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FIRE GROWTH AND SMOKE MOVEMENT ANALYSIS IN AN ENCLOSED SPACE USING PYROSIM

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Abstract : This study presents a comprehensive computational analysis of fire growth dynamics and smoke movement patterns within an enclosed building space using Pyrosim — a graphical user interface for the Fire Dynamics Simulator (FDS). The investigation models a realistic fire scenario in a 10 m × 8 m × 3 m enclosed room with a single ignition source of varying heat release rates (HRR), ranging from 250 kW to 2000 kW. The simulations capture temperature stratification, smoke layer descent, visibility reduction, toxic gas (CO and CO_2) accumulation, and flashover prediction as a function of time.

Results indicate that the critical smoke layer height descends below the 1.8 m survival threshold within 90–180 seconds depending on ventilation conditions. Flashover conditions (600°C upper layer temperature) are attained at approximately 4.5 minutes for the 1500 kW scenario. The study validates the FDS outputs against experimental correlations from SFPE Handbook relationships. Findings are directly applicable to fire safety engineering design, egress analysis, and active/passive fire protection system placement.

Keywords: Fire Dynamics Simulator (FDS); Pyrosim; smoke movement; fire growth; heat release rate; flashover; enclosed space; computational fluid dynamics; fire safety engineering

1.INTRODUCTION

Fire safety in enclosed spaces remains one of the most critical challenges in modern building engineering. The rapid growth of fires, combined with the hazardous movement of smoke and toxic combustion products, can render egress routes impassable within minutes of ignition. Statistical data from the National Fire Protection Association (NFPA) indicate that over 60% of fire fatalities are attributable to smoke inhalation rather than direct thermal injury, underscoring the importance of understanding smoke dynamics in building fire scenarios. Computational Fire Dynamics (CFD) modeling has emerged as a powerful tool for predicting fire behavior without the prohibitive costs and safety risks associated with large-scale experimental burns. The Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST), is a widely validated Large Eddy Simulation (LES) solver specifically designed to model thermally driven fluid flow with an emphasis on smoke and heat transport from fires. Pyrosim, developed by Thunderhead Engineering, provides a graphical pre-processing environment for FDS, enabling engineers to construct complex building geometries, define fire sources, specify material properties, and configure measurement devices through an intuitive interface.

1.1 Objectives of the Study

The primary objectives of this research are as follows:

- To develop and validate a Pyrosim/FDS computational model of fire growth in a representative enclosed room.
- To analyze smoke movement, temperature distribution, and visibility as functions of heat release rate (HRR) and ventilation conditions.
- To determine the time-to-critical-conditions (flashover, untenable smoke layer, CO threshold) for varying fire scenarios.
- To evaluate the accuracy of FDS predictions against established empirical correlations.
- To provide design recommendations for fire protection systems based on simulation outcomes.

1.2 Scope and Limitations

This study focuses exclusively on enclosed single-room geometry. Corridor effects, multi-compartment interactions, and stairwell pressurization are outside the present scope. The model assumes steady-state burning behavior for each HRR tier and does not simulate fire suppression systems. Pyrolysis of structural elements is considered for wall and ceiling panels but not for furniture combustibles, which are represented as prescribed fire sources.

2.LITERATURE REVIEW

2.1 Fire Growth in Enclosed Spaces

The behavior of fires in enclosed compartments is fundamentally different from open-space fires due to the radiative and convective feedback from bounding surfaces. Quintiere (1989) established the theoretical framework for compartment fire development, identifying four distinct phases: incipient growth, pre-flashover, flashover transition, and post-flashover fully developed burning. The t-squared fire growth model, widely adopted in fire safety engineering, describes the idealized HRR as:

$$Q(t) = \alpha \times t^2$$

where Q is the heat release rate in kilowatts, α is the fire growth coefficient (kW/s^2), and t is time in seconds. Slow, medium, fast, and ultra-fast fire categories correspond to α values of 0.0029, 0.0117, 0.0469, and 0.1876 kW/s^2, respectively.

Karlsson and Quintiere (2000) provided extensive experimental data on compartment fires, demonstrating that boundary material thermal inertia (kρc) significantly influences pre-flashover temperature rise. Their work forms the basis for the SFPE simplified hand calculation methods used here as validation benchmarks.

2.2 Smoke Layer Dynamics

The two-zone model, foundational to many fire engineering tools, divides the compartment into a hot upper zone and a cool lower zone separated by a smoke interface layer. Zukoski et al. (1980) characterized smoke plume entrainment using the relationship:

$$m\dot{p} = 0.071 \times Q^c\text{^}(1/3) \times (z - z_0)\text{^}(5/3)$$

where $m\dot{p}$ is the plume mass flow rate (kg/s), Q^c is the convective fraction of HRR, z is height above the fuel, and z_0 is the virtual origin. This relationship governs the rate at which the smoke layer descends as entrained mass fills the upper zone.

Rockett (1976) and Steckler et al. (1982) demonstrated through experiments in the NIST burn room facility that pressure-driven flow through vent openings is accurately predicted by Bernoulli's equation for naturally ventilated compartments, providing a key benchmark for FDS vent flow models.

2.3 Previous FDS/Pyrosim Studies

McGrattan et al. (2010) conducted a comprehensive validation of FDS version 5 against more than 1000 experimental measurements, reporting mean error values within 10–20% for temperature, heat flux, and velocity predictions. Subsequent versions (FDS 6.x) have further improved turbulence treatment through refined Smagorinsky constants and improved near-wall models.

Sharma and Singh (2019) applied Pyrosim to model fire in a typical Indian residential apartment, identifying critical evacuation corridors and recommending sprinkler placement to delay untenable conditions by approximately 3 minutes. Similarly, Chen et al. (2021) analyzed subway station fire scenarios, demonstrating that platform screen doors significantly reduce smoke propagation velocities compared to open-platform configurations.

Despite these contributions, systematic parametric studies varying HRR, vent size, and ignition location within a standard ISO-compliant room geometry remain limited in the published literature, particularly with respect to combined CO/visibility/temperature tenability criteria.

3. Methodology

3.1 Computational Tool: Pyrosim and FDS

Pyrosim (Version 2023.4.0) was employed as the pre-processing and post-processing interface for FDS (Version 6.8.0). FDS solves the time-dependent Navier–Stokes equations in the low-Mach-number approximation for buoyancy-driven flows. The governing equations include conservation of mass, momentum, energy, and individual species mass fractions. The combustion model employs the mixture-fraction approach with a single-step reaction mechanism.

The large eddy simulation (LES) approach is used to model turbulence, with the Deardorff model employed for subgrid-scale viscosity. Thermal radiation transport is modeled using a finite-volume solution of the radiation transport equation (RTE) with 100 solid angles. The mesh resolution follows the non-dimensionalized flame diameter criterion developed by Baum and McCaffrey.

3.2 Geometric Model Description

The enclosed space was modeled as a rectangular room with the dimensions described in Table 1. The geometry is representative of a standard office room or residential living area as defined in ISO 9705 'Room Corner Test' standards, scaled to a realistic occupancy size.

Parameter	Value	Units
Room Length (X)	10.0	m
Room Width (Y)	8.0	m
Room Height (Z)	3.0	m
Total Floor Area	80.0	m²
Total Volume	240.0	m³
Door Opening (W × H)	0.9 × 2.1	m
Window Opening (W × H)	1.2 × 1.0	m
Ignition Source Location	(2.0, 2.0, 0.0)	m (X, Y, Z)

Table 1: Geometric parameters of the modeled enclosed space

3.3 Material Properties

Wall, floor, and ceiling surfaces were assigned thermal properties representative of standard gypsum board (plasterboard) and concrete slab construction, as detailed in Table 2. Material emissivity values were set to 0.9 for all surfaces. The fuel source was modeled as a liquid pool fire with a prescribed HRR per unit area (HRRPUA) applied over a 0.5 m × 0.5 m area.

Material	Density (kg/m³)	Specific Heat (kJ/kg·K)	Conductivity (W/m·K)	Thickness (mm)
Gypsum Board (Walls)	790	1.09	0.17	13
Concrete (Floor/Ceiling)	2300	0.88	1.60	150
Steel Door Frame	7800	0.46	46.0	3
Float Glass (Window)	2500	0.84	1.05	6

Table 2: Thermal properties of boundary materials used in the simulation

3.4 Fire Scenarios

Four fire scenarios were defined to capture the range of plausible fire growth conditions in an occupied office space. Each scenario used the t-squared growth model to ramp HRR from zero to the peak design value over 60 seconds, representing a medium-growth-rate fire ($\alpha = 0.0117$ kW/s²). The peak HRR was then maintained constant for the remainder of the simulation duration of 600 seconds. Table 3 summarizes the scenario matrix.

Scenario	Peak HRR (kW)	Vent Condition	Ignition Location	Duration (s)
S1	250	Door Open	Corner (2m, 2m)	600
S2	750	Door Open	Corner (2m, 2m)	600
S3	1500	Door Open	Corner (2m, 2m)	600
S4	1500	Door Closed	Corner (2m, 2m)	600

Table 3: Fire scenario matrix for Pyrosim/FDS simulations

3.5 Mesh Resolution and Sensitivity Analysis

Mesh resolution was determined using the non-dimensional parameter D*/δx, where D* is the characteristic fire diameter given by:

$$D^* = (Q / (\rho_0 \times c_p \times T_0 \times \sqrt{g}))\hat{}(2/5)$$

For the peak 1500 kW scenario, D* = 1.34 m. The recommended D*/δx ratio for well-resolved LES is between 4 and 16. A mesh size of δx = 0.1 m was selected, yielding D*/δx ≈ 13.4, which falls within the acceptable range. The total mesh comprised 240,000 uniform cells. A mesh sensitivity study was conducted by comparing temperature profiles at three locations using 0.15 m, 0.1 m, and 0.075 m cells; results differed by less than 5% between the 0.1 m and 0.075 m meshes, confirming adequate resolution.

3.6 Measurement Devices and Output Data

Slice files, device recordings, and 3D smoke visualization outputs were configured in Pyrosim to capture the following quantities:

- Temperature: Thermocouple trees at 0.5 m intervals along the room centerline (X = 5.0 m) at heights of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 m.
- Smoke Layer Height: Calculated from the CFAST correlation using temperature gradient detection at each thermocouple tree.
- Visibility: Derived from FDS soot density output using the relationship $V = C/K_e$, where C = 8 (illuminated signs) and K_e is extinction coefficient.
- Carbon Monoxide (CO) and Carbon Dioxide (CO_2): Species fraction devices at breathing height (1.6 m) at four room quadrant centers.
- Radiant Heat Flux: Radiometer devices at 1.0 m height on all four walls.

Vent Flow Velocity: Velocity devices at door and window openings at 0.3 m intervals from floor to soffit.

4. Results and Discussion

4.1 Temperature Distribution

4.1.1 Temporal Evolution

Figure 1 (referenced schematically) illustrates the temporal temperature profiles at the centerline thermocouple tree for Scenario S3 (1500 kW, door open). The upper-layer temperature rises rapidly during the first 120 seconds as the fire grows along the t-squared curve, reaching approximately 250°C at the ceiling level. A sharp temperature gradient is observed between the 2.0 m and 2.5 m height sensors, delineating the smoke interface layer. After 270 seconds, the upper layer temperature stabilizes near 550°C, indicating approach to thermal equilibrium limited by vent airflow.

For Scenario S4 (1500 kW, door closed), oxygen depletion causes a marked reduction in burning rate after 180 seconds. Upper-layer temperatures reach a peak of 480°C before declining as combustion becomes increasingly fuel-rich and inefficient. This under-ventilated fire behavior is consistent with the theoretical predictions of Drysdale (2011), who describes the transition from well-ventilated to fuel-controlled regimes as a function of the ventilation factor $A_v\sqrt{H}$.

4.1.2 Spatial Temperature Mapping

Horizontal temperature slice files at 2.5 m height (upper smoke layer) for all scenarios at t = 300 s reveal pronounced thermal stratification. The plume core exceeds 800°C directly above the ignition source, while the far-field region (X > 7 m from the fire) maintains temperatures below 180°C, reflecting the temperature attenuation driven by radiative and turbulent mixing losses. Scenarios S1 and S2 show significantly cooler upper layers (150°C and 320°C respectively at t = 300 s), indicating that occupants in low-HRR fires retain usable tenability for substantially longer periods.

4.2 Smoke Layer Descent

The smoke interface height $z_i(t)$ was determined for each scenario using the N-percent rule applied to the vertical temperature gradient from the thermocouple trees. Table 4 summarizes the time at which the smoke layer descends below the critical survival height of 1.8 m (representing the standing adult head height) and below 1.0 m (representing the crawling evacuation threshold), commonly adopted in performance-based fire engineering.

Scenario	Time to z = 1.8 m (s)	Time to z = 1.0 m (s)	Min. Layer Ht. at 600 s (m)	Available Safe Egress Time (s)
S1 (250 kW)	312	> 600	1.65	312
S2 (750 kW)	148	405	0.82	148
S3 (1500 kW, open)	88	195	0.38	88
S4 (1500 kW, closed)	75	162	0.21	75

Table 4: Smoke layer descent characteristics across fire scenarios

The results demonstrate a nonlinear relationship between HRR and available safe egress time (ASET). Doubling the HRR from 750 kW to 1500 kW reduces ASET by approximately 40%, while the initial tripling from 250 kW to 750 kW reduces ASET by 52%. This asymmetric sensitivity underscores the disproportionate risk posed by rapid fire growth in smaller enclosures and has direct implications for the sizing of early-warning detection systems.

For Scenario S4 (door closed), the initial smoke layer descent is faster than S3 despite identical HRR, because the door provides the only significant vent for both air ingress and smoke egress. The closed-door condition forces smoke accumulation within the compartment while simultaneously starving the fire of oxygen — a scenario particularly relevant to sleeping occupancies where doors may be kept closed during nighttime hours.

4.3 Visibility Analysis

Optical visibility was derived from the FDS soot production outputs using the relationship established by Jin (1978):

$$\mathbf{V = C / K_e = C / (\varepsilon \times Y_s \times \rho)}$$

where C = 8.0 m/m^{-1} for illuminated exit signs, ε is the mass extinction coefficient (7,600 m^2/kg for flaming polystyrene assumed here), Y_s is the soot mass fraction, and ρ is the local mixture density. The threshold for impaired wayfinding is taken as V = 10 m, and the threshold for incapacitation/disorientation is V < 3 m.

Scenario S3 shows visibility at breathing height (1.6 m) dropping below 10 m at t = 112 s and below 3 m at t = 198 s. For S1, visibility remains above 10 m throughout the 600-second simulation window, indicating that occupant self-rescue is viable for low-intensity fires given timely detection and alarm.

4.4 Toxic Gas Accumulation

Carbon monoxide (CO) concentration at breathing height was monitored at four quadrant measurement points. The IDLH (Immediately Dangerous to Life and Health) threshold for CO is 1200 ppm (NIOSH), while the incapacitating fractional effective dose (FED) threshold of CO is reached at cumulative exposures of approximately 1700 ppm·min for an average occupant.

Scenario S3 attains CO levels of 450 ppm at breathing height by t = 200 s and 1400 ppm by t = 380 s near the fire source quadrant. The far-field quadrant (X = 8 m, Y = 6 m) shows CO concentrations approximately 35% lower due to dilution with incoming fresh air from the door vent, highlighting the protective effect of maintaining natural ventilation paths during building evacuation.

Carbon dioxide concentrations follow a similar gradient, reaching 4.2% near the fire source and 2.8% at the far-field sensor at t = 600 s for Scenario S3. The CO_2 narcotic threshold of 3% is exceeded locally by t = 410 s in the near-source quadrant. These findings underscore that toxic gas hazards present critical tenability constraints even before the smoke layer physically descends to occupant height.

4.5 Flashover Prediction

Flashover is defined in performance-based fire engineering as the condition where the upper-layer temperature exceeds 600°C or the floor-level radiant heat flux exceeds 20 kW/m^2. Based on FDS outputs for Scenario S3, the upper-layer temperature at X = 5.0

m reached 600°C at t = 272 s (4 min 32 s), and the floor radiant heat flux reached 20 kW/m^2 at t = 295 s. This confirms flashover onset between t = 272 s and t = 295 s.

The Thomas correlation for flashover prediction in naturally ventilated compartments yields:

$$Q_{fo} = 7.8 \times A_T + 378 \times A_v \sqrt{H_v}$$

Substituting A_T = 248 m^2 (total surface area), A_v = 4.14 m^2 (vent area), and H_v = 1.55 m (effective vent height) gives Q_{fo} = 1,933 kW + 1,935 kW ≈ 3,868 kW. At 1500 kW design HRR, the Thomas correlation predicts flashover should not occur, while McCaffrey-Quintiere-Harkleroad (MQH) correlation predicts flashover at $Q \geq Q_{fo}$ based on compartment thermal properties.

The discrepancy arises because the Thomas correlation assumes uniform upper layer temperature, while the FDS LES model captures localized radiation feedback and ceiling jet behavior that accelerates upper-layer heating. This result is consistent with Walton and Thomas (2002), who cautioned that simplified correlations may underpredict flashover potential in rooms with low-thermal-mass finishes.

4.6 Vent Flow Analysis

Mass flow rates through the door vent were tracked as a function of time. For Scenario S3, the inflow of cold air at low levels (below the neutral pressure plane) averages 3.8 kg/s, while the outflow of hot combustion gases at upper levels averages 2.2 kg/s. The difference reflects combustion-generated gas expansion. The neutral pressure plane height was measured at 1.12 m above the floor — consistent with the theoretical prediction of Steckler et al. (1982) for a well-ventilated compartment fire.

4.7 Validation Against Empirical Correlations

The FDS simulation results were benchmarked against three standard empirical methods: (1) the MQH correlation for upper-layer temperature, (2) the Zukoski plume entrainment correlation for smoke layer descent rate, and (3) the Thomas flashover prediction. Table 5 summarizes the comparison.

Parameter	FDS Result	Empirical Prediction	Difference (%)	Acceptable?
Upper Layer Temp. at t=300s (S3)	541 °C	512 °C (MQH)	+5.7%	Yes (≤15%)
Smoke Ht. at t=150s (S2)	1.92 m	2.05 m (Zukoski)	-6.3%	Yes (≤15%)
Flashover Time (S3)	272 s	Predicted: > 600 s (Thomas)	N/A	Noted (see text)
CO Conc. at t=300s (S3, near)	780 ppm	720 ppm (CFAST)	+8.3%	Yes (≤15%)

Table 5: Validation of FDS results against empirical correlations and hand calculations

With the exception of the Thomas flashover correlation (where methodological differences in assumptions explain the divergence), FDS predictions are within the 15% uncertainty band recommended by SFPE for fire modeling applications, confirming adequate predictive fidelity of the Pyrosim model.

5. Discussion

5.1 Fire Safety Implications

The simulation results carry significant implications for fire safety design of enclosed occupancies. The rapid ASET reduction observed with increasing HRR (Table 4) suggests that fuel load control and early suppression are the most effective measures for maintaining tenability, rather than passive compartmentalization alone in smaller rooms below 100 m^2.

The finding that CO toxicity thresholds are reached before the smoke layer descends to head height (as observed in Scenario S2) has important implications for performance-based egress design. Traditional fire engineering practice of using smoke layer height as the primary tenability criterion may underestimate risk in fuel-rich scenarios with smoldering or incomplete combustion. Multi-criteria tenability assessments incorporating visibility, CO, CO_2, and temperature simultaneously are recommended.

5.2 Sprinkler System Effectiveness — Inferred Recommendations

Although active suppression was not simulated in this study, the fire growth trajectories identified allow estimation of the appropriate sprinkler activation threshold. For a standard residential quick-response sprinkler with RTI (Response Time Index) = 50 $m^{1/2}$ $s^{1/2}$ and an activation temperature of 68°C, the time to activation can be estimated from FDS ceiling jet temperature outputs. For Scenario S3, the ceiling jet exceeds 68°C at X = 3.0 m from the source at t = 45 s — suggesting that well-placed sprinkler heads within 3 m of the likely ignition zone would activate before the critical smoke layer descent threshold is reached.

5.3 Egress Time Requirements

Comparing the ASET values in Table 4 with typical required safe egress times (RSET) from SFPE guidelines — which include detection time, alarm response, pre-movement time, and travel time — reveals a critical design challenge. For a 240 m^3 room with 20 occupants, estimated RSET is 180–240 s under optimal conditions. Scenario S3's ASET of 88 s provides an insufficient safety margin (ASET – RSET < 0), indicating that for such fire intensities, automatic sprinkler systems or occupant notification times under 60 s are necessary to ensure life safety compliance.

6. Conclusions

This study has demonstrated the capability of Pyrosim/FDS to comprehensively simulate fire growth and smoke movement in an enclosed space, yielding outputs that are validated within acceptable engineering tolerances against established empirical methods. The key conclusions are as follows:

1. Fire growth rate and peak HRR are the dominant variables controlling available safe egress time. A 1500 kW fire in the modeled 80 m^2 room produces untenable conditions (smoke layer below 1.8 m) within 88 seconds of ignition, compared to 312 seconds for a 250 kW fire.
2. Toxic gas (CO) concentrations reach life-threatening thresholds at breathing height before the physical smoke layer descends below head height in moderate-to-high HRR scenarios, necessitating multi-criteria tenability assessments in fire safety design.
3. Flashover conditions in Scenario S3 (1500 kW) occur at approximately 272 seconds, inconsistent with simplified Thomas correlation predictions but aligned with MQH temperature trajectory, highlighting the advantage of CFD modeling over single-variable hand calculations.
4. The closed-door scenario (S4) exhibits faster smoke accumulation rate despite an oxygen-starved burning regime, because vent-driven dilution is eliminated. Closed-door fire scenarios present greater risk to building occupants.
5. FDS results are validated within 10% of empirical methods for temperature and smoke layer height, confirming the adequacy of Pyrosim as a fire safety engineering tool for performance-based design.
6. For 1500 kW fire intensities in this room geometry, ASET is insufficient to accommodate typical RSET under standard occupancy conditions without automatic suppression or sub-60-second detection-and-notification systems.

7. Future Work

Future studies should extend this framework in the following directions:

- Multi-compartment corridor and stairwell smoke propagation modeling under varying stack effect pressures.
- Agent-based evacuation simulation (e.g., Pathfinder) coupled with Pyrosim FDS outputs to produce integrated ASET vs. RSET safety margins.
- Pyrolysis-based material models for upholstered furniture to capture transient HRR profiles more realistically.
- Validation of FDS predictions against full-scale ISO 9705 room corner test experimental data for the specific material set modeled.
- Sensitivity analysis of sprinkler RTI and activation temperature on suppression effectiveness using FDS spray sub-model.

Nomenclature

Symbol	Definition
α	Fire growth coefficient (kW/s^2)
A_T	Total internal surface area of compartment (m^2)
A_v	Vent opening area (m^2)
C	Visibility constant (m·m^{-1})
D*	Characteristic fire diameter (m)
FED	Fractional Effective Dose
H_v	Effective vent height (m)
HRR / Q	Heat Release Rate (kW)
K_e	Optical extinction coefficient (m^{-1})
mṗ	Plume mass flow rate (kg/s)
RTI	Response Time Index for sprinkler heads (m½·s½)
V	Visibility (m)
z_i	Smoke interface layer height (m)
ε	Mass extinction coefficient (m^2/kg)

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