Configuration Analysis of Integrated Thermal Management Based on the Turbine-Fan Refrigeration System

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Abstract

The on-board refrigeration systems on some special mission aircrafts provide a suitable working environment for the high heat flux electronics and the crew/cabin respectively. The liquid cooling system uses liquid to cool the electronic equipment with high heat flux (such as airborne radar, etc.), and the heat dissipation of the electronic equipment is transmitted to the cooling device through heat conduction, convection and radiation. The environmental control system is always in a dynamic thermal process to provide a comfortable pressure and temperature environment for the cabin. The crossover of the application occasion between the environmental control and the liquid cooling system makes it possible to realize the integrated thermal management configuration. The coupling design architecture takes into account the comprehensive use of heat/cooling capacity of the two refrigeration systems at different flight altitudes.

The integrated thermal management configuration takes advantage of the rich cooling capacity between the two refrigeration systems for the cross use on different altitudes with the ingenious structure. The ingenious system configuration widens the use altitude of the liquid cooling system, which effectively improves the efficiency of the aircraft, increases the integrated cooling capacity of the system and reduces the compensatory loss of the aircraft by 12%-15%.

Keywords: Turbine-fan high-pressure water separation air cycle refrigeration system·Integrated thermal management·Fan exhaust induced ram air·

1. Introduction

The key focus of the intense competition in the civil aviation industry lies in safety, comfort, economy, and environmental friendliness. In response to the design requirements of large aircraft, the air management system (AMS) has become increasingly important. The main function of the air management system is to maintain the pressure, temperature, humidity, airflow velocity and cleanliness of the cabin air within allowable ranges under various flight conditions[1][2][3]. It provides passengers with sufficient fresh air and improves the environmental conditions in the cargo and the electronic equipment compartment. In the rapid development of civil aviation today, the advancedness of the air management system technology will be an important indicator for evaluating the overall performance of an aircraft. Comfortable temperature environment inside the cabin, reasonable absolute pressure, imperceptible pressure change rate to the human ear, fresh air and appropriate airspeed have become important conditions for aircrafts to attract passengers.

The research of the turbine-fan air cycle refrigeration systems based on high pressure water separation method was studied in previous articles[4], and the purpose of this paper is to expand on the previous work.

In this paper, the air-liquid heat exchanger of the liquid cooling system and the air-air heat exchanger of the air cycle refrigeration system are innovatively arranged in series in the same ram air duct. Therefore, in the process of ground or low-altitude flight, the system configuration uses the suction effect of the turbofan in the air cycle refrigeration system to induce and amplify the air flow into the ram air duct, while meeting the cooling requirements of the liquid cooling system and the air cycle refrigeration system.It solves the problem of insufficient ram air when there is no ram air on the ground or the aircraft flies at low speed, which widenes the use height range of the airborne radar. In the process of high-altitude cruise, since the cold side outlet of the liquid heat exchanger of the liquid cooling system serves as the cold side entrance of the heat exchanger of the air cycle refrigeration system, and the air cycle refrigeration system is in heating working condition,which meets the cabin temperature needs for a long time. The operation of the liquid cooling system is conducive to the realization of the heating function of the air cycle refrigeration system.

2. The design technology of the Integrated thermal management based on the turbine-fan high-pressure water separation refrigeration

The independent electromechanical systems of aviation aircraft, such as power supply, fuel, hydraulic and environmental control system, are closely related to each other on the demand and use of the thermal. Many researches on thermal management are studied and the technologies have been applied in the aircraft with high performance requirements[5][6]. This section describes the design technology of the integrated thermal management based on the turbine-fan high-pressure water separation refrigeration,which includes the general idea of system designing, system parameter matching, control logic designing and ground test verification of the system.

2.1 The Turbine-fan high-pressure water separation refrigeration system

The basic connotation of the high-pressure water separation air cycle refrigeration system is: the temperature of the wet air in the system is reduced below the dew point before entering the turbine expansion of the air cycle machine. The water vapor is condensed in the air and the free water is removed through the water separator, which reduces the moisture content of the air. Because the air is relatively dry, the turbine outlet temperature can be reduced to a lower level, and greater refrigeration efficiency and cooling capacity can be obtained.

Advances in turbine-fan air cycle machine design technology help to use the cooling capacity of the air cycle machine itself as the secondary heat sink in the system architecture. The condenser is added at the turbine outlet and the outlet air of the heat exchanger is cooled twice, so that the temperature of the condenser hot side outlet is reduced to below the dew point, which highlights the advantages of the energy recovery theory.

The Turbine-fan high-pressure water separation refrigeration system configuration based on energy recovery is proposed and the schematic diagram is shown in Figure 1.

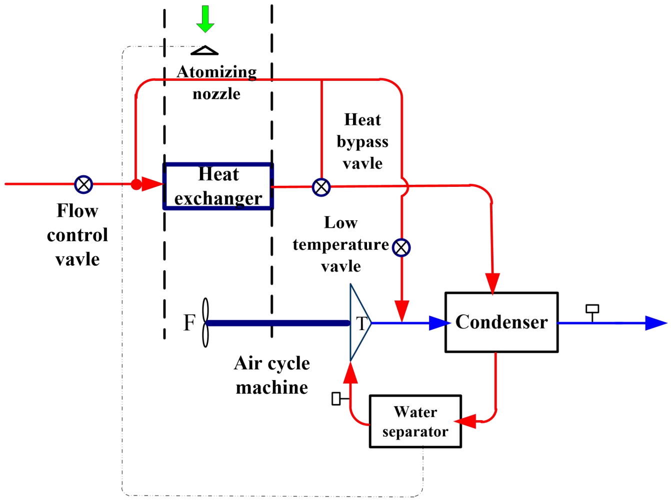

Figure 1–Schematic diagram of the Turbine-fan high-pressure water separation refrigeration system.

2.2 Integrated thermal management configuration

The integrated thermal management configuration was designed with the research object of some special aircraft`s environmental control cooling system and liquid cooling system. The air heat exchanger of the environmental control cooling system and the air-liquid heat exchanger of the liquid cooling system are placed in the same ram air duct for the project innovation. The schematic diagram of environmental control /liquid cooling integrated system based on ejection induced is shown in Figure 2.The ground experiment of the environmental control /liquid cooling integrated thermal management system is shown in Figure 3.

The thermal management configuration on the integrated system is designed according to the use demand of the two independent refrigeration systems: The integrated system configuration with shared air ducts utilizes the fan intake function of the air cycle machine to provide a large amount of ram air for the heat exchanger group (air heat exchanger of environmental control cooling system and the air-liquid heat exchanger of the liquid cooling system in tandem arrangement).

Since the cooling capacity of the liquid cooling system is small at low altitude, and the cooling capacity of the environmental control cooling system is large at low altitude while it is small at high altitude, the ingenious system configuration matches the cooling and heating requirements of the aircraft at different flight altitudes, combining with the actual scene of the aircraft and the engine;

The high heat flux electronic equipments start up at at high altitude, and the liquid cooling system works while meeting the high cooling capacity demand. The environmental control cooling system is working in the heating condition, and the exhaust waste heat flows through the air-liquid heat exchanger to provide thermal for environmental control cooling system. So the system configuration takes the rich cooling capacity between the two refrigeration systems for the cross use on different altitudes with the ingenious structure[7].

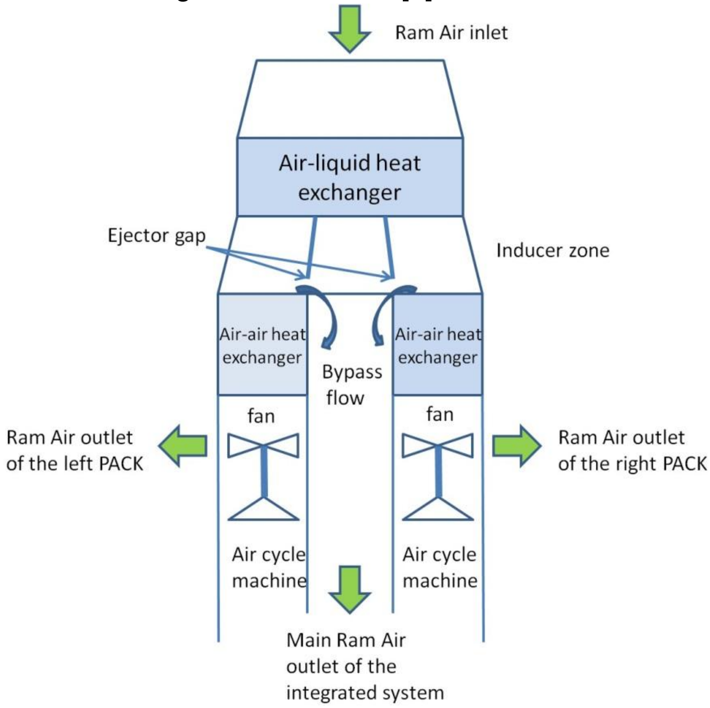

Figure 2–Schematic diagram of environmental control /liquid cooling integrated system.

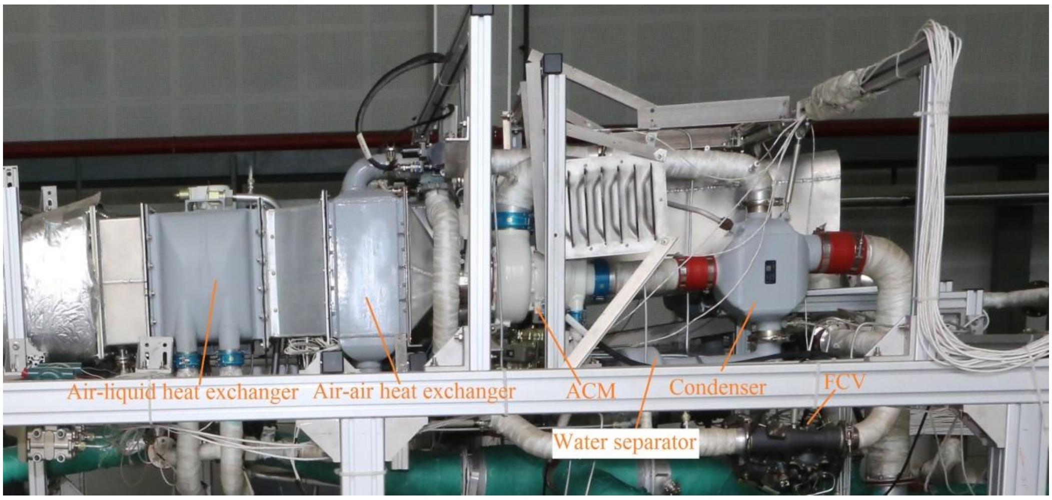

Figure 3–The ground experiment of environmental control /liquid cooling integrated system.

2.3 System parameter matching and control logic designing

2.3.1 The themodynamic parameters matching of the environmental control cooling system

The flow diagram about the parameters matching of the environmental control cooling system is shown in Figure 4.

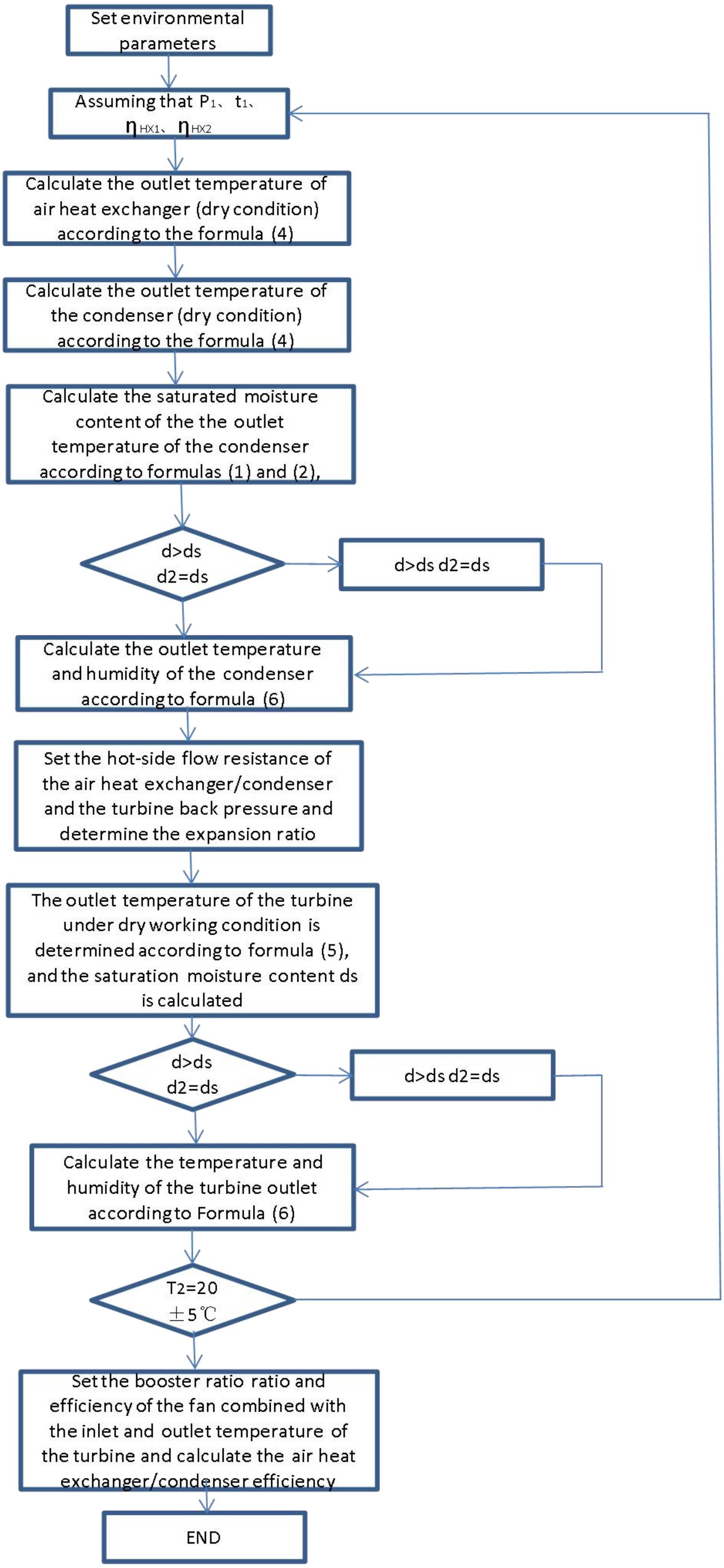

Figure 4– The flow diagram about the parameters matching of the environmental control cooling system.

2.3.2 The themodynamic parameters matching of the integrated thermal management system

The matching calculation process of the integrated thermal management system is shown in Figure 5. The matching process is carried out as follows:

1. Calculate the airflow of the cold ram air that can match the cooling requirements of the integrated system.

- Calculate the cold side inlet temperature of the air-liquid heat exchanger T_{cin-ky}

$$T_{cin-ky} = T \times (1 + 0.2Ma^2) - 273.15 \tag{1}$$

where, ***T***、***Ma*** respectively represents the ambient temperature and flight Mach number.

- Calculate the cold side outlet temperature of the air-liquid heat exchanger $T_{cout-ky}$

$$T_{cout-ky} = T_{cin-ky} + \frac{Q_{ky}}{Cp \times Gc} \tag{2}$$

where, $\boldsymbol{Q_{ky}}$ 、 $\boldsymbol{G_c}$ respectively represents the thermal load taken by the air-liquid heat exchanger of the liquid cooling system and the airflow of the ram air into the heat exchanger.

- Calculate the airflow of the cold ram air into the air-liquid heat exchanger G_{c_ky}

$$G_{c\_ky} = \frac{Q_{ky}}{Cp \times (T_{cout\_ky} - T_{cin\_ky})} \tag{3}$$

- Calculate the cold side outlet temperature of the air-air heat exchanger T_{cout_kk}

$$T_{cout-kk} = T_{cin-kk} + \eta_c \times (T_{cin-kk} - T_{hin-kk}) \tag{4}$$

where, $\boldsymbol{T_{hin-kk}}$、 η_c respectively represents the hot side inlet temperature of the air-air heat exchanger and the airflow of the efficiency of the air-air heat exchanger.

- Calculate the hot side outlet temperature of the air-air heat exchanger T_{hout_kk}

$$T_{hout-kk} = T_{cin-kk} + \eta_c \times (\frac{G_{h-kk}}{G_c})(T_{cin-kk} - T_{hin-kk}) \tag{5}$$

where, $\boldsymbol{G_{h-kk}}$ represents the airflow of the air-air heat exchanger hot side.

- Calculate the NTU and the heat capacity ratio C of the air-air heat exchanger

$$NTU = \frac{\Delta t_{\max}}{\Delta t_{\mathrm{m}}} \tag{5}$$

$$C = \frac{W_{\min}}{W_{\max}} \tag{6}$$

$$\Delta t_{\mathrm{m}} = \frac{(\Delta t_{\max} - \Delta t_{\min})}{\ln(\Delta t_{\max} / \Delta t_{\min})} \tag{7}$$

where, $\Delta t_{\max}$ 、 $\Delta t_{\min}$ 、 $\boldsymbol{W_{max}}$、 $\boldsymbol{W_{min}}$ respectively represents the higher temperature difference of the air-air heat exchanger both sides, the lower temperature difference of the air-air heat exchanger both sides, the higher heat capacity of the air-air heat exchanger both sides and the lower heat capacity of the air-air heat exchanger both sides.

- Calculate the efficiency of the air-air heat exchanger η_j

$$\eta_j = 1 - \exp\{\frac{NTU^{0.22}}{C}[\exp(-C \times NTU^{0.78}) - 1]\} \tag{8}$$

- Calculate the airflow of the cold ram air into the air-air heat exchanger G_{c_j}

$$G_{c\_j} = \frac{Q_{kk}}{Cp \times (T_{cout\_kk} - T_{cin\_kk})} \tag{9}$$

where, $\boldsymbol{Q_{kk}}$ represents the thermal load taken by the air-air heat exchanger of the environmental control system.

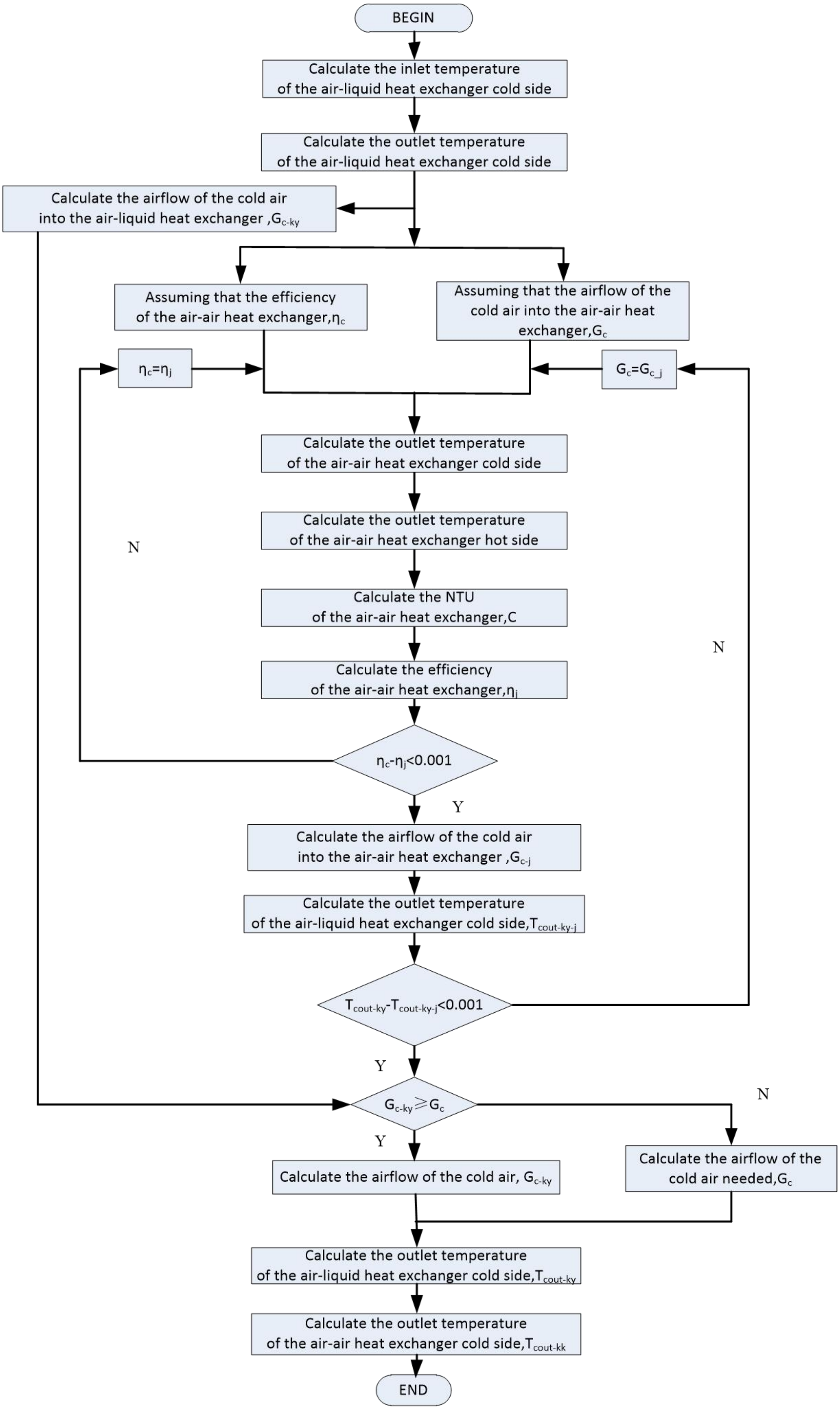

Figure 5–The flow diagram about the parameters matching of the the integrated thermal management system (ram air flow into the heat exchangers).

2. Calculate the performance parameters of the fan side in the ACM(the booster ratio π_c and the emperature rise Δt_c of the fan that providing pressurized source to the air-liquid heat exchanger). The increase in enthalpy of the flow through the fan is equal to the decrease in enthalpy of the

flow through the turbine when coaxial Turbine-fan air cycle machine is working.

$$q_{m,t}\Delta h_t = q_{m,c}\Delta h_c \tag{9}$$

$$\Delta t_c = \frac{q_{m,t}}{q_{m,c}}\Delta t_t \tag{10}$$

where, $\Delta h_t, \Delta h_c$ respectively represents the enthalpy increase of the flow through the fan and the enthalpy decrease of the flow through the turbine, π_c represents the booster ratio of the fan, and t_{ci} represents the inlet temperature of the fan.

3. The internal energy of the air decreases and its temperature and pressure decrease when the air expands in the turbine. The calculation formula of the power consumption of the turbine side and the fan side in the ACM is as follows:

$$P_t = q_m c_p (T_{in} - T_{ex}) \tag{11}$$

$$P_c = \frac{Q \bullet \Delta p}{\eta} \tag{12}$$

where, T_{in}， T_{ex} respectively represents the inlet and the outlet temperature of the turbine, Q represents the volume flow rate of the fan, Δp represents the pressure increase of the fan, and η represents the efficiency of the fluid machinery.

2.3.3 The control logic designing of the integrated thermal management system

The control logic of the heat bypass valve and the trim valves is as follows:

The error between the actual temperature and the set temperature of the pack outlet or the cabin is defined as the control error $e(n) = T_{actual} - T_{set}$;

The change rate of the error at time *n* is defined as: $\Delta e(n) = e(n) - e(n\text{-}1)$;

The control amount at time *n* is defined as: $u(n) = K_p e(n) + K_d[e(n) - e(n\text{-}1)]$.

where, K_p-proportional adjustment coefficient, K_d - differential adjustment coefficient

1) When $|e(n)| > 10℃$，the output duty cycle of the vavle is calculated as follows:

$$u(n) = 2{*}K_p e(n) + K_d[e(n) - e(n\text{-}1)] \tag{13}$$

2) When $2 < |e(n)| \le 10℃$,

   If $e(n) < 0$ and $\Delta e(n) < 0$，the output duty cycle of the vavle is calculated as follows：

$$u(n) = 2{*}K_p e(n) + K_d[e(n) - e(n\text{-}1)] \tag{14}$$

   If $e(n) > 0$ and $\Delta e(n) > 0$，the output duty cycle of the vavle is calculated as follows：

$$u(n) = 2.5{*}K_p e(n) + K_d[e(n) - e(n\text{-}1)] \tag{15}$$

   Otherwise，the output duty cycle of the vavle is calculated as follows:

$$u(n) = K_p e(n) + K_d[e(n) - e(n\text{-}1)] \tag{16}$$

3) If $|e(n)| \le 2℃$，the output duty cycle of the vavle is defined as follows: $u(n) = 0$.

According to the above results of parameter matching and control logic designing, the system capability is tested and verified.The environment and themodynamic conditions of the verification are shown in Table 1.

Table 1 The themodynamic parameters calculation of the independent systems

Cooling capability verification	The aircraft is on standby on the ground and both refrigeration systems are working.	
	The system inlet pressure	450kPa
	The system inlet temperature	120℃
	The external environment temperature	40℃
	The external environment moisture content	22g/kg (dry)
Heating capability verification	The aircraft flew at 0.4Ma and both refrigeration systems are working.	
	The system inlet pressure	250kPa
	The system inlet temperature	120℃
	The external environment temperature	-50℃
	The external environment moisture content	0

The outlet temperature curve of the both cooling packs and the change trend curve of the independent cabin (cooling state and heating capability) are shown in Figure 6 and Figure 7.

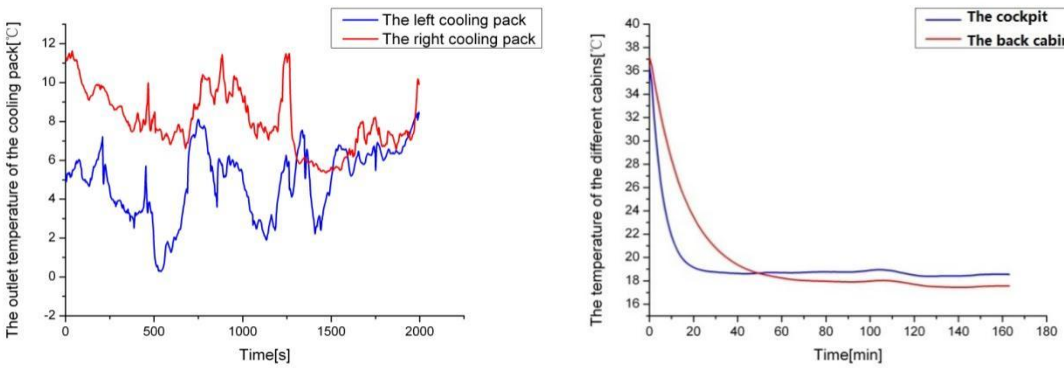

Figure 6–The outlet temperature curve of the cooling packs and the cabin(Cooling state)

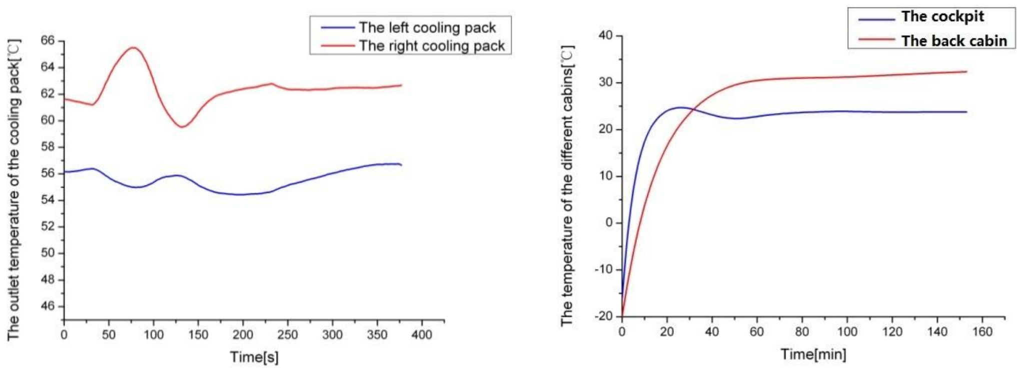

Figure 7–The outlet temperature curve of the cooling packs and the cabin(Cooling state)

3. The thermodynamic analysis of the integrated thermal management system

The air heat exchanger of the environmental control cooling system and the air-liquid heat exchanger of the liquid cooling system are installed in series in the same ram air duct. The fan of the environmental control system can be used as a pressurized source to provide cold ram air to the environmental control system and the liquid cooling system when the pressure head is insufficient. The cold ram air flow into the air-air heat exchanger/ the air-liquid heat exchanger and the performance parameters of them can be calculated according to the given system thermal load.

3.1 The themodynamic parameters calculation of the independent systems

If the environmental control system and liquid cooling system are arranged independently, both independent ram air ducts will be designed to provide ram air for the environmental control system and the liquid cooling system respectively. The parameter matching problem between the both systems will no longer exist. Two independent systems will be designed according to their own design guidelines to meet the system design requirements.

The themodynamic parameters of the environmental control system and liquid cooling system are respectively calculated according to the performance matching results of the cold ram air duct. The calculation conditions are as follows: The both refrigeration systems of the aircraft take the minimum speed of the flight envelope and 3km flight altitude as the design point. The thermal load of the liquid cooling system is 65kW when the ground temperature is 38℃ and it is carried away by the air-liquid heat exchanger. The supply temperature of the liquid cooling system is 50℃ and the supply flow of the liquid hot side is 230L/min. The hot side inlet temperature of the environmental control system is 120℃. The themodynamic parameters of the air-liquid heat exchanger and air-air heat exchanger are shown in the table 2.

Table 2 The themodynamic parameters calculation of the independent systems

Flight altitud		3km
The air-liquid heat exchanger	The cold side inlet temperature	18.5℃
	The cold side outlet temperature	46.4℃
	The hot side inlet temperature	55℃
	The hot side outlet temperature	50.3℃
	The efficiency	0.75
	The airflow of the cold air into the heat exchanger	9000kg/h
The air-air heat exchanger	The cold side inlet temperature	18.5℃
	The cold side outlet temperature	33℃
	The hot side inlet temperature	120℃
	The hot side outlet temperature	59℃
	The airflow of the cold air into the heat exchanger	1800kg/h

The required ram air flow rate for the liquid cooling system is 9000kg/h and the required ram air flow rate for the environmental control system is 3600kg/h. In conclusion, the required ram air flow rate for the independent systems configuration is 12600kg/h.

3.2 The themodynamic parameters calculation of the integrated thermal management system

The air heat exchanger of the environmental control cooling system and the air-liquid heat exchanger of the liquid cooling system are installed in series in the same air duct. The fan of the environmental control system is used as a pressurized source to provide cold ram air. The calculation conditions are the same as those in 3.1 and the themodynamic parameters of the system are shown in the Table 3.

Table 3 The themodynamic parameters calculation of the integrated thermal systems

Flight altitud		3km
The air-liquid heat exchanger	The cold side inlet temperature	18.5℃
	The cold side outlet temperature	46.4℃
	The hot side inlet temperature	55℃
	The hot side outlet temperature	50.3℃
	The efficiency	0.75
	The airflow of the cold air into the heat exchanger	7300kg/h
The air-air heat exchanger	The cold side inlet temperature	46.4℃
	The cold side outlet temperature	65℃
	The hot side inlet temperature	120℃
	The hot side outlet temperature	72℃
	The airflow of the cold air into the heat exchanger	2000kg/h

Table 3(continued) The themodynamic parameters calculation of the integrated thermal systems

The fan	The temperature rise	10℃
	The booster ratio	1.1
	The outlet temperature	95℃
	The outlet pressure	76.3kPa
	The air flow rate	2000kg/h
	The power consumption	7.9KW
The turbine	The expansion ratio	3.5
	The expansion power	8.375KW
	The outlet temperature	5℃
	The air flow rate	800kg/h
The ram air duct	The windward area	0.023㎡

3.3 The analysis of the system performance compensation loss

Most aircraft cooling systems have been evaluated by the performance compensation loss analysis method based on the first law of thermodynamics[8][9]. Usually, the three factors that play a role in compensation loss are system fixed mass, engine bleed air and ram air. In general, the impact of these three factors on the aircraft can be evaluated through intuitive parameters, which means how much fuel is consumed by the engine and the power generated can support the normal operation of the system. The analysis is carried out from the perspective of performance compensation loss:

- The system fixed mass

The air-liquid heat exchanger adopts double flow heat exchanger in the independent system configuration, while the air-liquid heat exchanger adopts plate-fin heat exchanger with low flow resistance in the integrated thermal management system configuration. After estimating the weight of equipments, pipes and mounting brackets, the weight of independent system configuration is about 560kg while the system weight of the integrated environmental control/liquid cooling system configuration is about 390kg.

- The resistance of the ram air

The required ram air flow rate for the liquid cooling system is 9000kg/h and the required ram air flow rate for the environmental control system is 3600kg/h. In conclusion, the required ram air flow rate for the independent systems configuration is 12600kg/h. If the air heat exchanger of the environmental control cooling system and the air-liquid heat exchanger of the liquid cooling system are installed in series in the same ram air duct, the required ram air flow rate for the integrated environmental control/liquid cooling system configuration can be reduced to is 7300kg/h.

- The engine bleed air

The environmental control system extracts engine bleed air in the both system configurations and the flow rate of the engine bleed air is 1600 kg/h.In conclusion, the system performance compensation loss calculation for the independent systems and the integrated environmental control/liquid cooling system configuration is listed in the Table 4.The ingenious system configuration widens the use altitude of the liquid cooling system, which effectively improves the efficiency of the aircraft, increases the integrated cooling capacity of the system and reduces the compensatory loss of the aircraft by 12%～15%.

Table 4 the system performance compensation loss calculation for of the different systems

Parameter	The independent systems	The integrated system
Flight altitud（km）	3	
Flight speed（m/s）	62.5	
Flight time（h）	4	
lift-drag ratio	14	
Specific of the fuel（kg/N·h）	0.483	
The flow rate of the engine bleed air（kg/s）	0.361	
The flow rate of the ram air（kg/s）	3.5	2
The system fixed mass（kg）	560	390
The fuel compensatory loss（kg）	384.4	339.2

3.4 Self-protection function of coupling structure

The environmental control/liquid cooling integrated system is designed based on the principle of fan exhaust induced ram air. The system configuration using the principle of constant entropy ejector solves the problems that trouble the normal operation of the system, such as the windmill effect and the overturning at high altitude caused by the air cycle machine with airfoil bearing[10].

1)The Turbine-fan air cycle machine adopts airfoil bearing, which improves the reliability of the air cycle machine. But the bearing capacity of the bearing also changed and the floating pressure of the turbine reduced correspondingly, which brings a new problem -- the windmill effect of the turbine: If the air cycle machine is not working and the airfoil bearing does not float. The ram air flows into the fan part of the ACM and the dynamic pressure brought by the ram air will make the fan rotate and drive the turbine to rotate, which will cause friction damage to the airfoil bearing and lead to the product failure.

The air heat exchanger of the environmental control cooling system and the air-liquid heat exchanger of the liquid cooling system are placed the same ram air duct in the system configuration. It limits the ram air flow through the fan part of the air cycle machine with the principle of constant entropy ejector. The integrated cooling system with the fan exhaust induced of ram air, combined with the parameter matching between the resistance of heat exchanger group and the ram air flow dynamic pressure, can effectively avoid the phenomenon of windmill.

2)The other problem that the Turbine-fan refrigeration system faced is the over-running of the ACM. Because the Turbine-fan air cycle machine is for two wheel, namely all the power generated by the turbine passes to the fan. So the rotate speed will increases gradually as the flight altitude increased and the atmospheric density gradually decreased, which will also cause the damage of the air cycle machine.

The cold air flowed through the air cycle machine and the hot supply air flowed through the trim air vavle is mixed for cabin area zonal temperature control. The trim air vavle is located the downstream of the flow control vavle(FCV), which is not pressure reduced processed. Therefore, by adjusting the trim air vavle can reduce the turbine inlet pressure so as to achieve the purpose of controlling the rotate speed of the air cycle machine will not exceed the permitted range.

The paper makes full use of the fan flow and pressure distribution characteristics in the inlet and outlet of the ram air duct at different speeds and working conditions, and realizes the function of bidirectional ejection through the structural design, so as to solve the problem of the fan of the air cycle refrigeration system in different conditions. Innovative fan adaptive protection structure based on bidirectional ejection is adopted. The flow resistance of heat exchanger is used to match the dynamic pressure brought by the ram air. And the principle of constant entropy ejection is used to stabilize the ram air flow of the fan, which effectively avoid the windmill effect, surge, speeding and other problems caused by the application of airfoil bearing.

4. Conclusion

The integrated thermal management configuration takes advantage of the rich cooling capacity between the two refrigeration systems for the cross use on different altitudes with the ingenious structure. The ingenious system configuration widens the use altitude of the liquid cooling system, which effectively improves the efficiency of the aircraft, increases the integrated cooling capacity of the system and reduces the compensatory loss.The system configuration has the following innovation points：

1) The key technologies such as system configuration design, parameter matching, adaptive protection design have been broken through, which makes the Turbine-fan high-pressure water separation refrigeration system and the integrated thermal management system high reliability.

2)The integrated thermal management configuration takes advantage of the rich cooling capacity between the two refrigeration systems for the cross use on different altitudes with the ingenious structure. Combined with the actual application scenarios of aircraft/engine, the cooling and heating requirements of aircraft at different flight altitudes were matched with the ingenious system configuration.

3) The environmental control/ liquid integrated cooling system with the fan exhaust induced of ram

air using the principle of constant entropy ejector which can make the phenomenon of windmill and the over-running in high altitude of the ACM generated effectively avoided, which can solve the problems that troubled the normal operation of the air cycle machine with airfoil bearing.

4) In summary, the energy/heat between the systems comprehensively reduces the demand of the system's ram air by 30% to 40%, which is conducive to the cross-use of heat from two independent systems. The fuel compensation loss of the aircraft is reduced by 12% to 15%, and the aircraft performance and range are improved.

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6. Copyright Statement

References

[1] Society of Automotive Engineers (2001) Environmental control systems terminology,(Aerospace Recommended Practice, ARP147 Rev. E), SAE International, Warrendale,PA, 2001

[2] Lawson CP. Environmental control systems. In: Blockley RH, Shyy W (Eds) Encyclopedia of aerospace engineering. Wiley, Hoboken, pp 4985–4994, 2010

[3] Mäkelä L . Model-based fault diagnosis of an aircraft environmental control system. In: Programme in Automation Engineering, Master of Science Thesis, Tampere University of Technology, Tampere, Finland, 2016

[4] H C Ma, J B Bai, T G.Configuration Analysis of the Turbine–Fan High Pressure Water Separation Refrigeration System Based on the Energy Recovery Technology The Proceedings of the 2021 Asia-Pacific International Symposium on Aerospace Technology (APISAT 2021), Volume 2, Lecture Notes in Electrical Engineering 913, 2023

[5] Li N,Jiang Z Y. The Preliminary Research on Integration Thermal and Energy Management System for some Aircraft[J]. Civil Aircraft Design and Research, 2013(2):13-17.

[6] Xu X.The research and simulation technology of aircraft environmental control system based on air/steam combined cycle [D]. Beijing: Beijing University of Aeronautics and Astronautics, 2004.

[7] Ma H C, Liu Y L,Dang X M. Configuration analysis of integrated thermal management about high altitude long-endurance unmanned aerial vehicle[J].CIESC Jounal,2020,71(S1):417-424

[8] SOCIETY OF AUTOMOTIVE ENGINEERS. Environmental Control Systems Life Cycle Cost,(Aerospace Information Report, AIR1812 Rev. B), SAE International, 2017, Warrendale, PA,USA.

[9] SOCIETY OF AUTOMOTIVE ENGINEERS. Aircraft Fuel Weight Penalty Due to AirConditioning, (Aerospace Information Report, AIR1168/8), SAE International, 1989, Warrendale,PA, USA.

[10]Bringhenti C, Tomita JT, de Andrade CR (2020) Air conditioning systems for aeronautical applications: a review. Aeronaut J 124 (1274): 499-532. https://doi.org/10.1017/aer.2019.159