Research Article
Comprehensive Performance Analysis for the Rotating Detonation-Based Turboshaft Engine

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The potential advantages of rotating detonation combustion are gradually approved, and it is becoming a stable and controllable energy conversion way adopted to the propulsion devices or ground-engines. This study focuses on the rotating detonation-based turboshaft engine, and the architecture is presented for this form of engine with compatibility between the turbomachinery and rotating detonation combustor being realized. The parametric performance simulation model for the rotating detonation-based turboshaft engine are developed. Further, the potential performance benefits as well as their generation mechanism are revealed, based on the comprehensive performance analysis of the rotating detonation-based turboshaft engine. Comparisons between the rotating detonation turboshaft engine and the conventional one reveal that the former holds significant improvements in specific power, thermal efficiency, and specific fuel consumption at lower compressor pressure ratios, and these improvements decrease with the increase of compressor pressure ratio and increase as turbine inlet temperature increases. The critical compressor pressure ratio corresponding to the disappearance of specific power improvement is higher than that corresponding to the disappearance of thermal efficiency and specific fuel consumption. These critical compressor pressure ratios are positively correlated with flight altitude and negatively correlated with flight velocity. The conductive research conclusion is guidable for the design and engineering application of rotating detonation-based engines.

1. Introduction

The helicopters have promising development and application foreground in both military and civil fields, owing to their superior performance operating at low altitude, low velocity, and maneuvering flight conditions. The turboshaft engine is the unique powerplant for the helicopter; therefore, advanced technologies for turboshaft engines have attracted significant interest in both academia and industry. The regenerative cycle and variable capacity technologies have the potential for improving the overall performance of the turboshaft engine, but the low technical maturity and poor technical versatility currently may be unacceptable. The turboshaft engine with simple cycle is still the first choice of advanced technology programs at present [1, 2].

For the conventional turboshaft with simple cycle, the key to enhancing the overall performance is to improve the total pressure ratio and temperature ratio [3]. After several decades of developments, the performance improvement of conventional turboshaft engine has entered a bottleneck period, as shown in Figure 1 [2]. Pressure-gain combustion is a prospective technology for the further performance improvement of the turboshaft with simple cycle [4]. Rotating detonation is a form of pressure-gain combustion, and it holds many potential advantages, such as high intensity of reaction, high thermal efficiency, and low entropy increase [5–7], which are helpful to improve the thrust and fuel consumption performance and reduce the structural weight. In the past decades, numerous studies relating to the ignition and detonation initiation performance, the operating diagram, and the unstable modes and their generation mechanism of the rotating detonation combustor (RDC) are experimentally performed, and the detailed flowfield structure and cellular structure information are revealed by multidimensional numerical methods [8–12]. The above studies have made the rotating detonation technology being
regarded as a stable and controllable energy conversion way. Naples et al. [13, 14] studied the interaction between the RDC and conventional turbine elements by the integration system of the T63 turboshaft engine embedded with an RDC. With the main combustor of GTD-350 engine being replace by an RDC, the feasibility of the RDC being applied to turboshaft engine has been confirmed by Wolanski [15]. George et al. [16, 17] experimentally investigated the axial turbine performance operating under pulsating flows, which hold the similar features with the detonation chamber exhaust, and approved that the pressure oscillations may lead to undesirable turbine performance degradation. With the performance of the supersonic turbine being characterized by the power extraction and total pressure loss parameters, Liu et al. [18, 19] numerically studied the effects of unsteady inlet conditions on the operating characteristics of the supersonic turbine and revealed that leading edge shock waves were the main factor for the unsteady loss mechanism. Sousa et al. [20] analyzed the thermodynamic performance of the gas turbine with an RDC with the T-MATS software coupled with the MOC solver of RDC model; the result showed that the thermal efficiency of the rotating detonation turbine engine could be 5% higher than that of the conventional one at low compressor pressure ratios, but the performance benefits decreased as the compressor pressure ratio increased. With the accumulation of the achievements on rotating detonation turbine engine, the feasibility and potential advantages of this new form of engine are gradually approved [20–23]. However, studies regarding the overall performance characteristics and the potential performance benefits as well as their generation mechanism of the turboshaft engine embedded with an RDC are quite scarce. Compared to the conventional turboshaft engine, the study of rotating detonation-based turboshaft engine is still in its infancy.

This study aims at revealing the potential performance benefits of the rotating detonation-based turboshaft engine and promoting further application of RDC in propulsion systems. Firstly, the parametric cycle analysis model of the rotating detonation-based turboshaft engine is developed based on the low-order analytical model of RDC and the compatibility relationship between the turbomachinery and RDC. Then, the overall performance characteristics of the new form of engine are achieved. Finally, a performance comparison between the rotating detonation-based turboshaft engine and the conventional one is performed, and the performance benefits as well as their generation mechanism are revealed.

2. Mathematical and Physical Model

2.1. System Formulation. With the compatibility between RDC and turbomachinery under consideration, the isolator and mixer chamber are arranged upstream and downstream from RDC, respectively, in the dual-duct rotating detonation aeroturbine engine (DRDATE) [22]. With the power turbine and power shaft arranged downstream from the turbine of the DRDATE (which is used as the gas generator), a configuration for the rotating detonation-based turboshaft engine is proposed, as shown in Figure 2(a). Figure 2(b) further displays the ideal thermodynamic cycle process comparison between the rotating detonation-based turboshaft engine and the conventional one. For the rotating detonation-based turboshaft engine, air flows into the engine at state 0; the process 0-3 is the integrated compression process proceeding in the intake, isolator, and compressor; the processes 3-3.5' and 3.5'-4' represent the shock compression and heat release due to combustion, respectively; the process 4'-9' represents the integrated expansion process proceeding in the turbine, power turbine, and nozzle; and the thermodynamic cycle is closed via the imaginary exothermic process 9'-0. The thermodynamic cycle processes of the conventional turboshaft engine can be analyzed in exactly the same manner.

The final temperature of the heating process in rotating detonation-based turboshaft engine is higher than that in the conventional turboshaft engine with the same heat addition, as the specific heat capacity of detonation process is lower than that of the deflagration process. Therefore, the former corresponds less entropy production, which implies the heat loss owing to exhaust (which can be estimated with the projected area of the exothermic process to s-axis, as shown in Figure 2(b)) of the rotating detonation-based turboshaft engine is higher than that of the conventional one. The above has revealed the thermal efficiency benefit of the rotating detonation turbine engine conceptually.
2.2. Parametric Cycle Analysis Model. The thermodynamic processes proceeding in the rotating detonation-based turboshaft engine can be simplified as “polytropic compression-rotating detonation-adiabatic mixing-polytropic expansion,” and the reduced order model which was developed based on the matching relationship between the injection process and pressure decay after the detonation front [22] is adopted in this study for the estimation of the rotating detonation process. The RDC is fueled by kerosene, and the reaction mechanism is taken from [24]. The models of the remaining processes are consistent with the conventional turboshaft engine. The thermodynamic process in the conventional compressor can be regarded as nonisentropic polytropic compression, and the mathematical model can be expressed as follows:

\[ p_3^* = \pi_c p_1^* , \]  
\[ \int_{r_1}^{r_2} \frac{dT}{T} = R_0 \ln \pi_c , \]  
\[ h_3^* = h_1^* + \int_{r_1}^{r_2} c_p dT , \]  
\[ \eta_c = \frac{h_{3i}^* - h_1^*}{h_{3i}^* - h_1^*} , \]  
\[ c_p = \sum_{i=1}^{N} c_{pi} Y_i , \]  
\[ \gamma = \frac{\sum_{i=1}^{N} c_{pi} Y_i}{\sum_{i=1}^{N} Y_i (c_{pi}/Y_i)} . \]

where \( h_{3i}^* \) is the total enthalpy corresponding to the isentropic compression with a compression pressure ratio \( \pi_c \). The thermodynamic process in the turbine can be modeled in exactly the same way.

The gas properties are a function of the gas temperature. In this study, the parametric performance simulation model of the engine is developed based on the “variable-\( \gamma \)” strategy. Firstly, the gas properties of the single component can be calculated by polynomial fitting of temperature (the polynomial coefficients are referred to NASA [25]); then, the gas properties of working medium can be obtained by mass flow average.

\[ c_{pi} = R_1 (a_{i0} T + a_{i1} T^2 + a_{i2} T^3 + a_{i3} T^4) , \]  
\[ c_p = \sum_{i=1}^{N} c_{pi} Y_i . \]  
\[ \gamma = \frac{\sum_{i=1}^{N} c_{pi} Y_i}{\sum_{i=1}^{N} Y_i (c_{pi}/Y_i)} . \]

Similar to the conventional turboshaft engine, specific power \( P_s \), thermal efficiency \( \eta_{th} \), and specific fuel consumption \( sfc \) are used as metrics to characterize the overall performance of the rotating detonation-based turboshaft engine. According to the parametric cycle analysis model and component matching equations, the performance metrics can be calculated by Equations (4)–(6). And \( \alpha \) represents the air split parameter, which is the ratio of the mass flow rate of the inner duct to that of the outer duct in DRDTE. \( \kappa \) is the power split parameter, which is adopted to characterized the power split between the power turbine and the nozzle. According to the representative turboshaft engines, the value of \( \kappa \) is taken as 0.96.

**Figure 2:** (a) Configuration and (b) ideal thermodynamic cycle processes of the rotating detonation-based turboshaft engine.
The subscripts 6 and 9 represent the parameters of power turbine inlet and exhaust nozzle outlet sections, respectively.

\[
P_s = \left(1 + \frac{f}{1 + \alpha}\right) k h^*_s \left[1 - \left(\frac{P_s}{P^*_s}\right)^{(\gamma-1)/\gamma}\right],
\]

(8)

\[
\eta_{th} = \frac{P_s}{[f \cdot H_f/(1 + \alpha)]},
\]

(9)

\[
sf \cdot c = 3600 f/[P_s(1 + \alpha)].
\]

(10)

The utilization of reduced order model of RDC can introduce calculation errors, owing to the assumptions. Compared to the 2D CFD solver, the calculation error of the reduced order model is below 10% [22, 23]. The overall uncertainty of the performance metrics of the rotating detonation-based turboshaft engine can be estimated by the sensitivity analysis of the calculation errors of RDC outlet parameters on overall performance of the engine. Assuming that \( \Psi \) is the performance metric; then, the overall uncertainty of \( \Psi \) can be calculated by

\[
u_1 = \left[\Psi(p_s^* + \epsilon p_s^*) - \Psi(p_s^*)/\Psi(p_s^*)\right],
\]

(11)

\[
u_2 = \left[\Psi(t_4^* + \epsilon t_4^*) - \Psi(t_4^*)/\Psi(t_4^*)\right],
\]

(12)

\[
u = \sqrt{\sum u_i^2} = \sqrt{u_1^2 + u_2^2},
\]

(13)

where \( \epsilon \) is the model error of RDC, \( u_i \) represents the uncertainty component, and \( u \) represents the overall uncertainty. Table 1 summarizes the uncertainty components and overall uncertainty of the \( P_s, \eta_{th} \), and \( sf \cdot c \), which are generated by the calculation errors of the RDC model. It shows that the overall uncertainties of performance metrics remain at a relatively low level (<10%). In addition, the uncertainty of \( P_s \) is lower than that of \( \eta_{th} \) and \( sf \cdot c \).

3. Results and Discussions

3.1. Sensitivity Analysis of Component Parameters on Overall Performance of the Engine. A sensitivity analysis is conducted below to reveal the variation in overall performance of the rotating detonation-based turboshaft engine versus the component parameters. The compressor pressure ratio \( \pi_c \) and turbine inlet temperature \( T_4^* \) play a major role in the overall performance of the engine. The variations in \( P_s, \eta_{th} \), and \( sf \cdot c \) with respect to \( \pi_c \) and \( T_4^* \) under standard sea-level and high altitude cruise conditions are, respectively, illustrated in Figures 3 and 4. In the figures, the coordinate values of each point are determined by the \( P_s \) and \( sf \cdot c \) of the cases with the corresponding values of \( \pi_c \) and \( T_4^* \), and the values of \( \eta_{th} \) are presented by the color scales. The sensitivity of performance metrics to the \( \pi_c \) and \( T_4^* \) can be presented intuitively by the trends of curves and color scales. It can be seen that, with an increase in \( \pi_c \), \( P_s \) and \( \eta_{th} \) first increase but then decrease, and \( sf \cdot c \) first decreases but then increases. As \( \pi_c \) increases, on the one hand, the power turbine pressure ratio \( \pi_t \) increases, and the sensitivity of \( \pi_t \) to changes in \( \pi_c \) decreases, as the pressure-gain of the RDC is negatively correlated with \( \pi_c \) [22]. On the other hand, the cycle heat addition decreases owing to the increase of combustor inlet temperature \( T_4^* \) and air split parameter \( \alpha \). In addition, the increase of \( \alpha \) can weaken the potential benefits relating to the pressure gain of the RDC. At low values of \( \pi_c \), the increase of \( \pi_t \) is the main factor influencing \( P_s \) and \( \eta_{th} \) increases with the increase of \( \pi_c \). As \( \pi_c \) increases, the increase of \( T_4^* \) and \( \alpha \) becomes the dominant factor influencing \( P_s \), and \( P_s \) decreases as \( \pi_c \) increases. The thermal efficiency \( \eta_{th} \) is positively correlated with \( P_s \), so the variation of \( \eta_{th} \) is consistent with that of \( P_s \). In addition, \( \eta_{th} \) is positively correlated with \( \alpha \) according to Equation (9), so the unfavorable impact of \( T_4^* \) can be weakened. Therefore, the downward trend of \( \eta_{th} \) at high values of \( \pi_c \) is less obvious than that of \( P_s \). On the basis of Equation (10), \( sf \cdot c \) is actually determined by \( P_s, \pi_c, \) and fuel-air ratio \( f \). When \( T_4^* \) remains constant, \( \alpha \) is positively correlated with \( \pi_c \), and \( f \) is negatively correlated with \( \pi_c \). At low values of \( \pi_c \), the increase of \( P_s \) and \( \alpha \) and the decrease of \( f \) are all favorable factors for reducing \( sf \cdot c \). When the value of \( \pi_c \) is relatively high, the favorable effects due to the increase of \( \alpha \) and decrease of \( f \) are not sufficient to overcome the effect unfavorable effect from the decrease in \( P_s \), and the variation of \( sf \cdot c \) shows opposing trend. As shown in Figures 3 and 4, the isoliths of \( \eta_{th} \) run nearly parallel to the horizontal ordinate, which implies that there is a strong correction between the variation of \( \eta_{th} \) and that of \( sf \cdot c \).

When the compressor pressure ratio \( \pi_c \) remains constant, \( P_s \) and \( \eta_{th} \) exhibit positive correlation with \( T_4^* \), and \( sf \cdot c \) exhibits negative correlation with \( T_4^* \). Furthermore, the performance metrics are less sensitive to changes in \( T_4^* \) than them to changes in \( \pi_c \). As \( T_4^* \) increases, the cycle heat addition increases, resulting in the proportion of heat loss owing to exhaust decreases, which is favorable for the improvement of \( \eta_{th} \). In addition, \( \eta_{th} \) is positively correlated with \( \alpha \), and \( \alpha \) decreases with the increase of \( T_4^* \). Therefore, the improvement of \( \eta_{th} \) due to the increase of cycle heat addition is weakened by the effect of \( \alpha \). In summary, \( \eta_{th} \) increases with an increase in \( T_4^* \), and the sensitivity of \( \eta_{th} \) to changes in \( T_4^* \) decreases with an increase in \( T_4^* \). The variation \( sf \cdot c \) can be explained in exactly the same manner. For a constant value

| Performance metrics | Cycle parameters | \( P_s^* \) | \( T_4^* \) | \( \eta_{th} \) | \( P_s^* \) | \( T_4^* \) | \( P_s^* \) | \( T_4^* \) | \( sf \cdot c \) |
|---------------------|-----------------|--------|-------|--------|--------|-------|--------|-------|---------|
| \( \pi_c \)         | 10%             | 10%    | 10%   | 10%    | 10%    | 10%   | 10%    | 10%   |
| \( u_i \) (i = 1, 2)| 0.96%           | 3.31%  | 2.14% | 9.39%  | 2.09%  | 9.37% |
| \( u \)             | 4.19%           | 9.63%  | 9.60% |

Table 1: Uncertainty analysis of the performance metrics of the rotating detonation-based turboshaft engine.
of $\pi_c$, $P_t$ is actually determined by the cycle heat addition. Therefore, $P_t$ increases monotonically with the increase of $T_{\pi}^*$. Generally, the application of rotating detonation technology does not change the variation trends of performance metrics of the turboshaft engine versus cycle parameters.

There is strong agreement between the variation trends of performance metrics under high-altitude cruise condition and those under standard sea-level condition versus cycle parameters. Under cruise condition, the total pressure ratio improves owing to the ram compression, and so do the performance metrics. As $H$ increases, the freestream temperature $T_0$ as well as the combustor inlet temperature $T_{\pi}^*$ decreases, which is favorable for the total pressure gain in the RDC. Therefore, the high-altitude cruise condition corresponds to higher $P_t$ and $\eta_{th}$ and lower $sfc$.

The cycle parameter comparison between the rotating detonation-based turboshaft engine and the conventional one with the same performance metrics is displayed in Figure 5. It can be seen that the former corresponds to a lower $\pi_c$ and $T_{\pi}^*$. The reduction in $\pi_c$ is conducive to improving the structural compactness and power weight ratio, and the reduction in $T_{\pi}^*$ is a benefit for increasing the service life of the turbine. Furthermore, the benefits of reducing $\pi_c$ and $T_{\pi}^*$ exhibit a positive correlation with $T_{\pi}^*$ and a negative correlation with $\pi_c$, and the internal mechanism is consistent with the variations in performance benefits versus $\pi_c$ and $T_{\pi}^*$, which have been expressed above.

The feedback pressure perturbation generated by the RDC can be reduced effectively by the isolator, but it cannot be eliminated thoroughly [22]. The weakened pressure perturbation may result in reduction in compressor efficiency. Similarly, the turbine inlet parameter distribution can be improved owing to the mixing process in the mixer, but the turbine inlet parameter distribution of the rotating detonation-based turboshaft engine, which has a direct relationship with the turbine efficiency, is still less uniform than that of the conventional one. Therefore, the sensitivity analysis of turbomachinery efficiency and the total pressure recovery of the isolator on overall performance of the rotating detonation-based turboshaft engine is of significance. As the turbomachinery polytropic efficiency $e_c$ and $e_t$ is hardly dependent on the pressure ratios $\pi_c$ and $\pi_t$ [3], $e_c$ and $e_t$ are utilized to characterize the turbomachinery efficiency in this study. Figure 6 displays the effects of compressor polytropic efficiency $e_c$, turbine polytropic efficiency $e_t$ and total pressure recovery coefficient of isolator $\sigma_{is}$ on the overall performance of the engine. As $\pi_c$ remains constant, the increase of $e_c$ and $e_t$ could improve the overall performance of the engine. And the performance metrics are more sensitive to changes in $e_c$ and $e_t$ at higher values of $\pi_c$. Furthermore, $P_t$ and $sfc$ are more sensitive to changes in $e_c$ than to changes...
Figure 6: Variations in performance metrics with (a) compressor polytropic efficiency $\epsilon_c$, (b) turbine polytropic efficiency $\epsilon_t$, and (c) total pressure recovery coefficient of isolator $\sigma_is$. 
in $e$, as the compressor pressure ratio is normally higher than the turbine pressure ratio. Unlike the influence mechanism of $e$ and $\epsilon$, the increase of $\sigma_{i0}$ has the same impact as improving the total pressure ratio of the engine. According to the sensitivity analysis of cycle parameters on overall performance of the engine, as $\pi_c$ increases, $P_s$ first increases but then decreases, and $sfc$ first decreases but then increases. At low values of $\pi_c$, the higher the value of $\sigma_{i0}$, the higher the value of $P_s$. When the value of $\pi_c$ is relatively high, the situation is the opposite. As the optimum compressor pressure ratios corresponding to the maximum $\eta_{th}$ and minimum $sfc$ are higher than that corresponding to the maximum $P_s$, when the values of $\pi_c$ are not quite high, the higher the value of $\sigma_{i0}$, the higher the value of $\eta_{th}$ and the lower the value of $sfc$.

### 3.2. Comparison Between the Rotating Detonation-Based Turboshaft Engine and the Conventional One

Figure 7 shows the variations in performance difference between the rotating detonation-based turboshaft engine and the conventional one with the same component parameters versus cycle parameters under the standard sea-level condition at takeoff. It can be seen that, at low values of $\pi_c$, the rotating detonation-based turboshaft engine exhibits significant potential benefits in $P_s$, $\eta_{th}$, and $sfc$. As $\pi_c$ increases, the potential benefits decrease and tend to disappear. Furthermore, the compressor pressure ratio range corresponding to the rotating detonation-based turboshaft engine exhibiting benefit in $P_s$ is wider than that corresponding to the engine exhibiting benefit in $\eta_{th}$ and $sfc$. The fuel-air ratio $f$ of the rotating detonation-based turboshaft engine is higher than that of the conventional one with the same cycle parameters. Then, the total pressure gain of the RDC is significant at low values of $\pi_c$, resulting in a higher power turbine pressure ratio $\pi_{pt}$ of the rotating detonation-based turboshaft engine compared to the conventional one. As the total pressure gain of the RDC decreases with an increase in $\pi_c$, so does the benefit of $\pi_{pt}$. For the $\eta_{th}$ and $sfc$ of turboshaft engines, the higher value of $f$ is an unfavorable factor, and the higher value of $\pi_{pt}$ is a favorable factor. The potential benefits of $\eta_{th}$ and $sfc$ can be achieved by the rotating detonation-based turboshaft engine under the premise that the favorable effects generated by $\pi_{pt}$ are sufficient to overcome the unfavorable effects of a higher value of $f$. Therefore, there is a strong agreement between the variations of the potential benefits in $\eta_{th}$ and $sfc$ and the variation of

**Figure 7:** Performance comparison of turboshaft engine based on rotating detonation and the conventional one for different cycle parameters. (a) $P_s$, (b) $sfc$, and (c) $\eta_{th}$.
the benefit of $\pi_{pt}$. The higher value of $f$ and the higher value of $\pi_{pt}$ are all favorable factors for the improvement of $P_\alpha$. Therefore, the rotating detonation-based turboshaft engine exhibits significant benefit in $P_\alpha$ at low values of $\pi_{pt}$. In addition, the power turbine inlet total enthalpy $h_{t1}^*$ of the rotating detonation-based turboshaft engine is lower than that of the conventional one, owing to the rear stage of compressor. Therefore, the benefit in $P_\alpha$ tends to disappear at high values of $\pi_{pt}$. It is not difficult to draw the conclusion that the critical compressor pressure ratio $\pi_{crit}$ corresponding to the disappearance of $P_\alpha$ improvement is higher than that corresponding to the disappearance of $\eta_\text{th}$ and $sfc$, according to the above explanation.

When the value of $\pi_{pt}$ remains constant, as $T_4^*$ increases, the potential performance benefits of the rotating detonation-based turboshaft engine increase continuously. And the potential benefits in $\eta_\text{th}$ and $sfc$ are more sensitive to changes in $T_4^*$ compared to the potential benefit in $P_\alpha$. Although the total pressure gain of the RDC is independent of $T_4^*$, the effect of the total pressure gain of the RDC can be enlarged owing to the decrease of $\alpha$. Therefore, the performance differences between the rotating detonation-based turboshaft engine and the conventional one increase with an increase in $T_4^*$. In addition, the fuel-air ratio difference increases as $T_4^*$ increases owing to the decrease of $\alpha$. As $\eta_\text{th}$ is positively correlated with $P_\alpha$ and negatively correlated with $f$, the potential benefits in $\eta_\text{th}$ is more sensitive to changes in $T_4^*$. According to the explanation in Section 3.1, there is a strong correlation between the variation of $\eta_\text{th}$ and that of $sfc$, so do the variations of performance benefits in $\eta_\text{th}$ and $sfc$. The variations in critical compressor pressure ratio $\pi_{crit}$ corresponding to the disappearance of $P_\alpha$ improvement and the critical compressor pressure ratio $\pi_{crit2}$ corresponding to the disappearance of $sfc$ improvement of the rotating detonation-based turboshaft engine versus $T_4^*$ are displayed in Table 2. It can be seen that $\pi_{crit}$ and $\pi_{crit2}$ exhibit positive correlation with $T_4^*$, and $\pi_{crit}$ is normally larger than $\pi_{crit2}$.

As the value of $\pi_{pt}$ remains constant at 12 and the value of $T_4^*$ remains constant at 1600 K, the variations in performance differences between the rotating detonation-based turboshaft engine and the conventional one versus flight parameters are shown in Figure 8. As $V_0$ increases, $P_\alpha$ and $\eta_\text{th}$ of the two forms of engines increase, and $sfc$ decreases monotonically. And the performance differences between the two forms of engines decreases with an increase in $V_0$. And the performance differences of $\eta_\text{th}$ and $sfc$ are more sensitive to changes in $V_0$ compared to the performance difference of $P_\alpha$. As $V_0$ increases, the total pressure ratio of the engine increases owing to the ram compression, which is favorable for improving the overall performance. The performance benefits of the rotating detonation-based turboshaft engine compared to the conventional one are mainly contributed by the total pressure gain of the RDC. As $V_0$ increases, the combustor inlet temperature $T_3^*$ increases, which is detrimental to the total pressure gain of the RDC [22, 23]. In addition, $\alpha$ increases with an increase in $V_0$, owing to the decrease of cooling capacity of the compressed air. Then, the effect of the total pressure gain of the RDC can be weakened. In summary, the potential performance benefits of the rotating detonation-based turboshaft decrease with an increase in $V_0$. $P_\alpha$ and $\eta_\text{th}$ of the two forms of engines exhibit a positive correlation with $H$, and $sfc$ exhibits a negative correlation with $H$. And the performance differences between the two forms of engines exhibit a positive correlation with $H$. With the increase of $H$, the freestream temperature $T_0$ decreases monotonically, which is favorable for the improvement of the overall performance. $T_4^*$ decreases with an increase in $H$, resulting in the improvement of the total pressure gain of the RDC. In addition, $\alpha$ decreases with an increase in $H$, and the effect of the total pressure gain of the RDC can be enlarged. With the combined effects of these two factors, the potential performance benefits of the rotating detonation-based turboshaft increase with an increase in $H$.

The effects of flight parameters on $\pi_{crit}$ and $\pi_{crit2}$ are displayed in Tables 3 and 4. According to the calculation results, $\pi_{crit}$ and $\pi_{crit2}$ are positively correlated with $H$ and negatively correlated with $V_0$.

### Table 2: Variations in critical compressor pressure ratios $\pi_{crit}$ and $\pi_{crit2}$ with $T_4^*$.

| $T_4^*$, K | $\pi_{crit1}$ | $\pi_{crit2}$ |
|------------|--------------|--------------|
| 1400       | 14.20        | 12.37        |
| 1500       | 18.23        | 13.87        |
| 1600       | 23.52        | 15.26        |
| 1700       | 30.69        | 16.5         |
| 1800       | 40.87        | 17.71        |

3.3. Optimum Pressure Ratios. On the basis of the variations in $P_\alpha$ and $sfc$ of the rotating detonation-based turboshaft engine versus $\pi_{pt}$, there exist an optimum compressor pressure ratio $\pi_{opt1}$ that maximizes the specific power and an optimum compressor pressure ratio $\pi_{opt2}$ that minimizes the specific fuel consumption. Table 5 shows the variations in $\pi_{opt}$ and $\pi_{opt2}$ versus $T_4^*$. It can be seen that $\pi_{opt1}$ and $\pi_{opt2}$ increase with an increase in $T_4^*$, as $P_\alpha$ exhibits a positive correlation with $T_4^*$ and $sfc$ exhibits a negative correlation with $T_4^*$. The variations in $\pi_{opt1}$ and $\pi_{opt2}$ versus flight parameters $V_0$ and $H$ are listed in Tables 6 and 7. With the increase of $V_0$, the optimum compressor pressure ratios decrease continuously owing to the ram compression. As $H$ increases, the RDC inlet temperature decreases, and the pressure gain of the RDC increases monotonically. In addition, $\alpha$ decreases as the freestream temperature decreases with an increase in $H$. For the effects of the above factors, $sfc$ performance improves with $H$ as does $\pi_{opt2}$.

4. Conclusion

In this study, a configuration of the rotating detonation-based turboshaft engine with the compatibility between the turbomachinery and RDC under consideration is presented. Then, the performance characteristics of this new form of engine are investigated based on the parametric
Figure 8: Performance comparison of turboshaft engine based on rotating detonation and the conventional one for different cycle parameters. (a) $P_s$, (b) $sfc$, and (c) $\eta_{th}$.

Table 3: Variations in critical compressor pressure ratios $\pi_{\text{crit1}}$ and $\pi_{\text{crit2}}$ with $V_0$.

| $V_0$, km h⁻¹ | $\pi_{\text{crit1}}$ | $\pi_{\text{crit2}}$ |
|---------------|---------------------|---------------------|
| 0             | 23.52               | 15.26               |
| 150           | 23.32               | 15.1                |
| 300           | 22.72               | 14.63               |
| 450           | 21.77               | 13.89               |

Table 4: Variations in critical compressor pressure ratios $\pi_{\text{crit1}}$ and $\pi_{\text{crit2}}$ with $H$.

| $H$, km      | $\pi_{\text{crit1}}$ | $\pi_{\text{crit2}}$ |
|--------------|-----------------------|-----------------------|
| 0            | 21.77                 | 13.89                 |
| 2            | 23.72                 | 15.4                  |
| 4            | 25.94                 | 17.17                 |
| 6            | 28.45                 | 19.27                 |
| 8            | 31.35                 | 21.77                 |

Table 5: Variations in optimum compressor pressure ratios $\pi_{\text{opt1}}$ and $\pi_{\text{opt2}}$ with $T_4^*$.

| $T_4^*$, K   | $\pi_{\text{opt1}}$ | $\pi_{\text{opt2}}$ |
|--------------|---------------------|---------------------|
| 1400         | 4.18                | 11.04               |
| 1500         | 4.95                | 14.07               |
| 1600         | 5.79                | 17.67               |
| 1700         | 6.68                | 21.93               |
| 1800         | 7.71                | 26.52               |

Table 6: Variations in optimum compressor pressure ratios $\pi_{\text{opt1}}$ and $\pi_{\text{opt2}}$ with $V_0$.

| $V_0$, km h⁻¹ | $\pi_{\text{opt1}}$ | $\pi_{\text{opt2}}$ |
|---------------|---------------------|---------------------|
| 0             | 5.79                | 17.67               |
| 150           | 5.73                | 17.56               |
| 300           | 5.55                | 17.28               |
| 450           | 5.31                | 16.81               |
thermodynamic cycle analysis model. In order to reveal the potential performance benefits and their generation mechanism, the performance comparison between the rotating detonation-based turboshaft engine and the conventional one is performed. The major conclusions are summarized as follows.

(1) When the flight parameters remain constant, as the compression ratio $\pi_c$ increases, the specific power $P_s$ and thermal efficiency $\eta_{th}$ of the rotating detonation-based turboshaft engine first increase but then decrease, and the specific fuel consumption $sfc$ first decreases but then increases. As the turbine inlet temperature $T_{4\ast}^\ast$ increases, $P_s$ and $\eta_{th}$ increase, and $sfc$ decreases continuously. When the component parameters remain constant, with the increase in flight velocity $V_0$ and flight altitude $H$, $P_s$ and $\eta_{th}$ increase, and $sfc$ decreases monotonically. There exist optimum compressor pressure ratios $\pi_{opt1}$ and $\pi_{opt2}$ which maximizes the specific power and minimizes the specific fuel consumption, respectively, and $\pi_{opt1}$ is nominally larger than $\pi_{opt2}$. Furthermore, $\pi_{opt1}$ and $\pi_{opt2}$ are positively correlated with $T_{4\ast}$ and $H$ and are negatively correlated with $V_0$.

(2) Compared to the conventional turboshaft engine, the thermal efficiency of the rotating detonation-based turboshaft engine can be improved above 7% at lower values of $\pi_c$, and the benefits decrease with an increase in $\pi_c$. As $\pi_c$ remains constant, the performance improvements increase with the increase of $T_{4\ast}$. As $T_{4\ast}$ remains constant at 1600 K, the value of $\pi_{crit1}$ is about 23.5 corresponding to the disappearing of benefit in $P_s$, and value of $\pi_{crit2}$ is about 15.3 corresponding to the disappearing of benefit in $\eta_{th}$ and $sfc$. The critical compressor pressure ratios are positively correlated with $T_{4\ast}$ corresponding to the disappearance of performance benefits.

(3) When the value of $\pi_c$ is not quite high and the value of $T_{4\ast}$ is not relatively low, the rotating detonation-based turboshaft engine exhibits competitive potential benefits within the typical flight envelope of helicopters (i.e., $V_0 < 450$ km/h and $H < 8$ km). The potential benefits of the rotating detonation-based turboshaft engine exhibit a positive correlation with $H$ and exhibit a negative correlation with $V_0$.

| $H$, km | $\pi_{opt1}$ | $\pi_{opt2}$ |
|---------|-------------|-------------|
| 0       | 5.40        | 16.98       |
| 2       | 5.66        | 18.73       |
| 4       | 5.94        | 20.76       |
| 6       | 6.25        | 23.13       |
| 8       | 6.60        | 25.92       |

Furthermore, the values of $\pi_{crit1}$ and $\pi_{crit2}$ increase with the increase in $H$ and decrease with an increase in $V_0$.

**Nomenclature**

$c_p$: Specific heat at constant pressure

$f$: Fuel-air mass flow ratio

$H_c$: Fuel heating value

$h$: Enthalpy

$Ma$: Mach number

$m$: Mass flow rate

$P_s$: Specific power

$p$: Pressure

$R$: Universal gas constant

$sfc$: Specific fuel consumption

$T$: Temperature

$u$: Overall uncertainty

$V$: Velocity

$\gamma$: Ratio of specific heats

$\eta_0$: Overall efficiency

$\eta_{th}$: Thermal efficiency

$\kappa$: Power split parameter

$\pi_c$: Compressor pressure ratio.

**Superscripts**

*: Total or stagnation parameters.

**Subscripts**

0: Freestream at the intake entrance

1: Compressor inlet section

3: Combustor inlet section

4: Turbine inlet section

6: Power turbine inlet section

9: Nozzle outlet section.

**Abbreviations**

DRDATE: Dual-duct rotating detonation aeroturbine engine

RDC: Rotating detonation combustor.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that there is no conflict of interest regarding the publication of this paper.

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