Based on Calculation and Analysis of the Influence of External Atmospheric Temperature on Air-conditioning System of Floating Nuclear Power Plant at Sea

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Abstract: External atmospheric temperature is the design input of air-conditioning system of the floating nuclear power plant at sea, which affects the calculation of heat load and air supply volume of air conditioner. The typical cabin A of the floating nuclear power plant is selected. The external atmospheric temperature selection range is obtained by comparing different standard specifications and references. The single variable method is adopted, and the external atmospheric temperature is used as the variable factor. The calculation and comparison of the air volume and cooling capacity of the typical cabin A should be made. The analysis and calculation results show that the external atmospheric temperature has little influence on the air volume of the cabin A air conditioning system, and has a great influence on the cooling influence of the external atmospheric temperature on the air conditioning system of the floating nuclear power plant and the variation of the energy consumption are obtained, along with the external atmosphere. With the increase of temperature, the energy consumption of air conditioning system increases almost linearly. From the perspective of economics, it is concluded that the increase of energy consumption of air conditioning system will reduce the economic benefits of floating nuclear power plants at sea.

1. Introduction
Floating nuclear power plant at sea is an organic combination of small nuclear reactors and ship engineering, which can provide safe and effective energy supply for offshore oil extraction and remote islands, and can also be used in the field of high-power ships and desalination. Floating nuclear power plant at sea technology can fill China's technological gap in the field of civilian nuclear-powered ships and form a core technology with independent intellectual property rights, which has great significance and profound impact on China's development and utilization of new energy and global energy development. Floating nuclear power plant at sea use single-point mooring for long-term operation in fixed sea areas, and air-conditioning systems play an important role in ensuring crew comfort and safe operation of equipment.

Ship air conditioners not only create a suitable artificial climate for the work and life of the crew and passengers, but also provide the necessary environment for the normal operation of the ship equipment[1]. According to statistics, the power consumption of ocean-going ship air-conditioning systems above 10,000 tons accounts for about 20% of the total capacity of the ship's power grid, which is the main energy-consuming device of modern ships [2]. The external atmospheric temperature directly affects the calculation of the heat load and air supply in the cabin, and then affects the selection of equipment and subsequent operation of the air conditioning system. Lam etc. Proposed
that the selection of air conditioning system capacity and investment should be avoided due to conservative selection of outdoor calculation parameters [3]. During the construction of the indoor environment, outdoor climate conditions, including outdoor air dry bulb temperature, wet bulb temperature (or specific enthalpy), and dew point temperature (or moisture content), are all important parameters that affect the building's thermal environment. The heat and humidity treatment process of air treatment equipment also has a direct impact [4]. If the system design adopts the extremely high outdoor temperature, which is rare for many years and lasts for a short time, it will inevitably lead to the huge air conditioning equipment and waste of resources, otherwise, the indoor environment may not meet the demand for use. Small changes in the outdoor calculated temperature will also have a significant impact on the air conditioning system design. So the outdoor temperature calculation of the air-conditioning must be carefully selected [5-7].

Due to the fact that floating nuclear power plant at sea are still blank in China, there are no ready-made standard specifications for reference. Different ship air-conditioning specifications have certain differences in the external environmental parameters. The selection of external environmental parameters of air-conditioning systems directly affects the design results of air-conditioning systems and selection, so how to select reasonable external environmental parameters according to existing standards and specifications is particularly important. Based on the calculation and analysis, the calculation and analysis of the air volume and cooling capacity of a typical A cabin were performed, and the operating law of the power consumption of the entire offshore floating nuclear power plant air conditioning system at different external atmospheric temperatures and its corresponding effects on the economic benefits of floating nuclear power plants.

2. Comparison of different standards and specifications for external environmental conditions

2.1 Comparison of ship standards

2.1.1 In the "General Rules for Ships", the standard atmospheric temperature and humidity in summer should be selected according to the provisions in Table 1 [8].

| Navigation area | Atmospheric temperature \(^\circ\text{C}\) | Relative humidity \(\%\) |
|-----------------|---------------------------------|----------------------|
| Offshore        | 34                              | 65                   |

2.1.2 "Design Method of Ship Air Conditioning System" The outdoor summer design temperature, relative humidity and other parameters of ship air-conditioning cabin are selected in Table 2 below [9].

| Route               | Domestic routes | International routes |
|---------------------|-----------------|----------------------|
|                     | Main application area | Bohai Sea, Yellow Sea, East China Sea | South China Sea | Yangtze | World navigation area |
|                     | temperature     | 32                   | 34               | 36      | 35      |
|                     | Relative humidity | 70                   | 65               | 60      | 70      |

2.1.3 "Design Conditions and Calculation Criteria for Air Conditioning and Ventilation of the Marine Engine Room Centralized Control Room", summer air conditions, outdoor and engine room air conditions, outdoor air dry bulb temperature: \(+35\ ^\circ\text{C}\), relative humidity 70% [10];

2.1.4 "Design Conditions and Calculation Criteria for Air Conditioning and Ventilation of Ships' Cabs" Summer air conditions. The outdoor summer air conditions are: outdoor dry bulb temperature: \(+35\ ^\circ\text{C}\), relative humidity 70% [11].
2.1.5 "Design parameters and calculation methods for air-conditioning regulation and ventilation of ship accommodation spaces" The summer design parameters inside and outside the cabin are selected as specified in Table 3 [12].

| Navigation area         | Dry bulb temperature °C | Relative humidity % |
|-------------------------|-------------------------|---------------------|
| South China Sea         | 35                      | 70                  |
| East China Sea          | 32                      | 60                  |
| North of the Yellow Sea | 32                      | 80                  |

2.1.6 "Ship Design Manual" The summer design conditions for extra-cabin air are selected according to Table 4 [13].

| Navigation area                              | Dry bulb temperature °C | Relative humidity % |
|----------------------------------------------|-------------------------|---------------------|
| Unlimited navigation area: Cargo ships, luxury passenger ships | 35                      | 70                  |
| Nansha and Xisha waters                       | 35                      | 80                  |
| East China Sea                                | 35                      | 60                  |
| Yellow sea                                    | 32                      | 60                  |
| Yangtze River route                           | 36                      | 65                  |

2.2 Value range of external atmospheric temperature for offshore floating nuclear power plant

The offshore floating nuclear power station has been standing in the Bohai Sea for a long time. Therefore, the relevant summer standards and data are summarized in Table 5 below.

| Standard or literature            | Summer temperature °C | Relative humidity in summer % |
|----------------------------------|------------------------|--------------------------------|
| Ship General Standard            | 34                     | 65                            |
| Design method of ship air-conditioning system | 32                     | 70                            |
| Air conditioning regulation and ventilation design parameters and calculation methods for ship accommodation | 32                     | 80                            |
| Design conditions and calculation basis for air conditioning and ventilation of marine engine room centralized control room | 35                     | 70                            |
| Air conditioning and ventilation design conditions and calculation basis for ship's cabin | 35                     | 70                            |
| Practical Handbook of Ship Design | 32                     | 60                            |

As can be seen from the table, the external atmospheric temperature is slightly different between different standards and specifications, with a range of 32 °C to 35 °C and a humidity of 60% to 80%.

3. Impact of external atmospheric temperature on air conditioning systems

Taking the typical cabin A of this offshore floating nuclear power plant as an example, an all-air air-conditioning system is used. The air-conditioning system design first calculates the air-conditioning supply air volume, then calculates the required cooling capacity based on the air supply volume, and
configures the appropriate air-conditioning end and cold source according to the air supply volume and cooling capacity. Because the offshore floating nuclear power plant uses abundant exhaust steam heat source in winter, only the design and calculation of air-conditioning system in summer are discussed. The parameter of external atmospheric temperature is selected as the variable, and the relative humidity of air in summer is 60%. Comparing and analyzing cabin A at different atmospheric temperatures The amount of cooling and air volume changes.

Combined with the range of the external atmospheric temperature selected in the standard specifications of the previous chapter, for the convenience of data analysis, five sets of data were analyzed, and the external ambient temperature was taken from 31 °C to 35 °C to analyze the impact on the air conditioning system design.

3.1 Supply air volume calculation
The air supply volume of cabin A shall be determined according to the largest one of the following calculated air volumes in the Ship Design Manual:

The air supply volume of the air-conditioned cabin shall be determined according to the largest one of the following calculation air volumes:

The air volume \( q_{vf} \) that meets the minimum fresh air requirements of personnel, m³/h; Cooling air supply \( q_{vs} \) in summer, m³/h; The air volume \( q_{vl} \) calculated according to the specified number of ventilations, m³/h.

which is:

\[
q_v = \text{MAX}\left\{q_{vf}, q_{vs}, q_{vl}\right\}
\]

Meet the minimum fresh air requirements of personnel.

The air supply volume of each air-conditioned cabin that meets the minimum fresh air requirement of the personnel is calculated as follows:

\[
q_{vf} = \frac{q_{vf} \cdot n_p}{a}
\]

In the formula:

\( q_{vf} \) — the supply air volume to meet the minimum fresh air requirements of personnel, m³/h;
\( q_{vf} \) — the number of people in the cabin;
\( a \) — new air ratio.

3.2 Summer heat supply air volume

\[
q_{vs} = \frac{Q}{(h_i-h_s) \cdot \rho_a}
\]

In the formula:

\( q_{vs} \) — Air supply in summer, m³/h;
\( \rho_a \) — Air density, 1.2 kg/m³;
\( h_i \) — design enthalpy in the cabin, kJ/kg;
\( h_s \) — supply air enthalpy, kJ/kg;
\( Q \) — Total heat in the cabin, kW.

3.2.1 Heat gain in summer cabin

Cabin heat includes sensible and latent heat, that is,

\[
Q = Q_S + Q_L
\]
\[ Q_S = q_t + q_{ps} + q_l + q_e \]  \( (5) \)

\[ Q_L = q_{pl} + q_{el} + q_{wl} \]  \( (6) \)

In the formula:
- \( Q_S \) — sensible heat in the cabin, kW;
- \( Q_L \) — latent heat in the cabin, kW;
- \( q_t \) — incoming heat in the cabin, kW;
- \( q_{ps} \) — the body emits sensible heat in the cabin, kW;
- \( q_l \) — cabin lighting heat, kW;
- \( q_e \) — heat generation of equipment and pipelines in the cabin, kW;
- \( q_{pl} \) — latent heat emitted by the human body in the cabin, kW;
- \( q_{el} \) — latent heat emitted by cabin equipment, kW;
- \( q_{wl} \) — latent heat emitted by evaporation of water in the cabin, kW.

Among them, related to the external atmospheric temperature is the incoming heat \( q_t \) in the cabin.

\[ q_t = q_{t1} + q_{t2} \]  \( (7) \)

In the formula:
- \( q_{t1} \) — incoming heat from sun deck, bulkhead, side and glazing, kW;
- \( q_{t2} \) — incoming heat in adjacent compartments, kW.

\[ q_{t1} = h \cdot A_1 \left( t_o - t_n \right) + h_g \cdot A_3 \left( t_o - t_n \right) + G_s \cdot A_s \]  \( (8) \)

In the formula:
- \( h \) — The heat transfer coefficient of the corresponding heat insulation structure on each heat transfer surface, W / m\(^2\)·K;
- \( A_1 \) — The area of each heat transfer surface is measured from steel wall to steel wall, deck to deck (with the heat transfer surface of the glass window must be deducted from the calculated area of the glass window), m\(^2\);
- \( h_g \) — The heat transfer coefficient on the calculated area of the glass window. According to the Practical Manual of Ship Design, the double glass window is 3.5W/m\(^2\)·K;
- \( A_3 \) — Calculated area of glass window. The calculation surface of a glass window is the glass window and its outer edge 100mm wide calculated area in one week, m\(^2\);
- \( G_s \) — The solar radiation heat transmission rate of glass windows, according to the Practical Manual of Ship Design, with a value of 210;
- \( A_s \) — Glass window area, m\(^2\);
- \( t_o \) — Design temperature of outside air, °C;
- \( t_n \) — Design temperature of cabin air, °C.

\[ q_{t2} = h \cdot A_3 \cdot \Delta t \]  \( (9) \)

In the formula:
- \( h \) — The heat transfer coefficient of the insulation structure of the non-air-conditioned compartment and the bulkhead or deck of the compartment, W/m\(^2\)·K;
- \( A_3 \) — The heat transfer surface area of adjacent bulkheads or decks;
- \( \Delta t \) — Temperature difference between adjacent compartments, °C.

When calculating the incoming heat, since the equivalent temperature of the sun deck and bulkhead are fixed values, which are 60 °C and 50°C respectively (the calculation of the incoming heat of the sun deck needs to consider the temperature rise of the solar radiation), so only the incoming heat from the outer window Related to external atmospheric temperature.

The outside air temperature is 31 °C, 32 °C, 33 °C, 34 °C, and 35 °C. According to the above calculation method, the total incoming heat of cabin A can be obtained as shown in Table 6 below.
Table 6 Summary of total incoming heat of cabin A at different temperatures

| Adjacent area                          | Area \( m^2 \) | Outdoor equivalent temperature \( ^\circ C \) | Interior design temperature \( ^\circ C \) | Heat transfer coefficient \( W/m^2\cdot K \) | Gain heat \( kW \) | Remark |
|----------------------------------------|----------------|-------------------------------------------|-------------------------------------------|---------------------------------------------|-----------------|--------|
| Weather deck                           | 133.56         | 60                                        | 25                                        | 0.8                                         | 3.74            |        |
| Outer wall heat transfer + radiation    | 31.95          | 50                                        | 25                                        | 0.85                                        | 0.68            |        |
| Inner wall                             | 70.35          | 39                                        | 25                                        | 0.9                                         | 0.89            |        |
| Outer window radiation                 | 12.15          | /                                         | /                                         | /                                           | 2.55            | 210 W/m²|
| Floor                                  | 133.56         | 20                                        | 25                                        | 1.5                                         | -1.00           |        |
| Outer window heat transfer              | 14.79          | 31                                        | 25                                        | 3.5                                         | 0.31            |        |
| Outer window heat transfer              | 14.79          | 32                                        | 25                                        | 3.5                                         | 0.36            |        |
| Outer window heat transfer              | 14.79          | 33                                        | 25                                        | 3.5                                         | 0.41            |        |
| Outer window heat transfer              | 14.79          | 34                                        | 25                                        | 3.5                                         | 0.47            |        |
| Outer window heat transfer              | 14.79          | 35                                        | 25                                        | 3.5                                         | 0.52            |        |
| Outside temperature31°C, Total heat qt \( kW \) |               |                                           |                                           |                                             | 7.165           |        |
| Outside temperature32°C, Total heat qt \( kW \) |               |                                           |                                           |                                             | 7.217           |        |
| Outside temperature33°C, Total heat qt \( kW \) |               |                                           |                                           |                                             | 7.269           |        |
| Outside temperature34°C, Total heat qt \( kW \) |               |                                           |                                           |                                             | 7.321           |        |
| Outside temperature35°C, Total heat qt \( kW \) |               |                                           |                                           |                                             | 7.372           |        |

In summary, it can be obtained that the total sensible heat of cabin A is \( = \) when the external temperature is 31°C to 35°C. The total heat and air supply of cabin A in summer are shown in Table 7 below. From the data in the table, it can be seen that with the increase of the outside atmospheric temperature, only the heat transfer of the outer window has changed, so the total heat of cabin A has increased slightly, and the air supply volume has also increased.

Table 7 Summary of total heat and air supply volume of cabin A at different temperatures Calculation of summer cooling capacity

| Outside temperature \( ^\circ C \) | 31  | 32  | 33  | 34  | 35  |
|-------------------------------------|-----|-----|-----|-----|-----|
| Human body emits heat \( kW \)      | 0.724 | 0.724 | 0.724 | 0.724 | 0.724 |
| Lighting heat \( kW \)              | 1.336 | 1.336 | 1.336 | 1.336 | 1.336 |
| Equipment, pipeline sensible heat load \( kW \) | 6.903 | 6.903 | 6.903 | 6.903 | 6.903 |
| Incoming heat \( kW \)              | 7.165 | 7.217 | 7.269 | 7.321 | 7.372 |
| Total heat \( kW \)                 | 16.128 | 16.180 | 16.232 | 16.283 | 16.335 |
| Air volumem³/h                      | 4814 | 4830 | 4845 | 4861 | 4876 |
3.3 Calculation of summer cooling capacity

The required cooling capacity of the air-conditioning unit of the whole air system is calculated as follows:

\[ Q_1 = q_v \cdot \rho_a \cdot \left( h_m - h_c \right) / 3600 \]  
\[ \text{(10)} \]

In the formula:
- \( Q_1 \) — the cooling capacity required by the air conditioning unit, kW;
- \( \rho_a \) — Air density, generally taken as 1.2 kg/m\(^3\);
- \( q_v \) — Air supply volume, m\(^3\)/h;
- \( h_m \) — Enthalpy of mixed air entering air-conditioning unit, kJ/kg;
- \( h_c \) — Evaporator enthalpy, kJ/kg.

When the external temperature is calculated from 31 °C to 35 °C, the cooling capacity results are shown in Table 8 below. As can be seen from the data in the table, although the supply air volume does not change much, as the external air temperature increases, the external air enthalpy value increases, and the cooling capacity required by the air conditioning unit to handle the fresh air increases, and the external ambient air for every 1 °C higher temperature design value, the cooling capacity of the air conditioning system increases by about 7%.

| Outside temperature °C | 31  | 32  | 33  | 34  | 35  |
|------------------------|-----|-----|-----|-----|-----|
| Air volume m\(^3\)/h   | 4814| 4830| 4845| 4861| 4876|
| Cooling capacity kW     | 32.20| 34.68| 37.27| 39.96| 42.81|
| Cooling capacity change%| -14 | -7  | 0   | +7  | +15 |

3.4 Impact on cabin A air conditioning system

The relationship between the outside air temperature and the cooling capacity and air volume is shown in Figures 1 and 2 below, which can be obtained from Figures 1 and 2.

- With the increase of the outside atmospheric temperature, the air supply volume of the cabin A gradually increases, but the increase is not large. For each temperature increase of 1 °C, the air volume change is only about 0.3%.
- When calculating the cooling capacity of the air conditioner in Cabin A, as the ambient air temperature rises, the enthalpy of the fresh air that needs to be processed by the air conditioning unit increases, so the required cooling capacity increases accordingly.
- For the use of all-air systems, the ambient air temperature has little effect on the design of the wind system due to the small change in air volume; and the end cold water coil capacity in the water system and the chiller capacity in the refrigeration station increase with the ambient air temperature While increasing.
3.5 Impact on the air conditioning system and power load of the entire floating nuclear power plant

From the analysis results of cabin A air conditioning system, the outside air temperature has a greater impact on the design of the air conditioning cold water system, that is, as the outside air temperature increases, the fresh air enthalpy value increases, and the cooling capacity of the air conditioning system increases.

According to this characteristic, the air supply fresh air ratio of the air-conditioning system of the offshore floating nuclear power plant is 0.4, and the change of the power load can be roughly estimated. Under the premise that the chiller efficiency is unchanged, the rated power is linearly proportional to the cooling capacity. According to statistics at 33 °C, the rated power of the air-conditioning system of the entire floating nuclear power plant is 586 kW. The power consumption of the air-conditioning system is shown in Table 9 below. It is known from the table that for every 1°C increase or decrease in external atmospheric temperature, the power consumption changes reduced by ~ 23kW.

### Table 9 Changes in power consumption of air conditioning systems

| Outside temperature ℃ | 31 | 32 | 33 | 34 | 35 |
|------------------------|----|----|----|----|----|
| rated power kW         | 510| 548| 586| 625| 664|
| effectiveness          | 0.8| 0.8| 0.8| 0.8| 0.8|
| Input total power kW   | 637.5| 685| 732.5| 781.25| 830|
| Load factor            | 0.485| 0.485| 0.485| 0.485| 0.485|
| Power consumption kW   | 309.19| 332.23| 355.26| 378.91| 402.55|
| Power consumption change kW | -46.07| -23.03| 0.00| 23.65| 47.29|

4. Economic analysis

Based on the calculation and analysis in the previous chapter, it is estimated that the tax-included sales price of floating nuclear power plant at sea is 1.8 yuan / kWh. According to the offshore floating nuclear power plant operating site in the Bohai Sea area, the air-conditioning system is expected to operate in July, August, and September, and is estimated based on an average of 60 days per year and 12 hours per day:

\[
60 \times 12 \times 23 \times 1.8 = 29808 \text{ yuan / year}
\]

For each 1°C higher design value of the external ambient air temperature, from the aspect of power consumption of the air conditioning system, it is estimated that the annual economic benefit will be reduced by about 30,000.
5. Conclusion

- By enumerating the relevant provisions in the existing standard specifications and design manuals for the external atmospheric temperature value of the air conditioning system of floating nuclear power plant at sea, and through the calculation and analysis of the air volume and cooling capacity of the air conditioning system, it can be known that as the external atmospheric temperature increases, the cooling capacity of the air conditioning system tends to increase linearly. For every 1°C increase in the design value of the external ambient air temperature, the cooling capacity of the air conditioning system increases by about 7%.

- Comparing the estimated power load of the air conditioning system under different external ambient air temperatures, the power consumption of the entire air-conditioning system of the floating nuclear power station increases by about 23kW for each 1°C higher design value of the external air temperature.

- Different external atmospheric temperatures have a certain impact on the economics of floating nuclear power plant at sea. For every 1°C higher design value of external atmospheric temperature, the initial investment in air conditioning systems may increase, and the economic benefits of operating floating nuclear power plant at sea will decrease by 30,000 yuan / year, and vice versa.

- From the perspective of energy saving and economy, and considering that floating nuclear power plant at sea is fixed-point work in the Bohai Sea, it is recommended that the maximum design temperature of the air conditioning system in summer should be the minimum value of 32°C specified in the standard specification.

References

[1] Fei Q. (2003) Ship auxiliary machine [M]. Dalian Maritime University Press, Dalian.
[2] Liu X.C. (2007) Discussion on energy-saving measures for marine air conditioning [J]. Journal of Qingdao Ocean Shipping Crew College, 2: 29-30.
[3] LAMLCL, TSANG CL, YANG L, et al. (2005) Weather data analysis and design implications for different climatic zones in China [J]. Building and Environment, 40 (2): 277-296.
[4] Zhao K., Liu X.H., Zhang T., et al. (2011) Discussion on calculation parameters of outdoor air conditioning in summer [J]. HVAC, 41 (1): 9-13.
[5] Liu B., Yang Z., Zhu N., et al. (2003) Research on comfort and energy consumption of air conditioning systems [J]. Journal of Tianjin University, 36 (4): 489-492.
[6] Zhang H., Yang B., Yang X.J., et al. (2004) Dimension design and energy-saving potential analysis of south-facing wall of residential building [J]. Journal of Tianjin University, 37 (7): 610-613.
[7] Tian Y., Li J.Q., Zheng S., et al. (2017) Determination of outdoor calculated temperature of air conditioner in summer based on GPD [J]. Journal of Tianjin University, 50 (7): 773-779.
[8] Naval Standards Institute. (2000) General Rules for Ships: GJB 4000-2000 [S]. Naval Bureau of the Armed Services Department, General Equipment Department.
[9] China Ship and Ocean Engineering Design and Research Institute. (1983) Design Method of Ship Air Conditioning System: CBZ 330-83 [S]. National Technical Committee for Ship Standardization.
[10] Shanghai Ship Research and Design Institute. (1996) Design Conditions and Calculation Criteria for Air Conditioning and Ventilation of the Marine Engine Room Centralized Control Room: CB / T 3773-1996 [S]. China Shipbuilding Industry Corporation.
[11] Shanghai Ship Research and Design Institute. (1997) Design Conditions and Calculation Criteria for Air Conditioning and Ventilation of Ships' Cabs: CB / T 3774-1996 [S]. China Shipbuilding Corporation.
[12] China Shipbuilding Industry Corporation 708. (1992) Design parameters and calculation methods for air-conditioning regulation and ventilation of ship accommodation spaces: GB / T 13409 [S]. State Technical Supervision Bureau.

[13] China Shipbuilding Industry Corporation. (2013) Ship Design Manual [S]. Beijing: National Defense Industry Press.