8%	2851/1.75
Jinan	36.60N	117.05E	Cold	3650/41.7%	2175/24.8%	1740/2.87
Lanzhou	36.05N	103.88E	Cold	4713/53.8%	2804/35.5%	2243/2.23
Zhengzhou	34.72N	113.65E	Cold	3763/43.0%	2249/25.9%	1799/2.78
Xi'an	34.30N	108.93E	Cold	3839/43.8%	2292/26.7%	1834/2.73
Nanjing	32.00N	118.80E	Hot summer & cold winter	3451/39.4%	2057/23.2%	1646/3.04
Hefei	31.87N	117.23E	Hot summer & cold winter	3302/37.7%	1971/22.1%	1577/3.17
Shanghai	31.40N	121.45E	Hot summer & cold winter	3073/35.1%	1811/20.4%	1449/3.45
Chengdu	30.67N	104.02E	Hot summer & cold winter	2890/33.0%	1691/19.4%	1353/3.70

Wuhan	30.62N	114.13E	Hot summer & cold winter	3171/36.2%	1879/20.5%	1503/3.33
Hangzhou	30.23N	120.17E	Hot summer & cold winter	3106/35.5%	1832/20.4%	1465/3.41
Lhasa	29.67N	91.13E	Cold	5965/68.1%	3523/47.2%	2819/1.77
Nanchang	28.60N	115.92E	Hot summer & cold winter	2915/33.3%	1717/18.7%	1374/3.64
Chongqing	29.58	106.47E	Hot summer & cold winter	2586/29.5%	1482/16.2%	1186/4.22
Changsha	28.22N	112.92E	Hot summer & cold winter	3167/36.2%	1855/20.6%	1484/3.37
Guiyang	26.58N	106.73E	mild	3212/36.7%	1891/22.3%	1513/3.30
Fuzhou	26.08N	119.28E	Hot summer & warm winter	1635/18.7%	929/9.7%	743/6.73
Kunming	25.02N	102.68E	mild	2518/28.7%	1465/17.8%	1172/4.27
Nanning	22.63N	108.22E	Hot summer & warm winter	925/10.6%	523/5.3%	418/11.96
Guangzhou	23.17N	113.33E	Hot summer & warm winter	903/10.3%	501/5.0%	401/12.47

Haikou	20.03N	110.35E	Hot summer & warm winter	25/0.3%	14/0.1%	11/462.11
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Table 4 Summary of applicability in different climates

Total time per year of $T_i - T_o > 11.5\text{ }^{\circ}\text{C}$	Energy-saving rate	Payback period (year)	Suggestion
>5000 h	>37%	<2.2	Ideal
4000~5000 h	29%~37%	2.2~2.6	Recommended
3000~4000 h	20%~29%	2.6~3.5	Recommended
2000~3000 h	10%~20%	3.5~6.0	Optional
<2000 h	<10%	>6.0	Limited

Fig. 1. Schematic diagram of the ISMT [33].

Fig. 2. Flow chart of **performance** simulation.

(a) Cooling capacity

(b) Internal pressure

Fig. 3. Comparison of calculated and experimental values of cooling capacity and internal pressure.

Fig. 4. Cooling capacity and circulation flow rate varied with height difference when temperature difference is 30 °C, riser length and down comer length are 2.0 m and 2.76 m, respectively.

Fig. 5. Cooling capacity and circulation flow rate varied with connection pipe length when temperature difference is 30 °C and height difference is 1.0 m.

Fig. 6. Performance varied with indoor and outdoor temperature difference when height difference is 1.0 m, riser length and down comer length are 2.0 m and 2.76 m, respectively.

Fig. 7. Flow chart of free cooling potential simulation.

(a) Hourly free cooling potential

(b) Total free cooling potential

Fig. 8. Free cooling potential of **Sining** (severe cold, 36.72N).

(a) Hourly free cooling potential

(b) Total free cooling potential

Fig. 9. Free cooling potential of Harbin (severe cold, 45.75N).

(a) Hourly free cooling potential

(b) Total free cooling potential

Fig. 10. Free cooling potential of Beijing (cold, 39.80N).

(a) Hourly free cooling potential

(b) Total free cooling potential

Fig. 11. Free cooling potential of Shanghai (hot summer & cold winter, 31.40N).

(a) Hourly free cooling potential

(b) Total free cooling potential

Fig. 12. Free cooling potential of Guangzhou (hot summer & warm winter, 23.17N).