Modeling and simulation of aircraft integrated thermal management system

LU Binbin, JI Honghu, TANG Mei, Wang Guofeng
Nanjing University of Aeronautics and Astronautics, Nanjing 210000, China
lbnnuaa@163.com

Abstract. The integrated thermal management system for a certain type of aircraft was studied. The integrated thermal management system, which takes fuel oil as the main heat sink, thermal protection structure and liquid evaporator as auxiliary heat sink, can comprehensively control and manage the heat of the whole aircraft. The mathematical model for simulation of integrated thermal management system was established. The simulation model of the system was built based on Flowmaster software for calculation. Results show that the system proposed in this paper can meet the overall thermal requirements of the aircraft, and provide a reference for the design of the aircraft integrated thermal management system and its subsystems.

1. Introduction
The integrated thermal management system is crucial to ensuring an acceptable operating ambient environment for airplane electromechanical equipments. The cabin must be neither too hot nor too cold regardless of the external thermal environment, which may change a lot during the whole flying range. A cabin with poor temperature control can lead to equipment failure or even an accident [1]. Besides, the engine system is designed to operate in a specified fuel temperature range. In order to meet the thermal design requirements of airplane systems, the management of heat dissipation over the whole aircraft is needed. The integrated thermal management system is to distribute and utilize the heat of the aircraft on the whole scale. Compared with the traditional environmental control system of the aircraft, it can distribute the heat more reasonably, absorb the heat of the parts that need to be cooled and preheat the fuel at the same time [2]. It can greatly improve the heat dissipation ability of the aircraft without introducing additional mass, so it has larger research space and application prospects.

Since the 1990s, many scholars have studied various aspects of the integrated thermal energy management system. Petley put forward the aircraft thermal energy management system with fuel cycle as the main cycle, and established the basic framework of the integrated thermal management system [3]. Qin studied the method to improve the heat sink utilization of fuel. Results show that the method to control of fuel mass flow rate or the height of cooling channel can effectively improve the fuel heat sink utilization [4].

At present, the research of integrated thermal energy management system is mostly focused on the subsystem, and there are few research about the whole system. This article studied the integrated thermal management system of a certain type of aircraft, aiming to provide reference for the design of integrated thermal management system and subsystem of aircraft.
2. Description of integrated thermal management system

2.1. Integrated thermal management system

As shown in Fig. 1, the external heat source of aircraft can be divided into two parts: aerodynamic heating and solar radiation. The internal heat source mainly comes from heat dissipation of airborne equipment. The integrated thermal management system can be described as follows: the system takes the thermal protection structure outside the fuselage as the first layer of heat sink, absorbs the aerodynamic heat and radiation heat from the outside. In terms of heat management inside the fuselage, it takes fuel as the main heat sink, and liquid evaporative cooling system as the auxiliary heat sink, so as to realize the comprehensive control of the heat of the whole machine. In the aspect of internal thermal control, fuel cycle is the main cycle. The temperature of equipment cabin is controlled by fuel cycle cooling system. When the temperature of equipment cabin exceeds the limit value, the valve of fuel cycle cooling system is opened to absorb the equipment heat during cabin. The fuel circulation system will absorb the heat dissipation of the subsystems such as lubricating oil and hydraulic oil, and eventually flow to the engine for combustion. The excess fuel will be cooled by ram air and liquid evaporator and then flow back to the fuel tank.

![Integrated thermal management system](image)

Figure 1. Integrated thermal management system

2.2. Simplification and assumptions

The flow and heat transfer process of aircraft in supersonic cruise is very complex. This paper focuses on the simulation calculation on system scale. To simplify the analysis, the analytical model is developed under the following assumptions:

1) The heat conduction in thermal protection structure is simplified to one-dimensional heat conduction along thickness direction.

2) Fuel is consumed at a constant mass flow rate and its temperature distribution is uniform at any time, changing only with time.

3) Ignoring the air flow in each equipment compartment, the temperature distribution is uniform at any time and only changes with time.

4) Fuel is used as heat sink to absorb the heat from insulation felt and airborne equipment to equipment cabin with fixed heat transfer coefficient.

3. Computational model

3.1. Aerodynamic heating

According to the theory of heat transfer and aerodynamic heating, an engineering algorithm can be used to estimate the aerodynamic heat outside the aircraft [5]. The aerodynamic heating of the intake port can be calculated with constant wall temperature as the boundary condition. For the laminar, the heat flux can be estimated by [6]:

\[
q = \frac{1}{2} \rho v^2 C_d A \cos \theta
\]
where $Pr$ is the Prandtl number; $\rho$ is the density of airflow; $v$ is the velocity of airflow; $Re$ is the local Reynolds number; $h$ is the enthalpy of airflow; $\mu$ is the viscosity of airflow. The subscript $e$ means the quantities in the boundary layer edge condition and the subscript $*$ means the quantities at reference temperature.

As for the turbulence, the heat flux can be given by:

$$q_w = 0.0296 Pr^{0.8} \rho v Re^{0.2} (h_t - h_w)^{0.8} \left( \frac{\rho e}{\rho e} \right)^{0.2}$$

3.2. Solar radiation
The heat flux of solar radiation fluctuates little in a year and can be considered as a constant [7]. The solar constant equals to 1367 W/㎡.

3.3. Thermal protection structure
The heat transfer form of thermal protection structure is similar to that of one-dimensional infinite plate. Combining with the boundary conditions of external heat source, the first-order difference method is adopted to solve the heat transfer problem of thermal protection structure.

3.4. Cabin model
The heat transfer in equipment cabin can be calculated by lumped parameter method. According to the closed system energy equation, the heat balance equation in the cabin can be obtained as follows:

$$c_m c_c \frac{dT}{dt} = \frac{\delta Q_{top,c}}{dt} + \frac{\delta Q_{bot,c}}{dt} + \frac{\delta Q_{e}}{dt} - \frac{\delta Q_{c}}{dt}$$

where $m_c, c_c, T_c$ is the mass, specific heat and temperature of cabin air; $\delta Q_{top,c}, \delta Q_{bot,c}$ is the heat flow conducted by thermal protection structures of cabin at the top/bottom; $\delta Q_e$ is the heat released by the equipment during cabin; $\delta Q_{ep,c}$ is the cabin heat absorbed by liquid evaporator; $\delta Q_c$ is the cabin heat absorbed by fuel.

3.5. Fuel tank model
According to the energy equation of the open system, the heat balance equation of the fuel tank can be obtained as follows:

$$m_f c_f \frac{dT_f}{dt} = \frac{\delta Q_{in}}{dt} + \frac{\delta Q_{top,f}}{dt} + \frac{\delta Q_{bot,f}}{dt} + \frac{\delta Q_c}{dt} - \frac{\delta Q_{ep,f}}{dt} - \frac{\delta Q_{out}}{dt}$$

where $m_f, c_f, T_f$ is the mass, specific heat and temperature of cabin air; $\delta Q_{in}, \delta Q_{out}$ is the heat carried by the inflow/outflow at a given time; $\delta Q_{top,f}, \delta Q_{bot,f}$ is the heat flow conducted by thermal protection structures of cfuel tank at the top/bottom; $\delta Q_c$ is the cabin heat absorbed by fuel; $\delta Q_{ep,f}$ is the fuel heat absorbed by liquid evaporator.

3.6. Liquid evaporator
The energy balance equation of coolant in liquid evaporator is as follows:

$$Q_{ep} = \dot{m}_{ep} \cdot \gamma$$
where $Q_{ep}$ is cooling power for liquid evaporator; $\dot{m}_{ep}$ is the mass flow rate of coolant; $\gamma$ is the latent heat of vaporization.

3.7. Subsystem heat dissipation
In order to simplify the calculation, the subsystems mentioned in this paper, such as lubricating oil and hydraulic oil, are calculated by means of thermal load.

4. Simulation and analysis

4.1. Simulation condition
The simulation was carried out based on Flowmaster software. The thermal management system performance was studied under the typical takeoff to cruise conditions. The flight altitude is stable at 7000m. The flight Mach number rises rapidly from $Ma=0.7$ at $t=0s$ to $Ma=3.5$ when $t=67s$. Then, the aircraft keeps cruising till $t=3600s$. The thermal design requirement of the system is that the fuel temperature flowing to the engine should not exceed 150°C, and the temperature of the cabin should not exceed 100°C. Other parameters are shown in Table 1.

| Parameter | Values |
|-----------|--------|
| Thermal protection structure | Thickness/mm 10, Initial temperature/°C 0 |
| Cabin | Initial temperature/°C 5 |
| 1# Equipment heat/kW 3.442, 2# Equipment heat/kW 0.424, 3# Equipment heat/kW 0.789 |
| Fuel tank | Initial temperature/°C 20, Fuel mass/kg 2200, Flow rate to engine/(kg/s) 0.61 |
| Liquid evaporator | 1# working power/kW 28, 2#working power/kW 10 |
| Subsystem heat dissipation | Lubricating oil system/kW 35.22, Hydraulic oil system/kW 12.31, Stamping air cooling system/kW 5 |

4.2. Simulation results

![Figure 2. Temperature distribution of thermal protection structure above the cabin](image-url)
Fig. 2 shows the temperature distribution of thermal protection structure above the cabin. As shown in the figure, the temperature of external node and internal node of thermal protection structure is 526℃ and 256℃ respectively, and the difference is 270℃. Thermal protection structure can effectively isolate external aerodynamic heating and solar radiation. Fig. 3 shows the temperature variation during cabin 1, 2 and 3. As can be seen from Fig. 3, the temperature of cabin 1, 2 and 3 is kept within 100℃ for the whole flight, and the integrated thermal management system can keep the working temperature of cabin within an appropriate range. Fig. 4 shows the temperature at each node in the fuel cycle system. It can be seen from Fig. 4 that under the framework of integrated heat/energy management, fuel can absorb the heat of subsystems in the system, preheat the fuel, finally flow to engine and burn. Taking the fuel as heat sink, the system has realized the complementarity of the aircraft internal energy. Under the effect of liquid evaporation system, the fuel temperature flowing to the engine does not exceed 150℃, which meets the working temperature requirement of the engine system.

5. Conclusions
In order to study the system performance of the integrated thermal management system, a simulation model of the system for a certain type of aircraft is established and calculated. The results show that the comprehensive thermal energy management scheme with fuel as the main heat sink, thermal protection structure and liquid evaporator as the auxiliary heat sink can meet the working requirements of the whole system. Thermal protection structure can isolate a large number of external heat sources, fuel circulation provides a large number of heat sink, liquid evaporator can be used as a supplementary heat sink when the fuel heat sink is insufficient. Under the combined control of various systems, the energy inside the aircraft is comprehensively utilized.

References
[1] Ahlers M. Aircraft Thermal Management: Systems Architectures[M]. SAE, 2016.
[2] Liu S, Zhuang D, Wanyan X. Simulation of Aircraft Fuel Thermal Management System Based on Simulink[J]. 2011.
[3] Petley D H, Jones S C. Thermal Management for a Mach 5 Cruise Aircraft Using Endothermic Fuel [J]. Journal of Aircraft. 1992, 29(3): 384-389.
[4] Qin J, Zhang S, Bao W et al. Thermal management method of fuel in advanced aeroengines[J]. Energy, 2013, 49:459-468.
[5] Zhao J S, Gu L X, Ma H Z. A rapid approach to convective aeroheating prediction of hypersonic vehicles[J]. Science China Technological Sciences, 2013, 56(8):2010-2024.
[6] Kamezawa H, Ruffin S M. Approximate Convective Heat Flux Calculation Methods for Hypersonic Vehicles[C]//2018 AIAA Aerospace Sciences Meeting. 2018: 0244.
[7] Yadav A K, Chandel S S. Solar radiation prediction using Artificial Neural Network techniques: A review[J]. Renewable & Sustainable Energy Reviews, 2014, 33(2):772-781.