

Scale-Resolving Simulation of Pressure Oscillations in a Radial-Inflow Solid Rocket Motor

Nabi Bux Kalhoro ^{a*, b}, Israr Ahmed ^a, Afaque Ahmed Bhutto ^b

^a Department of Mathematics, Shah Abdul Latif University, Khairpur, Sindh, Pakistan

^b Department of Basic Science and Related Studies, The University of Larkano, Sindh, Pakistan

* Corresponding author: Nabi Bux Kalhoro, Email: drnb_kalhoro@uolrk.edu.pk

Received: 08 January 2026, Revised: 21 April 2026, Accepted: 22 June 2026, Published: 01 July 2026

KEY WORDS

Combustion Instability
Pressure Oscillation
URANS
SRS
Vortex Formation
Fast Fourier Transform

ABSTRACT

Combustion instability in solid rocket motors (SRMs) arises from the coupling of unsteady pressure oscillations with chamber acoustic modes and can threaten structural integrity and operational reliability. This study examines how replacing a conventional axial inlet with a radial inlet affects internal flow dynamics, vortex-acoustic coupling, and pressure fluctuations in an SRM combustion chamber. Radial inflow introduces a circumferential velocity component that increases tangential shear near the walls, promotes earlier vortex roll-up around the inhibitor, and produces denser, more three-dimensional vortical structures, thereby strengthening vortex-acoustic interactions. Two-dimensional axisymmetric simulations were performed using scale-resolving simulation (SRS) and unsteady Reynolds-averaged Navier-Stokes (URANS) approaches. Pressure histories recorded at two monitoring points were analyzed using the fast Fourier transform (FFT) to identify dominant acoustic frequencies and normalized amplitudes. The SRS models agreed closely with the experimental data, accurately capturing the first four acoustic modes and the monotonic decrease in normalized amplitude with increasing mode number; LES with the WALE model produced the most reliable overall results. By contrast, the URANS models smoothed small-scale fluctuations, underpredicted higher-frequency modes, and misrepresented amplitude levels, particularly when the scale-adaptive simulation model was used. These findings show that the radial-inlet configuration substantially alters SRM flow physics and instability characteristics and demonstrate the value of advanced SRS approaches for inlet-specific designs intended to mitigate combustion instability.

1. Introduction

Combustion instability is a critical concern in propulsion systems, yet the unsteady characteristics of radial-inflow, high-aspect-ratio solid rocket motors remain poorly understood. Because of their structural simplicity, high thrust-to-weight ratio, and long storage life, SRMs are widely used in aerospace applications. However, self-sustaining pressure oscillations during propellant combustion can severely impair motor performance and may lead to mission failure [1-3]. Xu et al. [4] reproduced nonlinear pulse-triggered instability and showed that instability develops only when the pulse intensity exceeds the SRM damping threshold. Their nonlinear-response framework enables identification of the instability

boundary and provides a more comprehensive basis for predicting thermoacoustic instability in SRMs.

Combustion instability in SRMs results from complex interactions among unsteady heat release, internal flow dynamics, and chamber acoustics. Pressure oscillations superimposed on the mean chamber pressure may resonate with the chamber's natural acoustic modes, causing amplitude growth and potential structural failure [5,6]. Typical manifestations include fluctuations in burning rate and pressure, increased heat-transfer rates, and the formation of vortical structures within the combustion chamber [7,8]. Unlike many conventional propulsion systems, SRMs may employ parietal injection, in which gas enters through the chamber walls, producing complex internal flow fields.

Khokhar et al. [9] analyzed Newtonian-fluid flow in a channel containing a porous medium under combining and separating flow conditions. Using the finite-element method with the Taylor-Galerkin/pressure-correction scheme, they examined the effects of inertia, porosity, and flow-rate variation. Volkov [10] developed advanced multiscale numerical models for difficult processes in SRMs, with particular emphasis on two-phase flow involving nonspherical metal-oxide agglomerates. Xu et al. [11] developed an LES-based methodology to investigate corner-vortex-induced pressure fluctuations in an SRM with a backward-facing step and evaluated the effects of step position, head-cavity angle, and submerged-nozzle cavity height on vortex-acoustic coupling. Xi et al. [12] numerically investigated transient vortex flow and pressure oscillations in a large-aspect-ratio SRM using a two-dimensional LES model and assessed head-cavity modifications as a means of suppressing pressure oscillations.

The classical Taylor-flow model represents internal SRM flow as a combination of axial and radial velocity components [13]. Large segmented motors, including the Ariane 5 P230 and the Space Shuttle reusable solid rocket motor, have historically been susceptible to pressure oscillations. Full-scale testing is expensive and complex; consequently, subscale systems such as the LP6, a 1/15-scale model of the Ariane 5, are commonly used in experiments and numerical studies [14,15]. CFD simulations of such models have shown good agreement with experimental measurements of pressure-oscillation frequency and amplitude [16]. Pressure oscillations can cause thrust fluctuations, damage thermal-protection layers, and disturb the propellant-grain surface [17,18]. Vortex shedding has been recognized since the 1950s as a major source of internal-flow instability. Powell [19] and Howe [20] developed the theory of vortex-acoustic interaction, showing that coupling between vortices and acoustic modes can transfer energy to pressure waves and intensify instability. Experimental studies of scaled motors and

2. Governing Equations

2.1 Mathematical Formulation

The continuity, momentum, and energy equations form the fundamental governing equations of fluid dynamics. For the DES framework, RANS is applied near walls and LES is applied in separated-flow regions. For a radial inlet, cylindrical coordinates (r, θ, z) are convenient. The gradient (∇) and divergence ($\nabla \cdot$) operators in cylindrical coordinates are defined as [30,31]:

$$\nabla = \left(\frac{\partial}{\partial r}, \frac{1}{r} \frac{\partial}{\partial \theta}, \frac{\partial}{\partial z} \right) \quad (1)$$

hot-wire measurements supported the association between pressure oscillations and vortex shedding [21]. Flandro and Jacobs [22] further showed that vortex shedding can excite the natural acoustic modes of a chamber. The mechanism was also supported by cold-gas studies of motors such as Titan 34D and Ariane 5 [16,23]. The high-resolution AVBP LES solver developed by CERFACS has proved effective for simulating these aeroacoustic phenomena [14].

Computational studies, including those of Kourta et al. [24], have examined interactions between hydrodynamic and acoustic instabilities and highlighted the need to resolve turbulent length scales that govern vortex formation and decay. Dunlap et al. [21,25] noted that turbulence models that neglect these scales may overpredict instability. Recent work has also examined thermal inhibitors, which are rigid obstacles placed in the flow path to disrupt vortex development [26-28]. Su et al. [29] used LES to evaluate the effects of inhibitor position and temperature on pressure oscillations, whereas Zhang et al. [17] showed that mass injection at a pressure antinode can significantly amplify oscillation amplitude. Configurations without inhibitors have also been studied to isolate obstacle-vortex-shedding mechanisms [14]. Although previous research has addressed the fundamental causes of combustion instability, including acoustic coupling, flame dynamics, and chamber geometry, the specific role of obstacle vortex shedding remains insufficiently characterized. Vortices generated by surface, angle, and obstacle vortex shedding are convected downstream of the chamber obstacle. Recent LES studies [11,12] have shown that accurate resolution of vortex dynamics is essential for predicting pressure oscillations. In contrast to earlier work centered on axial inflow, the present study investigates radial-inlet effects using SRS and URANS models. An isothermal radial-inlet boundary condition is imposed to examine the development of vortex-induced instability in the combustion chamber.

$$\nabla \cdot \mathbf{A} = \frac{1}{r} \frac{\partial(rA_r)}{\partial r} + \frac{1}{r} \frac{\partial A_\theta}{\partial \theta} + \frac{\partial A_z}{\partial z} \quad (2)$$

Continuity Equation in Cylindrical Coordinates

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial(r\rho u_r)}{\partial r} + \frac{1}{r} \frac{\partial(r\rho u_\theta)}{\partial \theta} + \frac{\partial(\rho u_z)}{\partial z} = 0 \quad (3)$$

Momentum Equations in Cylindrical Coordinates
Radial Momentum (r -direction):

$$\frac{\partial(\rho u_r)}{\partial t} + \frac{1}{r} \frac{\partial(r\rho u_r u_r)}{\partial r} + \frac{1}{r} \frac{\partial(r\rho u_\theta u_\theta)}{\partial \theta} + \frac{\partial(\rho u_r u_z)}{\partial z} = -\frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial(r\tau_{rr})}{\partial r} + \frac{1}{r} \frac{\partial\tau_{r\theta}}{\partial \theta} + \frac{\partial\tau_{rz}}{\partial z} - \frac{\rho u_\theta^2}{r} + F_r \quad (4)$$

Tangential Momentum (θ -direction):

$$\frac{\partial(\rho u_\theta)}{\partial t} + \frac{1}{r} \frac{\partial(r \rho u_\theta u_r)}{\partial r} + \frac{1}{r} \frac{\partial(\rho u_\theta u_\theta)}{\partial \theta} + \frac{\partial(\rho u_\theta u_z)}{\partial z} = -\frac{1}{r} \frac{\partial p}{\partial \theta} + \frac{1}{r^2} \frac{\partial(r^2 \tau_{r\theta})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{\theta\theta}}{\partial \theta} + \frac{\partial \tau_{\theta z}}{\partial z} + \frac{\rho u_r u_\theta}{r} + F_\theta \quad (5)$$

Axial Momentum (z-direction):

$$\frac{\partial(\rho u_z)}{\partial t} + \frac{1}{r} \frac{\partial(r \rho u_z u_r)}{\partial r} + \frac{1}{r} \frac{\partial(\rho u_z u_\theta)}{\partial \theta} + \frac{\partial(\rho u_z u_z)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{r} \frac{\partial(r \tau_{rz})}{\partial r} + \frac{1}{r} \frac{\partial \tau_{\theta z}}{\partial \theta} + \frac{\partial \tau_{zz}}{\partial z} + F_z \quad (6)$$

The DES formulation selects between RANS and LES according to the local grid resolution. For the $k - \omega$ SST DES model:

Turbulent Kinetic Energy (k) Equation

$$\frac{\partial(\rho k)}{\partial t} + \frac{1}{r} \frac{\partial(r \rho u_k)}{\partial r} + \frac{1}{r} \frac{\partial(\rho u_\theta k)}{\partial \theta} + \frac{\partial(\rho u_z k)}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left(r \left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial \theta} \right) + \frac{\partial}{\partial z} \left(r \left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial z} \right) + P_k - \rho \beta^* k \omega \quad (7)$$

Specific Dissipation Rate (ω) Equation

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{1}{r} \frac{\partial(r \rho u_\omega)}{\partial r} + \frac{1}{r} \frac{\partial(\rho u_\theta \omega)}{\partial \theta} + \frac{\partial(\rho u_z \omega)}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left(r \left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial \theta} \right) + \frac{\partial}{\partial z} \left(r \left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial z} \right) + \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + (1 - F_1) \frac{2\rho}{\sigma_{\omega 2}} \frac{1}{\omega} \nabla k \cdot \nabla \omega \quad (8)$$

where $\alpha, \beta, \beta^*, \sigma_k, \sigma_\omega$ are the model constants and F_1 is a blending function. The DES length scale L_{DES} determines the transition between RANS and LES:

$$L_{DES} = \min(L_{RANS}, C_{DES} \Delta)$$

where $L_{RANS} = \frac{\sqrt{k}}{\beta^* \omega}$ is the RANS length scale, C_{DES} is a constant (0.61 for the $k - \omega$ SST DES model), and Δ is the local grid spacing, defined as the maximum edge length of the grid cell.

2.2 Large Eddy Simulation

The LES formulation for a radial inlet in an SRM combustion chamber is based on the compressible Navier-Stokes equations filtered using Favre averaging to account for density variations typical of rocket-combustion environments. LES filters small-scale motion from the conservation equations, and the governing equations are obtained by applying a spatial filter to the Navier-Stokes equations in Fourier space. In ANSYS Fluent, the filtering operation is expressed as [18,32,33]:

$$G(x, x') = \begin{cases} \frac{1}{v}, & x \in v \\ 0, & x \notin v \end{cases} \quad (9)$$

where v represents the volume of a numerical cell. Favre averaging is used to simplify the compressible-flow equations by removing the triple correlation between velocity and density, as defined by:

$$\tilde{f} = \frac{(\rho_f)}{\bar{\rho}} \quad (10)$$

Neglecting multiphase effects and combustion kinetics, the filtered conservation equations are expressed as follows. The Favre-averaged mass-conservation equation is:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho} \tilde{u}_i}{\partial x_i} = 0 \quad (11)$$

$$\frac{\partial}{\partial t} (\bar{\rho} \tilde{u}_i) + \frac{\partial}{\partial x_j} (\bar{\rho} \tilde{u}_i \tilde{u}_j) = \frac{-\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} (\tilde{\sigma}_{ij} - \tau_{ij}) \quad (12)$$

$$\frac{\partial}{\partial t} (\bar{\rho} \tilde{e}) + \frac{\partial}{\partial x_i} (\bar{\rho} \tilde{u}_i \tilde{e}) = \frac{\partial}{\partial x_i} (\tilde{u}_i \sigma_{ij} - p \tilde{u}_i - \bar{q}_i - H_i^{sgs} - \sigma_i^{sgs}) \quad (13)$$

Here, $\bar{q}_i$ and $\tilde{\sigma}_{ij}$ represent the heat flux and molecular viscous-stress tensor, respectively, and are expressed as:

$$\tilde{\sigma}_{ij} = \mu \left[\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right] - \frac{2}{3} \mu \frac{\partial \tilde{u}_k}{\partial x_k} \delta_{ij} \quad (14)$$

$$\bar{q}_i = -\bar{k} \frac{\partial \tilde{T}}{\partial x_i} \quad (15)$$

The ideal-gas law is also applied:

$$p = \rho RT \quad (16)$$

The overall subgrid-scale stress tensor sgs is expressed as follows:

$$\tau_{ij} = 2\mu \left(\tilde{s}_{ij} - \frac{1}{3} \tilde{s}_{kk} \delta_{ij} \right) + \frac{2}{3} \bar{\rho} k^{sgs} \delta_{ij} \quad (17)$$

where the Favre-filtered strain-rate tensor is represented by S_{ij} .

$$\tilde{s}_{ij} = \frac{1}{2} \left[\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right] \quad (18)$$

The subgrid kinetic-energy model k^{sgs} and subgrid eddy viscosity μ_t are used to close the unresolved-scale stresses:

$$\mu_t = \bar{\rho} C_w^2 V^{2/3} \frac{(s_{ij}^d)^{3/2}}{(\tilde{s}_{ij} \tilde{s}_{ij})^{5/2} + (s_{ij}^d s_{ij}^d)^{5/4}} \quad (19)$$

With V denoting the average volume of a computational cell, s_{ij}^d is defined as:

$$s_{ij}^d = \frac{1}{2} \left(\frac{\partial \tilde{u}_i}{\partial x_k} \frac{\partial \tilde{u}_k}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_k} \frac{\partial \tilde{u}_k}{\partial x_i} \right) - \frac{1}{3} \frac{\partial \tilde{u}_k}{\partial x_k} \frac{\partial \tilde{u}_k}{\partial x_k} \delta_{ij} \quad (20)$$

Subgrid kinetic energy is

$$k^{sgs} = C_L V^{2/3} (\tilde{s}_{ij} \tilde{s}_{ij}) \quad (21)$$

The empirical constants and properties used in the models are $C_w = 0.325$, the dynamic coefficient for SGS eddy viscosity; $C_L = 0.094$, the coefficient in the SGS kinetic-energy model; $R = 287 J/kg$, the specific gas constant for air; μ , the dynamic viscosity, generally evaluated as a temperature-dependent quantity using Sutherland's law; and k , the thermal

conductivity. These equations are solved in ANSYS Fluent to simulate radial-inlet flow in SRMs and to

3. Computational Domain

3.1 Geometric Configuration

The present investigation uses the Anthoine cold-flow test case, which was designed to examine vortex-driven flow instability and the resulting pressure and thrust oscillations in a solid rocket motor chamber [34]. The computational domain is approximately 400 mm long. The cold-flow configuration and computational meshes are shown in Fig. 1. Gridgen was used to generate the computational domain and mesh.

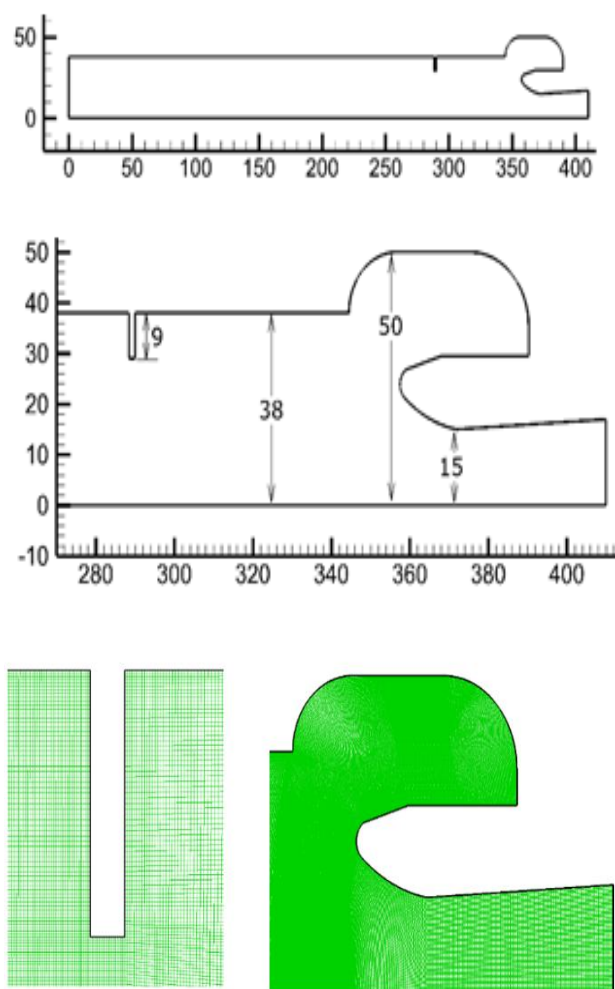


Fig. 1. Computational Domain Configuration and Meshes Near the Inhibitor and Nozzle

3.2 Boundary Conditions

The flow conditions from the Anthoine cold-flow experiment were applied as boundary conditions in ANSYS Fluent. The wall temperature was fixed at 285 K, and a no-slip condition was imposed. At the outlet, a pressure-outlet boundary condition with ambient static pressure was used to allow acoustic waves to leave the domain with minimal reflection. Pressure signals were recorded at two monitoring points, (0.0115, 0.038) and (0.366, 0.050), as shown in Fig. 2.

represent RANS- and LES-scale behavior as appropriate.

The signals were used to evaluate the frequencies and normalized amplitudes of pressure oscillations in the radial-inlet SRM chamber.

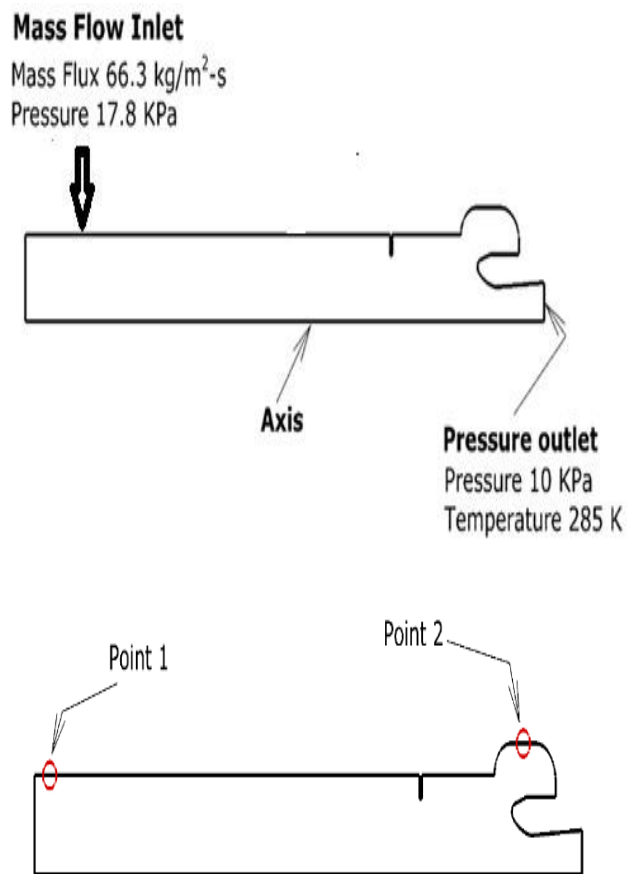


Fig. 2. Boundary Conditions and Monitoring Locations for the Cold-Flow Test Case Within the Combustion Chamber

4. Results and Discussion

This section presents the numerical results for vortex-driven flow instability in an SRM chamber with radial-inlet conditions. The same cold-flow configuration used in the investigations of Anthoine [34,35] and in the numerical study reported in [36] was adopted, except that the inlet boundary condition was changed from axial to radial, as shown in Fig. 2. This modification substantially alters the flow-field structure, shear-layer development, and vortex dynamics. Both URANS and SRS calculations were performed. The analysis focuses on pressure-oscillation frequencies and normalized amplitudes at the two monitoring points shown in Fig. 2.

4.1 Vortex Shedding and Flow Dynamics with Radial Inlet

Replacing the axial inlet with a radial inlet introduces a circumferential velocity component and increases tangential shear near the chamber walls. This

promotes earlier vortex roll-up around the inhibitor and increases vortex density in the central region of the chamber. Radial momentum injection also enhances the three-dimensional character of the flow. These modified vortex dynamics were captured effectively by the scale-resolving DES, IDDES, and LES models. By contrast, the URANS models averaged out small-scale fluctuations and could not **Table 1.**

Pressure Oscillation Frequencies at Point 1

Mode	Experimental	SRS				RANS			
		LES WALE	LES (SL)	DES	IDDES	SAS	k-omega	k-epsilon	SA
1st	408	375.8	367.03	384.6	378.02	386.8	389.01	10.8	371.4
2nd	874	760.4	815.4	756	767	775.8	780.2	65.9	749.5
3rd	1285	1211	1220	1229	1215	1163	1169	109.9	1209
4th	1744	1898	1563	1613	1589	1552	1558	162.6	1609

The present study evaluates the influence of a radial inlet, rather than the conventionally used axial inlet, on vortex shedding and pressure fluctuations in an SRM chamber. The chamber geometry and numerical methodology were retained from the earlier axial-inlet study [6], while the inlet direction was changed. Radial inflow generated circumferential shear layers and modified vortex roll-up near the inhibitor, thereby strengthening vortex-acoustic interaction. Pressure-time signals from the two monitoring points were analyzed using the FFT to identify dominant acoustic modes. At Point 1, the SRS predictions were close to **Table 2.**

Pressure Oscillation Frequencies at Point 2

Mode	Experimental	SRS				RANS			
		LES WALE	LES (SL)	DES	IDDES	SAS	k-omega	k-epsilon	SA
1st	411	461.5	525.2	384.6	378.02	386.8	389.01	10.9	487.9
2nd	874	942.9	707.7	756	767	775.8	780.2	59.34	749.5
3rd	1285	1134	1160	1211	1059	1163	1169	107.7	1209
4th	1883	1892	1563	1596	1589	1552	1558	162.6	1602

DES and IDDES produced moderately accurate frequency predictions but tended to underpredict the higher-frequency modes. At Point 1, the experimental normalized amplitude decreased monotonically from 0.5291 for the first mode to 0.0540 for the fourth mode. SRS reproduced this trend, with amplitudes of 0.6391, 0.2043, 0.1540, and 0.0421. Although the first mode was slightly overpredicted, the higher modes were represented well (Table 3). The RANS models

fully resolve the complex vortex interactions. The pressure-oscillation frequencies at Points 1 and 2 are central to the assessment of combustion instability because they represent the natural acoustic modes of the system. Experimental frequencies [34] were therefore compared with predictions from the SRS and RANS turbulence models.

the experimental values, particularly for the second and third modes, and the first four predicted frequencies showed good overall agreement with Table 1. The RANS-model predictions varied considerably. LES-WALE and LES-Smagorinsky-Lilly performed comparatively well for the first and third modes, whereas the SAS model substantially underpredicted the first mode. The same general trend was observed at Point 2, where SRS again outperformed the other approaches, as shown in Table 2.

generally overpredicted low-frequency amplitudes and underpredicted the higher modes. The FFT spectra of the Point 1 pressure signals obtained from the URANS and SRS models are shown in Fig. 3.

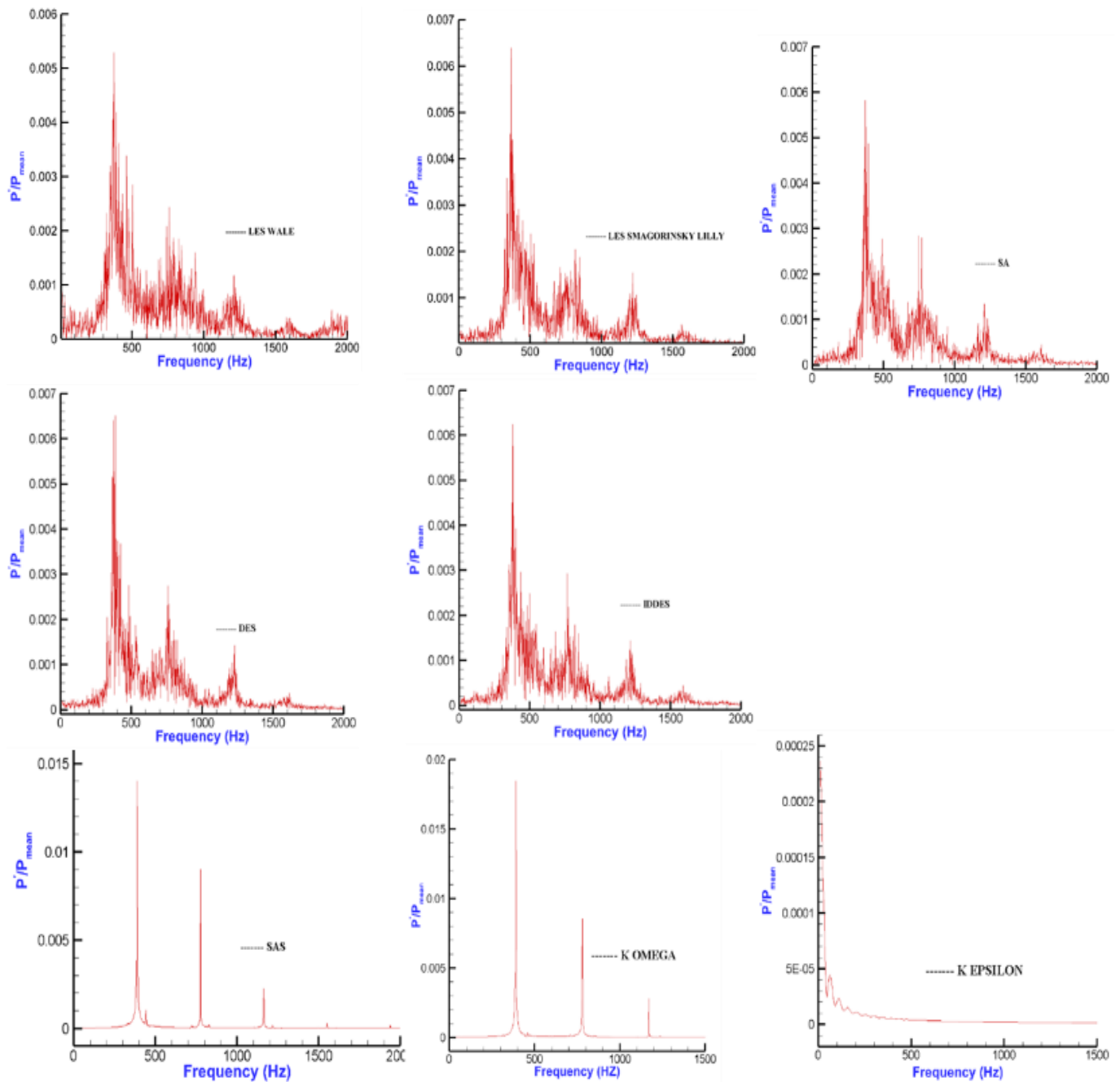


Fig. 3. FFT of the Pressure Time History at Point 1, Showing Dominant Acoustic Frequencies and Corresponding Oscillation Amplitudes Associated with Combustion Instability

A similar pattern was observed at Point 2. The SRS predictions followed the experimental trend closely, whereas the RANS models showed larger deviations (Table 4). LES-WALE and Smagorinsky-Lilly provided reasonable estimates for the first two modes

but were less consistent at higher modes. The SAS model substantially underestimated the first-mode amplitude. FFT spectra of the Point 2 pressure signals from the URANS and SRS calculations are shown in Fig. 4.

Table 3.
Normalized Oscillation Amplitudes at Point 1 (%)

Mode	Experimental	SRS				RANS			
		LES WALE	LES (SL)	DES	IDDES	SAS	k-omega	k-epsilon	SA
1st	0.0011	0.5291	0.6391	0.6509	0.6243	1.3998	1.8447	0.0236	0.5827
2nd	0.00094	0.2434	0.2043	0.2747	0.2936	0.9014	0.8536	0.0043	0.2847
3rd	0.00016	0.1178	0.154	0.1425	0.1432	0.2259	0.7281	0.0023	0.1348
4th	0.00008	0.0540	0.0421	0.037	0.0441	0.0302	0.0139	0.0014	0.0446

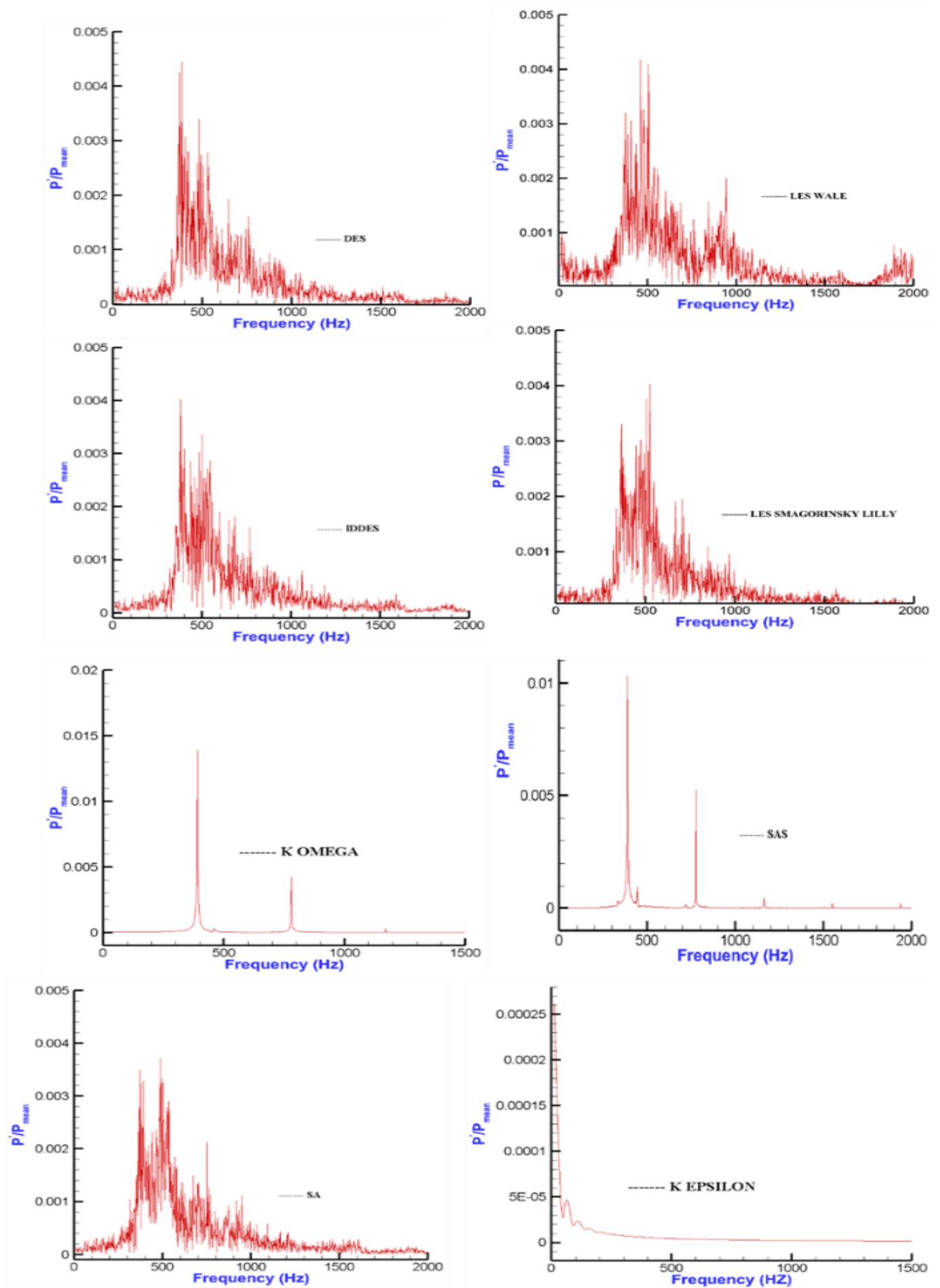


Fig. 4. FFT of the Pressure Time History at Point 2, Showing Dominant Acoustic Frequencies and Corresponding Oscillation Amplitudes Associated with Combustion Instability

Overall, SRS provided the most accurate representation of oscillation frequencies and normalized amplitudes under radial-inlet flow conditions. The LES-based scale-resolving models were acceptable at lower modes, although their performance deteriorated at higher frequencies. The SAS model consistently failed to reproduce both the frequency and amplitude of the pressure waves. These findings demonstrate the importance of advanced

turbulence modeling and the sensitivity of combustion-instability predictions to inlet configuration. The FFT results at Points 1 and 2 show that URANS simulations average out turbulent structures and do not capture flow acoustics accurately, whereas the SRS models resolve the dominant acoustic behavior. All four acoustic modes observed in the Anthoine cold-flow experiment were identified in the SRS results.

Table 4.
Normalized Oscillation Amplitudes at Point 2 (%)

Mode	Experimental	SRS				RANS			
		LES WALE	LES (SL)	DES	IDDES	SAS	k-omega	k-epsilon	SA
1st	0.00198	0.4178	0.4028	0.4439	0.4021	1.037	1.3894	0.0261	0.3713
2nd	0.00093	0.1992	0.1941	0.1608	0.1605	0.5239	0.4191	0.0045	0.2123
3rd	0.00016	0.0517	0.0406	0.0359	0.0793	0.0442	0.0288	0.0024	0.0413
4th	0.00036	0.0774	0.035	0.0251	0.035	0.0217	0.0256	0.0015	0.0279

4.2 Relative Error Comparison at Points 1 and 2

The relative-error results for Points 1 and 2 show that LES-WALE, DES, and IDDES generally produce lower errors and better agreement with the experimental data than the other models. LES-WALE provides the most reliable overall performance, particularly for the first and second modes. By

contrast, the $k - \varepsilon$ and $k - \omega$ models exhibit substantially larger errors, especially at the lower modes, and are therefore less suitable for predicting pressure-oscillation frequencies in this case. The comparison supports the use of scale-resolving methods rather than conventional RANS models for vortex-driven flow in SRM chambers. Relative frequency errors are listed in Tables 5 and 6.

Table 5.
Relative Errors in Frequency Predictions at Point 1 (%)

Mode	SRS				RANS			
	LES WALE	LES (SL)	DES	IDDES	SAS	k-omega	k-epsilon	SA
1st	7.89	10.04	5.71	7.34	5.19	4.65	97.35	8.97
2nd	12.9	6.70	13.5	12.24	11.23	10.73	92.45	14.24
3rd	5.75	5.05	4.35	5.44	9.49	9.02	91.44	5.91
4th	8.48	10.37	7.51	8.88	11.09	10.66	90.67	7.74

Table 6. Relative Errors in Frequency Predictions at Point 2 (%)

Mode	SRS				RANS			
	LES WALE	LES (SL)	DES	IDDES	SAS	k-omega	k-epsilon	SA
1st	12.28	27.78	6.41	8.02	5.88	5.35	97.34	18.71
2nd	7.88	19.02	13.50	12.24	11.23	10.73	93.21	14.24
3rd	11.75	9.72	5.75	17.58	9.49	9.02	91.61	5.91
4th	0.47	16.99	15.24	15.61	17.57	17.25	91.36	14.92

4.3 Flow Structure and Vortex Dynamics

The Z-vorticity contours demonstrate the influence of radial inflow on vortex evolution. DES and IDDES produced intensified radial-tangential vortex structures and captured early vortex formation. In contrast, the SAS and conventional URANS models

generated smoother, time-averaged fields that lacked the instantaneous shedding and convective-transport features. These results confirm the importance of scale-resolving methods for capturing the transient flow phenomena associated with combustion instability.

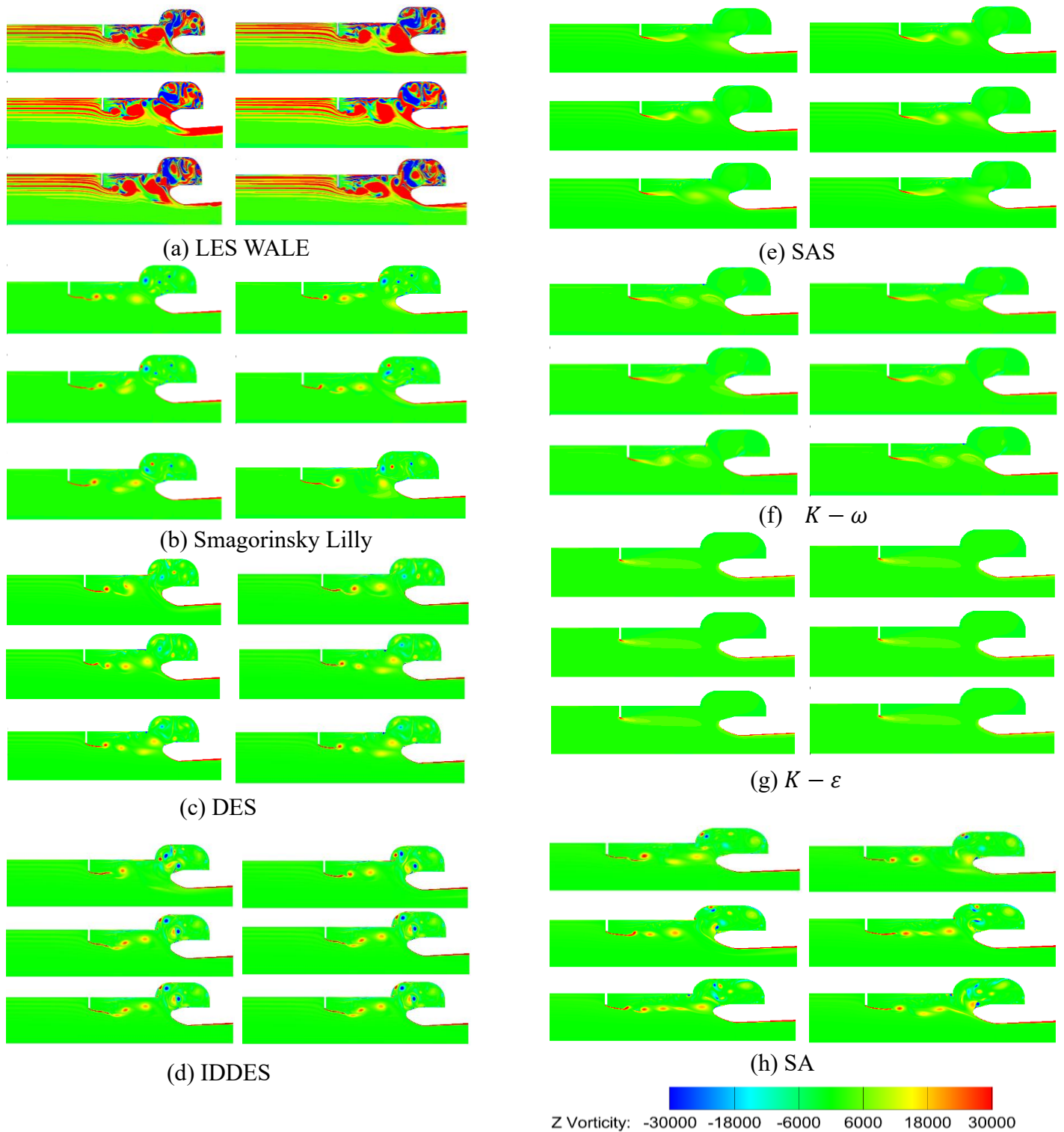


Fig. 5. Instantaneous Pressure and Z-Vorticity Contours for Different Models, Showing Variations in Vortex Structures and Pressure Fields

Conclusion

This study numerically examined the effects of radial inflow on vortex shedding and pressure oscillations in an SRM chamber using URANS and SRS models. The radial inlet generated strong shear layers near the injection location, promoted intense vortex formation, and strengthened vortex-acoustic interaction within the chamber. These interactions produced substantial variations in oscillation frequency and amplitude, particularly at the higher acoustic modes. Among the turbulence models evaluated, the SRS approaches (LES-WALE, LES-Smagorinsky-Lilly, DES, and

IDDES) were better able to resolve unsteady flow structures and both large- and small-scale turbulent features. The SAS model within the URANS framework substantially underpredicted oscillation frequencies and amplitudes, indicating its limitations for this class of flow. The results confirm the critical role of turbulence-model selection in predicting combustion instability and show that SRS methods are more appropriate for high-fidelity analysis of vortex-induced pressure oscillations under radial-inlet conditions. The study provides additional insight into SRM internal-flow physics and supports the use of

refined simulation methods for stability assessment and design optimization.

List of Abbreviations

Abbreviation	Full Form
SRM	Solid Rocket Motor
LES	Large Eddy Simulation
URANS	Unsteady Reynolds-Averaged Navier-Stokes
SRS	Scale-Resolving Simulation
FFT	Fast Fourier Transform
DES	Detached Eddy Simulation
IDDES	Improved Delayed Detached Eddy Simulation
SAS	Scale-Adaptive Simulation
SA	Spalart–Allmaras
CFD	Computational Fluid Dynamics
SGS	Subgrid Scale
AVBP	Advanced Burner Prediction (Solver)
OVS	Obstacle Vortex Shedding
SVS	Surface Vortex Shedding
AVS	Angle Vortex Shedding

List of Symbols

The following table lists the variables and symbols used in the governing equations, together with their corresponding units.

Symbol	Description	Unit
ρ	Density	kg/m ³
u, v, w	Velocity components (axial, radial, tangential)	m/s
p	Pressure	Pa
T	Temperature	K
t	Time	s
μ	Dynamic viscosity	Pa·s
k	Turbulent kinetic energy	m ² /s ²
ω	Specific dissipation rate	1/s
τ_{ij}	Viscous stress tensor	Pa
q	Heat flux	W/m ²
R	Gas constant	J/(kg·K)
Δ	Filter width/grid scale	m
f	Forcing frequency	Hz
S_{ij}	Strain rate tensor	1/s

References

- [1] C. Huo, H. Xu, J. Hu, and T. Luo, “Numerical Study on Pressure Oscillations in a Solid Rocket Motor with Backward Step Configuration Under Two-Phase Flow Interactions,” *Aerospace*, vol. 11, no. 12, 2024, doi: 10.3390/aerospace11121054.
- [2] R. S. Brown, R. Dunlap, S. W. Young, and R. C. Waugh, “Vortex shedding as a source of acoustic energy in segmented solid rockets,” *J. Spacecr. Rockets*, vol. 18, no. 4, pp. 312–319, 1981.
- [3] K. W. Dotson, S. Koshigoe, and K. K. Pace, “Vortex shedding in a large solid rocket motor without inhibitors at the segment interfaces,” *J. Propuls. Power*, vol. 13, no. 2, pp. 197–206, 1997, doi: 10.2514/2.5170.
- [4] G. Xu, B. Wang, B. Jin, Z. Wang, and P. Liu, “Numerical study of triggered thermoacoustic instability driven by linear and nonlinear combustion response in a solid rocket motor,” *Phys. Fluids*, vol. 36, no. 3, 2024.
- [5] I. Ahmed Bhutto, I. Khan, M. Furqan, A. H. Alzahrani, A. A. Bhutto, and A. Singh, “Wall film cooling mechanism in liquid fuel combustion chamber containing gaseous hydrogen,” *Int. J. Hydrogen Energy*, vol. 52, no. September, pp. 246–255, 2024, doi: 10.1016/j.ijhydene.2023.06.332.
- [6] A. A. Bhutto, K. Harijan, M. Hussain, S. F. Shah, and L. Kumar, “Numerical Simulation of Transient Combustion and the Acoustic Environment of Obstacle Vortex-Driven Flow,” *Energies* 2022, Vol. 15, Page 6079, vol. 15, no. 16, p. 6079, Aug. 2022, doi: 10.3390/EN15166079.
- [7] A. A. Bhutto, S. F. Shah, R. B. Khokhar, K. Harijan, and M. Hussain, “To Investigate Obstacle Configuration Effect on Vortex Driven Combustion Instability,” pp. 67–83, 2023.
- [8] F. E. C. Culick and K. Magiawala, “Excitation of acoustic modes in a chamber by vortex shedding,” *J. Sound Vib.*, vol. 64, no. 3, pp. 455–457, 1979.
- [9] R. B. Khokhar, A. A. Bhutto, I. A. Bhutto, F. Shaikh, K. N. Memon, and P. Kumar, “A numerical analysis of mixing and separating of Newtonian fluids in a channel filled with porous material,” *Mehran Univ. Res. J. Eng. Technol.*, vol. 43, no. 2, p. 46, 2024, doi: 10.22581/muet1982.2955.
- [10] K. Volkov, “Simulation of particulate flows in combustion chambers of solid rocket motors with a multiscale model,” *Acta Astronaut.*, vol. 238, no. PA, pp. 1342–1353, 2026, doi: 10.1016/j.actaastro.2025.07.039.
- [11] H. Xu, J. Hu, C. Huo, Y. He, and P. Liu, “Impact of the head cavity and submerged nozzle on corner vortices and pressure oscillations in a solid rocket motor with a backward-facing step,” *Def. Technol.*, 2025.
- [12] Y. Xi, J. Gao, Z. Wu, B. Zhang, L. Yang, and J. Xia, “Pressure oscillation and suppression method of large-aspect-ratio solid rocket

- motors,” *Chinese J. Aeronaut.*, vol. 38, no. 4, p. 103275, 2025, doi: 10.1016/j.cja.2024.10.007.
- [13] G. I. Taylor, “Fluid flow in regions bounded by porous surfaces,” *Proc. R. Soc. London. Ser. A. Math. Phys. Sci.*, vol. 234, no. 1199, pp. 456–475, 1956.
- [14] F. Vuillot, “Vortex-Shedding Phenomena in Solid Rocket Motors,” vol. 11, no. 4, pp. 626–639, 1995.
- [15] M. Bernardini *et al.*, “Large-eddy simulation of vortex shedding and pressure oscillations in solid rocket motors,” *J. AIAA*, vol. 58, no. 12, pp. 5191–5201, 2020.
- [16] S. Scippa, P. Pascal, and F. Zanier, “Ariane 5-MPS - Chamber pressure oscillations full scale firing results: Analysis and further studies,” 1994, doi: 10.2514/6.1994-3068.
- [17] Q. Zhang, Z. Wei, W. Su, J. Li, and N. Wang, “Theoretical modeling and numerical study for thrust-oscillation characteristics in solid rocket motors,” *J. Propuls. Power*, vol. 28, no. 2, pp. 312–322, 2012.
- [18] Q. Zhang, N. F. Wang, J. W. Li, W. X. Su, and Y. Zhang, “Effect of the head cavity on pressure oscillation suppression characteristics in large solid rocket motors,” *Sci. China Technol. Sci.*, vol. 58, no. 7, pp. 1250–1262, 2015, doi: 10.1007/s11431-015-5834-z.
- [19] A. Powell, “Theory of vortex sound,” *J. Acoust. Soc. Am.*, vol. 36, no. 1, pp. 177–195, 1964.
- [20] M. S. HOWE, “Contributions To the Theory of Aerodynamic Sound, With Application To Excess Jet Noise and the Theory of the Flute,” vol. 71, no. (OCTOBER 28, 1975), 1975.
- [21] R. Dunlap and R. S. Brown, “Exploratory experiments on acoustic oscillations driven by periodic vortex shedding,” *AIAA J.*, vol. 19, no. 3, pp. 408–409, 1981, doi: 10.2514/3.7783.
- [22] G. Flandro and H. Jacobs, “Vortex generated sound in cavities,” in *Aeroacoustics Conference*, 1973, p. 1014.
- [23] A. Flatau and W. K. Van Moerhem, “Vortex shedding induced sound inside a cold-flow simulation of a segmented chamber,” *J. Propuls. Power*, vol. 19, no. 2, pp. 287–296, 2003.
- [24] A. Kourta, “Computation of Vortex Shedding in Solid Rocket Motors Using Time-Dependent Turbulence Model,” vol. 15, no. 3, 1999.
- [25] R. Dunlap, A. M. Blackner, R. C. Waugh, R. S. Brown, and P. G. Willoughby, “Internal flow field studies in a simulated cylindrical port rocket chamber,” *J. Propuls. Power*, vol. 6, no. 6, pp. 690–704, 1990, doi: 10.2514/3.23274.
- [26] W. Li, Y. Wang, L. Zhang, and B. Gao, “Simulation Analysis on the Characteristics of Aerosol Particles to Inhibit the Infrared Radiation of Exhaust Plumes,” 2024.
- [27] A. Wang *et al.*, “Computational Fluid Dynamics Simulation of Combustion Efficiency for Full-Size Upstream Flare Experiments,” 2024.
- [28] G. Xu, P. Liu, W. Ao, Z. Wang, and B. Jin, “Numerical investigation of thermoacoustic instability caused by small disturbance in a solid rocket motor,” *Aerosp. Sci. Technol.*, vol. 113, p. 106678, 2021, doi: 10.1016/j.ast.2021.106678.
- [29] W. Su, S. Li, Q. Zhang, J. Li, Q. Ye, and N. Wang, “Influence of thermal inhibitor position and temperature on vortex-shedding-driven pressure oscillations,” *Chinese J. Aeronaut.*, vol. 26, no. 3, pp. 544–553, 2013.
- [30] K. G. Stevens, V. L. Peterson, and P. Kutler, “Introduction to Computational Fluid Dynamics,” *Handb. Fluid Dyn. Fluid Mach. Exp. Comput. Fluid Dyn.*, vol. 2, pp. 1191–1214, 1996.
- [31] F. M. L. M. M. Darwish, *The finite volume method in computational fluid dynamics*. 2016.
- [32] D. Wang, Y. Yang, W. Fan, X. Li, and Y. Gao, “Simulation of pressure oscillations in a combustion chamber under periodic inlet disturbances,” *Acta Astronaut.*, vol. 152, pp. 859–871, 2018.
- [33] B. Chaouat, “The State of the Art of Hybrid RANS/LES Modeling for the Simulation of Turbulent Flows,” *Flow, Turbul. Combust.*, vol. 99, no. 2, pp. 279–327, 2017, doi: 10.1007/s10494-017-9828-8.
- [34] J. Anthoine, “Experimental and Numerical Study of Aeroacoustic Phenomena in Large Solid Propellant Boosters,” *Sci. York*, no. September, 2000.
- [35] J. Anthoine, J. M. Buchlin, and J. F. Guéry, “Effect of nozzle cavity on resonance in large SRM: Numerical simulations,” *J. Propuls. Power*, vol. 19, no. 3, pp. 374–384, 2003.
- [36] M. Hussain, S. Jamshed, and M. Ozair, “Simulations and analysis of vortex-driven combustion instability,” in *2022 19th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, IEEE, 2022, pp. 765–770.