International Journal of Robotics and Control Systems
Vol. 6, No. 5, 2026
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

Optimal Control and Feasibility Assessment of Ozone Disinfection Systems in Large Indoor Environments: A CFD-Based Design Framework

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ARTICLE INFO

Article history
Received June 17, 2026
Revised August 15, 2026
Accepted August 31, 2026

Keywords
Disinfection Control Systems;
Computational Fluid Dynamics;
Optimization;
Large Indoor Spaces;
Ozone Treatment;
Control System Design

ABSTRACT

Large-volume indoor environments require carefully designed disinfection control strategies to achieve spatial uniformity of antimicrobial treatment while respecting safety and operational constraints. This study presents a computational fluid dynamics (CFD)-based control system design framework for ozone-based disinfection in a theatre-scale enclosure (1800 m³). Rather than empirical trial-and-error deployment, we employ CFD simulation as a virtual testbed to evaluate multiple control scenarios and determine optimal operational setpoints for ozone concentration, exposure duration, and injection point placement. Twelve operating scenarios were simulated, combining four concentration levels (25–100 mg·m⁻³) with three exposure durations (5, 10, 20 minutes). Results demonstrate that exposure duration (the primary control variable) is more influential than concentration magnitude in achieving spatial uniformity. Near-complete coverage was achieved at moderate concentrations (~50 mg·m⁻³) with 10-minute exposure, identifying an efficient operational setpoint balancing treatment efficacy and system cost. Concentration–time (CT) analysis provides a control-relevant feasibility metric, linking simulated exposure profiles to literature-reported disinfection thresholds. Post-treatment ventilation was evaluated as a critical safety constraint for residual ozone reduction below occupational limits (0.1 ppm). The proposed framework supports preliminary control system design, optimal parameter selection, and risk-based operational planning prior to physical implementation. This work demonstrates the utility of CFD-based virtual commissioning for complex environmental control applications in large spaces.

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1. Introduction

Controlling airborne contamination in large-volume indoor venues (theatres, auditoriums, and conference halls among them) remains an unresolved engineering problem. Aerosolized particles released within such spaces can stay suspended for extended periods and travel substantial distances once entrained in the complex, often poorly characterized airflow fields typical of high-ceiling rooms

[1]–[4]. Sampling campaigns conducted on HVAC components and indoor surfaces have reinforced this concern, indicating that both air and surfaces participate in contaminant transport within occupied buildings [5]–[7]. Taken together, these findings point to a persistent gap that clinical and public-health measures alone cannot close: the need for engineering-level control strategies capable of acting directly on the indoor environment itself [8], [9].

Several decontamination technologies have been proposed to address this gap, including UV-C irradiation, hydrogen peroxide vapor (HPV), ionization, and photocatalytic oxidation. Each, however, encounters a common limitation when scaled to large or geometrically irregular rooms: shadowing, restricted penetration depth, and airflow-driven heterogeneity tend to undermine spatial uniformity, regardless of how effective the agent may be at a localized level. Gaseous ozone treatment offers a partial remedy to this limitation, since ozone diffuses and disperses volumetrically rather than acting along a line of sight—provided that its concentration, exposure duration, and the surrounding environmental conditions are properly specified and controlled [10]–[14]. Supporting this view, room-scale investigations have reported substantial microbial load reductions once ozonation is carried out under favorable humidity conditions [15], [16], suggesting that ozone's effectiveness is less a question of intrinsic antimicrobial strength than one of correctly selecting and managing operating parameters.

That antimicrobial strength derives from ozone's character as a powerful oxidant (oxidation potential ≈ 2.07 V), which reacts readily with lipids, proteins, and nucleic acids and thereby disrupts a broad range of microbial structures [17]–[19]. In the specific case of enveloped viruses, oxidative attack on envelope components has been linked to loss of infectivity, while ozone itself decomposes to oxygen without leaving chemical residues under ordinary indoor conditions [20], [21]—a property that makes it attractive relative to liquid-phase or residue-forming disinfectants. This reactivity, however, is not fixed: ozone's decay kinetics and persistence vary considerably with humidity, surface chemistry, and the presence of competing reactive species, which is precisely why dose and exposure time cannot be treated as free parameters but must instead be deliberately controlled and characterized for each application context [22]–[24].

The CT product offers a convenient way of expressing this control relationship, combining the applied concentration ($mg \cdot m^{-3}$) and the treatment duration (min) into a single exposure descriptor. CT thresholds in the approximate range of 600–1000 $mg \cdot min \cdot m^{-3}$ have been reported to correspond with high inactivation levels for enveloped respiratory viruses under controlled laboratory conditions, and several studies have shown that this target can be reached using moderate ozone concentrations provided that exposure time and humidity are favorable [25]. Relative humidity, in turn, affects not only the oxidative chemistry of ozone but also aerosol stability and decay behavior, which means that any CT-based interpretation of disinfection performance must be read in conjunction with the humidity conditions under which it was obtained [26], [27]. Despite its conceptual usefulness, the CT metric is most often applied as a single-point, spatially averaged quantity—an assumption that becomes increasingly difficult to justify as room volume and airflow complexity increase.

Computational fluid dynamics (CFD) has emerged as the natural tool for examining whether such single-point assumptions hold, allowing ozone transport to be resolved spatially in settings where experimental mapping would be expensive, slow, or simply unsafe to perform at full scale. Combined experimental–numerical studies have already demonstrated that CFD can meaningfully reproduce ozone behavior and disinfection-related outcomes on surfaces and within enclosed volumes [28], and review-level work has likewise positioned CFD as a standard supporting tool across air-, water-, and surface-disinfection contexts [18], [29], [30]. The bulk of this literature, however, remains concentrated on small and medium-sized rooms, laboratory chambers, or hospital wards [19], [31]. Theatre-scale spaces—distinguished by high ceilings, large air volumes, and flow structures prone to stratification, recirculation, and delayed mixing—have received comparatively little attention, even though these very features make uniform ozone delivery substantially harder to achieve [32], [33].

A useful point of reference is the high-fidelity, experimentally validated modelling work of Jahromi et al. [34], who showed that local airflow structures and detailed transport dynamics can give rise to considerable spatial variation in effective ozone dose, even under carefully controlled injection

conditions. Their results underline the real risk of treating ozone exposure as spatially homogeneous. At the same time, the level of device- and chemistry-resolved detail employed in that study is not always necessary, nor practical, at the preliminary engineering stage, where the priority is to establish how large-scale dispersion, exposure duration, concentration, and ventilation interact—information that can guide parameter selection before a more detailed, validated design is pursued.

Beyond airflow structure, several environmental and operational factors further complicate ozone-based treatment in large volumes and must be accounted for in any control-oriented assessment. Relative humidity continues to govern decay rate and radical-mediated reactivity, while temperature gradients and buoyancy effects reshape dispersion patterns and local concentration fields [35]–[38]. Safety considerations impose an additional, non-negotiable constraint: because ozone is a regulated respiratory irritant, occupational guidelines typically restrict permissible exposure to around 0.1 ppm (≈0.2 mg·m^{-3}), which in practice requires that ozonation be carried out in unoccupied spaces and be followed by sufficient ventilation to bring residual concentrations back within safe limits before re-entry [13], [38]. Any practical operating strategy must therefore be designed around this constraint rather than treating it as an afterthought.

Several engineering-oriented gaps follow from this body of work. Large, theatre-scale venues remain markedly underrepresented relative to smaller enclosures, despite airflow and mixing characteristics that can directly compromise treatment uniformity [31]–[33]. Moreover, although the CT concept is widely used to contextualize disinfection potential, translating CT-based targets into operating instructions for large spaces calls for spatially resolved exposure data rather than the single-point assumptions on which the metric is conventionally based [25], [29], [30]. What is missing, in effect, is a systematic, design-stage account of how the principal operating parameters—injection layout, airflow configuration, exposure duration, and post-treatment ventilation—interact to determine achievable spatial coverage, so that feasibility can be assessed and operating parameters tentatively selected before any physical system is deployed [10], [12], [13], [39].

The present study responds to this gap by treating ozone-based disinfection in a large indoor venue as a parameter-selection problem to be explored, in the first instance, through simulation rather than physical trial. Specifically, an application-oriented CFD assessment is presented for ozone dispersion in a theatre-scale enclosure, evaluated across multiple combinations of concentration and exposure duration. CFD is used here as a virtual testbed for examining how these operating parameters jointly govern spatial coverage and residual heterogeneity, with the resulting concentration fields interpreted through CT-based exposure indicators drawn from the literature and discussed alongside the post-treatment ventilation requirements and safety limits that any unoccupied-cycle operation must satisfy [13], [18], [29], [30]. While many previous studies have focused on developing new CFD formulations, optimization algorithms, or closed-loop control strategies, the novelty of the present study lies not in proposing a new CFD formulation or control algorithm, but in establishing an engineering-oriented CFD-based design framework for preliminary feasibility assessment, parameter selection, and virtual commissioning of ozone disinfection systems in large indoor environments. By systematically evaluating multiple operating scenarios within a theatre-scale enclosure, the proposed framework provides practical guidance for identifying feasible operating windows and supports engineering decision-making prior to physical implementation. Rather than delivering a validated disinfection technology or a closed-loop control implementation, the study is intended to support the earlier, design-level task of identifying feasible operating windows and informing future parameter selection, ahead of the more detailed experimental and control-system development that physical deployment would ultimately require.

2. Materials and Method

2.1. System Geometry and Scenario Definition

This study examines ozone gas dispersion in a large-volume indoor theatre with an internal volume of 1,800 m³ (10 m × 30 m × 6 m). The geometry was selected to represent a realistic high-

capacity enclosed environment characterized by complex airflow structures, elevated ceilings, and potential spatial heterogeneity in gaseous transport. Such features are known to influence mixing behavior and exposure uniformity in large indoor spaces [31].

Five ozone injection locations were defined at a height of 5.5 m above the floor level, positioned below the ceiling and opposite the stage area, in order to promote downward and lateral dispersion across the seating volume. The three-dimensional theatre geometry and the computational mesh employed for the CFD simulations are illustrated in Fig. 1, which depicts the large theatre enclosure and the discretized computational domain used for numerical analysis. The injection points were spaced at 2 m intervals to provide distributed release rather than a single concentrated source, which is consistent with design recommendations for improving spatial coverage in large enclosures [28]. The modeled configuration represents a generic system layout intended for scenario-based evaluation rather than a validated experimental prototype.

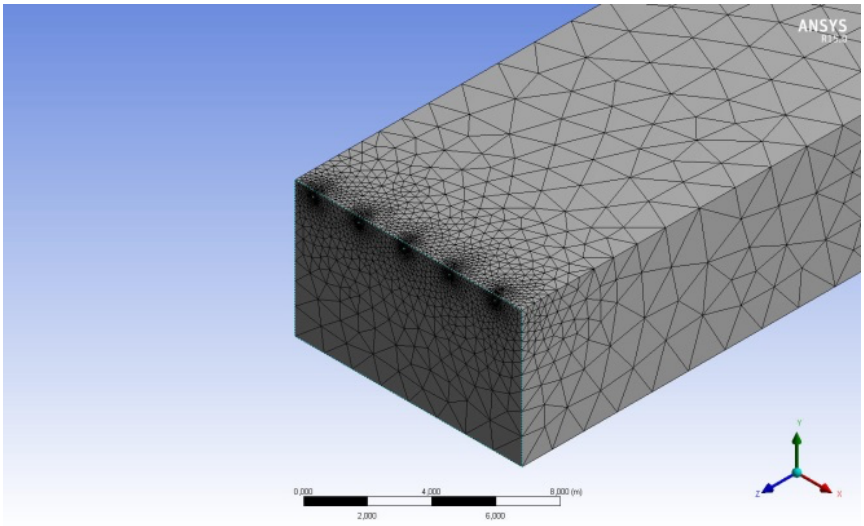


Fig. 1. View of the modeled theatre geometry used for CFD analysis

All ozonation scenarios considered in this study assume unoccupied operating conditions, consistent with established safety guidelines for indoor ozone application. Following each treatment scenario, a ventilation phase was included to reduce residual ozone concentrations to below commonly cited occupational exposure limits (0.1 ppm ≈ 0.2 mg·m^{-3}) prior to potential re-entry [13].

2.2. Operational Scenarios and Treatment Sequences

Rather than implementing adaptive or closed-loop control strategies, the present study adopts a scenario-based operational definition to evaluate the influence of ozone concentration and exposure duration on spatial dispersion characteristics. Ozone generation is conceptually assumed to be provided by a corona-discharge source operating with ambient air, consistent with commonly reported indoor ozonation systems [14]. Three predefined exposure durations were examined:

- Short duration: 5 min at 25–100 mg·m^{-3}
- Medium duration: 10 min at 25–100 mg·m^{-3}
- Extended duration: 20 min at 25–100 mg·m^{-3}

These durations were selected to represent typical operational windows relevant to large indoor facilities, such as rapid treatment between usage periods, intermediate cleaning intervals, and overnight disinfection cycles, as reported in prior application studies [15], [16]. Each scenario was structured into three sequential phases:

- ozone release,
- fixed dwell period, and
- forced ventilation.

This predefined operational sequence enables comparative assessment of dispersion patterns and exposure-time requirements without invoking real-time decision-making or feedback control mechanisms. Fig. 2 illustrates the assumed ozone generation and ventilation configuration, including the control unit, ozone generator, ventilation system, and theatre enclosure. Fig. 3 illustrates the assumed operational workflow, comprising ozone release, a fixed dwell period, and forced ventilation.

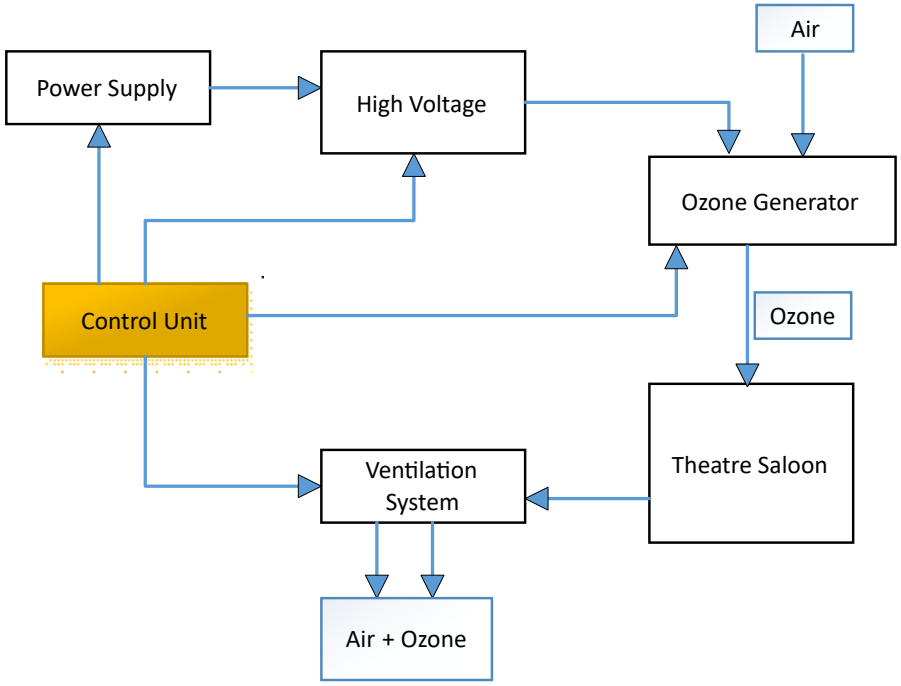


Fig. 2. Schematic representation of the assumed ozone generation and ventilation configuration

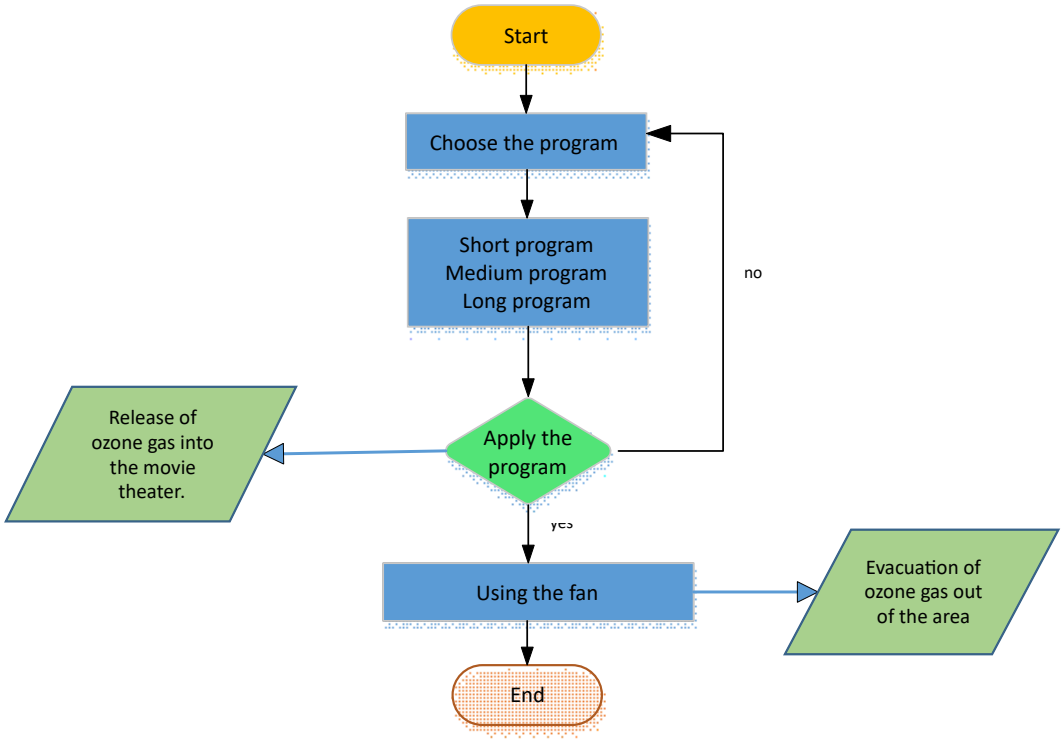


Fig. 3. Operational sequence defining ozone release, dwell, and ventilation phases

2.3. CFD Modeling Approach and Boundary Conditions

Numerical simulations were performed using ANSYS Fluent 2023 R2 with a transient finite-volume formulation. The unsteady Reynolds–averaged Navier–Stokes equations were solved together with the species transport equation to resolve the time-dependent dispersion of ozone from the initial release condition. The transient simulations were performed from an initial condition (t = 0 s) to total physical times of 300, 600, and 1200 s, corresponding to the 5, 10, and 20 min operating scenarios, respectively. Accordingly, the concentration fields presented for each operating scenario represent the transient evolution of ozone within the theatre rather than steady-state equilibrium distributions. Turbulent airflow was modeled using the standard k–ε model, which has been widely applied and validated for buoyancy-driven and mechanically ventilated indoor environments [31].

The computational domain was discretized using approximately 1.2 million tetrahedral elements, with localized refinement applied near the ozone injection points, ceiling regions, and expected high-gradient zones to improve the resolution of jet-induced mixing and species concentration gradients. The grid was selected as a practical compromise between spatial resolution and computational cost for the present scenario-based feasibility assessment. However, a formal multi-grid grid-convergence analysis was not available for the present model. Consequently, the reported results are interpreted primarily in terms of comparative spatial trends and operating-scenario differences rather than as fully grid-verified absolute predictions. Systematic mesh-independence and grid-convergence analyses should be included in subsequent model validation studies.

The present CFD model considers transient airflow and species transport but does not explicitly include ozone surface deposition or chemical decay kinetics. Consequently, the simulated concentration fields represent conservative estimates of airborne ozone dispersion during the selected operating scenarios. The objective of the present study is the comparative evaluation of alternative operating scenarios under identical modeling assumptions rather than the prediction of absolute ozone depletion kinetics or surface reaction processes. Accordingly, the reported CT-based exposure assessments are intended for comparative evaluation of operating scenarios rather than as absolute predictions of disinfection performance. Boundary conditions were defined as follows:

- Inlets: Five ozone injection sources located at 5.5 m height, directed toward the interior domain
- Outlets: Three exhaust openings positioned near the rear ceiling zone
- Walls: No-slip, impermeable boundaries with zero species flux
- Initial conditions: 25 °C, 1 atm, and zero background ozone concentration

Ozone properties were specified as a density of 2.144 $kg \cdot m^{-3}$, molecular weight of 48 $g \cdot mol^{-1}$, and molecular diffusivity of 1.5×10^{-5} $m^2 \cdot s^{-1}$, consistent with reported values in the literature [14]. Pressure–velocity coupling was handled using the SIMPLE algorithm, and second-order upwind discretization schemes were applied for both momentum [40] and species transport equations. Convergence was achieved by reducing residuals below 10^{-6} for all solved variables.

A total of twelve scenarios (four concentration levels combined with three exposure durations) were simulated to evaluate spatial distribution trends and CT characteristics relevant to ozone-based disinfection assessments reported in previous studies [30], [41]. The CT framework was employed here as a comparative exposure metric, recognizing that intrinsic viral properties and environmental conditions can influence apparent inactivation kinetics even under identical disinfectant doses [42]. Sensitivity considerations related to relative humidity were interpreted based on reported ozone decay behavior and reaction pathways across a range of indoor RH levels [36], [37].

Overall, the adopted CFD framework provides an application-oriented basis for evaluating dispersion uniformity, exposure duration requirements, and ventilation constraints associated with ozone treatment in large indoor spaces, without reliance on experimental validation.

3. Results and Discussion

3.1. Ozone Dispersion and Spatial Distribution

The CFD simulations revealed distinct dispersion characteristics depending on the applied exposure duration and ozone concentration scenarios. During the initial injection phase, ozone - having a higher molecular weight than air - exhibited a tendency toward vertical stratification, particularly near the ceiling-level injection points. Over time, turbulent diffusion and recirculating airflow structures promoted progressive mixing throughout the theatre volume.

Fig. 4 illustrates the simulated ozone distribution for concentrations of 25, 50, 80, and 100 mg·m^{-3} under the short-duration (5 min) scenario. In this case, ozone penetration remained spatially non-uniform, with elevated concentration regions observed near the ceiling and stage-facing areas. Although higher injection concentrations increased the penetration depth, full volumetric uniformity was not achieved within the 5 min exposure window, indicating that short-duration operation primarily supports rapid but partial spatial coverage. Fig. 4(a)–Fig. 4(d) further demonstrates that localized high-concentration regions remain near the injection area, indicating that a 5 min exposure is insufficient to achieve complete volumetric mixing.

When the exposure duration was increased to 10 min (medium-duration scenario), the simulated results demonstrated substantially improved spatial coverage (Fig. 5). Fig. 5(a)–Fig. 5(d) further demonstrates that increasing the exposure duration to 10 min substantially improves ozone penetration and reduces spatial concentration gradients throughout the theatre volume. Ozone reached deeper into the seating area and rear sections of the theatre. At concentrations of 50 mg·m^{-3} and above, near-complete volumetric penetration was observed across the 1800 m^3 domain. These results indicate that exposure duration plays a dominant role in mitigating spatial heterogeneity, consistent with previous CFD-based analyses of large indoor environments [32], [33].

For the long-duration scenario (20 min), ozone distribution became effectively uniform throughout the domain for all tested concentrations (Fig. 6). Fig. 6(a)–Fig. 6(d) demonstrates that extending the exposure duration to 20 min largely eliminates the remaining low-concentration regions, resulting in a nearly uniform ozone distribution throughout the theatre volume. Buoyancy-driven mixing and large-scale recirculation eliminated residual low-concentration pockets, suggesting that extended exposure durations are effective for overcoming airflow-induced heterogeneity in high-ceiling indoor spaces.

3.2. Concentration–Time (CT) Exposure Interpretation

To provide a comparative exposure framework, CT values were calculated as the product of the spatially averaged ozone concentration and exposure duration. The CT metric is widely used in the literature as an indicator for contextualizing ozone exposure levels relative to reported inactivation ranges, rather than as a direct measure of biological efficacy [26], [29], [30]. Based on the simulated scenarios, the following trends were observed:

- At 25 mg·m^{-3}, CT values ranged from 125 mg·min·m^{-3} (5 min) to 500 mg·min·m^{-3} (20 min).
- At 50 mg·m^{-3}, CT values reached approximately 1000 mg·min·m^{-3} under the 20 min exposure scenario.
- At higher concentrations (80–100 mg·m^{-3}), CT values exceeded 1600 mg·min·m^{-3} for extended exposure durations.

These CT ranges are comparable to values reported in previous experimental and review studies investigating ozone-based treatment under controlled conditions [25], [30]. In the present work, CT is employed strictly as a relative exposure indicator to compare operational scenarios, acknowledging that actual inactivation outcomes depend on pathogen characteristics, humidity, surface interactions, and other environmental factors [42].

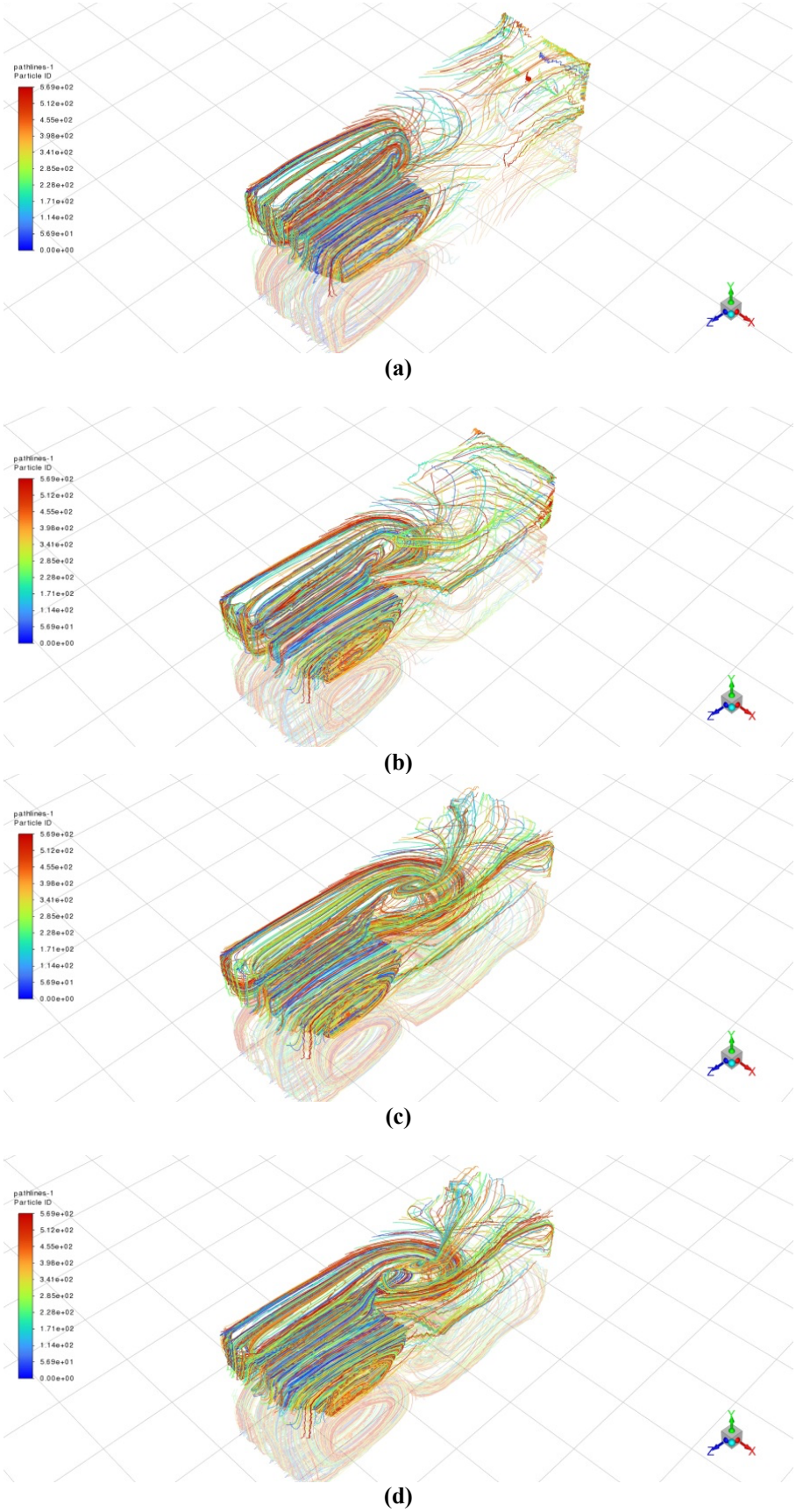


Fig. 4. Simulated ozone concentration distribution under short-duration exposure (5 min)

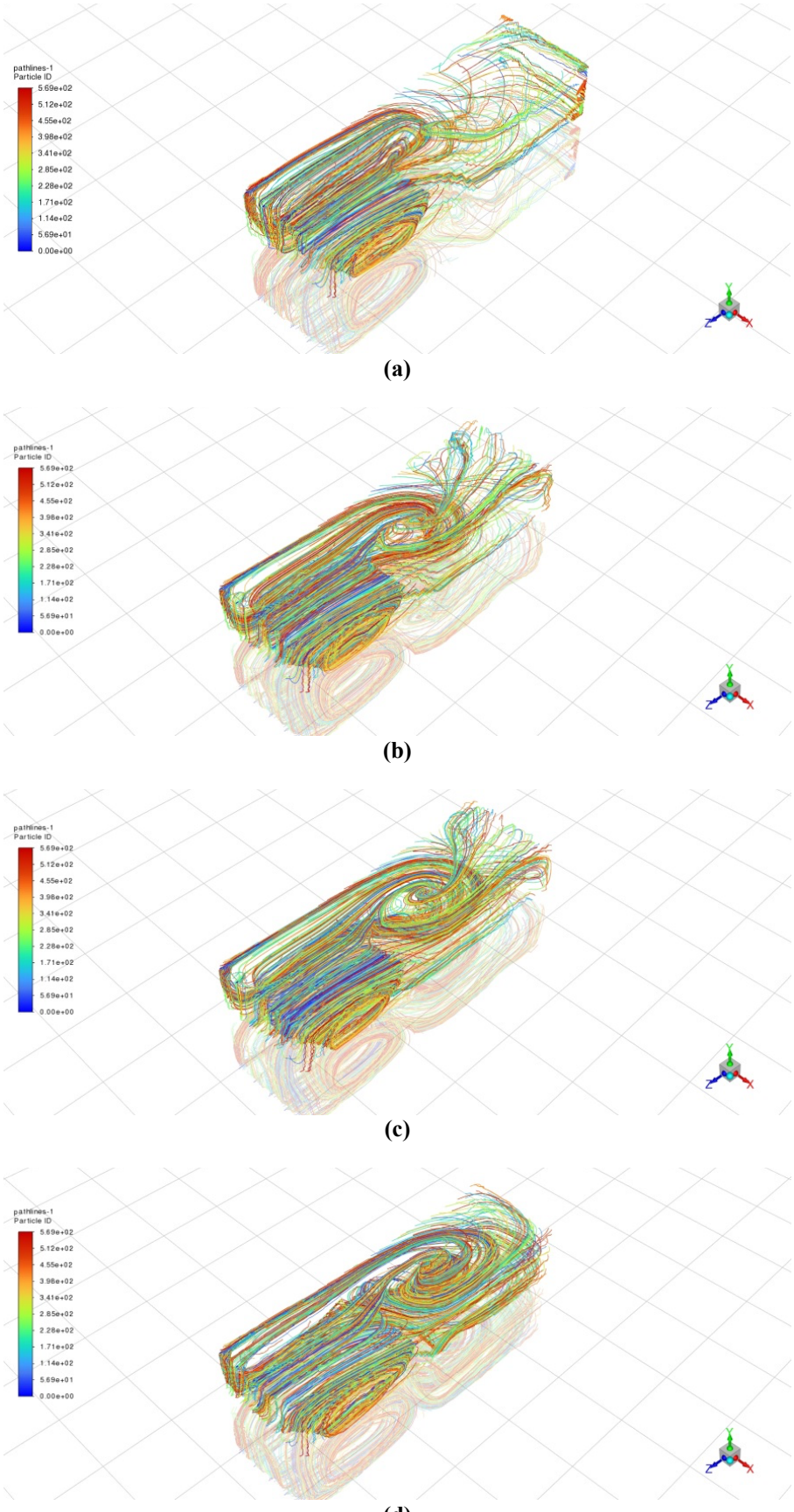


Fig. 5. Simulated ozone concentration distribution under medium-duration exposure (10 min)

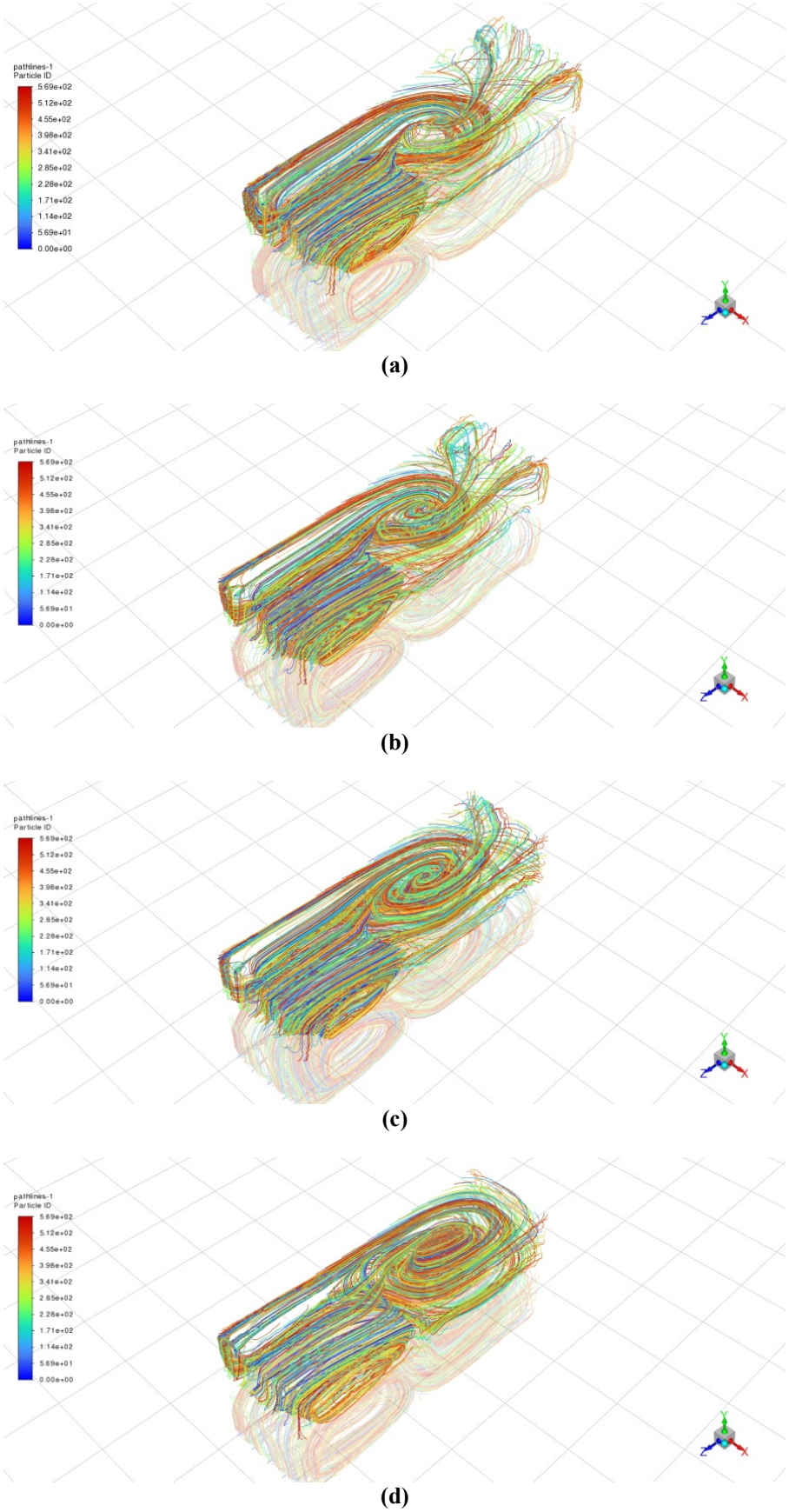


Fig. 6. Simulated ozone concentration distribution under long-duration exposure (20 min)

3.3. Influence of Relative Humidity and Airflow Structure

Relative humidity (RH) is known to influence ozone decay behavior and oxidative pathways, and its impact was considered here through literature-supported interpretation. Reported studies indicate that increasing RH from approximately 40 % to 80 % can enhance ozone persistence and radical-mediated oxidation processes [36], [37]. Accordingly, the simulated dispersion results were interpreted within this commonly recommended indoor operating range.

CFD velocity field visualization revealed that recirculation zones near the stage-facing region initially concentrated ozone plumes during early injection stages. As exposure time increased, these gradients were progressively reduced through large-scale mixing, highlighting the importance of inlet placement and airflow configuration in minimizing stagnant zones. Similar observations have been reported in prior CFD studies addressing ozone dispersion in complex indoor geometries [28], [32].

3.4. Ventilation Phase and Safety-Oriented Interpretation

Following each simulated ozonation scenario, a ventilation phase was conceptually included to represent post-treatment air exchange prior to potential re-occupancy. Although direct decay measurements were not performed, the ventilation strategy was evaluated relative to widely cited occupational exposure limits for ozone (0.1 ppm ≈ 0.2 mg·m^{-3}) [13]. The CFD framework enables estimation of residual concentration trends and identification of regions where ventilation effectiveness is critical. From an engineering perspective, this highlights the necessity of adequate exhaust placement and sufficient ventilation duration to ensure safe re-entry conditions, particularly in large-volume spaces where air exchange may be non-uniform [38].

3.5. Engineering Implications for Large Indoor Spaces

From an application-oriented standpoint, the results demonstrate that exposure duration has a stronger influence on spatial uniformity than concentration magnitude alone. Moderate ozone concentrations combined with sufficient residence time were found to be more effective for achieving uniform volumetric coverage than short-duration, high-concentration injections.

These findings provide design-level insight for preliminary evaluation of ozone-based treatment in large indoor environments. Rather than optimizing real-time control strategies, the present CFD-based assessment supports scenario comparison, identification of limiting conditions, and estimation of feasible operating windows prior to experimental implementation. From a comparative engineering perspective, the simulations indicate that extending exposure duration from 5 min to 10 min produces a substantially greater improvement in spatial coverage than increasing ozone concentration alone, supporting exposure duration as the dominant operational parameter for design-stage evaluation.

Although the transient concentration fields provide a comparative representation of spatial ozone dispersion, concentration variance could not be retrospectively quantified because the complete cell-level concentration dataset required for statistical post-processing was not available. Therefore, the present assessment relies on comparative spatial-distribution patterns and CT-based exposure indicators rather than variance-based validation. Future validation studies will calculate the volume-weighted concentration variance and coefficient of variation at successive physical times and compare these metrics with spatially distributed experimental measurements. The incorporation of ozone surface deposition and chemical reaction kinetics into the CFD model represents a further refinement for applications requiring prediction of absolute airborne ozone concentrations under specific environmental conditions.

4. Conclusions

This study has examined ozone-based disinfection in a large-volume indoor theatre (1800 m^3) as a parameter-selection problem, addressed through an application-oriented CFD assessment rather than through physical deployment of a validated treatment system. The underlying premise is that, before any disinfection system can be sensibly specified, the principal operating parameters—concentration,

exposure duration, and the resulting spatial coverage and ventilation requirements—need to be understood well enough to identify a feasible and defensible operating window. The simulations reported here were designed to provide exactly that understanding for a high-ceiling, geometrically complex enclosure of the type that has received little prior attention in the literature. Twelve scenarios were evaluated, combining four ozone concentrations (25, 50, 80, and 100 $mg \cdot m^{-3}$) with three exposure durations (5, 10, and 20 minutes), and the resulting concentration fields were compared in terms of spatial uniformity. Across this parameter space, exposure duration emerged as the dominant control variable: raising the concentration alone, without allowing sufficient dwell time, was not enough to overcome the spatial heterogeneity introduced by the theatre's airflow structure. Once exposure duration reached 10 minutes, however, near-complete volumetric coverage was obtained at concentrations of approximately 50 $mg \cdot m^{-3}$ and above, identifying this combination as an efficient operating setpoint that avoids the cost and safety penalties associated with unnecessarily high concentrations. Extending exposure further, to 20 minutes, removed most of the remaining low-concentration pockets, confirming that duration continues to compensate for residual non-uniformity even after the bulk of the volume has already been reached. The CT values computed from these simulations were used strictly as a comparative, control-relevant indicator for ranking operating scenarios against ranges reported elsewhere in the literature, rather than as a direct prediction of biological inactivation. This distinction is deliberate: actual disinfection outcomes depend on factors—pathogen-specific susceptibility, ambient humidity, surface interactions—that lie outside the scope of a purely fluid-dynamic simulation and would need to be established through dedicated experimental work. Within its intended role, however, the CT metric proved useful for distinguishing scenarios that merely achieve numerical exposure targets from those that achieve them with genuine spatial consistency. Post-treatment ventilation was incorporated as a safety-oriented constraint on the overall operating sequence rather than as an incidental detail. Because ozonation is only permissible in unoccupied spaces, any feasible operating strategy must also specify how residual concentrations are brought back below the commonly cited occupational exposure limit before re-entry is allowed. The CFD results indicate that exhaust placement and ventilation duration are not secondary considerations in this respect: in a volume as large and unevenly mixed as the one studied here, inadequate attention to either can leave localized pockets of elevated concentration well after the nominal treatment cycle has ended.

Taken together, these findings support the central argument of this work: that CFD-based scenario analysis can supply the kind of design-level, control-oriented insight—covering achievable spatial coverage, required exposure duration, and ventilation adequacy—that is needed to assess the feasibility of ozone-based treatment in large indoor spaces such as theatres before committing to a physical implementation. The framework presented here is offered as a preliminary feasibility and parameter-selection tool, intended to narrow the design space and inform subsequent system specification; it does not, and is not intended to, substitute for the experimental validation and biological efficacy testing that any deployed system would ultimately require. Extending this framework toward transient and humidity-coupled simulations, and eventually toward sensor-informed adjustment of operating parameters during treatment, represents a natural direction for future work building on the feedforward analysis carried out in the present study. Overall, the proposed framework is intended to serve as a practical engineering tool for preliminary system design and parameter selection, while providing a foundation for future experimental validation and advanced control-system development. Quantitative metrics such as volume-weighted concentration variance and coefficient of variation were not included in the present study because its primary objective was the comparative evaluation of transient operating scenarios rather than comprehensive statistical characterization of spatial dispersion. Accordingly, the reported results should be interpreted as comparative engineering assessments based on transient concentration fields and CT-based exposure indicators.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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