THE OPTIMUM DESIGN OF AIR CYCLE REFRIGERATION SYSTEM WITH HIGH PRESSURE WATER SEPARATION

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ABSTRACT

Air cycle refrigeration system with high pressure water separation has many advantages. But there are some problems which prevent this system from wide application in Chinese aviation industry. The main difficulties are : when the parameters of the cooling unit are not matched properly, it has the problems such as freezing at the condenser outlet, difficulties in the design of the cooling turbine, etc. The mathematical model and the method for design and computation presented in this article can estimate the performance of the cooling unit with high pressure water separator,so it can anticipate the working condition of the system such as freezing at the condenser outlet and working state of the turbine. This paper also analyses the influence of the parameters of the main components of the cooling unit to the general performance of the system and so gives direction to select the best parameters. Through experimental verification, the computed results are in agreement with the experimental results satisfactorily. It has practical value in engineering design.

INTRODUCTION

The air cycle refrigeration system of bootstrap configuration with high pressure water separation has wide application prospect. Compared with the conventional systems, it has advantages described as follows.

- The dew point in high pressure is higer and so the moisture is easier to condense. The water removal efficiency can exceed 90 percent. The turbine outlet temperature can be lower than 0℃ free from the limit of freezing so the cooling capacity is improved.
- Improved reliability and maintainability can be achieved by the elimination of the low pressure water separator. The penalty of the system is also decreased.
- The system of bootstrap configuration can work relatively steadily with the change of flight condition

One way to design a system is to select proper components of finished product to compose the system. In this case, all the performance curves of the components are known and it is not difficult to calculate the system performance. But to a totally new system, the performance curves can't be obtained at the beginning state of the design. To the latter condition, the method presented here gives some simplification to the calculation so that system performances of different matches of the parameters can be estimated for the designer to choose the best one.

REFRIGERATION SYSTEM DESCRIPTION

As shown in Fig.1, the engine bleed air that is supplied to the system passes through the primary heat exchanger where it is cooled by ram air. Then it passes through the system flow modulating pressure regulator to the compressor. The secondary heat exchanger provides additional cooling to eliminate the heat produced by the compression using ram air as the heat sink. After passing through the reheater the bleed air is close to the saturation point. Then it enters the condenser to condense the vapor. Some of the water condensed is ejected directly from the condenser, the other larger droplets are blown out with the airstream into the high pressure water separator where they are removed. The water extracted from the bleed airflow is ducted to the secondary heat exchanger and sprayed into the secondary cooling inlet airstream to improve the heat transfer. The air leaving the water separator contains only a few water droplets which re–evaporate when they pass through the cold side of the reheater. This kind of "dry" air expands in the cooling turbine and the temperature is lowered extremely. The cool air leaving the turbine enters the condenser again to condense the moisture in the hot side airstream with its low temperature while its own rise of temperature evaporate the few grains of ice separated out of the low temperature airflow at the turbine outlet. Finally, the cool, dry air is obtained at the condenser outlet.

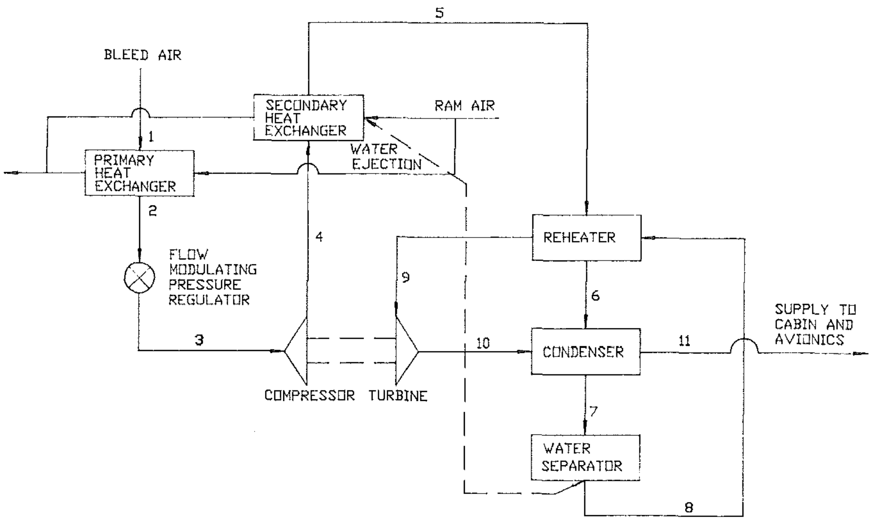

Fig.1 Air Cycle Refrigeration System With High Pressure Water Separation

CHOICE OF DESIGN POINT

The usual practice of engineering design is to choose a typical critical working condition as the design point. The system is designed in the basis of this point and checked by some other main working states to ensure the performance of the system meet the requirements within the whole working range.

Generally both the bleed pressure and temperature are higher in a low flying altitude and at a high speed. This means the design point should be near the maximum flight envelope as shown in Fig.2. The highest temperature and humidity pile up when flying with high speed on the sea level. Usually this condition is chosen as the design point of the refrigeration system.(1)(2)

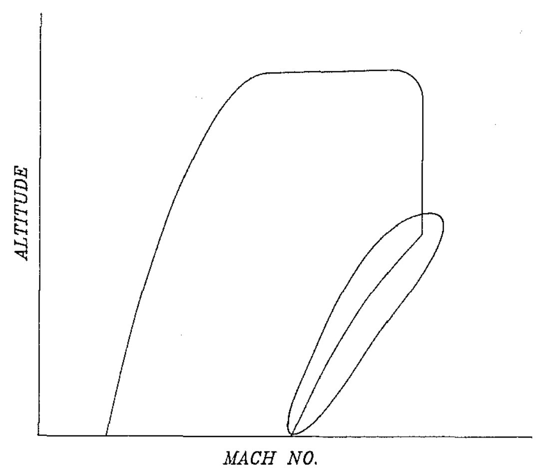

Fig.2 Flight Envelope

BASIC EQUATIONS OF THE MATHEMATICAL MODEL

- Power balance of turbine and compressor

$$\eta_m \cdot N_t = N_c$$

$$\pi_B = \frac{\theta}{\pi_c}\left[1 - \frac{\delta}{\eta_B}(\pi_c^{\ 0.286} - 1)\right]^{-3.5}$$

$$\pi_B = \frac{P_3}{P_{10}},\ \delta = \frac{T_3}{T_9},\ \theta = \frac{P_4}{P_9}$$

$$\eta_B = \eta_c \cdot \eta_t \cdot \eta_m$$

usually, $\theta = 1.04 \sim 1.08$

- Balance of humidity

$$(d_H - d_7)\eta_w = d_H - d_{11}$$

- Conservation of the enthalpy

$$H_5 - H_6 = H_9 - H_8$$

$$H_6 - H_7 = H_{11} - H_{10}$$

- Through the compressor

$$P_4 = \pi_c \cdot P_3$$

$$T_4 = T_3\left(1 + \frac{\pi_c^{0.286} - 1}{\eta_c}\right)$$

- Through the turbine

$$P_9 = \pi_t \cdot P_{10}$$

$$T_9 = \frac{T_{10da}}{1 - \eta_t (1 - \pi_t^{-0.286})}$$

$$T_{10da} = T_{10} - \Delta T_t$$

- Turbine outlet temperature rise caused by condensation

$$\Delta T_t = \frac{d_{11} - d_{10}}{1000} \cdot \frac{\gamma + \xi}{c_p}$$

- Efficiencies of the heat exchangers

$$\eta_2 = \frac{T_4 - T_5}{T_4 - T_r}$$

$$\eta_3 = \frac{H_5 - H_6}{H_5 - H_8}$$

$$\eta_4 = \frac{H_6 - H_7}{H_6 - H_{10}}$$

- At saturation point, the pressure of vapor

$$P_v = 602.4 \cdot 10^{\frac{7.45 \cdot T}{235 + T}}$$

the relative humidity

$$d = 622.0 \cdot \frac{P_v}{P - P_v}$$

CALCULATION AT THE DESIGN POINT

When calculating the performance of the design point, the ram and bleed pressure, temperature, humidity and flow have been known. The parameters needed to be selected are efficiencies of the turbine, compressor and the water separator, pressure distribution among the components between the turbine and the compressor and the outlet temperature of the turbine. Usually,$\eta_t = 0.75 \sim 0.85$,$\eta_c = 0.70 \sim 0.80$,$\eta_w = 0.90 \sim 0.98$,$\eta_m = 0.93 \sim 0.97$.The turbine outlet temperature will be decided upon the system outlet temperature , its value will affect the condenser efficiency which will be discussed later. The result of computation of a system is shown in Fig.3. It is the basis to design or select each components.

CALCULATION NOT AT THE DESIGN POINT

The Simplifying Assumption

When the system doesn't work at the design point, all the components work deviating the design point also. The system performance can be precisely calculated only after how the components' performance changes has been known.But theoretical calculation of the compressor and turbine is very complicated. This brings difficulties to the performance calculation.

Theoretical and experimental research that have been done show that within the actual work range of the refrigeration system

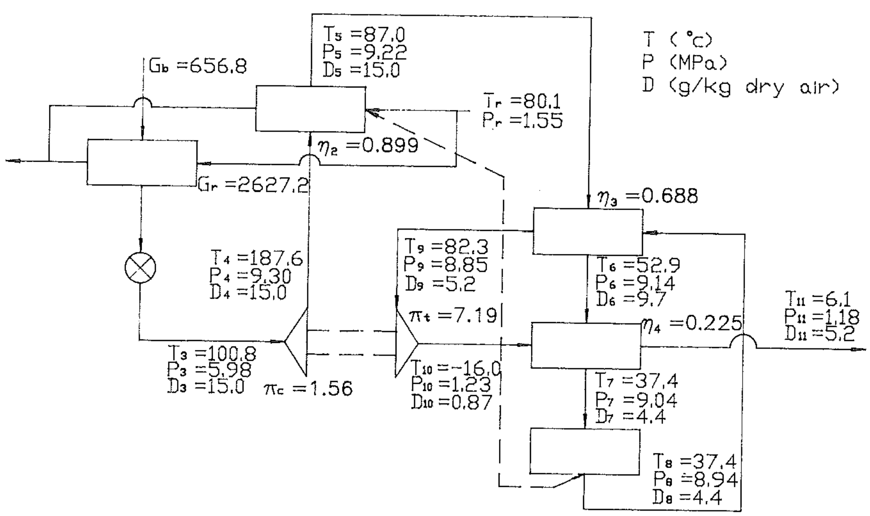

Fig.3 Performance of the Design Point

of bootstrap configuration ($\pi_t = 2.5 \sim 6.5$, $\pi_c = 1.5 \sim 2.2$, inlet temperature of compressor and turbine is between 50℃ and 120℃, system outlet temperature is 5℃ or so), it has such characteristics described as follows.

- little change of turbine and compressor efficiencies
- little change of velocity ratio χ_0 and flow factor $\bar{G}$ of the turbine
- almost constant value of θ an δ

Fig.4 are a group of test curves of the cooling turbine unit of bootstrap configuration which also leads to the same conclusion.

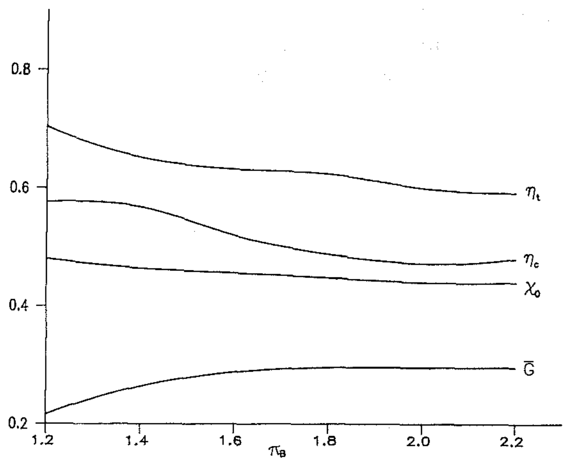

Fig.4 Test Performance of the Cooling Turbine Unit

According to the above–mentioned characteristics, such an assumption can be made that the efficiencies η_t、η_c、η_m、η_w,the velocity ratio χ_0 and flow factor $\bar{G}$of the turbine and the pressure ratio θ all remain constant along with the change of the flight condition.The calculation of system performance is simplified greatly but it also keeps enough precision.

Results Of Calculation

Performances of the system shown in Fig.3 at several different flight condition are calculated after proper geometrical parameters of the components are chosen. The computed results are arranged in Table 1.

Experimental Verification

Fig.5 shows the calculated results and test results of the temperature at each point of the system in a certain flight condition. The horizontal axis represents the points along the airstream sequently. It can be seen from the figure that they are in agreement in the main.

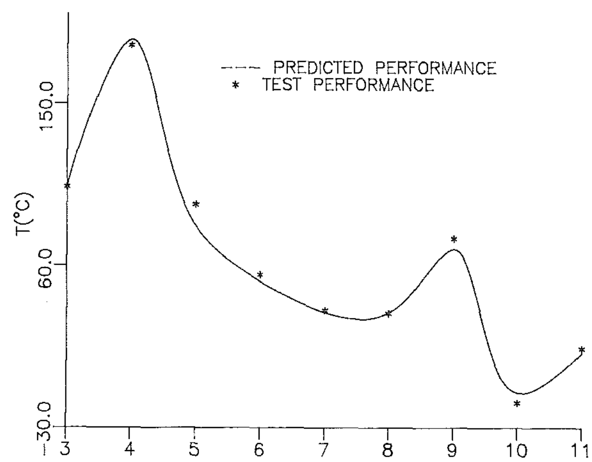

Fig. 5 Comparison of the Test Results and the Calculated Results

PARAMETERS	PERFORMANCES OF THE SYSTEM							
	DESIGN POINT	CHECKING POINTS						
H(km)	0	0	2.0	3.0	5.0	5.0	12.0	15.0
M	0.8	0.84	0.94	1.02	1.06	1.06	1.62	2.00
d_H (g / kg dry air)	15.0	18.2	14.0	2.21	10.25	1.25	2.87	0
$P_3\,(kg/cm^2)$	6.10	6.16	6.06	5.14	4.96	4.96	3.74	4.48
T_3 (℃)	100.8	104.4	103.1	110.0	99.5	99.5	106.5	120.0
G_b (kg / h)	656.8	656.6	676.4	567.1	557.4	557.5	417.8	526.9
G_r (kg / h)	2627.2	2700.0	2800.0	2880.0	2900.0	2900.0	1900.0	1100.0
$P_r\,(kg/cm^2)$	1.58	1.58	1.60	1.80	1.80	1.80	1.60	1.20
T_r (℃)	80.1	81.0	85.0	90.0	92.0	92.0	110.0	102.0
π_c	1.55	1.54	1.56	1.51	1.55	1.55	1.55	1.68
π_t	7.19	7.11	8.18	7.41	7.89	7.85	7.45	13.25
$P_{11}\,(kg/cm^2)$	1.20	1.20	1.05	0.95	0.88	0.88	0.69	0.49
T_{11} (℃)	6.1	12.4	12.5	−7.9	8.3	−8.3	9.23	3.2
d_{11} (g / kg dry air)	5.20	4.72	5.08	1.35	4.61	1.18	3.88	0
n_t (rpm)	72657	71686	76919	74476	75986	75358	76641	85240

Table 1 Performance of the Refrigeration System

DISCUSSION

It is obvious that the higher the efficiencies of the turbine, compressor and water separator are, the better. The water separator efficiency should at least be big enough to prevent the formation of water droplets at the outlet airflow of the system. The secondary heat exchanger has high efficiency, usually about 90 percent.

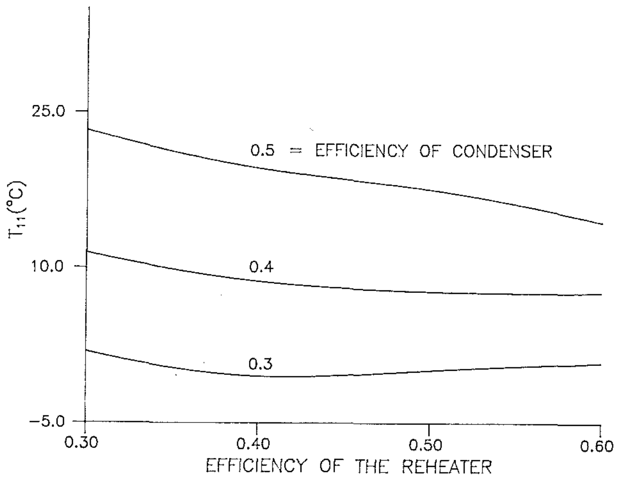

Fig. 6 Influence of Efficiencies of Reheater and Condenser

Fig. 6 shows the influence of the reheater efficiency and condenser efficiency to the outlet temperature. The increase of reheater efficiency results in rise of turbine inlet temperature and more drop in temperature through the turbine which is beneficial to the system . Increasing the condenser efficiency causes more water to be condensed, but the temperature rise through the cold side of the condenser also increases, which leads to a higher temperature at the system outlet. Therefore the reheater efficiency should be as high as possible within the range of weight permission, while the condenser efficiency be as low as possible after meeting the requirement of moisture remove.

The increase of ram air flow can lower the efficiency and the weight of the secondary heat exchanger, but it increases the penalty of the system. So it has an optimum intermediate value.

The computed results in Table 1 indicate relatively steady performance of the system. To the cooling turbine, the main factor affecting the rotational speed is the pressure at the exit as shown in Fig.7. It has a higher pressure ratio when the altitude is high and the cabin pressure is low. The rotational speed may be too high in this condition and this problem should be prevented to occur and considered in the design point.

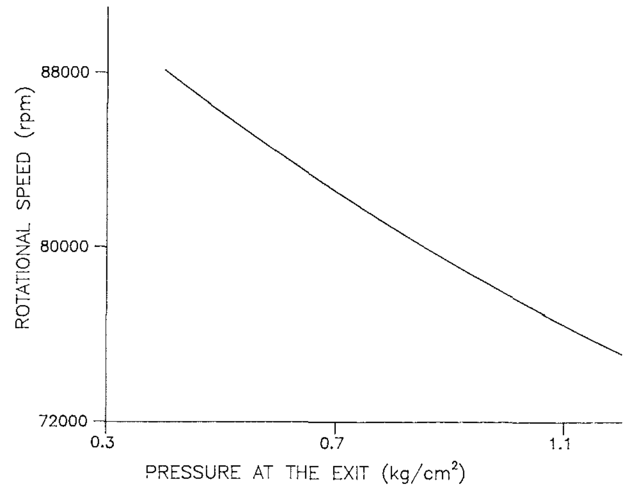

Fig. 7 Rotational Speed vs. Cabin Pressure

To the condenser, the biggest problem is the probability of freezing. The humidity of air is very low at a high altitude so that freezing is out of the question. When flying at low altitude and the humidity is lower than that of the design point, less potential heat is transferred and therefore the condenser has higher temperature drop which may lead to excessive low temperature in the condenser and freezing. The ice will block up the condenser and obstruct the normal work of the refrigeration system. To the cross–flow condenser, the outlet temperature of the hot side is not even. The end near the cold side inlet has lower temperature and is easier to freeze. The numerical calculation of the temperature field of the condenser can anticipate the freezing more accurately. Except for adjusting the parameters properly, an anti–ice airstream should be drawn into the condenser when the temperature is too low to prevent freezing.

SUMMARY

Quick calculation and comparison of the refrigeration system can be made by using the method and the relevant computer program presented in this article for the designer to select the best scheme. The computed results indicate that this kind of system can work steadily in different flight conditions and is suitable for various aircrafts.

SYMBOLS

c_p–specific heat at constant pressure (KJ / kg.K)
d –Relative humidity (g / kg dry air)

d_H–Bleed air humidity (g / kg dry air)
G_b, G_r–Total flow of bleed, ram air (kg / h)

$\overline{G}$ –Flow ratio of turbine $\frac{G_b\sqrt{T_9}}{P_9}$

H–Enthalpy (KJ / kg)
M–Mach Number
n_t –Rotational speed (rpm)
N_t, N_c–Power of turbine, compressor (kw)
P –Pressure (P_a)
T –Temperature (℃)
π_c –Pressure ratio of compressor
π_t –Pressure ratio of turbine
π_B –Pressure ratio of the cooling turbine unit P_3 / P_{10}
η_c, η_t, η_w, η_B–Efficiency of compressor, turbine, water separator, the cooling turbine unit
η_m– Mechanical efficiency
θ – Pressure ratio P_4 / P_9
δ – Temperature ratio T_3 / T_9
γ – Heat of vaporization (KJ / kg)
ξ – Melting heat of ice (KJ / kg)
χ_0 –Velocity ratio of turbine

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