A Calculation Model for Typical Data Center Cooling System

Jianwen Huang¹, Cheng Chen¹, Guiyang Guo¹, Zhang Zhang¹* and Zhen Li²*

The National Computer Network Emergency Response Technical Team/Coordination Center of China, 100029 Beijing, China
Tsinghua University

* Corresponding author, email: zhang.z@139.com; lizh@tsinghua.edu.cn

Abstract: This paper has established a typical calculation model for typical data center cooling system, including the inside room CRAC system, outside free cooling usage system and chiller. The aim of establishing such method is to calculate the power consumption of the data center and to guide the work of energy conservation. The results show that, higher inside room temperature, lower water mass flow rate and lower outside air temperature lead to lower PUE.

1. Introduction

Data center has grown rapidly all over the world. The data center is a room where IT servers are centrally stored. Thus, the heat generation rate can be very high usually as high as 10 kW per rack. The IT server should be operated in a safe and reliable environment, otherwise the CPU or other electron device will damaged if the temperature is high. As a result, the cooling system may consume a lot of energy [1]. For a typical data center, as can be seen in figure 1[2,3], the IT equipment consumes 30% of the total electric in data center, while the cooling system (including the air condition system, humidifier and chiller) consumes about 45% of the total electric. The power consumption on cooling system is even much higher than the IT system. Such results show that the energy control method is not fit well with the whole system, thus, the cooling system consumes lots of energy. As a results, it is important to reduce the energy consumption in cooling system.[4]

Figure 1 Energy consumption in typical data center [2]
A typical data center cooling system can be seen in figure 2. As can be seen in the figure 2, such system contains two cycles. The first is the chilled water circle, and the second is the chiller which is used to produce chilled water. If the outside air temperature is colder than the chiller water (usually the chilled water’s inlet and outlet temperature is about 9/14℃), than the air can be used to cool down the chiller water. Thus, a water and air heat exchanger can be equipped in the chilled water cycle before the chiller water flows into the chiller.

The second cycle is the chiller’s cooling cycle, which contains the throttling value, compressor, evaporator and condenser. Evaporator is used to produce chilled water and condenser is cooled by outside air.

In this paper, a model is established based on the physical model to calculate the power consumption in data center. The aim of the model is to calculate the effect of temperature or mass flow rate on the energy consumption.

2. Model established

2.1 The model for chiller water cycle

The chiller water cycle contains two heat exchanger (the evaporator of the chiller belongs to the chiller cycle) and three power consumption equipment (two fans and a water pump). The heat exchanger is the inside room CRAC [5,6] system, and the outside cold air-chilled water heat exchanger. The inside room CRAC system can be simplified as an air-water heat exchanger. The chilled water flows into the CRAC and cooled the hot air coming back from the racks. The cold air-chilled water heat exchanger is also simplified as an air and water heat exchanger. After cooling the hot air inside the room, the chilled water temperature raised up and it is cooled by the outside cold air before the chilled water flows back to the chiller.

Here, define $Q_1$ is the heat transfer capacity by the cold air-chilled water heat exchanger, $Q_2$ is the heat transfer capacity of the evaporator (chiller’s refrigeration capacity), and $Q_3$ is the data center’s heat generation capacity (kW). According to the principle of energy conservation, $Q_3=Q_1+Q_2$. Besides, $Q_1, Q_2$ and $Q_3$ is calculated by equation 1-3.

\[
Q_3 = m_i(T_i - T_3)Cp_w
\]  

(1)

\[
Q_1 = m_i(T_i - T_2)Cp_w
\]

(2)
For CRAC system, it can be simplified as equation 4-6 according to Newton’s cooling law.

\[ Q_3 = m_b (T_{h1} - T_{h2})Cp_c \]  

\[ \Delta T_1 = (T_{h1} + T_{h2}) / 2 - (T_i + T_3) / 2 \]  

\[ Q_3 = KA_1 \Delta T_1 \]  

For cold air-chilled water heat exchanger system, it can also be simplified as equation 7-9 according to Newton’s cooling law.

\[ Q_1 = m_c (T_{c1} - T_{c2})Cp_c \]  

\[ \Delta T_2 = (T_i + T_2) / 2 - (T_c + T_{c3}) / 2 \]  

\[ Q_1 = KA_2 \Delta T_2 \]  

2.2 The model for chiller

Since the chiller contains the compressor, it is a kind of work and energy conservation system. In the chiller, compressor is used to compress the coolant so as to hold the pressure difference between the evaporator and the condenser by consuming electric (P1). The evaporator is used to absorb heat (Q2) from chiller water and the condenser is used to release heat (Q4) to the outside air. According to the principle of energy conservation, Q4=Q2+P1.

The chiller’s cycle contains two heat exchanger, including evaporator and condenser. Equation 10-14 is used to describe the cooling system.

\[ Q_2 / P_1 = COP \]  

\[ Q_4 = Q_2 + P_1 \]  

\[ Q_4 = (T_{e1} - T_{c2})Cp_m \]  

\[ Q_2 = [(T_3 + T_2) / 2 - T_{ev}] KA_e \]  

\[ Q_4 = Q_2 + P_1 = [-(T_{c4} + T_{c1}) / 2 + T_{co}] KA_c \]  

In these equations, COP is the coefficient of performance, which is defined as the cooling capacity of the evaporator/the energy consumption of the compressor. The overcool and overheat in the evaporator and condenser is omitted. Thus, the Tev means temperature of evaporator and Tco is the temperature of the condenser.

2.3 The model of power consumption system

In the cooling system, the power consumption system includes the water pump in the chiller water cycle, fans of the heat exchanger is the inside room CRAC system, fans of the cold air-chilled water heat exchanger system and fans of the condenser. The power consumption is proportional to the mass flow rate. Thus, the power consumption can be calculated by 15-18[7].
\[ P_{\text{water}} = \alpha m_1^3 \]  
(15)

\[ P_{\text{airoutside}} = \beta m_c^3 \]  
(16)

\[ P_{\text{CRAC}} = \gamma m_h^3 \]  
(17)

\[ P_{\text{water-coldair}} = \theta m_b^3 \]  
(18)

And finally, PUE is used to evaluate the energy consumption level of the whole data center by equation 19.

\[ P_{\text{total}} = P_1 + P_{\text{water}} + P_{\text{airoutside}} + P_{\text{CRAC}} + P_{\text{water-coldair}} + Q_3 \]  
(19)

\[ PUE = \frac{P_{\text{total}}}{Q_3} \]

3. Calculation results

3.1 Coefficient and known quantity

Before calculation by the model, COP of the chiller and \( \alpha, \beta, \gamma, \theta \) should be known. Here COP is related to mainly three quantities, including evaporator and condenser temperature and cooling capacity. In order to make the model more reliable, the data of a commercial used compressor is used to get the relation between the COP and the three quantities by linear regression. And \( \alpha = 0.2, \beta = 0.1, \gamma = 0.001, \theta = 0.15 \).

\[ \text{COP} = 0.0198 \times T_{\text{ev}} - 0.0685 \times T_{\text{co}} + 0.0488 \times Q_2 + 3.94 \]

In the model, the heat transfer capacity of each heat exchanger should be given before calculation, \( K_{A1} = 5 \text{kW/K}, K_{A2} = 1 \text{kW/K}, K_{Ae} = 6 \text{kW/K}, K_{Ac} = 3 \text{kW/K} \). \( Q_3 = 50 \text{kW} \), \( mc = 2 \text{kg/s} \), \( mh = 10 \text{kg/s} \) and \( mb \) is \( 2 \text{kg/s} \).

3.2 Calculation results

3.2.1 A typical result

A typical result is shown in figure 3. Here, \( Th_2 = 20 \text{°C} \), \( Tc_2 = 0 \text{°C} \), \( Q_3 = 50 \text{kW} \), \( m_1 = 3 \text{kg/s} \), \( mc = 2 \text{ kg/s} \), \( mh = 10 \text{ kg/s} \), \( mb = 2 \text{ kg/s} \).

As can be seen from the results, the chiller water inlet and outlet temperature is 10.49/14.48°C, and the data center’s temperature is 20-24.97°C. Since the outside cold air temperature is 0°C, free cooling occupies about 22% of the total heat load.

![Figure 3 A typical result of data center](image-url)
3.2.2 The calculation results in winter

Since the cold air is used to produce the chilled water, the operation results in winter and summer is calculated. In theoretical, there are many variables can influence the PUE. Especially the chiller water’s mass flow rate (m1), inside CRAC’s outlet temperature (Th2), and outside cold air temperature. If the chiller water’s mass flow rate increase, the chiller water’s temperature difference will decrease. However, since the m1 increase, the pump’s power consumption will greatly increase. The variation trend of m1 and PUE is shown in the table 1. Here, Th2=20, Tc2=0, Q3=50kW, mc=2, mh=10, mb=2.

| m1(kg/s) | Th1(℃) | T3(℃) | COP | Q2 (kW) | PUE  |
|----------|--------|-------|-----|---------|------|
| 2.5      | 24.97  | 10.1  | 4.011| 38.53   | 1.315|
| 2.611    | 24.97  | 10.2  | 4.011| 38.59   | 1.324|
| 2.722    | 24.97  | 10.29 | 4.011| 38.64   | 1.333|
| 2.833    | 24.97  | 10.38 | 4.012| 38.69   | 1.344|
| 2.944    | 24.97  | 10.46 | 4.012| 38.74   | 1.355|
| 3.056    | 24.97  | 10.53 | 4.012| 38.79   | 1.367|
| 3.167    | 24.97  | 10.6  | 4.012| 38.83   | 1.381|
| 3.278    | 24.97  | 10.66 | 4.012| 38.87   | 1.395|
| 3.389    | 24.97  | 10.72 | 4.012| 38.9    | 1.41 |
| 3.5      | 24.97  | 10.78 | 4.013| 38.94   | 1.426|

In the theoretical, if the inside room temperature increase, than the chiller water’s temperature will also increase and the chiller’s COP will increase which means the power consumption of the chiller will decrease and the PUE will also decrease. Detail information can be seen in table 2. Here, Tc2=0℃, Q3=50kW, m1=3 kg/s, mc=2 kg/s, mh=10 kg/s, mb=2 kg/s.


3.2.3 The calculation results in trans-season

In trans-season, the Tc2 increase, but the free cooling can still be used. In theoretical, if Tc2 increase, the occupation of free cooling (Q1) will decrease, which means the load of chiller will increase, see figure 4. Thus, the PUE of the system will also increase. The relation between PUE and Tc2 has been listed in table 3. Here, Th2=20, Q3=50kW, m1=3, mc=2, mh=10, mb=2.

Table 2 The variation trend of Th2 and PUE

| Th2 (℃) | Th1 (℃) | T3 (℃) | COP | PUE |
|---------|---------|--------|-----|-----|
| 15      | 19.97   | 5.494  | 3.885 | 1.388 |
| 16.11   | 21.08   | 6.605  | 3.914 | 1.382 |
| 17.22   | 22.19   | 7.716  | 3.942 | 1.376 |
| 18.33   | 23.3    | 8.827  | 3.97  | 1.37  |
| 19.44   | 24.42   | 9.938  | 3.998 | 1.364 |
| 20.56   | 25.53   | 11.05  | 4.026 | 1.358 |
| 21.67   | 26.64   | 12.16  | 4.053 | 1.353 |
| 22.78   | 27.75   | 13.27  | 4.08  | 1.347 |
| 23.89   | 28.86   | 14.38  | 4.108 | 1.342 |
| 25      | 29.97   | 15.49  | 4.135 | 1.337 |

Table 3 The relationship between PUE and Tc2

| Tc2 (℃) | Th1(℃) | PUE | T3(℃) | COP | Q1(kW) | Q1/Q3 |
|---------|---------|-----|--------|-----|--------|-------|
| 0       | 24.97   | 1.361 | 10.49  | 4.012 | 11.24  | 0.2248 |
| 1.333   | 24.97   | 1.372 | 10.49  | 3.906 | 10.2   | 0.204  |
| 2.667   | 24.97   | 1.383 | 10.49  | 3.799 | 9.167  | 0.18334 |
| 4       | 24.97   | 1.395 | 10.49  | 3.691 | 8.132  | 0.16264 |
| 5.333   | 24.97   | 1.408 | 10.49  | 3.581 | 7.097  | 0.14194 |
| 6.667   | 24.97   | 1.421 | 10.49  | 3.469 | 6.062  | 0.12124 |
| 8       | 24.97   | 1.436 | 10.49  | 3.354 | 5.027  | 0.10054 |
| 9.333   | 24.97   | 1.452 | 10.49  | 3.238 | 3.993  | 0.07986 |
| 10.67   | 24.97   | 1.47  | 10.49  | 3.118 | 2.958  | 0.05916 |
| 12      | 24.97   | 1.489 | 10.49  | 2.995 | 1.923  | 0.03846 |
4. Conclusion

Many variables can influence the PUE of the data center. Especially the chiller water’s mass flow rate (m1), inside CRAC’s outlet temperature (Th2), and outside cold air temperature (Tc2).

The calculation results show that if the m1 increases, the power consumption of the water pump will increase, which will lead to the increment of PUE. Th2 increase means the heat sink (chiller water) temperature will also increase, the chiller’s power consumption will decrease, thus the PUE will decrease. Tc2 increase, the occupation of free cooling (Q1) will decrease, which means the load of chiller will increase. Thus, the PUE will also increase.

All in all, higher inside room temperature, lower water mass flow rate and lower outside air temperature lead to lower PUE.

Reference

[1] Li Z, Kandlikar S G. Current status and future trends in data-center cooling technologies [J]. Heat Transfer Engineering, 2015, 36(6): 523-538.

[2] Ding, Tao, et al. "Application of separated heat pipe system in data center cooling." Applied Thermal Engineering 109 (2016): 207-216.

[3] V.A. Chiriac, F. Chiriac, Novel energy recovery systems for the efficient cooling of data centers using absorption chillers and renewable energy resources, in: Proceedings of 13th IEEE Intersociety Conference, San Diego, CA, May 30-June 1 2012, 2012.

[4] Research on Data Center Energy Consumption and Energy Efficiency Level, Energy of China, vol. 32, no. 11, pp. 42–45, 2010.

[5] Srinarayana, N., Fakhim, B., Behnia, M., and Armfield, S. W., Thermal Performance of an Air-Cooled Data Center With Raised-Floor and Non-Raised-Floor Configurations, Heat Transfer Engineering, vol. 35, no. 4, pp. 384–397, 2014. doi:10.1080/01457632.2013.828559.

[6] Lu T, Lü X, Remes M, et al. Investigation of air management and energy performance in a data center in Finland: Case study [J]. Energy and Buildings, 2011, 43(12): 3360-3372.

[7] D.P. Mehta, A. ThumannHandbook of Energy Engineering Liiburn, GA, Fairmont Press (1989).