

Article

Numerical Validation of a Multi-Dimensional Similarity Law for Scaled STOVL Aircraft Models

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Abstract

The complex jet-ground interactions of Short Take-off and Vertical Landing (STOVL) aircraft are critical to flight safety and performance, yet studying them with traditional full-scale wind tunnel tests is prohibitively expensive and time-consuming, hindering design optimization. This study addresses this challenge by developing and numerically verifying a “pressure ratio–momentum–geometry” multi-dimensional similarity framework, enabling accurate and efficient scaled-model analysis. Systematic simulations of an F-35B-like configuration demonstrate the framework’s high fidelity. For a representative curved nozzle configuration (e.g., the F-35B three-bearing swivel duct nozzle, 3BSD), across scale factors ranging from 1:1 to 1:15, the plume deflection angle remains stable at $12^\circ \pm 1^\circ$. Concurrently, axial force (F) and mass flow rate (Q) strictly follow the square scaling relationship ($F \propto 1/n^2$, $Q \propto 1/n^2$), with deviations from theory remaining below 0.15% and 0.58%, respectively, even at the 1:15 scale, confirming high-fidelity momentum similarity, particularly in the near-field flow direction. Second, a 1:13.25 scale aircraft model, constructed using Froude similarity principles, exhibits critical parameter agreement (intake total pressure and total temperature) of the prototype—including vertical axial force, lift fan mass flow, and intake total temperature—all less than 1.5%, while the critical intake total pressure error is only 2.2%. Fountain flow structures and ground temperature distributions show high consistency with the full-scale aircraft, validating the reliability of the proposed “pressure ratio–momentum–geometry” multi-dimensional similarity criterion. The framework developed herein has the potential to reduce wind tunnel testing costs and shorten development cycles, offering an efficient experimental strategy for STOVL aircraft research and development.

Keywords: STOVL aircraft; Multi-Dimensional Similarity Law; scaled model; numerical simulation; Jet-Ground Interference Effect



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1. Introduction

Short Take-off and Vertical Landing (STOVL) aircraft exhibit unique operational capabilities and combat flexibility, yet their ground proximity operations induce complex jet-ground interactions [1,2]. These interactions generate flow phenomena such as ground vortex systems, fountain flows, and Hot Gas Ingestion (HGI) [3,4]. HGI occurs when high-temperature exhaust is drawn into the engine intakes [5]. HGI can lead to significant thrust losses, sometimes as high as 25% [6,7]. Furthermore, the excessive heat load

risks causing thermal damage to engine components. Early research by VanOverbeke and Holdeman established that thermal damage and HGI during STOVL operations are directly linked to jet flow mechanics [8,9]. Although traditional wind tunnel testing can partially replicate these flow characteristics [10,11], it necessitates full-scale models with realistic gas compositions (e.g., aviation kerosene combustion products). This approach faces significant cost and cycle challenges [12]: A single test requires over US\$20 million for full-scale model construction [13] and high-temperature gas supply, while comprehensive flow characterization demands 10–15 operational condition repetitions. Preparatory activities, including model assembly and safety protocols, further extend timelines by at least six months. These constraints severely limit design iteration efficiency [14]. Consequently, developing cost-effective wind tunnel testing strategies through similarity laws (e.g., scaled model design) is therefore a critical technical challenge.

While established similarity criteria exist for scaling straight nozzles—achieving flow field reproduction through Nozzle Pressure Ratio (NPR) [15] and Mach number (Ma) matching [16,17]—these prove inadequate for curved nozzles employed in STOVL aircraft (e.g., the F-35B's three-bearing swivel duct, 3BSD) [18]. The complex internal flow within these thrust-vectoring nozzles exhibits significant three-dimensional boundary layer separation and 'counter-rotating vortex pair' (CVP) effects [19,20], violating traditional scaling assumptions [21]. Early numerical studies reveal substantial deviations when applying conventional criteria: simulations of a 1:10 scaled curved nozzle using the $k-\epsilon$ turbulence model yield a 12° error in plume deflection angle and an 18% discrepancy in shear layer thickness compared to the full-scale prototype [22]. This inaccuracy is attributed to momentum flux gradient alterations induced by wall curvature. Traditional similarity laws lack correction mechanisms for geometric curvature's influence on flow direction, preventing scaled models from replicating the prototype's plume spatial deflection characteristics [23–25].

Existing research predominantly focuses on binary coupling effects between individual nozzles and ground surfaces. Conversely, systematic analysis of the full-aircraft flow field—accounting for multi-component coupling mechanisms such as lift fans, air intakes, and tail jets—remains limited [26,27]. The inherent complexity of these nonlinear, multi-physics interactions (encompassing compressible jets, thermal buoyancy, and boundary layer effects) poses significant challenges for traditional scaling methodologies. Specifically, approaches relying on isolated similarity parameters (e.g., geometric scale) fail to preserve dynamic flow-field characteristics in full-aircraft scale models. For instance, 1:10 scale testing revealed the fountain flow height was approximately 18% lower than in the full-scale configuration, with intake Distortion Index (DI) errors reaching 25%. These discrepancies underscore the inability of the traditional Froude similarity criterion to accurately represent full-scale aircraft aerodynamics [28]. The analysis of prior work reveals a fundamental challenge: the flow physics of STOVL aircraft in ground effect are governed by a tight, non-linear coupling of compressible jet dynamics (driven by pressure ratio), complex 3D flow structures (sensitive to geometry), and powerful jet-induced interactions like fountain flows (dominated by momentum flux). Traditional single-parameter similarity laws inherently fail because they cannot preserve the balance between these competing physical mechanisms across scales [29,30]. To address these limitations, this study presents a novel "pressure ratio–momentum–geometry" multi-dimensional similarity framework. Through systematic numerical simulations, the framework resolves scaling challenges for curved nozzles and achieves dynamic similarity in full-aircraft flow fields. The research comprises two primary components:

- (1) Curved Nozzle Scaling Criterion

Plume deflection characteristics across 1:5–1:15-scale ratios were analyzed, focusing on concave-wall offset angles and shear layer thickness evolution. A new simi-

larity criterion was developed using initial inclination angles and momentum flux ratios, overcoming traditional methods' limitations in handling three-dimensional complex geometries.

(2) Full-Aircraft Dynamic Similarity Validation

Quantitative evaluation of a 1:13.25-scale aircraft model demonstrated key parameter consistency with the full-scale configuration—including fountain flow morphology and intake Distortion Index (DI). This phase elucidated the dynamic similarity laws governing multi-physics coupled flow fields [30].

The established “pressure ratio–momentum–geometry” criterion provides a theoretically rigorous and engineering-practical solution for STOVL jet plume studies, significantly enhancing scaled wind tunnel testing accuracy and reliability.

2. Computational Model and Setup

2.1. Scaled Curved Nozzles

The nozzle geometry in this study was extracted from an updated F-35 full-aircraft digital model. The nozzle component was isolated at full scale to establish an isolated nozzle free-flow model. Key external dimensions are shown in Figure 1.

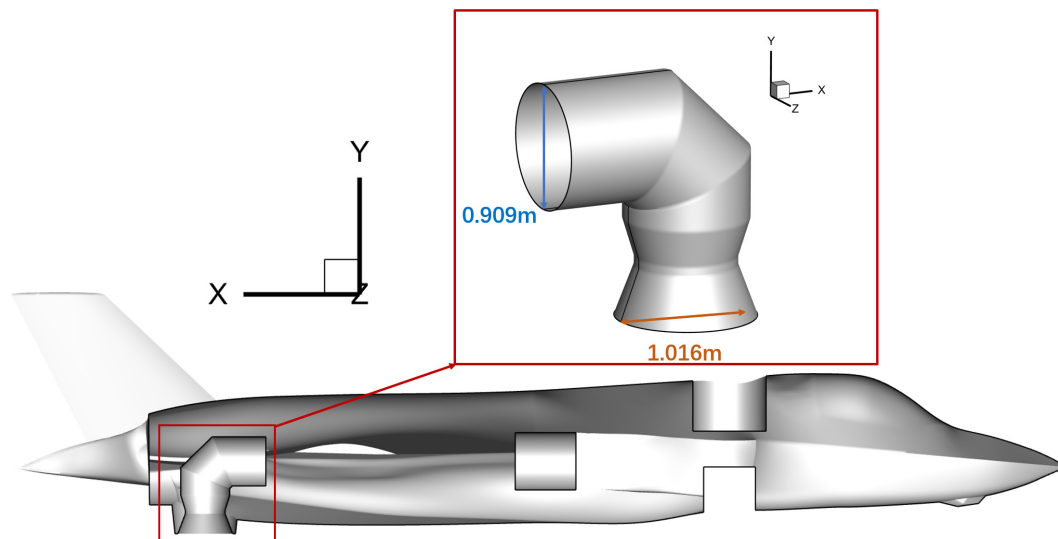


Figure 1. Schematic diagram of the nozzle model.

To accurately simulate the plume characteristics of a vertical take-off and landing (VTOL) curved tail nozzle, a geometrically complete production-representative nozzle configuration was employed. To adhere to typical wind tunnel model size constraints, we simulated geometrically scaled models at ratios of 1:1 (full-scale), 1:5, 1:10, and 1:15. The computational domain and boundary condition specification are presented in Figure 2.

A grid independence study was conducted by comparing solutions obtained using meshes ranging from 3 million to 8 million cells. The results indicated that variations in the nozzle pressure gradient were below 1%. Consequently, a T-Rex boundary layer unstructured grid comprising 5.23 million cells was selected. The near-wall grid was refined to ensure y^+ values remained below 1, enabling proper resolution of the viscous sublayer and accurate prediction of wall-bounded effects. This final grid configuration was chosen to achieve an optimal balance between solution accuracy and computational efficiency [31,32]. The overall grid topology and a detailed view of the boundary layer region are presented in Figure 3.

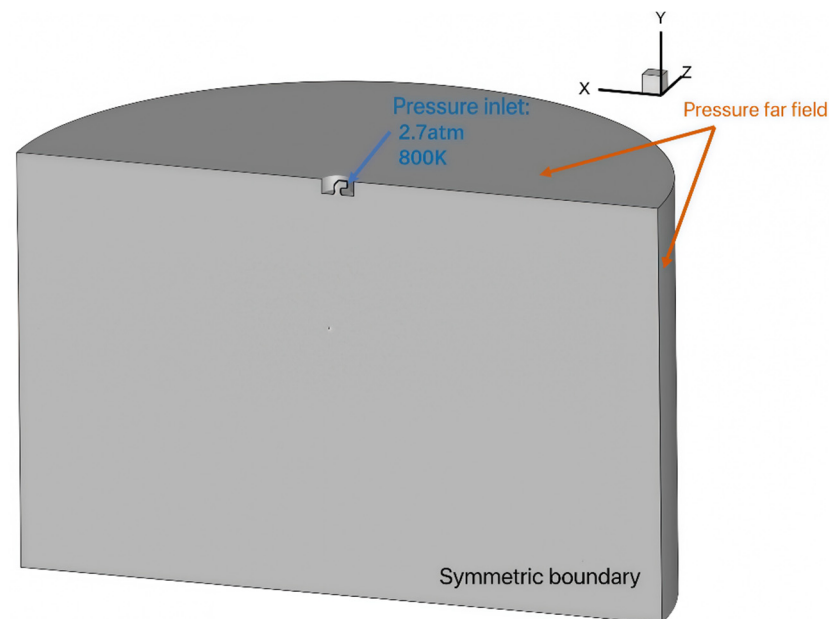


Figure 2. Schematic diagram of the simulated boundary conditions for a single nozzle.

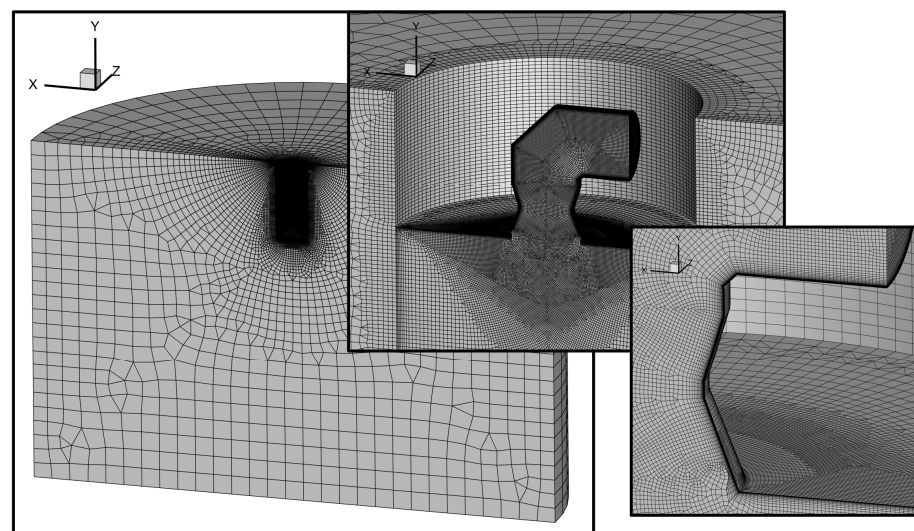


Figure 3. Overall grid topology and detailed boundary layer view.

The fluid used in the simulation is a mixture of oxygen (O_2 , 20 vol%) and nitrogen (N_2 , 80 vol%). The properties of the fluid are shown in Table 1. Transient simulations were performed using a dual time-stepping approach to advance the Navier–Stokes equations. Because of the high Reynolds number of the cases ($>8 \times 10^5$), the turbulence model is used. Although the $k-\omega$ SST model is effective for predicting the boundary layer and overall flow features, as a RANS model, it cannot directly resolve transient vortex structures in the flow field in the way higher-fidelity methods. Nevertheless, for the primary objective of this study—validating a similarity framework based on time-averaged aerodynamic forces, pressures, and flow angles rather than transient turbulence physics—the $k-\omega$ SST model was selected as the optimal compromise [31,32]. Due to its demonstrated superior performance in capturing boundary layer separation and secondary flow effects near curved walls [33]. This model also provides enhanced reliability for adverse pressure gradient flows compared to standard $k-\epsilon$ formulations, which exhibit deflection angle errors exceeding 12% in similar geometric configurations [34]. The Roe flux scheme was employed for its capability to precisely resolve shock waves and contact discontinuities,

thereby ensuring numerical stability within the jet compression wave system. Boundary conditions specified a stagnation temperature of 800 K and stagnation pressure of 2.7 atm (corresponding to nozzle pressure ratio $\text{NPR} = 2.7$) at the inlet. This configuration represents typical vertical take-off and landing (STOVL) operational conditions, consistent with nozzle pressure ratios (2.5–2.8) documented for platforms such as the F-35, ensuring engineering relevance of the simulated flow regime [35].

Table 1. Properties of the fluid.

Property	Value
Density (kg/m^3)	1.184
Specific heat at constant pressure ($\text{kJ}/\text{kg}\cdot\text{K}$)	1.005
Dynamic viscosity ($\text{Pa}\cdot\text{s}$)	1.85×10^{-5}
Thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)	0.026

2.2. Scaled Full-Configuration

The computational model derives from an updated F-35 full-aircraft digital prototype. External dimensions are presented in Figure 4.

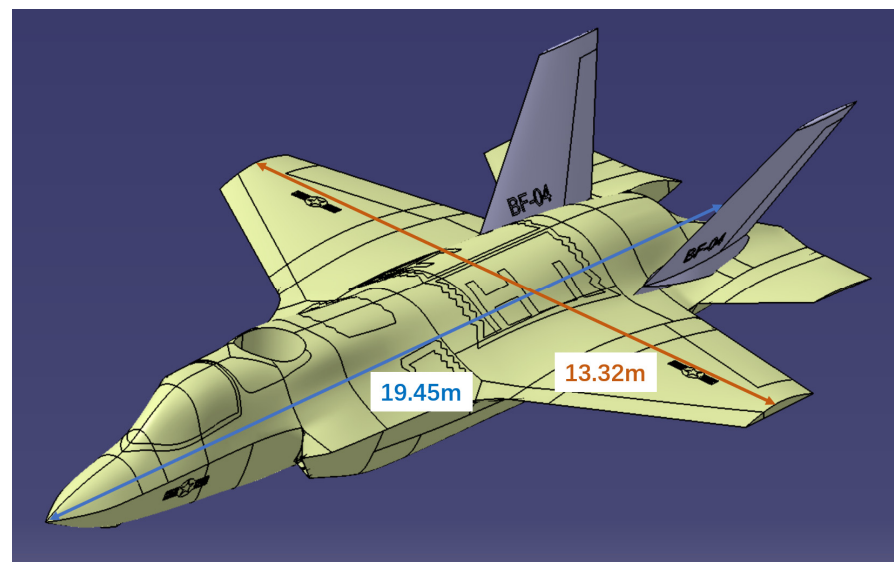


Figure 4. F-35 full-aircraft computational model.

The aircraft model has a length of 19.45 m, wingspan of 13.32 m, and height of 4.46 m. The upper lift fan features a circular inlet with a diameter of 1.36 m and depth of 1.02 m, while the lower lift fan employs a rectangular outlet measuring $0.96 \text{ m} \times 0.87 \text{ m} \times 0.80 \text{ m}$ (length $\times$ width $\times$ depth). The engine pressure inlet is circular (diameter: 1.06 m), and the nozzle section is circular (diameter: 1.016 m). The nozzle lower edge is positioned 1.0 m above ground level. Boundary conditions for the full configuration are detailed in Figure 5.

The full-configuration aircraft was meshed using a similar unstructured grid topology to the isolated nozzle case, resulting in a total cell count of approximately 12 million cells, as depicted in Figure 6. The boundary layer was carefully resolved using prism layers to maintain a y^+ value of less than 1 on all critical aircraft surfaces, including the fuselage, wings, and control surfaces, ensuring accurate modeling of the near-wall flow physics.

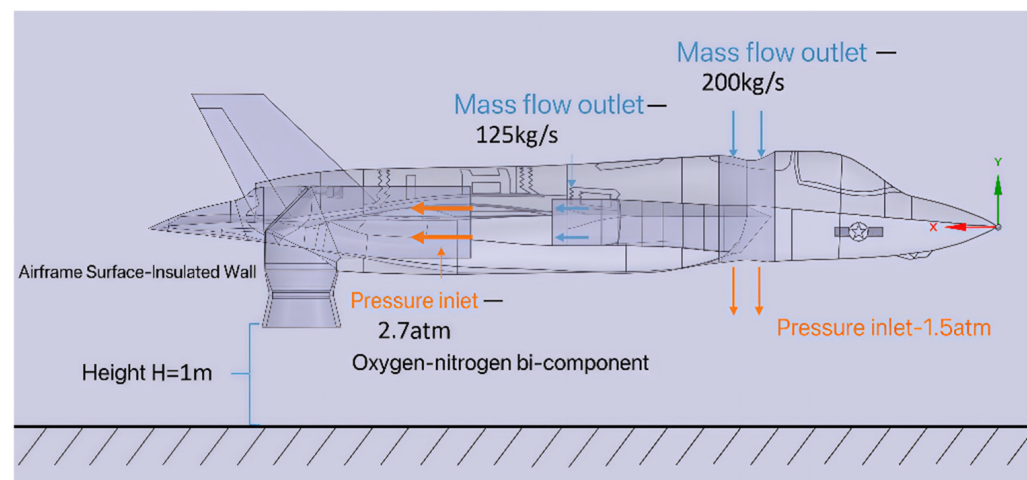


Figure 5. Full-configuration boundary condition schematic.

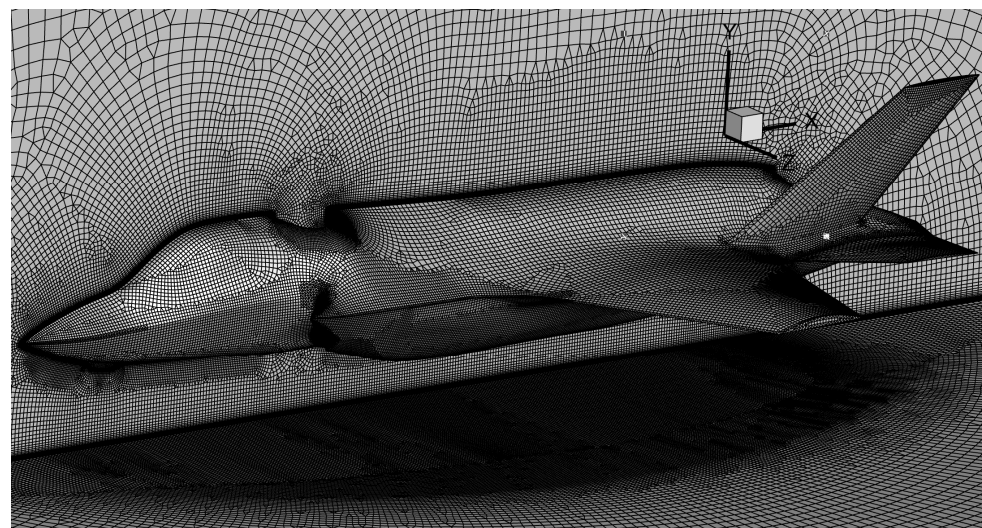


Figure 6. Overall grid topology of full configuration.

Numerical simulations were performed at scaling ratios of 1:1 and 1:13.25 [36]. The 1:13.25 scale factor was specifically chosen to match an existing physical wind tunnel model, ensuring the direct comparability of this numerical study with experimental campaigns. The inlet mass flow rate of the lift fan and outlet mass flow rate of the intake duct were scaled proportionally [37]. All other boundary conditions and flow solver parameters are detailed in Table 2.

Table 2. Boundary condition parameters.

Model	Ground Height (m)	Main Engine Pressure Ratio	Main Transmission Temperature (K)	Lift Fan Pressure Ratio	Lift Fan Flow Rate (kg/s)	Lift Fan Nozzle Temperature (K)	Inlet Flow Rate (kg/s)
1:1	1	2.7	800	1.5	200	330	125
1:13.25	1	2.7	800	1.5	1.1392	330	0.711997152

Scaled-model design adheres to Froude similarity criteria. Mass flow rates scale with the square of the geometric ratio ($1:n^2$, $Q_{model} = Q_{full}/n^2$) to preserve momentum similarity ($F \propto \rho V^2 L^2$), while maintaining constant nozzle pressure ratio ($NPR = 2.7$) and temperature.

3. Results and Discussion

3.1. Effects of Different Scaled Curved Nozzles on Plume Characteristics

Simulations were performed for geometrically scaled nozzle models at ratios of 1:1, 1:5, 1:10, and 1:15. Residual histories of the vertical axial force and inlet mass flow rate monitored during mid-simulation are presented in Figure 7. The figure demonstrates minimal variation in monitored flow parameters beyond this computational stage, confirming solution convergence.

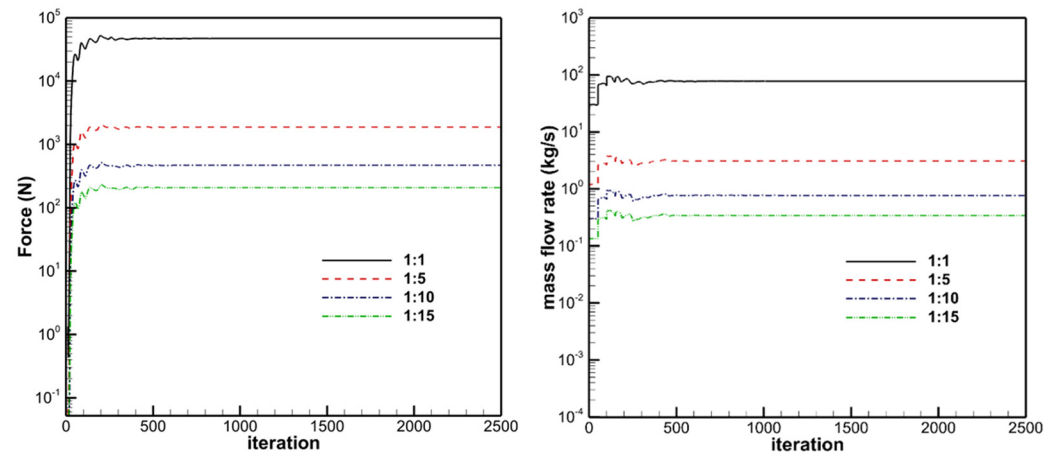


Figure 7. Convergence history of vertical axial force and inlet mass flow rate.

Statistical data for vertical axial force and nozzle mass flow rate at convergence are presented in Table 3 for each geometrically scaled configuration. The results demonstrate that vertical axial force scales proportionally with the square of both inlet mass flow rate and model scale factor, consistent with dynamic similarity principles [38] where axial thrust follows $F \propto \rho V^2 L^2$. Under constant dynamic pressure (ρV^2), a scaling factor of 1:n consequently yields the theoretical force relationship $F_{model} = F_{full} / n^2$. The measured force ratio of 25.00 for the 1:5 scaled model exhibits exact agreement with the theoretical value of 25, validating momentum similarity. This correspondence further verifies mechanical similarity in scaled configurations and provides secondary confirmation of solution accuracy. For the 1:15 model, observed deviations were 0.15% in axial force and 0.58% in mass flow—both below 1%—confirming flow self-similarity at Reynolds numbers exceeding 10^5 [39].

Table 3. Measured parameters for geometrically scaled models.

Scale	Axial Thrust (KN)	Inlet Mass Flow Rate (kg/s)	1:1 Model and Its Ratio	
			Axial Thrust	Mass Flow
1:1	47.061	77.4414	1.00	1.00
1:5	1.882	3.0942	25.00	25.03
1:10	0.470	0.7729	100.13	100.20
1:15	0.209	0.3433	225.15	225.58

Figures 8–10 present pressure, temperature, and velocity distributions on the symmetry plane, respectively. The results show the flow path through the curved nozzle. As the jet traverses the nozzle, it first impinges on the wall, leading to flow acceleration. This interaction causes the jet to exhibit a bulk deflection toward the nozzle's concave side. All scaled models yield similar plume morphologies. This value, determined by post-processing the velocity field to calculate the thrust vector angle at the nozzle exit plane, confirms a

consistent plume deflection angles of $12^\circ \pm 1^\circ$ across all scales—consistent with full-scale experimental data—confirming that geometric scaling preserves flow directionality while modifying physical dimensions [40]. This gives confidence that the CFD setup accurately captures the dominant flow physics and can serve as a reliable baseline for the scaling study. Furthermore, identical inlet stagnation conditions (total pressure and temperature) produce similar plume morphology across all scaling ratios, as shown in the symmetry plane distributions. This flow similarity indicates that geometric scaling does not alter the dominant flow mechanisms governing the jet behavior [41].

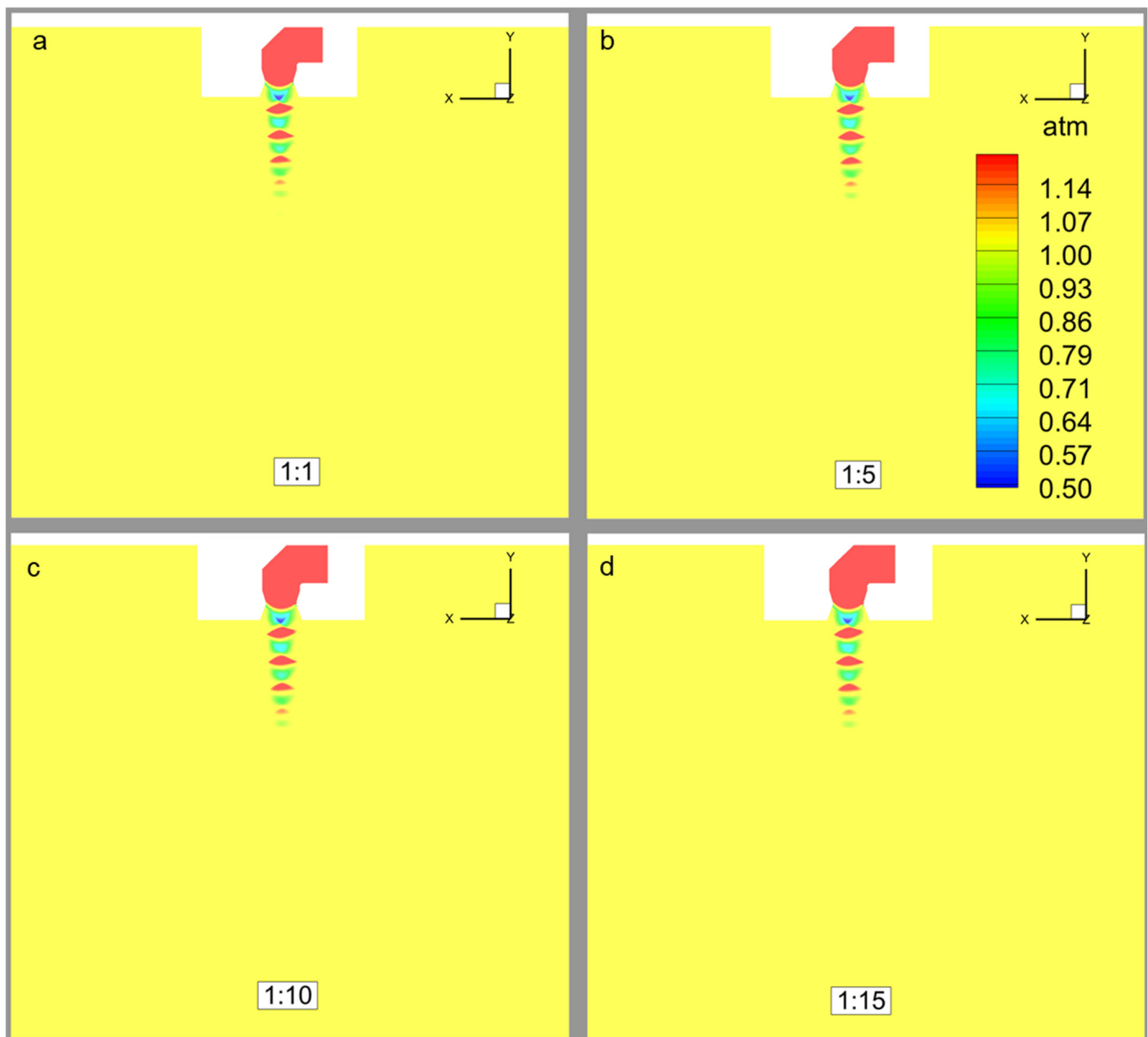


Figure 8. Comparative Pressure contours on symmetry planes of scaled test models: (a) Scale 1:1; (b) Scale 1:5; (c) Scale 1:10; (d) Scale 1:15.

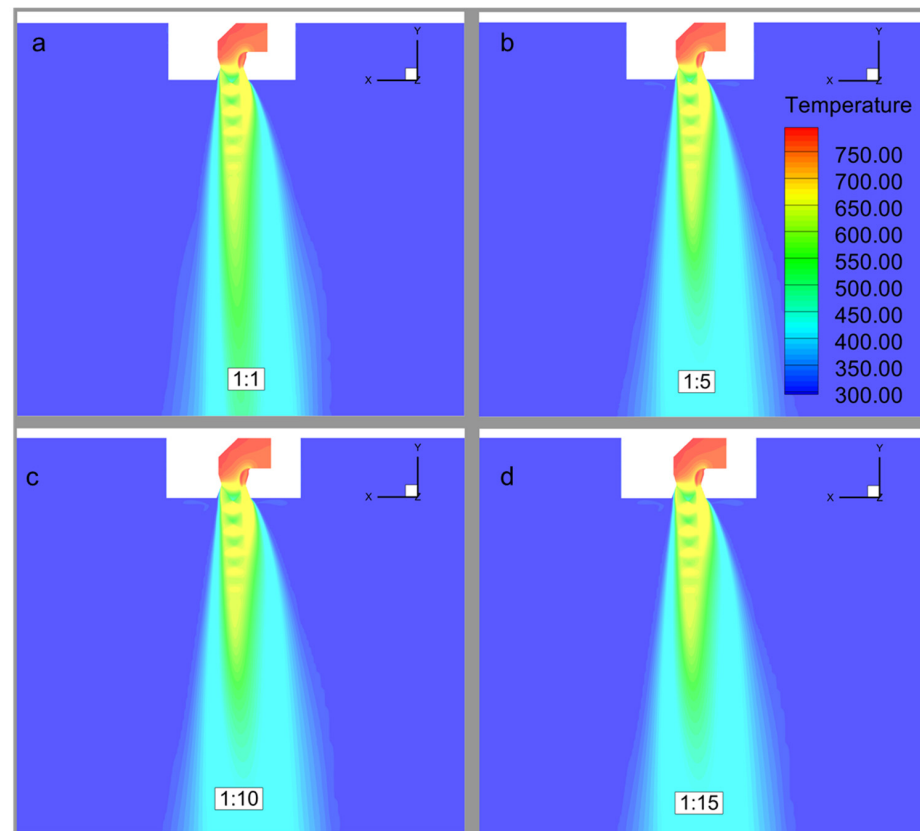


Figure 9. Comparative Temperature contours on symmetry planes of scaled test models: (a) Scale 1:1; (b) Scale 1:5; (c) Scale 1:10; (d) Scale 1:15.

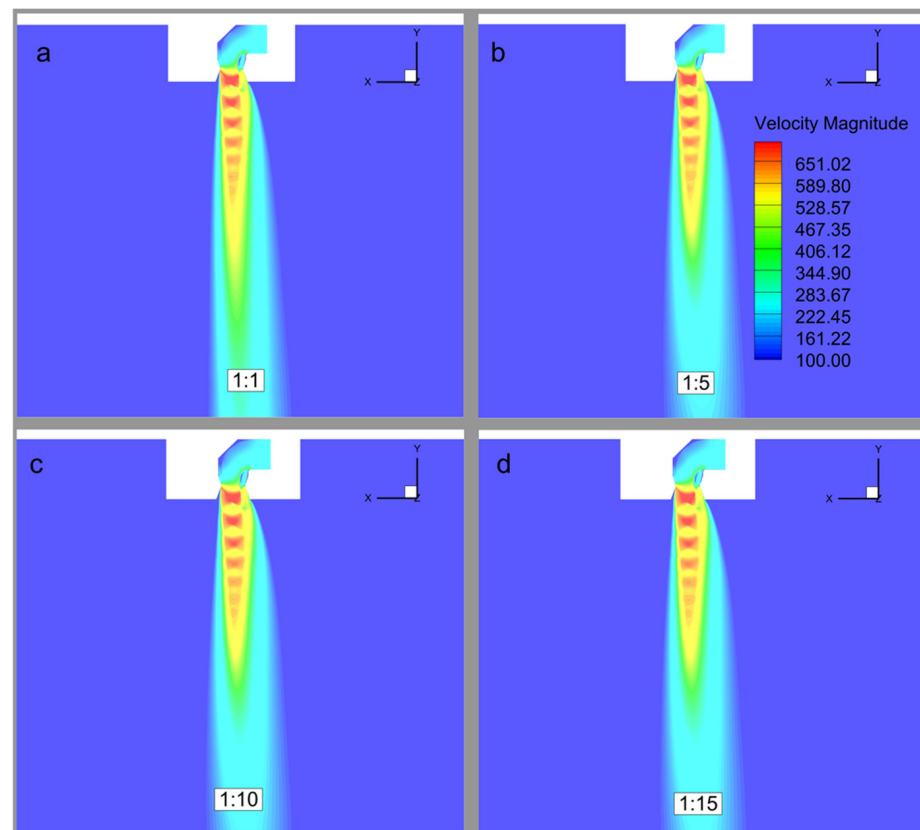


Figure 10. Comparative velocity contours on symmetry planes of scaled test models: (a) Scale 1:1; (b) Scale 1:5; (c) Scale 1:10; (d) Scale 1:15.

To provide a more quantitative assessment of the flow field similarity, Figure 11 presents the velocity magnitude along the jet centerline for all scaled models. The results show a remarkable collapse of the data, with all four scaling ratios producing nearly identical velocity profiles. The characteristic oscillations in velocity correspond to the shock-cell structure typical of an under-expanded jet. The fact that the location, magnitude, and decay rate of these shock cells are preserved across all scales provides strong quantitative evidence that the fundamental compressible flow physics are correctly captured by the scaling approach.

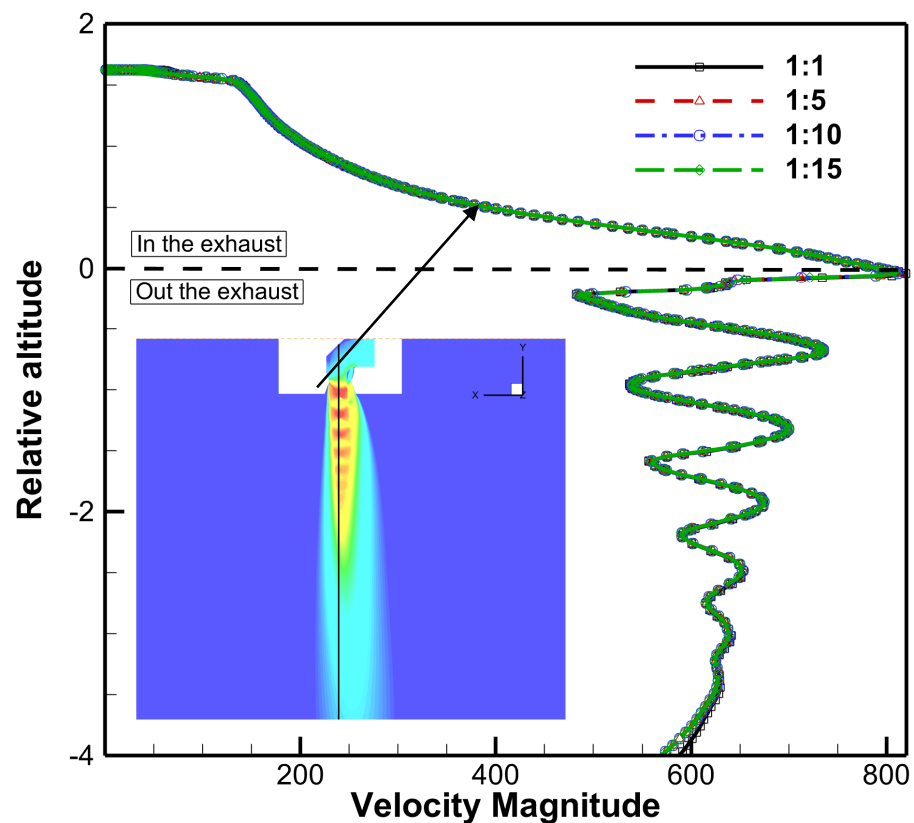


Figure 11. Comparative velocity at the central axis of scaled test models.

Figures 12–14 present pressure, temperature, and velocity contours at the nozzle exit and downstream axial stations (1D, 2D, 3D). The asymmetric distributions demonstrate significant flow deflection toward the nozzle's concave curvature, confirming plume bias induced by the curved geometry. Furthermore, contour similarity across geometrically scaled models at equivalent stations indicates structural consistency in plume characteristics when nozzle inlet boundary conditions (stagnation pressure/temperature) are maintained.

The observed self-similarity of the plume across different scales can be explained by the governing physics. The near-field plume structure, including the shock-diamond patterns and shear layer growth, is primarily dictated by the nozzle exit Mach number and pressure ratio (NPR). Since our similarity criterion strictly maintains these parameters, the fundamental compressible flow dynamics are preserved. Furthermore, the constant 12° deflection angle is a direct result of the non-uniform momentum flux distribution at the nozzle exit, which is governed by the internal nozzle geometry. Strict geometric similarity ensures this internal flow topology is maintained. Furthermore, the flow remains in a fully turbulent regime ($Re > 10^5$), where the large-scale turbulent mixing that drives plume development is insensitive to viscous effects, thus ensuring dynamic similarity.

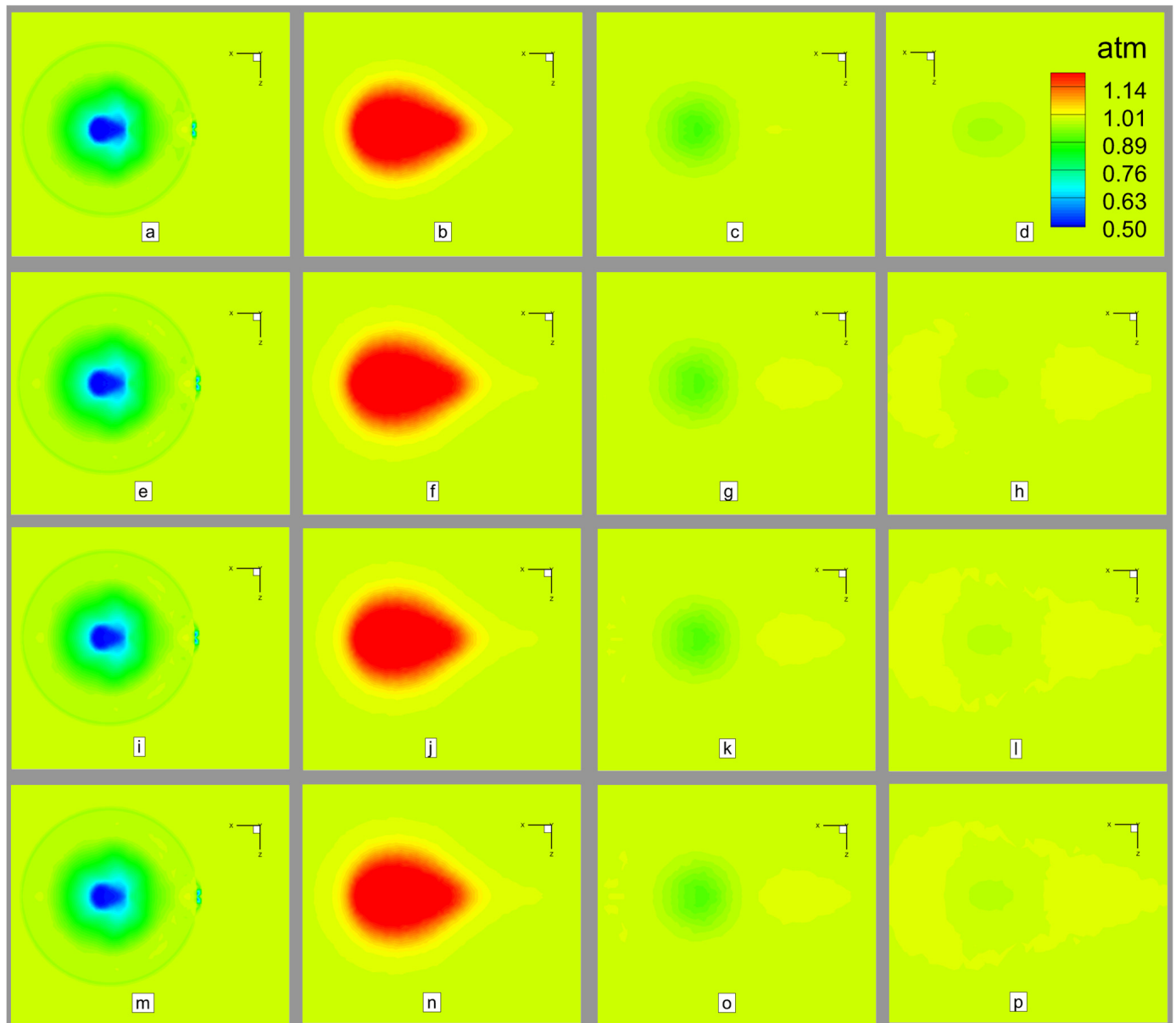


Figure 12. Comparative Pressure contours at cross-sections downstream of nozzle exit for scaled test models: (a–d) Scale 1:1 model at (a) 0D, (b) 1D, (c) 2D, (d) 3D; (e–h) Scale 1:5 model at (e) 0D, (f) 1D, (g) 2D, (h) 3D; (i–l) Scale 1:10 model at (i) 0D, (j) 1D, (k) 2D, (l) 3D; (m–p) Scale 1:15 model at (m) 0D, (n) 1D, (o) 2D, (p) 3D.

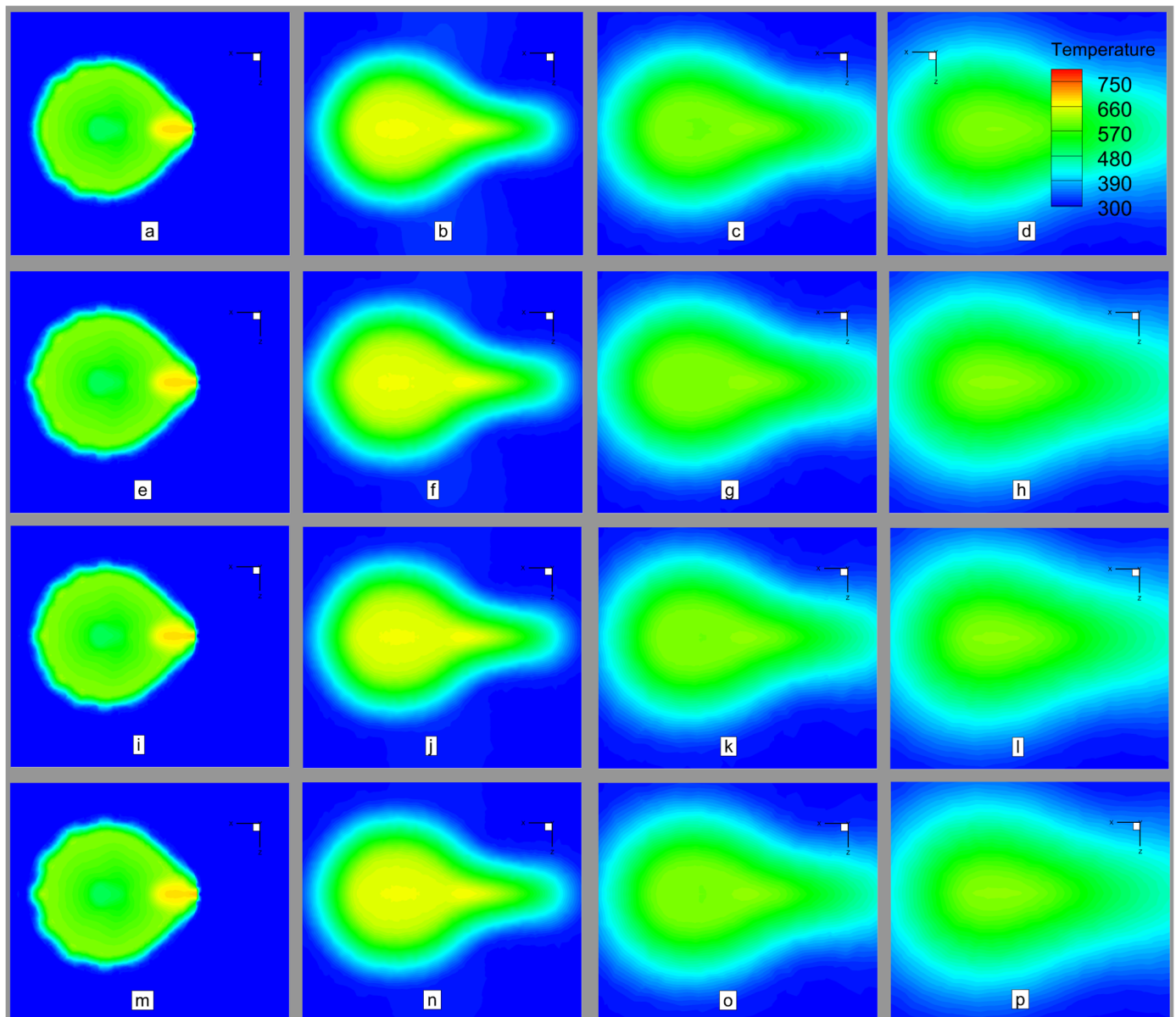


Figure 13. Comparative Temperature contours at cross-sections downstream of nozzle exit for scaled test models: (a–d) Scale 1:1 model at (a) 0D, (b) 1D, (c) 2D, (d) 3D; (e–h) Scale 1:5 model at (e) 0D, (f) 1D, (g) 2D, (h) 3D; (i–l) Scale 1:10 model at (i) 0D, (j) 1D, (k) 2D, (l) 3D; (m–p) Scale 1:15 model at (m) 0D, (n) 1D, (o) 2D, (p) 3D.

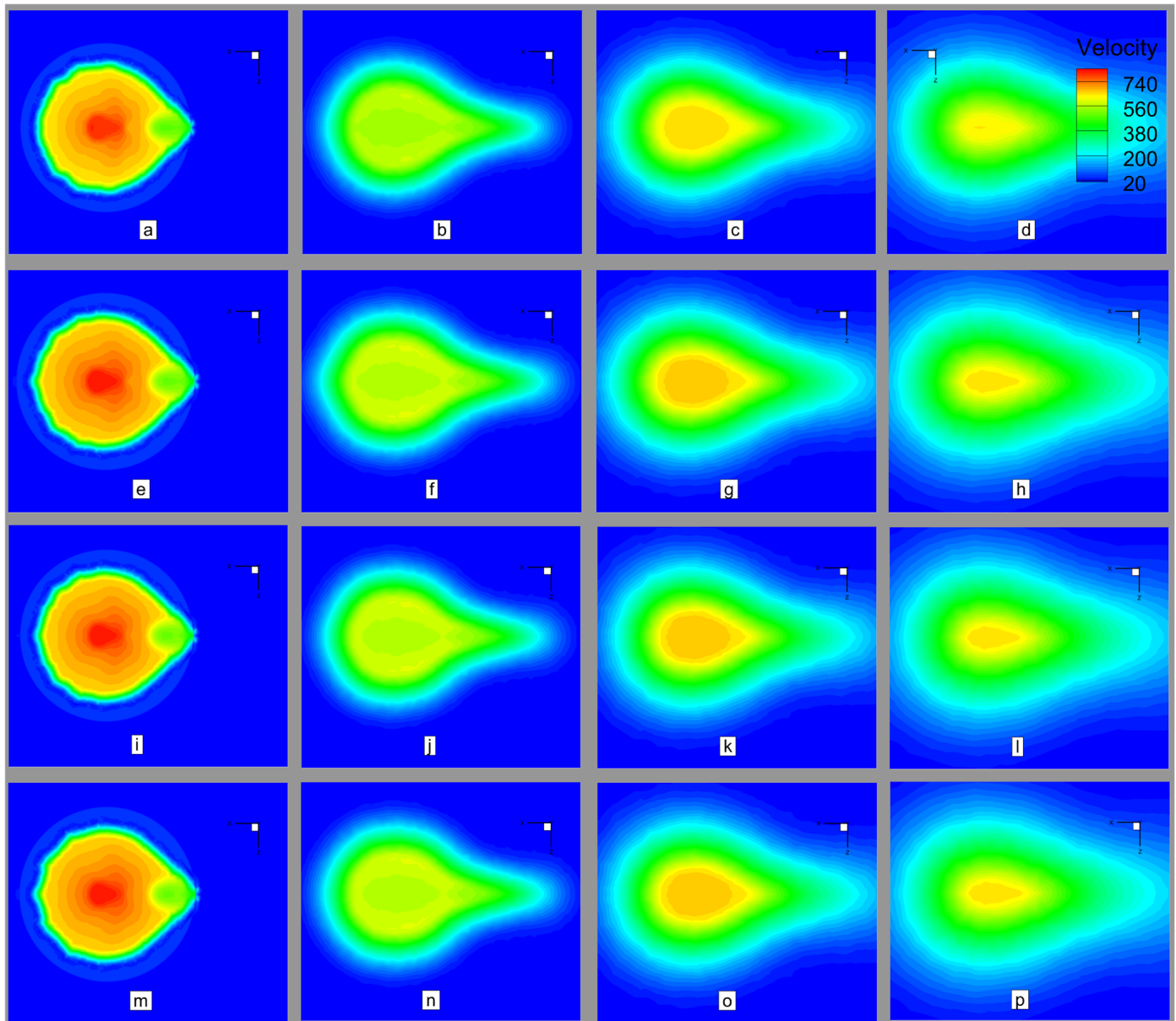


Figure 14. Comparative Velocity contours at cross-sections downstream of nozzle exit for scaled test models: (a–d) Scale 1:1 model at (a) 0D, (b) 1D, (c) 2D, (d) 3D; (e–h) Scale 1:5 model at (e) 0D, (f) 1D, (g) 2D, (h) 3D; (i–l) Scale 1:10 model at (i) 0D, (j) 1D, (k) 2D, (l) 3D; (m–p) Scale 1:15 model at (m) 0D, (n) 1D, (o) 2D, (p) 3D.

3.2. Effects of Geometric Scaling Ratios on Full-Configuration Flow Field Characteristics

For the full-configuration model, convergence histories for key parameters at both scaling ratios are presented in Figures 15–17, including:

- Total pressure at intake duct inlet;
- Total pressure at lift fan inlet;
- Mass flow rate at lift fan outlet;
- Mass flow rate at nozzle inlet;
- Axial force.

All parameters achieve statistical stationarity within 5000 iterations. Solutions satisfy the residual convergence criterion ($R < 10^{-4}$ for all governing equations), with key physical quantities exhibiting iterative fluctuations below 0.1%, confirming flow field convergence.

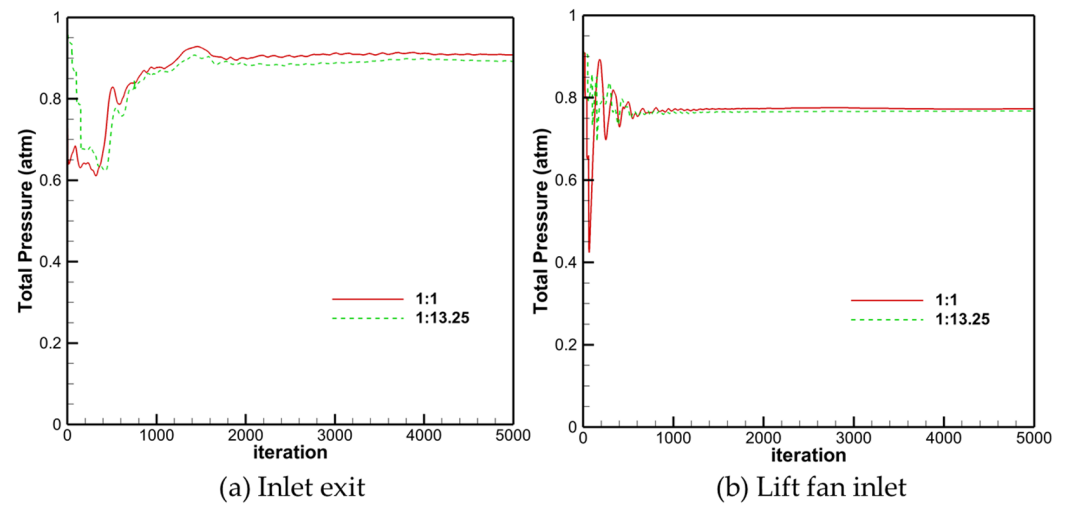


Figure 15. Total Pressure Convergence History.

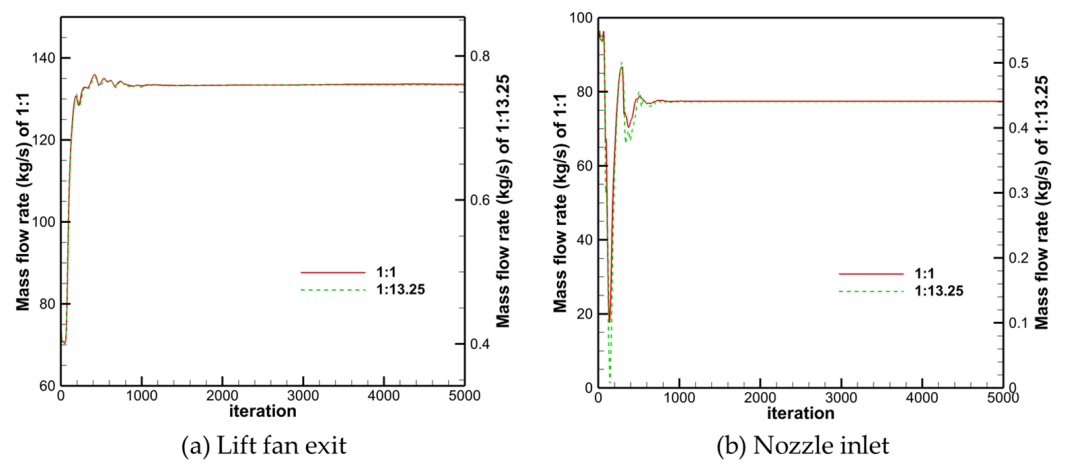


Figure 16. Mass flow rate convergence history.

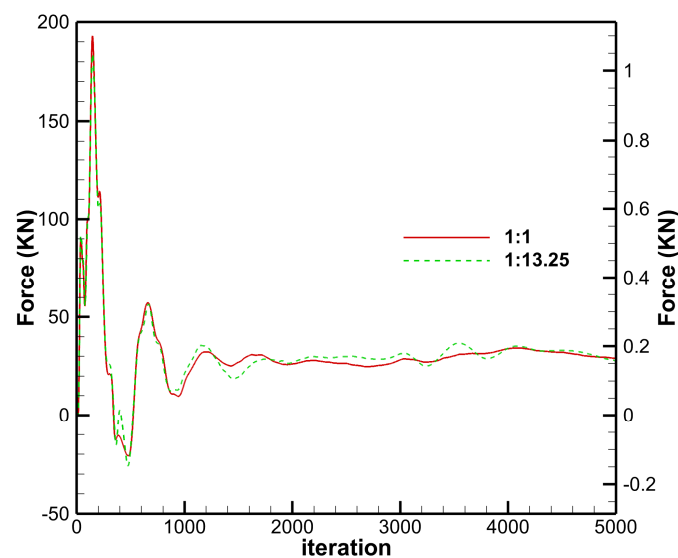


Figure 17. Axial thrust convergence history.

Table 4 compares key flow field parameters. Values for the vertical axial force, lift fan outlet mass flow rate, intake duct outlet total temperature, and nozzle inlet mass flow rate in the 1:13.25 model are scaled to 1:1 equivalent conditions. Results demonstrate negligible differences in primary monitoring values between scale models, confirming scaled-model feasibility for flow parameter simulation.

Specifically:

- Mass flow rates and intake port total temperature exhibit near-perfect agreement;
- Axial force prediction error remains within 1.47%;
- Total pressure error at intake port outlet is 2.2%, below the 5% tolerance threshold for STOVL aircraft design;
- Lift fan total inlet pressure shows essential equivalence.

These computational results validate the scaled-model approach for flow field parameter simulation.

Table 4. Monitored parameters for geometrically scaled models.

Model	Vertical Axial Force (KN)	Nozzle Inlet Mass Flow Rate (kg/s)	Lift Fan Outlet Mass Flow Rate (kg/s)	Inlet Outlet Total Pressure (atm)	Inlet Outlet Total Temperature (K)	Lift Fan Inlet Total Pressure (atm)
1:1	31.94	77.44	133.59	0.91	300.45	0.77
1:13.25	32.41	77.28	133.34	0.89	300.08	0.77
Error	1.47%	0.21%	0.19%	2.20%	0.12%	0.00%

Figure 18 presents symmetrical-plane flow patterns for both scale models. The lift fan's cold downward jet impinges on the ground and deflects rearward, while the nozzle's hot downward jet impinges and deflects forward. These flows merge approximately 1/3 chord lengths ahead of the nozzle–lift fan axis, subsequently developing into an upward fountain flow. This fountain transports heated fluid toward the aircraft underside, inducing thermal loading. Streamline topology demonstrates exceptional similarity between scale models, validating scaled-model fidelity for flow structure simulation [42].

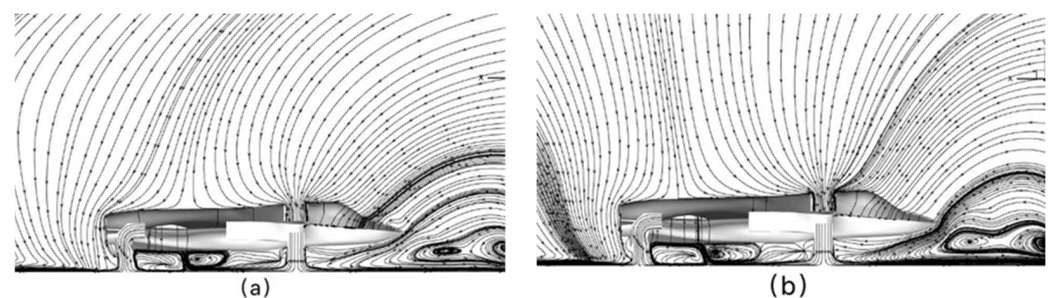


Figure 18. Comparative streamline patterns on symmetry planes of scaled test models: (a) Scale 1:1 model; (b) Scale 1:13.25 model.

Figure 19 presents symmetrical-plane contour distributions of pressure, temperature, and velocity simulated with different turbulence models. Results demonstrate close agreement between scaling conditions in

- Spatial location of high-pressure regions;
- Thermal diffusion extents;
- Fountain flow position and structure.

Both parameter magnitudes and distribution patterns exhibit consistent behavior. For instance, in both scaled models, the fountain flow regions predominantly extended from directly beneath the nozzle to a position two-thirds of the distance between the nozzle and the lift fan. The recirculation intensity was quantified at a consistent minimum velocity magnitude of 20 units across all cases. This confirms the applicability of the 1:13.25 scaling condition for accurate flow and thermal field prediction. The topology of the fountain flow is primarily governed by the momentum flux ratio of the impinging jets and the geometric parameters (e.g., ground height, jet spacing), all of which are preserved by the proposed similarity framework.

Prior studies establish that 1:13.25 scale models achieve similarity at Reynolds numbers $Re > 10^5$. For smaller scales (e.g., 1:20), viscous effects necessitate correction factors. Consequently, subsequent boundary condition investigations employ the 1:13.25 scaling configuration.

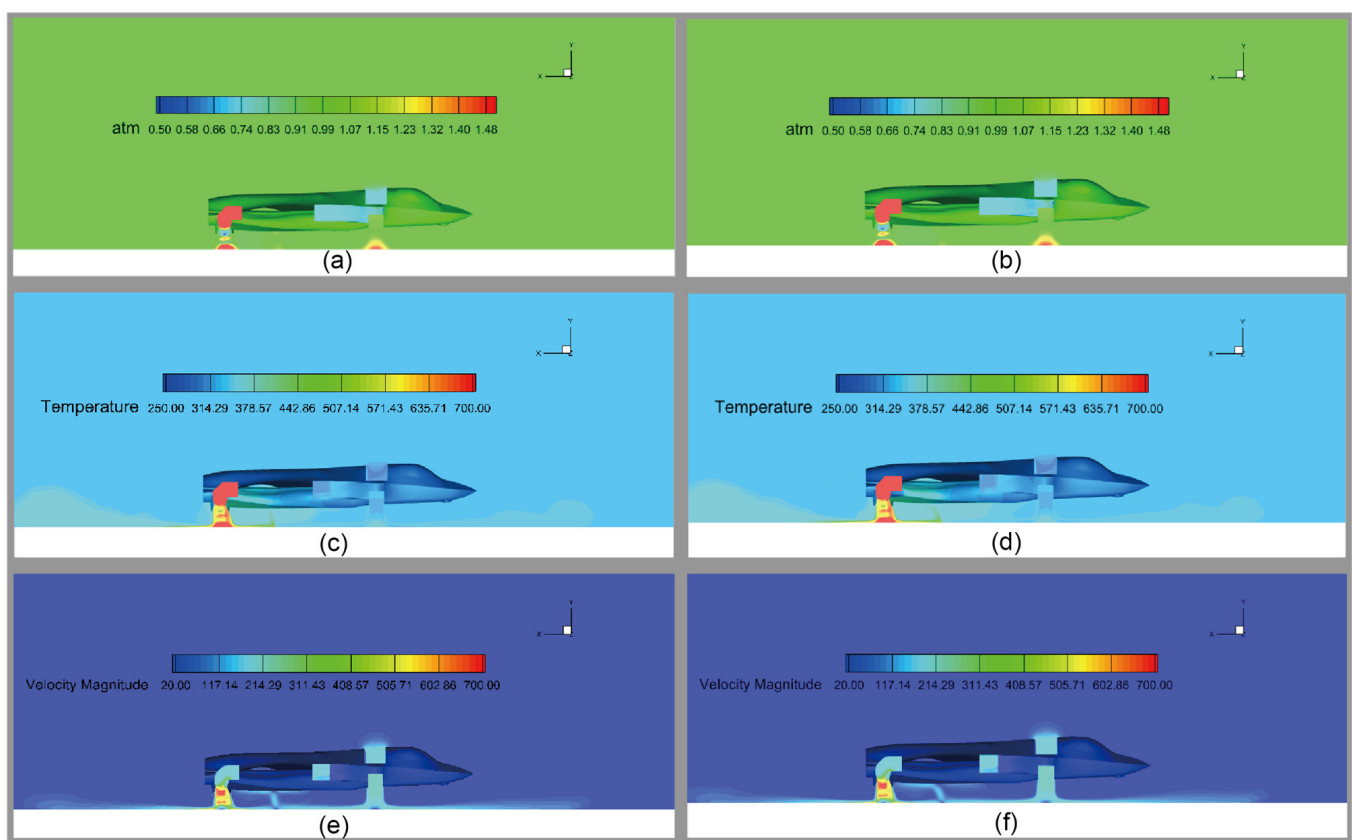


Figure 19. Comparative flow field distributions on symmetry planes of scaled test models: (a,b) Pressure contours: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) Temperature contours: (c) Scale 1:1, (d) Scale 1:13.25; (e,f) Velocity contours: (e) Scale 1:1, (f) Scale 1:13.25.

Figure 20 compares inlet pressure, temperature, and velocity distributions for different scale models. Results demonstrate strong agreement between 1:1 and 1:13.25 models in

- Spatial distribution of low-temperature/low-pressure/high-speed regions;
- Morphology and magnitude of characteristic zones;
- Parameter magnitudes throughout the domain.

This indicates minimal scaling influence on aerodynamic parameter distributions.

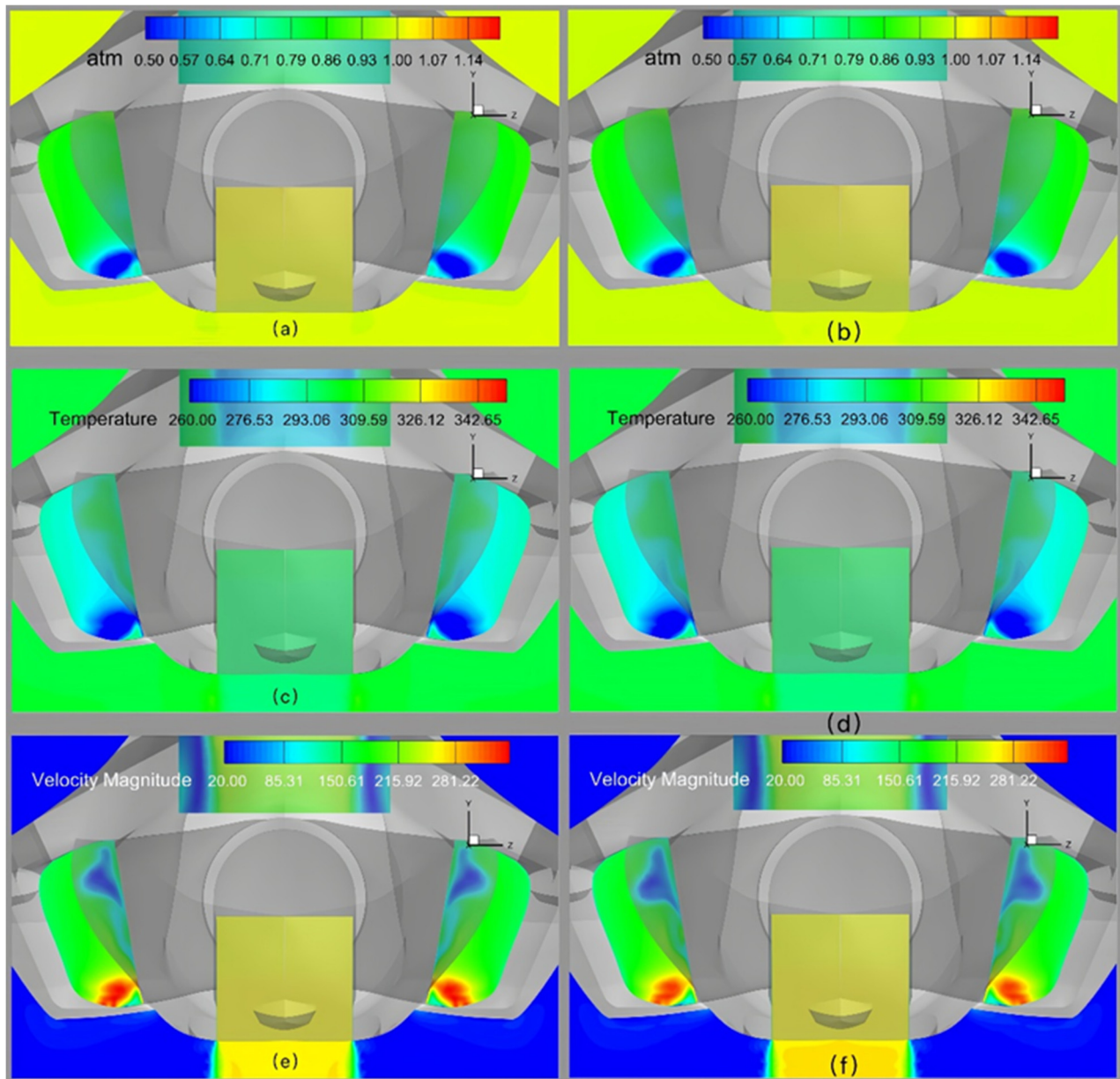


Figure 20. Comparative inlet entry flow characteristics of scaled test models: (a,b) Pressure contours: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) Temperature contours: (c) Scale 1:1, (d) Scale 1:13.25; (e,f) Velocity contours: (e) Scale 1:1, (f) Scale 1:13.25.

Figure 21 presents the contour distributions of pressure, temperature, and velocity at the nozzle exits for different scaled models. Figure 22 provides a comparative analysis of partial pressure data at the exit planes for the two scaled models. Parameter distributions exhibit bilateral symmetry due to convergence of the semi-circular intake ducts. While pressure, temperature, and velocity contours show substantial similarity between 1:1 and 1:13.25 models, dimensional variations exist:

- High-pressure regions display greater spatial extent in the 1:1 configuration;
- Low-pressure zones exhibit marginally larger coverage at full scale;
- Temperature and velocity distributions follow analogous scaling trends. Relative errors of pressure are kept at a very small level, less than 2%.

These dimensional discrepancies notwithstanding, fundamental flow structures maintain consistent topology across scales [43].

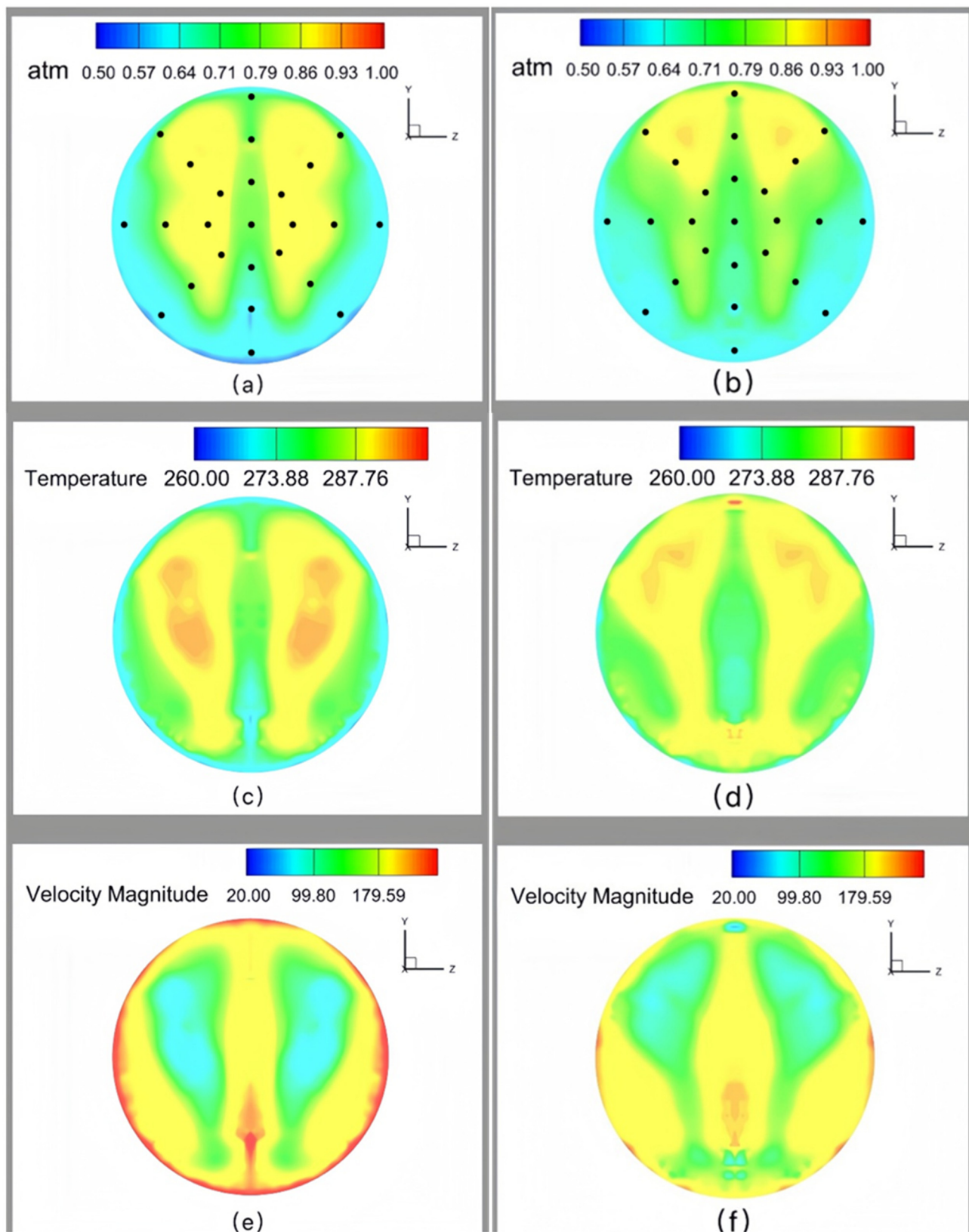


Figure 21. Comparative inlet exit flow characteristics of scaled test models: (a,b) Pressure contours: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) Temperature contours: (c) Scale 1:1, (d) Scale 1:13.25; (e,f) Velocity contours: (e) Scale 1:1, (f) Scale 1:13.25.

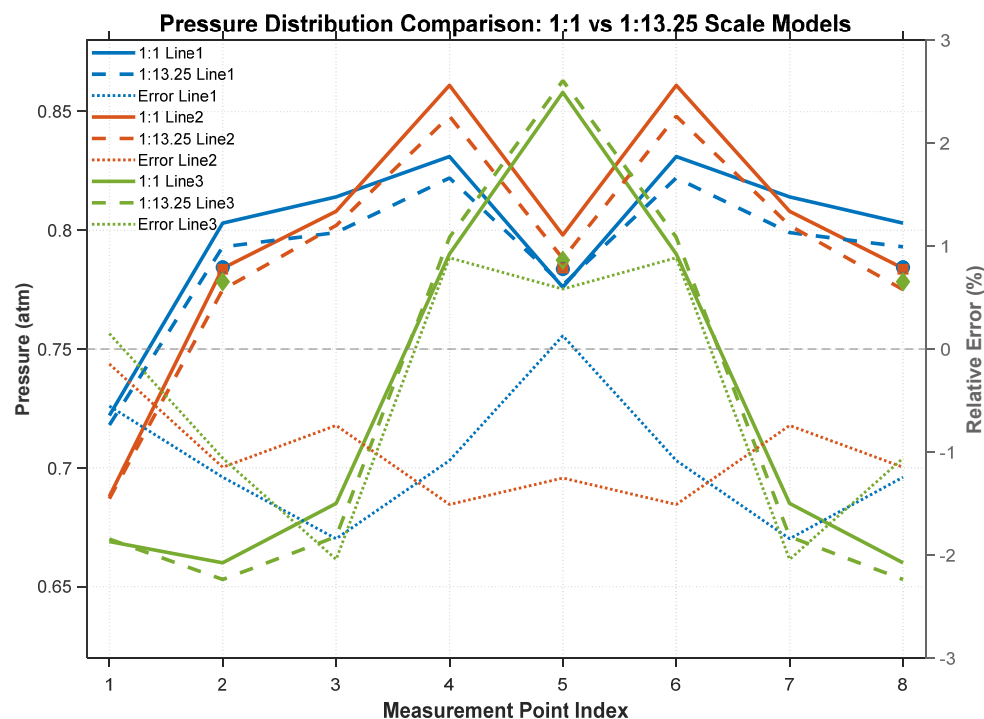


Figure 22. Pressure and Relative Error ($(P_{\text{scaled}} - P_{\text{full}})/P_{\text{full}}$) Distribution Comparison at Intake Outlet: 1:1 vs. 1:13.25 Scale Models.

Figures 23 and 24 present thermal footprint distributions on aircraft undersides and ground surfaces for both scale models. The 1:1 and 1:13.25 configurations exhibit consistent thermal loading characteristics in

- Spatial extent of heating zones;
- Magnitude profiles of surface heat flux;
- Temperature distribution patterns.

This agreement validates scaled-model fidelity for thermal environment simulation [44]. This consistency in the thermal footprints is explained by the convection-dominated nature of the heat transfer. At the high Reynolds numbers in this study, heat is transported primarily by the mean flow. Since the velocity fields are dynamically similar, the convective transport of hot gas is also similar, resulting in consistent thermal patterns.

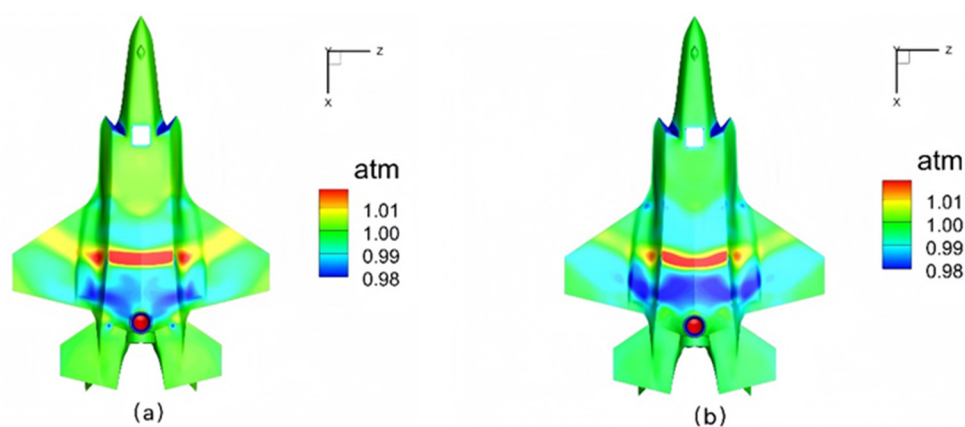


Figure 23. Cont.

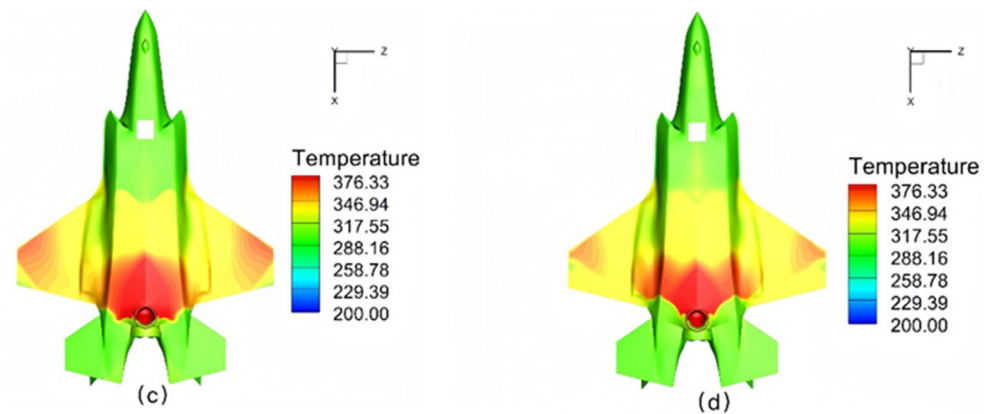


Figure 23. Comparative ventral surface flow characteristics of scaled test models: (a,b) Pressure contours: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) Temperature contours: (c) Scale 1:1, (d) Scale 1:13.25.

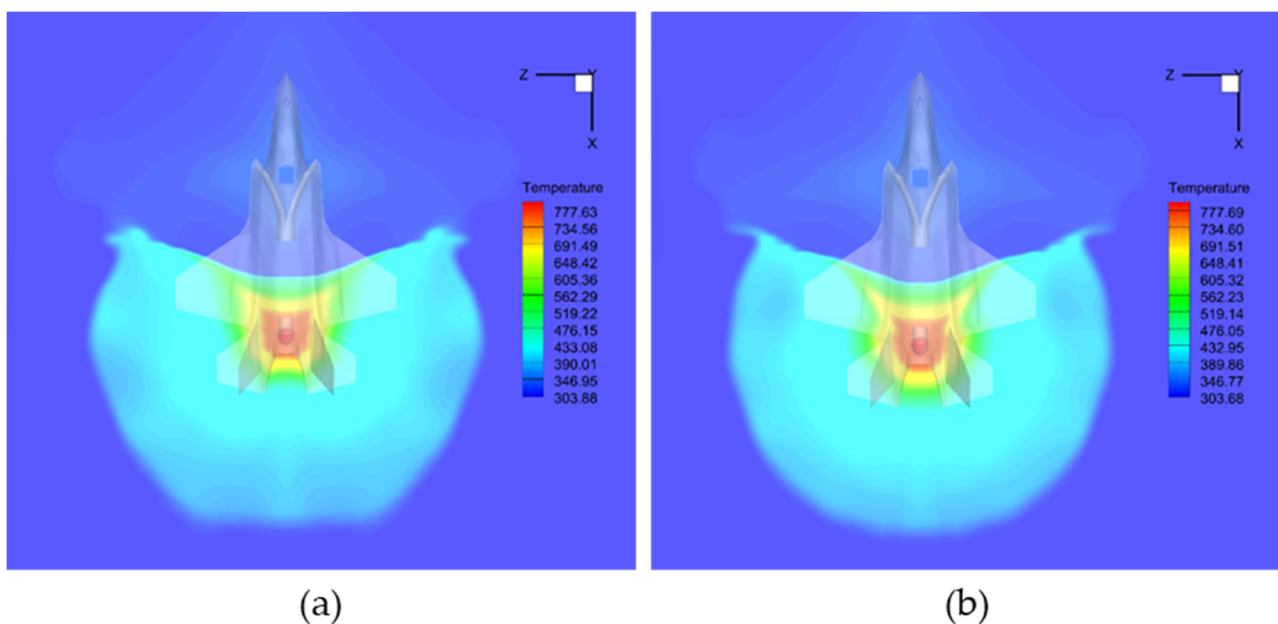


Figure 24. Comparative ground plane temperature distributions for scaled test models: (a) Scale 1:1; (b) Scale 1:13.25.

Cross-section planes are selected to better conduct thermal analysis (Figure 25). Figures 26–29 present temperature contour distributions at geometrically scaled positions (1 m, 2 m, 3 m) forward, aft, port, and starboard of the aircraft. Distances for the 1:13.25 model represent equivalent full-scale positions (e.g., 1 m section corresponds to 0.0755 m actual distance; see Figure 25 for plane locations). Temperature distributions exhibit close alignment between scale models across all sections, with minimal variation in

- Thermal influence extents;
- Temperature extremal values;
- Distribution morphology.

This spatial coherence preservation demonstrates scaled-model capability for simulating vertically impinging flow structures [45].

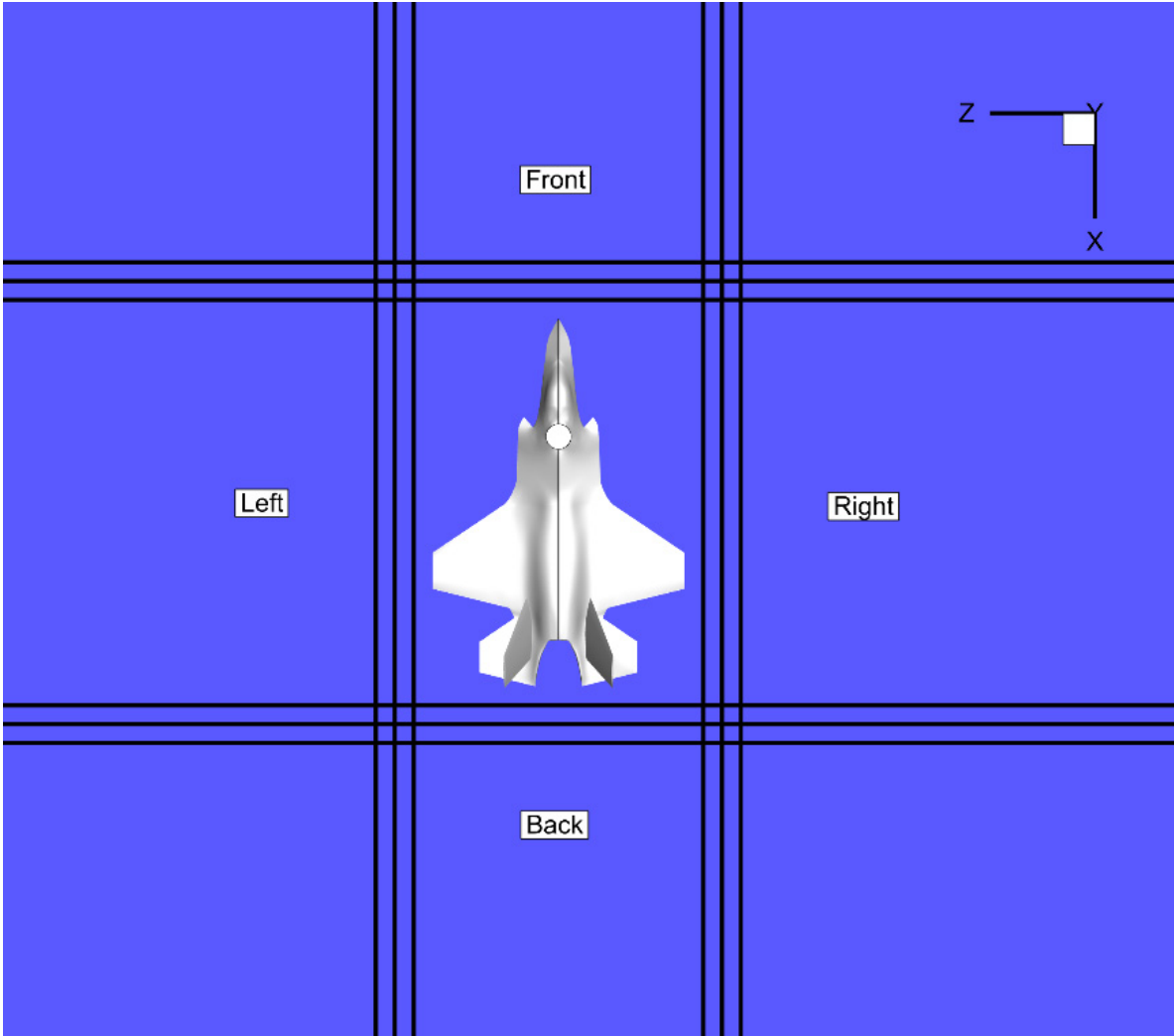


Figure 25. Reference plane location schematic.

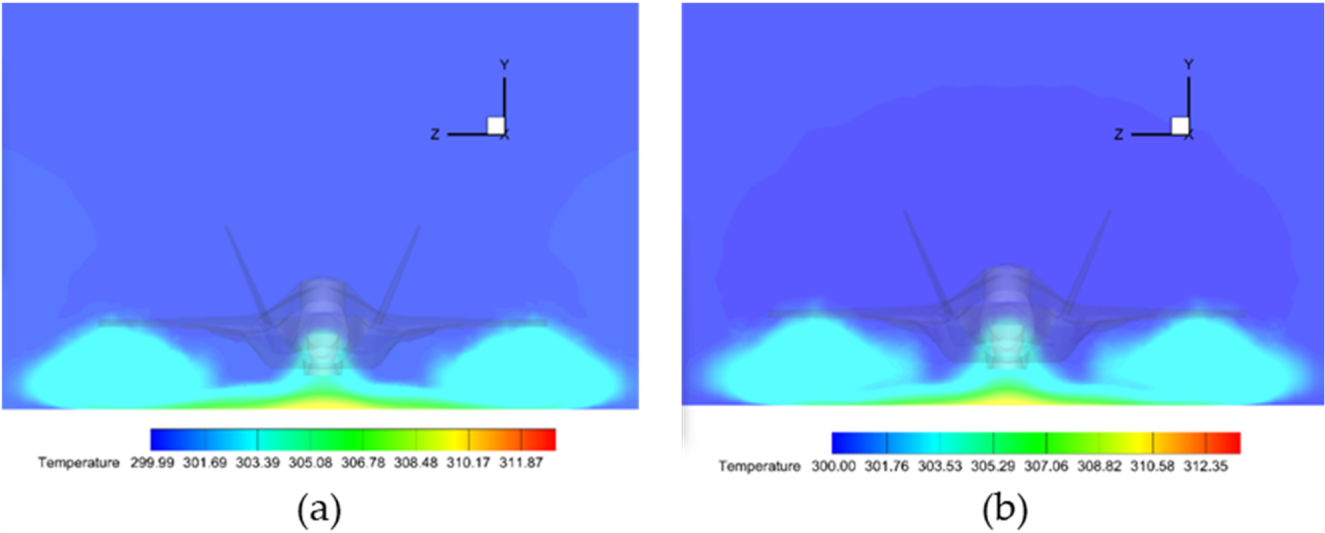


Figure 26. Cont.

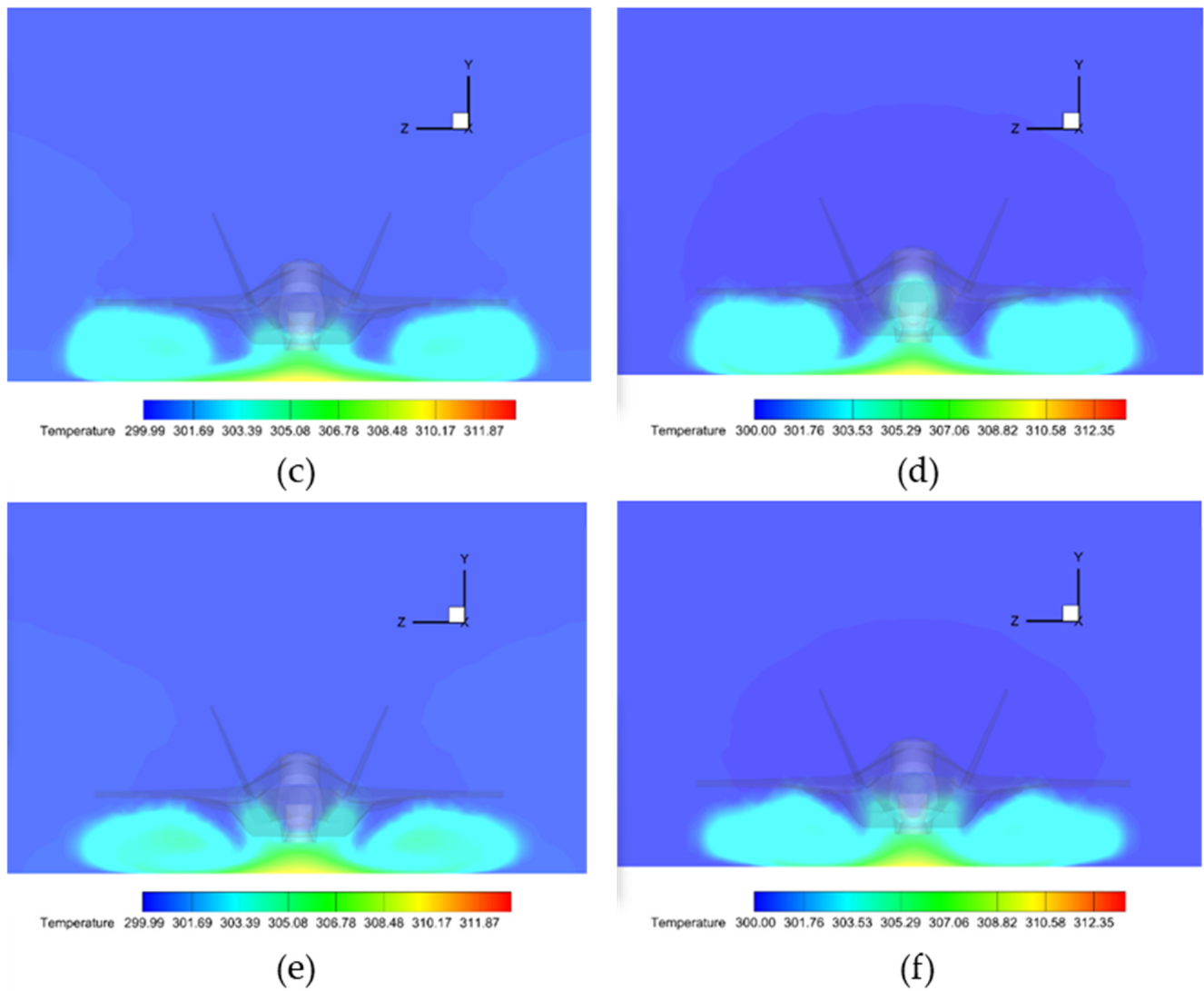


Figure 26. Comparative temperature distributions on vertical planes at forward distances from scaled test models: (a,b) 1 m plane: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) 2 m plane: (c) Scale 1:1, (d) Scale 1:13.25; (e,f) 3 m plane: (e) Scale 1:1, (f) Scale 1:13.25.

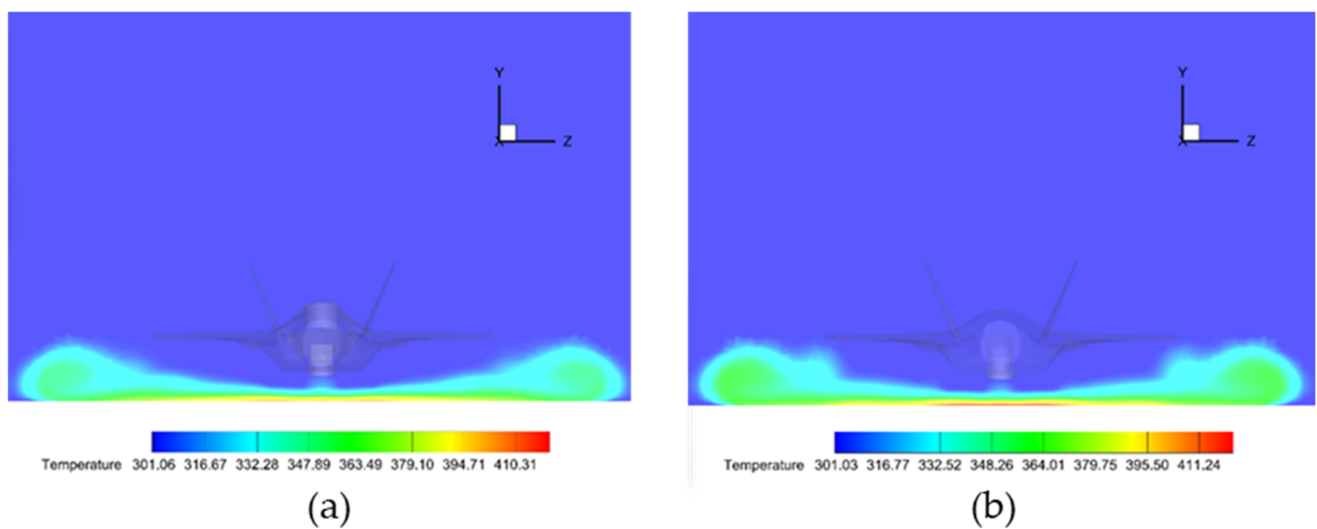


Figure 27. Cont.

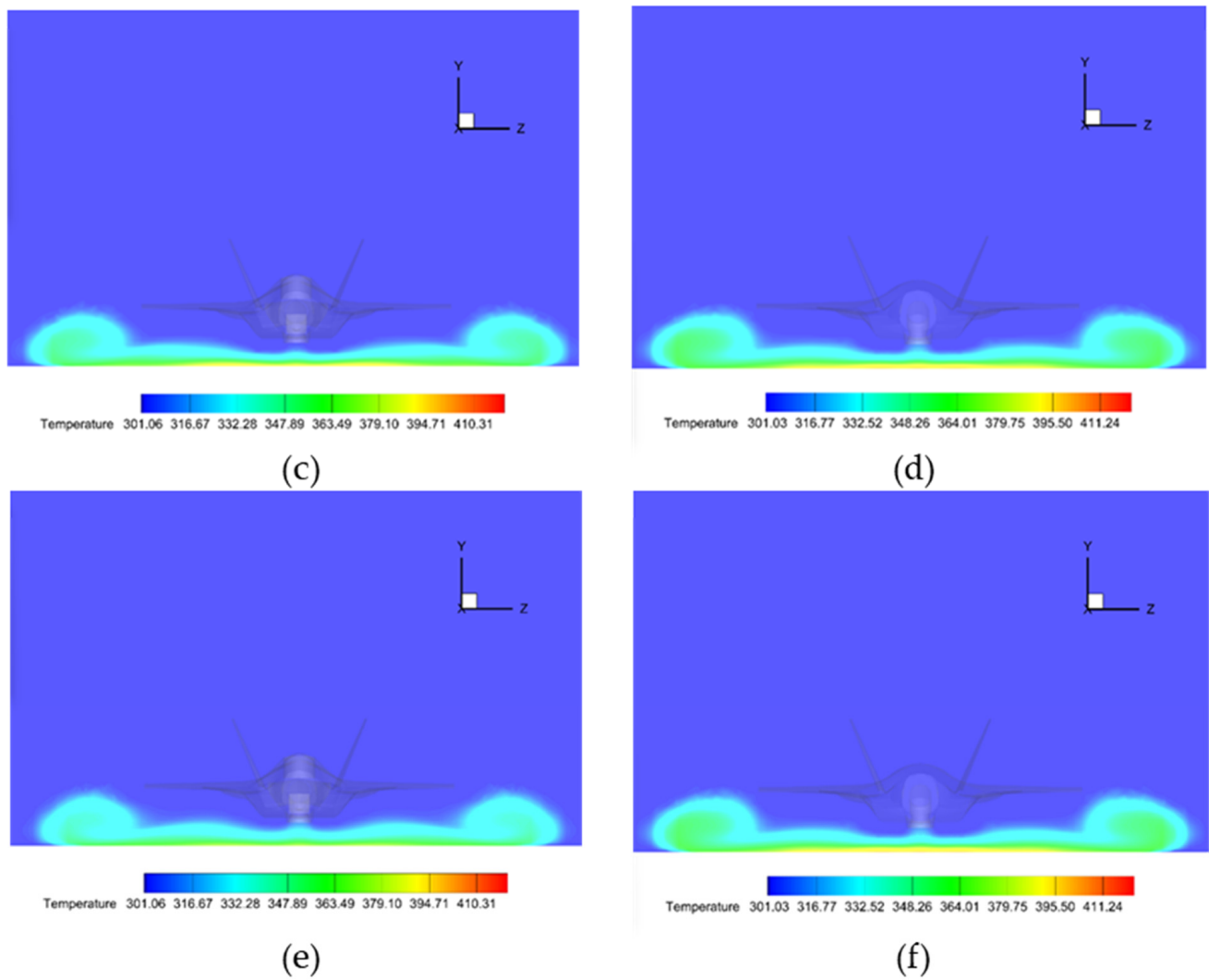


Figure 27. Comparative temperature distributions on vertical planes at aft distances from scaled test models: (a,b) 1 m plane: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) 2 m plane: (c) Scale 1:1, (d) Scale 1:13.25; (e,f) 3 m plane: (e) Scale 1:1, (f) Scale 1:13.25.

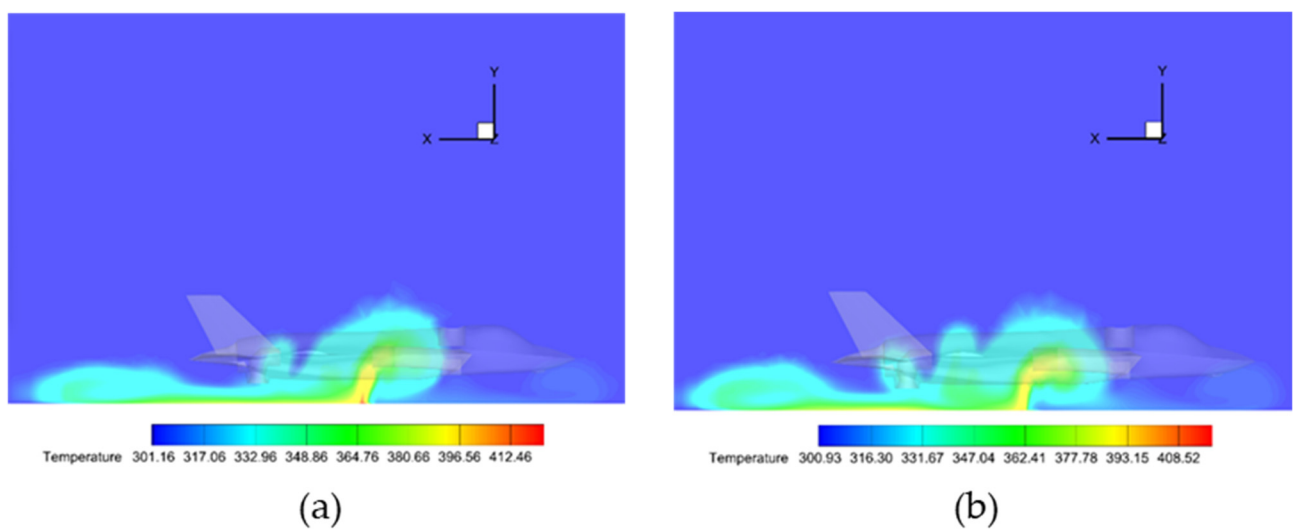


Figure 28. Cont.

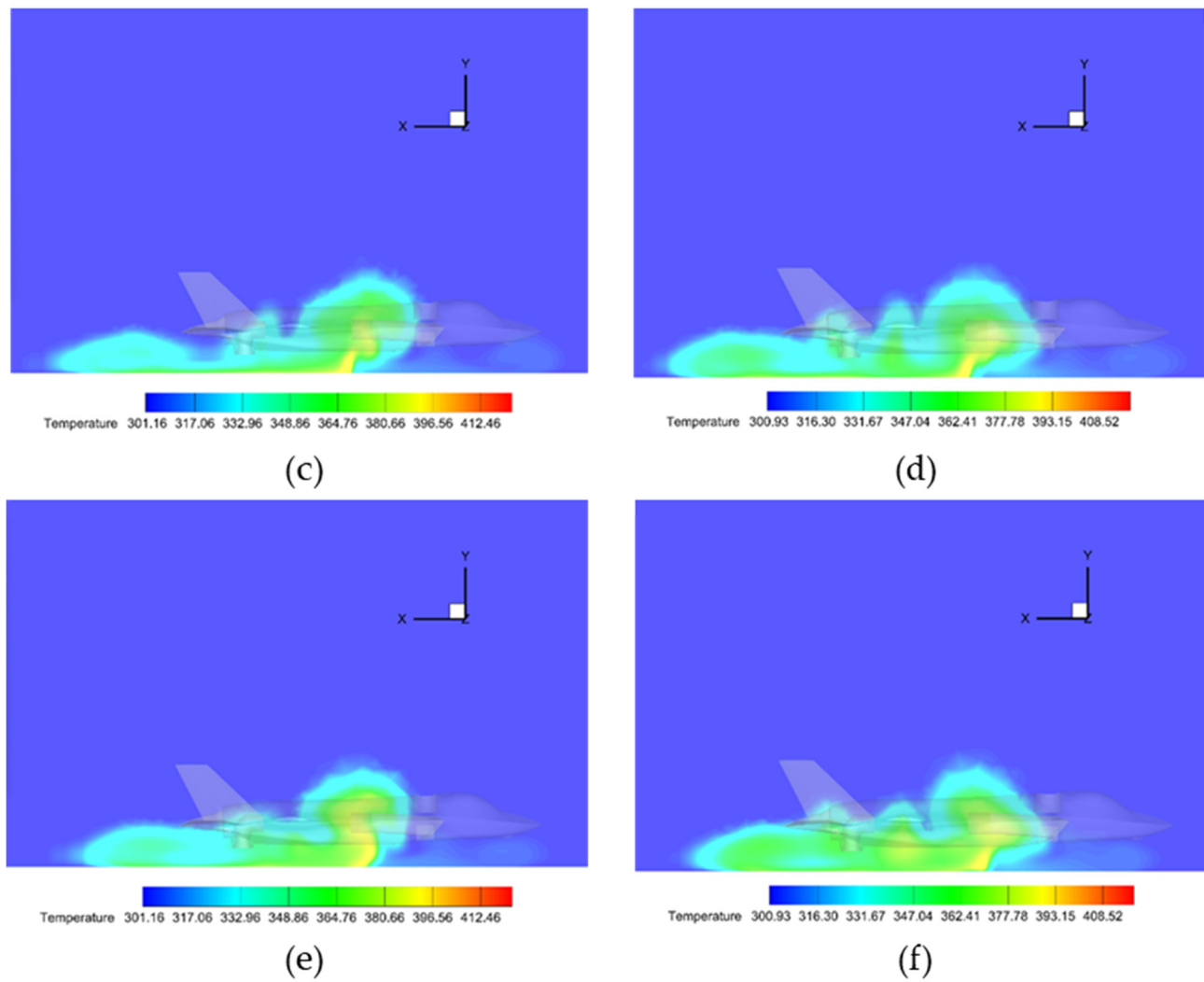


Figure 28. Comparative temperature distributions on vertical planes at starboard distances from scaled test models: (a,b) 1 m plane: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) 2 m plane: (c) Scale 1:1, (d) Scale 1:13.25; (e,f) 3 m plane: (e) Scale 1:1, (f) Scale 1:13.25.

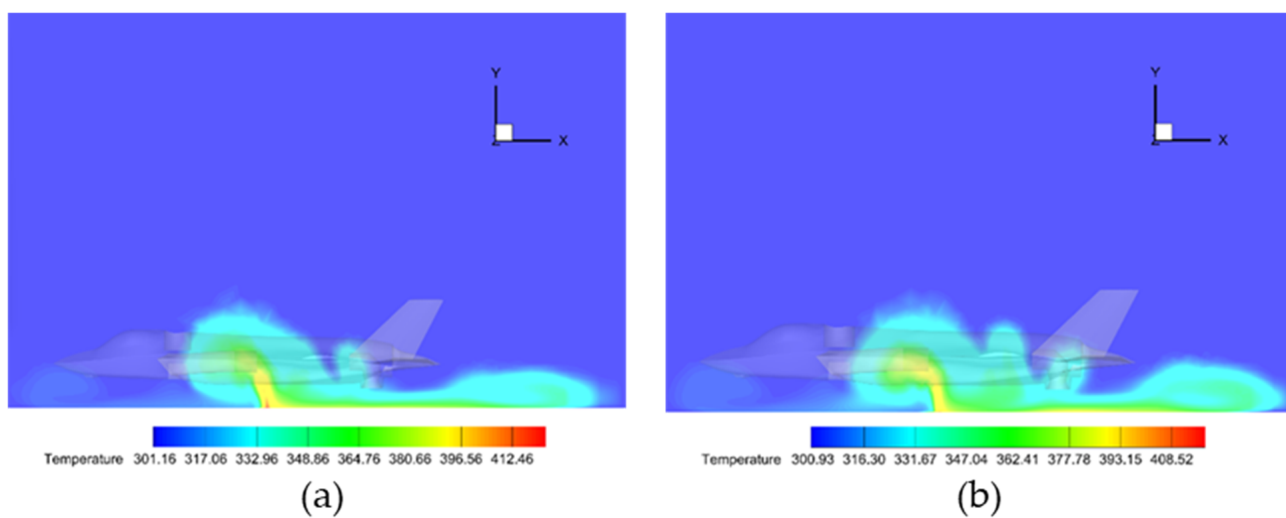


Figure 29. Cont.

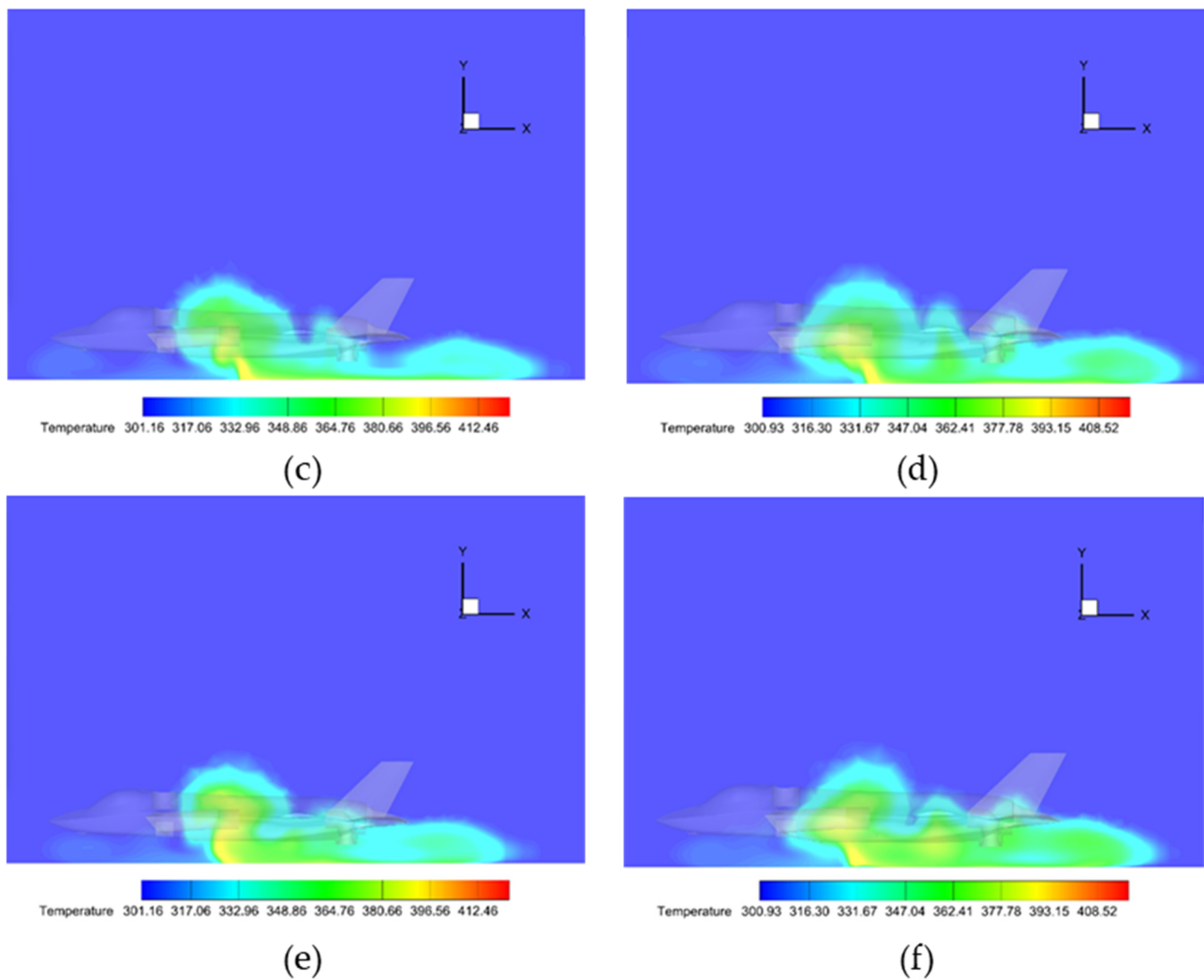


Figure 29. Comparative temperature distributions on vertical planes at port distances from scaled test models: (a,b) 1 m plane: (a) Scale 1:1, (b) Scale 1:13.25; (c,d) 2 m plane: (c) Scale 1:1, (d) Scale 1:13.25; (e,f) 3 m plane: (e) Scale 1:1, (f) Scale 1:13.25.

Prior studies confirm strong agreement between the 1:13.25 scale model and full-scale configuration in

- Key aerodynamic parameters (vertical axial force error: 1.47%; intake total pressure error: 2.2%);
- Flow structure characteristics (fountain topology, ground thermal footprints) [46].

This validates dynamic similarity preservation across scales for integrated STOVL configurations.

4. Conclusions

To address the limitations of conventional wind tunnel testing for STOVL aircraft, this study proposes and systematically validates a novel “pressure ratio–momentum–geometry” multi-dimensional similarity framework. The core contribution of this work is to demonstrate, for the first time, that a unified set of similarity criteria can achieve high-fidelity reproduction of critical dynamic flow characteristics for a complete, full-scale STOVL aircraft system involving complex multi-jet interactions, ground effect, and coupled aerothermal physics. The key novel findings of this research are as follows:

- (1) A scaling criterion for complex curved nozzles was established, providing a foundation for the full-configuration similarity study. For F-35B-class 3-bearing swivel nozzles, this work confirms consistent jet-core deflection characteristics (concave-side offset: $12^\circ \pm 1^\circ$) across 1:1 to 1:15 scaling ratios. Axial thrust (F) and mass flow rate (Q) adhere to geometric scaling laws ($F \propto 1/n^2$; $Q \propto 1/n^2$) [47]. This overcomes traditional similarity limitations for complex curvature effects, validating the momentum-flux-based scaling framework for high-fidelity nozzle component testing.
- (2) The effectiveness and high fidelity of the full-aircraft dynamic similarity framework were systematically validated. Numerical simulations confirm that the scaled model accurately reproduces the critical dynamic flow characteristics of the prototype aircraft, with minimal errors in key parameters: total pressure at the intake outlet ($<2.2\%$), total temperature ($<0.2\%$), axial force ($<1.5\%$), and lift fan mass flow rate ($<0.2\%$). These values significantly outperform standard engineering design tolerances (e.g., the typical 5% tolerance for intake total pressure). Furthermore, the scaled model accurately reproduces
 - The formation, propagation, and thermal load distribution of fountain flow upon ground/wall impact;
 - Fuselage thermal load profiles;
 - Flow parameter distributions at intake duct inlet/outlet sections;
 - Temperature field structures in the surrounding fuselage space (front/rear/left/right orientations).

In summary, the contribution of this research is not merely to verify a known scaling law with CFD, but rather to provide the first systematic, validated, and comprehensive multi-dimensional similarity solution for the complex engineering problem of STOVL aircraft in ground effect. The establishment of this framework provides a solid theoretical foundation and a reliable technical pathway for developing cost-effective and efficient scaled wind tunnel testing methodologies. However, it is important to acknowledge that the current study is limited to static hover conditions and requires further experimental validation. Future work should therefore prioritize a comprehensive wind tunnel campaign and extend the framework to include critical transition flight and crosswind effects.

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