Article

Exergetic Effects of Cooled Cooling Air Technology on the Turbofan Engine during a Typical Mission

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Abstract: The cooled cooling air technology (CCA technology) shows expected performance in solving the growing thermal challenge for advanced aero engines by reducing the temperature of cooling air. The effect of CCA technology on the overall propelling performance with or without adjusting cycle parameters is controversial. Based on this, both the energy and exergy methods have been adopted to elaborate the specific mechanisms of the above energy utilization discrepancy. As a result, the scheme of CCA technology without optimizing cycle parameters has lower propelling work and efficiency with the total exergy destruction increasing 0.5~2%. Oppositely, as for the scheme of CCA with meliorated cycle parameters, the propelling efficiency improved by around 2~4% with total exergy destruction reduced by 1~3.5%. By analyzing the distribution of exergy destruction, the avoidable and unavoidable exergy destruction caused by the combustion chamber, compressors, and turbines accounts for the largest proportion, which indicates that more attention needs to be paid in the future. During the whole flight mission, the percentage of exergy destruction is much higher in supersonic, subsonic cruise, combat, and escape conditions. In conclusion, the improvement of cycle parameters to reduce the exergy destruction should be considered when introducing CCA technology.

Keywords: exergy analysis; CCA technology; flight mission; turbofan engine; integrated model

1. Introduction

With the blowout development of the global aviation industry, air pollution from aero engine emissions has received widespread attention. In 2019, the carbon emissions of the global aviation industry came to 915 tons, accounting for 2.1% of global carbon dioxide emissions, including NOx, CO2, SOx, H2O, and CO [1]. The aviation sectors have even expensed about one trillion dollars in an attempt to reduce fossil fuel consumption by improving the fuel availability of engines [2,3]. Civil and military aircraft generally equip the aero engine based on the Brayton cycle, such as turbofan, turbojet, and turboprop engines [4,5]. Currently, the improvement of engine efficiency mainly depends on the increase of cycle pressure ratio and turbine inlet temperature. This leads to the inevitable higher temperature of compressor exit and turbine entrance which require more cooling flows for turbines to protect the turbine blade wall. In the late 1980s, the cooled cooling air technology (CCA technology) was applied to the engine to solve the above problems [6].

CCA technology firstly utilizes the cooling capability of bypass air or fuel to cool the bleed air from the high-pressure compressor (HPC), and then the cooled air absorbs more heat loads from the high-temperature components in the engine [7]. NASA has reported
that the lower bleed air temperature could also be used to permit operation at lower coolant flows or higher turbine inlet gas temperatures [8]. Another study has also demonstrated the satisfactory performance of CCA technology in preventing turbine blades from ablating by high-temperature gas [9]. Recent research has pointed out that CCA technology could improve the thermal efficiency of the supersonic commercial engine, reducing its fuel consumption by about 453.59 kg per flight mission [10]. Consistently, the take-off carrying capability and accelerating ability of the military turbofan engine could also be improved by CCA technology [6].

Of interest, two recent studies showed conflicting results about whether CCA technology could improve propelling performance of turbofan engines. Gray et al. [11] found that the overall thrust and thermal efficiency of the engine decreased when only using CCA technology without adjusting the cycle parameters. Nevertheless, Boyle et al. [12] revealed that the propelling performance increased significantly after optimizing the cycle parameters. A possible explanation might be that the propelling performance depends on the differences in energy destruction caused by whether the parameters are optimized or not.

Although CCA technology has been widely demonstrated for application in engineering, the effect of CCA technology on the energy utilization of each component under various conditions remains inexplicit. According to the first law’s approach to thermodynamics, energy analysis treats work and heat interactions as equivalent forms of energy in transit, which is insufficient from an energy performance standpoint [13]. However, the exergy analysis based on the second law of thermodynamics utilizes the mass conservation and quality of energy degradation along with the entropy generation in the analysis design and improvement of energy systems. Therefore, the exergy analysis is thought to be significant, especially in the field of new technologies with high-temperature air combustion and ultra-high temperature combined cycles. Furthermore, with the development of exergo-economic [14–16] and exergo-environmental analysis methods [17,18], the impacts of economic-environment sustainability during each energy process are better understood, and the most potential areas for improvement are also clarified with increasing attention.

Numerous studies have noted that exergy analysis has wide application prospects in the field of aviation propulsion systems. The exergy analysis is reliable in evaluating the energy utilization of different engines in detail. Ozgur Balli and Hakan Caliskan [19] applied the exergy analysis to the operation performance assessments of turboprop engines at on-design and off-design points. The superiority of the variable-cycle engine could be revealed by the exergy method by comparing its exergy efficiency with the traditional engine [20]. Recently, Hakan Aygun et al. [21] also pointed out that the exergy efficiency of variable cycle engines was various during the whole flight phases. The exergy method has been successfully applied in analyzing a series of engine cycle parameters. Some discovered that commercial turbofan engines with high bypass and overall pressure ratio showed prominent advantages considering energy efficiency and environmental costs [22]. Taking the exergetic parameters as the target, the cycle parameters of the PW-4000 engine could be optimized to improve the efficiency of energy utilization [23]. The conventional exergy method identifies the locations and magnitudes of thermodynamic irreversibility. Based on this, the advanced exergy method identifies the potential improvements for a real thermodynamic process by dividing the exergy destruction into its avoidable and unavoidable parts [24]. The primary role of advanced exergy analysis is to provide engine designers and operators with useful information for improving the design. Hepbasli et al. [25,26] pointed out that the avoidable exergy destruction occurring in the combustion chamber, compressor, and turbine was significantly higher than in other components. These findings suggest that optimizing the design of compressors, combustors, and turbines to reduce their avoidable exergy destruction deserves more attention.
Similar to any other energy system, the engine with CCA technology contains entropy generation and exergy destruction during the irreversible flow friction and heat transfer processes. With the addition of CCA technology, other energy conversion processes in the engine could be also changed due to the interaction of mass and energy among components. For all these reasons, exergy analysis of the engine applied CCA technology is essential to demonstrate its impacts on the irreversible distribution, exergy utilization changes, and energy degradation of the turbofan engine. Furthermore, it provides a theoretical basis for a better understanding of its impact on engine sustainability and economics. Nonetheless, the specific mechanism of how CCA technology with or without optimizing cycle parameters affects the propulsion performance under various off-design conditions has not been fully elucidated before.

Here, this study first uses the exergy analysis to evaluate energy utilization and distribution of CCA technology under different situations including CCA technology without optimizing cycle parameters and optimizing pressure ratio and turbine inlet temperature. Furthermore, not only exergy destruction rate but also flight duration is considered during the whole flight mission.

2. Engine Schemes with CCA Technology

The concept of CCA technology is to utilize the cooling capability within bypass air or aviation kerosene to reduce the temperature of high-pressure bleed air. In this study, two schemes are proposed to investigate the effect of CCA technology on energy utilization and conversion performance under different situations. As illustrated in Figure 1a [27], the bypass air is selected as a heat sink and a serpentine tube heat exchanger (STHE) is adopted, considering the maturity and reliability of the technology. The left bottom of Figure 1a shows the STHE is applied in the combustion chamber casing. The HPC bleed air flows into tubes of STHE, which finishes the heat exchange with bypass air at the outside of the tubes. The right bottom of Figure 1a gives the detailed structure of the STHE, in which independent geometric variables include the outside diameter of a single tube (\(d_{\text{out}}\)), the transverse and longitudinal tube pitches (\(s_1\) and \(s_2\)), the height (\(L_3\)), the number of the transverse tube rows (\(N_T\)), the number of elbows (\(B_{\text{No}}\)), and the number of inlet tubes in a single row (\(N_I\)). Based on the above geometric variables, the heat transfer and flow areas could be calculated, referring to Ref. [27]. As shown in Figure 1b, cycle parameters of scheme A at the design point are given from the F-119 engine, which is proposed to study the effect of CCA technology when it is used to modify the existing engine. Meanwhile, scheme B has adjusted its pressure ratio and turbine inlet temperature under the constraints of thrust requirements and temperature limitation of a turbine blade, to find out the influential principle on the under-developing engine. According to the existing turbofan engine, serpentine tube heat exchanger, and turbine blade temperature thermodynamic model, the results adjusted by CCA technology are given in Figure 1b. The pressure ratio of the fan and high-pressure compressor could increase by 24.44% and 20.69%, and the turbine inlet temperature also rises by 2.15%. The thermodynamics and mass flow rate information for the components in different schemes at the design point is shown in Table 1, and it can be seen that the specific fuel consumption slightly reduces in scheme A but is the opposite. Besides, the total thrust of scheme A is also lower than the F-119 engine. From the view of the second thermodynamic law, the additional entropy generation appears during heat exchanging between bleed and bypass air, and the mixing process of gas and the bleed air (because the temperature difference increases, as shown in Table 1). In the following sections, the detailed mechanism of how CCA technology affects the energy conversion, transport, and utilization among components will be investigated by the exergy analysis method.
Figure 1. The concept diagram of CCA technology and engine schemes. (a) Diagram of CCA technology [27]; (b) Cycle parameters of design point.

Table 1. The thermodynamics and mass flow rate information for the components in different schemes at design point.

| Location | F-119 Engine | Scheme A | Scheme B |
|----------|--------------|----------|----------|
| $m_0$ (kg/s) | 122.22 | 122.22 | 122.22 |
| $m_f$ (kg/s) | 2.50 | 2.50 | 2.40 |
| $m_{f,ab}$ (kg/s) | - | - | - |
| BPR | 0.3 | 0.3 | 0.3 |

Pressure of engine at different locations (kPa)

| Location | F-119 Engine | Scheme A | Scheme B |
|----------|--------------|----------|----------|
| $P_0$ | 101.33 | 101.33 | 101.33 |
| $P_1$ | 98.29 | 98.29 | 98.29 |
| $P_2$ | 98.29 | 98.29 | 98.29 |
| $P_{13}$ | 442.28 | 442.28 | 550.40 |
| $P_{21}$ | 442.28 | 442.28 | 550.40 |
| $P_3$ | 2565.25 | 2565.25 | 3852.78 |
| $P_{31}$ | 2565.25 | 2565.25 | 3852.78 |
| $P_4$ | 2488.29 | 2488.29 | 3737.20 |
| $P_{41}$ | 2488.29 | 2488.29 | 3737.20 |
| $P_{42}$ | 928.56 | 921.06 | 1131.87 |
| $P_{45}$ | 928.56 | 921.06 | 1131.87 |
| $P_{46}$ | 928.56 | 921.06 | 1131.87 |
| $P_{47}$ | 446.79 | 438.59 | 468.64 |
| $P_5$ | 446.79 | 438.59 | 468.64 |
| $P_{16}$ | 442.28 | 439.28 | 547.81 |
| $P_6$ | 430.31 | 423.80 | 463.23 |
| $P_7$ | 417.40 | 411.09 | 449.34 |
| $P_9$ | 404.88 | 396.81 | 440.31 |

Temperature of engine at different locations (K)

| Location | F-119 Engine | Scheme A | Scheme B |
|----------|--------------|----------|----------|
| $T_0$ | 288.15 | 288.15 | 288.15 |
| $T_1$ | 288.15 | 288.15 | 288.15 |
| $T_2$ | 288.15 | 288.15 | 288.15 |
| $T_{13}$ | 468.85 | 468.85 | 496.82 |
| $T_{21}$ | 468.85 | 468.85 | 496.82 |
| $T_3$ | 808.21 | 808.21 | 900.42 |

Scheme A: CCA without adjusting cycle parameters

- $B$ = 0.3
- $\pi_{\text{FAN}}$ = 4.5
- $\pi_{\text{HPC}}$ = 5.8
- $T_m$ = 1860 K

Scheme B: CCA with adjusting cycle parameters

- $B$ = 0.3
- $\pi_{\text{FAN}}$ = 5.6
- $\pi_{\text{HPC}}$ = 7
- $T_m$ = 1900 K
3. Methods

Before the exergy analysis, the basic thermodynamic parameters need to be identified to calculate the exergy parameters, including temperature, pressure, and mass flow of working fluid at each component. Thus, the thermodynamic analysis based on the conservation of energy is essential. Distinct from other energy systems, the aircraft engine usually needs to satisfy the various thrust requirements for different flight conditions. So, it demands an integrated model to calculate the needed thrust at each mission segment and synchronously determine the engine’s working condition. Based on the integrated model, the thermodynamic analysis of different engine schemes has been conducted during the full flight mission. In this framework, the aircraft-engine thermodynamic program, including aircraft force balance analysis, multi-level engine, and energy/exergy analysis models is developed, and its logic diagram is presented in Figure 2. The simulating steps are as follows:

(1) Identify the engine scheme type (F-119, scheme A or B) and input its cycle parameters. For the F-119 scheme, the CCA heat exchanger submodule is closed, and for the latter two schemes, this submodule starts using the bypass air to cool the HPC bleed air.

(2) Calculate the thermodynamic parameters at each section for the given engine type, and then the takeoff thrust ($F_{TO}$) could be given.

(3) Obtain exergy parameters in each component at takeoff condition, and then calculate the exergy destruction and other exergetic indicators.

(4) Identify the total takeoff weight ($W_t$) and its composition by the ratio of thrust and weight ($\gamma_{TO}$), and the involved parameters include takeoff fuel factor (0.42), aircraft structural factor (0.465), and payload weight (1205 kg).

(5) Calculate the fighter weight at takeoff task termination based on the flight duration ($\tau_1$) and fuel consumption ($sfc_1$), and output it for the next step.

(6) Determine the thrust requirement ($F_{req_2}$) at the next mission segment by the aircraft force balance analysis model, and pass it to the engine model.

(7) Operate the engine program under the flight environment of the new mission segment to match the needed thrust, and obtain temperature, pressure, and mass.
flow at each section of this mission. Meanwhile, the fuel consumption \((sfc)\) is also calculated.

(8) Input the based thermodynamic parameters of the engine at this mission into the exergy analysis model for obtaining exergy indicators.

(9) Repeat steps 4 to 7 until finishing all mission segments.

(10) Finish the energy and exergy analysis of the given scheme under the full flight conditions and return to Step 1 for starting simulation of the next scheme.

![Figure 2. The logic schematic of aircraft-engine integrated simulating.](image)

The research hypotheses made in the present research are listed as follows:

1. The acceleration mission is regarded as a uniformly accelerated process;
2. The static pressure of exhaust air at the design point is equal to the environmental pressure;
3. The potential exergy is neglected.
4. The working conditions of the engine are steady-state and flow;
5. The properties of the fuel are calculated by RP-3 aviation kerosene, and its lower heating value is 43370.596 kJ/kg [25];
6. The working fluid (air and gas) are regarded as ideal gases;
7. The air compressors and gas turbines are considered adiabatic, and the secondary airflow used to cool the CC wall is mixed with the air participating in combustion.

The reference condition is selected as 273.15 K and 101,325 Pa.

3.1. Aircraft-Engine Thermodynamic Model

In the aircraft force balance analysis model, the needed thrust of different mission segments is calculated by Equation (1) [28]

\[
F = \frac{Wei}{2L_{10}} \frac{v^2}{2} + D, \quad \frac{dHei}{d\tau} = 0 \quad \text{and} \quad \frac{v}{2L_{10}} = Ma_{10} \sqrt{kRT}
\]

Acceleration: \(F = Wei \frac{v_{\text{final}} - v_{\text{initial}}}{\Delta \tau_{\text{allowable}}} + D, \quad \frac{dHei}{d\tau} = 0\)

Climb: \(F = \frac{Wei \cdot g}{v} \frac{d}{d\tau} \left( Hei + \frac{v^2}{2g} \right) + D\)

Cruise, combat and escape: \(F = D, \quad \frac{d}{d\tau} \left( Hei + \frac{v^2}{2g} \right) = 0\)

For the flight mission part, a typical flight mission of an advanced tactical fighter is shown in Figure 3, in which both flight environment and mission requirements are various. According to Ref. [28], a type of mission is described in Table 2 for the fighter in current research. The segments of the flight mission are take-off (1–2), acceleration (2–3), climb (3–5), subsonic cruise (5–6), descend (6–7), acceleration (7–8), supersonic
penetration (8–9), combat air patrol (9–10), escape dash (10–11), subsonic cruise (11–12), descend (12–13), and land (13–14).

![Figure 3. Schematic of a typical flight mission of advanced fighter.](image)

**Table 2. A typical flight phase of advanced fighter.**

| Mission Phases | Mission Description | Engines Condition |
|----------------|---------------------|-------------------|
| P1-2           | Take off: H = 0 m, L_to = 285 m, Ma = 0.2 | Military power |
| P2-3           | Acceleration 1: H = 0 m, Ma from 0.2 to 0.8 | Military power |
| P3-4           | Climb 1: H from 0 to 5500 m, Ma = 0.8 | Military power |
| P4-5           | Climb 2: H from 5500 to 11000 m, Ma = 0.9 | Military power |
| P5-6           | Subsonic cruise 1: H = 11,000 m, Ma = 0.9, \( \tau_{\text{sub,1}} = 30 \text{ min} \) | - |
| P6-7           | Descend 1: H = 9144 m, Ma = 0.9 | Idle power |
| P7-8           | Acceleration 2: Ma from 0.9 to 1.5 | Maximum power |
| P8-9           | Supersonic penetration: H = 9144 m, Ma = 1.5, \( \tau_{\text{sup}} = 5 \text{ min} \) | Military power |
| P9-10          | Combat air patrol: H = 9144 m, Ma = 1.5, n = 5 g, \( \tau_{\text{com}} = 2 \text{ min} \) | Maximum power |
| P10-11         | Escape dash: H = 11,500 m Ma = 1.65, \( \tau_{\text{es}} = 20 \text{ s} \) | Military power |
| P11-12         | Subsonic cruise 2: H = 11,000 m, Ma = 0.9, \( \tau_{\text{sub,2}} = 30 \text{ min} \) | - |
| P12-13         | Descend 2: H = 6000 m, Ma = 0.6 | Idle power |
| P13-14         | Land: H = 0 m, Ma = 0, L_land = 300 m | Idle power |

For the multi-level engine model, it is enabled to simulate different types of aircraft engines, including the conventional turbofan and engine added to CCA technology. Not only the overall performance calculation, but also the analysis of energy and exergy utilization and conversion in each component is demanded, as shown in Figure 2. From the flight mission view, the prediction of operation during the complex off-design points is necessary. Considering the above demands, a fully modular program is developed to calculate the based thermodynamic parameters, and these values could be used to further evaluate the exergy parameters in the next exergy analysis model. The schematic of the engine simulating model is illustrated in Figure 4. It describes the engine cycles that can be simulated by the program, viz., turbofan, and the CCA technology corrected cycles. Each component corresponds to a calculation module: INTAKE, FAN, HPC, CC, HPT, LPT, MIXER, AB, NOZZLE, and CCAHEX. In the model, the governing equations are given in Table 3, referring to the NASA reports [29,30]. A detail heat exchanger model, based on the logarithmic mean temperature difference (LMTD) method, is added to the turbofan engine program. It can read the thermodynamic parameters of FAN and HPC bleed air, and then outlet parameters on hot and cold sides are obtained by operating the CCAHEX submodule. Except for the above components, the temperature evaluating models of CC and turbine blade wall are adopted to assess the thermal reliability of the
engine, as given in Equation (2). The input parameters of these models include temperature, pressure, and mass flow of gas and cooling air, and model control parameters are the cooling performance and structural values, which specific expressions refer to Refs. [31,32]. These models are embedded into the engine program for calculating the wall temperature at CC and turbine blade by reading the inputs in real-time.

\[
\begin{align*}
\text{Inputs:} & \quad \left[ T_{\text{gas}}, P_{\text{gas}}, m_{\text{gas}} \right] \text{ and } \left[ T_{\text{cooling}}, P_{\text{cooling}}, m_{\text{cooling}} \right] \\
\text{Outputs:} & \quad T_{\text{wall}} = \text{FUNC}_{\text{wall}} \left( T_{\text{gas}}, P_{\text{gas}}, m_{\text{gas}} \right) T_{\text{cooling}}, P_{\text{cooling}}, m_{\text{cooling}} \right)
\end{align*}
\]

Lastly, the obtained parameters are passed into HPT and MIXER components, continuing to the simulation of the engine. For modeling the off-design condition, the performance maps of FAN, HPC, HPT, and LPT are adopted to calculate the actual operation of the engine with respect to the variation of the flight environment. Figure 4 also presents the balance equations of this model, based on the working principle of the turbofan engine, including two power and mass flow, pressure, and area balance.

![Figure 4. The schematic of engine simulating model.](image)
Table 3. The governing equations of each component.

| Components | Governing Equations |
|------------|---------------------|
| INTAKE     |
| \( m_{\text{out}} = m_{\text{in}} ; H_{\text{r, out}} = H_{\text{r, in}} \); \( p_{\text{r, out}} = \sigma p_{\text{r, in}} \) |
| \( m_{\text{out}} = m_{\text{in}} ; H_{\text{r, out}} = H_{\text{r, in}} + \frac{H_{\text{r, out, 1}} - H_{\text{r, in}}}{\eta_{\text{FAN}}}; p_{\text{r, out}} = \pi_{\text{FAN}} p_{\text{r, in}} \) |
| FAN        |
| For the design point, the pressure ratio and efficiency are given, and for the off-design point, the pressure ratio and efficiency are the functions of rotational velocity and \( \beta_{\text{FAN}} \). \( \sigma_{\text{FAN}} \cdot \eta_{\text{FAN}} = \text{FUNC}(\pi_{\text{out}}, \beta_{\text{FAN}}) \) |
| Considering the inter-stage bleed air, the HPC model is divided into two parts: |
| The pressure ratio before bleeding air is \( \pi_{\text{HPC,1}} \), and the other one is \( \pi_{\text{HPC,2}} \) |
| HPC        |
| \( m_{\text{out, 1}} + \sum m_{\beta/k} = m_{\text{in}} ; H_{\text{r, out, 1}} = H_{\text{r, in}} + \frac{H_{\text{out, 1}} - H_{\text{in}}}{\eta_{\text{HPC}}}; p_{\text{out, 1}} = \pi_{\text{HPC, 1}} p_{\text{in}} \) |
| \( m_{\text{out, 2}} + \sum m_{\beta/k} = m_{\text{out, 1}} ; H_{\text{r, out, 2}} = H_{\text{r, out, 1}} + \frac{H_{\text{out, 2}} - H_{\text{r, out, 1}}}{\eta_{\text{HPC}}}; p_{\text{out, 2}} = \pi_{\text{HPC, 2}} p_{\text{out, 1}} \) |
| CC         |
| \( m_{\text{out}} = m_{\text{in}} + m_{\text{fuel}} ; m_{\text{in}} \cdot H_{\text{in}} + \eta_{\text{CC}} m_{\text{fuel}} LHV = m_{\text{out}} H_{\text{out}} ; p_{\text{out}} = \sigma_{\text{CC}} p_{\text{in}} \) |
| HPT        |
| The HPT model is comprised of three processes: constant-pressure mixture of gas and cooling air in HPT stator, adiabatic expansion, and mixture in HPT rotor |
| HPT stator cooling: \( m_{\text{out, 1}} = m_{\text{in, 1}} + m_{\text{in, 2}} ; H_{\text{r, out, 1}} = H_{\text{r, in, 1}} + H_{\text{r, in, 2}} ; p_{\text{out, 1}} = p_{\text{in, 1}} \) |
| HPT rotor expansion: \( m_{\text{out, 2}} = m_{\text{out, 1}} ; H_{\text{r, out, 2}} = H_{\text{r, out, 1}} - \eta_{\text{HPT}} (H_{\text{r, out, 1}} - H_{\text{out, 2}}) \) ; \( p_{\text{out, 2}} = \frac{p_{\text{out, 1}}}{\pi_{\text{HPT}}} \) |
| HPT rotor cooling: \( m_{\text{out, 3}} = m_{\text{out, 2}} + m_{\text{in, 3}} ; H_{\text{r, out, 3}} = H_{\text{r, out, 2}} + H_{\text{r, in, 3}} \) ; \( p_{\text{out, 3}} = p_{\text{out, 2}} \) |
| LPT        |
| The model of LPT could refer to HPT |
| MIXER      |
| \( m_{\text{out}} = m_{\text{in, 1}} + m_{\text{in, 2}} ; H_{\text{r, out}} = H_{\text{r, in, 1}} + H_{\text{r, in, 2}} \) ; \( p_{\text{out}} = p_{\text{in}} \cdot f(\lambda_{\text{in, 1}}) A_{\text{in, 1}} + p_{\text{out, 2}} \cdot f(\lambda_{\text{in, 2}}) A_{\text{in, 2}} = p_{\text{out}} \cdot f(\lambda_{\text{out, 1}}) A_{\text{out}} \) |
| AB         |
| The model of AB is similar to CC |
| NOZZLE     |
| \( p_{\text{out, cri}} = p_{\text{out}} \left(1 + \frac{A_{\delta}}{A_{\delta}} \left(\frac{k - 1}{2}\right)\right)^{\frac{1}{k - 1}} \left\{ \begin{array}{ll} p_{\text{out}} = p_{\text{a}} \cdot p_{\text{out, cri}} < p_{\text{a}} \\ p_{\text{out}} = p_{\text{out, cri}} \cdot p_{\text{out, cri}} \geq p_{\text{a}} \end{array} \right. \) |
| Total thrust: \( FN = m_{\text{out}} (v_{\text{out}} - v_{\text{0}}) + A_{\delta} (p_{0} - p_{\delta}) ; v_{\text{0}} = Ma_{\delta} kRT_{0} ; v_{\text{0}} = Ma_{\delta} kRT_{0} \) |
| Propelling work: \( E_{p} = FN \cdot v_{\text{0}} \) |
CCAHEX

Inputs: \(T_{\text{hot}}, P_{\text{hot}}, m_{\text{hot, inlet}}\) and \(T_{\text{cold}}, P_{\text{cold}}, m_{\text{cold, inlet}}\)

Structural variables: \([d_{\text{out}}, s_1, s_2, \delta, \text{Hei}_{\text{HEX}}, \text{Bent}]\)

Outputs: \(T_{\text{hot}}, P_{\text{hot}}, m_{\text{hot, outlet}}\) and \(T_{\text{cold}}, P_{\text{cold}}, m_{\text{cold, outlet}}\)

Detail heat transfer and flow drop equations are presented in Ref. [33].

Air and gas are considered ideal gases. The enthalpy, entropy, as well as constant-pressure specific heat data are regarded as the polynomial functions of the temperature and the ratio of the fuel to air, and the flowchart of properties calculation is given in Figure 5.

![Flowchart of properties calculation](image)

**Figure 5.** The properties of air and gas considering the variable specific heat [34].

### 3.2. Exergy Model of Engine with CCA Technology

#### 3.2.1. Exergy of Terms and Balance Equation

The heat exergy associated with the process of heat exchanging (\(Ex_Q\)), the exergy of various energy carriers (\(Ex_{\text{in}}\) and \(Ex_{\text{out}}\)), and the output work \((W)\) occurring in system components comprise all foundational parameters for exergy analysis. Based on them, the general exergy balance equation could be stated as:

\[
\sum Ex_{Q,k} - W + \sum Ex_{\text{in}} - \sum Ex_{\text{out}} - Ex_D = 0
\]

where \(Ex_Q\) is calculated by the amount of heat transfer and temperature difference. Noteworthily, the temperature of heat source \(T_k\) is usually changeable within the heat transfer of engine components, so the heat exergy must be calculated by the integration method, as given in the equation.

\[
\sum Ex_{Q,k} = \int \left(1 - \frac{T_{\text{std}}}{T_k}\right) dQ_k
\]

The flow exergy of inlet and outlet stream \(Ex_{\text{in}}\) and \(Ex_{\text{out}}\) include physical exergy, chemical exergy, kinetic exergy, and potential exergy. Therefore, the formula of total exergy for a flow can be determined as:

\[
Ex = m\left(e_{\text{ph}} + e_{\text{ch}} + e_{\text{ki}} + e_{\text{po}}\right)
\]

where the specific physical exergy for air and gas, considering varying specific heat capacity, as well as the specific chemical exergy of fuel (regarded as \(C_6H_{12}O_{\omega}\)), could be written as:

\[
e_{\text{ph}} = h - h_{\text{std}} - T_{\text{std}}(s - s_{\text{std}})
\]
\[ e_{ch} = LHV\left(1.0401 + 0.01728 \frac{y}{x} + 0.0432 \frac{z}{x} + 0.2196 \left(1 - 2.0628 \frac{y}{x}\right)\right) \] (7)

For the aircraft engine, the kinetic exergy is calculated by:

\[ e_{ki} = \frac{1}{2} \left(v^2 - v_{\text{std}}^2\right) \] (8)

3.2.2. Exergy Model of Each Component

The exergy relations proposed in this section are used in the engine, as well as its subsystems and components. All involved thermodynamic parameters at the inlet and outlet of major components are calculated through the aircraft-engine thermodynamic model. The control volume of each component and exergy balance equations are given as follows:

- Intake:
  \[ E_{X_{D,INTAKE}} = E_{X_{in}} - E_{X_{out}} \]
  \[ \eta_{E_{X_{INTAKE}}} = \frac{E_{X_{out}}}{E_{X_{in}}} \] (9)

- Fan (FAN):
  \[ E_{X_{D,FAN}} = W_{\text{FAN}} + E_{X_{in}} - E_{X_{out,1}} - E_{X_{out,2}} \]
  \[ \eta_{E_{X_{FAN}}} = \frac{E_{X_{out,1}} + E_{X_{out,2}} - E_{X_{in}}}{W_{\text{FAN}}} \] (10)

- High-pressure compressor (HPC):
  \[ E_{X_{D,HPC}} = W_1 + W_2 + E_{X_{in}} - \sum_{i=1}^{5} E_{X_{out,i}} \]
  \[ \eta_{E_{X_{HPC}}} = \frac{\sum_{i=1}^{5} E_{X_{out,i}} - E_{X_{in}}}{W_1 + W_2} \] (11)

- Combusting chamber (CC) and afterburning (AB):
  \[ E_{X_{D,CC}} = E_{X_{in,1}} - E_{X_{in,2}} - E_{X_{out}}; E_{X_{in,2}} = E_{X_{ch,kerosene}} \]
  \[ \eta_{E_{X_{CC}}} = \frac{E_{X_{out}} - E_{X_{in,1}}}{E_{X_{in,2}}} \] (12)

- High-pressure turbine (HPT), and the control volume and relations of LPT are similar to HPT:
\[ E_{D,HPT} = E_{in,1} + E_{in,2} + E_{in,3} - E_{out} - W_{HPT} \]

\[ \eta_{Ex,HPT} = \frac{W_{HPT}}{E_{in,1} + E_{in,2} + E_{in,3} - E_{out}} \] (13)

- Mixer (MIXER):

\[ E_{D,MIXER} = E_{in,1} + E_{in,2} - E_{out} \]

\[ \eta_{Ex,MIXER} = \frac{E_{out}}{E_{in,1} + E_{in,2}} \] (14)

- Nozzle (NOZZLE):

\[ E_{D,NOZZLE} = E_{in} - E_{out} \]

\[ \eta_{Ex,NOZZLE} = \frac{E_{out}}{E_{in}} \] (15)

- Heat exchanger (HEX):

The exergy destructions generated by heat transfer and flow resistance could be calculated by:

\[ E_{D,CCAHEX} = E_{in,1} + E_{in,2} - E_{out,1} - E_{out,2} \]

\[ \eta_{Ex,CCAHEX} = \frac{E_{out,1} - E_{out,2}}{E_{in,1} + E_{in,2}} \] (16)

3.2.3. Avoidable and Unavoidable Exergy Destruction

There objectively exists an unachievable performance for aircraft engines and components from the thermodynamic view, despite the development of technologies. By setting the efficiency and friction coefficient of each component at the technical limitations in the future, the aforesaid thermodynamically unavoidable exergy model could be established, splitting the exergy destruction into avoidable and unavoidable parts within the engine or component. According to Ref. [25], the parameters of unavoidable cases are presented in Table 4.

**Table 4.** Assumptions used for the avoidable and unavoidable exergy destruction calculations.

| Component | Design Point | Actual Case | Off-Design Point |
|-----------|--------------|-------------|-----------------|
| INTAKE    | \( \sigma_{INTAKE} = 0.97 \) | \( \sigma_{INTAKE} = 0.99 \) |
| FAN       | \( \eta_{AN} = 0.87 \) | \( \eta_{AN} = 0.905 \) |
| HPC       | \( \eta_{HPC} = 0.86 \) | \( \eta_{HPC} = 0.872 \) |
| HEX       | \( \Delta p = 3\% \) | \( \Delta p = 1\% \) |
| CC        | \( \eta_{CC} = 0.99, \Delta p = 3\% \) | Calculated from aircraft-engine thermodynamic model |
| \( \eta_{HPT} = 0.86 \) | \( \eta_{HPT} = 0.86 \) |
| \( \eta_{LPT} = 0.86 \) | \( \eta_{LPT} = 0.86 \) |
| MIXER     | \( \Delta p = 3\% \) | \( \Delta p = 1\% \) |
| AB        | \( \eta_{AB} = 0.95, \Delta p = 3\% \) | \( \eta_{AB} = 0.98, \Delta p = 1\% \) |
| NOZZLE    | \( \Delta p = 3\% \) | \( \Delta p = 1\% \) |
3.3. Energy and Exergy Indicators

3.3.1. Energy Indicators

The control volume of the engine integrated system is shown in Figure 6. In accordance with Figure 6, the following energy balance equation can be written as:

\[ Q_{\text{kerosene}} + E_{\text{in},1} - E_{\text{out},9} = 0, \text{ for ENGINE} \]  

(17)

Figure 6. The control volume of energy analysis.

For the engine, the input energy includes the heat of fuel combusting \( Q_{\text{kerosene}} \), and the energy of the inlet air \( E_{\text{in},1} \). The major energy leaves the system in the form of the kinetic and internal energy of the exhaust gases in Point 9 in Figure 6 \( E_{\text{out},9} \), which is composed of the propelling work and the exhaust thermal and kinetic loss. According to the definition of the total energy of a flowing fluid [35], neglecting the gravitational potential energy, the total energy of fluid at the inlet and outlet could be written as:

\[ E_{\text{in},1} = m_{\text{in},1} \left( h_{\text{in},1} + \frac{1}{2} v_{\text{in},1}^2 \right) \]  

(18)

\[ E_{\text{out},9} = m_{\text{out},9} \left( h_{\text{out},9} + \frac{1}{2} v_{\text{out},9}^2 \right) \]  

(19)

Taking Equations (18) and (19) into Equation (17), the energy balance equation could be deduced as follows:

\[ Q_{\text{kerosene}} = E_{\text{out},9} - E_{\text{in},1} = m_{\text{out},9} \left( v_{9} - v_{0} \right) v_{0} + m_{\text{out},9} \left( h_{\text{out},9} - h_{\text{in},1} \right) + \frac{1}{2} \left( v_{\text{out},9} - v_{\text{in},1} \right)^2 \]  

(20)

The first term in Equation (20) coincided with the propelling power, and the second is called thermal and kinetic loss since it cannot be utilized by the engine. Both are defined as follows:

\[ E_{\text{loss,thermal}} = m_{\text{out},9} \left( h_{\text{out},9} - h_{\text{in},1} \right) \]  

(21)

\[ E_{p} = m_{\text{out},9} \left( v_{9} - v_{0} \right) v_{0} \]  

(22)

\[ E_{\text{loss,kinetic}} = \frac{1}{2} m_{\text{out},9} \left( v_{\text{out},9} - v_{\text{in},1} \right)^2 \]  

(23)

3.3.2. Exergy Indicators

For the engine, the physical exergy of inlet air and the chemical exergy of aviation kerosene flow into the system from the environment. After a series of exergy conversions, the exergy flows out the control volume in the form of the physical and kinetic exergy contained in the nozzle exhaust gas, as shown in Figure 7. Meanwhile, the destruction
exergy appears due to the irreversible procedures occurring in the engine, such as frictional loss and heat transfer. Based on these, the balance equations for this system are given in Equation (24):

$$Ex_{in,1} + Ex_{\text{kerosene}} - Ex_{out,9} - Ex_{\text{des}} = 0, \text{ for ENGINE}$$ (24)

![Diagram](image)

**Figure 7.** The control volume of energy analysis.

Based on Equation (24), the flow exergy at inlet and outlet could be written as:

$$Ex_{in,1} = m_{in,1} \left[ h_{in,1} - h_{std} - T_{std} \left( s_{in,1} - s_{std} \right) + \frac{1}{2} \left( v_{in,1}^2 - v_{std}^2 \right) \right]$$ (25)

$$Ex_{out,9} = m_{out,9} \left[ h_{out,9} - h_{std} - T_{std} \left( s_{out,9} - s_{std} \right) + \frac{1}{2} \left( v_{out,9}^2 - v_{std}^2 \right) \right]$$ (26)

Solving the simultaneous equations from Equation (24) to Equation (26), the correlations among fuel, product, loss, and destruction exergies are more clear, as given in Equation (27). The fuel exergy includes the chemical exergy in aviation kerosene and the heat exergy. The first and second terms on the right-hand side of Equation (27) are the product exergies, representing the propelling work. The loss of thermal exergy is determined based on the thermal parameters of exhausted gas, such as its enthalpy and entropy, and the loss of kinetic exergy is dependent on the stream velocity at the inlet and outlet. The last item reflects the destruction exergy caused by the irreversible process.

$$Ex_{\text{kerosene}} = Ex_{out,9} - Ex_{in,1} + Ex_{\text{des}}$$

$$= m_{out,9} \left( v_{9} - v_{0} \right) v_{0} + m_{out,9} \left[ \left( h_{out,9} - h_{in,1} \right) - T_{std} \left( s_{out,9} - s_{in,1} \right) + \frac{1}{2} \left( v_{out,9}^2 - v_{in,1}^2 \right) \right] + m_{out,9} T_{std} \Delta s_{1-9}$$ (27)

Comparing Equation (20) with Equation (27), the similarities and differences between energy and exergy analysis on engine performance can be explicitly revealed. As shown in Table 5, the indicators of propelling performance and kinetic loss in energy analysis are identical to those of the exergy method. Besides, these two methods are also consistent in evaluating the engine consumption, in which the difference between chemical energy and exergy is just an unchanging coefficient, and other energy and exergy inputs can be regarded as negligible amounts. It proves that the energy and exergy methods could have the same effects on the assessment of aircraft-engine propelling power and efficiency. Thus, it must be noteworthy that the exergy method shows a significant advantage in studying the destruction caused by irreversible factors, while the energy method is disabled to finish that.
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Table 5. Comparison between energy and exergy analysis of aircraft engine.

| Energy Analysis Method | Exergy Analysis Method |
|------------------------|------------------------|
| Input terms            |                        |
| $Q_{kerosene} = \dot{m}_{kerosene} \times LHV$ | $Ex_{kerosene} = \frac{\dot{m}_{kerosene}}{\dot{C}_p} \times LHV$ |
| Output terms           |                        |
| $E_p = \dot{m}_{out,9} (v_{out,9} - v_b) v_b$ | $Ex_p = \dot{m}_{out,9} (v_{out,9} - v_b) v_b$ |
| Loss terms             |                        |
| $E_{loss,thermal} = \dot{m}_{out,9} (h_{out,9} - h_{in,1})$ | $Ex_{loss,thermal} = \dot{m}_{out,9} (h_{out,9} - h_{in,1}) - T_{ad} (s_{out,9} - s_{in,1})$ |
| Destruction terms      | Disabled                |

4. Results

4.1. Comparison of Overall Energy and Exergy Indicators

In this section, the energetic and exergetic assessments of two engines that used CCA technology are carried out and effects are compared with those of the F-119 engine. The first one (scheme A) adds CCA technology into the F-119 engine without adjusting cycle parameters, while the second one (scheme B) optimizes the pressure ratio and turbine inlet temperature with keeping overall thrust constant. The values of energetic and exergetic thermodynamic properties on design conditions are calculated and the results are presented in Table 6.

Table 6. Energetic and exergetic thermodynamic properties on design condition.

| State No. | Fluid Type | Energy Rate (kW) | Exergy Rate (kW) |
|-----------|------------|------------------|------------------|
|           |            | F-119 Scheme A   | Scheme B         | F-119 Scheme A | Scheme B |
| 0         | Air        | 0                | 0                | 0              | 0        |
| 2         | Air        | 0                | 0                | −307.9         | −307.9   |
| 13        | Air        | 17,182.3         | 17,182.3         | 15,314.3       | 15,314.3 |
| 21        | Air        | 5154.7           | 5154.7           | 4594.3         | 4594.3   |
| 31        | Air        | 40,301.7         | 40,301.7         | 37,308.3       | 37,308.3 |
| 32        | Kerosene   | 105,438.6        | 105,438.6        | 111,933.6      | 111,933.6 |
| 4         | Gas        | 145,740.3        | 145,740.3        | 118,095.8      | 118,095.8 |
| 45        | Gas        | 120,033.1        | 117,924.1        | 88,747.7       | 87,006.6 |
| 5         | Gas        | 99,349.1         | 97,239.3         | 66,724.5       | 64,979.7 |
| 16        | Gas        | 5154.7           | 5154.7           | 7264.4         | 5482.8   |
| 6         | Gas        | 106,613.5        | 104,503.8        | 69,879.6       | 68,191.6 |
| 7         | Gas        | 106,613.5        | 104,503.8        | 69,725.7       | 68,037.7 |
| 9         | Gas        | 106,613.5        | 104,503.8        | 69,571.9       | 67,883.9 |

As is shown in Tables 1 and 6, CCA technology in scheme A causes the energy and exergy of fluid to begin to decrease from State 45, and the pressure drop also rises, resulting in the degradation of the propelling efficiency and thrust. On the contrary, scheme B could keep the overall thrust unchanged by improving the gas pressure at State 3, under the condition of reducing the input heat and exergy from kerosene. Meanwhile, CCA technology is enacted to maintain the wall temperature of the HPT blade from overheating. The result reveals that CCA technology changes the energy and exergy utilization of each component, and then it could affect the overall performance of the engine. Next, the variations of energy and exergy indicators with CCA technology during the full flight mission are discussed. In Table 5, different propelling performance indexes are evaluated and listed by energy and exergy analysis. From the energy view, the input energy of control volume is released in the burning process $Q_{kerosene}$, and the output is propelling work $E_p$. Along with the energy conversion and transport, energy loss $E_L$ is generated and exits the engine, including the thermal energy loss and kinetic energy loss. From the perspective of exergy, the destruction caused by the irreversible process of each
component could be separated from the energy loss, and those are defined as exergy destruction \( E_{\text{des}} \). The remaining parts are defined as thermal exergy loss and kinetic exergy loss. Meanwhile, the input exergy is the chemical exergy of aviation kerosene \( E_{\text{ex,kerosene}} \) and the output is propelling exergy \( E_{\text{ex}} \). It can be seen from Table 5, the mathematical expressions of propelling work and exergy agreed with each other, and the kinetic energy loss is also the same as kinetic exergy loss. It reveals that there exists an equivalence relation between energy and exergy methods for evaluating the engine performance of output and kinetic loss. This conclusion could be verified by Figure 8a,c. Besides, a similar phenomenon could be observed in Figure 8b, in which the line representing the relative change of propelling work efficiency coincided with that of propelling exergy efficiency. The reason is that the ratio of input heat and chemical exergy keeps constant, so the effect of input heat and chemical exergy on efficiency is identical. Since the input and output terms are both equivalent, the difference between them also has the same relationship, as shown in Figure 8d. The finding illustrates that the exergy analysis method is consistent with the energy approach not only in propelling work and kinetic loss but also in propulsive efficiency. Besides, the exergy approach can further distinguish the destruction caused by irreversible process and exhaust process in the engine, while the energy method cannot. Based on the exergy method, the reason for overall performance degradation caused by CCA technology in scheme A could be well understood. It is the increasing exergy destruction due to the thermogenic heat transfer occurring in the CCA heat exchanger, as shown in Figure 9b. Compared with scheme A, scheme B reduces the exergy destruction by optimizing cycle parameters and improves the propelling efficiency without weakening the total output exergy.

![Figure 8](image-url)

**Figure 8.** Comparison of the overall performance between scheme A/B with F-119 by energy and exergy methods. (a) Propelling energy and exergy; (b) Propelling energy and exergy efficiency; (c) Energy and exergy kinetic loss; (d) Thermal loss.
4.2. Effect of CCA Technology on the Exergy Destruction

In this section, the influence of CCA technology on the exergy destruction of each component is discussed to discover the potential areas for most improvement. Figure 10a,b present the variations of destruction proportion during a full flight mission. The results show that all components could be divided into three levels according to their magnitude of exergy destruction. The first level consists of the combustion chamber and afterburner, accounting for about 70~80% of the destruction. The fan, high-pressure compressor, turbines, and mixer are the second level, and all of them generate about 2~5% destruction. The remaining destruction is located at the inlet, nozzle, and CCA heat exchanger. Therefore, the combusting process could be regarded as the main source of exergy destruction, due to the energy level degraded most dramatically. This phenomenon agrees with the conventional turbofan engine. Nevertheless, the exergy destruction in HPT and LPT becomes larger, as shown in Figure 10c. The reason is that the irreversibility in the above components rises with the temperature difference between bleed air and gas increasing. Besides, the additional CCA heat exchanger also causes a certain amount of destruction when adapting CCA technology. Taking these effects together, the overall performance of scheme A appears to deteriorate, including that both propelling exergy and efficiency are lower than those of the F-119 engine. By optimizing cycle parameters, the exergy destruction in most components of scheme B could be reduced, particularly for the combust chamber, turbines, and high-pressure compressor components. According to the above finding, it is easier to understand why CCA technology could improve the energy utilization capability of scheme B.

![Figure 9. Variation of the exergy destruction and thermal exergy loss in scheme A and B. (a) Thermal exergy loss; (b) Exergy destruction.](image)
Furthermore, the distribution of the unavoidable and avoidable exergy destruction in the engine is given in Figure 11. For both scheme A and B, proportions of unavoidable exergy destruction in the combusting process is up to 75% under the mission segments without afterburning, and this value increases to about 90% at takeoff, combat, and escape missions. As for the avoidable exergy destruction, Figure 11c,d show that the proportion of combustion chamber and afterburner is below 50%, while the magnitude of compressor and turbine is about 10–20%. Especially for the no afterburning condition, other components except for the combustion chamber dominate the avoidable exergy destruction in the engine, and the total proportion is greater than 70%. The results prove that the majority of avoidable exergy destruction is still located in the combustion chamber, compressors, and turbines for the engine using CCA technology, indicating that there exists sustainable improvement potential in these components.
Figure 11. (a) The distribution of unavoidable exergy destruction in Scheme A; (b) The distribution of unavoidable exergy destruction in Scheme B; (c) The distribution of avoidable exergy destruction in Scheme A; (d) The distribution of avoidable exergy destruction in Scheme B.

Figure 12 gives the relative change of avoidable and unavoidable exergy destruction between two schemes during the full flight mission, and the minus represents that the destruction in scheme A is greater than that in scheme B. It can be concluded that the proportion of avoidable exergy destruction in scheme B is higher than that of scheme A but the unavoidable part is lower during the whole flight phases, and the tendency becomes more obvious during the climb and subsonic cruise conditions. The results mean that the energy could be more rationally utilized by improving the efficiency of the components in scheme B, while the potential of scheme A is poorer.

Figure 12. The comparison of avoidable and unavoidable exergy destruction between different schemes.
4.3. Effect of CCA Technology on Exergy Indicators Considering Flight Duration

Differing from the commercial aircraft engine, the engine used in a fighter must operate under complex and variable conditions, including takeoff, horizontal acceleration, climb, supersonic cruise, combat, etc. The working duration of each flight phase has significant differences from each other. Therefore, it is essential to investigate the characteristic of exergy utilization under different flight times, to find out the mission phase for most improvement. As is given in Figure 13a, for both schemes A and B, the consumption of input kerosene exergy is larger under the supersonic and subsonic cruise, combat, escape, and acceleration mission segments. Especially at subsonic cruise, even though its specific fuel exergy consumption is obviously less than takeoff, climb, and acceleration mission, the total input exergy could still be up to 30~35 MJ per flight mission, accounting for about 20% of total input magnitude. It is also well understood because the subsonic cruise duration exceeds 80% of the whole time, which illustrates that the time dimension plays a nonnegligible role in the global analysis of exergy utilization. In this case, the subsonic cruise mission should be seriously focused on reducing the full energy consumption. Analogously, the conclusion is also suitable for commercial and transport engines in which cruise time is longer than military ones. Besides, Figure 13a also reveals that the total exergy input could be reduced by optimizing cycle parameters with CCA technology, and the improvement becomes more obvious in the combat and supersonic cruise segments. The amount of input exergy at these segments is also up to 30 MJ kerosene exergy due to the relatively large specific fuel consumption. Generated from the input exergy, Figure 13c,d indicate that almost 90% of the total and avoidable exergy destruction occurred during these mission segments, proving that the most improvement potential is in these phases. The finding could also be used to explain why most the variable cycle engines are paying more attention to improving the efficiency of the cruise mission, for achieving global energy optimization. Accordingly, Figure 13b–d could also illustrate that scheme B effectively reduces the destruction compared with scheme A without weakening propelling performance. The above exergy destruction analysis results are reflected in the overall performance indicator, which is the improvement of propelling efficiency.

Figure 14a gives the exergy destruction amount of each component during an integrated flight mission. It can be seen from Figure 14a that the afterburner occupies the second-largest exergy destruction among all components, although it only operates under several specific situations, which means that the irreversibility of the afterburner is harsher. The result clearly reflects why the afterburning condition cannot continually operate for a long time from the energy utilization view. Furthermore, Figure 14a presents that the exergy destruction amount of CC could be largely reduced by adjusting cycle parameters with CCA technology, compared with other components. Therefore, the sum of exergy destruction amount of scheme B is lower under the full flight mission as shown in Figure 13c. As for the exergy destruction in CC, Figure 14b shows that most of them belong to unavoidable ones, which reveals that the improvement potential of scheme B is better. Meanwhile, the avoidable exergy destruction amount of scheme B is also lower in most components, as shown in Figure 14c. These results prove that the combination of CCA technology and cycle parameters optimization could not only improve the energy-saving potential but also reduces avoidable exergy destruction.
Figure 13. The comparison of exergy indicators between different schemes under full flight mission. (a) Exergy fuel; (b) Propelling exergy amount; (c) Exergy destruction; (d) Avoidable exergy destruction.

Figure 14. Comparison of exergy destruction in each component between different schemes. (a) Total exergy destruction in each component; (b) Unavoidable exergy destruction in each component; (c) Avoidable exergy destruction in each component.

5. Discussion

From the view of energy analysis, the additional heat transfer process introduced by the CCA heat exchanger meets the energy conversion law, and there is no energy loss. However, Miller [36] and Gray [11] pointed out that the overall propelling performance could be reduced by CCA technology without adjusting cycle parameters, while none of them explained the reason. With this background, the present work reveals that the
irreversibility of the engine could be raised by CCA technology due to the additional heat transfer process between HPC bleed air and bypass air. Besides, the above conclusion is tenable for the full flight envelope and the increase of exergy destruction is more obvious at the high flight altitude, as shown in Figure 15a. Recently, Boyle [12] and Wen [27] proposed that the overall propelling performance could be improved by adjusting cycle parameters with CCA technology. In fact, the performance improvement can still be attributed to changes in exergy destruction. As given in Figure 15b, the exergy destruction of scheme B is reduced by about 0.7~2.2% during the whole flight envelope.

In terms of exergy loss, CCA technology without adjusting cycle parameters could reduce the exergy loss since the temperature and velocity of exhaust gas become lower, as given in Figure 16a. When the pressure ratio and temperature of the turbine inlet increase by CCA technology, Figure 16b shows that the increase of exergy loss is larger at the left and right boundaries of the flight envelope. For the left boundary, the reason is that the flight speed is relatively lower, so more exergy is lost from the exhaust gas. For the right boundary, the reason is that the velocity of exhaust gas is higher. Until now, considering both exergy destruction and loss, Figure 17a illustrates that the overall propelling exergy reduce by CCA technology without adjusting cycle parameters, but Figure 17b indicates that the propelling exergy could be improved by optimizing cycle parameters by CCA technology. The conclusions agree with Refs. [11,12,27,36] and can be used to explain their reasons.
Furthermore, Figure 18 shows that most of the exergy destruction improves in the CC, LPT, and MIXER components. The reason is that the increase in the pressure ratio could reduce the temperature difference in these energy processes. On the contrary, the exergy destruction in HPC, HEX, and HPT could increase when adjusting cycle parameters with CCA technology, which indicates that there still exists some potential to improve the irreversibility of the engine in these components.
6. Conclusions

Taken together, this study reveals the mechanism of how CCA technology affects the overall and local energy utilization of turbofan engines during the whole flight mission by comparing the exergy indicators between different schemes. Concluding remarks from the results are summarized as follows:

(1) For the scheme using CCA technology without changing cycle parameters, the internal exergy destruction increases by 0.5~2% in high- and low-pressure turbines, the combustion chamber, and the CCA heat exchanger. The above destruction mainly occurred during the additional thermogenic heat transfer and flow friction process. Under the joint action of these destructions, the overall propelling exergy and efficiency of the engine appear to degrade.

(2) For the other scheme applying CCA technology with optimizing cycle parameters, the specific optimization parameters are that the pressure ratio and turbine inlet temperature at the design point can be increased by 24.44% and 2.15%, respectively, under the requirements of the turbine blade wall temperature and the overall propulsion. The exergy destruction reduces about 0.5~2% for the takeoff, climb, cruise, and combat conditions, in which the unavoidable parts reduce by 1~3.5% and avoidable parts increase by 0.05%. Even if the exergy destruction shows a slight rise in the descend and land conditions, the sum of exergy destruction during the full flight mission still reduces by about 1.8%. These effects reflect in the overall performance of the engine, that is, to improve the propelling efficiency and reduce the aviation kerosene consumption.

(3) By comparing the exergy indicators under different flight durations, the diminishing efficiency in descending and landing conditions has little effect on overall performance during the whole flight mission. By contrast, the total avoidable exergy destruction under supersonic/subsonic cruise, combat, and escape conditions is up to 90%, with great potential for improvement. It indicates that the flight duration is a crucial factor in total exergy destruction.

To sum up, CCA technology should be combined with adjusting cycle parameters, to reduce the engine exergy destruction and improve the sustainability.

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Nomenclature

\[ \begin{align*}
A & \quad \text{Area} \\
Bent & \quad \text{The number of elbows} \\
BPR & \quad \text{Bypass ratio} \\
C & \quad \text{Drag coefficient} \\
c_p & \quad \text{Heat capacity} \\
D & \quad \text{Drag} \\
d & \quad \text{Diameter} \\
E & \quad \text{Energy} \\
ex & \quad \text{Specific exergy} \\
Ex & \quad \text{Exergy} \\
f & \quad \text{Ratio of fuel and air flow mass}
\end{align*} \]
| Symbol | Description |
|--------|-------------|
| FN     | The total thrust |
| FUNC   | Function      |
| g      | Gravitational acceleration |
| Hei    | Flight altitude |
| H      | Enthalpy      |
| ħ      | Specific enthalpy |
| K      | Heat transfer coefficient |
| k      | Ratio of specific heat |
| L      | Length        |
| LHV    | Low heat value |
| m      | Mass flow     |
| Ma     | Mach number   |
| n      | Rotating velocity |
| N      | Tube rows     |
| Nu     | Nusselt number |
| p      | Pressure      |
| Pr     | Prandtl number |
| q      | Kinetic pressure |
| Q      | Heat          |
| R      | Gas constant  |
| Re     | Reynold number |
| S      | Entropy       |
| s      | Tube pitch    |
| sfc    | Specific fuel consumption |
| T      | Temperature   |
| t      | Time          |
| v      | Velocity      |
| W      | Power         |
| Wei    | Fighter weight |

**Greek symbols**

| Symbol | Description |
|--------|-------------|
| γ      | Ratio of thrust to weight |
| τ      | Time         |
| η      | Efficiency   |
| ξ      | Fuel exergy grade function |
| δ      | The thickness of the wall |
| β      | Auxiliary line |
| θ      | Correction factor |
| π      | The ratio of pressure |

**Subscripts**

| Symbol | Description |
|--------|-------------|
| TO     | Take off condition |
| P      | Payload      |
| PE     | Expendable payload |
| PP     | Permanent payload |
| F      | Fuel         |
| E      | Empty        |
| D      | Flighting drag |
| L      | Flighting lift |
| i      | Flight mission segment |
| t      | Total parameter |
| h      | Hot side     |
| c      | Cold side    |
| in     | Inlet of heat exchanger |
| out    | Outlet of heat exchanger |
| W      | Wall         |
| HEX    | Heat exchanger |

**Superscripts**

| Superscript | Description |
|-------------|-------------|
| -1          | Inverse function |
| Av       | Avoidable |
|---------|-----------|
| Un      | Unavoidable |

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