Optimization design of heat dissipation scheme for submarine data center based on analytic hierarchy process

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Abstract. Aiming at the problem of heat dissipation optimization design of submarine data center, firstly, the placement mode of server is designed, and on this basis, the heat generation power of server is analyzed by Newton cooling method of convective heat transfer to determine its feasibility. Secondly, based on the relationship between fluid velocity and pressure and the relationship between fluid velocity and heat dissipation through the container surface, the container structure design and its placement direction are clarified. Then, the optimal container shell material is determined by using multi-attribute decision-making model and analytic hierarchy process. Finally, the quadratic composite function of shell cost and seawater depth with respect to shell thickness is constructed to calculate the appropriate seawater depth. According to the research, considering the structure, placement method, heat dissipation effect and seawater temperature of the container, on the basis that a single container shell can be placed with up to 609 servers, Maraging 300 Steel is selected as the most suitable container shell material.

Keywords: Newton Cooling Formula, Data Normalization, Multi-attribute Decision Model, Analytic Hierarchy Process.

1. Introduction

In the context of the development of big data, cloud storage, and cloud computing, a large number of servers and electronic devices that support their operations will emit huge amounts of heat, and cooling them requires a lot of power and cooling water resources. Building a data center on the seabed [1] is an energy-saving and environmentally friendly way. How to store more servers in the limited volume of the container and rationally design the structure of the container to help heat dissipation is an important issue to be solved. The seawater itself has a certain corrosiveness, so it is necessary to select the appropriate material, which can not only reduce the cost, but also better heat dissipation and improve the service life.

Based on the 3D simulation, this study determined the number and mode of server placement, and designed the container structure and placement mode based on the conditions of fluid flow rate. Based on the above basic conditions, the multi-attribute decision-making model and the analytic hierarchy process are used to comprehensively achieve the purpose of determining the optimal container shell material.

2. Materials and Methods

2.1. Data Sources and Analysis

In this paper, the heat dissipation optimization design of submarine data center in MathorCup 2021 (http://www.mathorcup.org/detail/2345) is analyzed and studied. Descriptive statistics of the obtained data show that the number of servers in scheme 2 is the largest, and up to 609 servers can be placed in a single container. After calculation, the heat generated by the server under this scheme can be absorbed in time by seawater, and the container temperature will not exceed 80℃.

2.2. Method introduction

2.2.1. Analysis of four server placement schemes

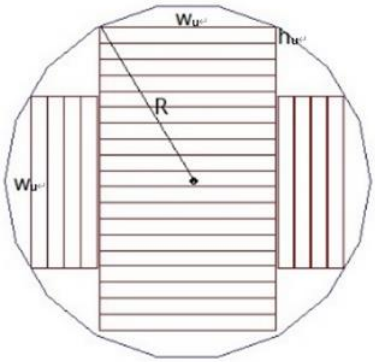


Figure 1. Section of the first scheme

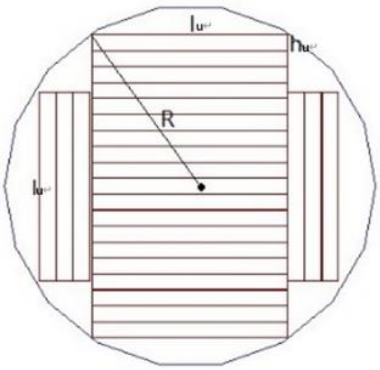


Figure 2. Section of the second scheme

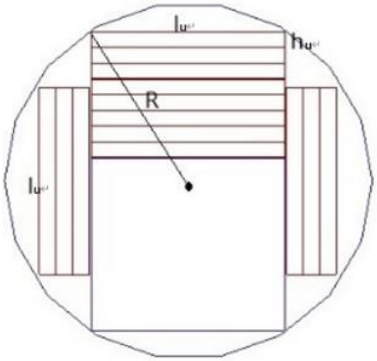


Figure 3. Section of the third scheme

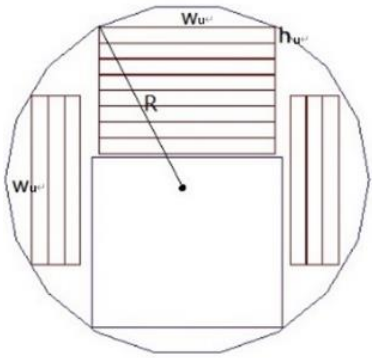


Figure 4. Section of the fourth scheme

The width of the server is w_u, the length is l_u, the height is h_u, the radius of the tangent circle is R, and the height of the cylinder is H. The symbol [ ] in the formula denotes rounding.

On the basis of 3D simulation, four schemes are tried. The section is shown in Figure 1 to Figure 4.Finally, scheme 2 is selected. The specific design is as follows :

The server is stacked as shown in Figure 2: the long l_u and high h_u of the server are on the tangent circle, and the server is connected to the cylindrical shell and stacked along the axial direction of the cylinder. The number of servers in this scheme is n_2. According to the geometric relationship in the graph, the following formula is obtained:

$$n_2 = \left(\left[\frac{2\sqrt{R^2-\left(\frac{l_u}{2}\right)^2}}{h_u} \right] + 2\left[\frac{\sqrt{R^2-\left(\frac{l_u}{2}\right)^2}-\frac{l_u}{2}}{h_u} \right] \right) \times \left[\frac{H}{w_u} \right] + \left[\frac{\left(\frac{H}{w_u}-\left[\frac{H}{w_u}\right]\right)\times w_u}{h_u} \right] \quad (1)$$

Through the calculation of four schemes, the number of servers is obtained: 604 in scheme one, 609 in scheme two, 605 in scheme three and 577 in scheme four. After comparing the four schemes, the second scheme is the optimal scheme. The container based on the second scheme can be placed on 609 servers.

2.2.2. Analysis and comparison of server heat generation power and seawater heat transfer power

For server heat generation power: under the scheme with the most servers, the temperature limit should also be considered. The increase of container temperature is because the server emits huge heat when it works. The heat generation power of a single server is $w_i = 500w$, so the total power generated by the server under scheme 2 is $W = n_2 w_i$.

For the heat transfer power of seawater: First of all, according to the topic, the cooling method of solid in liquid is mainly convective heat transfer. In this paper, Newton cooling formula [2] is used to calculate the heat transfer power of seawater:

$$\Phi = \alpha \mathrm{A}\left(t_w - t_f\right) \tag{2}$$

In this formula, α is the heat transfer coefficient. When α is larger, the heat transfer is faster, and the heat transfer coefficient of seawater changes due to the heat transfer mode. When the heat transfer mode is natural convection, α ranges from 200 to 1000 $W/(m^2 \cdot k)$. When the heat transfer mode is forced convection, α ranges from 1000 to 8000 $W/(m^2 \cdot k)$. However, this paper only refers to the minimum heat transfer coefficient of seawater under natural convection α = 200 $W/(m^2 \cdot k)$, the surface area of the cylinder is $A = 2R\pi H + 2\pi R^2$, $\left(t_w - t_f\right)$ is the temperature difference between the container shell and seawater. Finally, the heat transfer power of seawater is calculated by substituting the parameters given in the topic.

After the above calculation, in the case of the smallest α heat transfer coefficient, the heat transfer power Φ of seawater is greater than the total heat production power W of the server. Therefore, through the convective heat transfer of seawater, the container temperature in scheme 2 will not exceed 80 degrees Celsius, and the server can work normally.

3. Establishment and solution of the model

3.1. Structural design of container shell

3.1.1. Selection of container model

The ideal cross section of the circular and square containers in Figure 5, the diameter of the circle is equal to the side length of the square. According to the relevant knowledge of fluid mechanics, at the same horizontal distance, the distance of the fluid flowing from the upper part of the circle is $s_1 = \pi \times R$, and the distance flowing from the upper part of the square is $s_2 = R$, obviously $s_1 > s_2$.

According to the kinematic formula $v = s/t$, where s is the distance that the fluid passes through the side of the container, and t is the movement time of the fluid passing through the side of the container. At the same time, the fluid velocity on the side of the cylinder is larger, which can take away the heat generated by the container faster. Therefore, in terms of heat dissipation, the cylindrical model is better than the rectangular model.

At the same time, the fluid velocity above the circle is faster than that of the cuboid, according to the Bernoulli [3] energy equation.

$$P + \frac{\rho v^2}{2} + \rho g h = C \text{ (Constant)} \tag{3}$$

The energy equation reflects the pressure energy of the fluid, and $\rho v^2/2$ reflects the kinetic energy of the fluid. From the equation, it can be seen that when the kinetic energy increases, the pressure energy will inevitably decrease, so the pressure is small where the flow rate is fast; on the contrary, when the kinetic energy decreases, the pressure energy will inevitably increase, so the pressure is large where the flow rate is slow. Therefore, the pressure of seawater on the surface of the circle will be smaller than that of the cuboid. In terms of compressive capacity, the cylinder model is superior to the cuboid model.

3.1.2. Design of fin structure

The designed fin structure is shown in Figure 6. The fin is connected to the shell, and the heat emitted in the air inside the fin can be transferred to the shell and the pipe embedded in the fin through the fin (that is, the heat conduction water pipe is inserted into the circular hole in the picture [4]). The seawater in the pipe can be exchanged with the external seawater through the drain outlet evenly distributed on the cylindrical shell. The two bottom surfaces of the cylindrical container are equipped with a water pump, which is pumped into the pipeline to promote seawater convection and accelerate heat dissipation.

Several servers are assembled into a cabinet [5] to facilitate later maintenance and early transportation. Each cabinet is equipped with an independent liquid cooling system, and the hot water

after heat exchange is transported to the nearest main pipeline. The main pipeline is connected to the nearest hole, and the hot water is discharged in time, and the cold water is introduced into the pipeline in time.

After reasonable calculation, some recommended parameters are given in this paper: the fin thickness is $0.5cm$, the outer diameter of the circular hole is $5cm$, the fin spacing is $3.5cm$, the total number of annular fins is about 300, the spacing between 1U servers is $2.38cm$, and the height of a single cabinet parallel to the cylindrical side is $204cm$. Considering that the spacing between cabinets is $10cm$, a pipeline can be placed in up to five cabinets, and the remaining space is used for the placement of wires and pumps, as shown in Figure 7.

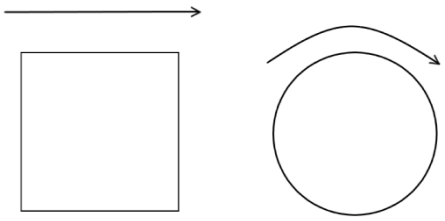


Figure 5. Cross-section diagrams of cylindrical and rectangular containers



Figure 6. Fin structure design

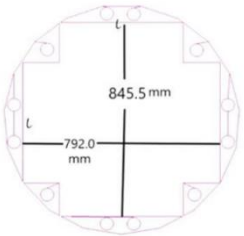


Figure 7. Fin structure section

3.2. Container material selection

3.2.1. Establishment of the model

This paper uses the analytic hierarchy process [6], and uses a_{ij} $(\mathrm{i,j} = 1, 2 \ldots \mathrm{n})$ to represent the relative importance of the ith factor to the jth factor in the hierarchy. The value of a_{ij} is positive integers 1-9 and its reciprocal. The value rules of a_{ij} are shown in Table.1.

Table.1 The relative importance of factor i to factor j

Element	Scale	One of the of a factor as a criterion, the importance of this layer of factors
a_{ij}	1	i is as important as j
	3	i is slightly more important than j
	5	i is more important than j
	7	i is more important than j.
	9	i is more important than j.
	2, 4, 6, 8	The importance is between the degrees represented by adjacent numbers.

Although it can reduce the interference of other factors when constructing the comparison discriminant matrix, it is very likely to contain a certain degree of inconsistency when synthesizing all the comparison results. In order to make the comparison results consistent, the elements in the matrix should also satisfy:

$$a_{ij} \times a_{ik} = a_{jk}, \forall i, j, k = 1,2 \cdots, n \tag{4}$$

(1) Calculate the consistency index CI

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{5}$$

(3) Find the corresponding average random consistency index RI, When $n = 1, 2 \ldots 9$, the corresponding values of RI are shown in Table.2.

Table.2 Average random consistency index

N	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

(3) Calculate the consistency ratio CR

$$CR = \frac{CI}{RI} \tag{6}$$

When $CR < 0.1$, the consistency of the discriminant matrix is acceptable, otherwise the discriminant matrix should be adjusted appropriately.

3.2.2. Solution of the model

The hierarchical structure established in this paper [7] is shown in Figure 8.

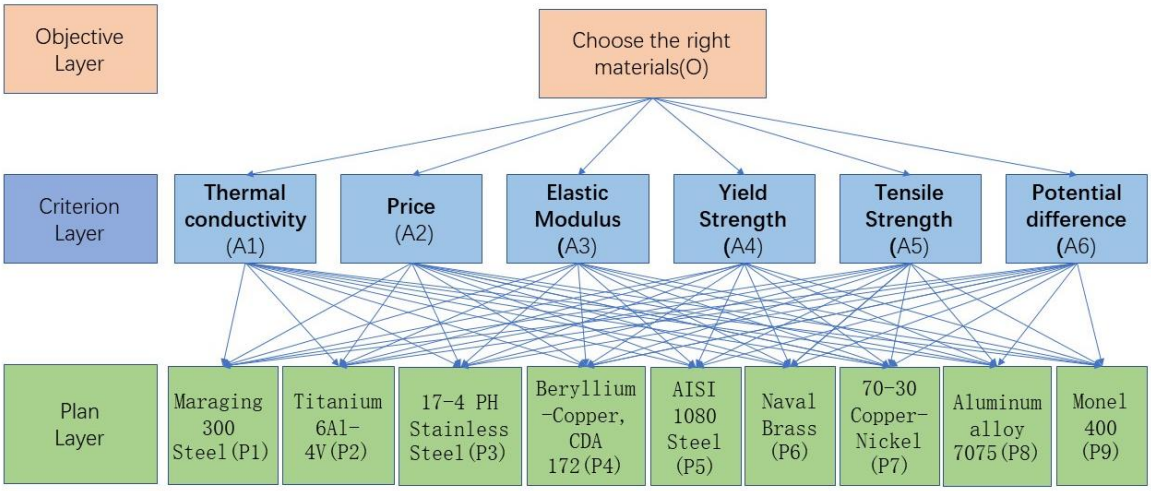


Figure 8 Hierarchical structure diagram

In this paper, 9 materials were selected as the scheme layer.

By consulting the data, the influence degree of each level index on the corresponding index of the higher level is compared in pairs. According to the value rule, the comparative judgment matrix is as follows:

$$A = \begin{bmatrix} 1 & 4 & 1/5 & 1/4 & 1/3 & 1/3 \\ 1/4 & 1 & 1/5 & 1/5 & 1/4 & 1/7 \\ 5 & 5 & 1 & 2 & 5 & 3 \\ 4 & 5 & 1/2 & 1 & 1 & 1/3 \\ 3 & 4 & 1/5 & 1 & 1 & 1/3 \\ 3 & 7 & 1/3 & 3 & 3 & 1 \end{bmatrix} \tag{7}$$

According to the matrix, the weight of each level element is solved, and the index weight of each criterion layer is evaluated. The specific results are shown in Table.3.

Table.3 Index weight and ranking

Tag	A2	A1	A3	A4	A5	A6
Weight	w_2=0.034	w_1=0.0672	w_3=0.3849	w_4=0.15	w_5=0.1168	w_6=0.2471

From the data in the table, it can be seen that Elastic Modulus has the largest weight. This shows that the size of Elastic Modulus has a great influence on the choice of materials. The larger the Elastic Modulus, the stronger the pressure resistance of the material. At the same time, it can also be seen that the weight of price and Thermal Conductivity is relatively small, which has little effect on the choice of materials. According to the index weight, the weighted sum will be calculated in the later process.

In this study, the data of each property index of 9 kinds of materials were sorted out [8], but before calculating the weighted sum, the data need to be normalized [9], and the data attribute type should also be analyzed during normalization [10]. The data in the criterion layer can be divided into two attribute types: benefit type and cost type. The Thermal Conductivity, Elastic Modulus, Yield

Strength and Tensile Strength in the criterion layer are benefit-based, while the price and potential difference are cost-based, as shown in Table 4.

(1) The cost formula is

$$r_{ij} = \frac{\min_i b_{ij}}{b_{ij}} \tag{8}$$

Table 4. Cost data

Material	Price (CNY / kg)	Potential difference
Maraging 300 Steel	25	0.01
Titanium 6Al-4V	240	0.01
17-4 PH Stainless Steel	8	0.15
Beryllium-Copper, CDA 172	158	0.15
AISI 1080 STEEL	10	0.1
Naval Brass	50	0.07
70-30 Copper-Nickel	130	0.05
Aluminum alloy 7075	87	0.11
Monel 400	260	0.1

The data are normalized according to the cost formula, and the results are shown in Table.5.

Table 5. Cost data normalization results

Material	Price (CNY / kg)	Potential difference
Maraging 300 Steel	0.32	1
Titanium 6Al-4V	0.033333333	1
17-4 PH Stainless Steel	1	0.066666667
Beryllium-Copper, CDA 172	0.050632911	0.066666667
AISI 1080 STEEL	0.8	0.1
Naval Brass	0.16	0.142857143
70-30 Copper-Nickel	0.061538462	0.2
Aluminum alloy 7075	0.091954023	0.090909091
Monel 400	0.030769231	0.1

(2) The benefit formula is

$$r_{ij} = \frac{a_{ij}}{max_i a_{ij}} \tag{9}$$

Similarly, the benefit data are normalized according to the benefit formula, and the results are shown in Table.6.

Table 6. Benefit data normalization results

Material	Thermal Conductivity	Elastic Modulus	Yield Strength	Tensile Strength
Maraging 300 Steel	0.196153846	0.97	1	1
Titanium 6Al-4V	0.117230769	0.55	0.518394649	0.552980132
17-4 PH Stainless Steel	0.140769231	0.95	0.608695652	0.662251656
Beryllium-Copper, CDA 172	0.807692308	0.60	0.568561873	0.662251656
AISI 1080 STEEL	0.2153846	1.00	0.474916388	0.629139073
Naval Brass	0.892307692	0.50	0.220735786	0.291390728
70-30 Copper-Nickel	0.446153846	0.73	0.264214047	0.281456954
Aluminum alloy 7075	1	0.35	0.244147157	0.274834437
Monel 400	0.167692308	0.87	0.367892977	0.397350993

The weighted sum formula is as follows:

$$\overline{x} = \sum_{i=1}^{6} r_{ij} w_i \tag{10}$$

Calculate the weighted sum $\overline{x}$ of each index, and then compare the $\overline{x}$ of various materials.

Table 7. Weighted sum of various materials

Material	Maraging 300 Steel	Titanium 6Al-4V	17-4 PH Stainless Steel	Beryllium-Copper, CDA 172	AISI 1080 Steel	Naval Brass	70-30 Copper-Nickel	Aluminum alloy 7075	Monel 400
$\overline{x}$	0.575	0.420	0.265	0.258	0.220	0.187	0.182	0.175	0.172

The normalized data and the weight of the criterion layer are substituted into the weighted sum formula to obtain the corresponding weighted sum of various materials. By comparing their sizes, it can be seen that the weighted sum of Maraging 300 Steel is the largest, that is, Maraging 300 Steel is a suitable material for containers.

The consistency index value $CI = 0.1073$, the consistency ratio $CR = 0.0789$, that is, the consistency index ratio is less than 0.1, and the consistency test is passed.

4. Conclusions

After research and analysis, firstly, it is calculated that a single container can be placed up to 609 servers under ideal conditions, and the fin structure is designed. Secondly, the data provided are preprocessed, and the materials that do not conform to the actual application are eliminated, and the database is established with the remaining materials. Then the data were normalized, and 9 materials with relatively poor indicators were removed. Finally, the multi-attribute analytic hierarchy process is used to calculate the corresponding weights of the six decision factors. After normalization, the Maraging 300 Steel with the highest score is used as the container shell material.

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