

## **A Twin-S-Shaped Two-Dimensional Exhaust System with High Thrust and Low Infrared Signature: Postprint**

**Authors:** Wang Ding, Jihong Lake, Wei Huang

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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 ( $S_m/D$ ) and outlet offset-diameter ratio ( $S_o/D$ ) greater than was established. This dual S-shaped two-dimensional exhaust system achieved shielding of high-temperature components such as turbines inside the exhaust system by the nozzle profile for all other azimuth angles studied, except for the angular range of  $0^\circ$  to  $20^\circ$  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  $0^\circ$  azimuth angle, and by 62.1%, 26.1%, and 34.9% respectively in the  $90^\circ$  direction on the side, upper, and lower detection planes.

### **Full Text**

## **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 ( $S_m/D$ ) and an exit offset-diameter ratio ( $S_o/D$ ) 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  $0^\circ$  to  $20^\circ$  on the upper detection plane. Numerical investigations of the thrust and infrared characteristics of the serpentine 2-D exhaust system were conducted and compared with a baseline axisymmetric exhaust system. The results demonstrate that the small  $S_m/D$  and large length-diameter ratio enable the serpentine 2-D exhaust system to avoid thrust loss; compared with the baseline axisymmetric system, thrust increases by 0.2%. 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. Relative to the baseline axisymmetric system, the integrated infrared radiation intensity reduces by over 97% at  $0^\circ$  azimuth, and by 62.1%, 26.1%, and 34.9% at  $90^\circ$  on the side, upper, and lower detection planes, respectively.

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

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To enhance battlefield survivability, modern aircraft require high levels of stealth performance. Infrared stealth, as a critical component of aircraft signature reduction, has received increasing attention. The engine exhaust system represents the primary infrared radiation source within the mid-wave range (3–5  $\mu\text{m}$ ) for aircraft, contributing over 90% of the total aircraft radiation in this band. This radiation consists mainly of high-temperature wall radiation and hot gas radiation. At small detection angles behind the exhaust system, internal high-temperature components—including the turbine, center cone, and mixer—account for more than 90% of the total exhaust system radiation. Among various infrared suppression measures, the serpentine 2-D nozzle effectively blocks infrared radiation from high-temperature engine components such as the turbine and center cone through its dual-curvature centerline, demonstrating outstanding infrared suppression capability.

Foreign research on serpentine 2-D nozzle technology began relatively early and has been applied to certain military aircraft. Brunet et al. designed a profile-shielded serpentine nozzle with a centerline that deviates from the turbine axis at the middle section but returns to it at the exit. Darrell et al. numerically investigated the effects of different nozzle lengths and exit aspect ratios on wall temperature distribution at the nozzle exit. Domestic researchers including Liu Changchun, Zhang Yechuan, Wei Yongbin, and Sun Xiaolin have designed S-shaped and serpentine nozzles and numerically studied their aerodynamic and infrared characteristics. The middle offset-diameter ratio significantly impacts

thrust loss in exhaust systems. In available literature, to ensure effective infrared suppression, the minimum middle offset-diameter ratio is 0.25 with an exit offset-diameter ratio of 0 and a length-diameter ratio of 1.8, resulting in a minimum thrust loss of 1.6% compared with axisymmetric exhaust systems. Thus, thrust loss remains a challenge for serpentine exhaust system applications. This paper designs a serpentine 2-D exhaust system with a small middle offset-diameter ratio and an exit offset-diameter ratio greater than zero based on an axisymmetric exhaust system. Numerical calculations investigate its thrust and infrared characteristics compared with a baseline axisymmetric system. The proposed serpentine 2-D exhaust system achieves both thrust preservation and excellent infrared suppression.

## 1. Design of the Serpentine 2-D Exhaust System

### 1.1 Design Objective and Baseline

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

[Figure 1: see original paper] illustrates the baseline axisymmetric exhaust system, which comprises the final-stage turbine disk (core inlet), bypass inlet, mixer, center cone, strut, and axisymmetric nozzle. The serpentine 2-D exhaust system is constructed by replacing the axisymmetric convergent nozzle section in [Figure 1: see original paper] with a serpentine 2-D nozzle while retaining all other components, as shown in [Figure 2: see original paper].

The geometric parameters of the serpentine 2-D nozzle include inlet diameter  $D$ , inlet area  $A_{in}$ , exit area  $A_{out}$ , exit aspect ratio  $AR_{out}$ , nozzle length  $L$ , middle offset  $S_m$ , and exit offset  $S_o$ , where  $S_m$  represents the maximum distance the nozzle centerline deviates from the turbine axis at the middle section. The design schematic is shown in [Figure 3: see original paper].

The length-diameter ratio is defined as  $L/D$ , the middle offset-diameter ratio as  $S_m/D$ , the exit offset-diameter ratio as  $S_o/D$ , and the exit area ratio as  $A_{out}/A_{in}$ .

### 1.2 Design Basis

From an infrared suppression perspective, the serpentine 2-D nozzle employs dual curvature to achieve effective masking of high-temperature components such as the center cone and turbine by the nozzle profile behind the exhaust exit, thereby reducing detectable infrared radiation signatures. From an aerodynamic performance perspective, nozzle curvature inevitably increases flow resistance, which adversely affects performance. The following analysis examines the influence of two key parameters—middle offset-diameter ratio ( $S_m/D$ ) and length-diameter ratio ( $L/D$ )—on aerodynamic performance.

**1.2.1 Influence of Middle Offset-Diameter Ratio ( $S_m/D$ )** compares the non-dimensional thrust ( $F/F_{axis}$ ) of exhaust systems with different  $S_m/D$  values while maintaining identical other design parameters and an exit offset-diameter ratio ( $S_o/D$ ) of zero, where  $F_{axis}$  represents the actual thrust of the baseline axisymmetric exhaust system. The results show that  $F/F_{axis}$  decreases with increasing  $S_m/D$  due to increased flow resistance in the serpentine duct. The middle offset-diameter ratio significantly impacts aerodynamic performance; therefore, this design substantially reduces  $S_m/D$  while appropriately increasing  $S_o/D$  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 ( $L/D$ )** compares the non-dimensional thrust of exhaust systems with different  $L/D$  values while maintaining  $S_o/D = 0$  and identical other parameters. The non-dimensional thrust  $F/F_{axis}$  increases with  $L/D$ . [Figure 4: see original paper] illustrates the half-convergence angle of the axisymmetric nozzle, which significantly affects the maximum discharge coefficient  $C_{d,max}$ . [Figure 5: see original paper] shows the relationship between  $C_{d,max}$  and for convergent nozzles, revealing that smaller yields larger  $C_{d,max}$ . 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 is substantially longer ( $L/D = 2.5$ ), resulting in a much smaller effective half-convergence angle. Consequently, the serpentine 2-D exhaust system exhibits a significantly higher  $C_{d,max}$  than the axisymmetric system. Although increased nozzle length raises frictional losses, the net effect is a higher discharge coefficient for the serpentine 2-D exhaust system, leading to increased thrust. The enhanced aerodynamic performance associated with increased  $L/D$  justifies the selection of a larger  $L/D$  value for the serpentine 2-D nozzle to compensate for aerodynamic losses induced by duct curvature.

### 1.3 Design Results

Considering the aerodynamic performance impacts 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  $S_m/D$  value is very small (0.12), substantially reducing aerodynamic losses. The  $S_o/D$  value is appropriately increased to exceed zero, meaning the exit axis deviates 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 critically enhancing aerodynamic performance.

## 2. Calculation Methods

Exhaust system infrared characteristic calculations consist of two parts: flow field computation and infrared radiation characteristic computation. The flow field calculation provides wall temperatures, jet temperature fields, pressure fields, and species concentration fields required for infrared analysis.

### 2.1 Flow Field Calculation Method

Fluent software was employed for flow field calculations using an implicit coupled solver. Second-order upwind discretization schemes were applied to the continuity, momentum, and energy equations. The SST (Shear Stress Transport)  $k-\omega$  turbulence model was selected, species transport model for gas composition calculation, and the DO (Discrete Ordinates) model for radiation heat transfer.

Due to model symmetry, a half-model of the exhaust system was used. The computational domain is a semi-cylindrical region with an outer diameter of  $10D$  (where  $D$  is the nozzle inlet diameter) and an axial length of  $30D$ . Structured hexahedral grids were employed 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 is ground test, with freestream Mach number of 0. Both core and bypass flows use pressure inlet boundary conditions: turbine pressure ratio of 2.25, total temperature of 830 K for core flow; bypass pressure ratio of 2.3, total temperature of 385 K for bypass flow. The external flow field uses pressure outlet boundaries with atmospheric pressure and temperature. The center cone and struts are adiabatic, while the mixer and nozzle walls are coupled with surrounding fluid for heat transfer. In radiation calculations, all wall emissivities are set to 0.8.

### 2.2 Infrared Radiation Intensity Calculation Method

Infrared radiation was calculated using the independently developed aircraft infrared signature analysis software NUAA-IR, employing the reverse Monte Carlo method for radiation intensity computation.

Three detection planes were established throughout the rear hemisphere for the serpentine 2-D exhaust system, as shown in [Figure 7: see original paper]: upper detection plane ( $\alpha = 0^\circ-90^\circ$ ), lower detection plane ( $\alpha = 0^\circ-90^\circ$ ), and side detection plane ( $\beta = 0^\circ-90^\circ$ ).

### 2.3 Calculation Method Validation

Due to the difficulty of obtaining full-scale engine infrared signature data under realistic conditions, a 1/3-scale exhaust system model was used for method validation. The turbofan engine infrared radiation characteristic simulation

experimental system is shown in [Figure 8: see original paper]. The test rig consists of a mainstream subsystem, bypass subsystem, and exhaust subsystem. The mainstream 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 core flow. The bypass subsystem generates 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 the turbine, center cone, mixer, struts, and axisymmetric nozzle.

[Figure 10: see original paper] compares experimental measurements and computational results of infrared signature distribution for the axisymmetric exhaust system in the 3-5  $\mu\text{m}$  band, where  $C_1$  is a constant for non-dimensionalization. The computational method shows good agreement with experimental results, with average error not exceeding 15%.

### 3. Results and Analysis

#### 3.1 Aerodynamic Performance Results

presents the non-dimensional thrust ( $F/F_{axis}$ ) 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 reduction, instead showing a 0.2% thrust increase. compares discharge coefficients, revealing a 0.005 increase for the serpentine system, which accounts for the thrust improvement.

#### 3.2 Flow Field Results

[Figure 11: see original paper] compares 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's profile creates asymmetric static pressure distribution due to duct curvature. Comparison of static pressure near the nozzle exit shows that the serpentine nozzle's exit pressure is closer to ambient pressure, indicating more complete expansion of hot gas within the serpentine nozzle. The relatively short axisymmetric nozzle causes significant under-expansion at the exit, which is detrimental to aerodynamic performance.

[Figure 12: see original paper] compares Mach number ( $Ma$ ) distributions on the symmetry plane. The  $Ma$  distribution in the serpentine nozzle is affected by duct curvature, with the  $Ma = 1$  contour line near the exit forming an angle with the vertical geometric throat. The axisymmetric nozzle exit Mach number is approximately 0.9, whereas the serpentine nozzle achieves  $Ma = 1$ , demonstrating superior aerodynamic performance.

[Figure 13: see original paper] compares temperature distributions on the symmetry plane, where  $T^*$  is the total temperature at the core inlet. The strong

three-dimensional effects induced by the serpentine nozzle's rectangular-to-round transition, flow path deflection, and cross-section contraction, combined with its greater length, significantly enhance core-bypass mixing. Consequently, the high-temperature jet length in the external flow field is notably reduced for the serpentine system, thereby enhancing infrared suppression of jet radiation.

### 3.3 Spectral Radiation Characteristics Analysis

[Figure 14: see original paper] presents the non-dimensional spectral radiation intensity distribution of the serpentine 2-D exhaust system on the upper detection plane at azimuth angles of  $0^\circ$ ,  $5^\circ$ ,  $10^\circ$ ,  $15^\circ$ ,  $30^\circ$ ,  $60^\circ$ , and  $90^\circ$  within the 3–5  $\mu\text{m}$  wavelength range, where  $C\lambda$  is a non-dimensionalization constant. The spectral radiation intensity consists of two components: solid wall radiation from high-temperature surfaces in the 3–4.16  $\mu\text{m}$  and 4.63–5  $\mu\text{m}$  bands, and gas radiation in the 4.16–4.6  $\mu\text{m}$  band. Solid radiation exhibits continuous broadband characteristics, while gas radiation is selective, with peaks and valleys in the 4.16–4.6  $\mu\text{m}$  band resulting from strong  $\text{CO}_2$  emission and absorption. From  $0^\circ$  to  $90^\circ$  azimuth, gas radiation spectral amplitude gradually increases due to larger projected area of high-temperature gas, whereas solid radiation amplitude first increases then decreases, peaking at  $10^\circ$  where the projected area of internal high-temperature components is maximal.

### 3.4 Infrared Signature Distribution

#### 3.4.1 Serpentine 2-D Exhaust System Infrared Signature Distribution

[Figure 15: see original paper] shows the integrated radiation intensity distribution of the serpentine 2-D exhaust system on the side detection plane within the 3–5  $\mu\text{m}$  band, including contributions from hot jet and solid walls, where  $C_2$  is a non-dimensionalization constant. The integrated radiation intensity is relatively small on the side detection plane, dominated by hot jet contribution, because 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. On the lower detection plane, the infrared signature is similar to the side plane, with hot jet radiation dominating. On the upper detection plane, radiation is relatively large in the  $0^\circ$ – $20^\circ$  range because turbine, center cone, and mixer components are partially exposed, as shown in [Figure 17: see original paper]. Beyond  $20^\circ$ , the projected area of internal high-temperature components decreases to zero, and the infrared signature is dominated by hot jet 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  $0^\circ$  azimuth and by 62.1% at  $90^\circ$  azimuth compared with the baseline axisymmetric system.

[Figure 19: see original paper] compares integrated radiation intensity on the upper and lower detection planes. On the upper plane, the serpentine system exhibits maximum infrared radiation at  $10^\circ$  azimuth, where it still achieves over 70.6% reduction compared with the baseline system. At  $90^\circ$  on the upper plane and  $-90^\circ$  on the lower plane (pure jet radiation angles), reductions of 26.1% and 34.9% are achieved, respectively. The serpentine nozzle's masking effect significantly suppresses solid wall infrared radiation, while its profile deflection and rectangular-to-round transition enhance core-bypass mixing, markedly improving jet radiation suppression.

#### 4. Conclusions

This paper 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, and numerically investigated its thrust and infrared characteristics. The main conclusions are:

1. Due to the smaller half-convergence angle, the serpentine 2-D exhaust system increases discharge coefficient by 0.005 and thrust by 0.2% compared with the baseline axisymmetric system.
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  $10^\circ$  azimuth where turbine and center cone components are partially exposed, yet still achieving over 70.6% reduction compared with the baseline system.
3. Compared with the baseline axisymmetric system, the serpentine 2-D exhaust system reduces infrared radiation by over 97% at  $0^\circ$  azimuth, and by 62.1%, 26.1%, and 34.9% at  $90^\circ$  on side, upper, and lower detection planes, respectively.

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