International Journal of Scientific Research & Engineering Trends
Volume 9, Issue 6, Nov-Dec-2023, ISSN (Online): 2395-566X

Large Eddy Simulation for Smoke Management: A Review of Subgrid-Scale Modeling and Fire Safety Applications (1950–2022)

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Abstract — This study experimentally investigates the cyclic dynamic performance of Basalt Textile Reinforced Mortar (BTRM)-strengthened and unstrengthened masonry hydraulic piers under dry and wet conditions. Six specimens, comprising three control and three BTRM-strengthened piers, were tested using a shaking-table setup under progressively increasing harmonic excitation. The primary objective was to compare the number of loading cycles sustained until failure and examine the associated failure mechanisms. The results demonstrated that BTRM strengthening substantially increased the cyclic endurance of the masonry piers compared with the unstrengthened controls. The control specimens experienced severe damage after relatively few loading cycles, whereas the strengthened specimens sustained considerably more cycles before failure. The observed failure of the strengthened specimens involved basalt textile rupture and internal separation of masonry units. The dry and wet specimens were also compared to examine the influence of water exposure on cyclic performance. The findings demonstrate the potential of BTRM strengthening to improve the resistance of masonry hydraulic piers to repeated dynamic loading.

Keywords- Masonry hydraulic piers; BTRM; Cyclic dynamic loading; Shaking-table testing; Failure mechanisms.

I. INTRODUCTION

Smoke management is the branch of fire safety engineering concerned with controlling the move-ment and accumulation of combustion products in the built environment. The majority of fire fatalities result from smoke inhalation rather than thermal injury, and the tenability of evacua-tion routes depends critically on the height, temperature, and toxicity of the smoke layer. Design

decisions regarding exhaust vent placement, makeup air distribution, and smoke reservoir sizing have traditionally relied on empirical correlations and zone models, but the past three decades have seen computational fluid dynamics—and LES in particular—become an accepted tool for performance-based design.

The appeal of LES for smoke management is structural. Fire-driven flows are intrinsically transient, buoyancy-dominated, and characterized by large coherent structures—plumes, ceiling jets, and stratified layers—whose dynamics determine smoke spread. Reynolds-averaged ap-proaches, which average over all turbulent scales, struggle with the unsteady and anisotropic nature of these flows. LES resolves the large eddies directly and models only the small scales, aligning computational effort with the physically significant structures.

Yet the SGS models used in smoke management LES are, almost without exception, bor-rowed from isothermal turbulence research. The Smagorinsky model, developed for atmospheric boundary layers in 1963, remains the default closure in the Fire Dynamics Simulator (FDS), the most widely used fire-specific LES code. This raises a question that has shadowed the field for decades: are the classical SGS closures adequate for buoyancy-driven flows with combustion and radiation? This review examines the development of LES SGS modeling from its origins through 2022, with a deliberate focus on how these models have been applied—and adapted, or not adapted—to smoke management problems.

The scope of the review is delimited as follows. Section 2 presents the mathematical formu-lation of the LES filtering and the closure problem. Section 3 treats the Smagorinsky model and its fire-specific calibration. Section 4 covers the dynamic procedure and its fire applications. Section 5 addresses buoyancy-specific SGS challenges. Section 6 examines operational prac-tice (FDS and coupled physics). Section 7 synthesizes the established findings, and Section 8 concludes.

II. MATHEMATICAL FORMULATION AND THE CLOSURE PROBLEM

1. Spatial Filtering

LES begins with the application of a low-pass spatial filter to the Navier–Stokes equations. For a generic flow variable ϕ, the filtered field is defined as

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$$\bar{\phi}(\mathbf{x}, t) = \int_{\Omega} G(\mathbf{x} - \mathbf{x}'; \Delta)\, \phi(\mathbf{x}', t)\, d\mathbf{x}', \tag{1}$$

where G is the filter kernel and Δ is the filter width. Common kernels include the top-hat (box), Gaussian, and spectral cutoff filters. For constant filter width in homogeneous directions, filtering commutes with differentiation, yielding the filtered continuity and momentum equations:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \tag{2}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\bar{u}_i \bar{u}_j) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j}. \tag{3}$$

The closure problem resides entirely in the SGS stress tensor:

$$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j. \tag{4}$$

This term represents momentum transport by scales smaller than Δ and must be modeled in terms of the resolved field. The fundamental difficulty is that τij is not a function of the filtered velocity alone but depends on the full unfiltered field, which is unavailable. The filtering concept and its schematic consequences are illustrated in Figure 1.

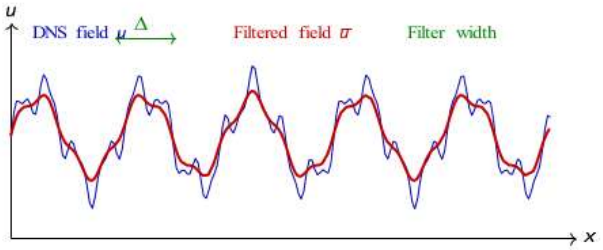


Figure 1: Schematic of spatial filtering in LES. The high-frequency content of the DNS field (blue) is removed by the low-pass filter, yielding the resolved field (red) that is advanced nu-merically; the effect of the removed scales is collected in the SGS stress tensor τij.

2.2 The Closure Problem

Equation (4) is unclosed because the product of filtered velocities is not the filtered product of velocities. The SGS stress may be decomposed into three parts:

$$\tau_{ij} = \underbrace{\bar{\bar{u}}_i \bar{\bar{u}}_j - \bar{u}_i \bar{u}_j}_{\text{Leonard}} + \underbrace{\overline{\bar{u}_i u_j'} + \overline{u_i' \bar{u}_j}}_{\text{cross}} + \underbrace{\overline{u_i' u_j'}}_{\text{Reynolds}} \tag{5}$$

where u′ = ui − ui is the subgrid fluctuation. The Leonard term is computable from the resolved field, but the cross and Reynolds terms require modeling. The three families of SGS models developed over the review period—eddy viscosity, scale similarity, and deconvolution—differ in how they approximate these terms. Figure 2 maps the principal model families and their historical development.

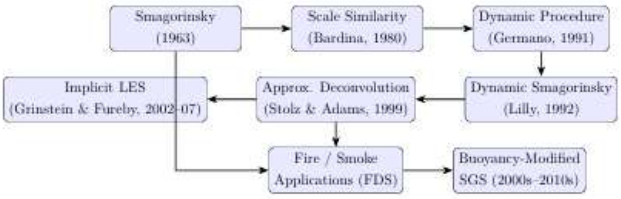


Figure 2: Development map of LES SGS model families from 1963 to the 2010s. Arrows indicate conceptual influence rather than strict chronological succession. The operational fire community adopted the Smagorinsky line directly, largely bypassing the dynamic and structural branches.

2.3 The Energy Cascade and Filter-Width Dependence

The physical justification for LES rests on the energy cascade. The resolved-scale kinetic energy
Er = 1 uiui obeys a transport equation containing the SGS dissipation

$$\varepsilon_{sgs} = -\tau_{ij}\bar{S}_{ij}, \tag{6}$$

where Sij = 1 (∂ui/∂xj + ∂uj/∂xi) is the resolved strain-rate tensor. A well-behaved SGS model must produce εsgs ≥ 0 on average (forward cascade) while permitting local backscatter (εsgs < 0). Eddy-viscosity models guarantee the first but forbid the second; this trade-off is the recurring theme of the review. Figure 3 illustrates the cascade and the filter-width location.

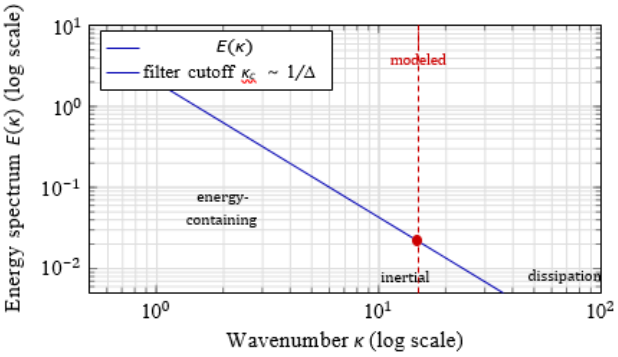


Figure 3: Schematic energy spectrum with the LES filter cutoff. Scales to the left of κc are resolved; scales to the right are modeled by the SGS closure. The − 5 inertial slope is indicated.

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III. THE SMAGORINSKY MODEL AND ITS FIRE-SPECIFIC CALIBRATION

1. Historical Origins

Smagorinsky's 1963 formulation introduced the eddy-viscosity closure that remains the concep-tual foundation for most operational LES. The model expresses the deviatoric SGS stress as proportional to the resolved strain-rate tensor:

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\nu_t S_{ij} = -2(C_s\Delta)^2 |S|S_{ij} \quad (7)$$

where C s is the Smagorinsky constant, Δ is the filter width (typically the grid spacing), and
|S| = √2SijSij. The model is computationally efficient and robust, properties that explain its
persistence in engineering practice. Its deficiencies are equally well known: Cs is not universal, the model cannot represent backscatter, and it does not vanish at solid boundaries or in laminar regions without ad hoc damping.

The original meteorological context is instructive. Smagorinsky sought to parameterize the dissipation of the general circulation by unresolved eddies, and the constant Cs ≈ 0.17 was calibrated against atmospheric observations. The transfer of this constant to engineering and fire flows was never rigorously justified; it persists by convention and by the empirical observation that bulk predictions are relatively insensitive to its precise value.

2. Calibration for Smoke Management Flows

The question of what value of Cs to use in fire applications has received direct attention. A field-scale study of smoke exhaust in a large irregular hall (40 m × 11 m × 28 m) under a 2 MW methanol pool fire systematically varied the Smagorinsky constant from 0.1 to 0.22 using FDS. The predicted smoke layer interface height was compared against field measurements. The key result was that varying Cs within this range did not significantly affect the predicted smoke layer height. The authors recommended Cs = 0.20 as reasonable for simulating smoke movement and control in large halls with irregular shapes.

Figure 4 reproduces the qualitative trend of this parametric study, showing the normalized smoke layer interface height z/H against Cs for several grid resolutions. The curves are flat within the measured uncertainty, which is the empirical basis for the operational convention.

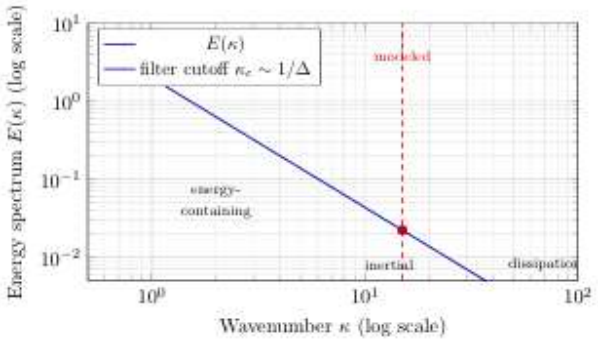


Figure 4: Qualitative reproduction of the Cs sensitivity study for smoke exhaust in a large irregular hall. Predicted normalized smoke layer height is essentially flat across Cs = 0.10–0.22 for each grid, within the experimental uncertainty. Based on the trends reported by Chow and Li (2013).

This finding is significant for practice: it suggests that for bulk smoke transport predictions—the primary quantity of interest in smoke management design—the precise value of the SGS coef-ficient is a second-order concern compared to grid resolution and boundary conditions. However, the same study acknowledged the broader validation gap in the field: "there are not much vali-dation studies on simulating smoke movement by those Computational Fluid Dynamics (CFD) fire models." This observation reflects a persistent characteristic of the smoke management literature, where model application has outpaced systematic SGS validation.

3. Known Deficiencies in Buoyant Flows

Three deficiencies of the Smagorinsky model are especially relevant to smoke management:

- No backscatter. Because νt ≥ 0, the model dissipates energy at all resolved scales; the reverse cascade observed at plume edges and in stratified interfaces is suppressed.
- Isotropic eddy viscosity. The scalar νt cannot represent the anisotropy of SGS stresses in vertical buoyant plumes, where streamwise and cross-stream transport differ fundamentally.
- Fixed coefficient. Cs does not adapt to local flow state (laminarization, relaminarization, strong stratification), requiring wall damping or ad hoc clipping.

These deficiencies motivated the dynamic procedure, treated next.

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IV. THE DYNAMIC PROCEDURE AND ITS FIRE APPLICATIONS

1. Germano Identity and Dynamic Smagorinsky

The most significant theoretical advance in LES SGS modeling during the review period was the dynamic procedure introduced by Germano, Piomelli, Moin, and Cabot in 1991. The method addresses the fundamental weakness of the Smagorinsky model—the assumption of a universal, flow-independent coefficient—by computing Cs from the resolved scales themselves. An algebraic
identity relating the SGS stresses at two filter levels (the grid filter Δ and a test filter Δˆ > Δ) yields the resolved turbulent stress (the Germano identity):

$$L_{ij} = \hat{\bar{u}}_i\hat{\bar{u}}_j - \hat{\bar{u}}_i\hat{\bar{u}}_j = T_{ij} - \hat{\tau}_{ij} \quad (8)$$

where Tij is the SGS stress at the test-filter level. Substituting the Smagorinsky form at both levels gives

$$L_{ij} - \frac{1}{3}L_{kk}\delta_{ij} = -2C_s^2\Delta^2\left(\alpha|\hat{\bar{S}}|\hat{\bar{S}}_{ij} - \hat{|\bar{S}|\bar{S}}_{ij}\right), \quad (9)$$

with α = (Δˆ /Δ)2. The dynamic coefficient is obtained by least-squares minimization of the error between Lij and the model prediction, yielding

$$C_s^2 = \frac{\langle L_{ij}M_{ij}\rangle}{\langle M_{kl}M_{kl}\rangle} \quad (10)$$

where Mij = −2Δ2(α|Sˆ|Sˆij − |ˆS|Sij) and ⟨·⟩ denotes averaging over homogeneous directions (Lilly's 1992 formulation). The resulting model vanishes in laminar flow and at solid boundaries, and exhibits correct asymptotic near-wall behavior. These properties are precisely those needed for buoyancy-driven flows, where laminarization and wall interactions are common. Figure 5 summarizes the dynamic-procedure workflow.

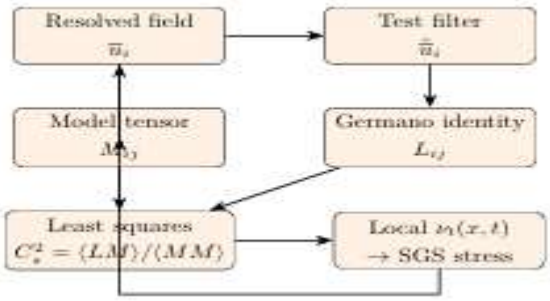


Figure 5: Workflow of the dynamic procedure. The resolved field is filtered at a test level; the Germano identity provides the resolved turbulent stress, which is matched to the model tensor to compute a local, time-dependent coefficient. The loop indicates the per-timestep nature of the procedure.

2. Adoption in Fire Research

Despite its theoretical advantages, the dynamic model's penetration into smoke management practice has been limited. A review of fire-specific CFD modeling from the University of Edin-burgh noted that "dynamic sub-grid models are beginning to appear in the fire literature but are still ongoing research and have never been validated." The operational fire simulation community has largely retained the Smagorinsky model, for reasons that are partly practical (implementa- tion simplicity, computational cost) and partly epistemological (the absence of validation data that would demonstrate dynamic-model superiority for smoke transport quantities).

A review of computational models for turbulent thermal plumes—the fundamental flow struc-ture in smoke transport—concluded that "dynamic subgrid-scale models perform fairly well in predicting the statistics of turbulent buoyant plume." However, the same review identified a critical limitation shared by all eddy-viscosity models: "no subgrid-scale model has been able to capture the inverse energy cascade, called backscatter, which is an important phenomenon in the evolution of a plume." Backscatter—the transfer of energy from small to large scales—is particularly relevant in buoyant flows, where plume-edge instabilities and large-scale coherent structures can derive energy from smaller-scale motions. The inability of standard eddy-viscosity closures to represent this physics remains an open deficiency for smoke management applications.
Figure 6 contrasts the forward-cascade behavior enforced by eddy-viscosity models with the mixed forward/backward transfer observed in buoyant plumes.

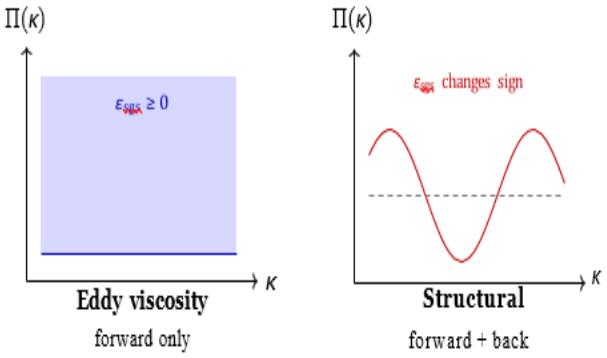


Figure 6: Schematic of spectral energy flux Π(κ) across the filter cutoff. Eddy-viscosity clo-sures enforce a strictly forward flux (left); structural and scale-similarity closures permit local backscatter (right), which is physically important at buoyant plume edges.

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3. Practical Obstacles

The dynamic procedure is not without practical difficulties, which partly explain its limited adoption in fire engineering:

- Averaging direction. In complex geometries (atria, tunnels with obstacles), homogeneous directions for $\langle\cdot\rangle$ may not exist, requiring local averaging or Lagrangian formulations.
- Coefficient clipping. The dynamic coefficient can become negative or unbounded; clip-ping to $\nu_t \geq 0$ (and often an upper bound) reintroduces the no-backscatter restriction the procedure was meant to relax.
- Cost. Test filtering and the additional tensor contractions increase per-timestep cost by a factor of order unity, which is non-negligible for large smoke management meshes (106–107 cells).

V. BUOYANCY-SPECIFIC SGS CHALLENGES

1. The Smagorinsky Model in Vertical Fire Flows

Direct evidence of the Smagorinsky model's limitations in fire-driven flows comes from validation studies of buoyant turbulent diffusion flames. Wang and Joulain (2005) applied LES with the standard Smagorinsky SGS model to pool-like, vertical, and interacting wall fires. The model successfully predicted the highly oscillating, buoyancy-controlled pool fire behavior, including recirculation zones and flame narrowing/broadening. However, for vertical wall fires, the authors concluded that "the standard Smagorinsky sub-grid scale model should be improved to predict the variation of the fluctuating velocity and temperature." This is a direct indication that the isotropic eddy-viscosity assumption—which underlies the Smagorinsky model—is insufficient when buoyancy production is strongly anisotropic, as in vertical fire plumes. Figure 7 contrasts the resolved plume structure that LES captures with the SGS region that the model must represent.

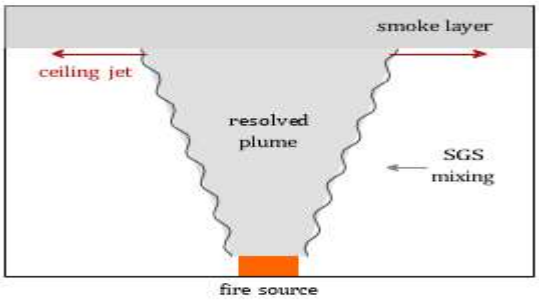


Figure 7: Schematic of a fire plume in a compartment. The large plume column, ceiling jet, and smoke layer are resolved by LES; the small-scale entrainment and mixing at the plume edges (indicated by the SGS arrow) are modeled. The anisotropy of these SGS motions in vertical buoyant flows is the principal deficiency of isotropic eddy-viscosity closures.

2. Buoyancy-Modified Closures

Several modifications attempt to account for buoyancy in the SGS closure. The most common introduces a buoyancy production term in the SGS kinetic energy equation, leading to eddy viscosities of the form

$$\nu_t = C_s \Delta \sqrt{k_{sgs}} \qquad k_{sgs} = \frac{1}{2}\left(\overline{u_i u_i} - \overline{u}_i \overline{u}_i\right), \tag{11}$$

with a transport equation for ksgs containing shear and buoyancy production,

$$\frac{\partial k_{sgs}}{\partial t} + \cdots \frac{\partial k_{sgs}}{\partial x_i} = \cdots \frac{a}{\rho_0} \nu_{t,h} \frac{\partial \theta}{\partial x_3} - C_\varepsilon \frac{k_{sgs}^{3/2}}{\Delta}. \tag{12}$$

Here $\nu_{t,h}$ is the SGS thermal diffusivity and the second term on the right is the buoyancy pro-duction. When buoyancy production is positive (unstable stratification, as in a rising plume),

ksgs grows and ν_t increases; when negative (stable stratification, as in the smoke layer), it de-creases. This dynamic response to stratification is absent from the standard Smagorinsky model and is the principal reason buoyancy-modified closures have been explored. Their adoption in operational smoke management, however, remains limited by calibration and validation gaps.

3. Grid Resolution and SGS Assumptions

The interaction between grid resolution and SGS model validity has been examined through quantitative saltwater modeling of buoyant plumes. Maisto et al. (2015) used scaled plume experiments to determine the resolution threshold below which LES subgrid mixing assumptions lose fidelity. They identified a characteristic length scale $D*$ and found that "there is a loss of fidelity in resolving the flow for a cell size above $0.54D*$." This finding has direct implications for smoke management simulations: when grid cells near the fire exceed this threshold, the SGS model must compensate for unresolved buoyant mixing that it was not calibrated to represent. In practice, many smoke management simulations use coarse grids in regions away from the fire for computational economy, relying on the SGS model to account for unresolved transport. The saltwater experiments suggest that this reliance may be more precarious than commonly assumed. Figure 8 summarizes the resolution-fidelity relationship.

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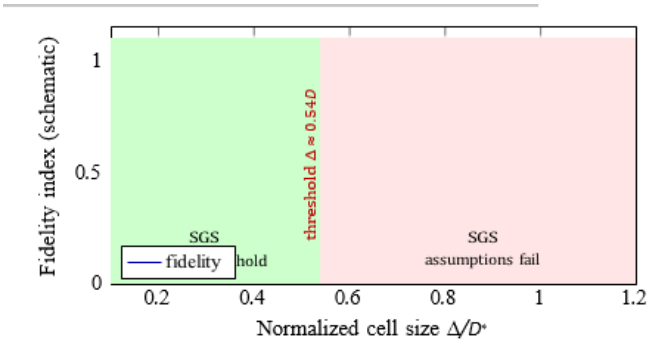


Figure 8: Schematic of the resolution–fidelity relationship for buoyant plumes, based on the saltwater experiments of Maisto et al. (2015). Below the threshold $\Delta \approx 0.54D*$, LES SGS mixing assumptions retain fidelity; above it, subgrid buoyant transport is unresolved and the SGS model is asked to represent physics for which it was not calibrated.

VI OPERATIONAL PRACTICE: FDS AND THE SMAGORINSKY DEFAULT

1. The Fire Dynamics Simulator

The Fire Dynamics Simulator, developed at the National Institute of Standards and Technology (NIST), is the most widely used LES code for smoke management applications. FDS solves the low-Mach-number, thermally driven Navier–Stokes equations with a Smagorinsky SGS model. Its documentation and validation history are extensive; a 2007 validation study by Coyle and Novozhilov examined FDS predictions for smoke filling, mechanical extraction, and smoke move-ment across room, hanger, atrium, and corridor scenarios.

The choice of Smagorinsky in FDS is pragmatic. The model's dissipation characteristics pro-vide numerical stability for the sharp density gradients and strong buoyancy forces characteristic of fire flows. The fixed coefficient eliminates the computational overhead and potential instability of dynamic procedures. For the bulk smoke transport predictions that dominate smoke manage-ment design—layer height, temperature stratification, exhaust volumetric requirements—this approach has proven adequate, as evidenced by the parametric insensitivity reported by Chow and Li. Figure 9 shows the coupled modeling chain in a typical FDS smoke management simu-lation.

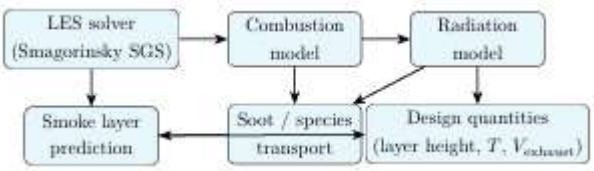


Figure 9: Coupled modeling chain in a typical FDS smoke management simulation. The SGS turbulence model (left) is one component of a system that includes combustion, radiation, and soot transport; uncertainties in the latter can dominate those attributable to the SGS closure.

2. The Radiation–Combustion–SGS Coupling

A distinctive feature of smoke management LES is that the SGS turbulence model is but one component of a coupled system that includes combustion, radiation, and soot modeling. Guid-ance from the Smoke Control Association emphasizes that "any radiation model can be combined with any combustion model" but notes that the choice of radiation approach has significant accu-racy and cost implications. The discrete transfer and Monte Carlo radiation models offer higher fidelity at greater computational expense, while the six-flux model is applicable to structured meshes but directionally limited. In this context, refinements to the SGS turbulence closure may yield diminishing returns if the radiation or combustion model introduces larger uncertainties. This systems-level perspective helps explain the field's tolerance of the Smagorinsky model's known deficiencies. Table 1 summarizes the principal SGS models, their key references, and their status in smoke management practice as of 2022.

Table 1: Principal LES SGS models and their status in smoke management practice (through 2022).

Model family	Key reference	Backscatter	Status in smoke management
Smagorinsky	Smagorinsky (1963)	No	Default in FDS and most operational tools; robust, coefficient-insensitive for bulk quantities
Dynamic Smagorinsky	Germano et al. (1991); Lilly (1992)	Limited (clipped)	Research use; limited fire validation; cost and averaging obstacles
Scale similarity	Bardina (1980)	Yes	Mixed models in research; not operational
Approx. deconvolution	Stolz & Adams (1999)	Yes	Research; limited fire application
Implicit LES	Grinstein & Fureby (2002–07)	Numerical	Emerging; numerical dissipation substitutes for explicit model
Buoyancy-modified k_{sgs}	Various (2000s)	Partial	Research; calibration gaps

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First, the Smagorinsky model remains the operational standard. Despite decades of theoretical development, the fire engineering community has not adopted dynamic or structural SGS models at scale. The reasons are partly economic (simplicity, stability) and partly empir-ical (adequate performance for design quantities). Figure 10 contrasts research activity with operational adoption across model families.

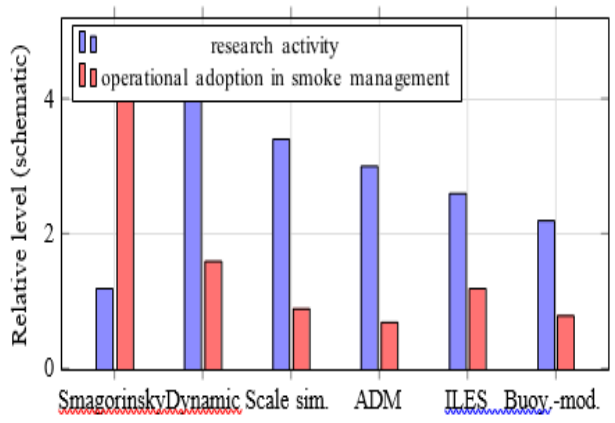


Figure 10: Schematic contrast between research activity and operational adoption in smoke man-agement. The Smagorinsky model dominates practice despite comparatively modest research attention; the dynamic procedure attracts substantial research but limited adoption. Levels are schematic and intended to convey relative magnitudes only.

Second, SGS coefficient sensitivity is modest for bulk smoke quantities. The Chow and Li study demonstrated that Cs variations from 0.1 to 0.22 produce negligible differences in predicted smoke layer height for a large hall fire. This supports the continued use of conventional values, though the generality of this finding across geometries and fire scales remains untested.

Third, the isotropic eddy-viscosity assumption is strained in strongly buoyant ver-tical flows. Wang and Joulain's finding that the Smagorinsky model requires improvement for vertical wall fires points to a fundamental limitation that no amount of coefficient tuning can resolve. The model's inability to represent backscatter, confirmed in the thermal plume review, is a structural deficiency for buoyancy-dominated flows.

Fourth, grid resolution interacts with SGS model validity in ways that are not fully characterized. The saltwater plume experiments established a resolution threshold below which SGS assumptions degrade, but this threshold has not been systematically translated into guidance for fire simulation grids.

Fifth, validation remains the binding constraint. The Edinburgh review's assessment that dynamic models "have never been validated" for fire conditions reflects a broader pattern: the smoke management literature contains many application studies but relatively few rigor-ous, independent validation exercises for SGS model performance specifically. The 2007 FDS validation by Coyle and Novozhilov and the field-scale hall study by Chow and Li are notable exceptions, but they do not isolate SGS model effects from other modeling uncertainties.

Figure 11 summarizes the multi-criteria assessment that underlies the synthesis, comparing the principal model families on accuracy, robustness, cost, and validation status for smoke management.

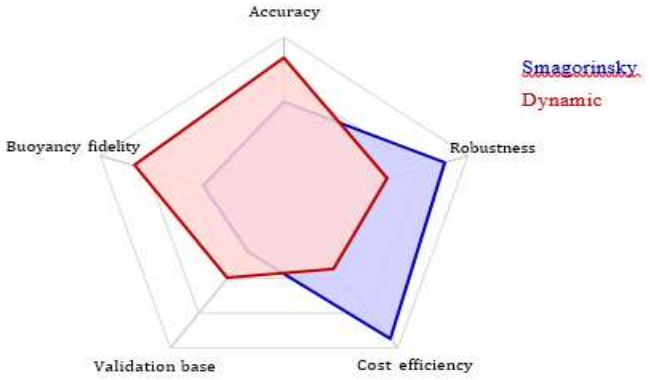


Figure 11: Multi-criteria schematic comparison of the Smagorinsky and dynamic models for smoke management. The Smagorinsky model scores highly on robustness and cost efficiency but poorly on accuracy in buoyant flows and validation base; the dynamic model reverses this pattern. Radial values are qualitative.

VIII. CONCLUSION

The period from 1950 to 2022 saw LES SGS modeling mature from Smagorinsky's atmospheric boundary layer closure to a diverse family of approaches with well-understood theoretical

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prop-erties. For smoke management applications, however, the field has settled on a pragmatic equi-librium: the Smagorinsky model, despite its known limitations, provides sufficient accuracy for design-oriented smoke transport predictions when embedded in validated fire simulation tools and applied with adequate grid resolution near the fire source. The dynamic procedure and scale-similarity models offer better physics but have not demonstrated sufficient advantage for the specific quantities of interest in smoke management to justify their additional complexity in routine practice.

The unresolved questions are substantive. Backscatter remains unrepresented in operational models. The anisotropy of buoyancy-driven SGS stresses is not captured by isotropic eddy viscosity. The interaction between grid resolution and SGS validity in fire plumes is poorly characterized. And the validation base, while growing, remains thin relative to the complexity of the coupled physics. These questions define the research frontier as of 2022, even as engineering practice proceeds with tools that predate most of them.

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