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Synergy Optimization Analysis of Heat Transfer Process and Its Application in Data Centers

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ABSTRACT

The power consumption of pumps and fans is quite high in the transport systems, especially in data centers. Nearly 60% of the computer room air conditioning (CRAC) system's energy consumption is consumed by pumps and fans in winter. In this paper, a synergy optimization method is proposed to save energy in heat transfer process. The heat transfer constraint equations of the heat transfer process are established, and taking the highest energy efficiency as the objective function, the synergistic relationship between the power consumption and temperature difference is derived analytically by using variation principle. A synergy operation factor is defined to guide the practical operation optimization of heat transfer process. The closer the synergy operation factor is to 1, the higher the system energy efficiency is. An experiment of a separated heat pipe system is carried out to verify the accuracy of the synergy optimization analysis.

Keywords: synergy optimization analysis, heat transfer, energy saving, data center

NONMENCLATURE

Abbreviations	
CRAC	Computer Room Air Conditioning
EER	Energy Efficiency Ratio
Symbols	
A、B	Performance parameters
C	Condenser air side
c	Condenser
c_p	Specific heat
E	Evaporator air side
e	Evaporator
F、f、g	Functional symbols
i	Inlet
KA	Heat transfer capacity
k	Counter symbol
m	Mass flow rate
o	outlet
Q	Heat transfer rate
T	Temperature
T_r	Evaporation/condensation temperature
W	Power consumption
λ	Lagrange multiplier
γ	Synergy operation factor

1. INTRODUCTION

The heat transfer process is widely used in energy transport and utilization. The most common form is a two-stream heat exchanger in which the thermal fluids are driven by pumps or fans and exchange thermal energy through one heat exchanger. The two-stream heat exchanger is widely used in heating, ventilation, air conditioning, industrial heat recovery and other fields[1-3]. So the optimization of the heat transfer process is of great significance in high-efficiency energy utilization.

A lot of optimization methods for the heat transfer process have been developed in recent decades. Some researchers take the heat transfer rate as the main concern in optimization designs of the heat transfer process. Zhou et al.[4] found that there was an optimal allocation ratio between heat exchangers and an optimal brine flow rate that provided maximum heat recovery

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efficiency in a ground-coupled liquid loop heat recovery ventilation system. Fan et al.[5] studied the influence of the heat capacity ratio of air and medial fluid to the efficiency of a run-around heat recovery system. Bejan [6] used the minimum entropy generation principle to optimize heat exchangers and studied the entropy generation number as the optimization criterion. Sanaye et al.[7] optimized the condenser heat transfer rate by appling genetic algorithm multi-objective optimization technique. Guo et al [8] introduced a new physical quantity, entransy, which represents the heat transfer ability of an object to analyze the heat transfer process. With the concept of entransy dissipation, many optimization studies of heat transfer process have been conducted [9-14].

The current researchers have optimized the transfer process from a design perspective. The thermal parameters were paid attention to obtain the maximum heat transfer rate. And the power consumption of the pumps and fans required to drive the thermal fluid was not considered. In fact, in the actual operation, the power consumption of pumps and fans can be quite high in the energy transport systems. Especially in data centers, nearly 60% of the computer room air conditioning (CRAC) system's energy consumption is consumed by pumps and fans in winter[15]. Therefore, it is of great significance to analyze the synergistic relationship between the power consumption and thermal parameters in the heat transfer process.

In this study, a separated heat pipe system was selected as the research object. Based on the variation principle, the synergistic relationship between the power consumption of fans and temperature changes of thermal fluids was derived analytically. A synergy operation factor was defined to guide the practical operation optimization of the system. A case and an experiment were carried out to verify the accuracy of the synergy optimization analysis. Finally, conclusions were drawn.

2. SYNERGY OPTIMIZATION ANALYSIS

The separated heat pipe system is a typical heat transfer device in data centers. As shown in Fig. 1, there is a fan to drive the air flow on the evaporator and condenser respectively. In order to facilitate the analytical analysis, the supercooling and overheating phenomenon of the heat pipe in the heat transfer process is not considered, that is, the evaporation temperature of the heat pipe is equal to the condensation temperature and remains unchanged. When the rate of heat transfer, inlet air temperatures of evaporator and condenser are set, in order to make the energy efficiency of the system be the highest, which means the sum of the fan power consumption is the lowest. At this time the system is in a synergistic operation state. Usually, the fan power consumption can be expressed as a cubic relationship of mass flow rate:

$$W_{fan} = \beta m^3 \tag{1}$$

where m is the mass flow rate, β is the fan performance parameter, which is related to the fan performance and duct structure.

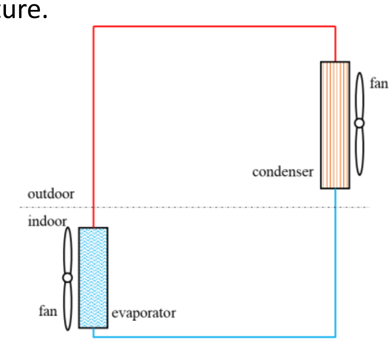

Fig 1 Schematic diagram of a separated heat pipe system

The objective function can be expressed as the sum of fan power consumption of evaporator and condenser:

$$f = W_e + W_c = Am_E^3 + Bm_C^3 \tag{2}$$

where *A* and *B* are the performance parameters of evaporator and condenser fan respectively, subscript *e* and *c* are evaporator and condenser respectively, subscript *E* and *C* are evaporator air side and condenser air side respectively.

The constraint equation is the heat transfer equations of the evaporator and condenser:

$$g_1 = m_E c_p (T_{E,i} - T_{E,o}) - Q = 0 \tag{3}$$

$$g_2 = KA_e \left(\frac{T_{E,i} + T_{E,o}}{2} - T_r \right) - Q = 0 \tag{4}$$

$$g_3 = m_C c_p (T_{C,o} - T_{C,i}) - Q = 0 \tag{5}$$

$$g_4 = KA_c \left(T_r - \frac{T_{C,i} + T_{C,o}}{2} \right) - Q = 0 \tag{6}$$

where c_p is the specific heat at constant pressure of the air, *T* is the temperature, *KA* is the heat transfer capacity of the heat exchanger, subscript *i* and *o* are inlet and outlet respectively, T_r is the evaporation or condensation temperature of the heat pipe. The optimization problem of the system's energy consumption can be described as the following multi-dimensional optimization problem:

$$\begin{gathered} \min f(m_E, m_C, T_{E,o}, T_{C,o}, T_r) \\ s.t.\, g_k(m_E, m_C, T_{E,o}, T_{C,o} T_r) = 0 (k = 1,2,3,4) \end{gathered} \tag{7}$$

Based on the variation principle, the Lagrangian function can be constructed as follows:

$$F = f + \sum_{k=1}^{4} \lambda_k g_k \tag{8}$$

where λ_k is the Lagrange multiplier. At the extreme point, the partial derivative of the undetermined parameter and the Lagrange multiplier is:

$$\frac{\partial F}{\partial x} = 0(x = m_E, m_C, T_{E,o}, T_{C,o}, T_r) \quad (9)$$

$$\frac{\partial F}{\partial \lambda_k} = 0(k = 1,2,3,4) \quad (10)$$

Substitute equation 8 into equation 9 and 10, and simplify to:

$$Am_E^4 = Bm_C^4 \quad (11)$$

By deforming equation 11, the following equation can be obtained:

$$\frac{W_e}{\Delta T_E} = \frac{W_c}{\Delta T_C} \quad (12)$$

where ΔT_E and ΔT_C are the air side temperature changes of the evaporator and condenser respectively. According to equation 12, for any rate of heat transfer and inlet temperature of the thermal fluid, when the energy efficiency of the system is the highest, the energy consumption per unit temperature rise on the air side of evaporator and condenser is always the same. Thus the synergy operation factor can be defined as:

$$\gamma = \frac{\Delta T_C W_e}{\Delta T_E W_c} \quad (13)$$

When the synergy operation factor is equal to 1, the energy efficiency of the heat transfer system is the highest. This conclusion is also applicable to other two stream heat transfer process as long as the power consumption of the pumps or fans can be expressed as a cubic relationship of mass flow rate.

3. CASE STUDY

In order to verify the synergy optimization analysis method, a simple separated heat pipe system was studied here, whose structure diagram is shown in Fig. 1. The parameters of this separated heat pipe system are listed in Table 1. The rate of heat transfer is fixed as 3000 W. The relation between the energy efficiency and the synergy operation factor can be studied by optimizing the air flux of evaporator and condenser. EER (Energy Efficiency Ratio) is adopted to evaluate the energy efficiency of the separated heat pipe system in this paper, which is defined as follows:

$$\mathrm{EER} = \frac{Q}{W} \quad (14)$$

where Q is the rate of heat transfer, W is the power consumption. The EER and the synergy operation factor are calculated when the air flux of evaporator changed from 0.18 kg/s to 0.28 kg/s. The results are shown in Fig. 2. It can be found that, with the increase of the air flux of evaporator, the EER of this system first increased then decreased, and the synergy operation factor gradually increased. When the air flux of evaporator is equal to 0.234 kg/s, the EER of this system reaches its maximum value, and the synergy operation factor is equal to 1.

Table 1 The parameters of the separated heat pipe system

	Inlet temperature (℃)	Heat capacity rate (W/K)	Performance parameter of fan
Evaporator	32	800	2000
Condenser	5	800	2500

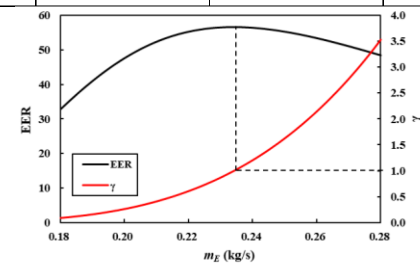

Fig 2 EER and synergy operation factor vary with air flux of evaporator

4. EXPERIMENTS

In order to verify the actual guiding effect of the synergy optimization analysis method, an enthalpy difference test was carried out on a separated heat pipe system. The experimental setups are shown in Fig. 3 and the main temperature measuring points are labeled. R134a was used as the refrigerant. The filling rate was set as 110%. During the experiments, two adiabatic chambers were used to simulate the indoor and outdoor environments. The air temperature of the indoor camber was set constant as 32℃, and the air temperature of the outdoor camber was set constant as 5℃. The rate of heat transfer could be calculated based on the air side temperature changes of the evaporator and the air flux. The measuring accuracy of temperature and air flux were 0.1℃ and 2% respectively. By changing the air flux of the evaporator and condenser, maintain the rate of heat transfer at about 10 kW. The temperatures and powers of evaporator and condenser fans were measured when the system reached equilibrium.

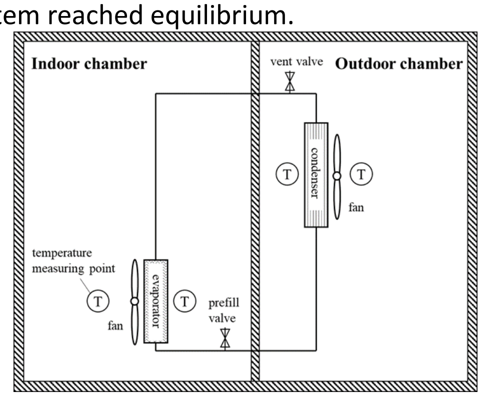

Fig 3 Experimental setups of the separated heat pipe system

Table 2 lists the test results and calculation results of 7 conditions. Fig. 4 shows the variation of EER with the synergy operation factor. According to the calculation results, with the increase of the synergy operation, the EER of the system first increased and then decreased. When the energy efficiency was the highest, the synergy operation factor was 0.95, which was the closest to 1.

Table 2 calculation results of the EER and synergy operation factor

No.	Rate of heat transfer (W)	Power consumption of evaporator fan (W)	Power consumption of condenser fan (W)	EER	Synergy operation factor
1	10894	74.7	362.1	24.94	0.06
2	10373	74.5	255.2	31.46	0.10
3	9936	74.7	156.1	43.07	0.20
4	9815	74.2	115.9	51.63	0.38
5	10116	90.7	97.6	53.73	0.95
6	9509	120.8	88.3	45.54	1.32
7	10624	189.7	88.0	38.26	2.49

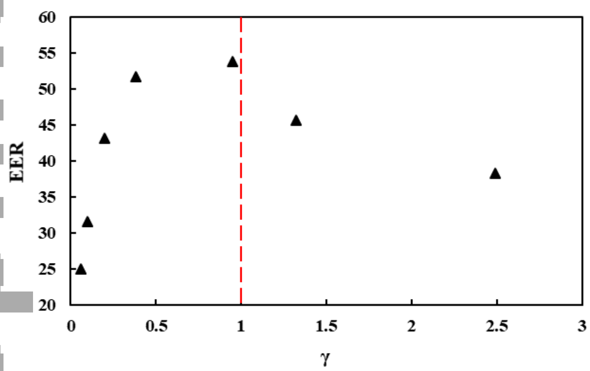

Fig 4 EER vary with the synergy operation factor

5. CONCLUSIONS

Based on the variation principle, the synergistic relationship between the power consumption of pumps or fans and temperature changes of thermal fluid was derived analytically. And the synergy operation factor was defined to guide the practical operation optimization of the heat transfer process. When the synergy operation factor is equal to 1, the energy efficiency of the heat transfer system is the highest. An experiment of a separated heat pipe system was carried out, and the results showed that the closer the synergy operation factor is to 1, the higher the system energy efficiency is.

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