

# Research on the Environmental Control System of the Equipment Bay for A High Altitude Long Endurance Solar-powered UAV

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**Abstract:** Substantial efforts have been focused on developing high altitude long endurance solar-powered unmanned aerial vehicles (LESP UAVs). With increasingly integrated and compact electronic equipment, the demand for effective heat dissipation becomes more critical but challenging. Aiming at LESP UAV's equipment bay with the cooling capacity demand of 5kW, after the availability of heat sink is analysed, a single-stage and two-stage vapor compression refrigeration cycle based on radiation cooling are proposed. By using thermodynamic analysis and quality estimation, the corresponding quantitative relationship is obtained, and the variation between cooling capacity and power consumption/system weight are calculated. Combined with the engineering application, the suitable conditions of two schemes are given. The results can provide theoretical and engineering guidance for the research in this field, and have good engineering application value.

## 1 INTRODUCTION

Solar-powered UAV is an unmanned aerial vehicle that uses solar radiation as a power to fly at high altitude for more than a few weeks. Because of the broad application prospects of solar aircraft, many countries and organizations are competing in the research of solar aircraft, and various models emerge in endlessly. Such as NASA's Helios prototype, HELIPLAT in Italy; and the Rainbow in China, etc. (Gao, et al., 1995; Jiang, 2017; Gao and Zhu, 2016; Zhang J and Zhang DH, 2016).

However, the development of solar UAVs is still facing many key technical issues that need to be addressed urgently. For example, the heat dissipation of equipment bay for the solar-powered unmanned aerial vehicle (UAV) directly affects the reliability of the UAV, which has been the focus of the research. To the authors' best knowledge, no relevant work has been published in open literature. In this paper, two vapor cycle refrigeration schemes are proposed to solve the heating demand for LESP UAV's equipment bay.

## 2 DESIGN REQUIREMENT

The flight altitude of the LESP UAV is in the range of 16~20km (day cruise at 20km with the cruise speed of 34m/s, night cruise at 17km with the cruise speed of 27m/s). The layout of the LESP UAV equipment modules is shown in Figure 1, and they are in symmetrical distribution arrangement, and each set of heat dissipating power is 2.5kW. The temperature control target of its equipment bay is no less than 40°C.

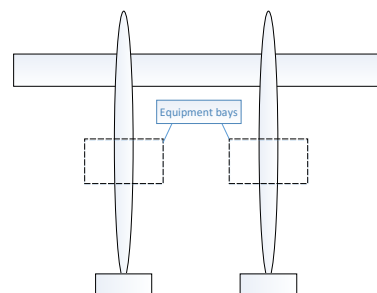


Figure 1: Layout of equipment bays.

### 3 HEAT SINK ANALYSIS

The first problem in the design of the cooling system is to find a suitable heat sink. Due to the high altitude of the LESP UAV with low atmosphere pressure and therefore low air density, the convective heat transfer is limited, and the radiation heat transfer becomes more dominant.

The calculation formula of the convective radiation intensity is

$$Q_a = h_a (T_w - T_0) \tag{1}$$

Wherein,  $T_w$  and  $T_0$  indicate the temperature of the radiant surface and the ambient temperature, respectively, K;

The calculation formula of convective heat transfer coefficient is (Ma, et al., 2010)

$$h_a = 0.664 \lambda_0 \sqrt{\frac{v_0}{\gamma_0 L}} P_r^{1/3} \tag{2}$$

Wherein,  $\lambda_0$  is the thermal conductivity of the corresponding atmosphere, W/(m·K);  $v_0$  is the air flow velocity, m/s;  $\gamma_0$  is the kinematic viscosity, m<sup>2</sup>/s;  $L$  is the characteristic length of the heat dissipating surface, m.

The calculation formula of radiation intensity is

$$Q_r = \varepsilon \sigma (T_w^4 - T_a^4) \tag{3}$$

Wherein,  $\varepsilon$  is the emissivity;  $\sigma$  is the Stephen Boltzmann constant;  $T_a$  is the ambient temperature, K.

Take the chord length of 2m as the feature size, the convection heat transfer coefficient at 20km with cruise speed of 34m/s can be calculated about 4W/(m<sup>2</sup>·K) by using Eq.2, herein, the ambient temperature is set to 290K.

The results of the calculation are shown in Figure 2. The radiation heat transfer is much higher than the convective heat transfer in the high temperature zone. Due to limited research on convective heat transfer in the high altitudes, the uncertainty of calculated convection heat transfer coefficient could be very high. Therefore, for conservative design, the heat sink in this paper is based on the worst condition in which only radiation heat transfer is considered. In practical application, the target heat transfer performance can be achieved with additional convective heat transfer component.

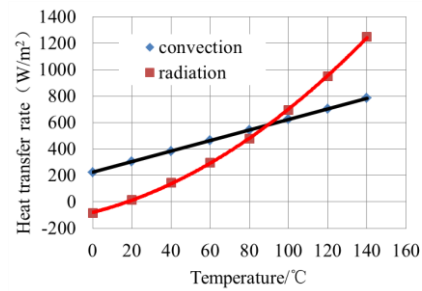


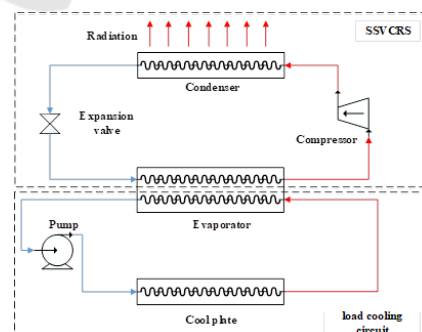
Figure 2: Comparison of heat transfer rate between convection and radiation heat transfer.

### 4 SYSTEM DESCRIPTION

Two vapor cycle refrigeration systems are proposed. Considering the centre of gravity of the system, the scheme below shows only a set of system schematics based on the symmetry of the equipment bay.

#### 4.1 STVCRS

The schematic diagram and thermodynamic process diagram of a single stage vapor cycle refrigeration system (STVCRS) are shown in Figure 3. The system is composed of load cooling circuit and refrigeration cycle, and load cooling circuit will remove heat dissipated by the equipment bay. Taking into account the low temperature condition at high altitude, the cooling liquid used in this system is ethylene glycol solution with mass fraction of 66%, and R134a as the refrigerant of vapor cycle refrigeration system (VCRS).



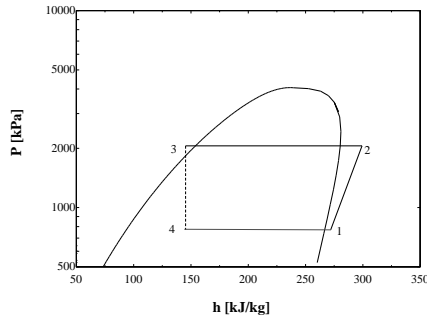


Figure 3: Single stage steam cycle cooling scheme and thermodynamic process diagram.

### 4.2 TSVCRS

At a higher wall temperature of condenser, heat transfer area and component mass become smaller. Therefore, a two stage vapor cycle refrigeration system (TSVCRS) is proposed to improve the condensing temperature (Fig.4).

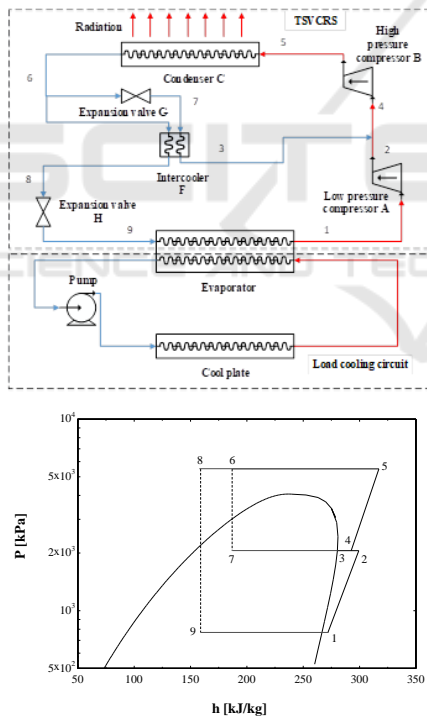


Figure 4: Schematic diagram and thermodynamic process of TSVCRS.

## 5 PERFORMANCE ANALYSIS

In order to explore the feasibility of the above-mentioned systems in the application of LESP UAV, the refrigeration system power consumption and system weight estimation are analysed.

### 5.1 Thermodynamic Calculation

Theoretical thermodynamic models for the above-mentioned two systems are referred to reference (Wu, 2007), and their performance results are shown in Table 2.

Table 2: Performance results of two systems.

	SSVCRS	TSVCRS
Evaporate temperature, °C	30	30
Condensing temperature, °C	68.7	90
Sub-cooling temperature, °C	5	5
Sub-heating temperature, °C	5	5
COP	4.63	1.88

### 5.2 Mass Estimation

#### (1) Evaporator

The evaporator employs the compact heat exchanger for aircrafts. Table 1 gives the relationship between the cooling capacity and the corresponding quality.

Table 1: Plate type for heat exchanger selection.

Heat exchange capacity / kW	Mass / kg
2.0	0.68
2.5	0.8
3.0	0.96
4.0	1.16
5.0	1.36

#### (2) Compressor

According to the light weight requirement of the airborne refrigeration compressor and our previous research work, the ratio of the total weight  $M_{rc}$  to the cooling capacity  $Q$  of the centrifugal refrigeration compressor can be estimated as

$$\frac{M_{rc}}{Q} = 1.85 \sim 2 \text{ kg/kW} \quad (4)$$

#### (3) Condenser

The selected condenser diagram is shown in Figure 5. Condenser pipe is  $\Phi 8 \times 1$  mm. The refrigerant flows in the tube, and the radiation plate is welded outside the tube.

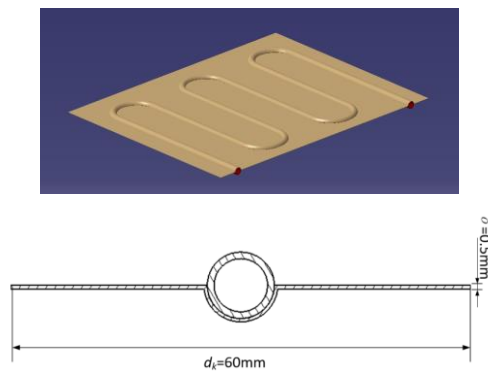


Figure 5: Schematic of radiation condensers.

The estimated correlations of the condenser mass with the cooling capacity of a SSVCRS and TSVCRS are shown below respectively:

$$M_{Con-SS} = 5.2Q \quad (5)$$

$$M_{Con-TS} = 2.9Q \quad (6)$$

(4) Expansion valve

The thermal expansion valve is selected by the Danfoss TCEL3.5 type thermal expansion valve (suitable for the range of refrigeration is not more than 12kW), its weight is about

$$M_{rv} = 0.37\text{kg} \quad (7)$$

$$M_{rv} = 0.37\text{kg} \quad (8)$$

(5) Refrigerant charge

The Enviro Consulting Ltd. "Refrigerant Charge Calculator" software is used to make a simple estimate of the weight and charging amount of the heat exchanger. There is no high or low pressure storage tank in the estimation. At the same time, the lubricating oil is not considered because of the oil-free centrifugal refrigerating compressor used in this work.

(6) Load cooling circuit

According to the market research, the ratio of the cold plate mass to the heat dissipation area is approximately equal to 8kg/m<sup>2</sup>. The length of the connecting pipe can be estimated approximately according to the length of the fuselage, and the pipe can choose the specifications of the aluminium tube of Φ8×1 with a mass density of 0.06kg/m.

The mass estimation method of the pump is according to Eq.4. In addition, the power consumption of the pump is less than 0.3kW within the operating range.

Therefore, the relationship between the cooling capacities with consuming power/mass of the two systems is given respectively in Figure 6. From the aspect of mass assessment, TSVCRS has substantial advantage but high power consumption is not favoured.

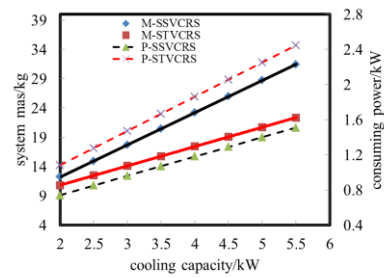


Figure 6: System mass varies with cooling capacity

## 6 CONCLUSION

This paper proposed two cooling systems of equipment bay for the long endurance solar-powered UAV, and conclusion based on systematic analysis can be summarized as follows:

(1) For the heat sink of the long endurance solar-powered UAVs in the near space, the conservative design and system reliability requires only considering heat transfer based on radiation without convective component.

(2) As far as system energy consumption concerns, it is suggested to adopt single stage vapor cycle system. While, from the perspective of mass concern, it is suggested to adopt two-stage vapor cycle system; however, the system is more complex.

(3) Limited by the high altitude thermal environment for condenser radiation, the condenser contributes to overall system weight in a larger portion. By increasing the condensing temperature, the heat transfer capability and the mass of the radiation condenser can be reduced. The condenser design and weight can be optimized in future's work.

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## REFERENCES

Gao GL, Song BF, Li ZK and Ding X, 2010. Key technologies of solar powered unmanned air vehicle. *Flight Dynamics*. 28 (1), p1-4. (in Chinese)

- Jiang JK, 2017. Successful flight of a new rainbow solar UAVs. *the third edition of the People's Daily Overseas Edition*, June 14th. (in Chinese)
- Gao F and Zhu DR, 2016. Design and optimization of solar unmanned aerial vehicle heat management system. *Refrigeration and air conditioning*. 16 (11), p32-37. (in Chinese)
- Zhang J and Zhang DH, 2016. Analysis on the main design points of high altitude long endurance solar UAVs. *Acta aeronautical journal*. 37 (S1), pS1-S7. (in Chinese)
- Ma W, Xuan YM and Han YG, 2010. Analysis on thermal environment in near space and thermal design method for ow-speed aircraft. *Journal of astronautics*. 31 (5), p1272-1277. (in Chinese)
- Yang SM, 2006. *Heat transfer*. Beijing: Higher education press. (in Chinese)
- Wu YZ, 2007. *Refrigeration principle and equipment*. 3rd ed. Xi'an: Xi'an Jiaotong University press. (in Chinese)
- Shou RZ and He HS, 2004. *Environmental control technologies for aircrafts*. Beijing: Beihang University press. (in Chinese)
- Morris T., Godecker W., Crowe L. and Metzler M., 1982. Environmental Control of an Aircraft Pod Mounted Electronics System. *SAE Technical Paper 820869*.
- Godecker W. J., Lentz J. C., Parme C. B., Wigmore D. B. and Winans K. B., 1992. Vapor Cycle System for a Fighter Aircraft - The Lantirn ECU Lessons Learned. *SAE Technical Paper 921184*.

