

Article

Task-Level Energy Efficiency Evaluation Method Based on Aero-Engine Thrust-Specific Fuel Consumption with Application to Environment Control System

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Abstract: There has recently been a considerable and dramatic change in the system design of some future aircraft. The use of electrical energy has led to a demand for rapid technology development in the environment control system (ECS). Extracting energy from the aero-engine in the form of compressed air and electric power to drive the ECS directly affects aero-engine fuel economy. There is an urgent demand for a task-level energy efficiency evaluation method to guide energy and heat sink scheduling. This paper takes the F22 Raptor fighter jet as the research object and analyzes the influence of bleed air and electric power on the thrust and thrust-specific fuel consumption (TSFC) based on the exergy analysis method. First, a two-step TSFC surrogate model is constructed, and a task-level energy efficiency evaluation method is proposed. The error of the TSFC surrogate model is less than 5%, which means the accuracy of the model is sufficient to meet the needs of engineering. Then, the task-level energy efficiency evaluation results show that the vapor cycle has significant fuel economy when the cooling capacity is large, while the air cycle has certain advantages with a small cooling capacity. The method of TSFC surrogate model reduces computational complexity of evaluation with enough accuracy, which can provide a reference for selecting ECS type and guide the optimization of the cooling capacity distribution of the air cycle and vapor cycle.

Keywords: aero-engine; thrust-specific fuel consumption (TSFC); energy efficiency; environment control system (ECS); surrogate model



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1. Introduction

There has recently been a considerable and dramatic change in the system design of some future aircraft [1]. Electrical systems are being used in applications that have traditionally been powered by hydraulic, mechanical, or pneumatic power sources. The F22 and the F35 fighter jets both have significantly larger electrical systems than any previous aircraft [2,3]. This increases the use of electrical energy, which has led to a demand for rapid technology development, particularly in the environment control system [4].

Along with enlarged electrical systems, the thermal load on aircraft has grown by an order of magnitude [5]. The traditional air cycle refrigeration system struggles to meet the cold demand, so the F22 fighter jet introduced the electric-driven vapor cycle and liquid cooling cycle to solve the heat dissipation problem of radar, electronic warfare, and other high-power electronic equipment [6,7]. However, extracting energy from the aero-engine in the form of compressed air and electric power directly affects the fuel economy of aero-engines [8]. Therefore, there is an urgent need for a task-level energy efficiency evaluation method to guide the whole aircraft's energy and heat sink scheduling [7].

The fuel penalty method based on thrust-specific fuel consumption (TSFC) is the most commonly used way to evaluate the energy economy of an aircraft system. This

method converts the fuel penalty caused by the system's weight, electric power extraction, compressor bleed air, and ram air into the increased fuel consumption during flying. It has been applied to the components parameter optimization [9,10], subsystem design, and system scheme selection of aircraft ECS [11,12]. However, limited by the level of aero-engine performance simulation technology, TSFC is calculated according to the average power [13]. In fact, the TSFC value of the aero-engine varies under different flight conditions, and the compressor bleed air and electric power extraction also have a great influence on the TSFC [14,15].

C. E. Lents [8] defined the normalized energy consumption rate and fuel mass consumption rate to evaluate the influence of system weight, drag, and power demand on aircraft energy consumption. The fuel consumption of the hybrid aircraft was evaluated and the results showed that 1.5% of total mission fuel burn for the thermal management system in a flight mission profile of 2 h. R. Slingerland and S. Zandstra [16] evaluated the influence of bleed air and electric power extraction on the performance of the aero-engines of a commercial passenger aircraft and compared the fuel penalty of electrically driven and bleed air-driven air cycle ECS. Their result showed that 2% TSFC can be saved by using an electrically driven instead of bleed air-driven system for air cycle ECS.

To more accurately evaluate fuel economy during flight, system-level co-simulation is required. Roberts et al. [17,18] carried out a co-simulation of the adaptive power and thermal management system with the flight dynamics system, aero-engine, and fuel thermal management system. The energy and heat load requirements were analyzed in detail from the perspective of the whole aircraft. Connell et al. [19] studied the influence of bleed air-driven and electric-driven compressors on the TSFC of the main engine in the adaptive power and thermal management system. However, all of them adopted the modular modeling and simulation method for aero-engine system, which involves complex thermodynamics processes and performance parameters matching between the turbomachinery [20]. Although some efforts have been made in the early stages of component model simplification [21,22] and coupling solution algorithms [17,23], the aero-engine model is still too complex to have a low computational efficiency.

The method of the surrogate model provides a new way to simplify aero-engine models. It is used to replace the original complex model or test process with a simplified model. Researchers have carried out research on surrogate model construction for aero-engine inlets, compressors, combustion chambers, and other components, which greatly reduces the difficulty of aero-engine modeling and optimization [24–26]. Research on the surrogate model of aero-engine performance was also carried out. By analyzing the characteristics of turboshaft engine performance curves, Zhou and Qiu [27] used the least square method to obtain accurate engine performance curves and establish an engine power surrogate model. The test flight showed that the surrogate model can reflect the real performance of the engine.

In this study, an exergy analysis method is used to compare the effects of bleed air and electric power extraction on thrust and TSFC under different flight conditions of the aero-engine. The results show that there is a linear relationship between TSFC and exergy extraction in a certain range. According to the linear relationship, a two-step TSFC surrogate model is proposed to simplify the calculation of aero-engine performance parameters. When the flight mission profile and thrust profile of the aircraft are known, the slope and intercept of the linear relationship at any given moment can be obtained using this surrogate model so that the TSFC of the aero-engine can be quickly obtained by knowing only the bleed air and electrical power extractions during flight. Furthermore, a task-level energy efficiency evaluation was developed and used in the air cycle and vapor cycle. The rationality of the cooling capacity distribution scheme of the two refrigeration methods was verified.

2. Flight Profile and Engine Parameters

2.1. Flight Mission Profile

This paper takes the F22 Raptor fighter jet as the research object, and the fighter jet's flight mission profile is shown in Figure 1 and Table 1, including climb, cruise, ground attack, descent, and landing.

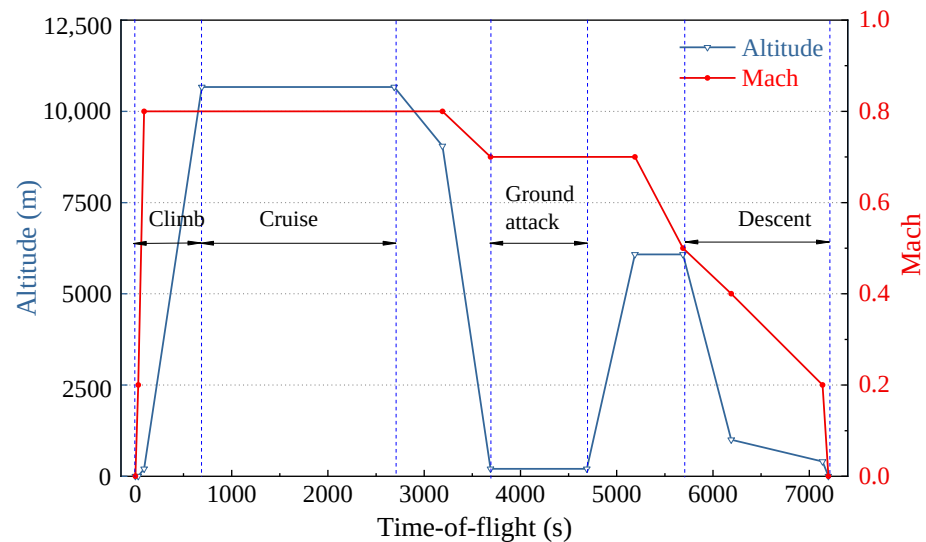


Figure 1. Flight mission profile of a fighter jet [18].

Table 1. State of flight mission phases.

NO.	$t(s)$	Altitude(m)	Mach	NO.	$t(s)$	Altitude(m)	Mach
1	0	0	0	8	4690	200	0.7
2	30	0	0.2	9	5190	6080	0.7
3	90	200	0.8	10	5690	6080	0.5
4	690	10,668	0.8	11	6190	1000	0.4
5	2690	10,668	0.8	12	7140	400	0.2
6	3190	9049	0.8	13	7200	0	0
7	3690	200	0.7				

2.2. Thrust Profile

When the aircraft is flying, the following relationships are satisfied between the lift F_L , the gravity F_G , the required thrust F_N , the drag F_D , and the true air speed v [18,28]:

$$m \frac{dv_x}{dt} = F_N - F_D - F_G \sin \theta \quad (1)$$

$$m \frac{dv_y}{dt} = F_L - F_G \cos \theta \quad (2)$$

$$F_L = \frac{1}{2} C_L \rho_{amb} v^2 S \quad (3)$$

$$F_D = \frac{1}{2} C_D \rho_{amb} v^2 S \quad (4)$$

$$C_L = C_{L\alpha 0} + C_{L\alpha} \cdot \alpha \quad (5)$$

$$C_D = C_{Dmin} + k_c (C_L - C_{LminD})^2 \quad (6)$$

where C_L and C_D are the lift coefficient and drag coefficient, respectively; $C_{L\alpha}$ is the derivative of the lift coefficient concerning the angle of attack; $C_{L\alpha 0}$ is $C_{L\alpha}$ at the zero lift coefficient; C_{Dmin} is the zero-lift drag coefficient; k_c is the induced drag coefficient; C_{LminD}

is the lift coefficient at C_{Dmin} ; ρ_{amb} is the ambient air density at the flight altitude, kg/m^3 ; and S is the wing area, m^2 .

The F22 Raptor fighter jet has a 19,700 kg empty weight, 8200 kg maximum fuel capacity, and 38,000 kg maximum take-off weight. In order to simplify the calculation, the mass of the fighter jet is assumed to be 30,000 kg [29]. According to the flight mission shown in Figure 1, Equations (1)–(6) are used to estimate the thrust at each flight mission point as shown in Figure 2.

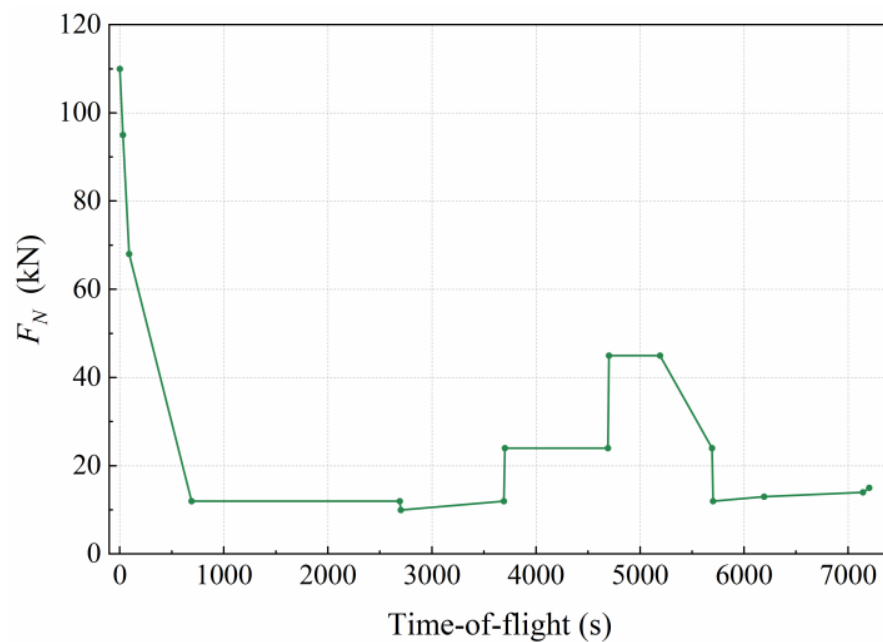


Figure 2. The required thrust profile of a flight mission.

2.3. Engine Design Parameters

Gasturb 12 is a gas turbine performance calculation and optimization program which has a complete aero-engine-type library and reliable calculation accuracy, so it is used worldwide in several industries as well as in science and education [30].

The F22 Raptor fighter jet uses two F119-PW-100 two-spool mixed flow turbofan engines (Figure 3), whose main parameters are as follows: a bypass ratio of 0.3, a fan pressure ratio of 2.5, a compressor pressure ratio of 10, and maximum thrust of 116 kN without afterburner [31]. The maximum thrust point on the ground is selected as the design point. Gasturb 12 is used to complete the design point parameter matching. Table 2 lists the design point parameter and the matching results.

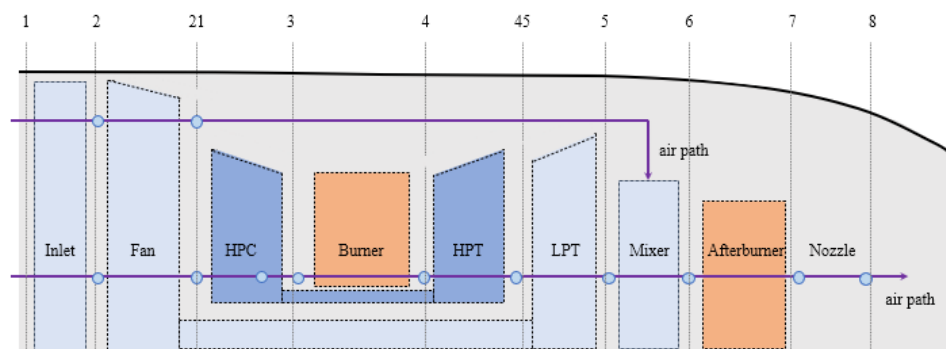


Figure 3. Schematic diagram of two-spool mixed flow turbofan engine.

Table 2. The design point parameters matching results.

(a) Design point parameters					
Variable	Unit	Value	Variable	Unit	Value
Intake Pressure Ratio		−0.99	Turb. Interd. Ref. Press. Ratio		0.98
No (0) or Average (1) Core dP/P		1	Design Bypass Ratio		0.3
Inner Fan Pressure Ratio		2.5	Burner Exit Temperature	K	1600
Booster Map Type (0/1/2)		0	Burner Design Efficiency		1
Fan Pressure Ratio		10	Burner Partload Constant		1.6
Compr. Interduct Press. Ratio		0.99	Overboard Bleed	kg/s	0
Bypass Duct Pressure Ratio		0.97	Power Offtake	kW	0
Fuel Heating Value	MJ/kg	43.124	Thrust	kN	116
(b) The result of parameter matching					
Station	Mass Flow (kg/s)	Total Temperature (K)	Total Pressure (kPa)	Corrected Flow	
amb	-	288.15	101.36	-	
1	-	288.15	101.36	-	
2	156.95	288.15	100.31	158.54	
21	120.74	398.36	250.79	57.36	
3	117.11	805.65	2482.78	7.99	
4	106.91	1600.00	2408.30	10.60	
45	118.99	1178.25	643.63	37.88	
5	122.61	1042.46	383.88	61.56	
6	122.61	1042.46	376.20		
8	158.82	908.39	323.31	88.38	
$F_N = 116$ kN					
TSFC = 18.46 g/(kN s)					

3. The Effect of Different Energy Extraction Methods on Engine Performance

3.1. Exergy Analysis Method

The thermodynamic exergy (the amount of work a system can perform when it is brought into thermodynamic equilibrium with its environment [32]) is introduced to unify the two energy forms of bleed air and electric power extraction. The exergy value of the electric power is equal to the amount of electric power extraction while the exergy value of bleed air can be calculated by the exergy equation of the stable flowing working fluid in the open system:

$$Ex = q_m [\Delta h - T_{amb} \cdot \Delta s] \quad (7)$$

$$\Delta h = \int_{T_{amb}}^{T_{bl}} c_p dT \quad (8)$$

$$\Delta s = \int_{T_{amb}}^{T_{bl}} c_p \frac{dT}{T} - R_g \ln \frac{p_{bl}}{p_{amb}} \quad (9)$$

where Ex is the exergy value of bleed air; W ; q_m is the mass flow rate of bleed air, kg/s; Δh is the enthalpy difference between bleed air and ambient air, J/kg; Δs is the entropy difference between bleed air and ambient air, J/(kg·K); c_p is the specific heat capacity of air at constant pressure, J/(kg·K); R_g is the gas constant of air, J/(kg·K); T and p is the temperature (K) and pressure (Pa) of the air, respectively. The subscript bl stands for bleed air, and amb stands for ambient air.

It is assumed that all the bleed air comes from the outlet of the high-pressure compressor, and the temperature and pressure of the bleed air are calculated by Gasturb 12. The ambient air state parameters are obtained by querying the international standard atmospheric parameters [33] according to the flight altitude of the aircraft.

3.2. Performance Impact Analysis of Design Point

Two-spool mixed flow turbofan engines usually adopt constant engine speed and constant turbine front temperature control mode. It can be obtained from Equations (7)–(9)

that the exergy value corresponding to the bleed air of 1 kg/s is 415.08 kW under the design point. Gasturb 12 software is used to calculate the changes of thrust and TSFC with bleed air and electrical power extraction.

Figure 4 shows the change of thrust and TSFC due to exergy extraction with different control modes. For the TSFC, we can see that the correlation between TSFC and exergy extraction is linear no matter what exergy extraction methods are selected. Therefore, the TSFC can be expressed as Equation (10). Additionally, the TSFC increases about 52.94% per 100 kW for bleed air compared with electrical power extraction under constant engine speed control mode. Similarly, the TSFC increases about 55.56% per 100 kW for bleed air compared with electrical power extraction under constant turbine front temperature control mode. This is because that bleed air results in less burner efficiency due to the reduced fuel–air ratio in the burner when extracting the same amount of exergy. The thrust change is similar to that of TSFC.

$$\varepsilon = kEx + \varepsilon_0 \quad (10)$$

where ε is the TSFC under the given operating conditions, g/(kN·s); k is the slope of the linear relationship between TSFC and the exergy extraction; ε_0 is the intercept of the linear relationship between TSFC and the exergy extraction, which also means the TSFC under the given flight conditions without exergy extraction, g/(kN·s).

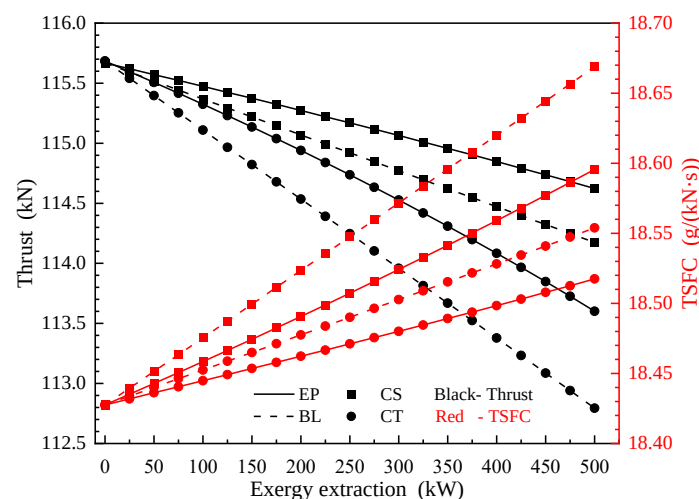


Figure 4. Influence of exergy extraction on engine performance parameters (EP, electric power extraction; BL, bleed air; CS, constant engine speed; CT, constant turbine front temperature).

4. Construction of TSFC Surrogate Model

According to the above analysis, the surrogate model of TSFC can be constructed. First, Gasturb 12 is used to obtain the changes of TSFC with the amount of bleed air and electrical power under different altitude H , Mach number Ma , and thrust F_N . Then, the linear relationship between TSFC and bleed air or electrical power extraction is determined through the fitting. The slope and intercept in TSFC relation are stored in the 3-D array which is constructed by H , Ma , and F_N as independent variables. The 3-D array is used as a sample database for interpolation calculation. Then, the first-order model of TSFC based on bleed air and electrical power is developed.

4.1. The First Step: Slope and Intercept Surrogate Model

TSFC can be expressed as a linear function of exergy as the independent variable. The slope and intercept of the line are related to the H , Ma , and F_N . According to Equation (7), the bleed air mass flow (q_m) is approximately linear with exergy value in a given flight condition. To facilitate the use of the surrogate model, q_m is directly taken as the independent variable. Based on the H , Ma , and F_N range in the flight mission profile and thrust profile shown in Figures 1 and 2, the sample levels of each factor are shown in Table 3.

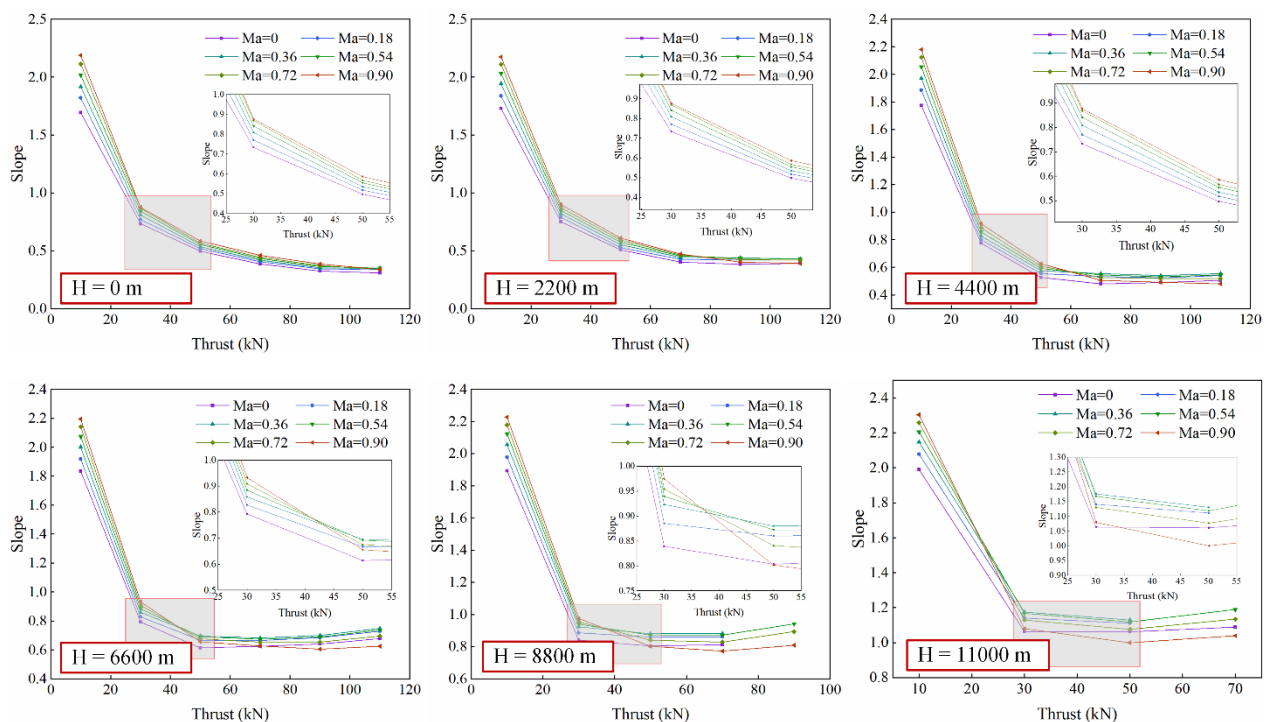
Table 3. Sample distribution.

Factors	Sample Level
H (m)	0, 2200, 4400, 6600, 8800, 11,000
Ma	0, 0.18, 0.36, 0.54, 0.72, 0.90
F_N (kN)	10, 30, 50, 70, 90, 110
q_m (kg/s)	0, 0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1, 2.4, 2.7, 3
W (kW)	0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100

Gasturb 12 software is used to obtain the TSFC of bleed air and electric power extraction (W) in each sample, and its linear relationship is obtained by fitting. The slope and intercept of the linear relationship with the change of q_m and W are shown in Figures 5–7, respectively.

It can be seen from Figures 5 and 6 that the slope of the fitted line is negatively correlated with F_N , that is, the smaller the F_N , the greater the slope of the fitted line. It also shows that when F_N is small, the influence of bleed air and electric power extraction on TSFC is more significant. However, the slope of the fitting line changes relatively little with the parameters of flight conditions.

Figure 7 shows the intercept of the fitting line varies with flight conditions. The intercept of the fitting line increases with the increase of Ma and decreases with F_N . This is because the increase in Ma brings larger flight drag, and it needs more fuel flow to produce more thrust to maintain a stable flight, which leads to a larger TSFC. When F_N is small, the intercept gradually decreases with the increase of H ; when F_N is large, the intercept gradually increases with the increase of H . Under the same flight conditions, the intercept of the fitted line decreases rapidly and then increases slowly with the increase in F_N . The inflection point roughly appears between 30 kN and 50 kN. At the left of the inflection point, the intercept decreases rapidly; to the right of the inflection point, the intercept slowly increases.

**Figure 5.** Influence of bleed air on the slope of the fitted line.

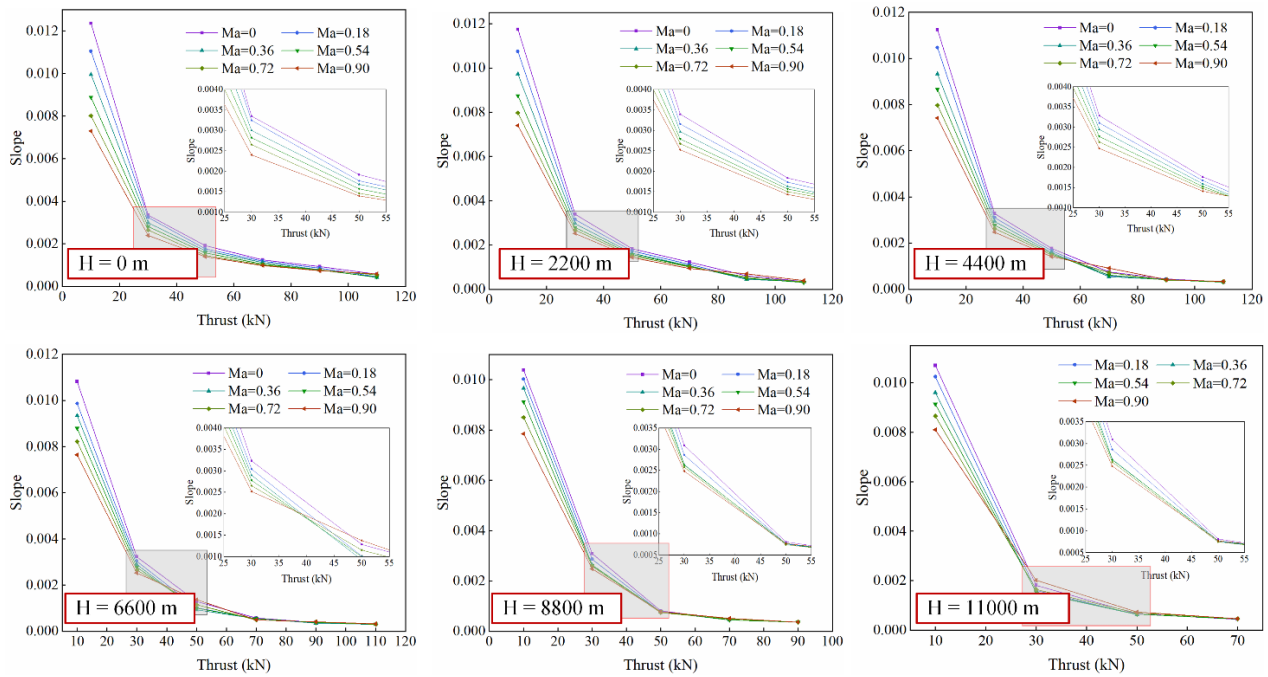


Figure 6. Influence of electric power extraction on the slope of the fitted line.

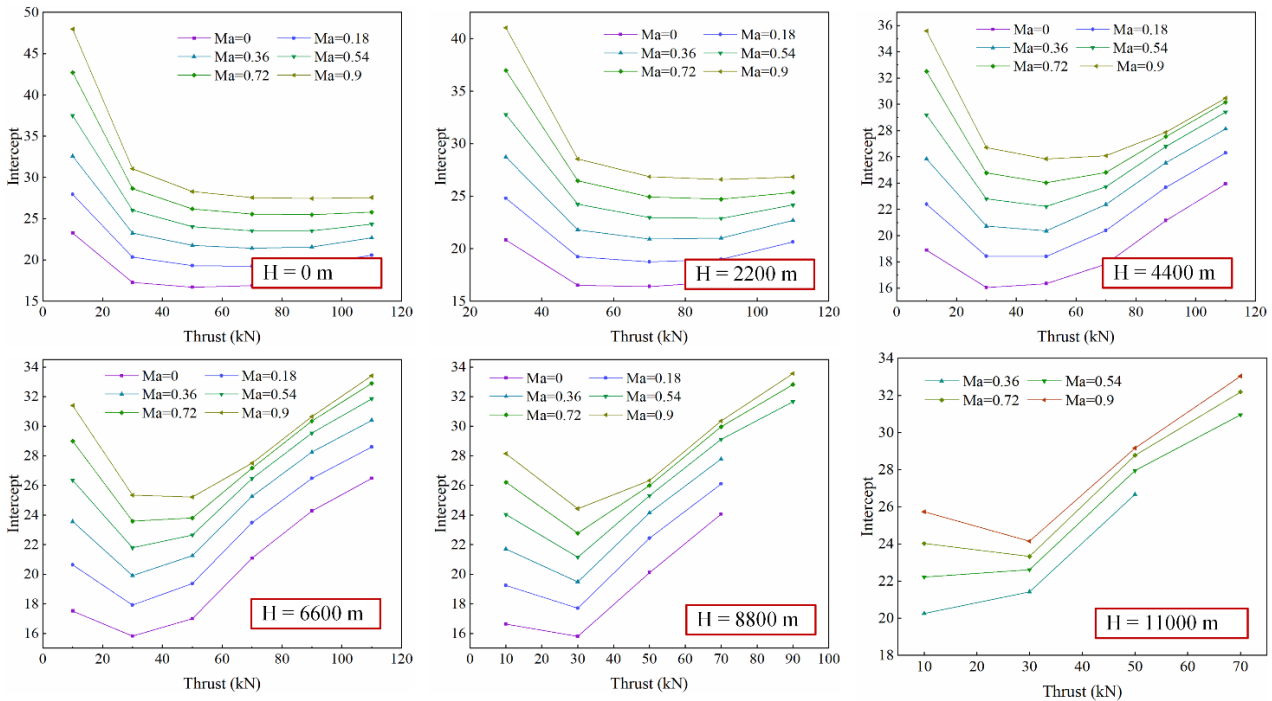


Figure 7. Changes in the intercept of the fitted line without energy extracted.

4.2. The Second Step: TSFC First-Order Response Surface Model

Since the effects of bleed air and electric power extraction on TSFC are independent of each other under the same H , Ma , and F_N , Equation (10) is further optimized to obtain Equation (11), which is used to calculate the TSFC under any operating conditions.

$$\varepsilon_i = k_{bl,i} q_{m,i} + k_{ep,i} W_i + \varepsilon_{0,i} \quad (11)$$

where k_{bl} is the slope of the linear relationship between TSFC and the amount of bleed air under the given operating conditions, $\text{k}^{-2}\text{N}^{-1}$; k_{ep} is the slope of the linear relationship

between TSFC and the amount of electric power extraction under the given operating conditions, $g/(kN \cdot W \cdot s)$. The subscript i stands for the i -th working condition.

4.3. The Two-Step TSFC Surrogate Model

Now, a two-step TSFC surrogate model is constructed, and the calculation process of the TSFC surrogate model is shown in Figure 8. When calculating the TSFC of a specific working condition, the sample database can be directly called, and the slope and intercept of the working condition can be obtained through interpolation. Considering that when F_N is small, the slope and intercept change greatly with F_N , if $F_N < 50$ kN, cubic spline interpolation can be used, and if $F_N \geq 50$ kN, linear interpolation can be used. Then, TSFC under this working condition is calculated by Equation (11).

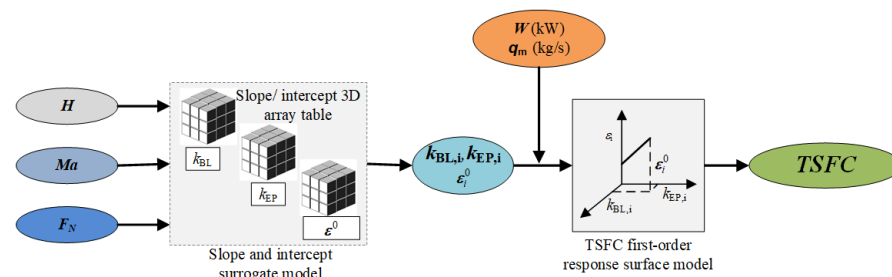


Figure 8. The calculation process schematic diagram of the TSFC surrogate model.

4.4. Validation of the TSFC Surrogate Model

Different combinations predicted by the point prediction feature of Gasturb 12 were used to validate the TSFC surrogate model. Four sets ((a) no energy extraction; (b) 10 kW electric power; (c) 1 kg/s bleed air; (d) 10 kW electric power and 1 kg/s bleed air.) of experiments were performed and the observed results were compared with the predicted results. Each of the sets contains, 10 mission points (1, 2, 3, 4, 6, 7, 8, 11, 12, 13), and all of them come from Table 1.

Figure 9 shows the predicted results of the TSFC surrogate model and Gasturb 12. The maximum error of the TSFC surrogate model is only 2.66%. It means the accuracy can meet the requirements of engineering applications. It is worth noting that the error is larger in missions 7, 11, 12, and 13. It is because that F_N is small during those flight missions so the slope and intercept of the fitting line change are relatively larger.

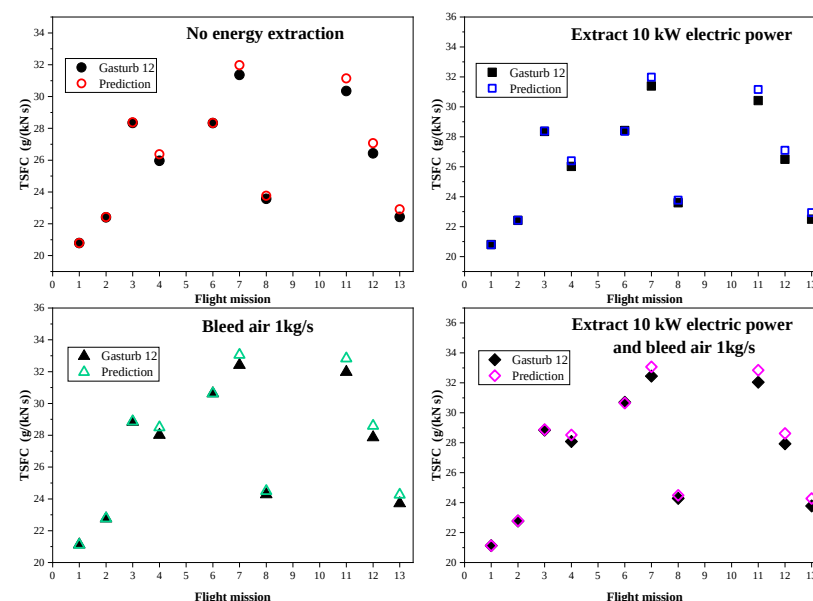


Figure 9. Comparison of TSFC calculation results.

5. Task-Level Energy Efficiency Evaluation of ECS

In this section, a task-level energy efficiency evaluation method of aircraft ECS is proposed using the TSFC surrogate model, and the fuel economy of the air and vapor cycle is analyzed.

5.1. Air Cycle Refrigeration System of Aircraft

A generic air cycle refrigeration system is shown schematically with its pressure–enthalpy diagram in Figure 10. From stations 0 to 8, we see that bleed air, which comes from engine, is cooled down in the primary heat exchanger, and after that, it is sucked into the compressor. Then it is compressed to a higher pressure and temperature and cooled down again in the secondary heat exchanger. Subsequently, the air is expanded in a turbine, which results in a low temperature. Next, the air enters the mixing chamber and mixes with the air coming from station 7 to obtain the required cabin temperature and pressure while doing useful work.

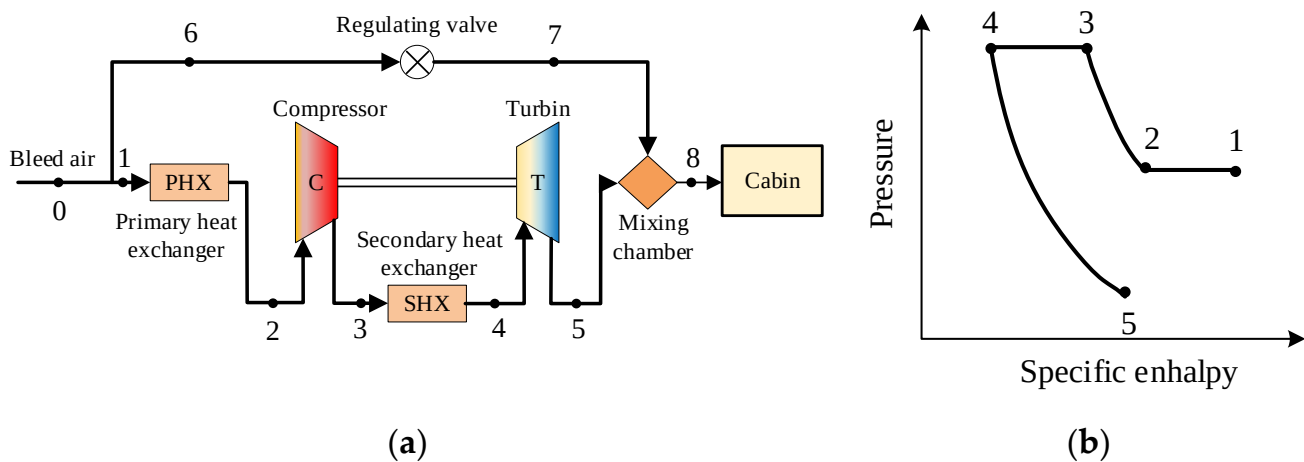


Figure 10. Schematic diagram and pressure–enthalpy diagram of air cycle refrigeration system. (a) Schematic diagram. (b) Pressure–enthalpy diagram.

The bleed air mass flow q_m required by the air cycle can be determined by the heat load and the temperature difference between the supply and exhaust air:

$$q_m = \frac{Q}{c_p(T_c - T_{acs})} \quad (12)$$

where Q is the heat load of the electronic equipment, W; T_c is the air temperature of the cabin, which is 20 °C; T_{acs} is the temperature of the supply air, which is generally −5 °C.

5.2. Vapor Cycle Refrigeration System of Aircraft

Figure 11 shows the schematic diagram and pressure–enthalpy diagram of the vapor cycle refrigeration system. In the vapor cycle, the refrigerant enters the electric compressor at a slightly superheated vapor state and is compressed to a higher pressure. The temperature of the refrigerant also increases after the compression step. Then, the refrigerant enters the condenser and is condensed into a saturated liquid state. Next, the refrigerant passes through the expansion valve, where it undergoes an abrupt reduction in pressure. That pressure reduction results in a lower boiling point of the liquid refrigerant. Following this, the liquid refrigerant absorbs thermal load in the evaporator and turns into a slightly superheated vapor state [34].

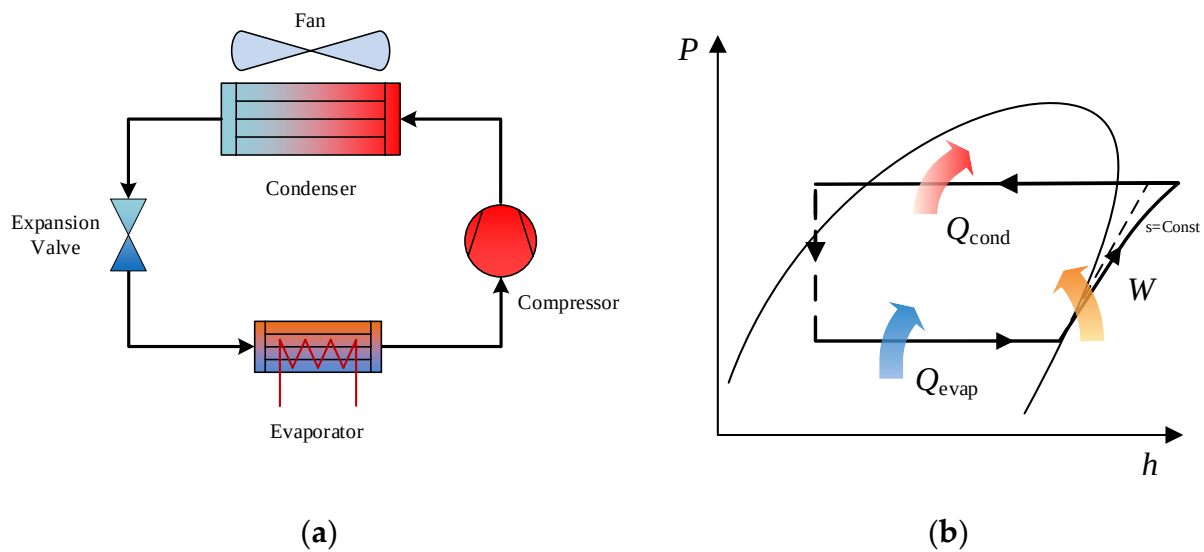


Figure 11. Schematic diagram and pressure–enthalpy diagram of vapor cycle refrigeration system. (a) Schematic diagram. (b) Pressure–enthalpy diagram.

In this study, R134a is considered as the refrigerant. The pressure of the refrigerant when it enters the compressor is referred to as the evaporation temperature, and the pressure of the refrigerant when it leaves the compressor is referred to the condensation temperature. As the refrigerant is generally condensed by fuel in the aircraft ECS, the condensation temperature is set to be 50 °C. The evaporation temperature is set to be −5 °C, and 5 °C superheating of the compressor suction is considered. The isentropic efficiency of the compressor is 0.75, and the equivalent efficiency of aircraft power generation and transmission is 0.8.

The electric power W consumed by the vapor cycle can be calculated according to the refrigeration coefficient COP :

$$W = \frac{1}{\eta} \frac{Q}{COP} \quad (13)$$

where the COP of the vapor cycle can generally be taken as 2.5, and η is the equivalent efficiency of aircraft power generation and transmission.

5.3. Bleed Air and Electric Power Extraction

Assuming that the thermal load Q of the fighter jet is 40 kW, 60 kW, and 80 kW, the engine bleed air or electric power required by the two kinds of the cooling method are shown in Table 4.

Table 4. Extracted energy required under different heat load requirements.

Refrigerating Capacity kW	Air Cycle Bleed Air kg/s	Vapor Cycle Electric Power kW
40	1.14	20
60	1.71	30
80	2.29	40

5.4. Results and Discussion

The flight mission and thrust profile data shown in Figures 1 and 2 with the bleed air and electric power required by the two cooling methods are substituted into the TSFC surrogate model, and the TSFC, along the flight mission, can be obtained, as shown in Figure 12.

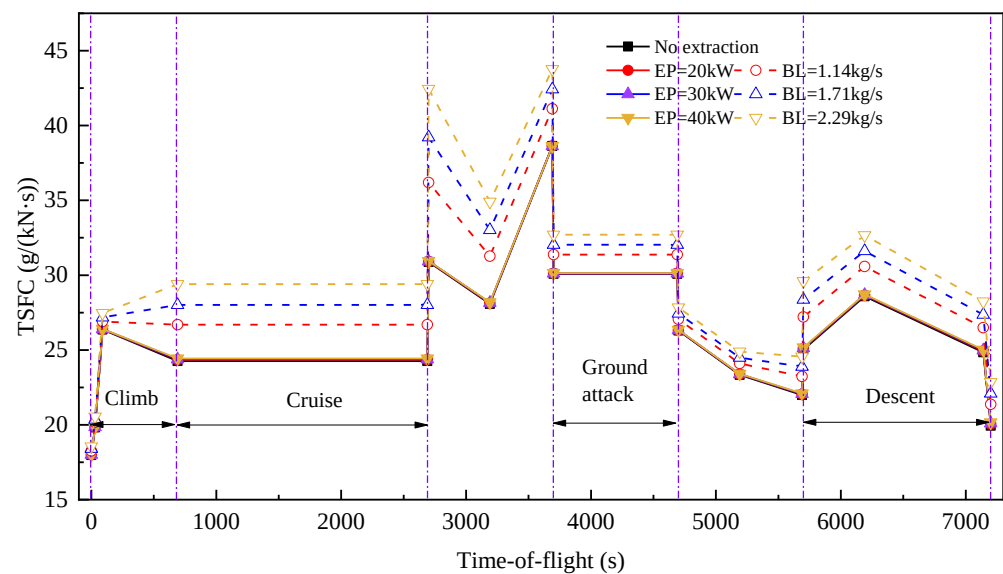


Figure 12. TSFC for each phase of the flight mission (EP, electric power extraction; BL, bleed air).

From Figure 12, the TSFC is high when the fighter jet is in the station of altitude cruise or descending. In the case of the climb, the difference between the two strategies is relatively small. In addition, the TSFC caused by the vapor cycle is significantly smaller than that of the air cycle. Compared with no power extraction, the TSFC of the air cycle is increased by at least 2%, while it is almost negligible for the vapor cycle.

Table 5 shows the total fuel consumption, M , of the flight mission profile, which is calculated by Equation:

$$M = \int_{t_s}^{t_e} \varepsilon(t) \cdot F_N(t) dt \quad (14)$$

where t_s is the start of mission time, s; t_e is the end of mission time, s; and $\varepsilon(t)$ and $F_N(t)$ are the TSFC and thrust at time t , respectively.

Table 5. The total fuel consumption.

Q kW	Electric Power Extraction				Bleed Air	
	W kW	M kg	$\frac{M-M_{base}}{M_{base}} \times 100\%$	q_m kg/s	M kg	$\frac{M-M_{base}}{M_{base}} \times 100\%$
Base	/	3837.63 kg	/	Base	3837.63 kg	/
40	20 kW	3844.47 kg	0.18%	1.14 kg/s	4060.33 kg	5.80%
60	30 kW	3847.89 kg	0.27%	1.71 kg/s	4178.51 kg	8.88%
80	40 kW	3851.33 kg	0.36%	2.29 kg/s	4301.80 kg	12.10%

According to Table 5, the base fuel consumption is 3837.63 kg when there is no power extraction. At 60 kW cooling capacity, the total fuel consumption by the vapor cycle is increased by 10.26 kg, but it is 340.88 kg for the air cycle. When the cooling capacity increases by 20 kW, the total fuel consumption of the vapor cycle increases by 0.18% and increases by about 5.80% for the air cycle. Therefore, in order to obtain the same cooling capacity, the air cycle has a more significant influence on the total fuel consumption. This is mainly because under the same working conditions, the refrigeration efficiency of the vapor cycle is much higher than that of the air cycle. At the same time, the temperature of bleed air coming from the engine is usually higher than 400 K, while the inlet temperature of the refrigeration turbine is generally lower than 350 K, which results in a large exergy loss.

From the perspective of direct fuel consumption, the energy efficiency of the vapor cycle is much higher than that of the air cycle. However, it is worth noting that the condenser and evaporator in the vapor cycle often have a large heat exchange area, resulting in a large volume and weight of the exchanger, which increases the load of the aircraft. Compared

with the air cycle, the vapor cycle requires more control parts and pipelines so its reliability is relatively reduced. In addition, to meet the demand for fresh air and pressurization in the cabin, the ECS often needs to provide a certain amount of high-pressure bleed air to the cabin, which also increases fuel consumption. Comprehensive analysis shows that the air cycle still has certain advantages in the application of aircraft ECS when the demand for cooling is small. When the refrigeration capacity is large, the additional fuel consumption generated by the air cycle is much larger than that of the vapor cycle, and the energy efficiency advantage of the vapor cycle is more clear.

6. Conclusions

In this paper, an exergy analysis method was introduced, and the influences of the exergy extraction method on TSFC were calculated by using Gasturb12 software. The results show there is a linear relationship between TSFC and exergy extraction. According to the linear relationship, a two-step TSFC surrogate model is proposed. Finally, a task-level energy efficiency evaluation of the air cycle and vapor cycle on the whole aircraft was carried out using the TSFC surrogate model. The main conclusions are as follows:

- (1) The error between the TSFC surrogate model and Gasturb12 is less than 5%, which means the accuracy of the TSFC surrogate model is sufficient to meet the needs of engineering.
- (2) According to the energy efficiency evaluation results of ECS, the vapor cycle has higher energy efficiency than the air cycle system when the cooling capacity is large. When the cooling capacity is small, the air cycle has certain advantages due to the low mass, reliable structure, and without the additional bleed air to fresh air and pressurization for the cabin.
- (3) The task-level energy efficiency evaluation method can provide a reference for the selection of the structure of the aircraft ECS and guide the cooling capacity distribution of coupled ECS with the air cycle and vapor cycle.

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Nomenclature

Subscripts

0	=	no energy extraction
acs	=	air cycle system
amb	=	ambient air
bl	=	bleed air
c	=	cabin
e	=	end
ep	=	electric power extraction
<i>i</i>	=	the <i>i</i> -th working condition
s	=	start

Variable

C_D	=	coefficient of drag (-)
C_{Dmin}	=	the zero-lift drag coefficient (-)
C_L	=	coefficient of lift (-)
$C_{L\alpha}$	=	the derivative of the lift coefficient concerning the angle of attack (-)
$C_{L\alpha 0}$	=	$C_{L\alpha}$ at the zero lift coefficient (-)
C_{LminD}	=	the lift coefficient at C_{Dmin} (-)
COP	=	the refrigeration coefficient (take $COP = 2.5$)
c_p	=	the specific heat capacity of air at constant pressure (J/(kg·K))
Ex	=	the exergy value of bleed air (W)
F_D	=	drag (kN)
F_G	=	gravity (kN)
F_L	=	lift (kN)
F_N	=	the required thrust (kN)
H	=	altitude (m)
h	=	the specific enthalpy (J/(kg K))
Δh	=	the enthalpy difference between bleed air and ambient environment (J/kg)
k	=	the slopes of the linear relationship between TSFC and the amount of bleed air
k_c	=	the induced drag coefficient (-)
M	=	fuel consumption (kg)
M_{base}	=	fuel consumption without power extraction (kg)
Ma	=	mach number (-)
p	=	pressure (Pa)
Q	=	the heat load of the electronic equipment (W)
q_m	=	the mass flow rate of bleed air (kg/s)
R_g	=	the gas constant of air (J/(kg K))
S	=	the wing area (m ²)
s	=	the specific entropy (J/(kg K))
Δs	=	the entropy difference between bleed air and ambient environment (J/(kg K))
T	=	temperature (take $T_{acs} = -5\text{ }^\circ\text{C}$)
t	=	the mission time (s)
v	=	true air speed (km/s)
W	=	electric power extraction (kW)
ρ	=	the air density (kg/m ³)
ε	=	thrust-specific fuel consumption (g/(kN s))
η	=	the equivalent efficiency of aircraft power generation and transmission, which can be taken as 0.8

Abbreviations

BL	=	bleed air
CS	=	constant engine speed
CT	=	constant turbine front temperature
ECS	=	environmental control system
EP	=	electric power extraction
TSFC	=	thrust-specific fuel consumption

References

1. Wheeler, P. Technology for the more and all electric aircraft of the future. In Proceedings of the 2016 IEEE International Conference on Automatica (ICA-ACCA), Curico, Chile, 19–21 October 2016; pp. 1–5. [\[CrossRef\]](#)
2. Robbins, D.; Bobalik, J.; De Stena, D.; Plag, K.; Rail, K.; Wall, K. F-35 Subsystems Design, Development, and Verification. In *The F-35 Lightning II: From Concept to Cockpit*; American Institute of Aeronautics and Astronautics, Incorporated: Reston, VA, USA, 2019; pp. 365–398. [\[CrossRef\]](#)
3. Sarlioglu, B.; Morris, C.T. More Electric Aircraft: Review, Challenges, and Opportunities for Commercial Transport Aircraft. *IEEE Trans. Transp. Electrification* **2015**, *1*, 54–64. [\[CrossRef\]](#)
4. Fanxin, M.; Ruiqi, W.; Zanjun, G.; Wenyuan, Z.; Wenchao, H. Research of key technology for the more electrical aircraft electric environmental control system. *Aeronaut. Sci. Technol.* **2018**, *29*, 1–8. [\[CrossRef\]](#)
5. Wang, J.; Yunze, L.; Liu, X.; Shen, C.; Zhang, H.; Xiong, K. Recent active thermal management technologies for the development of energy-optimized aerospace vehicles in China. *Chin. J. Aeronaut. Engl. Ed.* **2020**, *34*, 1–27. [\[CrossRef\]](#)

6. Price, D.C. A review of selected thermal management solutions for military electronic systems. *IEEE Trans. Compon. Packag. Technol.* **2003**, *26*, 26–39. [\[CrossRef\]](#)
7. Tu, M.; Yuan, G.; Xue, F.; Wang, X. Application of integrated thermal management in development of advanced fighter system. *Acta Aeronaut. Astronaut. Sin.* **2020**, *41*, 136–146. [\[CrossRef\]](#)
8. Lents, C.E. Impact of Weight, Drag and Power Demand on Aircraft Energy Consumption. In *AIAA Propulsion and Energy 2021 Forum*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2021. [\[CrossRef\]](#)
9. Zang, X.; Liu, Y.; Xu, X. Performance Simulation and Improvement of New Type Aircraft Environment Control System Base on AMESim software. *Aircr. Des.* **2018**, *38*, 56–60. [\[CrossRef\]](#)
10. Li, X.; Chen, Q.; Hao, J.-H.; Chen, X.; He, K.-L. Heat current method for analysis and optimization of a refrigeration system for aircraft environmental control system. *Int. J. Refrig.* **2019**, *106*, 163–180. [\[CrossRef\]](#)
11. He, H.; Hao, J. Optimum design for environmental control system of aircraft cabin. *J. Beijing Univ. Aeronaut. Astronaut.* **1996**, *22*, 563–569. [\[CrossRef\]](#)
12. Han, Y.; Zhang, X.; Chao, W.; Yang, C. Experimental and theoretical study on a novel energy-saving ECS for commercial airliners. *Appl. Therm. Eng.* **2017**, *127*, 1372–1381.
13. Shou, R.; He, H. *Aircraft Environmental Control*; Beijing University of Aeronautics and Astronautics Press: Beijing, China, 2003.
14. Rosales, M.A. *A Preliminary Study for Selecting and Optimizing the Environmental Control System*; Technical University of Madrid: Madrid, Spain, 2018.
15. Jingyang, Z.; Fengying, Z.; Yeping, X. Impact Analysis of Integrated Control of Shaft Power Extraction and Air Intake on Fuel Economy of Aeroengine. *Aeroengine* **2019**, *45*, 9–14. [\[CrossRef\]](#)
16. Slingerland, R.; Zandstra, S. Bleed Air versus Electric Power Off-takes from a Turbofan Gas Turbine over the Flight Cycle. In *Proceedings of the 7th AIAA ATIO Conference, 2nd CEIAT Int'l Conf on Innov and Integr in Aero Sciences, 17th LTA Systems Tech Conference, Followed by 2nd TEOS Forum, Belfast, Northern Ireland, 18–20 September 2007*; American Institute of Aeronautics and Astronautics: Belfast, Northern Ireland, 2007. [\[CrossRef\]](#)
17. Roberts, R.A.; Eastbourn, S.M. Modeling techniques for a computational efficient dynamic turbofan engine model. *Int. J. Aerosp. Eng.* **2015**, *2014*, 283479. [\[CrossRef\]](#)
18. Roberts, R.; Eastbourn, S. Vehicle level tip-to-tail modeling of an aircraft. *Int. J. Thermodyn.* **2014**, *17*, 107–115. [\[CrossRef\]](#)
19. O'Connell, T.C.; Lui, C.; Walia, P.; Tschantz, J. A hybrid economy bleed, electric drive adaptive power and thermal management system for more electric aircraft. *SAE Int. J. Aerosp.* **2010**, *3*, 168–172. [\[CrossRef\]](#)
20. Aghaei Tog, R.; Mesgarpoor Tousi, A. An empirical model for partially admitted turbine efficiency. *Aircr. Eng. Aerosp. Technol.* **2015**, *87*, 238–248. [\[CrossRef\]](#)
21. Yu, B.; Miao, R.C.; Shu, W.J. A Rapid Method for Modeling a Variable Cycle Engine. *Jove J. Vis. Exp.* **2019**, *150*, e59151. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Tsoutsanis, E.; Meskin, N.; Benammar, M.; Khorasani, K. An efficient component map generation method for prediction of gas turbine performance. In *ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*; American Society of Mechanical Engineers Digital Collection: New York, NY, USA, 2014. [\[CrossRef\]](#)
23. Kurzke, J. About simplifications in gas turbine performance calculations. In *ASME Turbo Expo 2007: Power for Land, Sea, and Air*; American Society of Mechanical Engineers Digital Collection: New York, NY, USA, 2007; pp. 493–501. [\[CrossRef\]](#)
24. Mack, Y.; Goel, T.; Shyy, W.; Haftka, R. Surrogate model-based optimization framework: A case study in aerospace design. In *Evolutionary Computation in Dynamic and Uncertain Environments*; Springer: Berlin/Heidelberg, Germany, 2007; pp. 323–342.
25. Liu, W.; Sivaramakrishnan, R.; Davis, M.J.; Som, S.; Longman, D.; Lu, T. Development of a reduced biodiesel surrogate model for compression ignition engine modeling. *Proc. Combust. Inst.* **2013**, *34*, 401–409. [\[CrossRef\]](#)
26. Dreżek, P.S.; Kubacki, S.; Żółtak, J. Multi-objective surrogate model-based optimization of a small aircraft engine air-intake duct. *Proc. Inst. Mech. Eng. Part G J. Aerosp. Eng.* **2022**. [\[CrossRef\]](#)
27. Zhou, L.; Qiu, L. A New Method to Deal with Engine Test Data and to Build Agent Model of Engine. *Helicopter Technol.* **2019**, *4*, 32–35.
28. Sha, Z. *Aircraft Design Manual. Volume 4, General Design of Military Aircraft*; Aviation Industry Press: Beijing, China, 2005.
29. Riccardo, L. *Lockheed Martin F/A-22 Raptor*; Istituto Tecnico Industriale: Andria, Italy, 2012.
30. Kurzke, J. *GasTurb 12-Design and Off-Design Performance of Gas Turbines-Manual*; GasTurb GmbH: Aachen, Germany, 2014.
31. Chen, J. Development trend of military aero engine. *Aeronaut. Sci. Technol.* **1994**, *5*, 9–12.
32. Jorgensen, S.E.; Svirezhev, Y.M. *Towards a Thermodynamic Theory for Ecological Systems*; Elsevier: Amsterdam, The Netherlands, 2004. [\[CrossRef\]](#)
33. Gooch, J.W. *Standard Atmosphere*; Springer: New York, NY, USA, 2007. [\[CrossRef\]](#)
34. Müller, C.; Scholz, D. *The Vapor Compression Cycle in Aircraft Air-Conditioning Systems*; Aircraft Design and Systems Group (AERO), Department of Automotive and Aeronautical Engineering, Hamburg University of Applied Sciences: Berlin, Germany, 2017; p. 23.