

# Performance analysis of aircraft low-power thermoelectric refrigeration system

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**Abstract:** An optimal design method for an aircraft low-power thermoelectric refrigeration system (TRS) is proposed using an existing experimental model as the research platform under given aircraft flight conditions. The variation curves of the cooling capacities and the refrigeration coefficients of the system running at three flight altitudes are investigated. The performance of the system is evaluated by the minimum-entropy-generation method and the performance penalty is also calculated. The power variation curves of the cooling system are obtained by an electric power experiment. The peak values of these curves are less than the maximal electric power supply of airborne equipment, proving that the use of the low-power TRS for airborne equipment is feasible. The COP, cooling capacity and entropy generation of the system are relative to the flight altitude and the current of the TRS. Through the analyses of these data, the optimal values of the COP are obtained, and the optimization measures are proposed to maximize the use of the advantages of the TRS.

**Key words:** thermoelectric refrigeration; entropy generation analysis; aircraft cooling system; performance penalty

A thermoelectric refrigeration system (TRS) is a semiconductor refrigeration system with the application of thermoelectric effects. When a direct current is entered into a loop which is composed of two different materials, the heat transfer between the two joints, the basis of thermoelectric refrigeration, occurs. Thermoelectric materials have a high thermoelectric potential. An n-type semiconductor and a p-type semiconductor can be connected by a brass slice. Subsequently, one joint becomes hot and the other becomes cold. The two connecting joints compose a thermoelectric refrigerating unit.

Compared with other cooling systems, the TRS has special characteristics, such as a small dimension and a long life<sup>[1-2]</sup>.

## 1 Design Conditions of TRS

The schematic diagram of an TRS for aircraft is shown in Fig. 1. Using the ambient ram air as a heat sink, the TRS absorbs the heat of the electronic components by thermal conduction. On the basis of the GJB181 standards and the ISO standards for characteristics of electric systems for aircraft, the power supply system is identified. Other design parameters are listed in Tab. 1<sup>[3]</sup>.

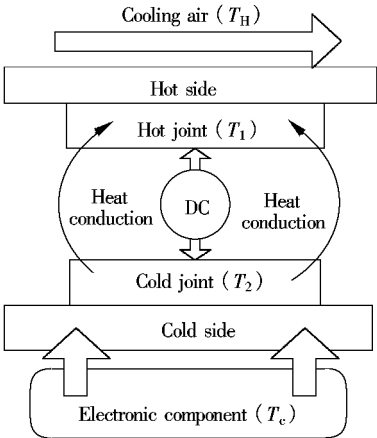


Fig. 1 Schematic diagram of TRS

Tab. 1 Design parameters of TRS

Parameter	Value
Transfer heat/W	100
Cold side temperature/K	290
Thermoelectric power/(mV·K <sup>-1</sup> )	0.15
Heat transfer coefficient of equipment/(W·K <sup>-1</sup> )	0.1
Heat transfer coefficient of radiation/(W·K <sup>-1</sup> )	0.01

## 2 Performance Analysis of Cooling System

### 2.1 Cooling capacity and COP

According to thermocouple analyses, we obtain the following equations<sup>[4]</sup>:

$$Q_1 = Q_H + Q_L = W + Q_2 \tag{1}$$

$$Q_2 = Q_C + Q_L \tag{2}$$

where  $Q_1$ ,  $Q_2$ ,  $Q_C$ ,  $Q_H$ ,  $Q_L$  are the heat transfers in the hot joint, the cold joint, the cold side, the hot side and the thermal-arm, respectively;  $W$  is the electric-power.

Furthermore, based on the knowledge of thermodynamics and thermoelectric refrigeration, we obtain

$$Q_L = K_L (T_1 - T_2) \tag{3}$$

$$Q_H = K_H (T_1 - T_H) \tag{4}$$

$$Q_C = K_C (T_C - T_2) \tag{5}$$

$$Q_1 = \alpha I T_1 + \frac{1}{2} I^2 R \tag{6}$$

$$Q_2 = \alpha I T_2 - \frac{1}{2} I^2 R \tag{7}$$

$$W = \alpha I \Delta T + I^2 R \tag{8}$$

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$$\varepsilon = Q_c / W \quad (9)$$

where  $\alpha$  is the thermoelectric power;  $K_H$ ,  $K_C$ ,  $K_L$  are the heat exchange coefficients of the hot side, the cold side and the thermal-arm, respectively;  $I$  and  $R$  are the current and the resistance, respectively;  $\Delta T$  is the temperature difference between the hot side and the cold side;  $\varepsilon$  is the COP.

During the process of analyzing the TRS, three states of altitude with different flight velocities are chosen. The atmospheric temperature is lower than 15 °C. And the temperature correction is

$$T' = T_0(1 + 0.2Ma^2) \quad (10)$$

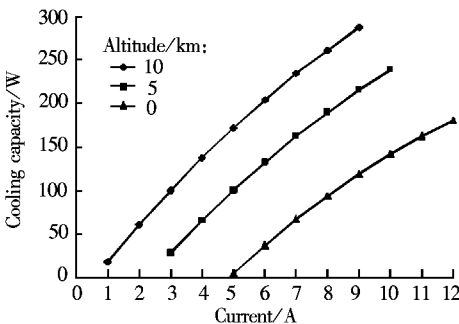
where  $T'$  is the stagnation temperature;  $Ma$  is the Mach number used for scaling the flight velocity.

The particular parameters are listed in Tab. 2. The states of altitude shown in Tab. 2 are selected as the design points. According to the demands of high altitude, a TRS which has a maximal COP is designed. Then, the current of the TRS and the temperature of the hot side are adjusted to analyze the performance of the TRS.

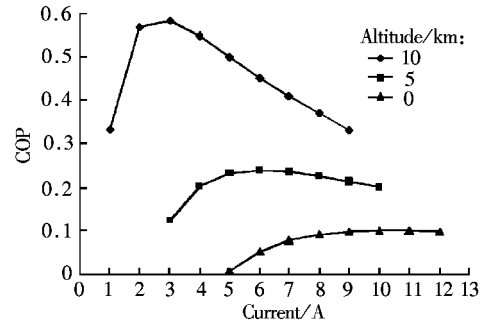
**Tab. 2** Conditions of aviation at different altitudes

Altitude/km	$Ma$	$T'/K$
0	0.1	290
5	0.5	275
10	1	260

The change in the cooling capacity with the current of the TRS is depicted in Fig. 2. Correspondingly, the relationship between the current of the TRS and the COP is shown in Fig. 3. It can be seen that with the increase in the current of the TRS, the COP increases first and then decreases. Especially under the design condition, the COP reaches a maximum value of 0.58. It means that this project can make full use of the electricity supply. At the same time, the maximal cooling capacity can achieve 300 W, indicating that the current of the TRS can be increased for a short period under some special conditions to obtain more cooling capacity. During flight at a low altitude, the performance of the cooling system, the cooling capacity and the COP decline rapidly. Therefore, the difference in temperature between the hot side and the cold side is determinant for the performance of the thermoelectric refrigeration system. In addition, the difference in temperature decreases when the system is used to make up the economic loss caused by the small COP of the thermoelectric refrigeration system.



**Fig. 2** Relationship between cooling capacity and current

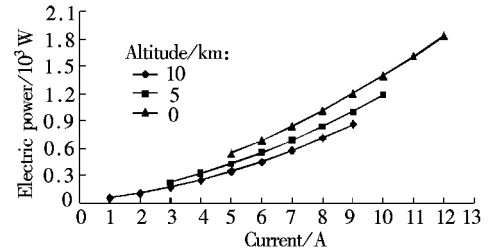


**Fig. 3** Relationship between COP and current

## 2.2 Electric power

Under flight conditions, the current supply is not enough for full-power equipment. Generally, the current is less than 10 A, and in this paper it is about 4 A. Therefore, we can easily realize the design.

The voltage of the power is approximately 45 V, which can be conveniently supplied by direct-current equipment. The power less than 200 W can be satisfied by common aircraft electric equipment. When the altitude is 5 km, the current and the voltage have an upward trend (see Fig. 4). Thus, the system cannot work under this condition for a long time.



**Fig. 4** Relationship between electric power and current

By the calculations of the electric power and the voltage, this cooling system is verified to meet the design requirements.

## 2.3 Entropy generation

The entropy generation of the system is composed of three parts: the heat convection on the hot side, the heat conduction on the cold side, and the heat conduction between the cold joint and the hot joint<sup>[5-6]</sup>. Thus, we can obtain

$$S = Q_H \left( \frac{1}{T_H} - \frac{1}{T_1} \right) + Q_C \left( \frac{1}{T_2} - \frac{1}{T_C} \right) + Q_L \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \quad (11)$$

where  $S$  stands for the entropy generation.

The intention of the minimum entropy generation method is to achieve the minimum summation of the entropy generation during the cooling course. Mathematically it can be expressed as

$$\frac{\partial S}{\partial x} = 0 \quad (12)$$

where  $x$  is a variable which is regarded as the current in this paper.

Fig. 5 shows the entropy generation of the TRS at different temperatures. It can be seen that the entropy increases with the increase in the temperature of the hot side. There-

fore, we can conclude that the thermoelectric refrigeration system should not be used when the cooling capacity is great. Meanwhile, during the whole process of flight, the cooling performance at a high altitude always outperforms others.

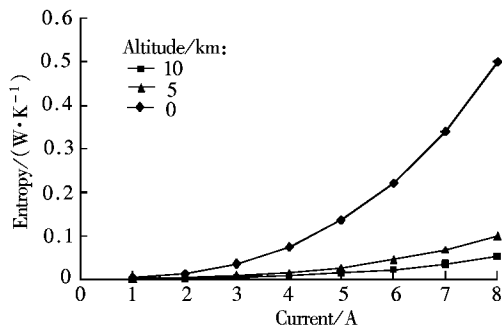


Fig. 5 Relationship between entropy and current

## 2.4 Performance penalty

In the design of the environmental control systems for aircraft, the performance penalty should be estimated. Three methods, the equal mass method (EMM), the take-off mass method (TMM) and the equal resistance method (ERM), are widely used for the calculations. As for the TRS which neither has a large weight nor needs a driving force from the actuating mechanism, the total mass never changes during flight. What's more, the take-off mass method, which has become the most popular way for aircraft design evaluation, takes into consideration a lot about fuel consumption. Thus, we adopt this method for the penalty estimation<sup>[7]</sup>. The penalties caused by the fixed system, ram air, axial power and take-off mass are estimated to be 3.4, 5, 0.01, 8.41 kg, respectively.

## 3 Conclusion

In this paper, the cooling capacity, the refrigeration coeffi-

cient and the entropy generation with different environmental temperatures and working currents are analyzed. The PCL of the TRS is also calculated. The results show that as an easy control cooling system with an outstanding COP value, the TRS can act as a backup cooling system for aircraft because it has a small volume and no revolving parts. Especially for a low-power electrical system, we can obtain the value of the current using the performance curves of different cooling capacities. All of these give guidance on the design of the TRS for aircraft. And it should be mentioned that although the system has wide use, the demands of economy and frame should also be considered to enhance the superiority of thermoelectric refrigeration.

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# 机载小功率热电制冷系统的性能分析

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**摘要:**在设定飞机参数的条件下,以现有的实验模型为研究平台,提出了一种机载小功率热电制冷系统的设计优化方法.考察了该系统在3种不同飞行高度运行时制冷量与制冷系数的变化曲线.然后,利用熵产最小法评估了系统的性能,并计算出系统的代偿损失.通过电功率实验,得出了制冷系统的功耗变化曲线,其峰值小于机载装备可提供的最大电量,由此证明了小功率热电制冷系统应用于机载设备的可行性.制冷系数、制冷量及系统熵产与飞行高度和电流有关,通过分析这些变化数据,得出工作状态下制冷系数的最优值,并提出可最大程度利用热电制冷系统优势的优化方案.

**关键词:**热电制冷;熵产分析;机载制冷系统;性能代偿

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