Analysis of Thermal Characteristics of Airborne Integrated Environmental Control System

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Abstract. Taking the simplified airborne integrated thermal management system as the research object, the change characteristics of the system under different control modes are analyzed, which provides a theoretical basis for the study of system control schemes. Using a combination of mathematical models and computer models to establish an integrated airborne thermal management system model with fuel as the main heat sink, air/fuel heat exchanger, fuel/PAO heat exchanger and other main components, and a fuzzy self-tuning PID control method is proposed to analyze system characteristics such as fuel/PAO heat exchanger and electronic equipment thermal changes. The results show that compared to open-loop control under thermal extreme conditions, the fuzzy self-tuning PID control mode can not only effectively control a series of equipment such as fuel pumps to maintain proper speed, but also ensure the electronic cabin and fuel/PAO heat exchanger the outlet temperature is kept within a predetermined range to meet the design requirements of the onboard thermal management system.

Keywords: Airborne integrated environmental control system, primary air heat exchanger, secondary air heat exchanger, thermal characteristics, thermal limit conditions.

1. Introduction

With the development of aircraft, more and more electronic devices are carried on the aircraft, and the heat generated by them is also increasing. Once the heat generated by the device cannot be released in time, it will have a great impact on the performance of the electronic device. Moreover, when the altitude and speed of the aircraft change, the flow and temperature of the impacting air will also change in actual flight, which will affect the thermal load of electronic equipment and other factors [1-2]. Therefore, how to efficiently use the limited heat sink on board to realize the collection, transmission and dissipation of heat is one of the contents urgently needed for research [3].

In foreign countries, the integrated environmental control system, as the key research technology of the third phase of the US Integrated Aircraft Energy Technology (INVENT) program, greatly reduces the total thermal load, reduces energy consumption, and finally achieves the goal of energy optimization [4-8]. Domestically, Xu Zhiying et al. proposed an aircraft system simulation model, and studied the flow, pressure, temperature and heat of each part of the aircraft fuel system through...
calculation simulation [9]; Ma Desheng et al. designed and built a new type of aircraft environment Thermal management system [10]; Yu Xikui and others took supersonic aircraft as the research object, built a simplified aircraft thermal management model, and discussed its thermal control strategy [11].

This paper takes the F-22 integrated environmental control system as a reference, designs and builds a simplified airborne integrated environmental control system model. Based on this model, the influence of the thermal load on the electronic equipment and other system thermal characteristics of the design model under the thermal limit condition of the ground temperature of 40℃ is discussed.

2. Airborne integrated environmental control system

2.1. System description

The schematic diagram of the airborne integrated environmental control system built in this article is shown in Figure 1. The whole system consists of four circuits, namely: evaporation circulation circuit, air circulation circuit, high temperature PAO circuit and low temperature PAO circuit. The cross-linking interface of the four circuits includes: air/PAO heat exchanger, evaporator and condenser, etc. The working process of the system is shown in Figure 1.

1) Air circulation circuit: the high temperature and high-pressure ram air starts from the engine, passes through the air/PAO heat exchanger, compressor for compression, and turbine for expansion and cooling. Finally, the ram air is cooled by an air condenser, and finally enters the electronic compartment A, so as to realize the cooling function of electronic equipment.

2) Evaporation circulation loop: The evaporation loop mainly uses the phase change process of refrigerant R134a for heat exchange, and the heat load generated by the electronic cabin B absorbed from the low-temperature PAO circulation loop. Pass through the condenser to the high temperature PAO circulation loop. The red line in the figure is the cooling backup circuit. When the evaporation circuit fails, the evaporation circuit will not be able to provide a cold source for the electronic cabin B. At this time, the low-temperature PAO circuit and the high-temperature PAO circuit will reconstruct the circuit through the tangential valve. Use high temperature pump or low temperature pump to deliver refrigerant PAO to cool the electronic cabin.

![Figure 1. Airborne integrated thermal management system model](image-url)
3) High temperature PAO circulation loop: The high temperature PAO circulation loop first absorbs heat from the evaporation loop through the condenser, then absorbs heat from the air circulation loop through the air/liquid heat exchanger, and finally transfers it to the fuel through the fuel/PAO heat exchanger.

4) Low-temperature PAO circulation loop: The refrigerant PAO of the low-temperature PAO circulation loop directly exchanges heat with electronic cabin B, and transfers the heat load of electronic cabin B to the evaporation circulation loop through the evaporator.

3. Airborne integrated environmental system modeling

3.1. Air circulation loop modeling

The two-wheel booster air circulation system is a modification of the booster air circulation refrigeration system. It is the most widely used aircraft air circulation system, such as F-18 fighter jets, T46A trainers, and Boeing 737 airliners. This kind of system, most of the aircraft produced in my country also use this kind of environmental control system [15-17]. This article refers to this system to model the airborne environmental control system.

3.1.1. Modeling of primary heat exchanger. In this model, the primary heat exchanger is composed of two mixed gas semi-heat exchangers and a heat flow efficiency calculation control. The model design is as follows:

Due to the wide variety of fins in the heat exchanger, the model uses equivalent heat exchange area

![Figure 2. Modeling of primary heat exchanger to replace various types of heat exchange fins](image)

The model is shown in Figure 3: The figure is divided into direct exchange surface (direct exchange surface) and indirect heat exchange surface (in-direct exchange surface), and the heat transfer efficiency of the fins (Heat transfer efficiency) and the overall heat transfer area (exchange surface). The mathematical model is:

\[ esarea = shxiarea + shxdarea \]

\[ effte = \frac{shxiarea}{esarea} \]  \hspace{1cm} (1)\]

Among them: \( esarea \) is the overall heat exchange area, \( shxiarea \) is the heat exchange area of the non-direct contact heat exchange surface; \( shxdarea \) is the heat exchange area of the direct contact heat exchange surface, \( effte \) is the fin heat exchange efficiency.
Figure 3. Diagram of equivalent heat transfer model

The mathematical model is as follows: the airflow heat capacity of the interface 1, 2 can be calculated as

\[ c_1 = d_{m1} \cdot c_{p1} \]
\[ c_2 = d_{m2} \cdot c_{p2} \]  \hspace{1cm} (2)

Among them:
- \( c \) is the specific heat capacity of each interface,
- \( d_m \) is flow rate generated by fluid 1 for each interface
- \( c_p \) is the constant pressure specific heat capacity of the fluid at each interface

And then, we can get the maximum and minimum \( c_{\text{min}} \) of \( c_1 \) and \( c_2 \). Considering the influence of the quality of the heat exchanger on the thermal fluid, the mathematical model of the heat flow value is:

\[ \phi_{1,\text{trans}} = a c_1 (T_{\text{wall}} - T_1) \]  \hspace{1cm} (3)
\[ \phi_{2,\text{trans}} = a c_2 (T_{\text{wall}} - T_2) \]  \hspace{1cm} (4)

\( T_{\text{wall}} \) is the tube wall temperature during heat exchange. The wall temperature \( T_{\text{wall}} \) needs to be calculated according to the instantaneous energy conservation equation, and its mathematical model is:

\[ \frac{dT_{\text{wall}}}{d_t} = \frac{\phi_{1,\text{trans}} + \phi_{2,\text{trans}}}{\text{mass} \cdot c_p} \]  \hspace{1cm} (5)

Among them:
- \( \text{mass} \) is the mass of the heat exchanger, which is the specific heat of the solid quoted by the solid type index at a certain temperature.
- Finally, we can use the NTU method to calculate the heat transfer efficiency as:

\[ \varepsilon = \frac{\text{MAX} (|\phi_{1,\text{trans}}|, |\phi_{2,\text{trans}}|)}{C_{\text{min}} \cdot (T_2 - T_1)} \]  \hspace{1cm} (6)

3.1.2. The overall model of the air circulation loop. The working process of the air circulation loop is as follows:
First, the bleed air will exchange heat with the ram air through the primary heat exchanger for preliminary cooling, and then the bleed air will enter the compressor for pressurization. Then, let it enter the secondary radiator and ram air for further heat exchange, so as to further cool the bleed air.
The cooled bleed air will enter the hot side of the regenerator, and then pass through the condenser to reduce the temperature of the bleed air. At this time, a large amount of moisture is generated due to the low temperature of the lead. Therefore, let the bleed air enter the water separator to separate most of the moisture in it, and then let the high-pressure air after separating the moisture enter the regenerator for heating, thereby further evaporating the moisture in the air. At this time, the bleed air becomes a dry, high-pressure saturated gas. Then it enters the turbine to perform expansion work, so that the temperature and pressure of the bleed air are reduced, and then through the heat exchange of the cold side of the condenser, the air meets the temperature design requirements for the cooling function of the electronic cabin. The AMEsim modeling simulation model is shown in Figure 4:

![Air circulation circuit model](image-url)

**Figure 4.** Air circulation circuit model

Although there is no limit to the complexity of the system established by the user in the Amesim software, in the modeling process, the higher the similarity between the model and the actual system, the better, but when the model is too complex, it will cause a huge amount of calculation, and due to the model, the matching problem between the two is prone to divergence in the built-in differential equations during the solution process, causing simulation failure. Therefore, in the simulation process, in order to improve the calculation efficiency of the simulation, some of the components were simplified without affecting the accuracy. These include:

1) Some complex components with small flow resistance are ignored in the system. Since these components will not have a major impact on the simulation results after they are ignored, the bends and joints in the pipeline are simplified, and the simulation model is established the more complicated valves and other components in the pipeline are omitted in the

2) The pipeline in the system is simplified, but in reality, the components in the pipeline will have an effect on the flow resistance of the pipeline system and other parameters. Therefore, in the process
of model establishment, the pipelines between the various components are first defined, including the length of the pipeline, flow resistance, and heat exchange with the outside to meet the system parameter requirements, but there are still some parameters that are still difficult to define.

4. Thermal characteristics analysis of the airborne integrated environmental control system

4.1. Model thermal analysis

4.1.1. Flight status and initial parameter settings. The flight envelope is mainly composed of five links, namely: ground maintenance, running, climbing, cruising, and landing [18]. The model mainly selects three main processes for simulation calculation, including: climb, cruise and landing process.

This article chooses to simulate under thermal extreme conditions: the ground temperature limit is 40°C, the flight limit altitude is 5000m, and the flight envelope is set as follows: reach the flight altitude 5000m at 1500s, then adjust to cruise mode, and land after cruising 3500s, Landing to the ground after 1000s. The model uses the AMEsim platform for simulation, and uses the fourth-order Runge-Kutta and fixed step size algorithm. The step size is 0.01 S, and the simulation time is set to 6000 S. The model parameter settings are shown in Figure 5.

| Title | Value | Unit | Name |
|-------|-------|------|------|
| Taxi out | 0 m | a1t2 |
| Take off 1 (until 100kts call) | 0 m | a1t4 |
| Take off 2 (until V1) | 0 m | a1t5 |
| Take off 3 (until Vf) | 0 m | a1t6 |
| Climb 1 (until lift off + 350 ft - screen height) | 10.668 m | a1t7 |
| Climb 2 (until lift off + 3500ft) | 5000 m | a1t8 |
| Cruise | 5000 m | a1t9 |
| Descent (until 50ft - Vref) | 15.24 m | a1t10 |
| Approach (until touch down) | 0 m | a1t11 |
| Landing (until last engine shut down) | 0 m | a1t12 |
| Taxi in (until last engine shut down) | 0 m | a1t13 |

Figure 5. Flight distance parameter Setting

4.1.2. Analysis of simulation results. The simulation results and analysis are as follows: Figure 6 and Figure 7 show the rotational speed characteristic curves of the heat dissipation pump and the hydraulic pump. They are affected by their respective control objectives. The speed of the heat dissipation pump and the liquid pump changes continuously over time. However, since each pump has a minimum speed, the speed of each pump reaches the minimum at the end of the time and remains unchanged.

From Figure 8 and Figure 9, we can see the changes in the outlet temperature of the electronic cabin B and the air/PAO heat exchanger. The dotted line is the upper temperature limit, and the black line is the simulation result. The results show that although the outlet temperature of the electronic cabin B and the air/PAO heat exchanger exceeds the upper temperature limit in a short period of time, they can meet the design temperature requirements most of the time, and the electronic cabin B and the heat exchanger can be used for a long time. The outlet temperature is maintained at the optimal design value of 35°C and 45°C. The results show that the system design parameters can basically meet the design control requirements, and the robustness is good.
Figure 6. Change of fuel pump speed in fuel circulation loop change diagram

Figure 7. Low-temperature PAO circulation circuit hydraulic pump speed

Figure 8. Air/PAO heat exchanger PAO refrigerant outlet temperature
5. Conclusions
This paper takes a simplified airborne integrated environmental control system as the research object, and uses AMEsim software to complete the design of the airborne integrated environmental control system, the construction of subsystems and the overall system model, and further analyze the thermal characteristics of the system. The study. Its main tasks are as follows:

1) The design of the model is completed. In response to the requirements of the airborne integrated environmental control system, five system sub-models were designed, including the evaporation loop, high temperature PAO loop, low temperature PAO loop, and air loop model, and an airborne integrated environmental control system model was designed.

2) Completed the model building and verification. The modeling work includes the following three aspects: the modeling of sub-controls, the establishment of the subsystem model, the establishment and packaging of the AMEsim model of the airborne integrated environmental control system.

3) Analyze the thermal characteristics of the environmental control model under thermal extreme conditions to explore the feasibility of model design. The design model can not only effectively control a series of equipment such as pumps, and ensure that these equipment maintain the appropriate speed, but also ensure that the temperature of the electronic equipment and the outlet of the heat exchanger can be stably maintained within a predetermined range during operation. Not only the robustness of the system output is better, but also the system design requirements are met.

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