Abstract

To solve the air-condition simulator operational problems in IMO crew training, this paper, taking "Yu Kun" ship as the study object, established the air-condition cooler and compartment temperature dynamic mathematical model. With the Matlab/Simulink real-time simulation tools, reasonable and appropriate algorithm simulation parameters, it achieved the real-time dynamic Simulation on Marine air-condition. This simulation not only provided a powerful guarantee for the ship Air-condition simulator design, but also provided an important basis for the marine air conditioning design.

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Keywords: Marine air-conditioning; Modeling; Simulation

1. Introduction

Marine air-condition provides a suitable working and living environment for the crew and passengers, while offers an important guarantee for the normal operation of ship machinery. So, it’s particularly important to hold the real-time dynamic operation of air-condition in time.

IMO, International Maritime Organization, demands the crew air-condition simulator practical operation training pre-service. As an important link of marine air-condition simulator, the modeling and simulation reveals realistic operating conditions, and provides a good simulation platform for the crew to master its running states timely and dynamics, while predict, diagnose the potential and the presence bug. It’s not only a teaching tool for training the crew, but also an important basis for the design of marine air-conditions.
2. Requirements for marine air-condition technology

Air-condition is mainly used to offer a comfortable working and living environment, meeting the crew and passengers’ requirements. It is the comfort air-condition\cite{1}, generally used the central air-condition unit and different with the CARA, which some of the production process and the precision instruments used.

Marine Air-condition unit should make the indoor air conditions meet following requirements, under the fixed outdoor design parameters.

1. Temperature
   Air-condition compartment of the ship design criteria is: summer temperature is 24 ～ 28 °C; indoor and outdoor temperature difference does not exceed 6 ～ 10 °C.

2. Humidity
   In summer, desiccant cooling method is used in air-condition, indoor humidity is generally in 40% to 50%.

3. Fresh degree
   If just meet the respiration oxygen needs, the minimum fresh air supply is 2.4 m\(^3\) / h • person. However, to make carbon dioxide, smoke and other harmful gases in the air in the allowed level below, the fresh air on the need is achieved 30 ～ 50m\(^3\) /h • person.

4. Air flow rate
   The indoor air flow rate to 0.15 ～ 0.2 m/s is appropriate; the maximum does not exceed 0.35 m/s.

3. Mathematical Model

3.1. The mathematical model of air cooler

The air cooler has the following functions: to provide a surface for low-temperature chilled water and air flow heat transfer, to drop the temperature of the air flew through the air cooler. It’s the copper tube aluminum fin air cooler. The heat transfer sketch of air cooler is shown in Figure 1.

In figure 1, supposing \(t_{li}\) is the inlet temperature of low-temperature chilled water; \(t_{lo}\) is the outlet temperature low-temperature chilled water; \(m_2\) is the flux of low-temperature chilled water; \(t_{hi}\) is the inlet temperature of the air flowing into the cooler; \(t_{ho}\) is the outlet temperature of air; \(m_1\) is the flux of the air. In the modeling process, in order to simplify it, the paper made the following assumptions according to the actual work of cooler.

1. Instantly, cold and hot fluid has the same temperature at a cross section perpendicular to the flow direction. In other words, it treats the cooler with the lumped parameters, at the same time excluding the condenser shell heat. If there is a large chilled water flux, the error of this deal is not great.

2. The inside and outside of the metal tub wall temperature is always similarly to equal. In fact, the condenser wall is thin and the heat capacity of the metal wall is small, while heat transfer coefficient \(\lambda\) is
large. Therefore, when the temperature range is small, this assumption can meet the precision requirements.

(3) Dirt degree of condenser bundle is the same.

According to the air side heat transfer relationship of air-cooler: accumulation of heat changed per unit time in air side = the heat brought in by air per unit time - the heat transferred to the low temperature chilled water side per unit time. Then, this equation is got [2-4]:

\[
\frac{dt_{ho}}{dt} = \frac{1}{W_1} \left[ m_k c_k (t_{hi} - t_{ho}) - \frac{1}{R} \Delta T_m \right]
\]

In the formula, \( \Delta T_m \) is the average temperature of the cooler; \( W_1 \) is the heat capacity of air side, \( W_1 = M_k c_k + M_b C_b \), where, \( M_k \) is the air quality of air-cooler; \( M_b \) is the quality of the air cooler material; \( c_k \) is the hot water specific heat; \( C_b \) is the material specific heat.

\( R \) is the thermal resistance of the air cooler, \( R = 1/KA \), K is cooler total heat transfer coefficient, \( A \) is the cooler cooling area.

Similarly, according to the low-temperature chilled water side heat transfer relationship: accumulation of heat changed per unit time in the low-temperature chilled water side = the heat passed from air to chilled water per unit time - the heat taken away by the low temperature chilled water per unit time. So, this equation is show:

\[
\frac{dt_{lo}}{dt} = \frac{1}{W_2} \left[ \frac{1}{R} \Delta T_m - m_c c_i (t_{lo} - t_{li}) \right]
\]

In the formula, \( W_2 \) is the heat capacity of low temperature waterside, \( W_2 = M_c c_i + M_b C_b \), where \( M_c \) is the quality of the chilled water, \( c_i \) is the heat capacity of chilled water.

The average temperature difference \( \Delta T_m \) takes for logarithmic mean temperature difference:

\[
\Delta T_m = \frac{t_{hi} - t_{li}}{\ln \frac{t_{ho} - t_{lo}}{t_{ho} - t_{li}}}
\]

Type (1) (2) and (3) is the mathematical model of heat transfer for air coolers. \( W_1, W_2 \) in the type can be calculated in the specification of the air coolers.

The prandtl number, motion viscosity, density and thermal conductivity of working medium affect the heat transfer and resistance properties of the heat exchanger. Prandtl number and movement viscosity of water decrease with the increase of water temperature, and thermal conductivity increased with the water temperature becomes larger [2-4]. Thus, with the coolant water temperature, the heat transfer coefficient becomes larger, while the resistance is smaller. Thus, the heat exchanger calculations, in which the working fluid is chilled water, can’t ignore the impact of water temperature. Usually, the parameters of water are taken as constant [5].

In the air-cooler, the process of heat transfer from the air flow to the chilled water, its thermal resistance include: the air side convection thermal resistance, the air side fouling resistance, thermal film thermal resistance, low-temperature chilled water side fouling resistance, chilled water side heat transfer resistance. Therefore, the overall heat transfer coefficient formula of the cooler is:

\[
\frac{1}{K} = \frac{1}{h_k} + r_1 + r_2 + r_3 + \frac{1}{h_i}
\]
In the formula: $K$ is the overall heat transfer coefficient of Cooler; $h_k$ is the heat transfer coefficient of Air-side; $r_1$ is the fouling resistance of Air-side; $r_2$ is the thermal resistance of thermal film; $r_3$ is the fouling resistance of low-temperature chilled water side; $h_f$ is the heat transfer coefficient of low-temperature chilled water side.

3.2. Mathematical model of compartment temperature

Compartment temperature is an important indicator of air-conditioned comfort. According to the conservation of energy, the energy into the room minus the energy outflow from the room at per unit time, equals to the indoor storage energy change rate. Then, can get the following equation \[^{[6-9]}\]:

$$Q_{in} + Q_{ex} + Q_{su} - Q_o = \left(V_r \rho_a\right) \times C_p \times \frac{dT_r}{dt}$$ \(5\)

In the formula: $Q_{in}$ is the internal heat source due to thermal cooling load including lighting, body heat and a variety of electrical equipment (such as computers, printers, etc.) cooling. The heat is nothing more than sensible heat and latent heat. The latent heat is calculated as instantaneous cooling load. The sensible heat is composed of the instantaneous and the delay cooling load; $Q_{ex}$ is the heat incoming from outdoor to air-conditioned room, therefore, this part of the cooling load is caused by solar radiation and the heat transfer near the cabin or the corridor;

$$Q_{ex} = \sum_{i=1}^{6} Q_{ex_i}$$ \(6\)

In the formula: $Q_{ex_i}$ is the solar radiation heat absorbed by compartment wall and cooling load or cooling load caused by air heat transfer in the cabin area or corridor

$$Q_{ex_i} = F \times \lambda \times (T_w - T_r)n + F \times \lambda \Delta T_y$$ \(7\)

In the formula: $F$ is the wall area; $\lambda$ is the transfer coefficient of the wall medium; $T_w$ is the temperature close to the compartment or corridor; $n$ is the correction factor for the temperature difference; $\Delta T_y$ refers to solar radiation.

In the formula: $Q_{su}$ is the energy which brings by the air through the cooling:

$$Q_{su} = K \times V_{su} \times (T_{su} - T_r)$$ \(8\)

In the formula: $V_{su}$ is the air supply; $T_{su}$ is the supply air temperature; $K$ is the capacity factor of the supply air:

$$Q_o = M \times C_p \times (T_r - T_{rt})$$ \(9\)

In the formula: $T_r$ is the room temperature; $T_{rt}$ is the return air temperature.

4. Simlink Block Diagram

4.1. Air cooler model block diagram
Adjust algebraic equations and differential equations from (1) to (4) so as to get the air conditioner module simulation model, including air cooler simulation model and air heater simulation model. Here is the simulation model of air cooler. The simulation model for air heater and air cooler is similar to each other, so just make the appropriate adjustments to change the corresponding parameters.

**Input:** $t_{h0}$, $m_1$, $t_i$, $m_2$;
**Coefficient:** $W_1$, $W_2$, $K$, $A$;
**Output:** $t_{ho}$, $t_{lo}$.

Air cooler input and output parameters simplified diagram are shown in Figure 2. Simulink simulation model of air cooler module shown as in Figure 3.

4.2. **Air cooler model block diagram**

Adjust cabin temperature all the algebraic equations and differential equations from (5) to (9) to get the simulation model.

**Input:** $T_{su}$, $V_{su}$;
**Coefficient:** $K$, $C_p$, $\rho_a$;
**Output:** $T_r$. 

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**Fig. 2 Air cooler parameters**

**Fig. 3 Modular model of air-cooler**

**Fig. 4 Cabin Parameters**
The input and output parameters Air conditioning compartment simplify the diagram shown as in Figure 4. The input and output parameters Air conditioning compartment simplify the diagram shown as in Figure 5.

![Fig. 5 Modular model of Cabin temperature](image)

5. Simulation results analysis

Simulation results as follows based on main parameters of mathematical model, Simlink block diagram and the “Yu Kun” air conditioning system above in Table one.

<table>
<thead>
<tr>
<th>Name of parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Name of parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh air flow of per person in individual cabin</td>
<td>25</td>
<td>m³/h</td>
<td>Fresh air flow of per person in individual cabin</td>
<td>25</td>
<td>m³/h</td>
</tr>
<tr>
<td>Fresh air flow of per person in public cabin</td>
<td>15</td>
<td>m³/h</td>
<td>Temperature of cooling water inlet</td>
<td>36</td>
<td>ºC</td>
</tr>
<tr>
<td>Compressor refrigerating capacity</td>
<td>235</td>
<td>kw</td>
<td>Temperature of cooling water outlet</td>
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<td>ºC</td>
</tr>
<tr>
<td>Heat transfer capacity of condenser</td>
<td>320</td>
<td>kw</td>
<td>Condensing temperature</td>
<td>45</td>
<td>ºC</td>
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<tr>
<td>Heat transfer capacity of condenser of evaporator</td>
<td>470</td>
<td>kw</td>
<td>Cooling water Consumption</td>
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<td>m³/h</td>
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<tr>
<td>Chilled water flow</td>
<td>67.3</td>
<td>m³/h</td>
<td>Flow of Chilled water circulating pump</td>
<td>70</td>
<td>m³/h</td>
</tr>
<tr>
<td>Pressure head of Chilled water circulating pump</td>
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<td>m</td>
<td>Design temperature of chilled water inlet</td>
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<td>ºC</td>
</tr>
<tr>
<td>Design temperature of chilled water outlet</td>
<td>12</td>
<td>ºC</td>
<td>Heating steam pressure</td>
<td>4</td>
<td>kg</td>
</tr>
</tbody>
</table>

Figure 6 shows the temperature curve of the air-cooler chilled water and air out. Air inlet temperature is 34 ºC, chilled water inlet temperature is 16 ºC. The figure formed that air outlet temperature is about 24 ºC, and chilled water outlet temperature is about 17 ºC, basically consistent with the thermodynamic calculation. There are some fluctuations in the temperature, within the scope of allowable error.

Figure 7 is the temperature curve of cabin, the room selected is the Chief Office cabin. The parameters can get from the appendix, Chief Office compartments Specifications. The initial temperature is 32 ºC. Supply air temperature is 23.8 ºC. As can be seen from the graph, from 0 to 1500 seconds, temperature...
drop is in a faster rate. Nearly after 2000 seconds, the supply air temperature is close to the room temperature, consistent with air-conditioning compartment situation.

In this simulation model, the supply air temperature $T_{su}$ is given, but the cabin temperature $T_r$ is obtained from the simulation curve. Figure 7 shows when the supply air temperature is 32 $^\circ$C, its cabin temperature $T_r$ is 24.5 $^\circ$C from which the temperature difference between the air temperature and indoor temperature can be calculated as the formula $\Delta T = T_{su} - T_r = 10 \, ^\circ$C (K), which meet the technical requirements $dT = 10K$ from the "Dalian Maritime University teaching practice Marian air conditioning, refrigeration technical agreement" [10]

**6. Conclusion**

This paper makes a detailed introduction about the technical requirements and operating principle for the Marine air conditioning and has established mathematical model for cabin cooling in the summer, and then verified this model taking the example of "Yu Kun" Chief Officer compartment, proved that the model is reliable.

The modeling and simulation of Marine air conditioning system concern much ancillary equipments and great variety of knowledge. It not only contains the thermodynamics, kinetics, heat transfer, but also control technique, simulation technology, computer technology and so on. But due to the time constraints and limited knowledge, there still need many improvements for the Marine air conditioning modeling and simulation. As some simulation parameter data is hard to get, all the parameters base on experience, inevitably to be inaccurate. As a result, more precise parameters are in need to make the model work practically

**References**

[1] Qian Fei, Shixun Lu, Shipping auxiliary, China Dalian, Dalian Maritime University Press, 2001


[10] Shanghai ship design institute, Dalian Maritime University teaching practice Marian air conditioning, refrigeration technical agreement, China Shanghai, Shanghai ship design institute, 2005.

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