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Theoretical and Numerical Energy Saving Analysis on the Multi-stage Data Center Cooling System

Xiaoxuan Chen[1], Lu Wang[1], Xinyi Wang[1], Zhen Li [1*], Tao Ding[2]

1 Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

2 Institute for Aero Engine, Tsinghua University, Beijing, 100084, China
(*Corresponding Author: lizh@tsinghua.edu.cn)

ABSTRACT

Data center cooling systems consume a significant amount of electricity. The temperature of heat source (hot indoor air) and cold source (outdoor air) is usually ungraded, which results in wasted heat transfer temperature difference. A novel multi-stage cooling system is proposed to match different temperature grades of heat sources with corresponding cold sources. The heat transfer process and energy saving principles of the cooling system are illustrated using T-Q diagrams. A theoretical model is established based on the system heat transfer characteristics. The mismatch coefficient $\boldsymbol{\delta}$ and entransy dissipation $\Delta\boldsymbol{J}$ of multi-stage cooling system both reduced by 6.7% compared to single-stage system, and the total temperature difference at natural cooling mode is reduced by 1.3 °C. The multi-stage cooling system offers a new approach to enable greater natural cold sources utilizations and lower power consumptions.

Keywords: data center, multi-stage cooling, structure optimization, temperature grade, energy saving

NONMENCLATURE

Abbreviations	
COP	Coefficient of Performance
IT	Information Technology
Symbols	
c_p	Specific heat (kJ/(kg·K))
KA	Total heat transfer coefficient (kW/K)
m	mass flow rate (kg/s)
P	Power (kW)
Q	Heat transfer capacity (kW)

1. INTRODUCTION

With the continuous development of the IT industry, data centers, as the infrastructure of data operation, transmission and storage, has been widely paid attention to. According to statistics, the numbers of data centers in China has been growing steadily in recent years. The widely development of data centers also brings large amount of energy consumption. The annual electricity consumption of data centers is expected to exceed 300 billion kWh in 2024 [1]. Studies show that the proportion of global greenhouse gas emissions in the IT industry will increase from 1%-1.6% in 2007 to more than 14% in 2040 [2]. Among the total power consumption of data centers, the cooling system accounts for a large proportion, at about 40% [3]. Therefore, reducing the power consumption in cooling system can effectively reduce the total power consumption.

Many researchers have proposed different forms of energy-saving data center cooling systems. Han [4] proposed the integrated system which also combines the vapor compression and thermosyphon, and the operation mode is adjusted based on the self-operated three-way valve. The system can save about 30% energy consumption compared with TRAC systems. Zhang [5] used a three-fluid heat exchanger to realize the combination of refrigeration and loop thermosyphon systems. The two loops are both independent to make the system more reliable. Wang [6] proposed an integrated cooling system with both compression cycle and heat pipe cycle, and the two mode can operate at the same time. The operation modes will be automatically adjusted based on the outdoor temperature.

However, current data center cooling systems still have some limitations. One of the problem is that the

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heat sources in the computer room are not graded. The heat generated by the servers is directly collected and transferred to the cold source for emission, which is easy to cause the waste of heat transfer temperature difference and the insufficient use of natural cold source.

This paper proposed a multiple-stage cooling system to match the heat source with cold sources of corresponding proper temperature grades, thereby enabling the cascade utilization of temperature differences, prolonging natural cooling time, and enhancing energy efficiency in cooling systems.

2. STRUCTURE OF MULTI-STAGE COOLING SYSTEM

2.1 Introduction of the system

In order to solve the problem of underutilization of temperature grade, a multi-stage data center cooling system is proposed, as shown in Fig.1. The system can be divided into two parts, the indoor side and the outdoor side. For the indoor side, two backplanes (evaporators) are vertically attached to the back of the cabinet. The indoor air flows through the cabinet under the force of the fans. The backplanes are tube-fin heat exchangers, and the refrigerant flows vertically inside the tubes to absorb the heat from the hot air (heat source). The indoor air is first heated by the high-temperature servers, then cooled by two backplanes successively (first the high-temperature evaporator then the low-temperature evaporator) to room temperature.

The two backplanes are connected to two sets of outdoor cooling systems, respectively. For one cooling system, it consists of an intermediate heat exchanger, a compressor, an expansion valve and two tube-fin heat exchangers (One is used for natural cooling, and the other is used for refrigeration cooling.). The low- and

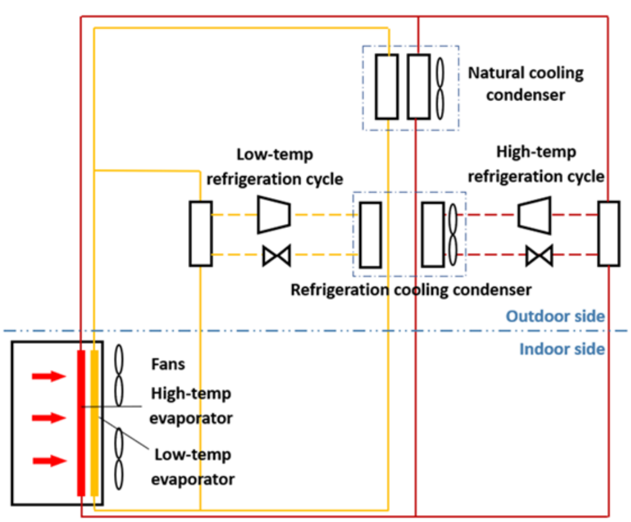


Fig. 1. Structure of multi-stage integrated cooling system

high- temperature natural cooling condensers are attached, and are cooled by cold outdoor air through fans. The cold outdoor air firstly cools the low-temperature condenser and then cools the high-temperature condenser.

2.2 Operation modes of the system

The multi-stage cooling system has three operation modes based on different outdoor temperatures to make full use of the natural cold sources.

➢ Refrigeration mode

When the outdoor temperature is relatively high in summer, the refrigeration mode operates, as shown in Fig. 2. At this time, the compressors of both refrigeration cycles and the fans of the refrigeration condenser operates. The refrigerant from the indoor evaporators releases heat to the intermediate heat exchanger (plate heat exchanger), and the heat is finally released to the environment through the refrigeration cycle.

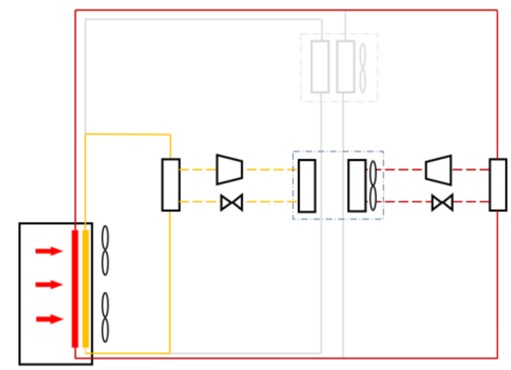


Fig. 2. Refrigeration operation mode

➢ Composite cooling mode

At lower outdoor temperature in transition season, the natural cooling cycle and the refrigeration cycle can operate simultaneously to maximum reduce energy consumptions, as shown in Fig. 3. At this time, both the compressors and the outdoor fans operates. The lower the outdoor temperature, the larger the cooling capacity of the natural cooling cycle.

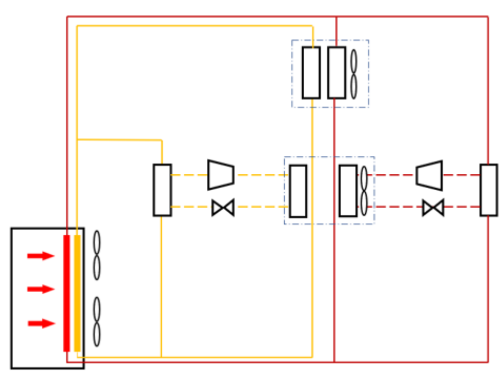


Fig. 3. Composite cooling operation mode

- Natural cooling mode

When the outdoor temperature is relatively low in winter, the natural cooling mode operates, as shown in Fig. 4. At this time, the heat transferred to evaporators is directly released to the outdoors through natural cooling condenser. Since no compressor operates at this mode, the longer the durance of natural cooling mode, the better the energy saving effect.

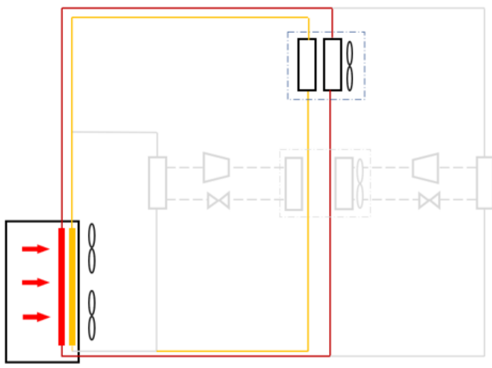


Fig. 4. Natural cooling operation mode

3. ANALYSIS OF MULTI-STAGE COOLING SYSTEM

3.1 Heat transfer analysis of indoor system

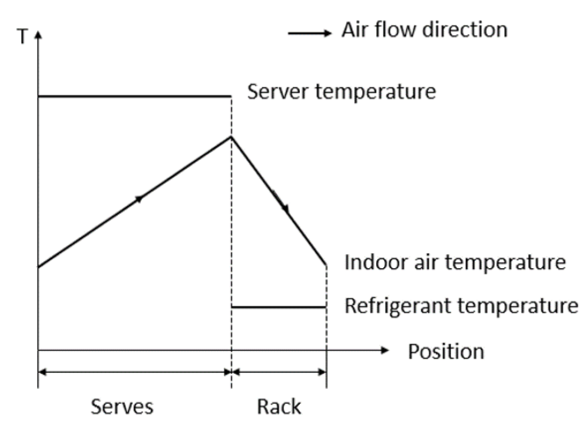
Since the hot air flows through the two backplanes successively, the temperature of the air through the two racks are different. Also, the two backplanes are connected to two sets of outdoor cooling systems, so the operating temperature and pressure of the refrigerant in the two backplanes are different, as shown in Fig. 5.

It can be seen from Fig. 5(a) that for single-stage cooling, since the saturate temperature of refrigerants is constant during heat transfer process, the large temperature difference between the hot air and the refrigerant will cause the waste of the heat transfer temperature difference.

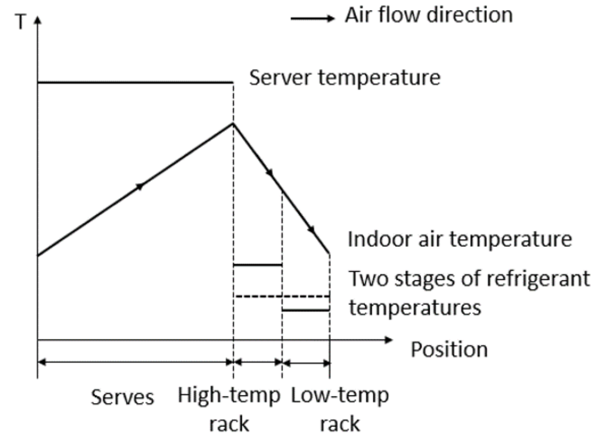
As shown in Fig. 5(b), the temperature gradation of refrigerants achieves better temperature matching between hot air and the refrigerants, and the average temperature of two-stages of refrigerants is higher than the refrigerant temperature in the single-stage system, thus decreasing the temperature difference at this heat transfer process.

3.2 Energy saving analysis at different cooling modes

The structure of multi-stage cooling will not only decrease the temperature between indoor hot air and the refrigerant in the evaporator, but will further reduce the total temperature difference of the cooling system. Fig. 6 is the T-Q diagram for both single-stage and multi-stage cooling systems.



(a) Single-stage system



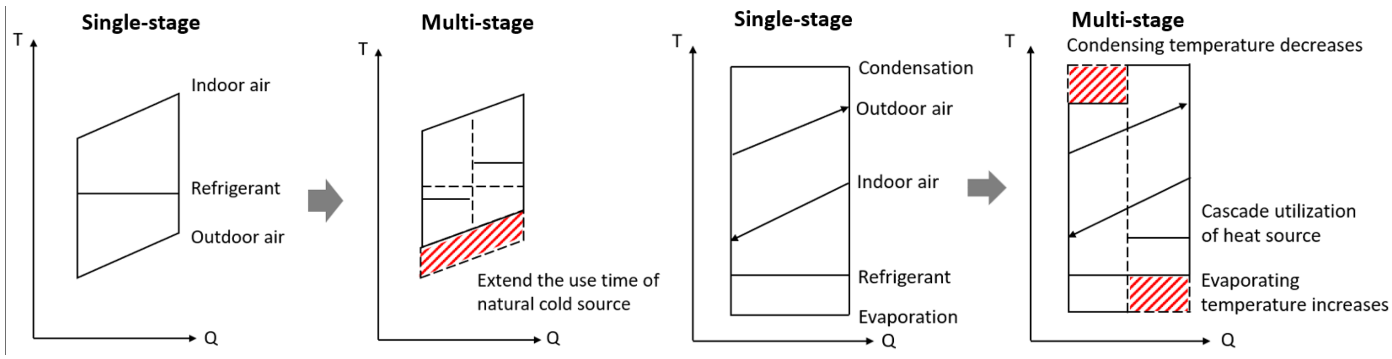
(b) Multi-stage system

Fig. 5. Temperature distributions of indoor cooling system

For natural cooling mode, as shown in Fig. 6(a), cpmpared with single-stage system, the increase of the refrigerant saturated temperature and the decrease of the total heat transfer difference in multi-stage system will increase the required outdoor temperature for natural cooling, therefore extend the usage time of natural cold source, thus reducing the total energy consumption of the cooling system.

As can be seen from Fig. 6(b), for refrigeration mode at the same indoor air and outdoor air temperature, the multi-stage system can reduce the temperature difference of the heat transfer processes. This will lead to the increase of the evaporating temperature and the decrease of the condensing temperature of refrigeration cycle, which will increase the Coefficient of Power (COP), and will further decrease the power consumption of compressor and total energy consumption.

By analysing the heat transfer process in the T-Q diagram, conclusions can be drawn that the multi-stage cooling system has energy saving advantages at all cooling modes. The quantitative analysis of the system are illustrated in Section 4.



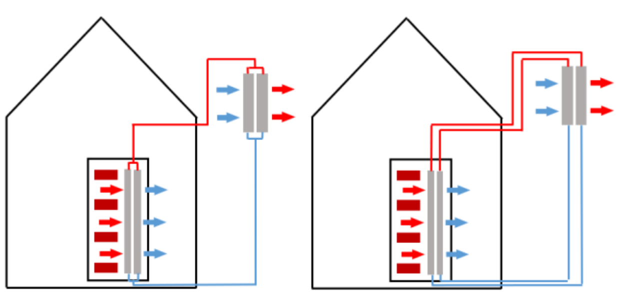
(a) Natural cooling (b) Refrigeration cooling

Fig. 6. T-Q diagram of the single-stage and multi-stage cooling system

4. MODELING OF MULTI-STAGE COOLING SYSTEM

4.1 System modeling description

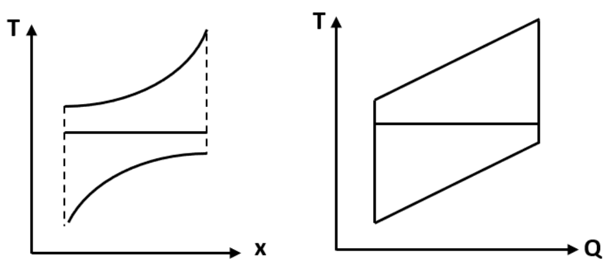
The single-stage and multi-stage cooling system models at natural cooling mode are established in Fig.7. The structures of the systems are the same except the temperature stages during heat transfer process.



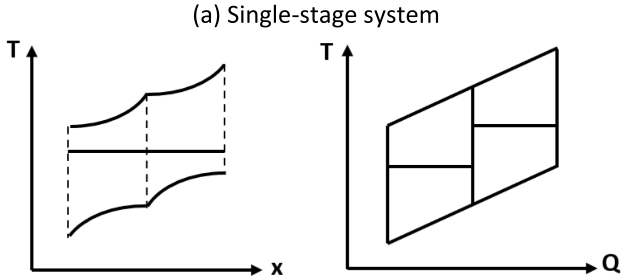
(a) Single-stage system (b) Multi-stage system

Fig. 7. Diagram of data center cooling models

The heat transfer process of the single-stage and multi-stage cooling systems reflected in T-x and T-Q diagrams are shown in Fig. 8.



(a) Single-stage system



(b) Multi-stage system

Fig. 8. Heat transfer process of different systems

The different stages of systems has the same total heat transfer areas and operating parameters. The detailed parameters are listed in Table 1.

Table 1 Operating parameters of cooling model

Operating parameters	Values
Heat load (kW)	10
Indoor side inlet air temperature (°C)	35
Indoor side outlet air temperature (°C)	25
Single-stage refrigerant temperature (°C)	20
Outdoor side inlet air temperature (°C)	5
Outdoor side outlet air temperature (°C)	15

The heat transfer quations to calculate the cooling processes are listed in Eqs.(1)-(2).

$$Q = UA \cdot \Delta t_m \tag{1}$$

$$\Delta t_m = \frac{\Delta T_{max} - \Delta T_{min}}{ln\frac{\Delta T_{max}}{\Delta T_{min}}} \tag{2}$$

During the heat transfer process, the mismatch coefficient δ and entransy dissipation ΔJ are introduced to describe the irreversible of heat transfer loss, which can be calculated using Eqs.(3)-(5).

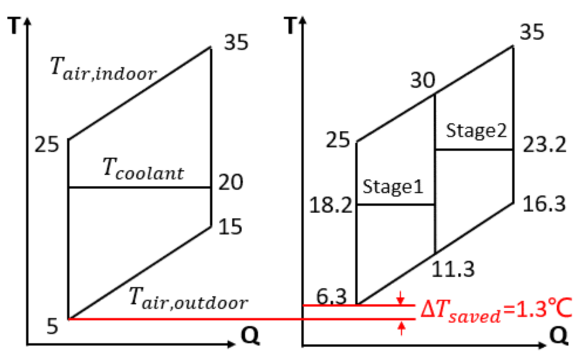
$$\delta = \frac{P}{2} \cdot \frac{e^P + 1}{e^P - 1} \tag{3}$$

$$P = \frac{UA}{cm_{air}} \tag{4}$$

$$\Delta J = \left[\frac{(T_{h,in} + T_{h,out})}{2} - \frac{(T_{l,in} + T_{l,out})}{2}\right] Q \tag{5}$$

4.2 Modeling results discussion

The temperature distributions of the two systems are shown in Fig. 9. The calculation results indicates that the required outdoor temperature using single stage system is 5 °C, and rises to 6.3°C when using multi-stage system, leading to a reduced total heat transfer temperature difference by 1.3 °C. The higher the required outdoor temperature, the longer the usage of natural cooling time, the better the energy saving effect.



(a) Single-stage system (b) Multi-stage system

Fig. 9. Temperature distributions of heat transfer process

The comparisions of mismatch coefficient $\boldsymbol{\delta}$ and entransy dissipation $\Delta\boldsymbol{J}$ of the two systems are listed in Table 2 and Table 3. According to the calculation results, the mismatch coefficients and entransy dissipations of multi-stage cooling system both reduced by 6.7% compared to single-stage system.

Table 2. Mismatch coefficient $\boldsymbol{\delta}$ of the two systems

Single-stage	δ_h	δ_l
	1.099	1.099
Multi-stage	$\boldsymbol{\delta}_{h,stage1/2}$	$\boldsymbol{\delta}_{l,stage1/2}$
	1.025	1.025

Table 3. Entransy dissipation $\Delta\boldsymbol{J}$ of the two systems

Single-stage	ΔJ_h	ΔJ_l
	100	100
Multi-stage	$\Delta J_{h,stage1/2}$	$\Delta J_{l,stage1/2}$
	46.65	46.65

5. CONCLUSIONS

This paper introduces a new structure of data center cooling system, and the theoretical analysis and numerical calculation are studied to illustrate the energy saving effect of the system. Three conclusions are drawn as follows.

(1) A new form of multi-stage cooling system is proposed, which clarifies the heat and cold sources into different temperature grades. Three operation modes, refrigeration mode, composite cooling mode and natural cooling mode are introduced.

(2) The temperature gradation will decrease the temperature difference between the hot and cold fluid, and will also reduce the total temperature difference of the system. The reduction of total temperature difference will decrease the power consumption of compressor and extend the natural cold source usage time, which will eventually reduce the total energy consumption.

(3) A numerical model at natural cooling mode is established to calculate the energy saving effect of multi-stage cooling system. The mismatch coefficient $\boldsymbol{\delta}$ and entransy dissipation $\Delta\boldsymbol{J}$ of multi-stage cooling system both reduced by 6.7% compared to single-stage system, and the total temperature difference at natural cooling mode is reduced by 1.3 °C, which indicates the energy saving potential of the cooling system .

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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