A Postprint of a High-Thrust, Low-Infrared-Signature Double S-Shaped Two-Dimensional Exhaust System

Authors: WANG Ding, JI Honghu, HUANG Wei

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Abstract

Based on a certain axisymmetric exhaust system, a dual S-shaped two-dimensional exhaust system model with small mid-section offset-diameter ratio (Sm/D) and outlet offset-diameter ratio (So/D) greater than 0 was established. This dual S-shaped two-dimensional exhaust system achieved nozzle-profile shielding of high-temperature components such as turbines inside the exhaust system at all remaining azimuth angles studied, except for the angular range of 0° to 20° on the upper detection plane. The thrust and infrared characteristics of the dual S-shaped two-dimensional exhaust system were investigated through numerical calculations and compared with the baseline axisymmetric exhaust system. The results indicate that the small mid-section offset-diameter ratio and large length-diameter ratio enabled the dual S-shaped two-dimensional exhaust system to avoid thrust loss; compared with the baseline axisymmetric exhaust system, the thrust of this dual S-shaped two-dimensional exhaust system increased by 0.2%; the infrared radiation intensity of the dual S-shaped two-dimensional exhaust system was minimal on the side detection plane and maximal on the upper detection plane; compared with the baseline axisymmetric exhaust system, the dual S-shaped two-dimensional exhaust system reduced by more than 97% at the 0° azimuth angle, and by 62.1%, 26.1%, and 34.9% respectively in the 90° direction on the side, upper, and lower detection planes.

Full Text

Preamble

A Serpentine 2-D Exhaust System with High Thrust and Low Infrared Signature

WANG Ding, JI Hong-hu, HUANG Wei (College of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)

Abstract: Based on an axisymmetric exhaust system, a serpentine 2-D exhaust system model with a small middle offset-diameter ratio (Sm/D) and an exit offset-diameter ratio (So/D) greater than zero was developed. This serpentine 2-D exhaust system achieves complete masking of high-temperature components such as the turbine by the nozzle profile across all studied azimuth angles except for the range of 0° to 20° on the upper detection plane. Numerical investigations were conducted on the thrust and infrared characteristics of the serpentine 2-D exhaust system, with comparisons made against a baseline axisymmetric exhaust system. Results demonstrate that the small Sm/D and large length-diameter ratio (L/D) prevent thrust loss, with the serpentine 2-D exhaust system exhibiting a 0.2% thrust increase compared to the baseline axisymmetric system. The infrared radiation intensity of the serpentine 2-D exhaust system is minimal on the side detection plane and maximal on the upper detection plane. Compared to the baseline axisymmetric exhaust system, the infrared radiation intensity decreases by over 97% at 0° azimuth angle, and by 62.1%, 26.1%, and 34.9% at 90° on the side, upper, and lower detection planes, respectively.

Keywords: exhaust system; serpentine 2-D nozzle; infrared radiation; thrust

1. Design Methodology

1.1 Design Objective and Baseline Configuration

Based on an axisymmetric exhaust system, this study aims to design a serpentine 2-D nozzle to replace the axisymmetric nozzle, creating a serpentine 2-D exhaust system with both favorable aerodynamic performance and infrared stealth characteristics.

The baseline axisymmetric exhaust system is illustrated in [Figure 1: see original paper], comprising components including the final-stage turbine disk (core inlet), bypass inlet, mixer, center cone, struts, and axisymmetric nozzle. The serpentine 2-D exhaust system is formed by replacing the axisymmetric convergent nozzle section in [Figure 1: see original paper] with a serpentine 2-D nozzle, while retaining all other components from the baseline system, as shown in [Figure 2: see original paper]. The serpentine 2-D nozzle and axisymmetric nozzle share identical exit areas.

The geometric parameters of the serpentine 2-D nozzle include: inlet diameter D, inlet area Ain, exit area Aout, exit aspect ratio ARout, nozzle length L, middle offset Sm, and exit offset So, where Sm represents the maximum distance that the nozzle centerline deviates from the turbine axis at the middle section. The design schematic is presented in [Figure 3: see original paper].

Key dimensionless parameters are defined as follows: length-diameter ratio L/D (nozzle length to inlet diameter), middle offset-diameter ratio Sm/D (middle offset to inlet diameter), exit offset-diameter ratio So/D (exit offset to inlet diameter), and exit area ratio Aout/Ain.

1.2 Design Rationale

From an infrared suppression perspective, the serpentine 2-D nozzle employs two bends in its profile to achieve effective masking of high-temperature components such as the center cone and turbine by the nozzle surface behind the exhaust exit, thereby significantly reducing detectable infrared radiation signatures.

From an aerodynamic performance standpoint, the nozzle profile curvature inevitably increases flow resistance, which adversely affects performance. The following analysis examines the influence of two key parameters—middle offset-diameter ratio Sm/D and length-diameter ratio L/D—on aerodynamic performance.

1.2.1 Influence of Middle Offset-Diameter Ratio (Sm/D) compares the non-dimensional thrust F/Faxis of exhaust systems with different Sm/D values while maintaining identical other design parameters and So/D = 0, where Faxis represents the actual thrust of the baseline axisymmetric exhaust system. The results reveal that the non-dimensional thrust decreases with increasing Sm/D, attributable to increased flow resistance in the serpentine duct as Sm/D grows.

Evidently, the middle offset-diameter ratio significantly impacts aerodynamic performance. Therefore, this design substantially reduces the Sm/D value while appropriately increasing So/D to ensure complete masking of internal high-temperature components directly behind the nozzle exit. This approach effectively minimizes flow resistance while enhancing both aerodynamic performance and infrared suppression capability.

1.2.2 Influence of Length-Diameter Ratio (L/D) presents the non-dimensional thrust comparison for exhaust systems with different L/D values while keeping other parameters identical and So/D = 0. The data indicates that non-dimensional thrust increases with L/D.

[Figure 4: see original paper] illustrates the half-convergence angle of the axisymmetric nozzle, a critical factor affecting the maximum discharge coefficient Cd,max. [Figure 5: see original paper] shows the relationship between Cd,max and for convergent nozzles, demonstrating that smaller yields larger Cd,max. In this study, the axisymmetric convergent nozzle is relatively short (L/D = 0.55) with a large half-convergence angle, whereas the serpentine 2-D nozzle features a much longer length (L/D = 2.5), resulting in a significantly smaller equivalent half-convergence angle. Consequently, the serpentine 2-D exhaust system achieves a substantially higher Cd,max than the axisymmetric system. Although increased nozzle length raises frictional losses, the net effect is a higher overall discharge coefficient for the serpentine 2-D exhaust system, thereby increasing thrust.

The aerodynamic performance benefits considerably from increased L/D. Therefore, this design adopts a relatively large L/D value of 2.5 for the serpentine 2-D nozzle—approximately 4.5 times that of the axisymmetric nozzle—to compensate for aerodynamic losses induced by the serpentine flow path.

1.3 Final Design Parameters

Considering the aerodynamic performance trade-offs discussed above, this study selected a set of serpentine 2-D nozzle design parameters that balance aerodynamic and infrared suppression performance, as listed in . The Sm/D value is minimized at 0.12, substantially reducing aerodynamic losses. The So/D value is appropriately increased to exceed zero, meaning the exit axis is offset upward from the inlet axis. This ensures ideal masking of internal high-temperature components while sacrificing minimal aerodynamic performance. The L/D value of 2.5 is approximately 4.5 times that of the axisymmetric nozzle, significantly reducing the half-convergence angle and playing a crucial role in improving aerodynamic performance.

2. Computational Methodology

The infrared characteristic calculation for the exhaust system consists of two parts: flow field computation and infrared radiation characteristic calculation. The flow field computation provides necessary data including wall temperatures, jet temperature fields, pressure fields, and species concentration fields for subsequent infrared calculations.

2.1 Flow Field Calculation Method

Flow field calculations were performed using Fluent software with an implicit coupled solver. Second-order upwind discretization schemes were employed for the continuity, momentum, and energy equations. The SST (Shear Stress Transport) k- turbulence model was selected, with species transport model for combustion gas composition and DO (Discrete Ordinates) model for radiative heat transfer.

Due to geometric symmetry, a half-model of the exhaust system was used. The computational domain is a semi-cylindrical volume with an outer diameter of 10D (where D is the nozzle inlet diameter) and an axial length of 30D. Structured hexahedral grids were applied throughout the flow field, with refined meshes near walls and within the exhaust system internal flow, as shown in [Figure 6: see original paper]. Grid independence verification led to a final mesh count of approximately 3 million cells.

The engine operating condition corresponds to ground test status with freestream Mach number of 0. Both core and bypass flows used pressure inlet boundary conditions: turbine pressure ratio of 2.25 and total temperature of 830 K for the core flow, and pressure ratio of 2.3 and total temperature of 385

K for the bypass flow. The external flow field used pressure outlet boundaries matching atmospheric conditions. The center cone and struts were treated as adiabatic walls, while the mixer and nozzle were coupled with surrounding fluid for heat transfer. For radiation calculations, all wall emissivities were set to 0.8.

2.2 Infrared Radiation Intensity Calculation Method

Infrared radiation was computed using the independently developed aircraft infrared signature analysis software NUAA-IR, employing the reverse Monte Carlo method [11] for radiation intensity calculations.

Three detection planes were established across the rear hemisphere for the serpentine 2-D exhaust system, as illustrated in [Figure 7: see original paper]: upper detection plane (= 0°-90°), lower detection plane (= 0° to -90°), and side detection plane (= 0°-90°).

2.3 Validation of Computational Method

Due to the difficulty in obtaining experimental data for full-scale engines under realistic conditions, validation was performed using a 1/3-scale exhaust system model. The turbofan engine infrared radiation characteristic simulation experimental system is shown in [Figure 8: see original paper], consisting of mainstream, bypass, and exhaust subsystems. The mainstream subsystem generates high-temperature core flow: approximately 0.6 kg/s of ambient air from a core blower passes through a combustor to produce 830 K high-temperature gas. The bypass subsystem supplies bypass flow: approximately 1 kg/s of air at 321 K from a bypass blower. Core and bypass flows mix after the mixer component and exit through the nozzle. [Figure 9: see original paper] shows the scaled experimental model of the axisymmetric exhaust system, simulating structures including the turbine, center cone, mixer, struts, and axisymmetric nozzle.

[Figure 10: see original paper] compares experimental measurements and computational predictions of infrared signature distribution for the axisymmetric exhaust system in the 3-5 m band, where C1 is a constant for non-dimensionalization. The computational method shows good agreement with experimental results, with average errors not exceeding 15%.

3. Results and Analysis

3.1 Aerodynamic Performance Results

presents the non-dimensional thrust F/Faxis of the serpentine 2-D exhaust system compared with the baseline axisymmetric system. Contrary to expectations, the serpentine 2-D exhaust system exhibits no thrust penalty, instead showing a 0.2% thrust increase. compares the discharge coefficients, revealing a 0.005 increase for the serpentine 2-D system, which accounts for the thrust improvement.

3.2 Flow Field Results

[Figure 11: see original paper] compares the static pressure distributions on the symmetry plane for both exhaust systems, where p* represents the average total pressure at the nozzle inlet. The serpentine nozzle profile creates asymmetric static pressure distribution due to flow path curvature. Comparison of exit plane static pressures shows that the serpentine nozzle exit pressure is closer to ambient, indicating more complete expansion of hot gas within the serpentine nozzle. The axisymmetric nozzle' s short length results in significant under-expansion at the exit plane, which is detrimental to aerodynamic performance.

[Figure 12: see original paper] compares Mach number distributions on the symmetry plane. The serpentine nozzle exhibits Mach number contours influenced by flow path curvature, with the Mach 1 isocline forming an angle relative to the vertical geometric throat. At the exit plane, the axisymmetric nozzle achieves Ma 0.9, while the serpentine 2-D nozzle essentially reaches Ma = 1, demonstrating superior aerodynamic performance.

[Figure 13: see original paper] compares temperature distributions on the symmetry plane, where T* represents the total temperature at the core inlet. The strong three-dimensional effects induced by the serpentine nozzle' s rectangular transition, flow path deflection, and cross-section contraction, combined with its greater length, significantly enhance mixing between core and bypass flows. Consequently, the high-temperature jet plume length in the external flow field is noticeably reduced for the serpentine 2-D exhaust system, thereby enhancing infrared suppression of plume radiation.

3.3 Spectral Radiation Characteristics Analysis

[Figure 14: see original paper] presents the non-dimensional spectral radiation intensity distribution in the 3–5 m wavelength range for the serpentine 2-D exhaust system at various azimuth angles (0°, 5°, 10°, 15°, 30°, 60°, and 90°) on the upper detection plane, where C is a non-dimensionalization constant. The spectral radiation intensity consists primarily of two components: solid wall radiation from high-temperature surfaces in the 3–4.16 m and 4.63–5 m bands, and gas radiation in the 4.16–4.6 m band. Solid radiation exhibits continuous broadband characteristics, while gas radiation displays selective features—the peaks and valleys in the 4.16–4.6 m band result from strong CO emission and absorption. From 0° to 90°, gas radiation spectral amplitude gradually increases due to growing projected area of high-temperature gas, whereas solid radiation amplitude first increases then decreases, peaking at 10° where the projected area of internal high-temperature components is maximized.

3.4 Infrared Signature Distribution

3.4.1 Serpentine 2-D Exhaust System Infrared Characteristics [Figure 15: see original paper] shows the integrated radiation intensity distribution in the 3–5 m band on the side detection plane for the serpentine 2-D exhaust system, with contributions from hot plume and solid walls, where C2 is a non-dimensionalization constant. The integrated radiation intensity is relatively small on the side detection plane, dominated by hot plume contribution, as the serpentine nozzle profile completely masks internal high-temperature components such as the turbine and center cone in this narrow-side view.

[Figure 16: see original paper] presents the integrated radiation intensity distribution on the upper and lower detection planes, including plume and wall contributions. On the lower detection plane, the infrared signature is similar to the side plane, with hot plume dominating. On the upper detection plane, radiation is substantial in the small angular range of 0°-20° due to significant projected areas of high-temperature components (turbine, center cone, mixer) within this field of view, as shown in [Figure 17: see original paper]. Beyond 20°, the projected area of internal high-temperature components diminishes to zero, and the infrared signature is dominated by hot plume radiation.

3.4.2 Comparison with Baseline Axisymmetric Exhaust System [Figure 18: see original paper] compares integrated radiation intensity distributions on the side detection plane. The serpentine 2-D exhaust system reduces integrated radiation intensity by over 97% at 0° azimuth angle and by 62.1% at 90° azimuth angle compared to the baseline axisymmetric system.

[Figure 19: see original paper] compares integrated radiation intensity distributions on the upper and lower detection planes. On the upper plane, the serpentine 2-D exhaust system exhibits maximum infrared radiation at 10° azimuth angle, yet achieves over 70.6% reduction compared to the baseline system at this angle. At 90° on the upper plane and -90° on the lower plane (pure plume radiation angles), reductions of 26.1% and 34.9% are achieved, respectively. These results demonstrate that the serpentine 2-D nozzle' s masking effect significantly suppresses solid wall infrared signatures, while the nozzle profile deflection and rectangular transition enhance mixing between hot core flow and cool bypass flow, markedly improving plume radiation suppression.

4. Conclusions

This study designed a serpentine 2-D exhaust system with small middle offset-diameter ratio and exit offset-diameter ratio greater than zero, based on an axisymmetric exhaust system. Numerical investigations of its thrust and infrared characteristics yielded the following conclusions:

1. Due to the smaller half-convergence angle of the serpentine 2-D nozzle, the discharge coefficient increased by 0.005 compared to the baseline axisymmetric exhaust system, resulting in a 0.2% thrust increase.
2. The serpentine 2-D exhaust system exhibits low infrared radiation on side and lower detection planes. Radiation is higher on the upper detection plane, peaking at 10° azimuth angle where turbine and center cone com-

ponents are partially exposed, yet still achieving over 70.6% reduction compared to the baseline system at this angle.

3. Compared to the baseline axisymmetric exhaust system, the serpentine 2-D exhaust system reduces infrared radiation by over 97% in the 0° direction, and by 62.1%, 26.1%, and 34.9% in the directions perpendicular to the nozzle exit axis on the side, upper, and lower detection planes, respectively.

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