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Conditional extremum optimization analyses and calculation of the active thermal control system mass of manned spacecraft

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HIGHLIGHTS

- The model for the lightweight optimization of ATCS in manned spacecraft is set up.
- The ATCS mass equation is established with the governing equations from energy conservation analyses as constraints.
- The optimization equations are solved by the Newton iterative method.
- The effects of influencing parameters on the system mass are discussed.
- There is always a power consumption value that leads to the minimum system mass.

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ABSTRACT

The global lightweight optimization of the active thermal control system (ATCS) is of great importance to the manned spacecraft. The governing equations for the parameters that should be optimized for the minimum mass of the ATCS with dual liquid loops are established based on the energy conservation analyses, which makes the lightweight optimization become a conditional extremum problem. The ATCS mass equation is set up. The optimization equations are formulated by pursuing the extremum value of this mass equation and solved by the Newton iterative method. The optimization results for a typical ATCS in manned spacecraft are presented and the effects of the influencing parameters on the system mass are discussed. The results show that there is always an optimal value of the power consumption that leads to the minimum system mass, and the decrease in the specific mass of the power system leads to the reduction of the minimum system mass. The minimum system mass will reduce remarkably with decreasing total heat load or increasing working temperature of the thermal devices within a certain range.

1. Introduction

In manned spacecraft, the thermal control system (TCS) is indispensable for maintaining the appropriate temperature for the astronauts and apparatuses [1,2]. Its design is of great significance to the performance of the spacecraft and has attracted great attentions [1–8].

The TCS always occupies quite a few proportions in the total mass of the spacecraft, which directly affects the launching cost and working performance of the spacecraft [9–11]. Mark and David [11] pointed out that the objective of the TCS design should be lightweight in 1985. During the last decades, many relevant studies for the lightweight design were carried out [9–22].

The TCS in spacecraft is commonly categorized as passive TCS and active TCS (ATCS). The passive TCS has been used in almost all the spacecrafts because it is simple and reliable [1]. For instance, the lightweight, high performance heat pipe system is extraordinary as a passive TCS and has great potential in the spacecraft application [14]. However, for the applications with environmental extremes or high heat dissipation, the ATCS is the dominant choice for the thermal bus, especially for large space platforms [6] due to its high abilities in heat transfer and temperature control [1,2]. Dual liquid loop configurations of the ATCS are very often adopted in manned spacecrafts. The inner loop liquid uses the coolant that is harmless to the health of astronauts in case of leakage and the external loop should use the coolants that have low freezing point and high heat capacity, such as the ATCS design of ISS [7], space shuttle [8], and HERMES [12,13].

Efforts have also been made on the lightweight design of the ATCS with dual liquid loops. For instance, Zhang et al. [15] optimized

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the flow distribution coefficient to reduce the mass of the parallel thermal network in ATCS with liquid loop by using the nonlinear mathematical programming method. However, it is hard to apply this method to complex parallel thermal networks because of the complexity and large amount of calculations. Cheng et al. [16–18] applied another two methods, the variable substitution method and the Lagrange multiplier method, to optimizing the parallel thermal networks. Efforts were also made on the lightweight design of the other components in the ATCS with liquid loop. For instance, the lightweight radiators were developed by using advanced materials [19–21], the heat exchangers were optimized by improving their operating parameters [22,23], etc. These investigations focused on the lightweight designs of the components of ATCS and are not for the overall optimization of ATCS mass.

The global lightweight analyses of the whole ATCS are much more complicated. Malozemov et al. [24] investigated the mass and power optimizations of the ATCS for long term spacecraft in which the state parameters and the reliability of the instrument and equipment were taken as the constraint condition. However, the detailed model and method were not mentioned. Zhang et al. [25,26] established the mathematical model of the ATCS with dual liquid loops in the spacecraft, and attempted to solve the global lightweight point by the directly searching method. Such a searching calculation may not be very efficient for complex systems with multiple variable parameters. Therefore, it is worth making further investigations on the lightweight optimization of the ATCS.

The ATCS with dual liquid loops is analyzed in this paper. The system parameters are optimized under conditional extremum for the global lightweight optimization of the system by the Newton iterative method. The influencing factors on the lightweight optimization, such as the power consumption, the heat loads, etc., are discussed.

2. Model and theoretical analyses

2.1. Model of the ATCS with dual liquid loops

The configuration of the ATCS with dual liquid loops is shown in Fig. 1. The system is mainly composed of the internal and external loops, and some accessories. In the ATCS, heat flow Q_0 from the spacecraft cabin is transferred to the internal loop through heat exchanger 1 (HE_1), and heat flows Q_1 and Q_2 from thermal devices 1 and 2 are transferred to the internal loop through cold plates 1 and 2. The internal and external loops are coupled by interface heat exchanger 2 (HE_2) through which heat is exchanged between the internal loop and the external one. Finally, all the waste heat from the external loop is released to the outer space through the radiator. The coolants in the internal loop and external loop are respectively driven by pumps 1 and 2 whose powers are provided by the power system. The mass flow rates through the two cold plates are distributed by the valve located at the outlet of HE_1.

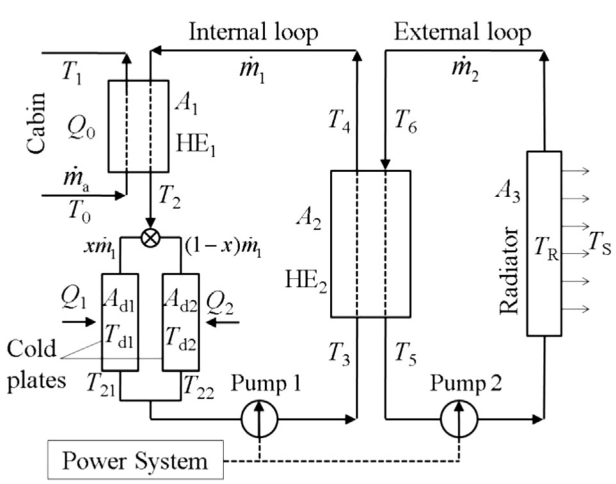

Fig. 1. Configuration of the ATCS with dual liquid loops.

Due to the requirements on the comfort of astronauts and reliability of apparatuses, the air temperature in the spacecraft cabin, T_0, and the working temperatures of the thermal devices, T_{d1} and T_{d2}, are fixed. The total power consumption of the ATCS is limited because it depends on how much power can be supplied by the power system. The objective of this problem is to obtain the optimal system parameters that lead to the minimum mass of the ATCS, such as the mass flow rates of the loop coolant, the flow distribution, the diameters of the loop pipes and the areas of the heat exchangers, cold plates and radiator.

2.2. Energy conservation analyses

2.2.1. The counter flow heat exchanger

For the counter flow heat exchanger in Fig. 2, the heat flow from the hot stream to the cold one is

$$Q_e = \dot{m}_h c_h (T_{h-i} - T_{h-o}) = \dot{m}_c c_c (T_{c-o} - T_{c-i}), \tag{1}$$

where $\dot{m}$ is the mass flow rate, c is the specific heat capacity, T is the temperature, subscripts h and c represent the hot and cold streams, respectively, while i and o represent the inlet and outlet, respectively.

On the other hand, according to the logarithmic mean temperature difference method [27], Q_e can be calculated by

$$Q_e = kA \frac{T_{h-i} - T_{c-o} - T_{h-o} + T_{c-i}}{\ln[(T_{h-i} - T_{c-o})/(T_{h-o} - T_{c-i})]}, \tag{2}$$

where k is the heat transfer coefficient, and A is the heat transfer area. Combination of Eqs. (1) and (2) leads to

$$T_{h-i} = \frac{Q_e/(\dot{m}_h c_h) - Q_e/(\dot{m}_c c_c)}{1 - e^{-kA\left(\frac{1}{\dot{m}_h c_h} - \frac{1}{\dot{m}_c c_c}\right)}} + T_{c-o}. \tag{3}$$

2.2.2. The ATCS with dual liquid loops

Based on Eq. (3), for the internal loop heat exchanger HE_1, there is

$$T_0 = \frac{Q_0/(\dot{m}_a c_a) - Q_0/(\dot{m}_1 c_1)}{1 - e^{-k_1 A_1\left(\frac{1}{\dot{m}_a c_a} - \frac{1}{\dot{m}_1 c_1}\right)}} + T_2, \tag{4}$$

where Q_0 is the heat flow from the cabin; T_0 is the air temperature in the cabin; T_2 is the outlet coolant temperature of HE_1; $\dot{m}_a$ and $\dot{m}_1$ are the mass flow rates of the air and the coolant through HE_1; k_1 is the heat transfer coefficient, and A_1 is the heat transfer area of HE_1, respectively.

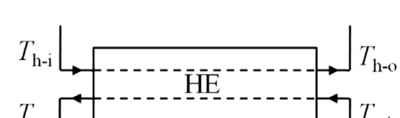

Fig. 2. Sketch of the counter flow heat exchanger.