

Research Article

Analysis of Entropy Generation and Potential Inhibition in an Aeroengine System Environment

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From a system perspective, the entropy generation of an aeroengine is directly related to the thermal efficiency when the Brayton cycle pressure ratio and maximum temperature remain constant. The lower the entropy generation of the engine is, the higher the thermal efficiency. However, the secondary air system of the engine generates a large quantity of entropy compared to the components of the main flow channel, because the irreversible losses of the internal flow and heat exchange between the air system components generate considerable entropy within the system. In this study, the theoretical method is used to build entropy generation model for different characteristics of air system components during the aerothermal process. In this basis, an integrated model of the whole engine is introduced to identify the key components for entropy generation in the system environment. The results show that the labyrinth at outlet of unloading cavity is recognized as the one that generates the most entropy in the entire aeroengine system, and the total entropy generation of the system is highly related to this component. Besides, in the system environment, entropy generation is the sum of the local entropy generated by the components and the total entropy generated by mixing of airflows in each component. High local entropy generated by components does not necessarily result in a high system entropy production, and vice versa. Therefore, when the minimum system entropy generation is the design goal, the most critical operations for entropy generation should be identified according to the corresponding sensitivity and parameter variation range, and the design should be improved accordingly.

1. Introduction

As an aeroengine is the heart of an aircraft, engine performance is vitally important to aircraft operation. Trends in modern aeroengine development include a continuous increase in the engine's thrust-to-weight ratio, fuel consumption reduction, and enhanced engine reliability. Increasing the turbine inlet temperature is generally considered to be an effective way to achieve the first two objectives [1, 2]. However, an excessively high turbine inlet temperature would deteriorate the working environment of the turbine blades, resulting in short service life and poor stability

[3]. Therefore, further improving the engine performance without changing the turbine inlet temperature is an issue that needs to be addressed [4, 5].

Generally, the entropy generation is the energy loss from irreversible processes. So, in aeroengine system, the entropy generation or energy loss is generated as a result of viscous dissipation, heat transfer driven by temperature gradients, metal friction, and mixing. Moreover, reducing the entropy generation or energy loss of the system without changing the turbine inlet temperature would improve performance. Thus, any form of entropy generation or energy loss in an aeroengine system could be reflected in the turbine inlet

temperature under fixed performance constraints [6]. In general, viscous dissipation is mainly associated with the operation of the compressor, turbine, secondary air system, and oil system; heat dissipation driven by temperature gradients mainly occurs in the combustion chamber and secondary air system; metal friction mainly originates from bearings; and mixing losses are mainly incurred in the combustion chamber, turbine, and secondary air system.

From a system perspective, when the Brayton cycle pressure ratio and the maximum engine temperature remain constant, entropy generation is directly related to the thermal efficiency of the aeroengine. Moreover, the lower the entropy generation of the engine is, the higher the thermal efficiency, the higher the work performed by the engine cycle under a fixed cycle heat absorption, and the lower the heat absorption temperature of the engine under fixed cycle work. Here, it should be pointed out that the major effect of the secondary air system in aeroengine is cooling to decrease the high temperature of components. Thus, the secondary air system is in the internal of aeroengine with very complex structures. Compared with the components of the main flow channel, the wind resistance of the rotating parts, bleed air of the air system, heat exchange between the main flow and the air system, and the irreversible losses of the internal flow and heat exchange within the air system components all generate considerable entropy within the system [7, 8]. Therefore, although the secondary air system has low velocity and low mass flow, it generates a large quantity of entropy. Besides, in the current design and manufacture level of aeroengine, it is very difficult to further improve the efficiency or decrease entropy generation, and the low entropy generation design through the secondary air system optimization is become the most potential growth point.

Scholars have conducted many studies to analyze entropy generation during basic flow and heat transfer processes [9, 10]. Although some scholars in the field of aeroengines have used the nonnegativity of entropy generation to determine the flow direction of fluids, there has been relatively limited analysis on entropy generation related to engine systems.

In view of the abovementioned issues, the entropy generation mechanisms in an engine system are investigated in this study. The entropy generation is related to the component characteristics by analyzing the entropy generation of typical air system components during the aerothermal process. Then, an entropy generation model is formulated for an aeroengine system, and the key components for entropy generation in the system environment are identified. The purpose of this study is to tap the entropy generation potential of the air system and reduce the entropy generated by the engine system.

2. Theoretical Analysis of Entropy Generation

In general, the secondary air system network is mainly composed of chambers, tubes, labyrinths, and holes. Within this structure, entropy generation mainly comes from the processes of viscous dissipation, heat transfer driven by temperature gradients, and mixing. In this basis, a theoretical

analysis is performed under general conditions in this section. Here, the air is assumed to be an ideal gas with piecewise constant physical properties. Nevertheless, the entropy generation level is not influenced by this assumption. From the point of view of mechanism, the entropy generation can be considered as a degree of deviation between average polytropic index and average adiabatic index in process, and the entropy generation is increased with the enlarged deviation. It means that the entropy generation can be restrained when the adiabatic index is as close to the polytropic index as possible. Then, the air system components can be regarded as an open system, and the corresponding entropy equation is

$$\delta Sg = dSCV - \frac{\delta Q}{Tr} + s_2 \delta m_2 - s_1 \delta m_1, \quad (1)$$

where s_g denotes the entropy generation and Tr denotes the wall temperature. For a stable flow system, $dSCV = 0$. For 1 kg of a working fluid, the formula presented above simplifies to:

$$s_g = s_2 - s_1 - \int \frac{\delta q}{Tr}. \quad (2)$$

2.1. Entropy Generation from Viscous Dissipation. If considering that entropy is only generated by viscous dissipation loss, it can be divided into two situations. Figure 1 presents that the viscous dissipation loss consists of contributions from the pressure drop, and Figure 2 shows that the viscous dissipation loss consists of contributions from the wind resistance. Nevertheless, for this two situation, there is $\delta q/Tr = 0$.

2.1.1. For System with Only Pressure Loss. Typically, the total pressure recovery coefficient σ is used to characterize the total pressure drop, and the inlet and outlet total temperature are denoted by T_1^* and T_2^* , respectively, as follows:

$$\sigma = \frac{p_2^*}{p_1^*}, \quad (3)$$

$$T_1^* = T_2^*.$$

Then, the entropy generation sg for system with only pressure loss can be expressed as:

$$s_g = s_2 - s_1 = c_p \ln \frac{T_2^*}{T_1^*} - R \ln \frac{p_2^*}{p_1^*} = R \ln \sigma. \quad (4)$$

2.1.2. For System with Only Wind Resistance Loss. In this condition, there is $p_1^* = p_2^*$, and the total enthalpy is $h^* = h + V^2/2$, so the energy equation is:

$$-w_s = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} = h_2^* - h_1^* = cp(T_2^* - T_1^*). \quad (5)$$

Then, the entropy generation sg for system with only

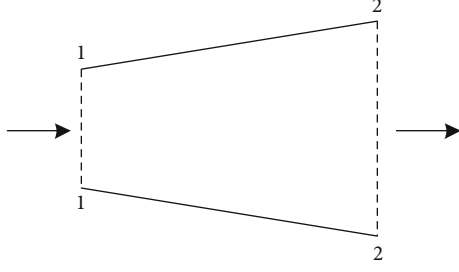


FIGURE 1: A system with only pressure loss.

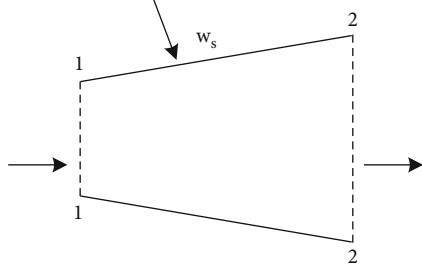


FIGURE 2: A system with only wind resistance loss.

wind resistance loss can be written as:

$$s_g = s_2 - s_1 = c_p \ln \frac{T_2^*}{T_1^*} - R \ln \frac{p_2^*}{p_1^*} = c_p \ln \left(1 - \frac{w_s}{c_p T_1^*} \right). \quad (6)$$

2.2. Entropy Generation Associated with Heat Transfer Driven by Temperature Gradients. Figure 3 presents a system with only heat transfer loss driven by a temperature gradient. The energy equation for the system is given by:

$$q - w_s = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}. \quad (7)$$

Because $w_s = 0$, $h^* = h + (V^2/2)$, and $h_2^* - h_1^* = c_p(T_2^* - T_1^*)$, there is:

$$q = c_p(T_2^* - T_1^*). \quad (8)$$

Then, s_g can be written as:

$$s_g = s_2 - s_1 - \int \frac{\delta q}{Tr} = c_p \ln \frac{T_2^*}{T_1^*} - \int \frac{\delta q}{Tr} = c_p \ln \left(\frac{q}{c_p T_1^*} + 1 \right) - \int \frac{\delta q}{Tr}. \quad (9)$$

In the basis the Nusselt number definition, there is $Nu = \alpha d/\lambda$ and $q = Nu \lambda \Delta T/d$. Then, the entropy flow can be written as:

$$s_{f,Q} = \int_1^2 \frac{\delta q}{Tr} = - \frac{Nu \lambda}{d} \cdot \frac{\Delta T}{Tr}, \quad (10)$$

where the temperature difference is defined as $\Delta T = Tr - T$. So, the entropy generation associated with heat transfer

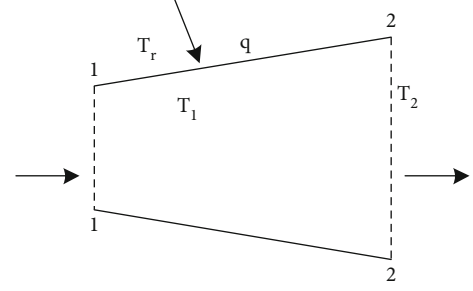


FIGURE 3: A system with only heat transfer loss.

driven by temperature gradients in Equation (9) can be constitutively expressed as:

$$s_g = c_p \ln \left[\frac{Nu \lambda \Delta T}{dc_p T_1^*} + 1 \right] + \frac{Nu \lambda}{d} \cdot \frac{\Delta T}{Tr}. \quad (11)$$

2.3. Mixing-Induced Entropy Generation. Figure 4 presents a system in which entropy generation is only induced by mixing loss. The entropy generation in this condition can be obtained by combine the continuity equations, energy equation and momentum equation.

2.3.1. Continuity Equation. The differential form of the continuity equation is given by

$$\frac{dm}{m} = \frac{d\rho}{\rho} + \frac{dV}{V}, \quad (12)$$

where m is the mass flow rate of the main flow, ρ is the gas density, and V is the gas velocity, respectively.

2.3.2. Energy Equation. The energy equation can be written as:

$$h^* = c_p T^* = c_p T + \frac{V^2}{2} = \text{Constant}. \quad (13)$$

Differentiating the equation above and substituting the specific heat at constant pressure $c_p = (k/k - 1)Rg$ and sound velocity $c^2 = kRgT$ yields, there is:

$$\frac{dT}{T} + (k - 1)Ma^2 \frac{dV}{V} = 0, \quad (14)$$

where Ma denotes the Mach number.

2.3.3. Momentum Equation. The momentum equation in the X direction can be written as:

$$pA + (p + dp)A = (m + dm)(V + dV) - mV - dmV_{\text{mixing}}. \quad (15)$$

Substituting $y = V_{\text{mixing}}/V$, mass flow rate $m = \rho VA$

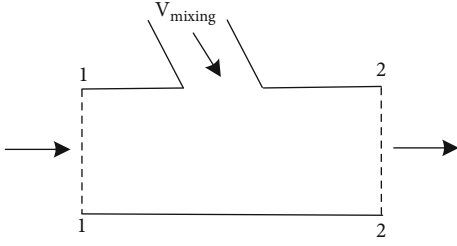


FIGURE 4: The entropy generation is only induced by mixing loss.

yields the momentum equation as:

$$dp + \rho V dV + \rho V^2 (1 - \gamma) \frac{dm}{m} = 0. \quad (16)$$

Dividing the equation presented above by p and substituting $p/\rho = c^2/k$ yield the following equation after simplification:

$$\frac{dp}{p} + kMa^2 \frac{dV}{V} + kMa^2 (1 - \gamma) \frac{dm}{m} = 0. \quad (17)$$

The following equation can then be derived:

$$\frac{dp^*}{p^*} = \frac{dp}{p} + \frac{kMa^2}{1 + (k - 1/2)Ma^2} \cdot \frac{dMa}{Ma}. \quad (18)$$

Because for the case of $T^* = \text{constant}$, there is:

$$\frac{ds}{c_p} = \frac{k - 1}{k} \cdot \frac{dp^*}{p^*}. \quad (19)$$

So, the mixing-induced entropy generation s_g can be expressed as:

$$s_g = s_2 - s_1 = -R \int \frac{dp^*}{p^*} = -R \ln \sigma - R \int \left(\frac{kMa^2}{1 + (k - 1/2)Ma^2} \cdot \frac{dMa}{Ma} \right). \quad (20)$$

3. Entropy Generation by the Components of the Air System

In the basis of the theoretical analysis of entropy generation in Section 2, the entropy generation of the air system can be calculated, respectively, by different components and the analysis is given in this section.

3.1. Entropy Generation for Holes, Slits, Pipes, and Elbows Components. The holes, slits, pipes, and elbows in the air system can be regarded as constituting an adiabatic and isochoric system ($dQ = 0$ and $dW = 0$) with one inlet and one outlet that mainly generates entropy through pressure loss.

Then, s_g can be expressed as:

$$s_g = -R \ln \sigma. \quad (21)$$

Entropy generation in an adiabatic and isochoric system depends on the total pressure ratio of the inlet and outlet of the system, that is, σ . As the dissipation increases, σ decreases, and more entropy is generated. For a constant entropy process, $\sigma = 1$ and the total inlet and outlet pressures of the system remain unchanged.

3.2. Entropy Generation for Heat Exchange Components. The heat exchange components in the air system can be approximated by a nonadiabatic system with one inlet and one outlet. Here, it should be pointed out that the essence of adiabatic hypothesis is assumed that the influence of flow field can be ignored by wall temperature distribution, and this assumption is suitable for static channel and low-speed rotor-stator system of aeroengine. Thus, the purpose of the assumption used in this paper is taken the entropy generation by heat exchange and the entropy generation by flow dissipation separately. Thus, the main sources of entropy generation are pressure loss and heat transfer driven by a temperature difference.

Then, s_g can be expressed as:

$$s_g = c_p \ln \left[\frac{Nu\lambda\Delta T}{dc_p T_1^*} + 1 \right] + \frac{Nu\lambda}{d} \cdot \frac{\Delta T}{Tr} - R \ln \sigma. \quad (22)$$

When the components with a fixed geometric structure, s_g can be expressed as:

$$s_g = f(\sigma, T_1^*, Tr, Nu, \Delta T). \quad (23)$$

Thus, it can be seen that the entropy increase of a non-adiabatic but isochoric system ($dQ \neq 0$ and $dW = 0$) mainly results from heat transfer driven by temperature differences and flow dissipation, which depends on σ , Nu , T_1^* , ΔT , and Tr .

3.3. Entropy Generation for Labyrinth Components. The labyrinth in the air system can be approximated as an adiabatic but nonisochoric system ($dQ = 0$ and $dW \neq 0$) with one inlet and one outlet. The main sources of entropy generation are pressure loss and wind resistance loss.

Then, s_g can be written as:

$$s_g = c_p \ln \left[1 + \frac{ws}{c_p T_1^*} \right] - R \ln \sigma. \quad (24)$$

For the labyrinth in the air system, ws mainly consists of the work done against friction. When the airflow passes through the gap of the labyrinth seal, which is rotating at high speed, the gas viscosity results in friction between the airflow and the walls of the rotor and stator of the labyrinth seal. The friction torque performs work, and heat is simultaneously generated due to air friction, which manifests as a temperature rise due to wind resistance.

Generally, the friction power can be written as follows [1]:

$$w_s = M\omega, \quad (25)$$

where the rotational angular velocity is denoted by ω . Because the dimensionless torque coefficient is defined as $C_m = M/0.5\rho\omega^2r^5$, there is:

$$w_s = 0.5C_m\rho\omega^3r^5. \quad (26)$$

Besides, the temperature rise due to wind resistance is written as:

$$w_s = mc_p\Delta T^*. \quad (27)$$

Substituting Equation (26) into the Equation (25), there is:

$$\Delta T^* = \frac{C_m\rho\omega^3r^5}{2mc_p}. \quad (28)$$

In view of the $m\sqrt{T^*}/p^* = f(\sigma)$, Equation (28) can be rewritten as:

$$\Delta T^* = T_2^* - T_1^* = \frac{C_m\rho\omega^3r^5\sqrt{T_1^*}}{2c_p f(\sigma)p_1^*}. \quad (29)$$

So, the entropy generation for labyrinth components s_g can be expressed as:

$$s_g = c_p \ln \left[1 + \frac{C_m\rho\omega^3r^5}{2c_p f(\sigma)p_1^*\sqrt{T_1^*}} \right] - R \ln \sigma. \quad (30)$$

For components with a fixed geometric structure, s_g can be expressed as:

$$s_g = f(\sigma, \omega, C_m, T_1^*, p_1^*). \quad (31)$$

It means that the entropy increase in an adiabatic but nonisochoric system ($dQ = 0$) mainly results from the frictional work done and flow dissipation, which depends on σ , T_1^* , p_1^* , ω , and C_m .

3.4. Entropy Generation for Turbine Disc Cavity Components. The turbine disc cavity in the air system can be approximated as a nonadiabatic and nonisochoric system ($dQ \neq 0$ and $dW \neq 0$) with one inlet and one outlet. Entropy in this cavity is mainly generated by the pressure loss, wind resistance loss, and heat transfer driven by the temperature difference. That is, s_g can be written as:

$$s_g = c_p \ln \left(1 + \frac{q - w_s}{c_p T_1^*} \right) + \frac{Nu\lambda}{d} \cdot \frac{\Delta T}{T_r} - R \ln \sigma. \quad (32)$$

where the friction power w_s is also $w_s = M\omega$ and the dimen-

sionless torque coefficient is defined as $C_m = M/0.5\rho\omega^2r^5$, and Equation (32) can be continuity expressed as:

$$s_g = c_p \ln \left(\frac{Nu\lambda\Delta T - 0.5C_m\rho\omega^3d^6}{c_p T_1^*d} + 1 \right) + \frac{Nu\lambda}{d} \cdot \frac{\Delta T}{T_r} - R \ln \sigma. \quad (33)$$

For components with a fixed geometric structure, the entropy generation for turbine disc cavity components s_g can be written as:

$$s_g = f(Nu, \Delta T, \sigma, T_r, T_1^*, \omega, C_m). \quad (34)$$

It means that the entropy increase in a nonadiabatic and nonisochoric system depends on σ , Nu , T_r , ω , T_1^* , ΔT , and C_m .

3.5. Entropy Generation for the Tube and Cavity Components. The tube and cavity of the manifold of the air system can be approximated by an adiabatic and isochoric system with two inlets and one outlet. The mixing of the two flows is the main source of s_g , which can be expressed as:

$$s_g = -R \ln \sigma - R \int \left(\frac{kMa^2}{1 + (k-1/2)Ma^2} \cdot \frac{dMa}{Ma} \right), \quad (35)$$

where it can be seen that the increase in the mixing-induced entropy depends on σ and Ma .

In summary, Table 1 presents the approximate models for the air system components, sources of entropy generation, and related parameters.

4. Integrated Model of the Whole Engine

To analyze the most sensitive factors that affect entropy generation in an aeroengine, an integrated model of the air system is established based on a specific engine design. For this integrated model, the main flow model is coupling with the secondary air system model for whole aeroengine. The flow, heat transfer, and windage of main flow and secondary air system can be coupled simulation in integrated model, and this model has the ability to analyze the most sensitive factors that affect entropy generation in an aeroengine. The details of this integrated model are given in reference [11]. Figure 5 shows the flow path in the high-pressure compressor. The temperature rise due to the wind resistance in the main labyrinth and rotating parts is considered in the simulation model. A thermal network is coupled with the fluid network to simulate convective heat transfer of the main flow and main air path of the air system, as well as heat conduction in the high- and low-pressure turbine discs, the high-pressure rear shaft neck, the casing, and the main pipe walls. The flow, heat transfer, and wind resistance of the main flow and secondary air flow are coupled in the integrated model, which is used to perform a sensitivity analysis on the design variables for entropy generation.

TABLE 1: Sources of entropy generation and parameters related to the components of the air system.

Component	Approximate model	Input parameter	Output parameter	Source of entropy generation	Parameters related to entropy generation
Hole, slit, tube, and elbow	Adiabatic and isochoric system	Total pressure	Total pressure	Viscous dissipation	σ
Component undergoing heat exchange	Nonadiabatic and isochoric system	Total pressure Total pressure temperature Static temperature Wall temperature	Total pressure Total temperature Static temperature	Heat transfer driven by a temperature difference and viscous dissipation	$\sigma, T_1^*, T_r, Nu,$ and ΔT
Labyrinth	Adiabatic and nonisochoric system	Total pressure Total temperature Static temperature Rotation speed	Total pressure Total temperature Static pressure	Temperature rise due to wind resistance and viscous dissipation	$\sigma, \omega, C_m, T_1^*$, and p_1^*
Turbine disc cavity	Nonadiabatic and nonisochoric system	Total pressure Total temperature Static temperature Static pressure Wall temperature rotation speed	Total pressure Total temperature Static temperature Static pressure	Heat transfer driven by a temperature difference and viscous dissipation	$Nu, \Delta T, \sigma, Nu, T_r, T_1^*, \omega,$ and C_m
Tube and cavity of manifold	Adiabatic and isochoric system	Total pressure Mach number	Total pressure	Flow mixing and viscous dissipation	σ and Ma

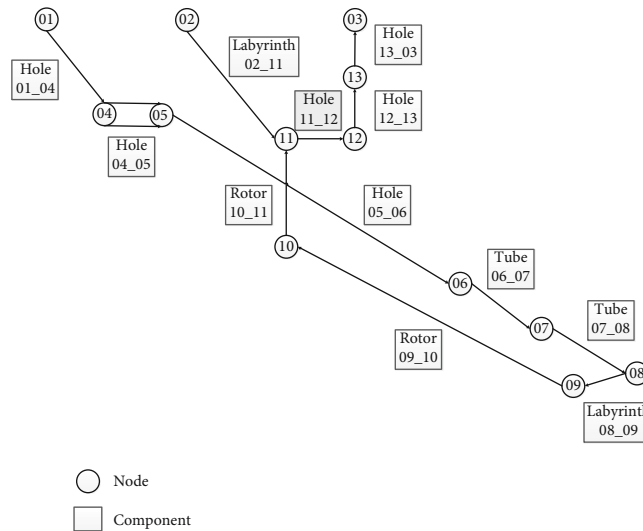


FIGURE 5: Flow path in the high-pressure unloading chamber.

In this analysis, the simulation results from integrated model of whole aeroengine are compared with experimental results to verify the integrated model. For rotation speed of low-pressure rotor from main flow, there is excellent agreements between model predictions and measurement data, and the maximum relative error is lower than 2% at 68% relative rotation speed. For front cavity pressure and temperature of high-pressure turbine from secondary air system, the

simulation results are small higher than test data, and the maximum relative error is lower than 5%.

5. Analysis of Entropy Generation of the System

The entropy generation theory for the components and the integrated model are applied to calculate the local entropy generation of the components based on the entropy

TABLE 2: Local entropy generation, changes in system entropy generation changes, and sensitivity of system entropy generation for different components.

Component	Local entropy generation (KJ/(kg·K))	Changes in system entropy generation (KJ/(kg·K))	Sensitivity of system entropy generation
Labyrinth02_11	324.74	2.52	34.46
Hole79_73	0.64	0.98	31.60
Hole76_72	0.65	0.97	31.08
Hole72_77	0.65	0.95	31.08
Hole70_73	0.75	0.99	17.82

TABLE 3: Corresponding boundary conditions of the most sensitive five components for system entropy generation.

Component	Flow(kg/s)	Inlet temperature (K)	Outlet temperature (K)	Inlet pressure (KPa)	Outlet temperature (KPa)
Labyrinth02_11	0.9259633	503.2007417	521.188	2198.036	732.3763
Hole79_73	0.004279	440.5267604	440.5268	1178.835	701.459
Hole76_72	0.0042485	440.5267604	440.5268	1167.865	684.887
Hole72_77	0.0042009	440.5267604	440.5268	1154.013	672.062
Hole70_73	0.0041827	440.5267604	440.5268	1141.858	610.47

parameters of the front and back nodes of the individual components of the secondary air system. Here, it should be pointed out that, before the convergence of the whole network in integrated model, the conditions of the downstream component are not known. So, at the beginning of the simulation, an estimated condition is given, and then, the results are corrected gradually based on the nonconservation in interface until the network conservation.

The flow coupling coefficient (the ratio between actual match flow and initial flow) of the component is directly related to the local entropy generation. It is not easy to achieve local entropy generation of the biasing component during actual operation. Therefore, a biasing flow coupling coefficient is used to obtain local entropy generation of the biasing component in this study. Here, it should be pointed out that the purpose of method is to investigate the change of system entropy generation influenced by local entropy generation variation. Because the local entropy generation is determined by flow and specific entropy generation, it can be obtained the effect of local entropy generation variation through flow deviation. For labyrinth, the local entropy generation is the product of flow and local specific entropy generation, so the local flow of labyrinth is proportional to total flow of labyrinth and local specific entropy generation, and it can be expressed as Equation (30). That is, the labyrinth flow variation introduces the change of local entropy generation, and the system entropy generation is also changed. Thus, the flow coupling coefficient of each component of the secondary air system is separately biased by 1% in the simulation calculation, and the changes in the local entropy generation for each component and the entropy generation of the system are determined. Thus, the sensitivity of the entropy generation of the system to the local entropy generation of each component is calculated.

The sensitivity of the entropy generation of the system is defined as:

$$\varepsilon = \frac{\partial S_{g,\text{system}}}{\partial S_{g,\text{local}}} \cdot \Delta\delta, \quad (36)$$

where $\Delta\delta$ is the error variation range. The geometric deviation of the hole is usually caused by processing deviation, and the variation range is usually less than 1%; the clearance deviation of the labyrinth components is usually caused by machining, assembly deviation, centrifugal deformation of the rotor, thermal deformation, and floating stators due to deformation, and the variation range can reach 0-200%.

Table 2 shows the five components to which the system entropy generation is most sensitive along with the local entropy generation, and the corresponding boundary conditions of these components are presented in Table 3. Changes in the system entropy are also provided in Table 2.

Labyrinth02_11 is the component that generates the most local entropy. The σ value of the Labyrinth02_11 reaches 3, and the entropy generation by pressure loss accounts for 89% of the local entropy generation. Labyrinth02_11 has a small gap, resulting in a high-speed gradient between the tooth tip and the sealing ring. The resulting dissipation is high, and the entropy generated by the wind resistance accounts for 10% of the local entropy generation. As the two air flows have quite different temperatures and pressures, the energy quality decreases after the flows mix, generating a high quantity of entropy that accounts for 1% of the local entropy generation. In summary, the overall entropy generation of the system is most sensitive to the local entropy generation of Labyrinth02_11. The higher the local entropy generation of Labyrinth02_11 is, the smaller the entropy generation of the entire system. This result can

be explained by the fact that the compressed air drawn from the high-pressure compressor and the high-quality gas enters the combustion chamber to mix and burn with fuel. As the main flow, the air-gas mixture participates in the thermal cycle of the engine and performs work. However, the air-gas mixture must be exhausted for the air system to function effectively, and the lost opportunity to perform work decreases the working power of the engine and generates a large quantity of entropy. Therefore, an increase in the local entropy generation of Labyrinth02_11 increases the entropy generation of the entire system and significantly reduces the entropy produced by external mixing. Therefore, overall, the higher the local entropy generation of Labyrinth02_11 is, the lower the entropy generation of the entire system.

In summary, Labyrinth02_11 is the component with the highest entropy generation of the whole engine system, and the entropy generation of the system is most sensitive to this component. In the system environment, the entropy generation of the system is the sum of the local entropy generation of the components and the entropy generation induced by multicomponent airflow mixing. High local entropy generated by components does not necessarily result in a high system entropy production, and vice versa. Therefore, when system entropy generation is the design goal, the most critical operations for entropy generation should be identified according to the sensitivity and parameter variation range, and the design should be improved accordingly.

6. Conclusion

In this study, the entropy generation of the components of a typical air system during the aerothermal process is analyzed with consideration of the component characteristics. An entropy generation model for an aeroengine system is established, and the key components that generate entropy in the system environment are identified. The results show that:

- (1) The theory of entropy generation is used to obtain theoretical expressions for the contributions to entropy generation from mixing, viscous dissipation, and heat transfer driven by a temperature gradient. The parameters related to entropy generation are analyzed for several typical components of the secondary air system, such as those involved in throttling, sealing, and heat exchange, rotating components, and the manifold
- (2) An integrated model of the air system of the whole engine is established for a specific engine design. The entropy generation theory is applied to each component to determine the local entropy generation and system entropy generation for the flow path in a high-pressure unloading cavity. The sensitivity of the entropy generation of the system to the local entropy generation by the components is calculated
- (3) High local entropy generated by components do not necessarily result in a high system entropy production, and vice versa

Nomenclature

A :	Air of inlet
C_m :	Dimensionless torque coefficient
c :	Sound velocity
c_p :	Specific heat at constant pressure
d :	Characteristic length
h :	Specific enthalpy
k :	Isentropic index
M :	Friction power
Ma :	Mach number
m :	Mass flow rate
Nu :	Nusselt number
p^* :	Total pressure
p :	Static pressure
Q :	Heat exchanging quantity
q :	Heat exchange per unit mass
R :	Universal gas constant
R_g :	Gas constant
S_{CV} :	Total entropy at stable flow system
S_g :	Entropy generation
s :	Specific entropy
$s_f Q$:	Thermal entropy flow
T :	Static temperature
T^* :	Total temperature
T_r :	Temperature of the heat source
ΔT :	Temperature difference
V :	Velocity
V_{mixing} :	Velocity of additional mixing flow
W :	Work
w_s :	Frictional work
α :	Convective heat transfer coefficient
$\Delta\delta$:	Error variation range
λ :	Heat conductivity coefficient
ρ :	Gas density
σ :	The total pressure ratio of the inlet and outlet of the system
ω :	Rotational angular velocity.

Data Availability

The simulation data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

(Supplementary Materials)

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